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A Spice-compatible Macromodel for Field Coupling to Underground Transmission Lines Based on the Analog Behavioral Modeling

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Research context and motivation

- Underground power or communication transmission systems have been widely leveraged in metropolitan areas with high population densities. For systems exposed to lightning, high-altitude electromagnetic pulse (EMP) or other intentional electromagnetic interference (IEMI), the insulation, electrical or electronic components connected to lines may suffer severe impact or damages due to induced interferences.
- A key issue for the propagation of the disturbances is represented by the proper correction terms on both per-unit-length (p.u.l) impedance and admittance terms, in the telegrapher's equation. We adopt a general semi-infinite integral analytic formulation here. For avoiding using a time-consuming numerical integration technique, approximation expressions for both ground impedance and admittance are also proposed.
- For most commonly used FDTD method, the first challenge is the numerical curve fitting required to realize the approximation and transformation of p.u.l parameters. It requires high order approximation to capture the characteristics in a wide frequency range. The potential loss of accuracy may also be generated in terms of fitting errors. Besides, the underground transmission systems are generally large. Consequently, the simulation requires large computing time and memory resource, especially for fast transients coupling to long multi-conductor underground lines.
- This research aims at presenting an algorithm that can estimate terminal responses in time domain by circuit solvers efficiently. In conjunction with proposed approximations for ground impedance and admittance, the proposed method can not only yield compact macromodels, but bring significant simplification and speed-up in modeling and simulation process for long underground multiconductor lines with nonlinear elements.

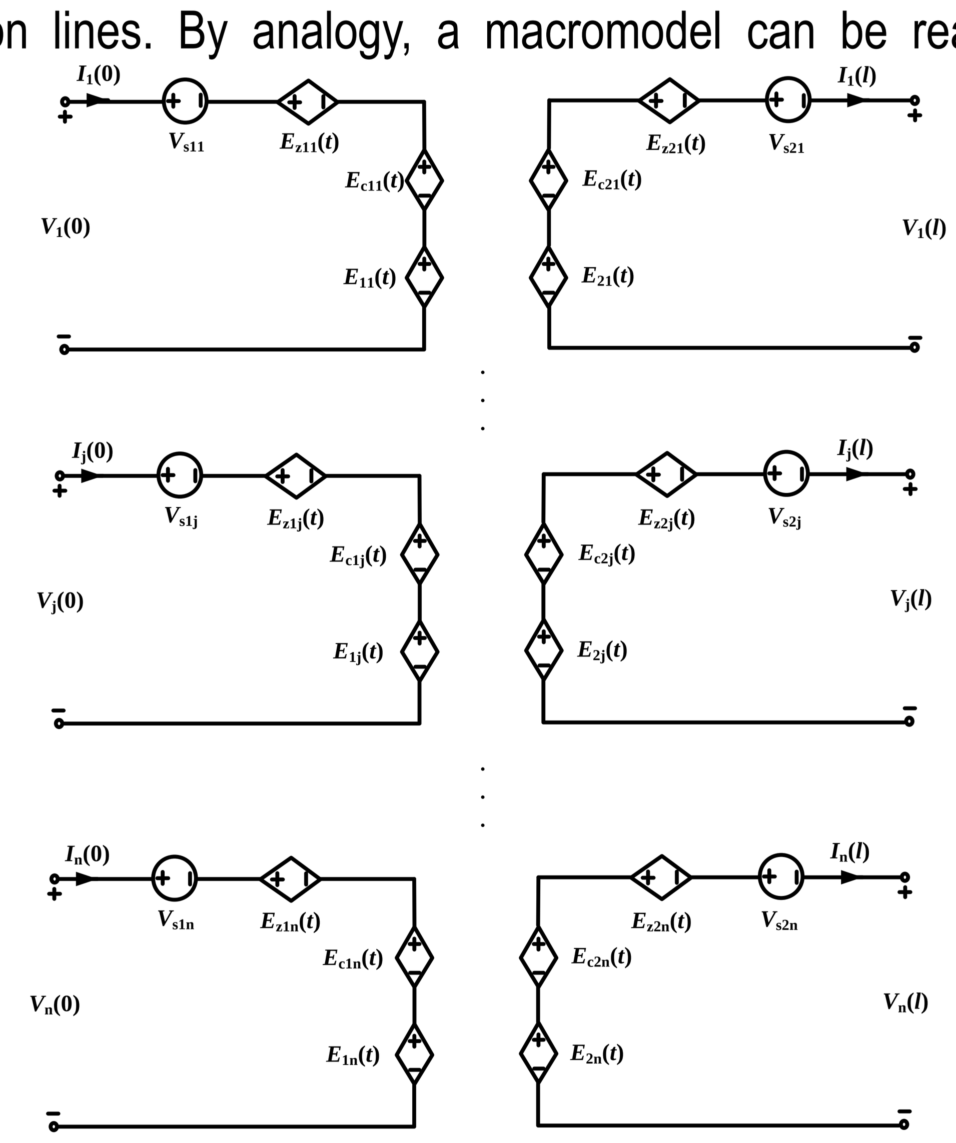
Adopted methodologies

- The voltages and currents along the buried cables induced by external field can be evaluated in terms of Agrawal's model equations in Laplace domain:

$$\frac{d}{dx}\mathbf{V}(x,s)+\mathbf{Z}(s)\mathbf{I}(x,s)=\mathbf{E}_x^{tran}(x,s) \qquad \Rightarrow \qquad \frac{d}{dx}\mathbf{V}(x,t)+\boldsymbol{\xi}(t)*\frac{d}{dt}\mathbf{I}(x,t)=\mathbf{E}_x^{tran}(x,t)$$

$$\frac{d}{dx}\mathbf{I}(x,s)+\mathbf{Y}(s)\mathbf{V}(x,s)=\mathbf{0} \qquad \Rightarrow \qquad \frac{d}{dx}\mathbf{I}(x,t)+\boldsymbol{\eta}(t)*\frac{d}{dt}\mathbf{V}(x,t)=\mathbf{0}$$

- We have proposed a time-domain macromodeling algorithm utilizing the ABM in SPICE and generalized MoC for cases of field coupling to overhead multiconductor transmission lines. This methodology is extended here to model above equations for underground power transmission lines. By analogy, a macromodel can be realized in terms of an equivalent circuit



Novel contributions

- A time-domain macromodeling method is proposed to calculate the transient responses of buried transmission lines to incident field coupling. The frequency-dependent variables are modeled using frequency response tables in ABM directly. Time-domain convolution is also calculated by the solver. There is no need to implement the procedures of time and spatial discretization and high order approximation generally used in FDTD method.
- Approximation expressions for integral formulation of self and mutual ground impedance and admittance is proposed by analogy with existing closed-form expressions. It has been assessed that the evaluation time is reduced to only about 2% time of that of analytic integral formulation on the same computing platform.

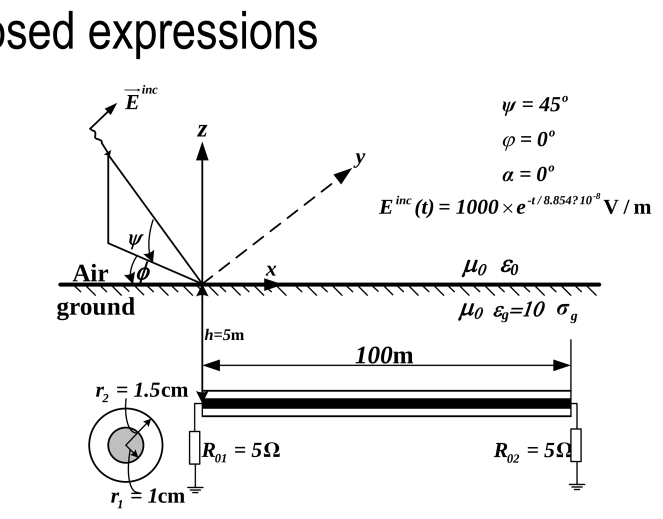
$$Z_{gjk}=\frac{s\mu_0}{2\pi}\left\{\ln\left[\frac{1+\sqrt{\gamma_g^2+k_x^2}\,y_{jk}}{\sqrt{\gamma_g^2+k_x^2}\,y_{jk}}\right]+\left[\frac{2e^{-(h_i+h_j)\sqrt{\gamma_g^2+k_x^2}}}{4+(\gamma_g^2+k_x^2)y_{jk}^2}\right]\right\}$$

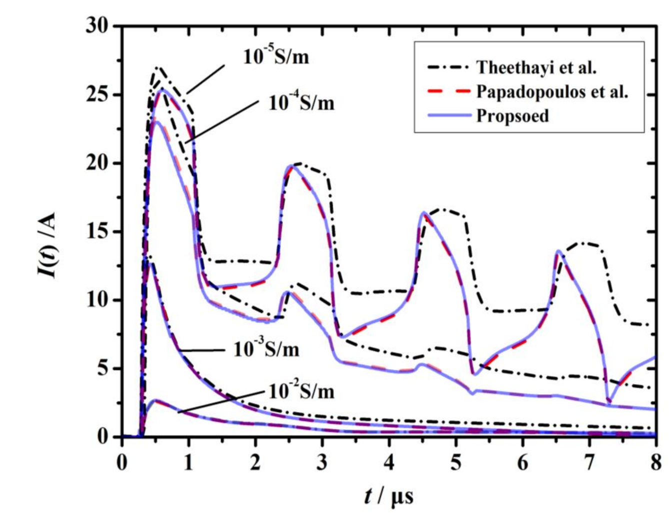
$$Y_{gjk}=sP_{gjk}^{-1}$$

$$P_{gjk}=\frac{s}{2\pi(\sigma_g+s\varepsilon_0\varepsilon_{rg})}\times\left\{\ln\left[\frac{1+\sqrt{\gamma_g^2+k_x^2}\,y_{jk}}{\sqrt{\gamma_g^2+k_x^2}\,y_{jk}}\right]+\left[\frac{2e^{-(h_i+h_j)\sqrt{\gamma_g^2+k_x^2}}}{4+(\gamma_g^2+k_x^2)y_{jk}^2}\right]+\int_0^{+\infty}G(\lambda)\cos(y_{jk}\lambda)\,d\lambda\right\}$$

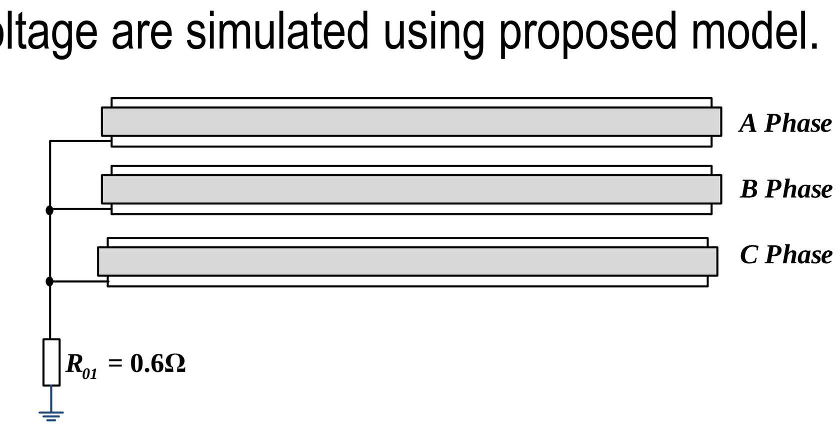
Addressed research questions/problems

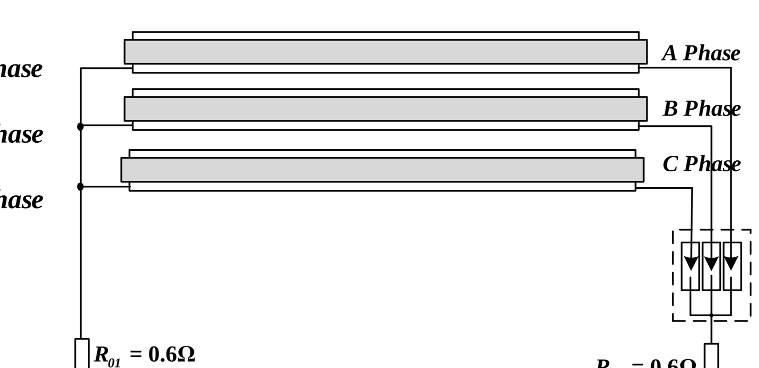
- The impact of different earth return formulations on transient responses of buried cables is considered. Transient responses at the far end of the cable obtained using AI expressions and proposed approximations have comparable results, which indicates the validity of the proposed expressions

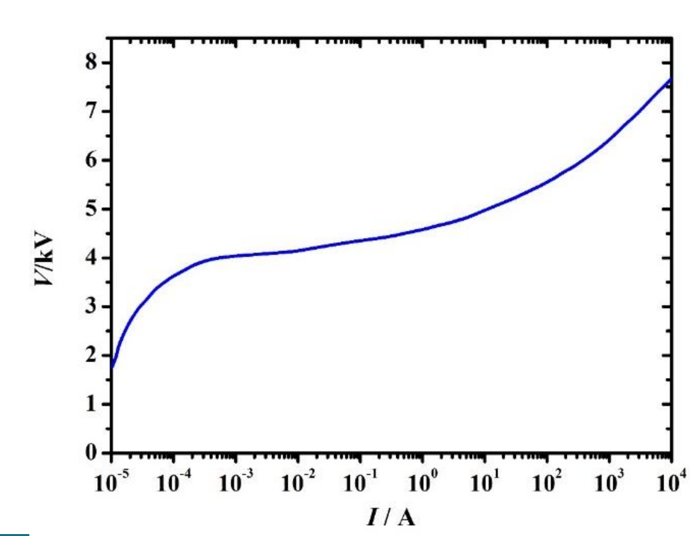


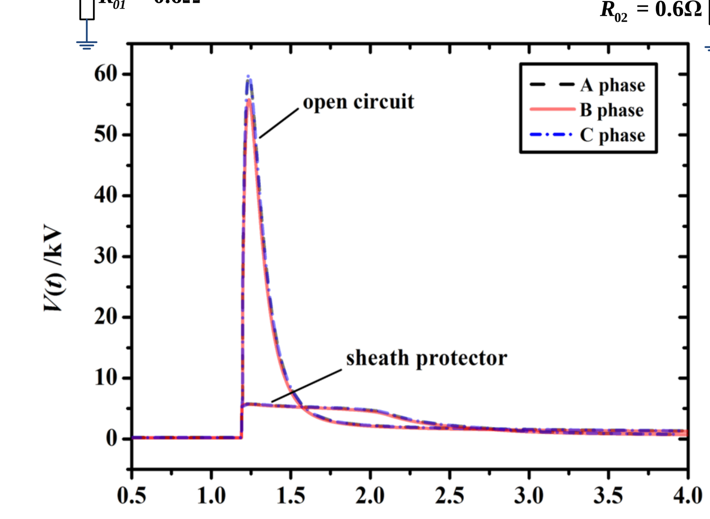


- The incident field couples to buried 500-m long horizontally-configured three-phase 110 kV power cables. For protection, the one end of the metallic sheath of the buried cable is connected to a sheath protector, which behaves as a nonlinear device. The induced voltage are simulated using proposed model.









Submitted and published works

- Ziweihua Du, Yan-zhao Xie, Flavio G. Canavero. A Spice-compatible Macromodel for Field Coupling to Multi-conductor Transmission Lines. IEEE Transactions on Electromagnetic Compatibility PP.99(2018):1-7.
- **Ziweihua Du**, Yan-zhao Xie, Ning Dong, Flavio G. Canavero.A Spice-compatible Macromodel for Field Coupling to Underground Transmission Lines Based on the Analog Behavioral Modeling.(submitted)
- **Ziweihua Du**, Yan-zhao Xie. A SPICE Model for Incident Field Coupling to Lossy Overhead Transmission line[C]// The 7th IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies(MAPE). October 2017, Xi'an, China. (Best Paper Award)
- **Ziweihua Du**, Yan-zhao Xie. Calculation of high electromagnetic pulse coupling to lossy transmission line based on DEPACT macromodel[C]// Asia-Pacific International Symposium on Electromagnetic Compatibility. 2016:818-820.

Future work

- Macromodeling method based on MoM. This method can consider the cases of lines in which the TEM mode is not valid anymore, such as non-uniform TLs and TLs with vertical risers.

List of attended classes

- None

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