STM JOURNALS
Journal of
Power Electronics & Power Systems
https://journals.stmjournals.com/jopeps

ISSN: 2249-863X (Online)
ISSN: 2321-4244 (Print)
Volume 15, Issue 1, 2025
January–April
DOI (Journal): 10.37591/JoPEPS

Review JoPEPS

Electromagnetic Transients in Strongly Non-Uniform Overhead High-Voltage Lines

Mohamed Mostafa Saied[1,]*

Abstract

This paper addresses the electromagnetic transients in high strongly non-uniform overhead voltage lines. For their simulation, a novel Laplace-domain approach has been introduced. The voltage and current patterns in terms of location and complex frequency are determined by a set of simultaneous algebraic and partial differential equations. To solve them numerically, an effective Mathematica code is proposed. By contrasting the outcomes of their application to multiple case studies with those acquired elsewhere using different methodologies, the model and related computer program are validated. For contemporary power systems, electromagnetic transients in overhead high-voltage lines pose special opportunities and challenges, especially in highly non-uniform setups. The basic causes, mathematical modelling, and applications of these transients are examined in this article. Transient behavior under non-uniform line conditions—such as changes in conductor shape, ground proximity, and environmental factors—is highlighted. In order to improve grid stability and reliability, the paper also examines mitigation strategies and suggests directions for further study.

Keywords: Electromagnetic, transients, simulation, non-uniform, high-voltage lines, *Mathematica*, numerical solutions, Laplace inversion. parameter studies

INTRODUCTION

The analysis and mitigation of transient stresses in high-voltage power networks have attracted the interest of researchers in recent years. A large percentage of the resulting investigations have focused on issues related to overhead transmission lines and/or underground cables. Most numerical solution approaches can be classified into time-domain and Laplace-s-domain-based techniques. The latter is limited to situations involving linear elements. Nonlinear situations, such as those involving corona discharges and magnetic saturation, require time-domain solutions.

However, special consideration is devoted to the location dependence of the circuit parameters of transmission lines. Uniform lines can be approximated as independent, which is the mainstream or default situation. Non-uniform lines with strong non-uniformity appear in several interesting cases, such as river crossings, transformer wingdings, and high-voltage towers. There are no general analytical solutions for such cases; therefore, only numerical time-domain or frequency-domain approaches are possible. The stability and safety of power systems depend heavily on the behavior of electromagnetic transients in high-voltage (HV) transmission lines. Transient phenomena are amplified by non-uniform overhead lines, which are defined by notable differences in the electrical and physical properties. Accurate modelling and analysis are crucial because these changes may be caused by complicated line geometry, a variety of terrain profiles, and proximity to other infrastructures [1].

Figure 1 depicts one such example. It exhibits dependence on the characteristic impedance of the

*Author for Correspondence
Mohamed Mostafa Saied
E-mail: mmsaied002@gmail.com

[1]Professor (Emeritus), Department of Electrical Engineering, Kuwait University, Kuwait

Received Date: December 20, 2024
Accepted Date: December 27, 2024
Published Date: January 07, 2025

Citation: Mohamed Mostafa Saied. Electromagnetic Transients in Strongly Non-Uniform Overhead High-Voltage Lines. Journal of Power Electronics & Power Systems. 2025; 15(1): 30–36p.

line Zc(x) on coordinate x, which is the distance of the point under consideration from the line's sending end in meters [2].

Reference presented a possible solution based on the proper sectionalizing of the line into a proper number of identical uniform cascaded sections and utilizing the well-known relations of linear two-port theory [3]. This was followed by a numerical Laplace inversion of the derived voltage and current expressions in the s-domain. Typically, this is implemented using a well-known method. Hosono's algorithm, the main drawback of this approach, is the relatively heavy computational burden in terms of computation time and required computer memory. This study attempts to improve this situation and presents an efficient, fast, and user-friendly technique in this area of power engineering research. It is believed that this contribution will be helpful for practicing protection engineers and students. In power systems, faults are a major source of electromagnetic transients, posing difficulties that require careful consideration and mitigation. To ensure grid stability and resilience in a changing energy landscape, utilities can reduce the impact of fault-induced transients by utilizing cutting-edge detection technology, resilient system designs, and creative research [4].

Electromagnetic Transient Causes

The source of electromagnetic transients is:

- *Switching actions:* Unexpected modifications to the line setup, such as switching capacitors or breaker actions.
- *Fault conditions:* Steep wavefronts are caused by lightning strikes or short circuits.
- *Variations in load:* The abrupt shifts in the load have the potential to spread temporary disruptions.
- *Line non-uniformity:* Variations in tower height, sag, and uneven conductor spacing all worsen transient behavior [5].

Attributes of Irregular Lines

There are various ways that strongly non-uniform lines vary from uniform configurations:

- *Variations in impedance:* Line impedance is affected by uneven conductor spacing and ground proximity.
- *Propagation speed:* Wave propagation velocity is impacted by modifications in line geometry.
- Transient reflections and refractions are caused by interfaces between segments having disparate electrical characteristics.

METHOD OF ANALYSIS

The first step in the proposed approach is to formulate the profile of the line's characteristic or surge impedance Zc(x), as indicated in the sample idealized overhead line shown in Figure 1.

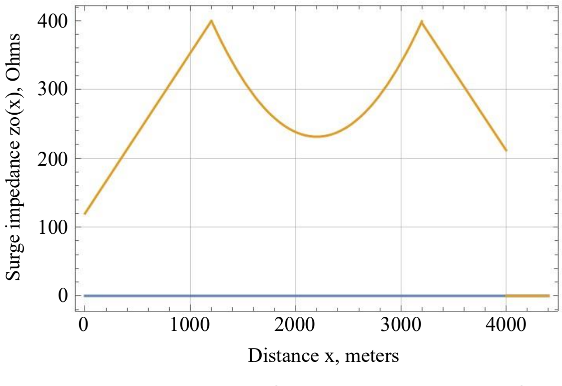

Figure 1. An Example for the dependence of the characteristic impedance *Zc(x)* of a strongly non-uniform overhead line on the distance *x* from the sending end.

The following formulas can be used to describe the impedance characteristic for this specific line:

$$Z1(x) = 400\left[0.3 + \left(\frac{0.7}{1200}\right)\right]x$$

$$Z2(x) = 240 + 160[(x - 2200)/1000]^2$$

$$Z3(x) = 400\left[0.3 + \left(\frac{0.7}{1200}\right)\right](4400 - x) \tag{1}$$

Where $Z_1(x)$, $Z_2(x)$, and $Z_3(x)$ are the impedance expressions for the left, middle, and right-line sections, respectively.

From the well-known relations among the speed of light, surge impedance, and line parameters/m *l* and *c*, the following relations can be derived:

$$c(x) = \frac{1}{\text{speed.zo}(x)} \tag{2}$$

$$l(x) = \frac{\text{zo}(x)}{\text{speed}} \tag{3}$$

This leads to the distributions of the line's capacitance and inductance per meter, as indicated in the plots shown in Figure 2(a) and (b), respectively.

The line's transient response is governed by the following simultaneous differential equations:

$$\frac{\partial v}{\partial x} = -l(\mathrm{x})\frac{\partial i}{\partial t} - i.r, \tag{4}$$

And

$$\frac{\partial i}{\partial x} = -\mathrm{c}(\mathrm{x})\frac{\partial v}{\partial t} \tag{5}$$

Subject to the boundary conditions, which are stated in terms of the line termination and the anticipated source voltage. They can be solved for the voltage and current s-domain expressions using the ParametricNDSolve software *Mathematica* (Version 14.0), [5, 6]. The time response can be obtained using the previously mentioned Hosono's algorithm for numerical Laplace inversion.

Useful Consequences

It is essential to comprehend electromagnetic transients in non-uniform lines for:

- Making sure that there is enough insulation to resist brief overvoltage is known as insulation design.
- System protection is the process of creating defenses against temporary disruptions.
- Preventing cascading failures brought on by transient propagation is known as grid reliability.

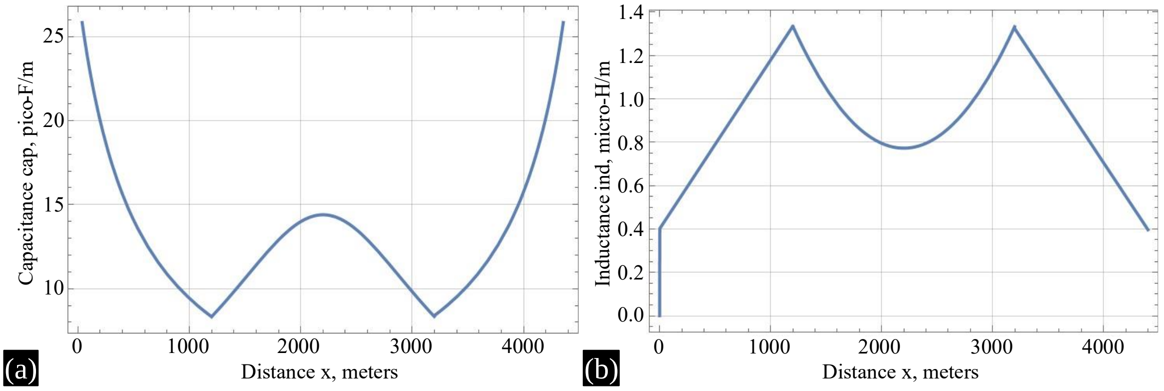

Figure 2. (a) The profile of the line's capacitance per meter, (b) The profile of the line's inductance per meter.

Strategies for Mitigation

A number of tactics deal with temporary problems:

- *Surge arresters:* Take in and release short-term energy.
- *Line surge capacitors:* Wavefronts that are smooth and temporary.
- *Shielding wires:* Lessen transients caused by lightning.
- *Optimized line design:* Reduce construction-related irregularities.

Behavior of Electromagnetic Transients in High-Voltage Transmission Lines

Modern power systems rely on high-voltage transmission lines to transmit electricity efficiently over long distances. These lines are vulnerable to electromagnetic transients, which are high-frequency brief disruptions caused by abrupt adjustments to the electrical system. It is crucial to comprehend how these transients behave to guarantee system dependability and avoid equipment damage [6–10]. The operation of power systems is seriously hampered by electromagnetic transients in high-voltage transmission cables. In power systems, electromagnetic transients are unavoidable occurrences that are usually caused by external events such as lightning strikes, faults, or switching activities. Fault circumstances such as equipment failures, ground faults, and short circuits are important contributors to this problem. Transients caused by faults can spread quickly throughout transmission and distribution networks, which presents problems for protective systems, equipment insulation, and grid stability in general. Utilities can improve grid resilience and stability by comprehending their behavior and using sophisticated modelling and mitigation strategies [11]. Addressing new issues in the ever-changing energy sector requires ongoing research and technological development. Current studies concentrate on the following:

- *Smart grid integration:* Using Internet of Things (IoT) and sophisticated sensors to detect transients in real-time.
- *Machine learning:* Forecasting ephemeral behavior for preventative action.
- Creating conductors and insulators with improved transient resistance is an example of material innovation.
- Enhancing models to better capture fleeting phenomena at higher resolutions is known as high-frequency modelling.

SAMPLE RESULTS

This section presents the line’s transient response in various case studies considering the line data, its termination impedance, and the waveform of the voltage source initiating the transient consideration. The plots in Figure 3 depict the waveforms of the transient voltage at 660 m from the source are shown in Figure 4 [12]. The source voltage had a unit step waveform. The case of short-circuit termination, described by plot in Figure 3(d), is of special interest. It can be seen that the final value agrees with the results available from the simple DC analysis, and the result is in acceptable agreement with those shown in Figure 5, which is obtained using the sectionalization technique implemented in reference in Figure 6 [13].

Prospective Research Paths

To improve our knowledge of electromagnetic transients in non-uniform lines, we need to

- *Improved simulation tools:* Creating algorithms that balance computing efficiency and accuracy.
- Investigating transient behaviors in grids with dispersed generation is the focus of smart grid integration.
- *Material innovation:* Researching cutting-edge materials to enhance insulation and conductivity.
- *Field measurements:* Increasing the scope of empirical research to support and improve theoretical models.

The acceptable agreement between the two current plots in Figures 3(a) and (b), addressing the short-term conditions using both sectionalization and the proposed technique, can be easily recognized. The rate of current increase with time in cases Figure 6-(a) and 6-(b) pertinent to the short-circuit case are almost identical [14].

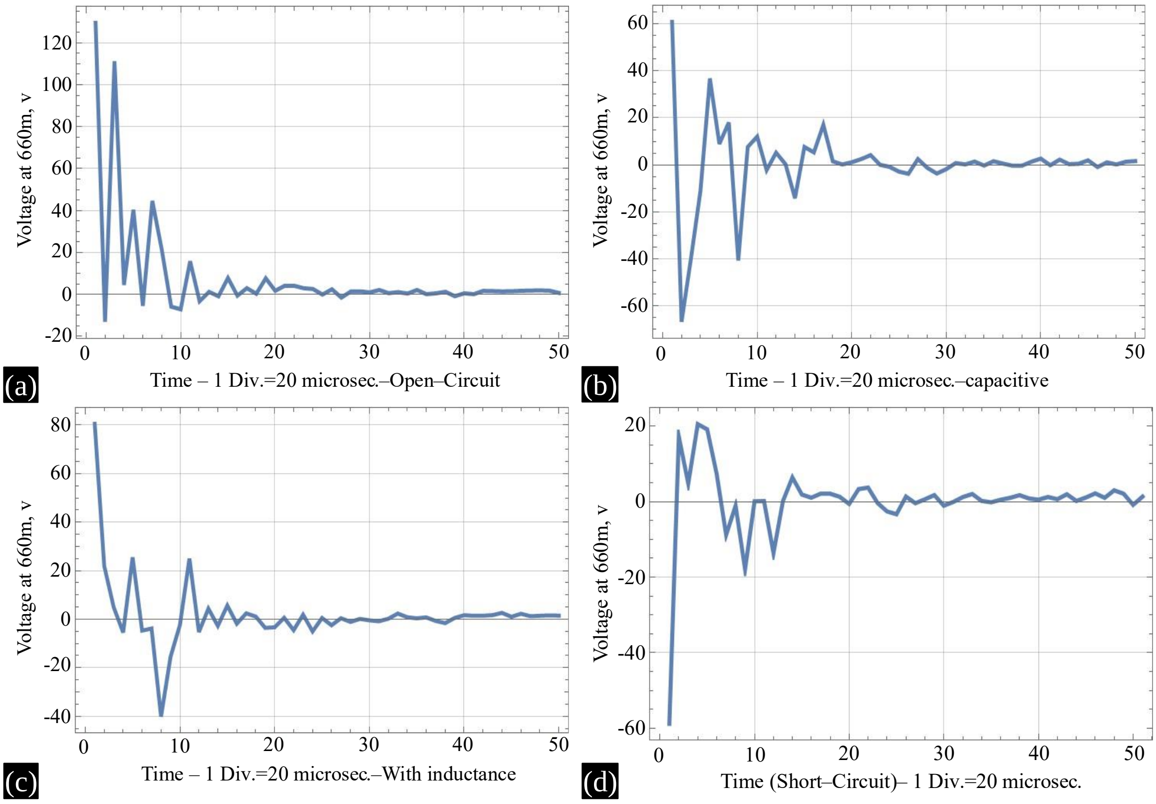

Figure 3. (a)–(d) Transient response of the voltage at *x*=660 meters for different line's terminations. The considered time range is from zero to 1000 microseconds, using the suggested technique.

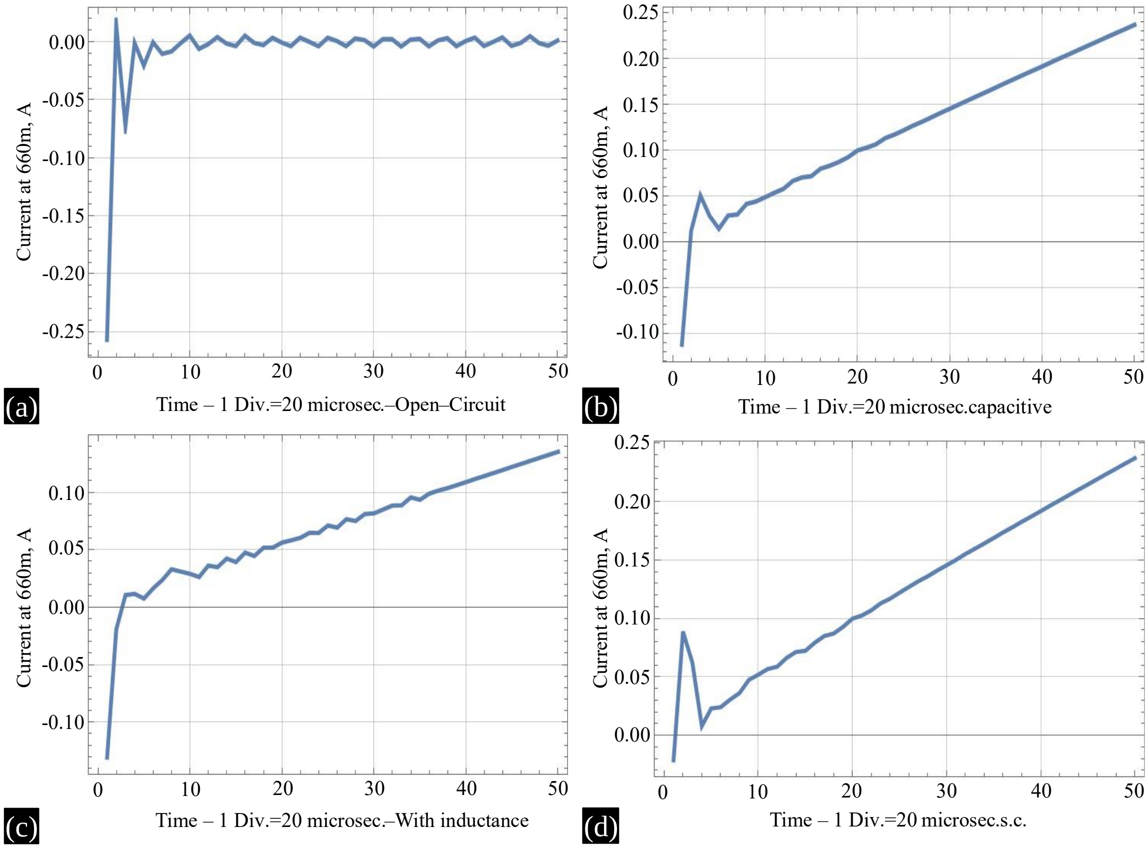

Figure 4. (a)–(d) Transient response of the current at x=660 meters for different line's terminations.

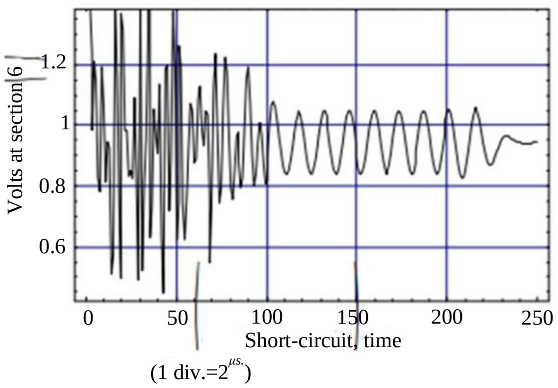

Figure 5. The transient voltage as determined using the sectionalization technique. Source: Adopted from [8].

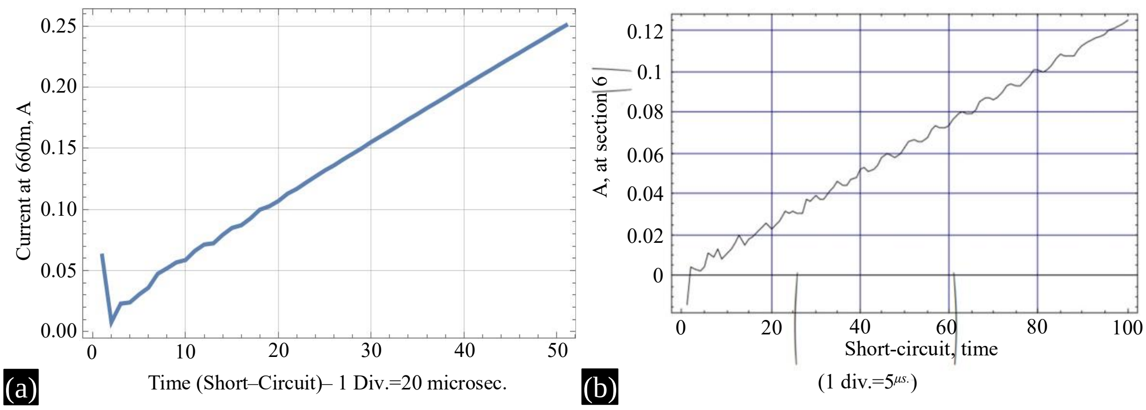

Figure 6. (a) and (b) Transient current determined using sectionalization technique. (a) Proposed technique.

An intricate yet crucial field of research for contemporary power systems is electromagnetic transients in very non-uniform overhead high-voltage lines. The power sector can improve grid resilience and guarantee dependable energy delivery under increasingly unpredictable conditions by advancing modelling methodologies, honing mitigation strategies, and encouraging innovation [15, 16].

CONCLUSIONS

A new model for analyzing electromagnetic transients in strongly non-uniform overhead lines is presented. The proposed approach considers the non-uniform lines' circuit parameters, their loading conditions, and the waveform of the source voltage. A *Mathematica* program was developed and applied to several case studies. The results illustrate the various transient voltages and currents along a typical strongly non-uniform line. Several computer runs were performed to validate the proposed model and results. The proposed procedure is simple, accurate, direct, and user-friendly. For practicing engineers, as well as graduate and undergraduate power engineering students, it can be a useful and efficient teaching and training tool.

REFERENCES

1. Grainger J, Stevenson WD. Editors. Current and Voltage Relations on a Transmission Line. In: Power System Analysis. United Kingdom: McGraw-Hill Education; 1994. Pages 193-237.
2. Elgerd OI. Electric Energy Systems – An Introduction. 2nd edn. United Kingdom: McGraw-Hill; 1982.
3. Weeks WL. Transmission and Distribution of Electrical Energy. New York City: Harper & Row Publishers; 1981.

4. Convery AM, Kaufman M. Regulation as a force for hybrid organization: Evidence from the Bonneville Power Administration (1980–2012). Account Audit Account J. 2022;35(3):658–80. doi:10.1108/AAAJ-12-2019-4327.
5. Saied MM. Novel Laplace-domain approach to the electromagnetic transients in compensated high voltage power lines. Int J Electr Mach Anal Des. 2024;2:15–21.
6. Begamudre RD. Extra-High Voltage AC Transmission Engineering. 2nd edn. Hoboken, New Jersey, United States: Wiley-Eastern Limited; 1986.
7. Safar YA, Saied MM. The feasibility of multiple-capacitor long line series compensation. Electr Mach Power Syst. 1995;23:483–99. doi:10.1080/07313569508955638.
8. Saied MM. Effect of the conductor sag on the electromagnetic transients in high voltage lines. Int J Analog Integr Circuits. 2024;10(1):8–16.
9. Musa BU, Siew WH, Judd MD. Computation of transient electromagnetic fields due to switching in high-voltage substations. IEEE Trans Power Deliv. 2010;25:1154–61. doi:10.1109/TPWRD.2009.2034008.
10. Saied MM. Optimal long line series compensation. IEEE Trans Power Deliv. 1986;1:248–53. doi:10.1109/TPWRD.1986.4307957.
11. Morgan L, Barcus JM, Ihara S. Distribution series capacitor with high-energy varistor protection. IEEE Trans Power Deliv. 1993;8:1413–9. doi:10.1109/61.252668.
12. Saied M. Transient response of power networks to pulse inputs of nonstandard wave forms: analysis and case studies. Int J Analog Integr Circuits. 2022;9:25–32.
13. Magadum RB, Kulkarni DB. Performance enhancement of distribution network by optimal placement of multiple capacitors using FKBC. In: Advances in Intelligent Systems and Computing (AISC, volume 1119). Springer; 2020. p. 591–602. doi:10.1007/978-981-15-2414-1_59.
14. Saied M. A new approach to the Laplace-domain transient analysis of non-uniform lines with application to power line towers. Trends Electr Eng. 2019;9:1–10.
15. Montella C, Diard JP. (2015). Comparing four methods of numerical inversion of Laplace transforms (NILT) [Online]. Wolfram Demonstrations Project. Available from: https://demonstrations.wolfram.com/ComparingFourMethodsOfNumericalInversionOfLaplaceTransformsN/
16. Hosono T. Numerical inversion of Laplace transform and some applications to wave optics. Radio Sci. 1981;16:1015–9. doi:10.1029/RS016i006p01015.