

IT308 - Tópicos em Técnicas de Alta Tensão II

Revisão:

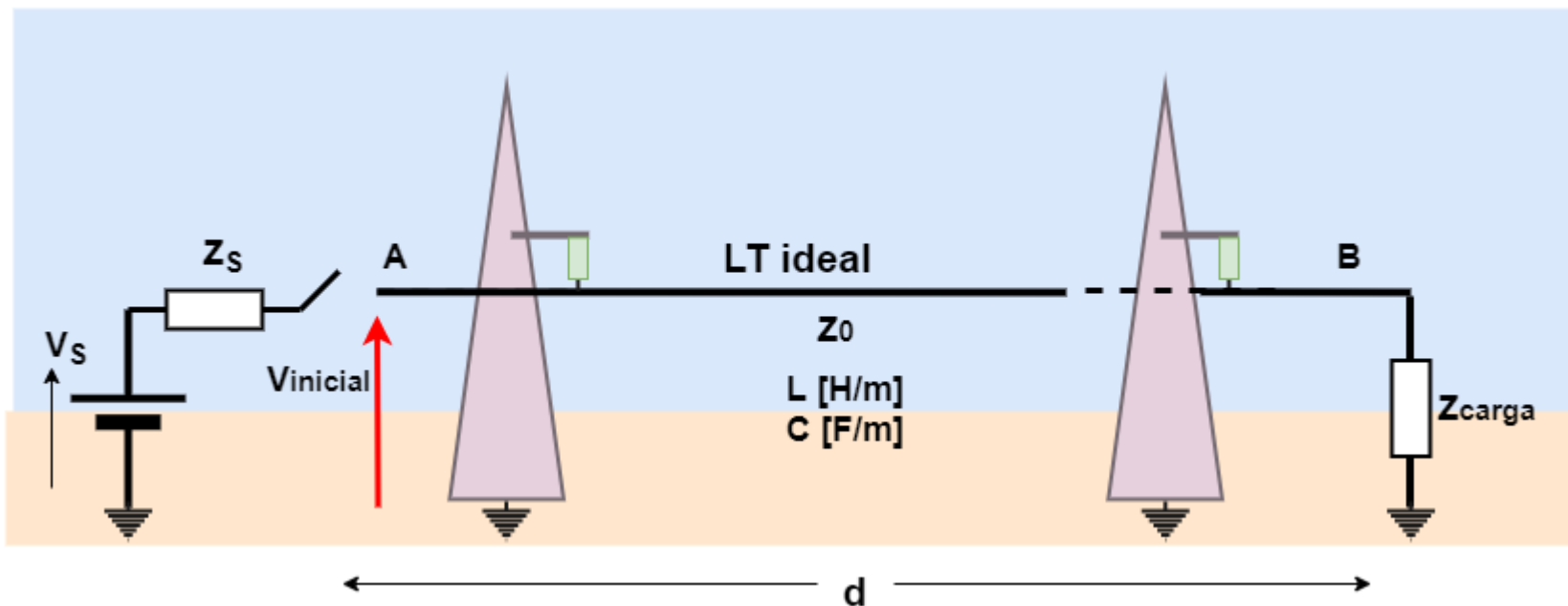
Transitórios em LTs, Modelagem de LTs,
Aterramento no Sistema Elétrico

Aula-06

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- Transitórios em linhas de transmissão
- Modelagem de LTs
- Aterramento no Sistema Elétrico
- Trabalho 2

Transitórios em LTs



$$V_{inicial} = \frac{Z_0}{Z_S + Z_0} V_S$$

Tensão de energização da LT

$$Z_0 = \sqrt{\frac{L}{C}}$$

Impedância característica

$$v = \sqrt{\frac{1}{LC}}$$

Velocidade de propagação

$$\tau = \frac{d}{v} = d\sqrt{LC}$$

Tempo de propagação

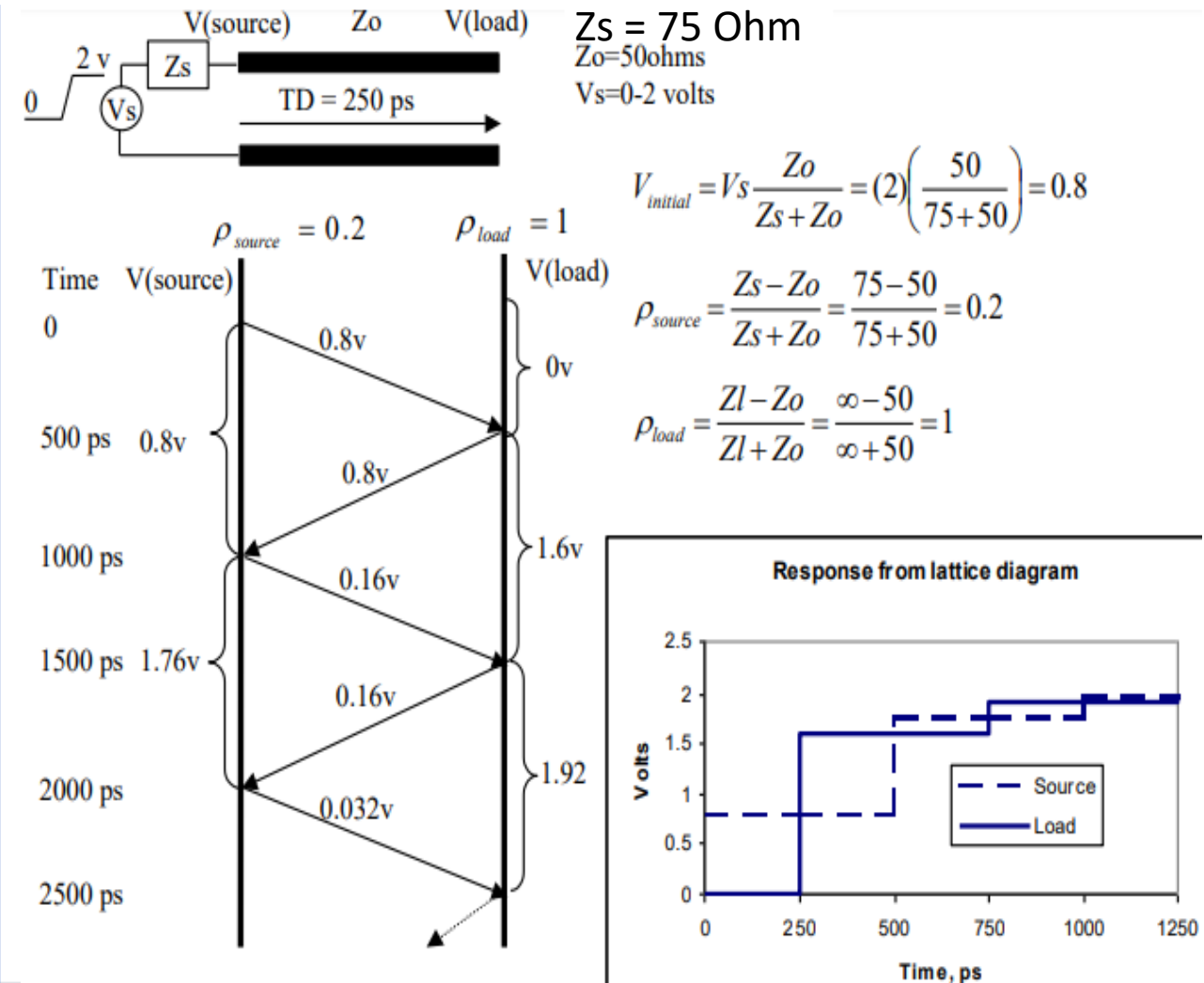
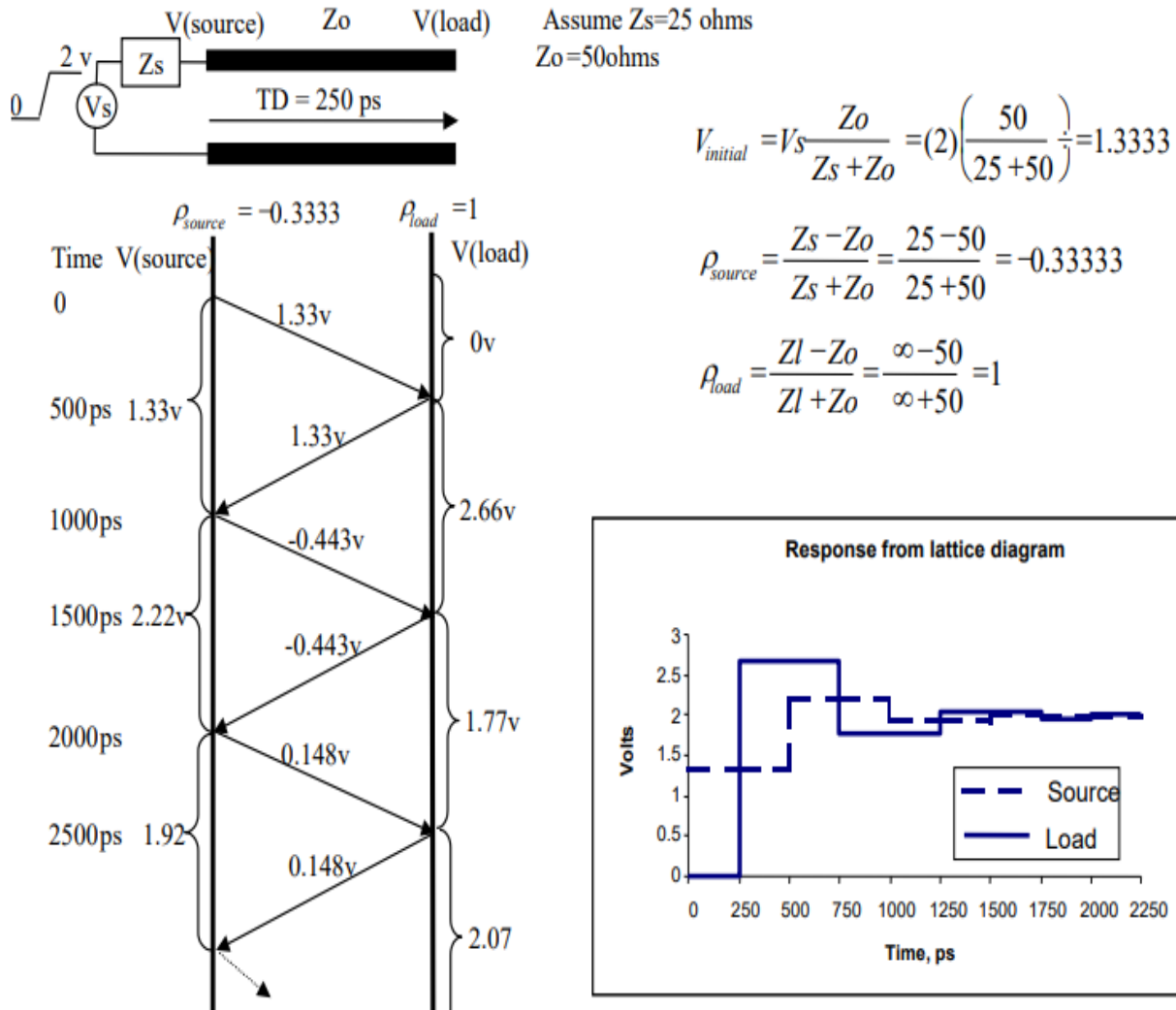
$$\rho_{source} = \frac{Z_S - Z_0}{Z_S + Z_0}$$

Coef. De reflexão (carga/LT)

$$\rho_{carga} = \frac{Z_{carga} - Z_0}{Z_{carga} + Z_0}$$

Coef. De reflexão (fonte/LT)

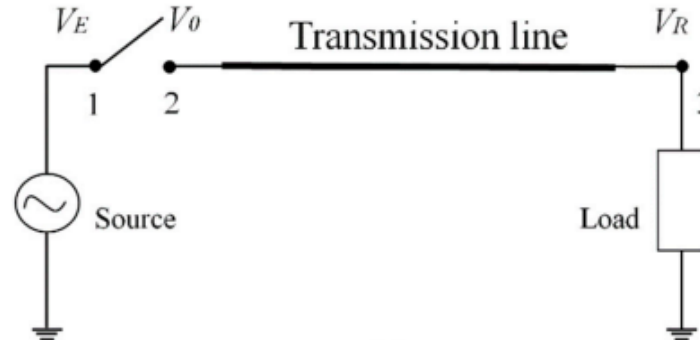
Exemplos Numéricos



Modelagem de LTs

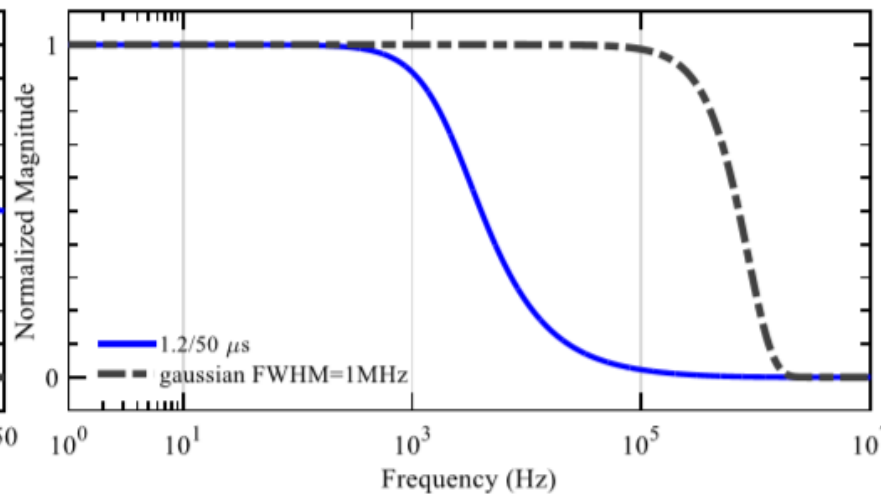
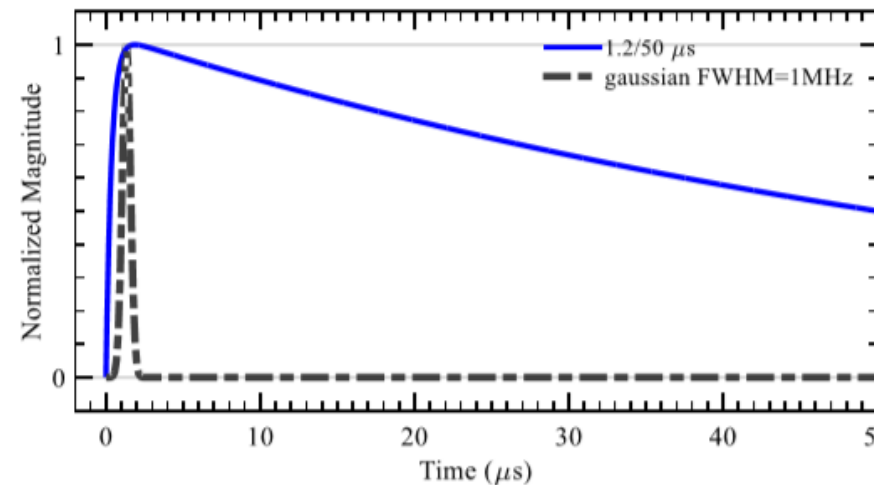
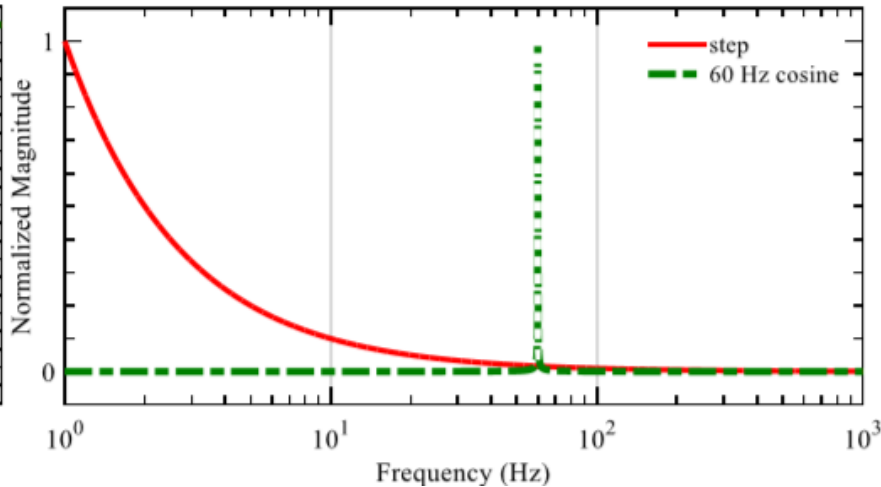
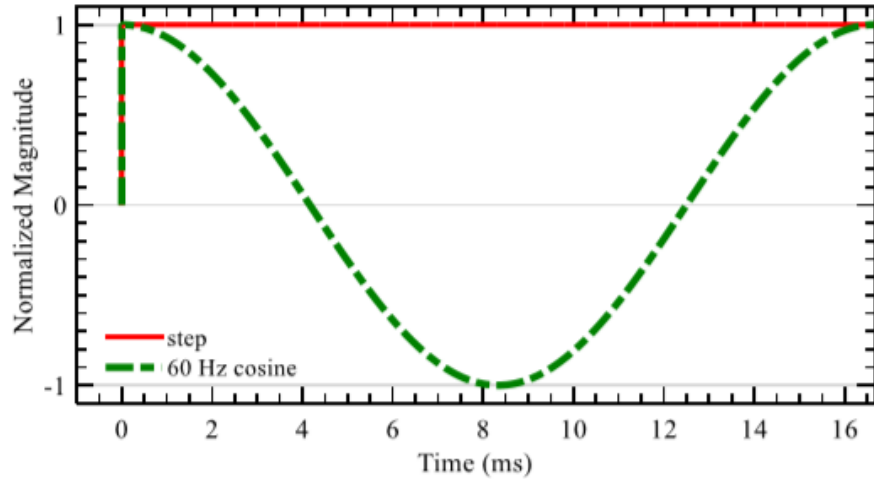
- Tabela Cigré¹

Origin	frequency range
Transformer energization ferroresonance	(DC) 0.1 Hz - 1 kHz
Load rejection	0.1 Hz - 3 kHz
Fault clearing	50/60 Hz - 3 kHz
Fault initiation	50/60 Hz - 20 kHz
Line energization	50/60 Hz - 20 kHz
Line reclosing	(DC) 50/60 Hz - 20 kHz
Transient recovery voltage	50/60 Hz - 20 kHz
Terminal faults	50/60 Hz - 20 kHz
Short line faults	50/60 Hz - 100 kHz
Multiple restrikes of circuit breaker	10 kHz - 1 MHz
Lightning surges, faults in substations	10 kHz - 3 MHz
Disconnecter switching (single restrike) and faults in GIS	100 kHz - 50 MHz



1-Adaptado de: Cigré 39. (1990). GUIDELINES FOR REPRESENTATION OF NETWORK ELEMENTS WHEN CALCULATING TRANSIENTS.

Espectro de frequência dos fenômenos que originam os TEMs¹



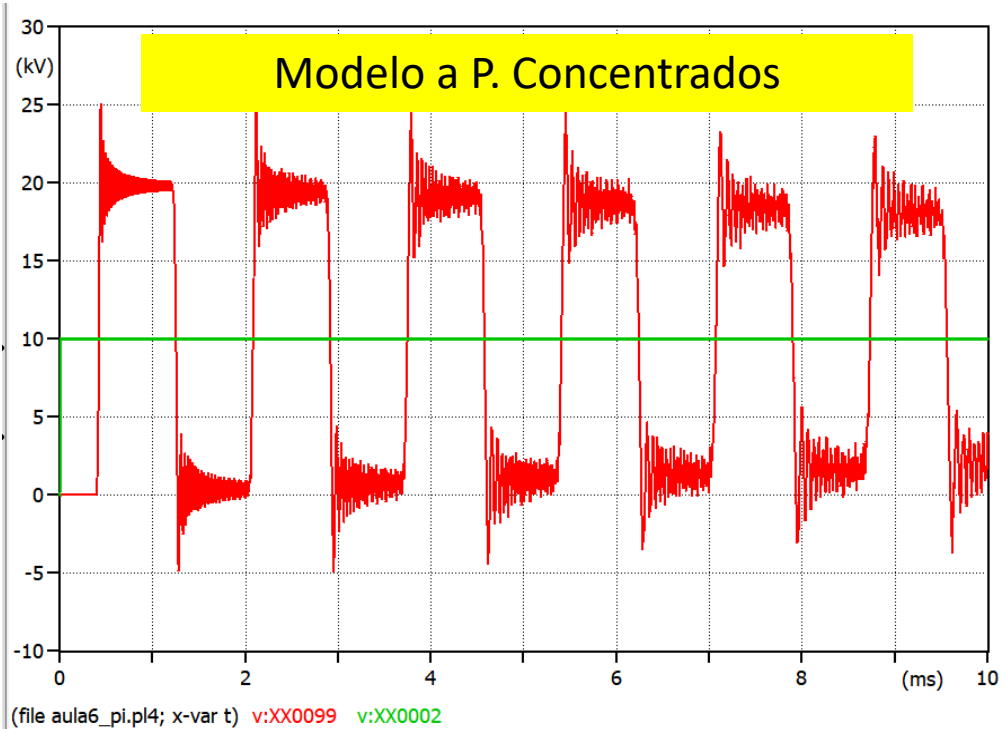
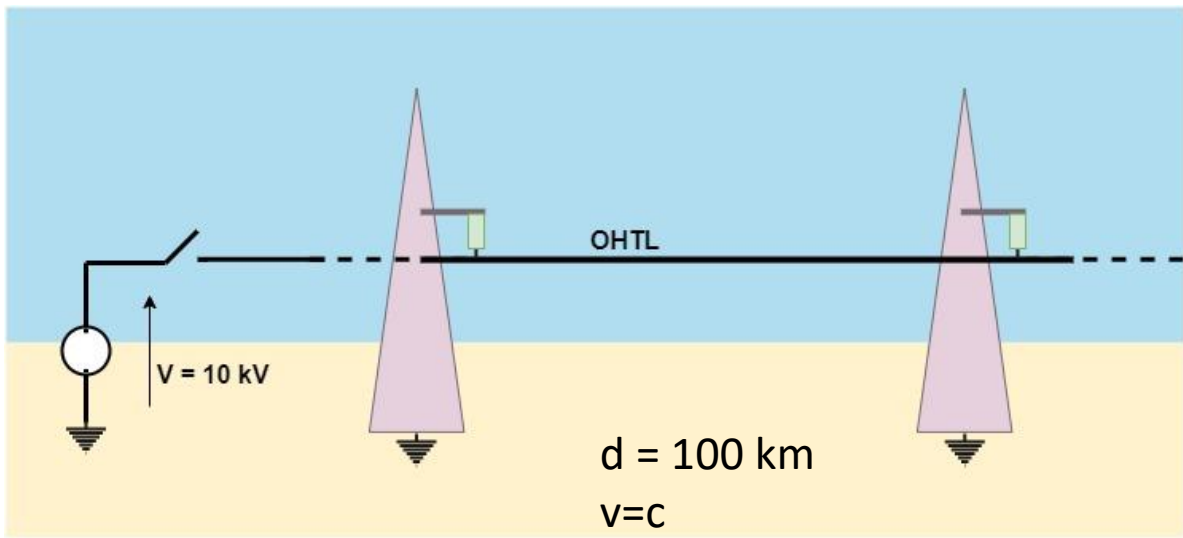
Sinal no domínio do tempo



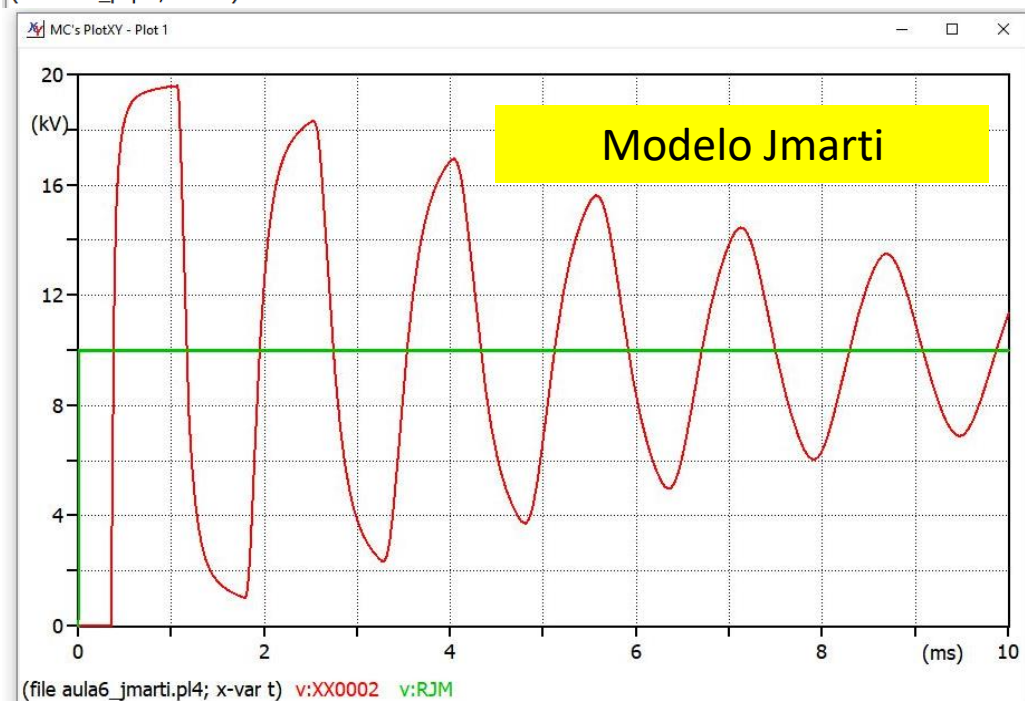
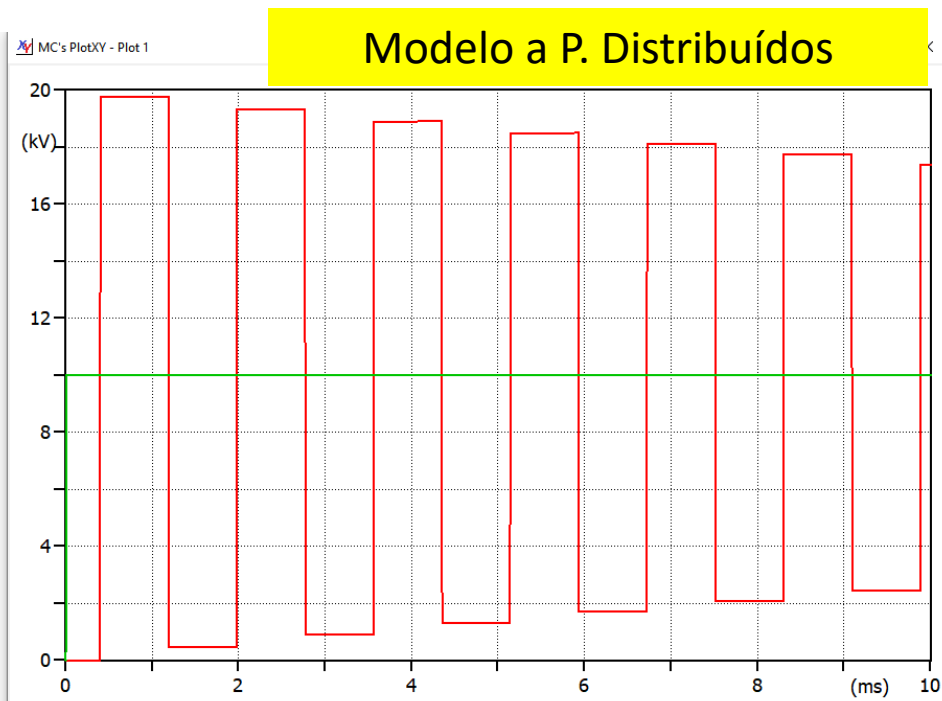
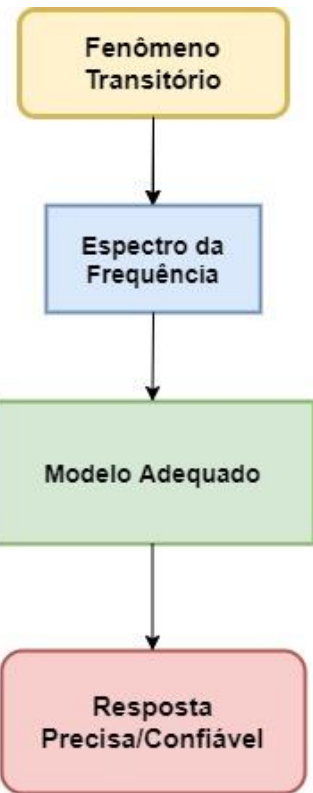
Aplicação da Transformada de Laplace.

Sinal no domínio da Frequência

1-Adaptado de: Caballero, P. T. (2018). INCLUSÃO DO EFEITO DA FREQUÊNCIA NO MODELO DE BERGERON: REPRESENTAÇÃO DE LINHAS DE TRANSMISSÃO CURTAS E LONGAS CONSIDERANDO TRANSITÓRIOS ELETROMAGNÉTICOS RESULTANTES DE OPERAÇÕES DE MANOBRAS E DE DESCARGAS ATMOSFÉRICAS. UNESP-Ilha Solteira (Tese).



(file aula6_pi.pl4; x-var t) v:XX0099 v:XX0002



(file aula6_jmarti.pl4; x-var t) v:XX0002 v:RJM

Aterramento Elétrico

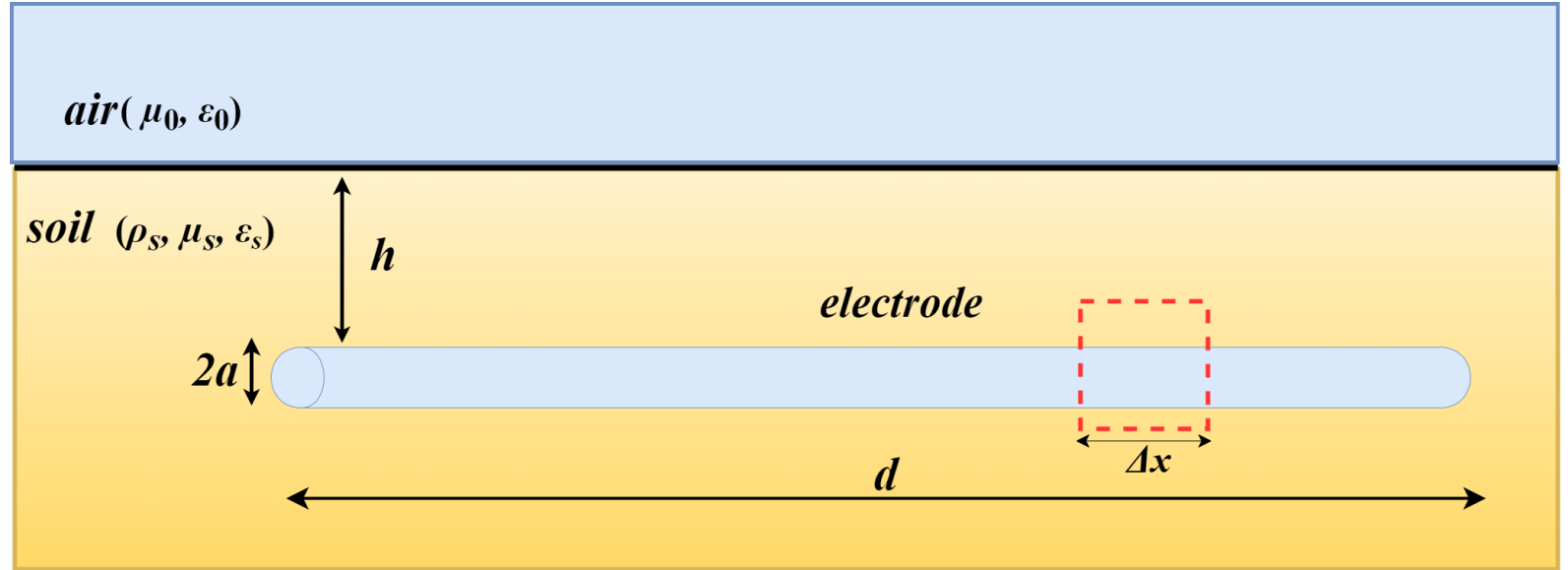
No modelo a parâmetros distribuídos, um segmento Δx pode ser representado pelo circuito elétrico infinitesimal.

Nesse circuito, verifica-se duas correntes: uma parcela longitudinal (I_L) e outra transversal (I_T);

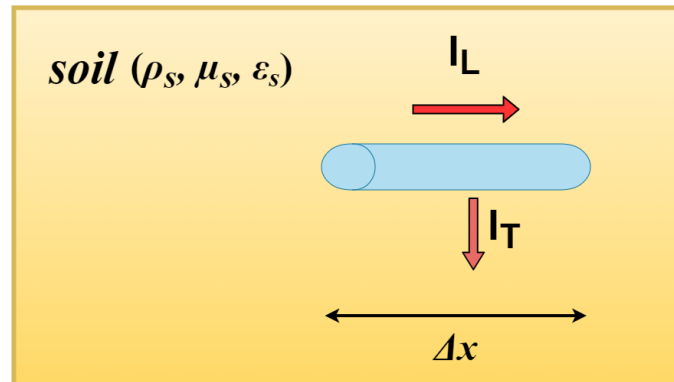
Os parâmetros r e L são a resistência e indutância longitudinais do eletrodo;

Os parâmetros R e C são a resistência de dispersão (ou aterramento) e a capacitância transversais do eletrodo.

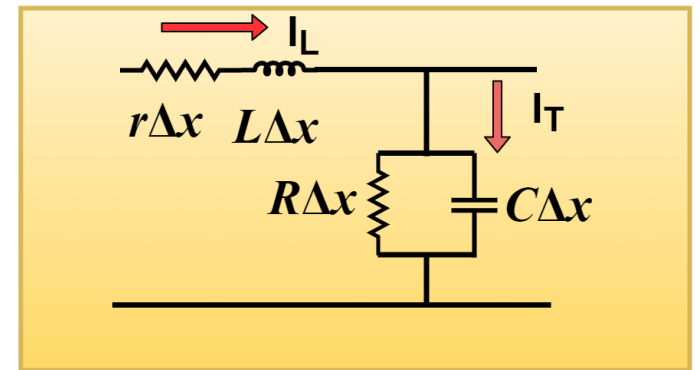
Observação: No modelo clássico de linhas de transmissão, o termo $R = 1/G$; Em linhas aéreas, $G \approx 0$. Entretanto para eletrodos, tem-se que $r \approx 0$.



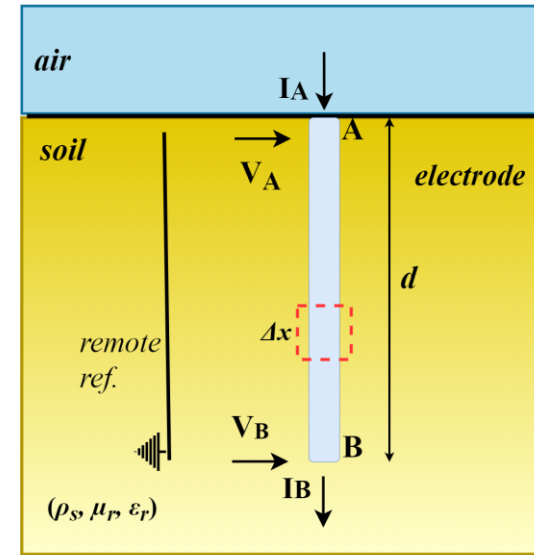
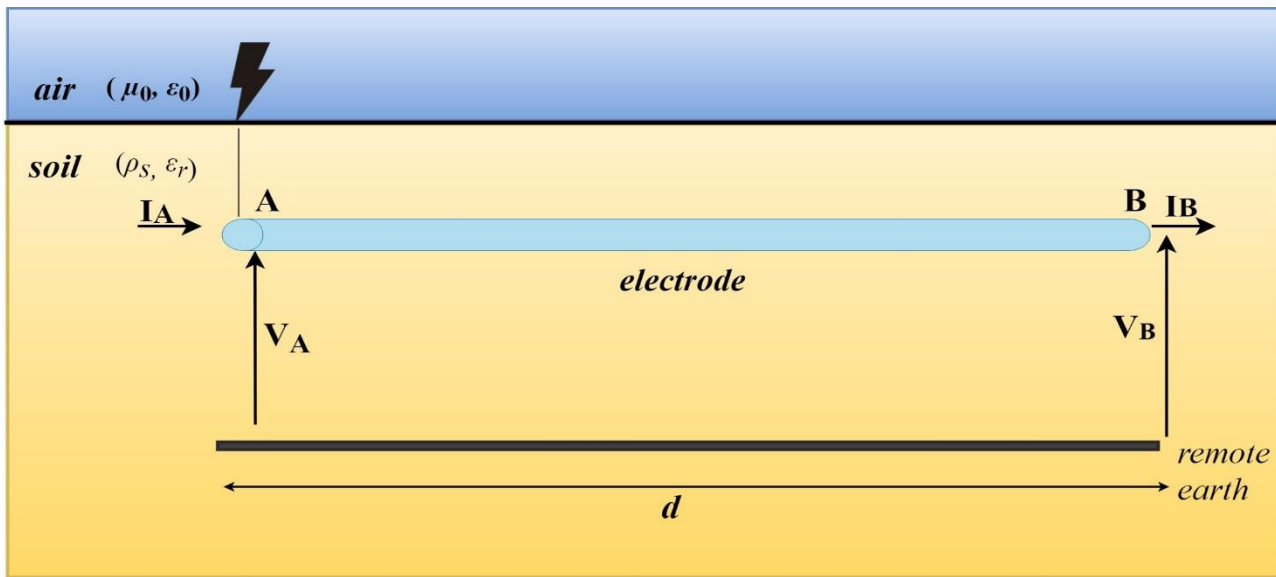
(a)



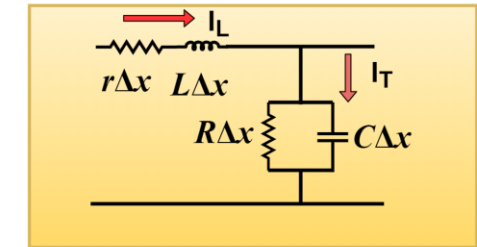
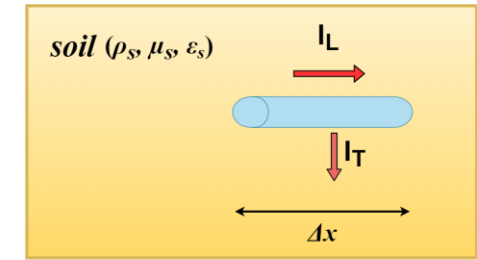
(b)



(c)



(a)



(c)

Transmission Line Equations

$$\gamma = \sqrt{(r' + j\omega L')(1/R' + j\omega C')}$$

$$V_A(x) = V_B(x) \cosh(\gamma d) - Z_C I_B(x) \sinh(\gamma d)$$

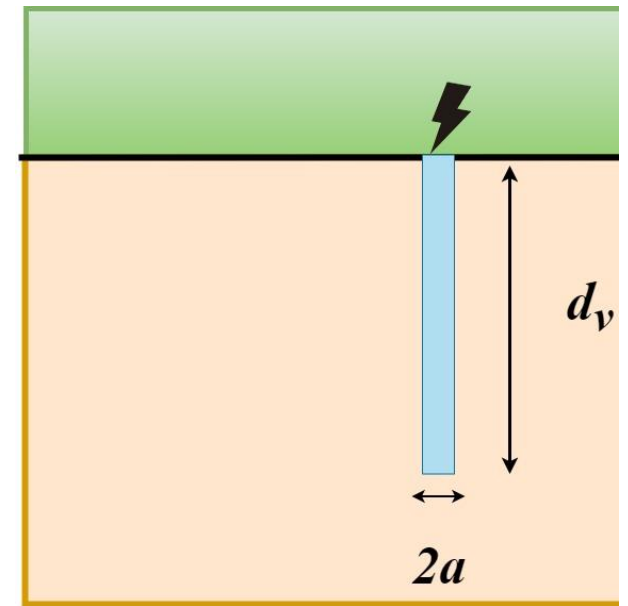
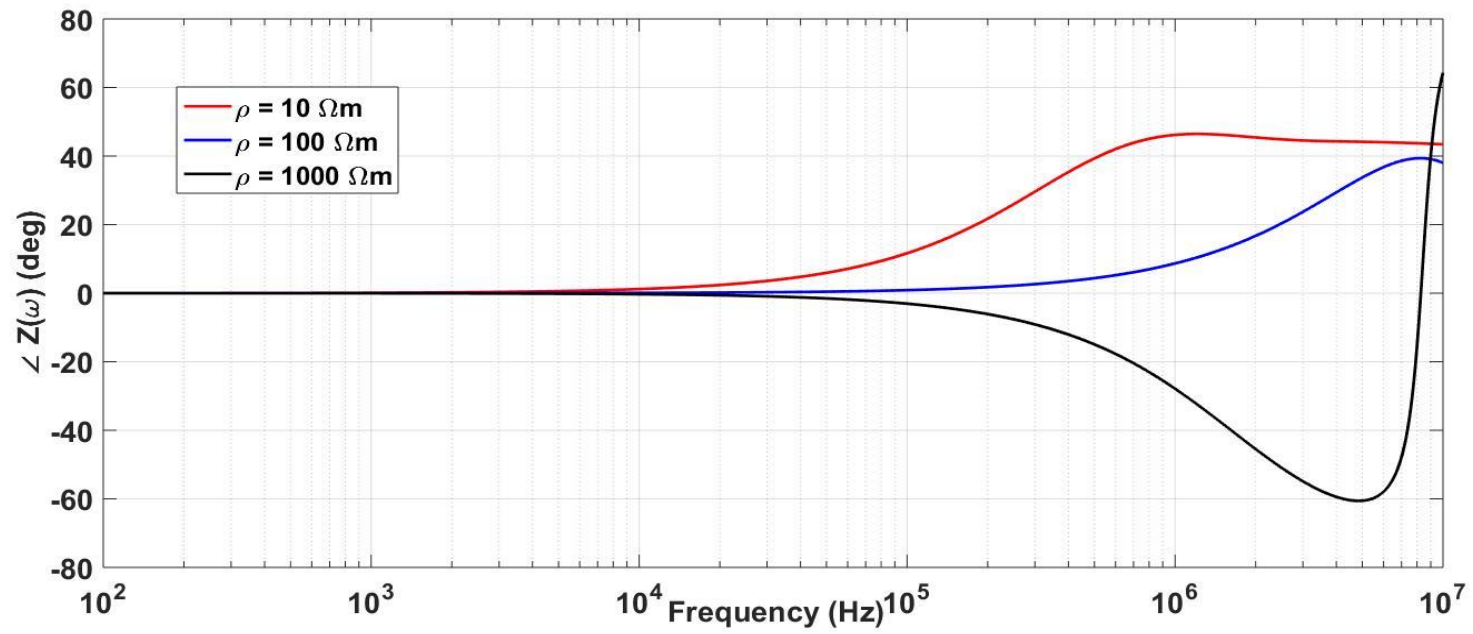
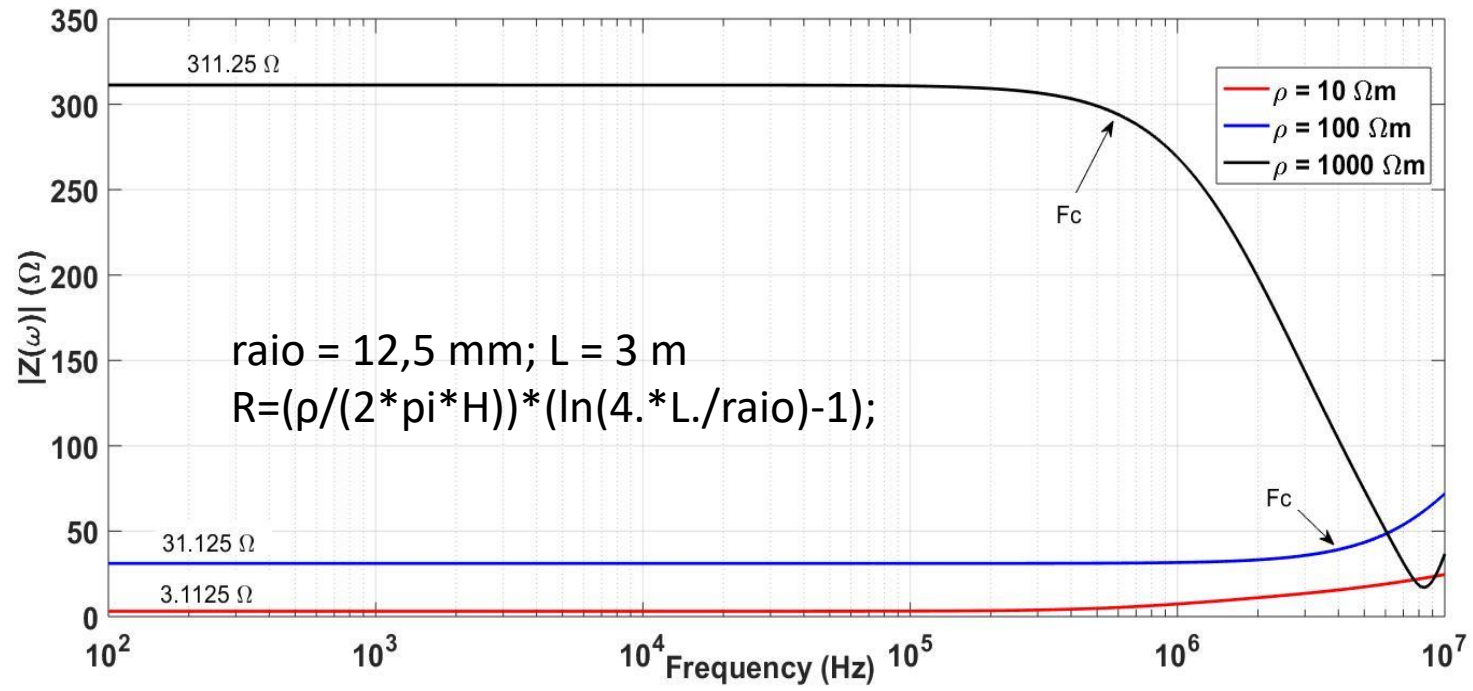
$$Z_C = \sqrt{\frac{r' + j\omega L'}{1/R' + j\omega C'}}$$

$$I_A(x) = \frac{1}{Z_C} V_B(x) \sinh(\gamma d) + I_B(x) \cosh(\gamma d)$$

$$Z_{gr}(\omega) = \frac{V_A}{I_A} = Z_C \coth(\gamma(\omega)d)$$

1 Adaptado de: "A Simplified Method for Calculating the Impedance of Vertical Grounding Electrodes Buried in a Horizontally Stratified Multilayer Ground", Caetano et al.

Impedância eletrodo vertical



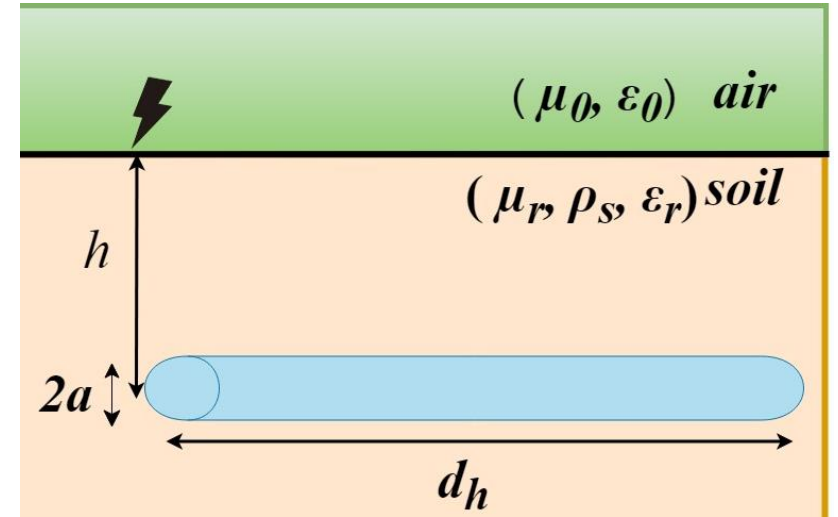
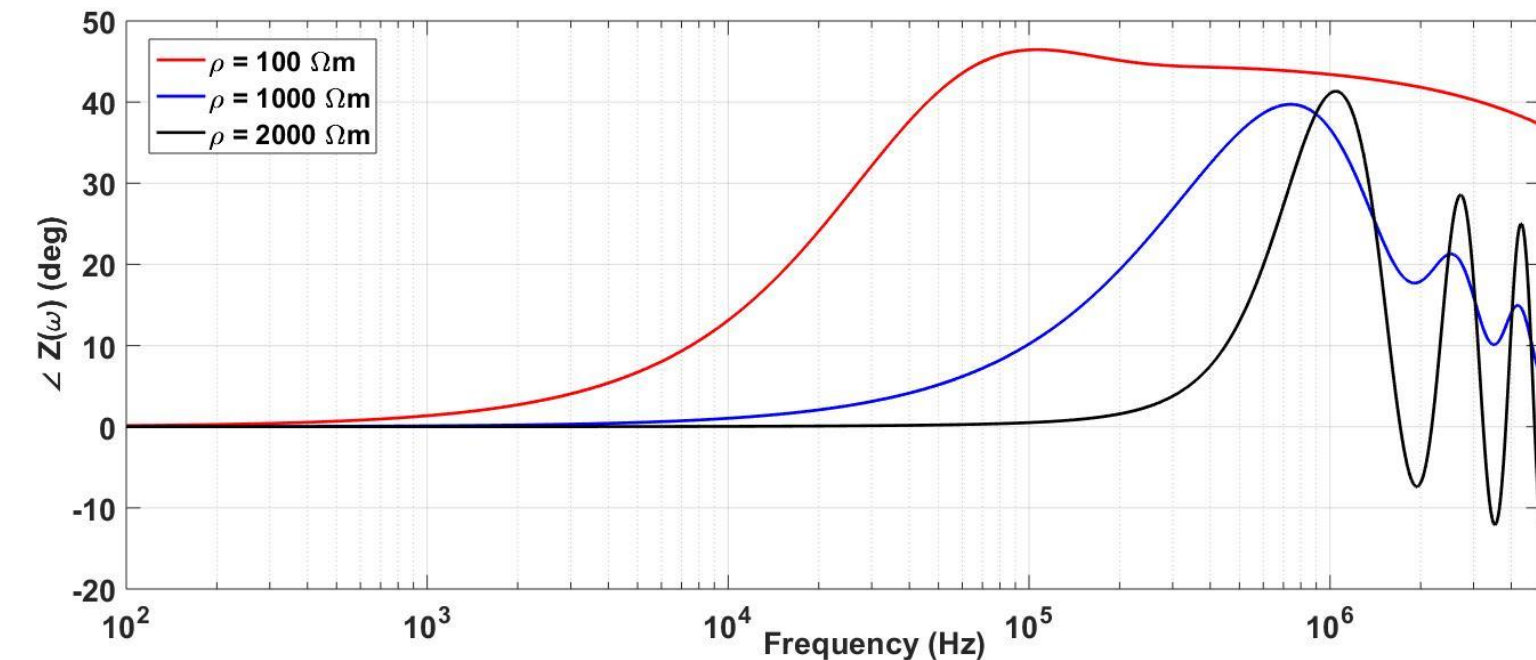
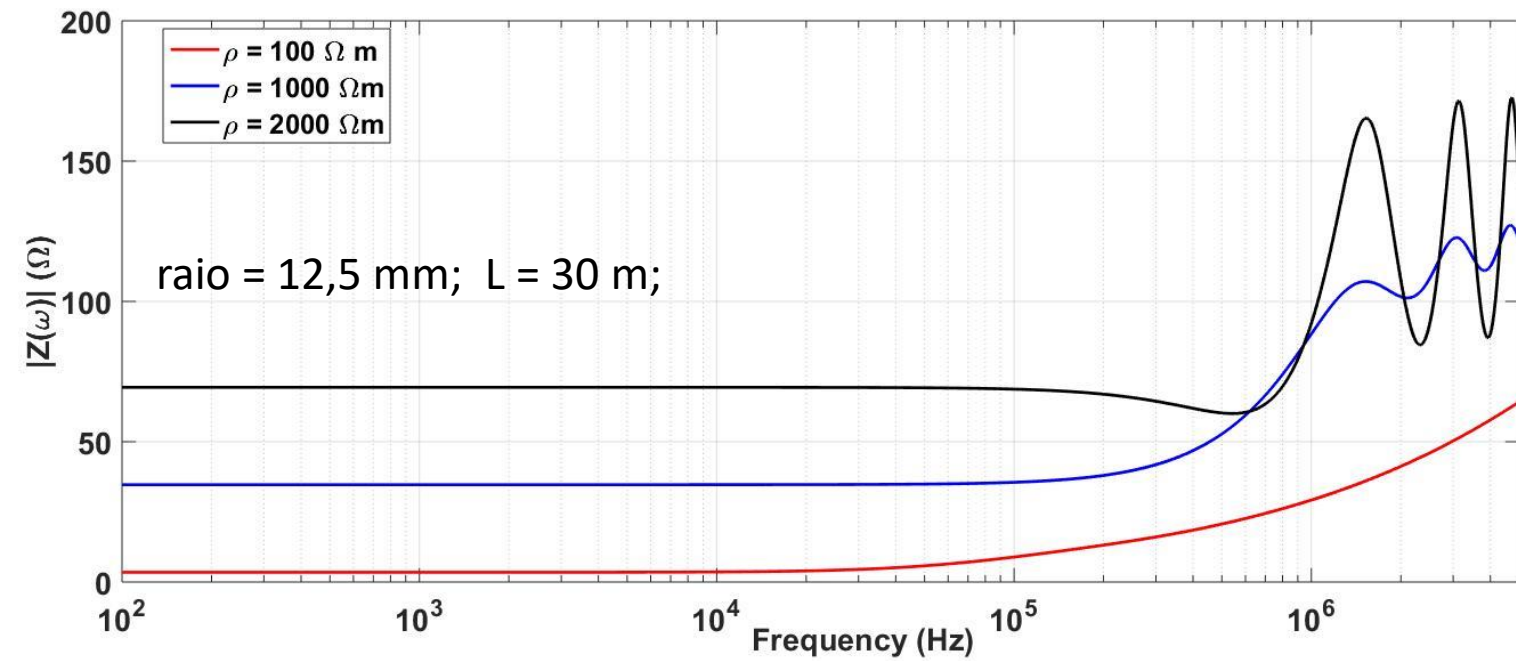
$$r_v = \frac{\rho_c}{\pi a^2}$$

$$L_v = \frac{\mu}{2\pi} \left[\ln \left(\frac{2d}{a} \right) - 1 \right]$$

$$C_v = \pi \epsilon_0 \epsilon_r(f) \left[\ln \left(\frac{4d}{a} \right) - 1 \right]^{-1}$$

$$G_v = R_v^{-1} = \frac{1}{\epsilon_0 \epsilon_r(f) \rho(f)} C_v$$

Impedância eletrodo horizontal



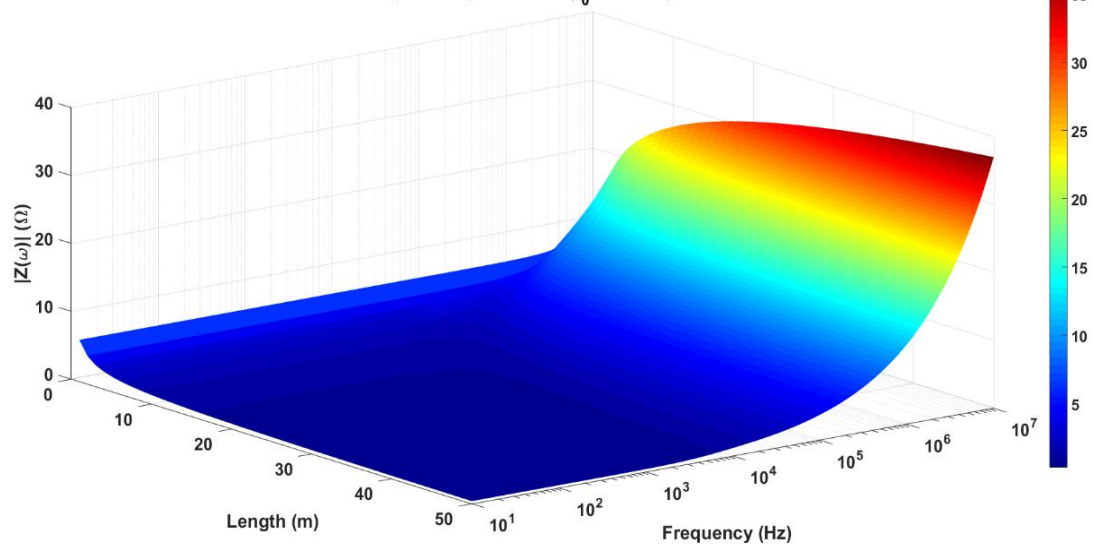
$$r_h = \frac{\rho_c}{\pi a^2}$$

$$L_h = \frac{\mu}{2\pi} \left[\ln \left(\frac{2d_h}{\sqrt{2ha}} \right) - 1 \right]$$

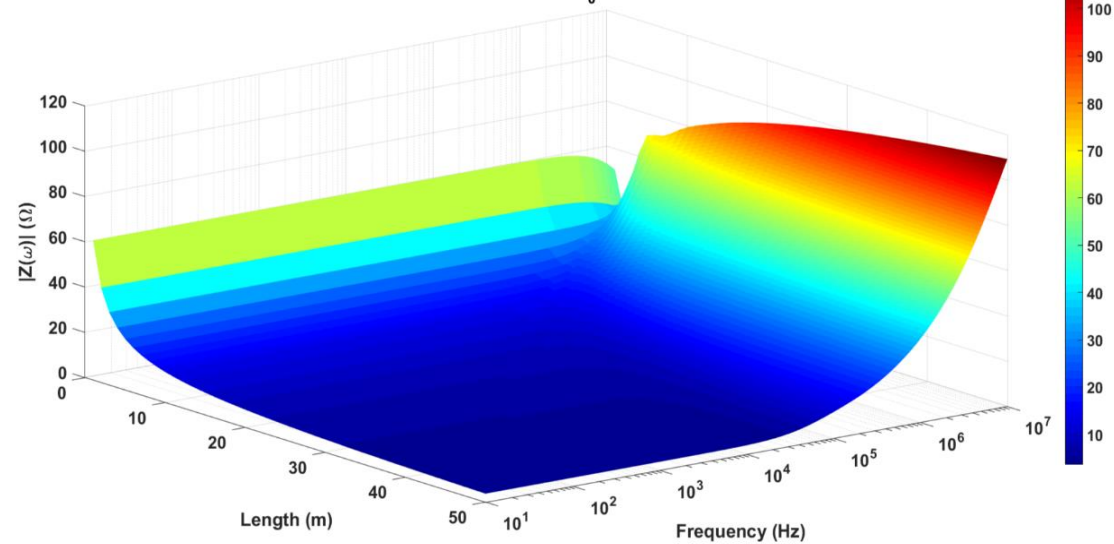
$$C_h = \pi \epsilon_0 \epsilon_r (f) \left[\ln \left(\frac{2d_h}{\sqrt{2ha}} \right) - 1 \right]^{-1}$$

$$G_h = R_h^{-1} = \frac{1}{\epsilon_0 \epsilon_r (f) \rho (f)} C_h$$

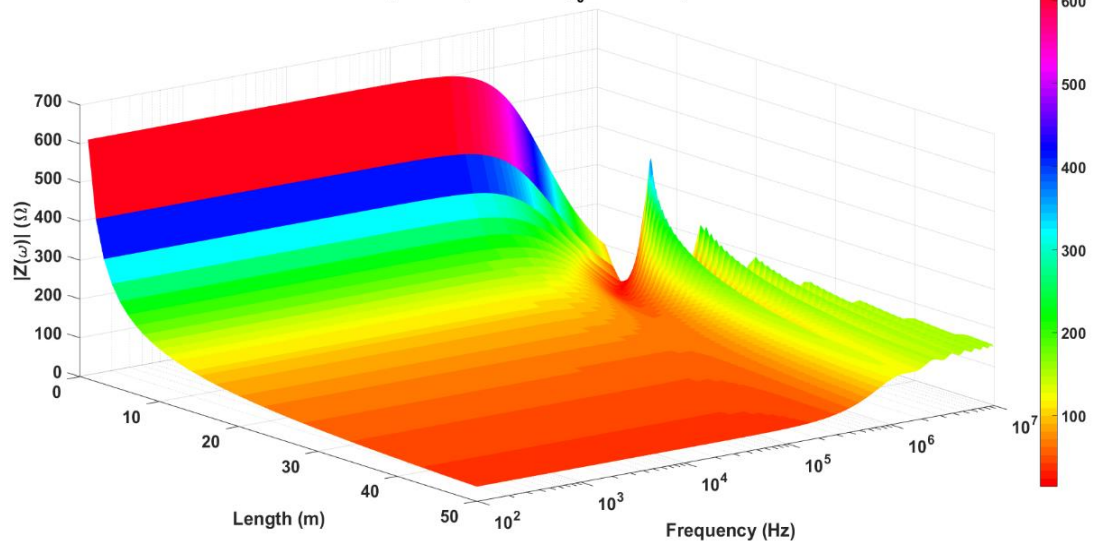
$|Z|$ with frequency-independent electrical parameters of soil
(constant parameters $\rho_0 = 10 \Omega\text{m}$)



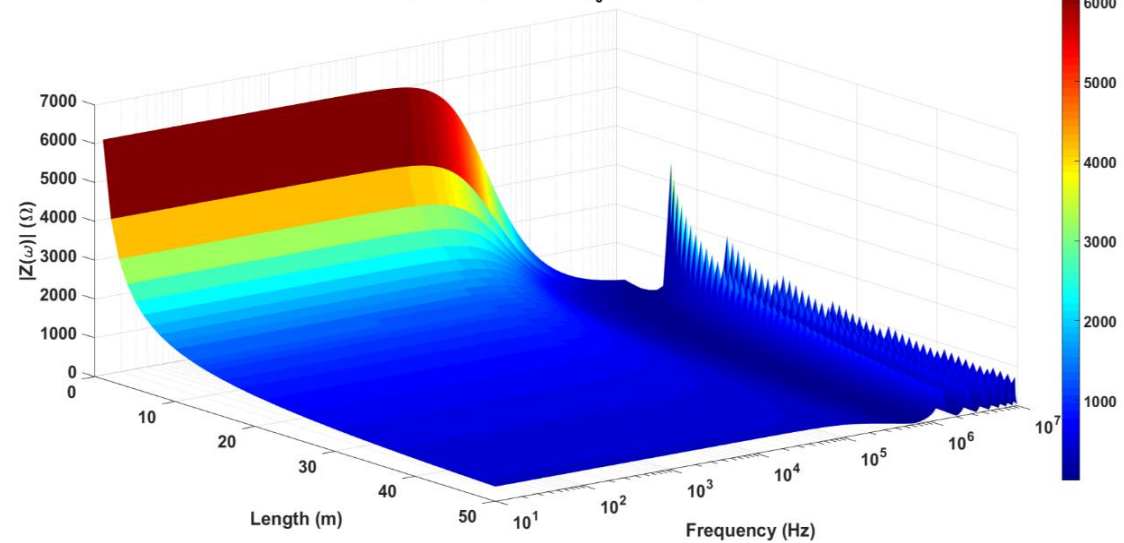
$|Z|$ with frequency-independent electrical parameters of soil
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$|Z|$ with frequency-independent electrical parameters of soil
(constant parameters $\rho_0 = 1000 \Omega\text{m}$)



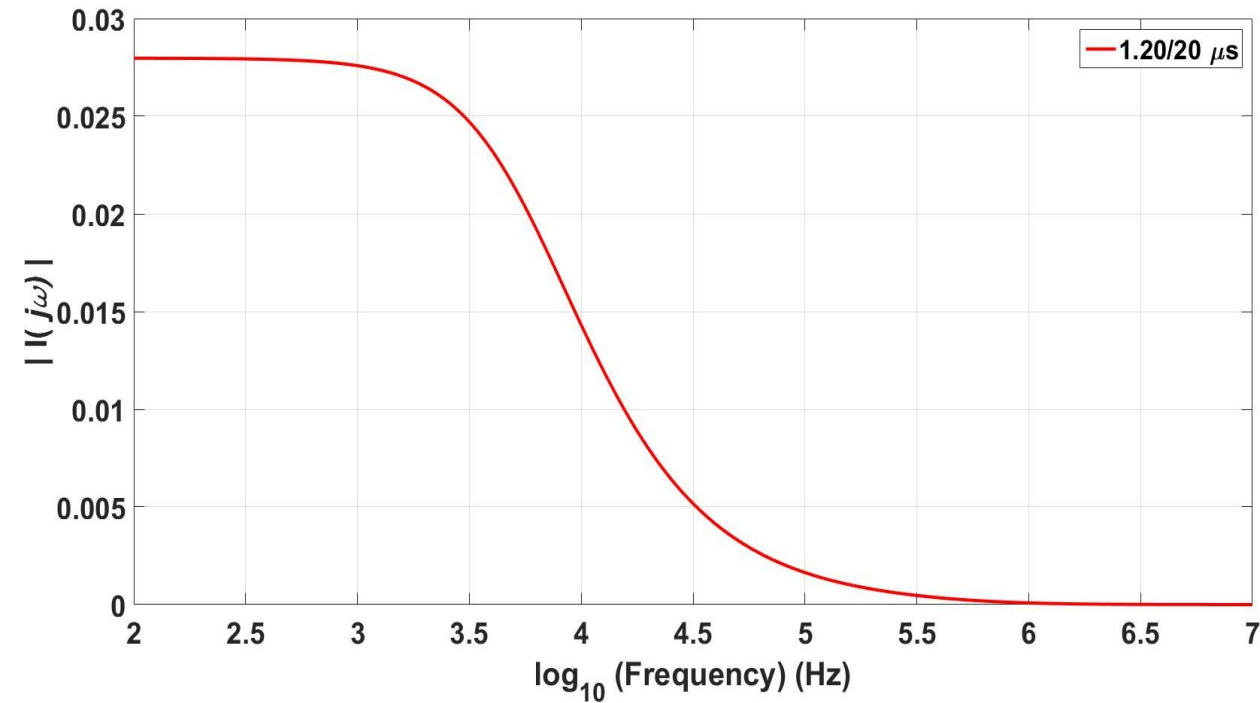
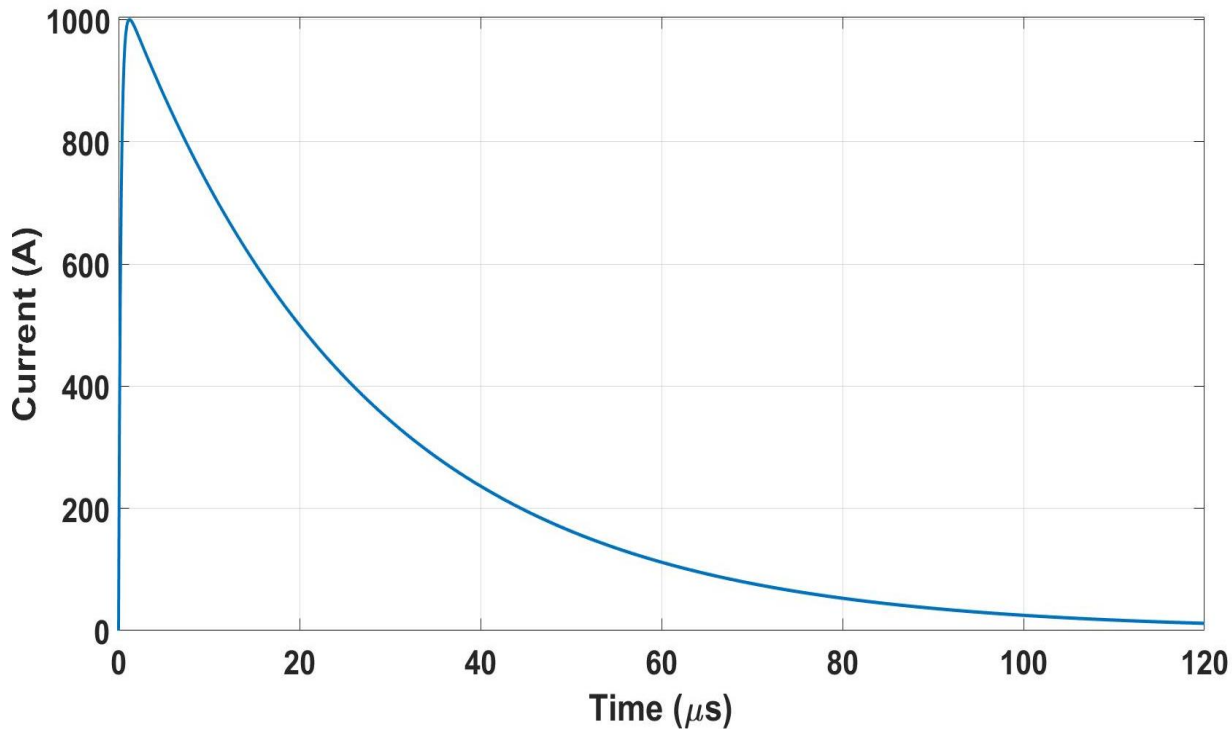
$|Z|$ with frequency-independent electrical parameters of soil
(constant parameters $\rho_0 = 10 \text{ k}\Omega\text{m}$)



Grounding Potencial Rise (GPR)

GPR é definido como o produto entre a impedância de aterramento e a corrente que flui pelo eletrodo.

(Uso da transformada inversa de Laplace)

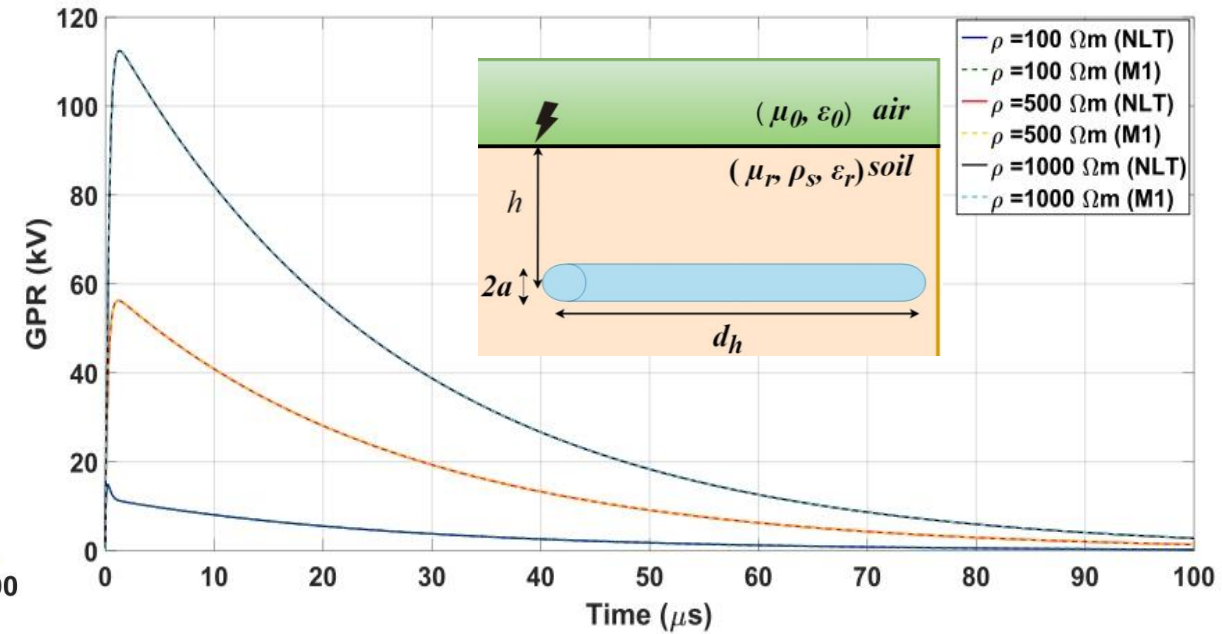
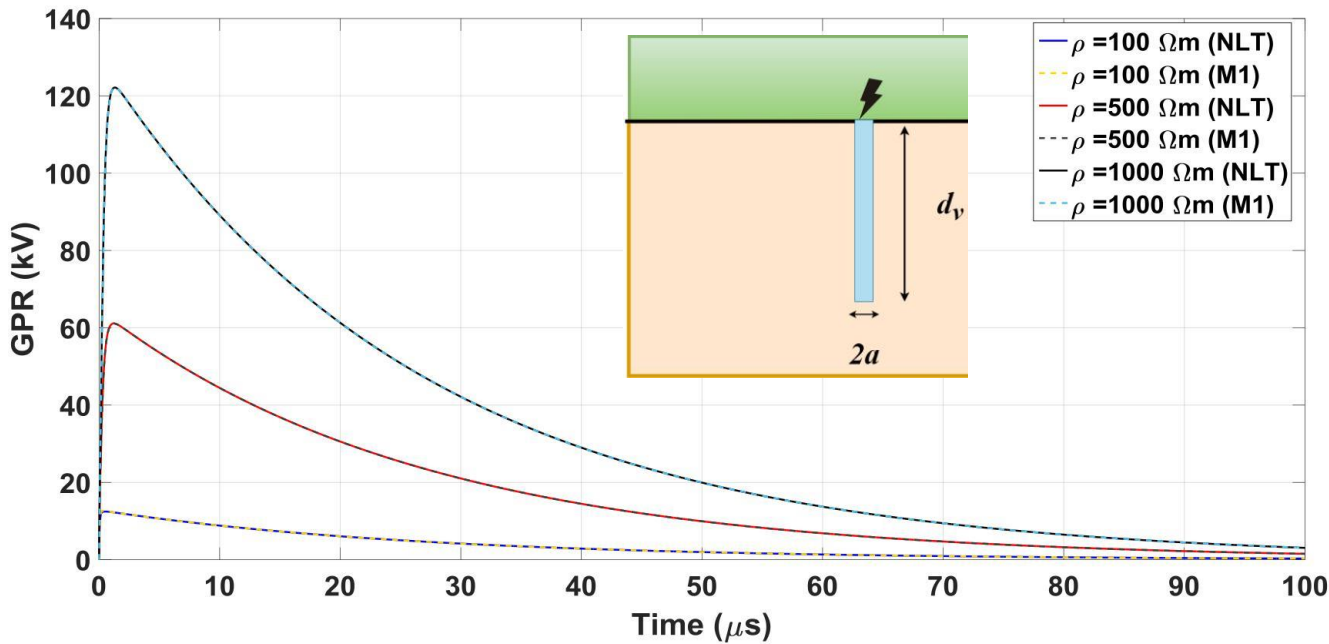
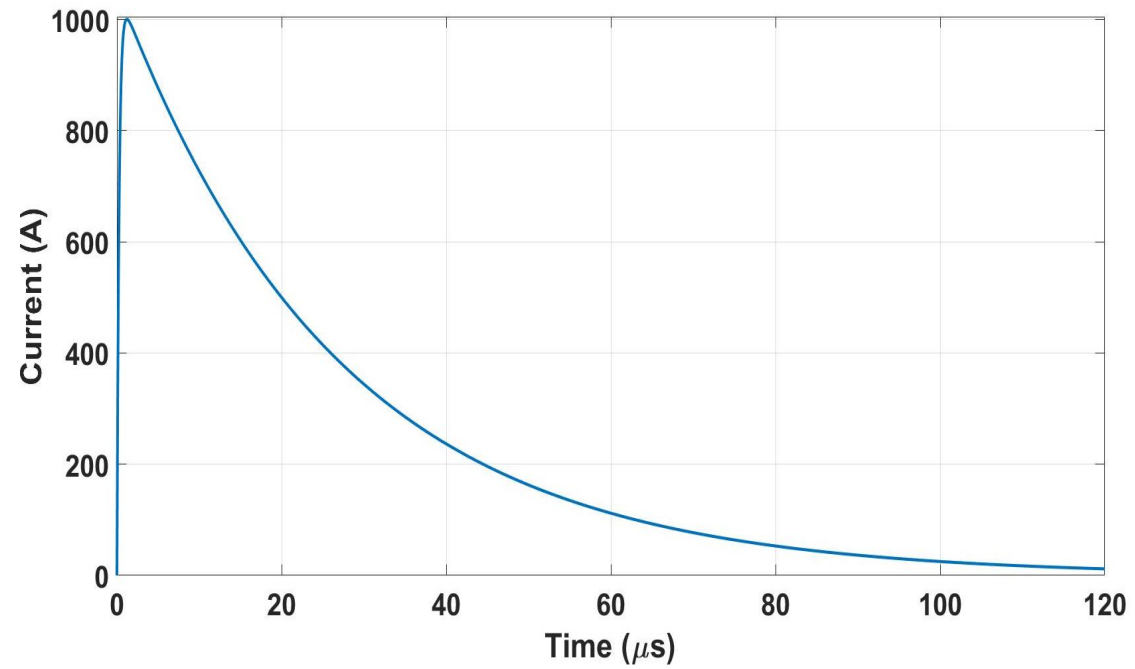


described as: $i_k(t) = I_0(e^{-\alpha t} - e^{-\beta t})$, where $I_0 = 1.057 \text{ kA}$, $\alpha = 3.7424 \times 10^4 \text{ s}^{-1}$

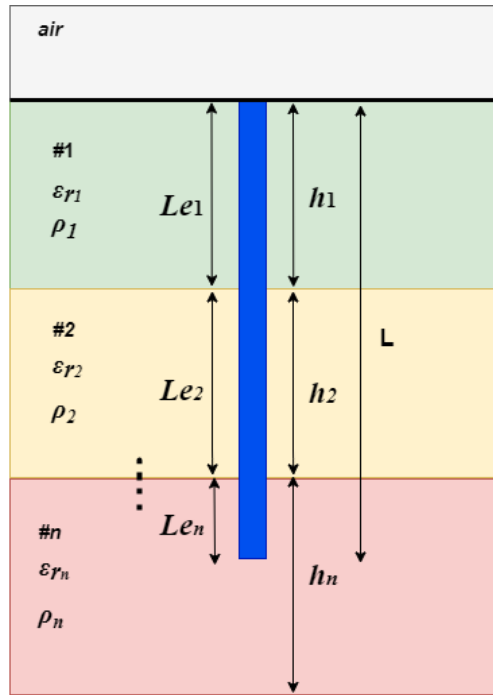
and $\beta = 3.8462 \times 10^6 \text{ s}^{-1}$ (1.20/20 μs exponential curve).

Grounding Potential Rise (GPR)

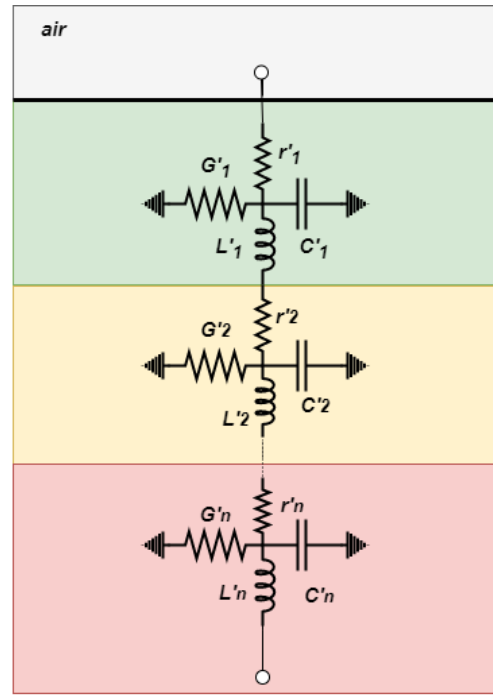
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and $\beta = 3.8462 \times 10^6 \text{ s}^{-1}$ (1.20/20 μs exponential curve).



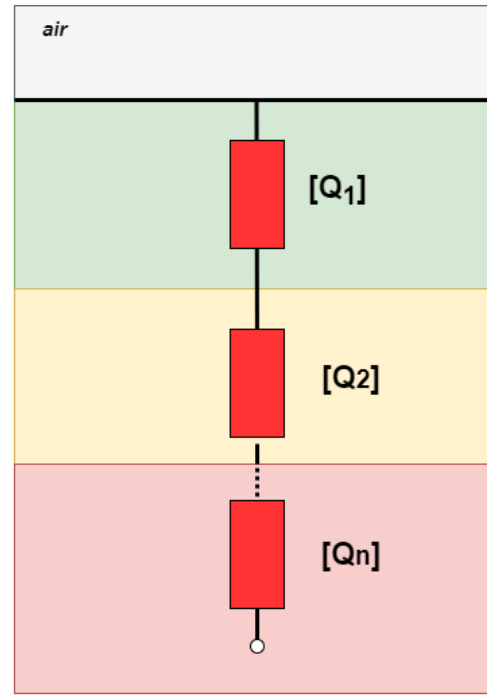
Modelo de Linha de Transmissão – Quadripolos em série



(a)



(b)



(c)

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

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

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

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

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

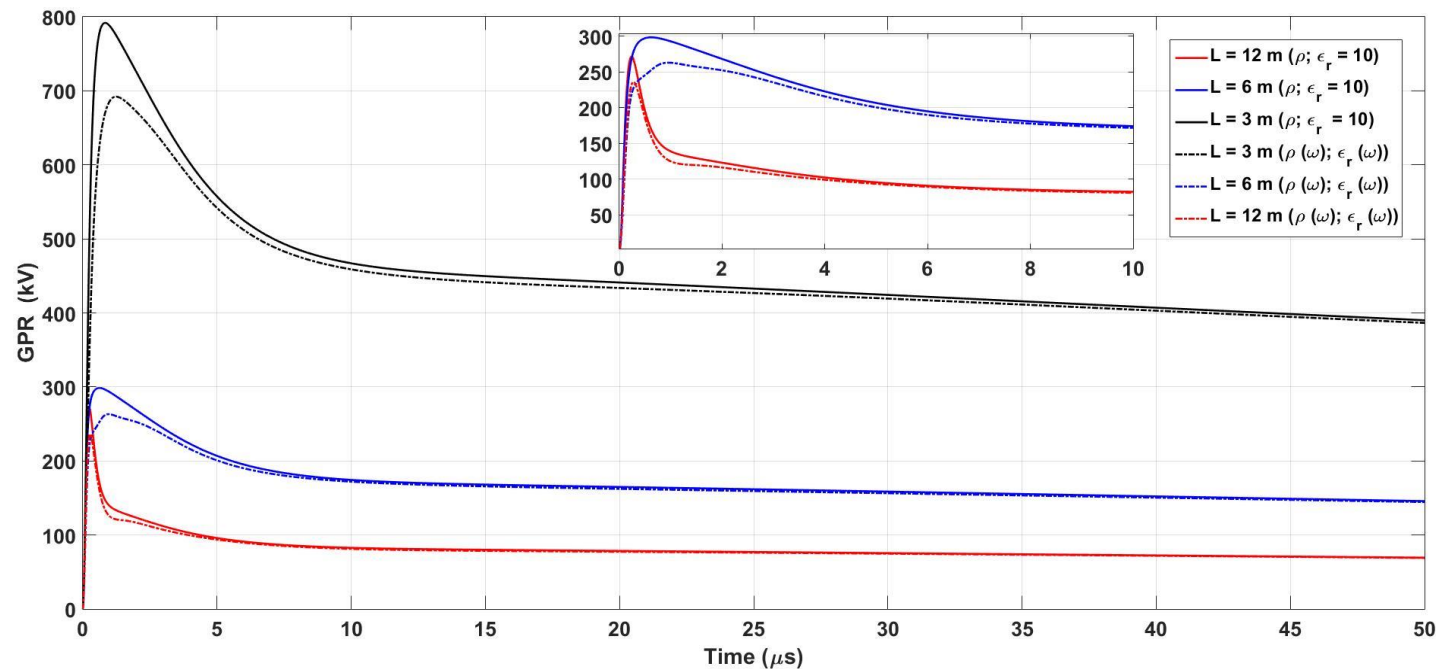
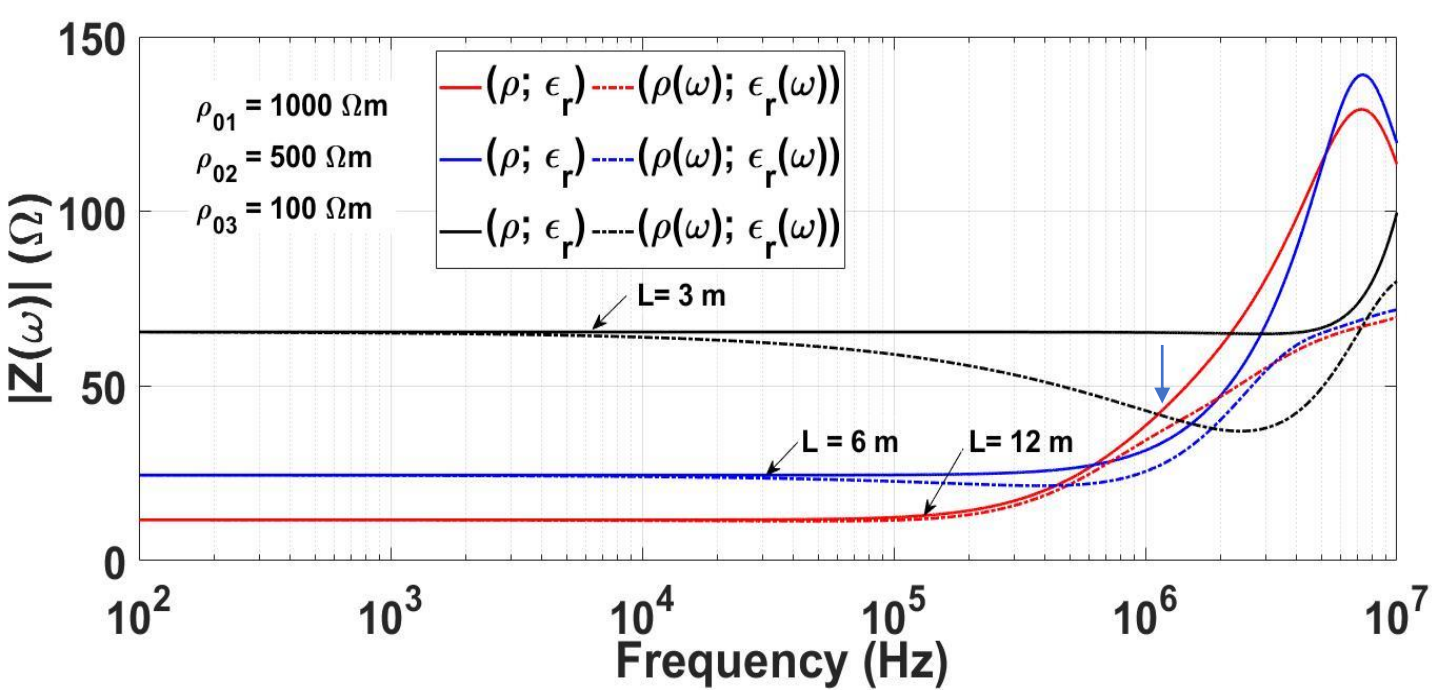
$$\gamma_i(s) = \sqrt{(r'_i + sL'_i)(G'_i + sC'_i)}$$

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

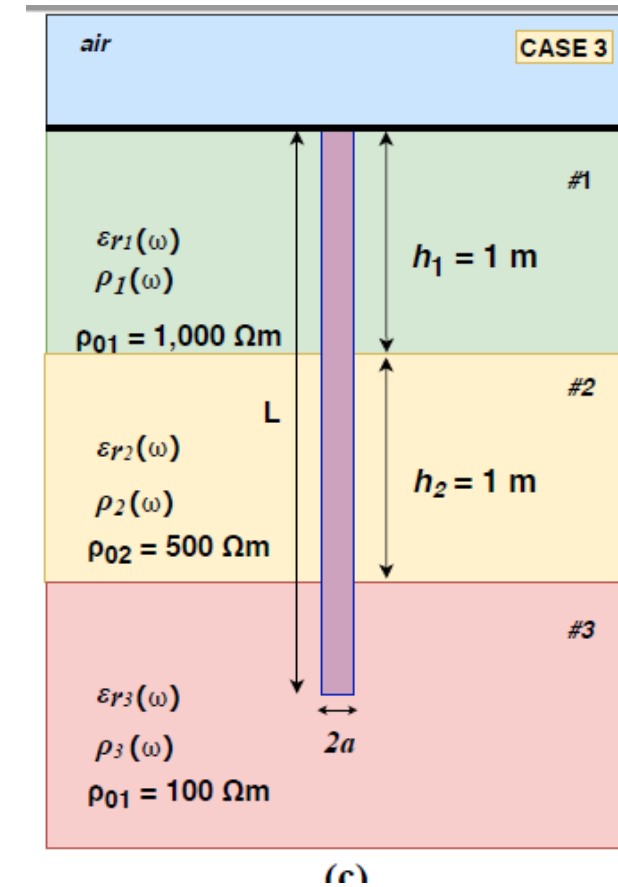
$$Z_{eq}(s) = \frac{A_{eq}(s)}{C_{eq}(s)} \Big|_{I_r(s)=0}$$

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

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



Inclusão da freq. Nos parâmetros do solo



O efeito da freq. É pronunciado para solos de alta resistividade (e homogêneo) ou eletrodos curtos

Comparação de Modelos (TLM, RLC e EMC)

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

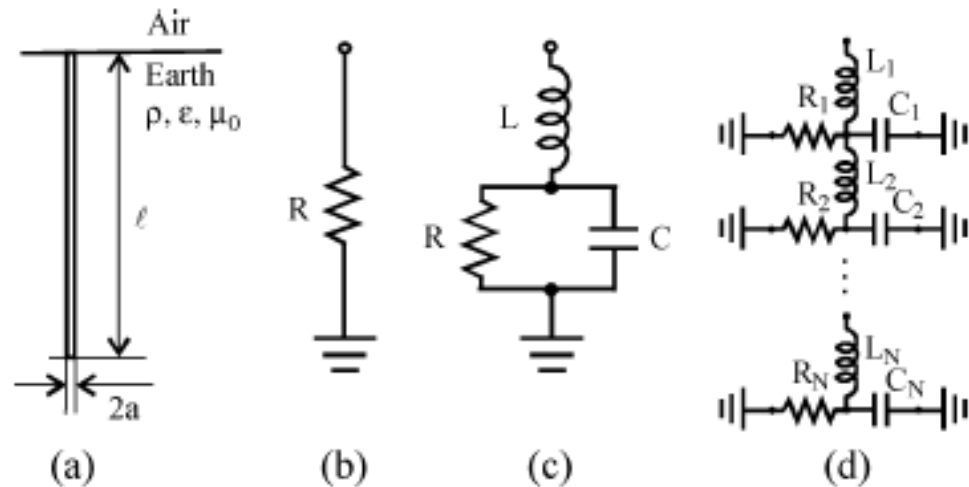


Fig. 1. Low-current models of a vertical ground rod. (a) Physical situation. (b) Low-frequency equivalent circuit. (c) High-frequency lumped R-L-C circuit. (d) High-frequency distributed parameters circuit.

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]

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

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

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

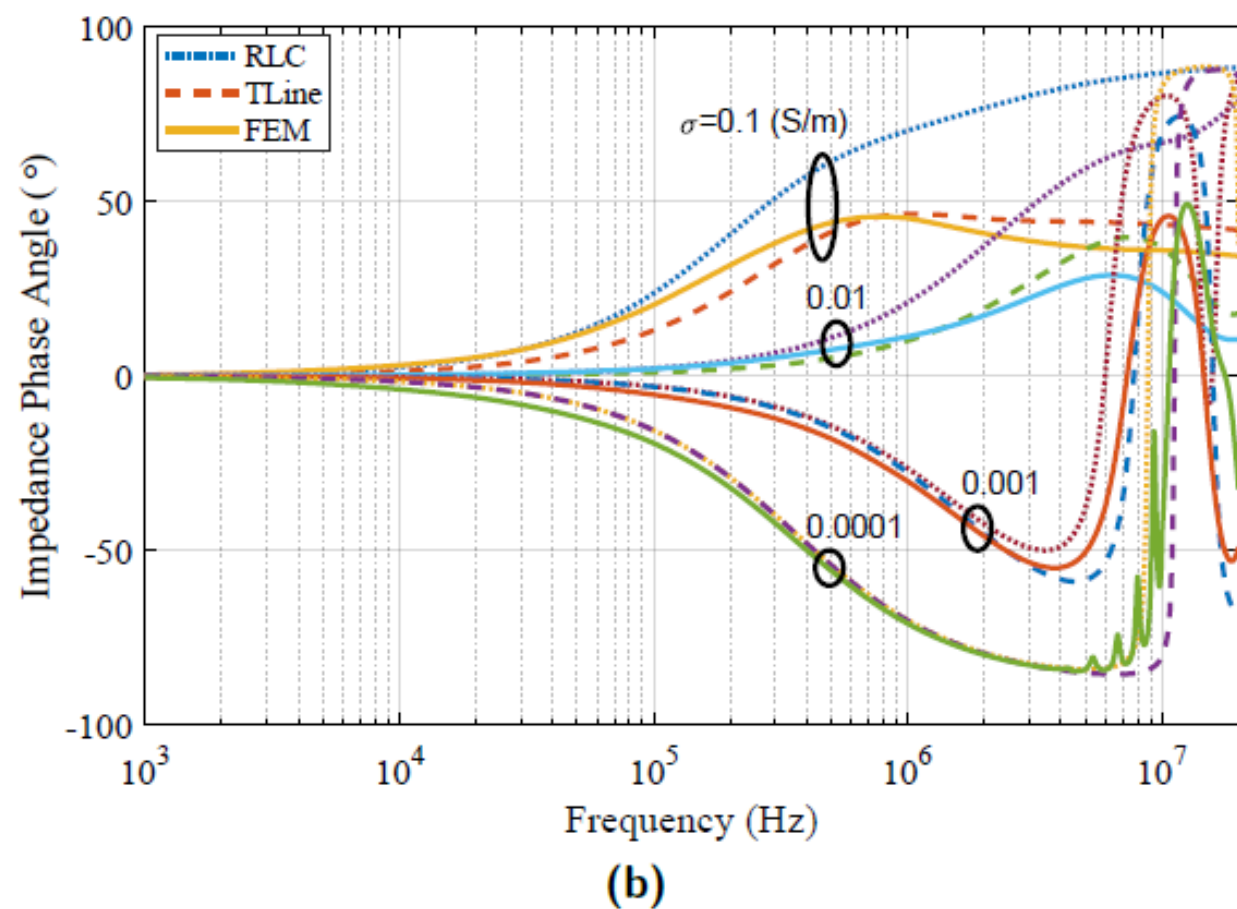
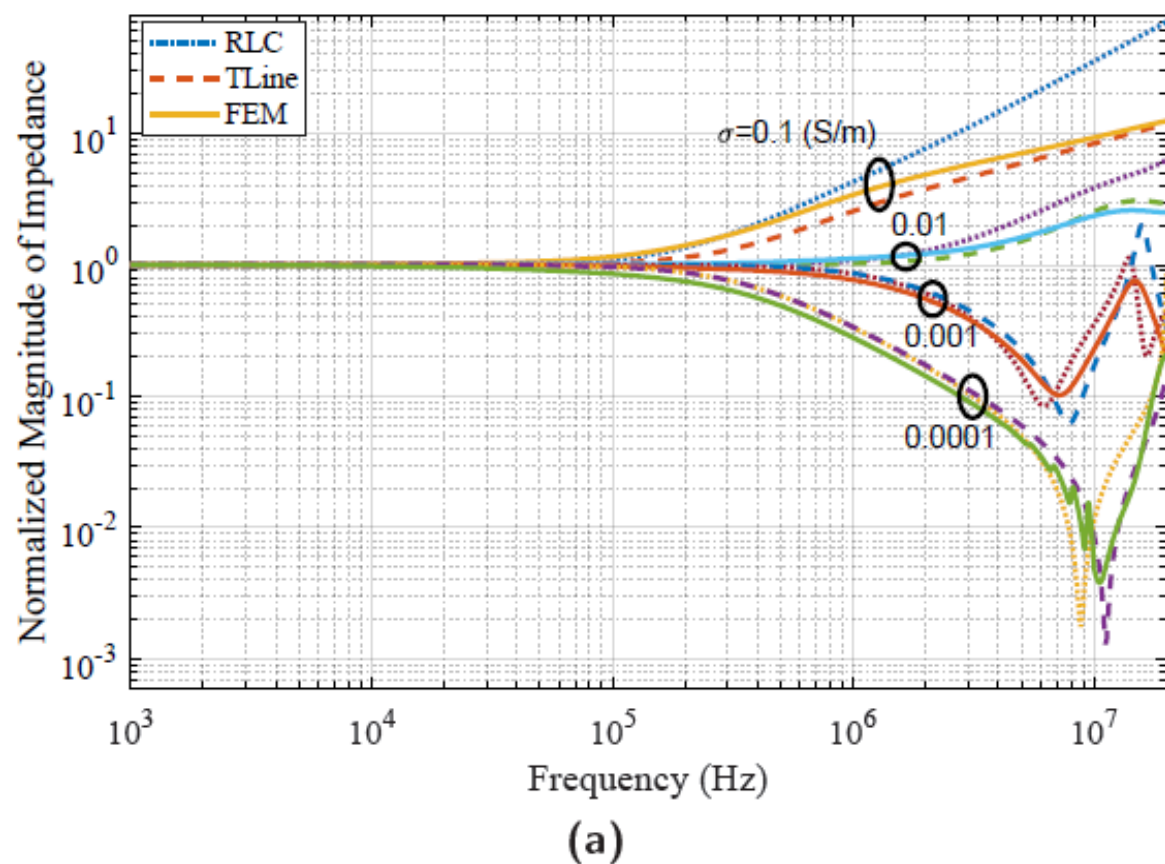
Electromagnetic Transient Modelling of Power Transmission Line Tower and Tower-Footing Grounding System

Thesis

Full-text available

January 2020

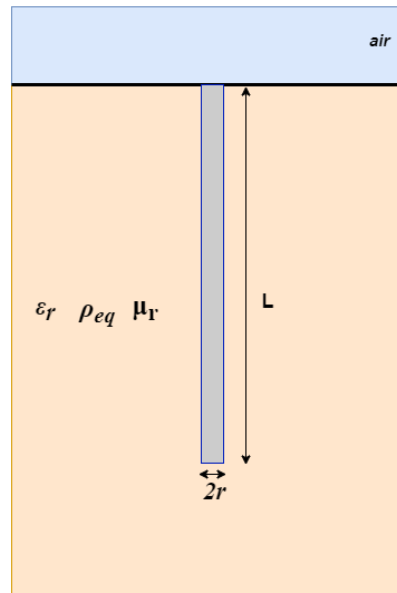
Fig. 3.13: Normalized magnitude (a) and phase angle (b) of harmonic impedance of 3 m vertical grounding electrode for $\epsilon_r = 10$ along with its phase angle.



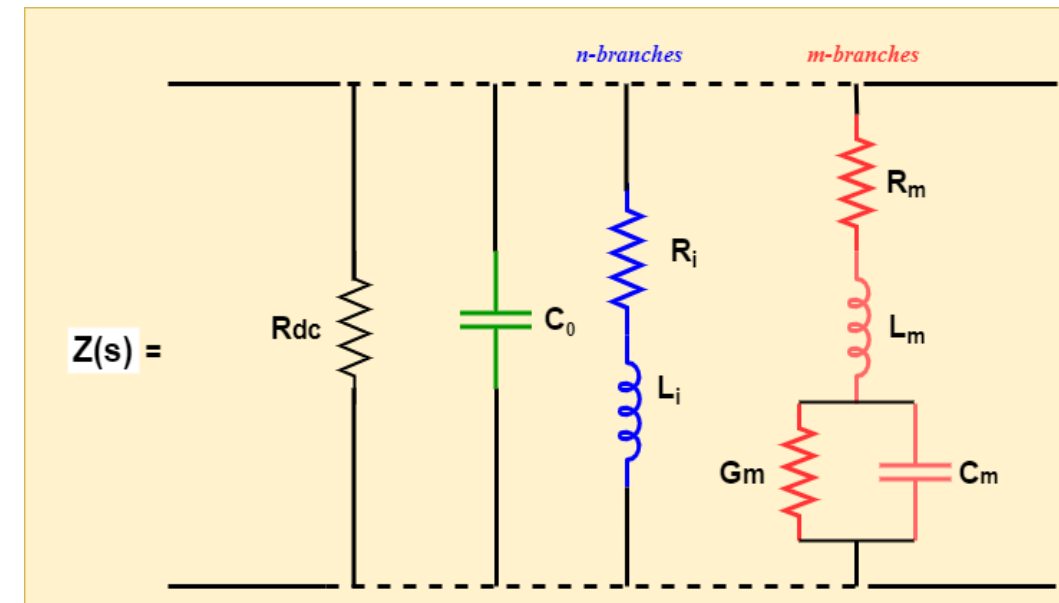
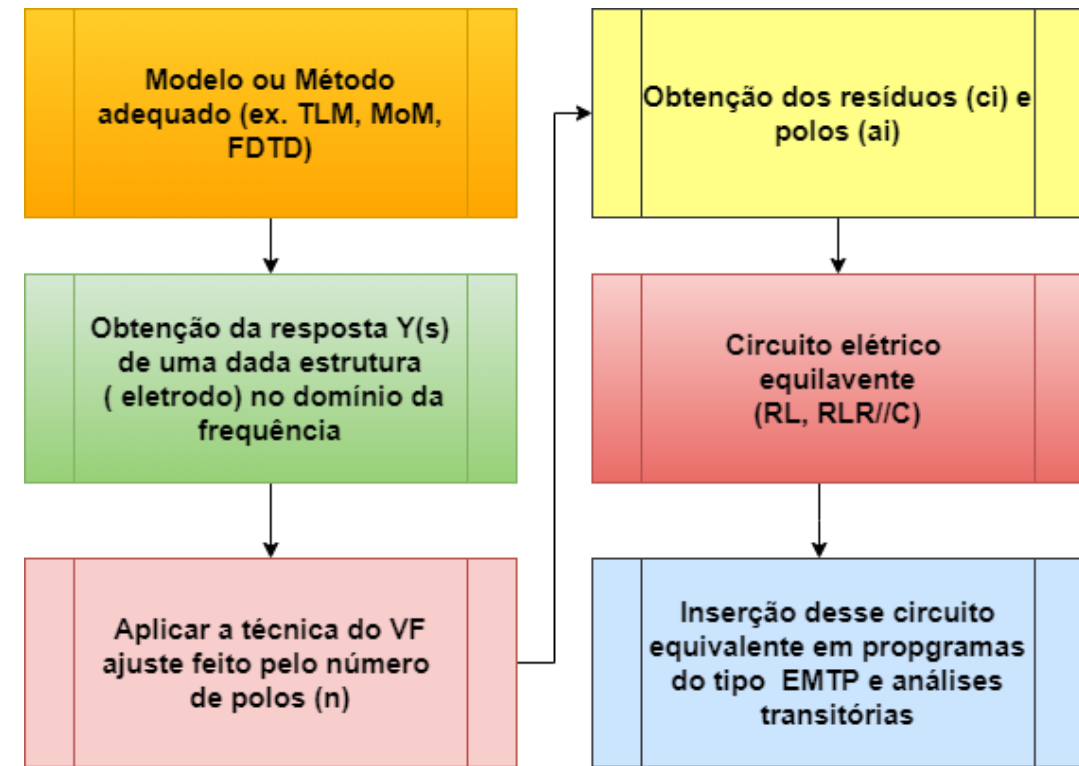
Vector Fitting

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

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).

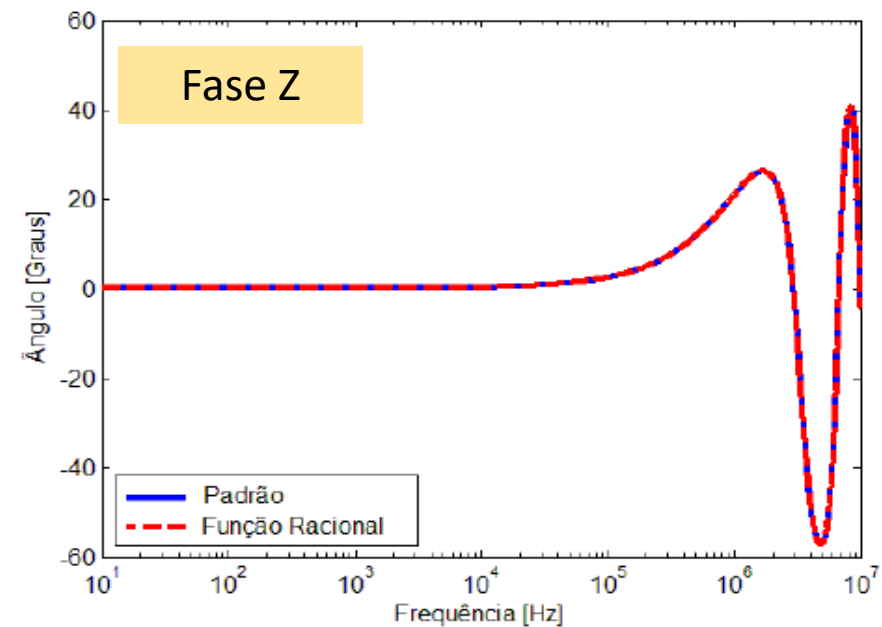
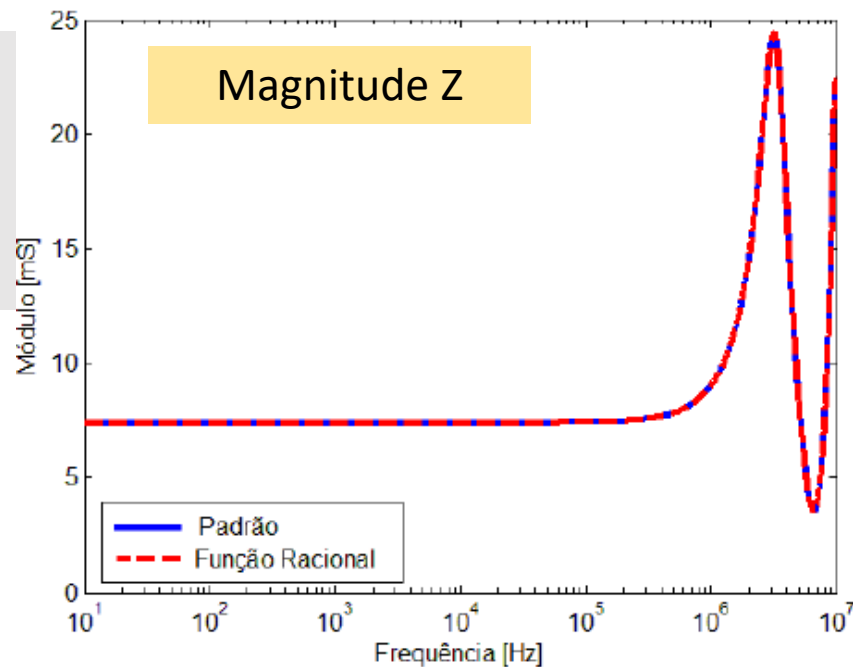


$$Y(s) = \frac{I(s)}{V(s)}$$

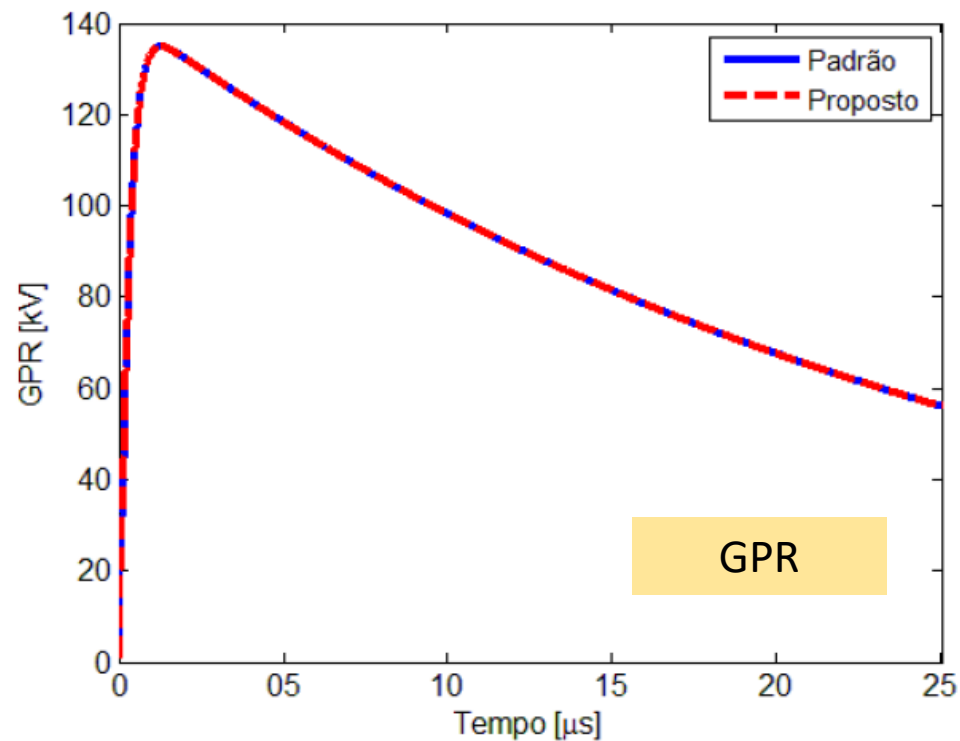
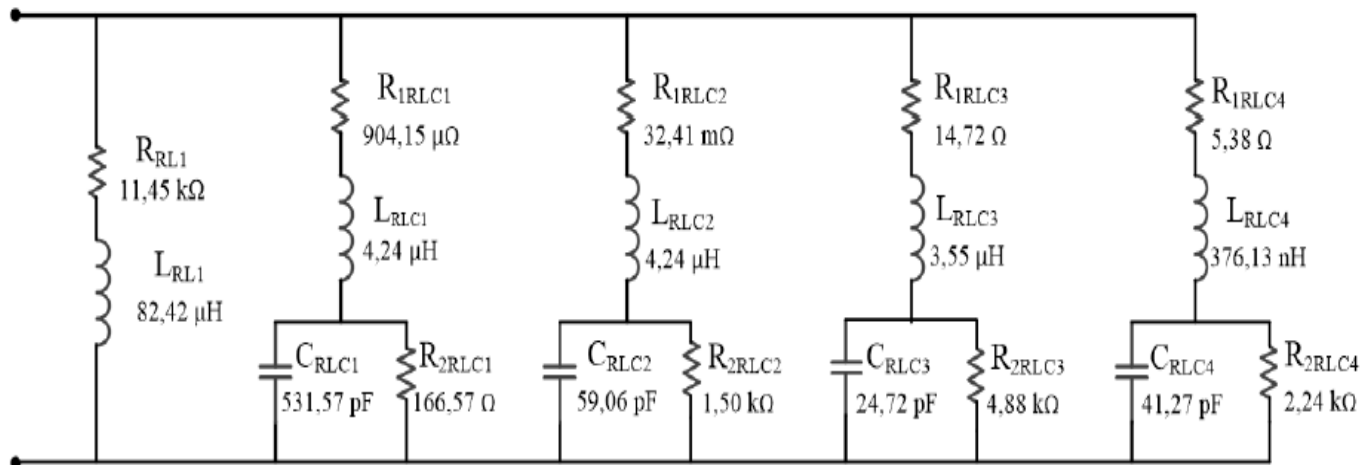


Ex. Vector Fitting

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

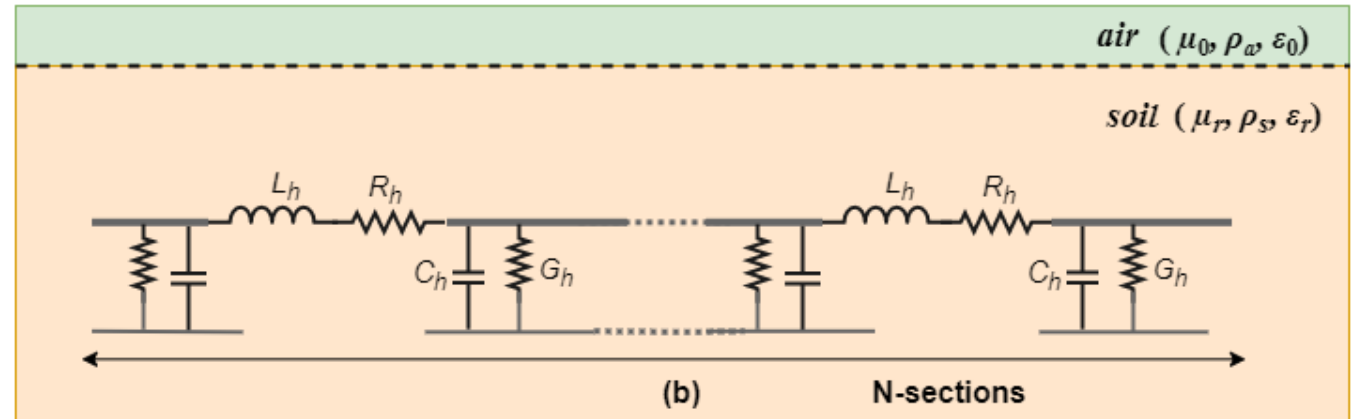
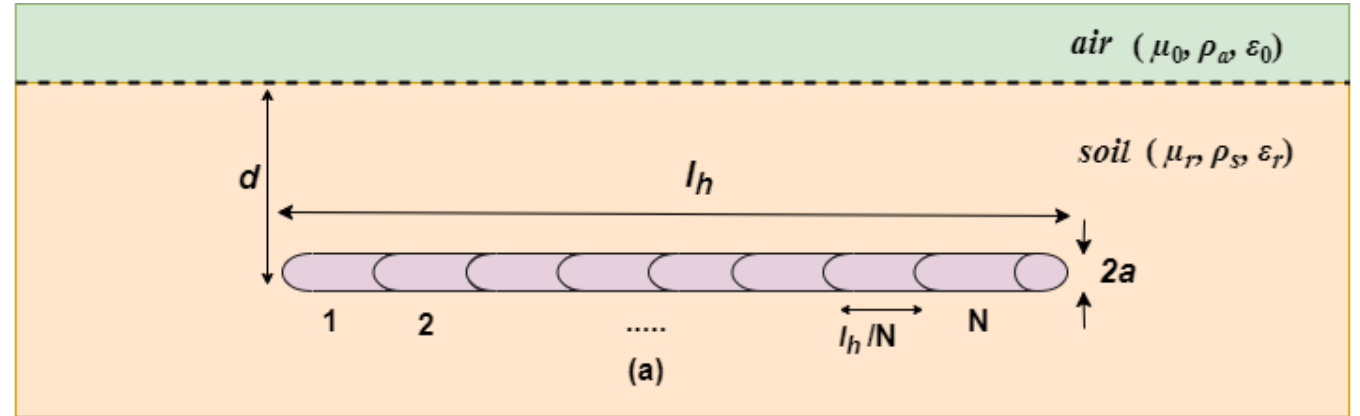


Circuito sintetizado



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 ?

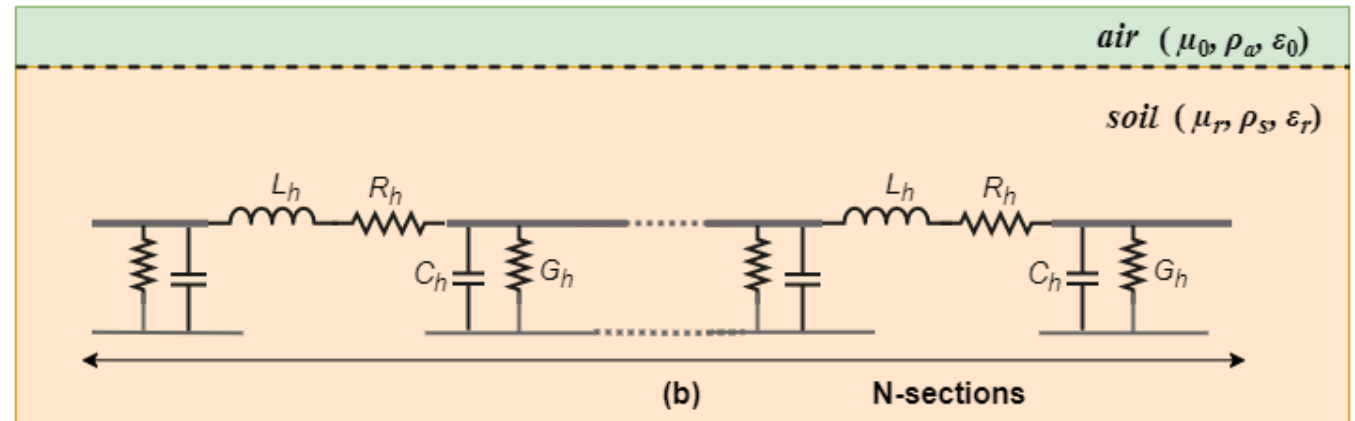
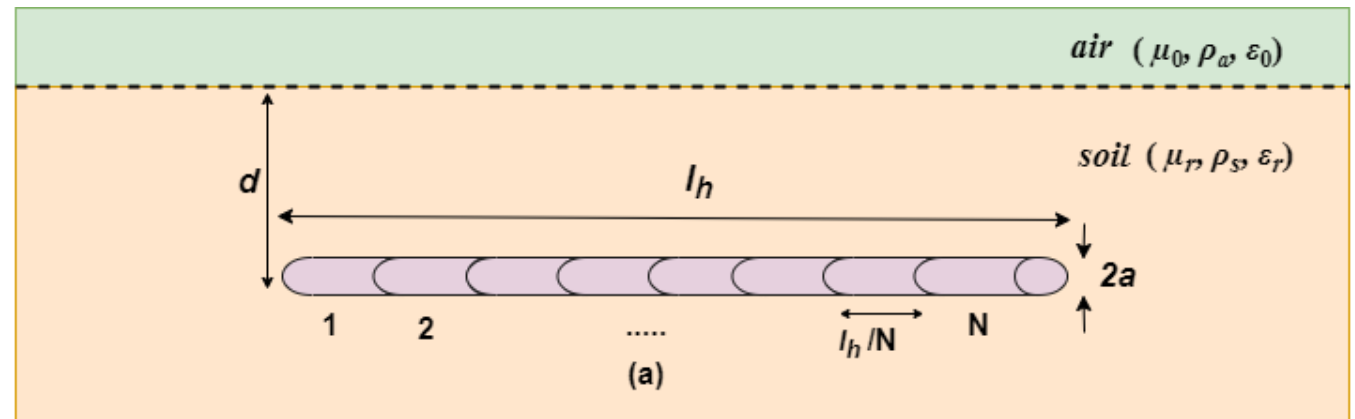


Teoria Eletromagnética corrente filamentar

- Os parâmetros R_h , L_h , G_h e C_h são a resistência, indutância, condutância e capacitância.
- Os parâmetros elétricos são μ , ϵ e ρ são a permeabilidade, permissividade e resistividade.
- O comprimento elementar é definido por:

$$l_e = l_h / N$$

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



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

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

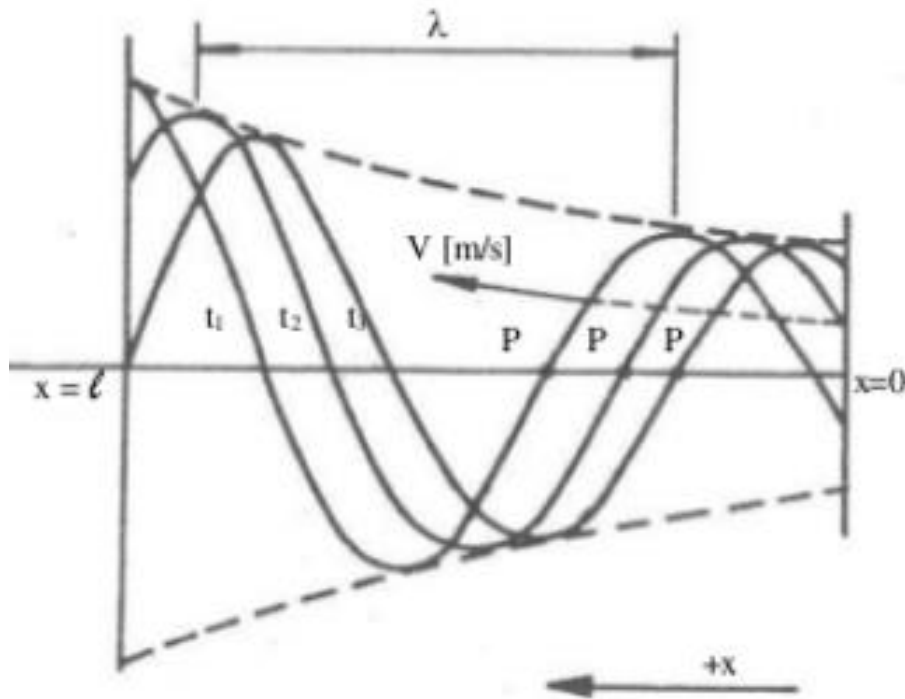
Critério para escolher (l_e)

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

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

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

Função de propagação de um meio (m)



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

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

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

Exemplo Numérico

Eletrodo horizontal-Raio = 12,5 mm, $d = 0,5$ m, $L = 30$ m, solo de $\rho_m = 500$ Ohmm, $\varepsilon_m = 10\varepsilon_0$, $\mu_m = \mu_0$.

Freq. Máx. Do sinal de entrada (descarga atmosférica): 10 MHz

1)-Cálculo da função de propagação

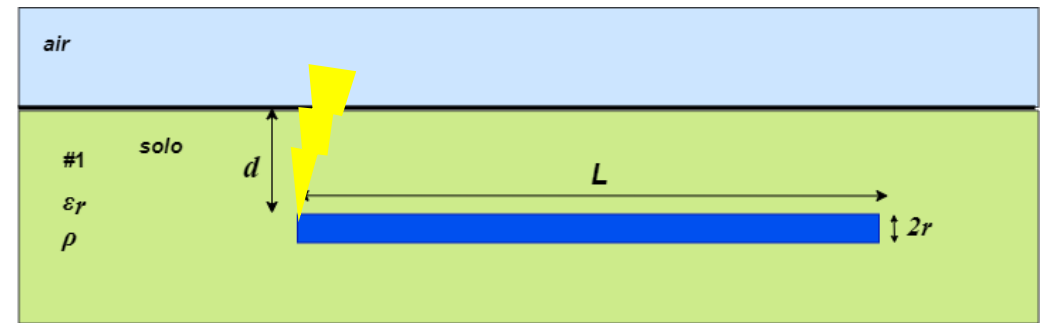
$$\gamma = \sqrt{\left(j2\pi 10^7 4\pi 10^{-7} \left(\frac{1}{500} + j2\pi 10^7 10 \cdot 8.85 10^{-12} \right) \right)} = \alpha + j\beta = 0,1173 + j 0,6731$$

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 para $N = 100$ pis $\rightarrow l_e = 0.3$ m



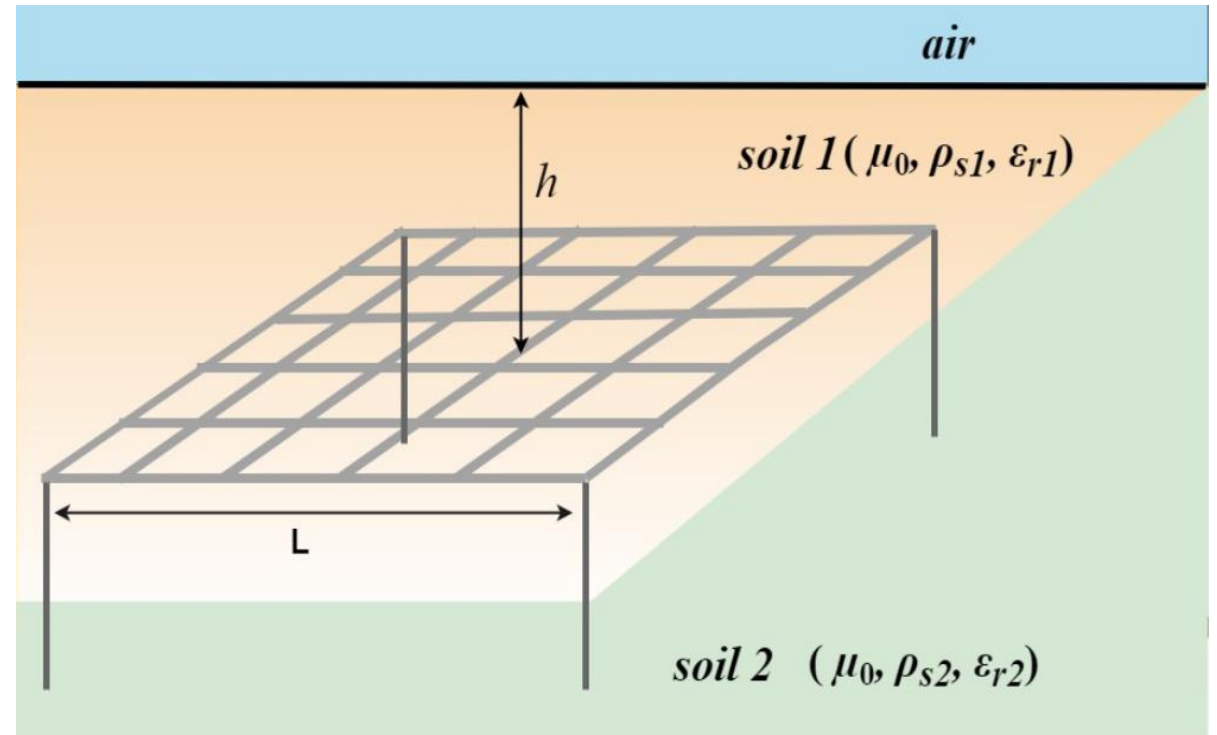
```
clear all ; close all ; clc;
|
%dados geometricos do eletrodo
L = 30; %comprimento do eletrodo
N = 100;% numero de circuitos pi
le= L/N; % comprimento elementar
%dados gerais do meio
pm=500;      %resistividade meio
sm=1/pm; % condutividade do meio
er=10;      %permissividade relativa
e0=8.854e-12; %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
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
```

Composição

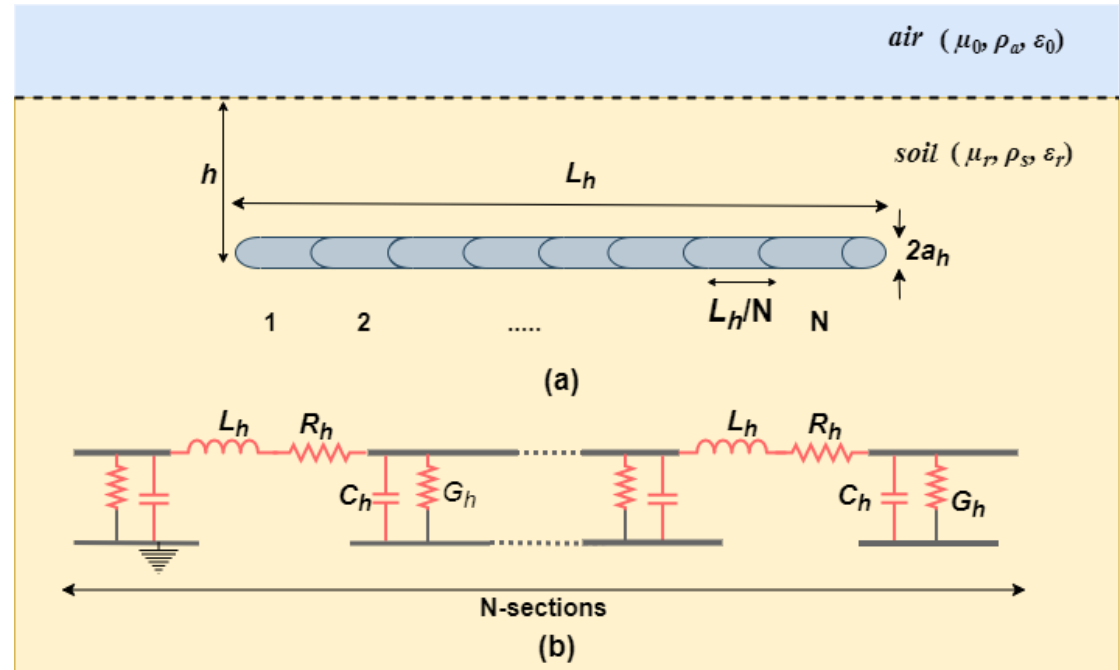
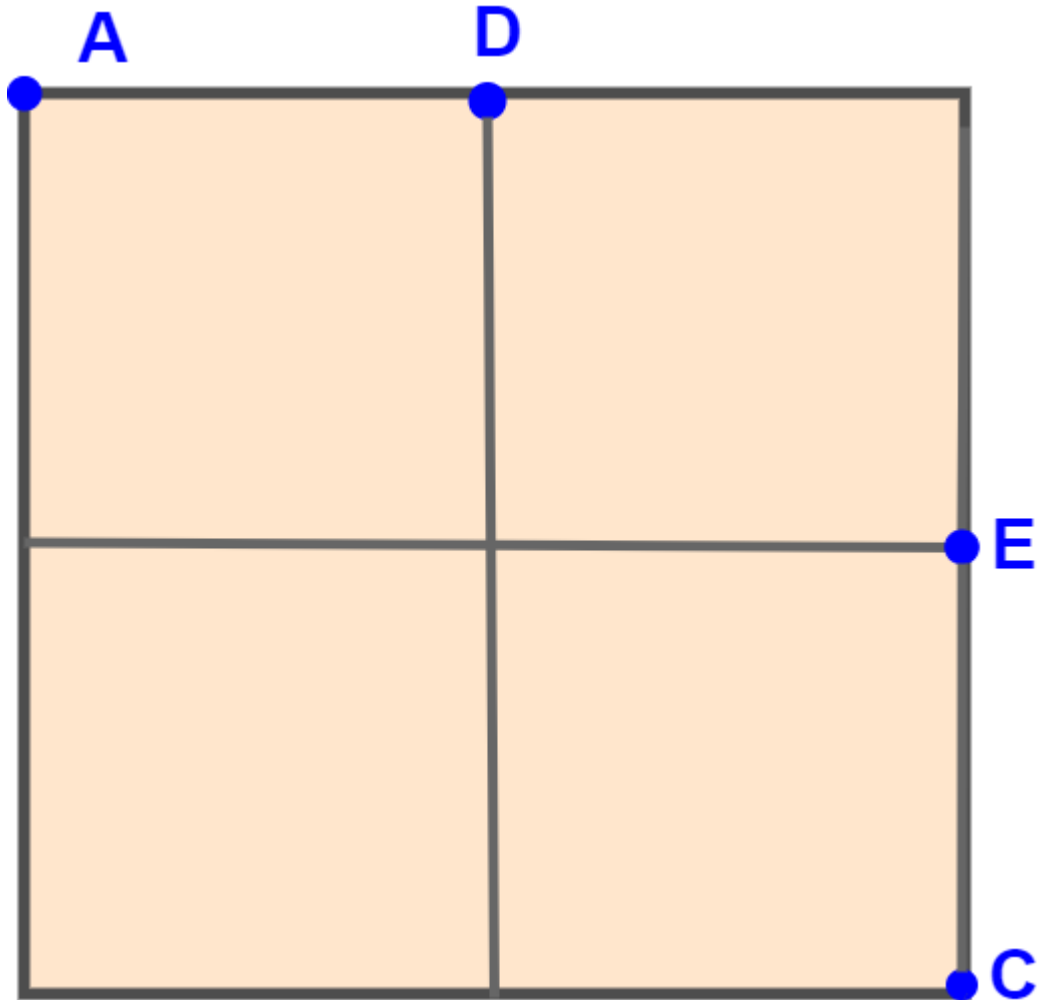
As MAs são constituídas por um grande reticulado de eletrodos horizontais (EHs) enterrados a uma dada profundidade e que são interligados por juntas mecânicas ou soldas em suas conexões cruzadas (nós).

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

Malhas de Aterramento



Abordagem a parâmetros concentrados



The studied grid electrode is a 4-meshe grid with dimensions of 12mx12m, 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 $\rho = 100 \Omega\text{m}$, $\epsilon_r = 36$ 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:

$$\hat{\gamma} = \sqrt{j2\pi \cdot f_x \mu_0 \mu_r (\sigma + j2\pi \cdot f_x \epsilon_0 \epsilon_r)} \Rightarrow$$

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

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

The phase constant β_2 is equal to 1,3 rad/m so the wave length has the value:

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

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

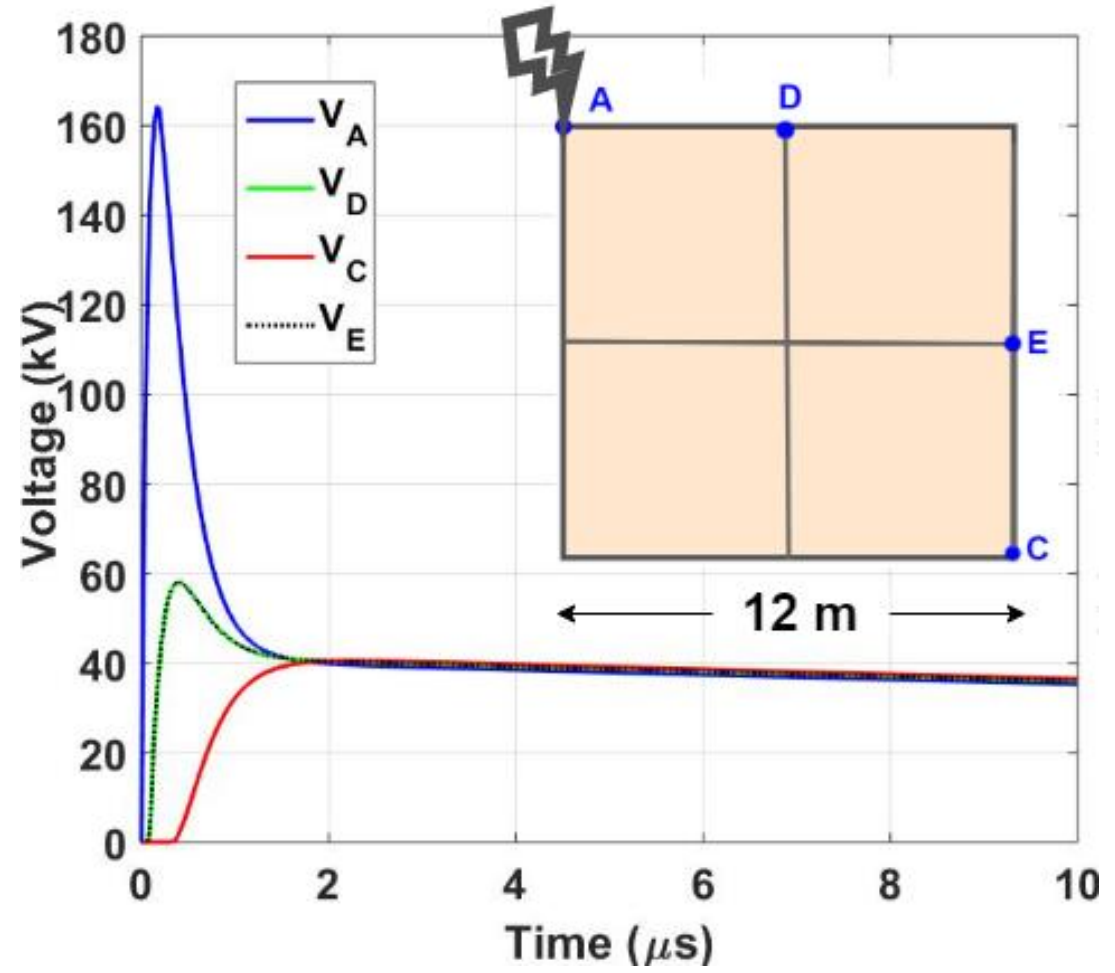
so the length, l , of an elementary cell is chosen:

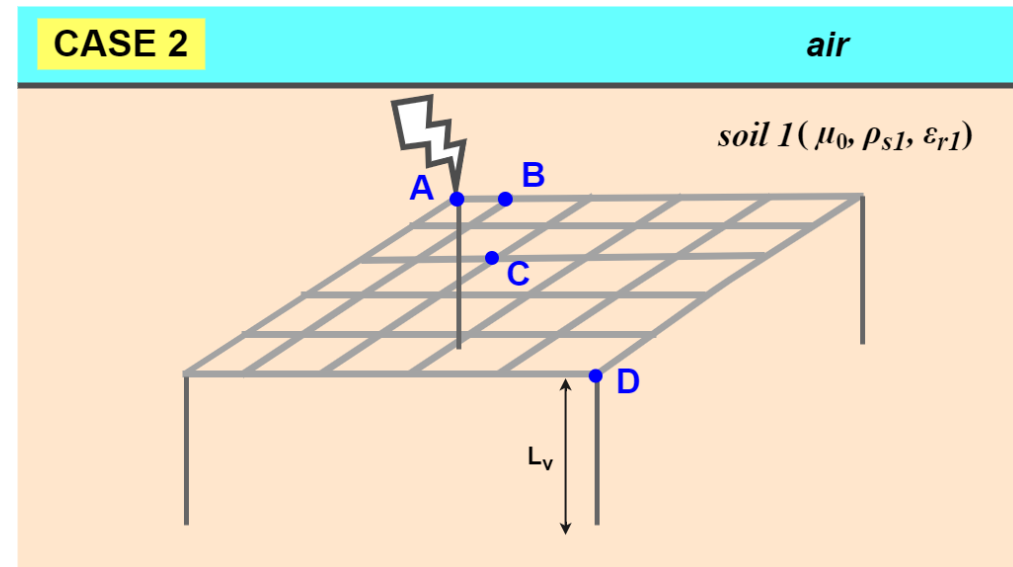
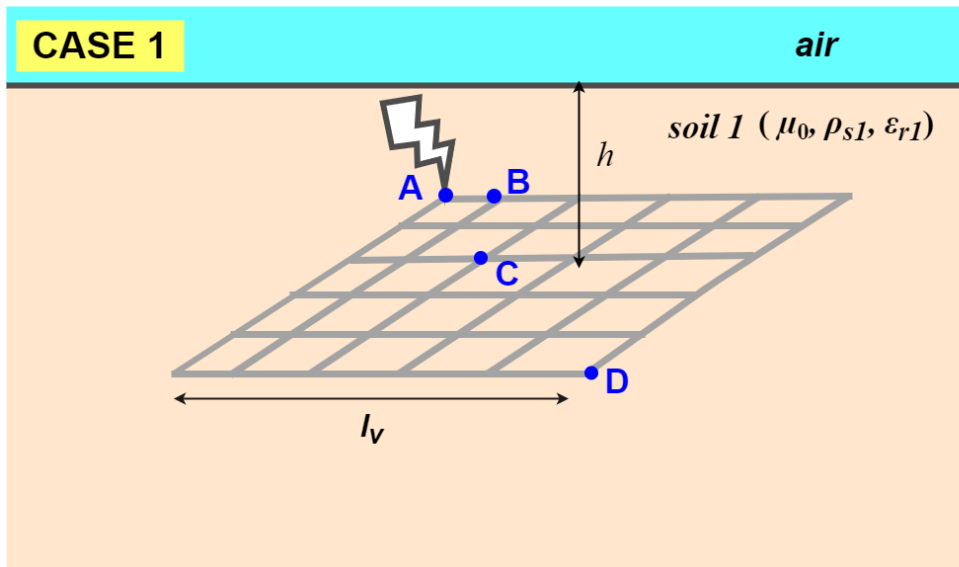
$$l = 0,24\text{m} < \frac{\lambda}{10} = 0,483\text{m}$$

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

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

Lumped paramet	grounding grid
R_E'	1300 Ω
L'	0,47 μH
C'	25 pF
R	27 $\mu\Omega$



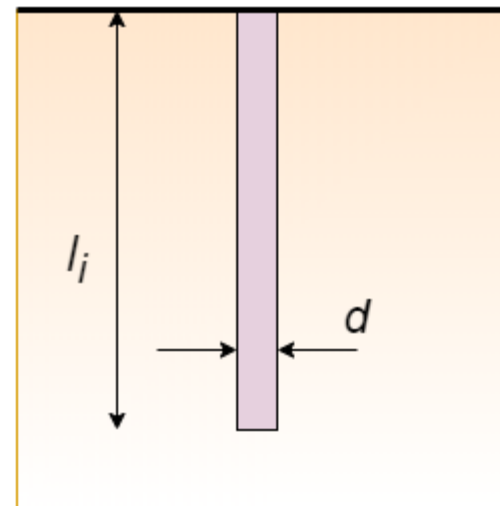


Hastes verticais modeladas por:

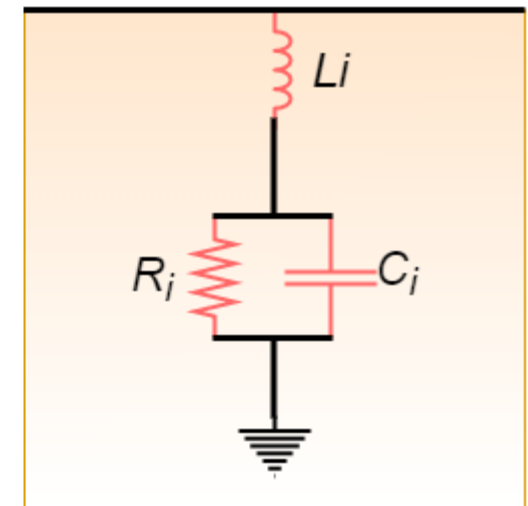
- técnica do Vector Fitting;
- Circuito equivalente (concentrado)

$$R_i = \frac{\rho_s}{2\pi l_i} \left[\ln \left(\frac{8l_i}{d} \right) - 1 \right]; \quad L_i = \frac{\mu_s}{2\pi} l_i \ln \left(\frac{4l_i}{d} \right);$$

$$C_i = \frac{\epsilon_r l_i}{18 \ln \left(\frac{4l_i}{d} \right)} \times 10^{-9}$$



(a)



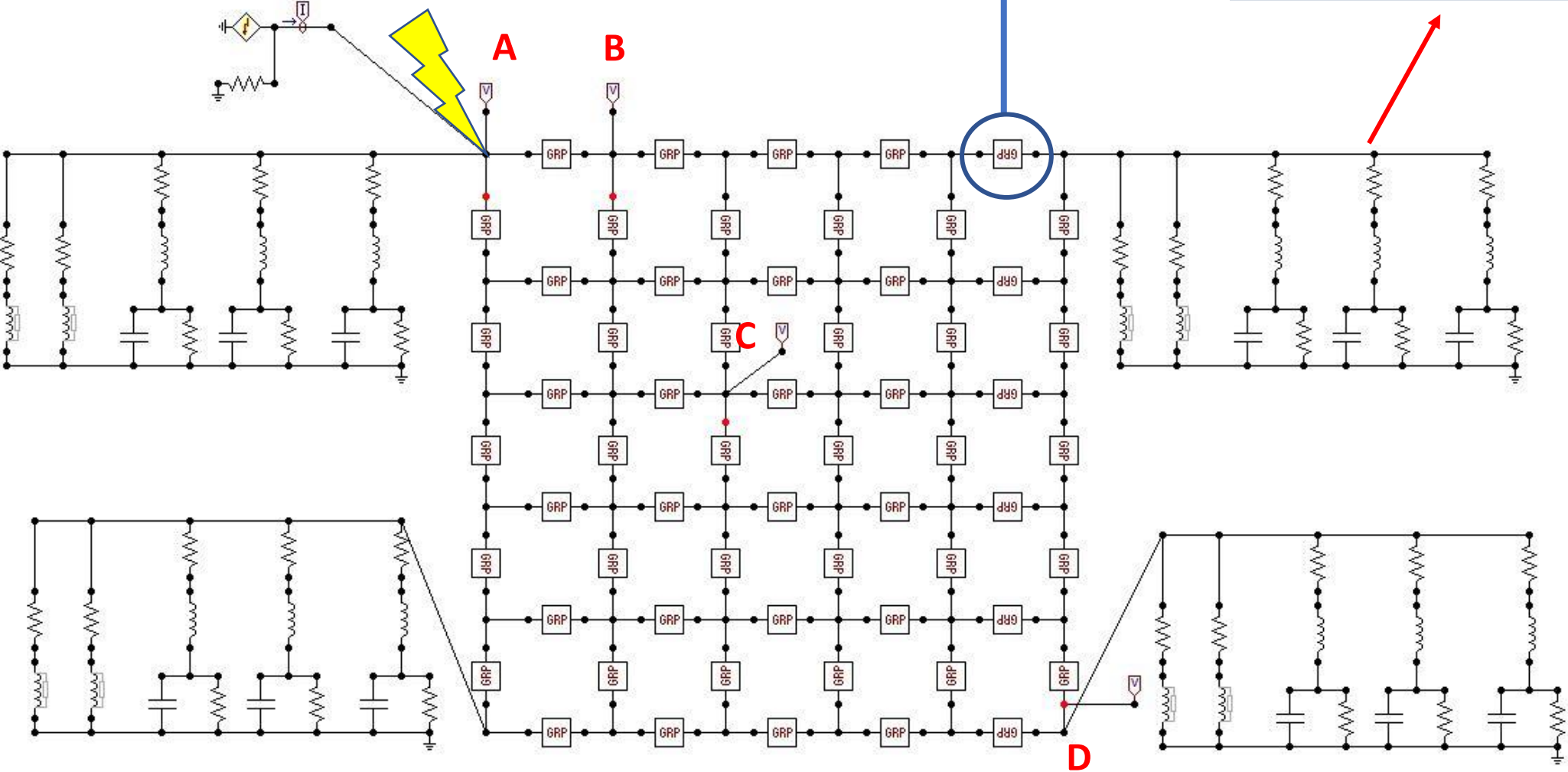
(b)

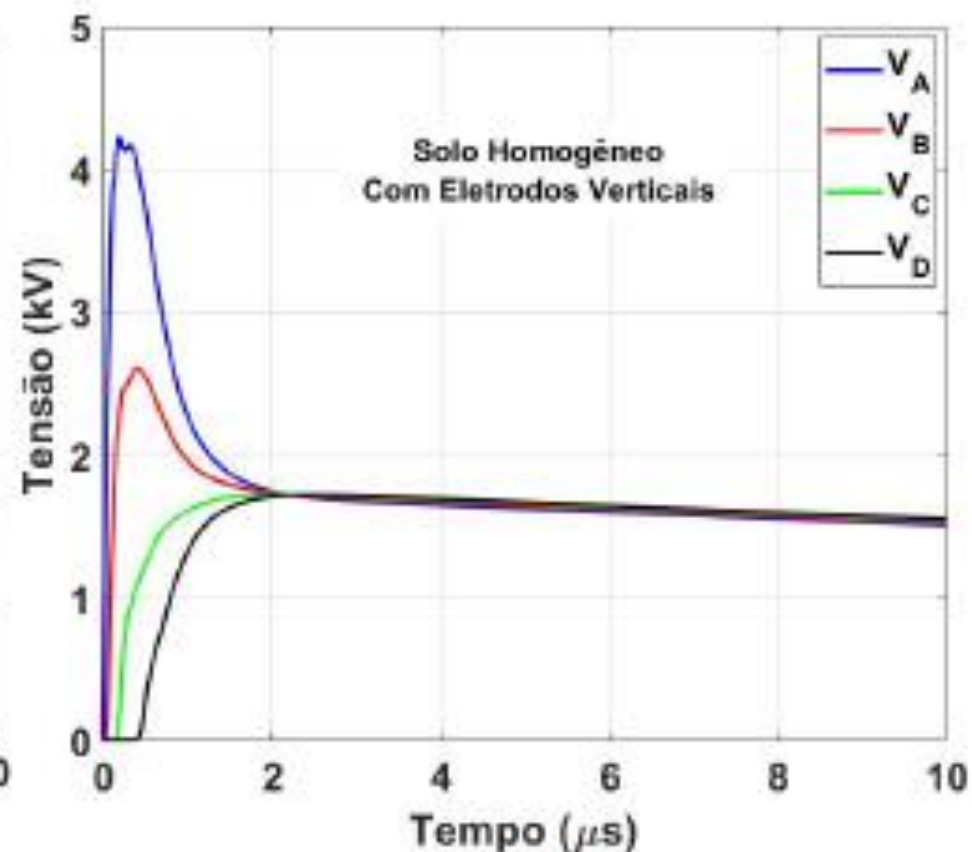
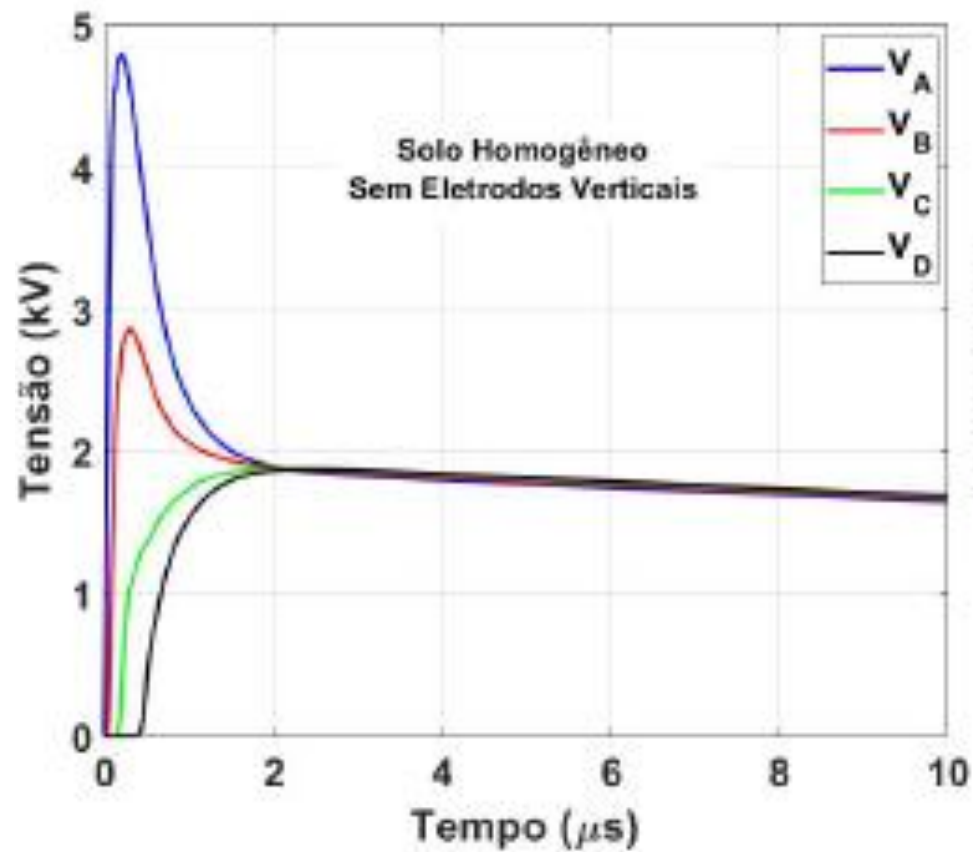
Circuito da Malha com hastes no ATP

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

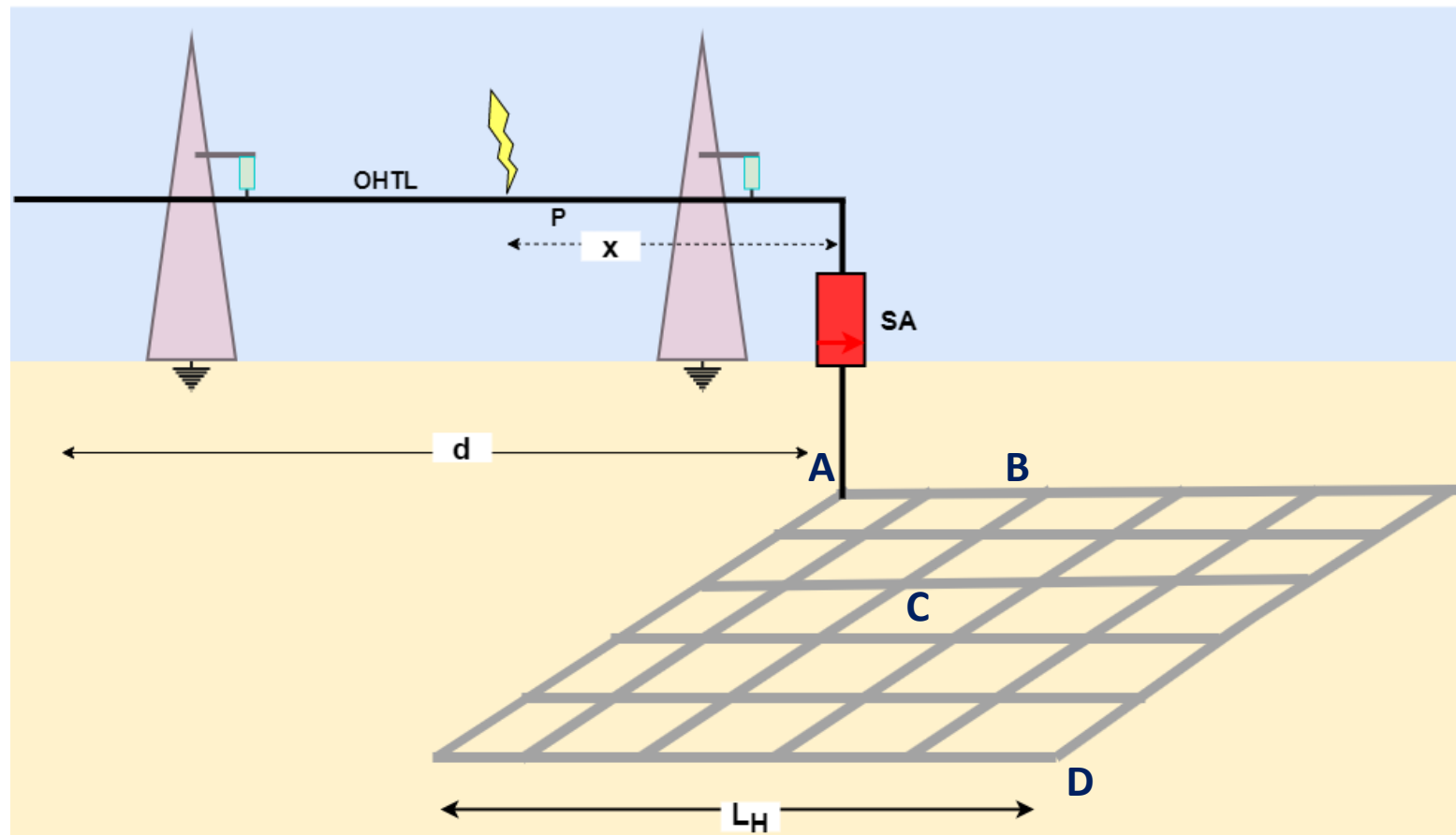
1,2/50 us





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

Trabalho 02



Uma linha de transmissão de comprimento $d = 20$ km é atingida por uma descarga atmosférica, modelada por uma fonte de corrente $1\text{kA}-(1,2/50)\mu\text{s}$ com uma impedância interna (do canal) de 400Ω , incidente em um ponto x a 10 km da subestação. Ondas de tensão impulsivas viajam até a subestação na qual um para-raios (SÁ) é instalado na entrada dessa subestação. Pede-se:

- (a) Calcular a impedância característica da linha de transmissão, velocidade de propagação e tempo de viagem das ondas de tensão.
- (b) Calcular as tensões transitórias nos pontos A, B, C e D na malha.
- (c) Inserir hastes verticais em alguns pontos da malha a fim de se reduzir as tensões transitórias.

Realizar as simulações no ATP. Enviar um relatório sucinto com as simulações junto com o arquivo .acp do ATP.

Dados

Linhas de transmissão: $r' = 0,05 \Omega/\text{km}$; $L' = 1 \text{ mH}/\text{km}$; $C' = 11.11 \text{ nF}/\text{km}$
(Modelar a par. Distribuídos)

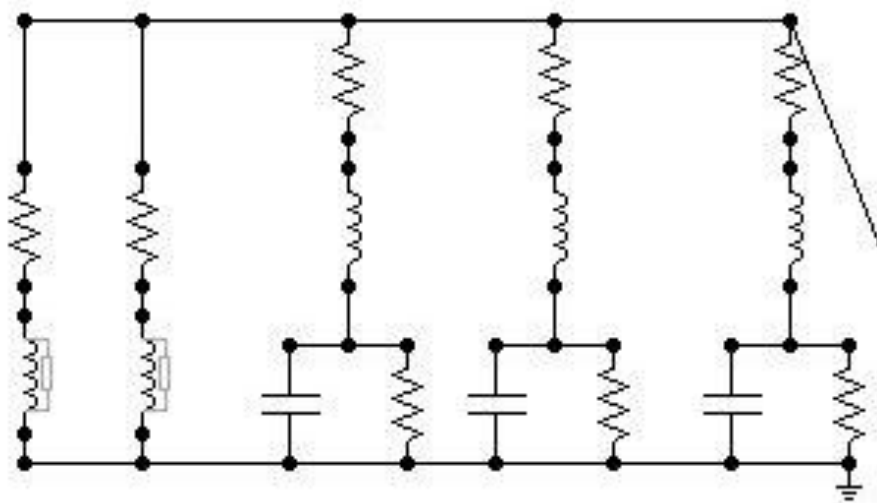
Pára-raios: Chave controlada por tensão ($V_{fl} = 10 \text{ kV}$) e $R_p = 10 \Omega$;

Malha de aterramento: $30 \times 30 \text{ m}$, raio = $12,5 \text{ mm}$; $h = 0,5 \text{ m}$;

Modelo a Par. Concentrados: $N = 30$ pis, agrupados em 5 grupos (6 m)
e $f = 1 \text{ MHz}$; Modelar os parâmetros pelas eqs. de Cecconi.

Solo: $\rho = 1.000 \Omega\text{m}$ e $\epsilon_r = 10$, $\mu_0 = 4\pi 10^{-7} \text{ H}/\text{m}$; $\epsilon_0 = 8,854 10^{-12} \text{ F}/\text{m}$

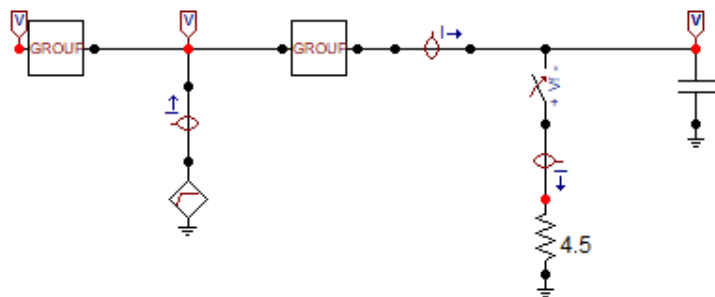
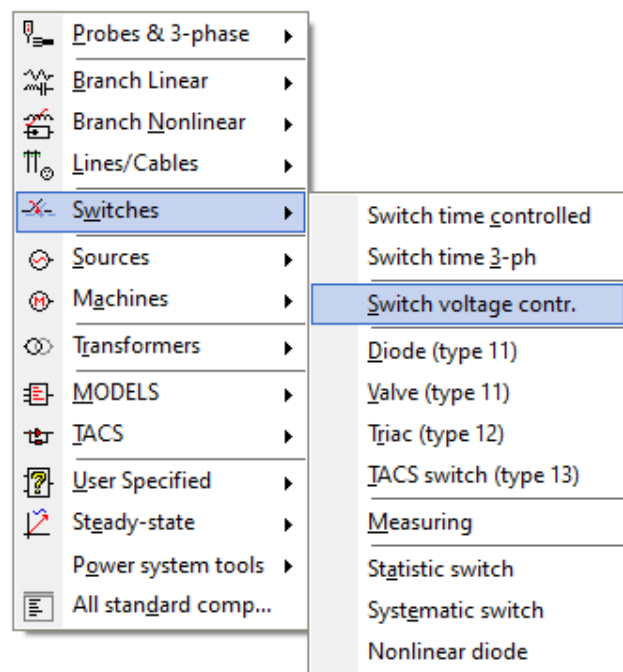
Haste vertical: Haste modelada pelo Vector Fitting



1000 ohmm raio=12.5mm comp = 12 m

Rx1	2.4412E+01	4.9772E+01	6.9983E+01
Rx2	1.1000E+02	1.5906E+03	6.0353E+03
Cx	9.0274E-10	8.2479E-11	3.4701E-11
Lx	9.0720E-06	9.2489E-06	7.6862E-06
Rr	1.5407E+04	7.8555E+01	
Lr	3.8029E-03	1.1442E-07	

Chave (Para-raios)



Component: SWITCHVC

Attributes

DATA	UNIT	VALUE	NODE	PHASE	NAME
T-cl		0	SWF	1	
T-de		0.001	SWT	1	
Imar		0			
V-fl		10000			

Se tensão maior que V-fl, chave fechada

Order: 0 Label:

Comment:

Output: 0 - No Hide

Informações de cada parâmetro

Edit definitions OK Cancel Help

Contato

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- Skype-andersonjusto3