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Electromagnetic Transients in Compensated Power Lines- Revisited: New Approach and Case Studies

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Abstract

This paper addresses the simulation of the electromagnetic transients developed in high voltage power lines, which are initiated by lightning discharges. The analysis can handle both individual and simultaneous series inductive and shunt capacitive compensation types. The sizes and locations of the compensating elements are included in the analysis. The derived Laplace s-domain mathematical model applies the concept of the ABCD transmission constants representing equivalent two-port networks. The resulting currents and voltages along the line will be functions of the location and the Laplace operator s. A Mathematica code based on the Hosono algorithm is used for the numerical inversion of these expressions in order to get the corresponding results in the time domain. The model and computer code are validated via discussing the results of case studies with available solutions.

Keywords: Electromagnetic, transients, simulation, high voltage lines, series, parallel, compensation, Mathematica, numerical Laplace inversion. Hooson algorithm, parameter study

INTRODUCTION

The stability and dependability of contemporary power systems are severely hampered by electromagnetic transients in compensated power lines. This paper revisits the phenomenon of electromagnetic transients in compensated power lines and presents a novel method for mitigating and analysing them. We employ sophisticated modelling techniques and real-time simulation tools, and we examine multiple case studies to demonstrate the usefulness of these approaches. Our results show that a more sophisticated view of these transients can result in better compensating schemes, boosting the resilience and overall performance of the system. The maximum power transmission capability of transmission lines can be effectively increased using series compensating capacitors [1–7, 14]. The achievable improvement depends greatly on their size and location. [11,13] References [8–10, 12] present procedures for identifying the optimal values of these parameters based primarily on economic considerations. Shunt coils at selected points along the line can be an important tool for controlling its voltage profile, [14]. Generally, multiple series capacitors and shunt coils can be used for both types of compensation.

In recent years, several investigations have been conducted into the transient concentrated stresses across these elements and the related protection issues, [8]. Sophisticated computer programs, such as the well known the Electromagnetic Transient Program (EMTP) [4], are being successfully used for assessing and mitigating the eventually excessive transient voltages and currents such as the use of high power varistors, [8]. In some cases, this can be accompanied by a considerable computation burden in terms of the required memory and long execution time. Most practicing engineers, however,

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need more affordable and user-friendly procedures and techniques for identifying, estimating and mitigating the adverse effects related to the transients developed in compensated high voltage power lines. This paper is a step in that direction.

THE METHOD OF ANALYSIS

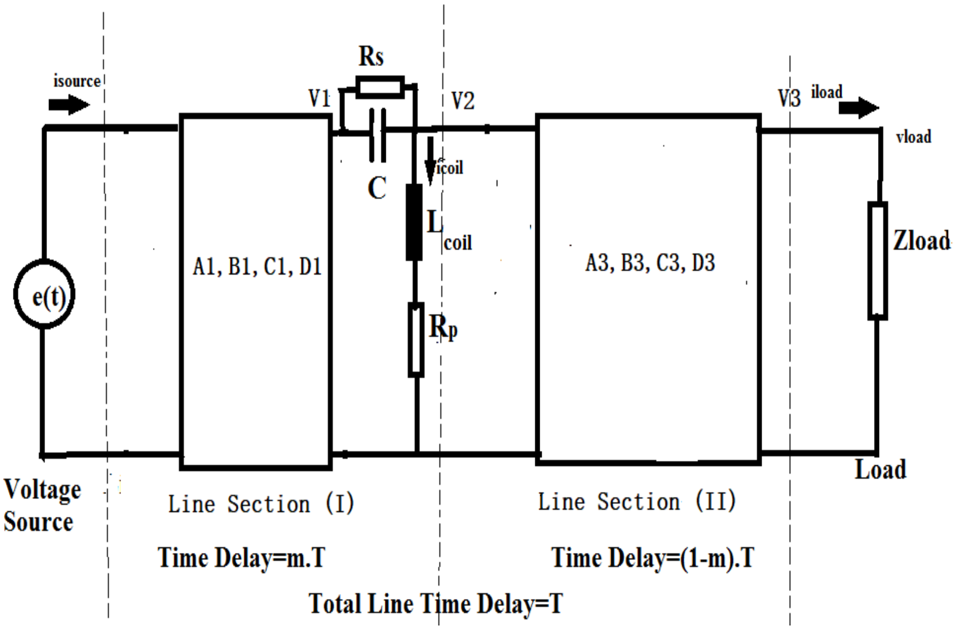


Figure 1. The assumed equivalent circuit

Figure.1 illustrates the compensated line under study. It has a time delay or wave propagation time of T seconds, or equivalently, a total length of $\mathrm{T} \times 3 \times 10^8$ meters. It is terminated by a general s-domain load impedance Z_{load}, which can be a function of the Laplace operator s. Without any loss of generality and for the sake of simplicity, the transients under study are assumed initiated by the ideal step voltage source of the time expression:

$$e(t) = 1000.u[t], \text{where } u[t] \text{ is the usual unit} - \text{step function.}$$

The compensating elements are located at a point dividing the long line with the ratio m:(1-m). The corresponding delay times of the two resulting line sections (I) and (II) are, therefore [m.T] and [(1-m). T], respectively.

According to references [1-3], the generalized circuit or transmission constants of the line section on the left-hand side are:

$$A1 = D1 = \cosh[m.T.s]$$

$$B1 = Zo \sinh[m.T.s]$$

$$C1 = \frac{\sinh[m.T.s]}{Zo}$$

Where Zo and T are the line's surge impedance and line’s total time delay, respectively. The fraction m denotes the per unit length of the left section based on the line's entire length.

Similarly, the constants representing the line section (II) on the right-hand side are:

$$A3 = D3 = \cosh[(1 - m).T.s]$$

$$B3 = Zo\sinh[(1-m).T.s]$$
$$C3 = \frac{\sinh[(1-m).T.s]}{Zo}$$

If the line is assumed lossless, the equivalent circuit shown in Figure.1 will describe the compensated line in the Laplace s-domain [1-3]. The series and shunt elements of both line sections will be pure inductive and pure capacitive, respectively.

It can be shown that the compensating network (located between the two-line sections) has the following transmission constants:

$$A2\ (S) = (Y(S).Z\ (S) + 1\,\frac{B2(S)=Z(S)}{C2(S)+Y(S)=D2(S)=1}$$

Where Z(s) represents the equivalent impedance of C and Rs connected in parallel and Y(s) is the admittance of the elements L and Rp connected in series, [6].

It can be shown that the required value of the concentrated series capacitor C required in order to achieve a ks per unit compensation of the total line inductive reactance is

$$C = \frac{1}{(Ksw2.Ind\ length}$$

Where ind, length are the inductance per unit length and the line's total length, respectively. Similarly, in order to achieve a kp per unit compensation level of the total line capacitive admittance, the required inductance L of the shunt coil is

$$\omega L = \frac{2kp}{\omega.c.length}\ \text{Henries.}$$

Where c is the capacitance per unit length. The circuit can simulate either the series or parallel (or both) compensation types depending on the proper selection of the two auxiliary resistances Rs and Rp. They can be selected either zero or infinity according to the following Table 1:

Table 1. Resistance comparison w. r. t. compensation type

Compensation Type	**Resistance Rs**	**Resistance Rp**
No Compensations	zero	Infinity
Both Types	Infinity	zero
Series Capacitive only	Infinity	Infinity
Shunt Inductive Only	zero	zero

Based on the relations governing the equivalent circuits of cascaded two-port networks listed in the Appendix A of reference [1], it is possible to find the input impedance Z_{input}[s] seen by the source of the voltage v_{source} [s]. The first step is to use the following equations for the total transmission constants (A_{total}, B_{total}, C_{total} and D_{total}) of the three cascade-connected two-port networks:

- A_{total} = A2(A1.A2)+B1.C2)+C3(A1.B2+B1.D2)
- B_{total} = B3(A1.A2+B1.C2)+(A1.B2+B1.D2)D3
- C_{total} = A2(A2.C1+C2.D1)+C3(B2.C1+D1.D2)
- D_{total} = B3(A2.C1+C2.D1)+(B2.C1+D1.D2)D3

  And

$$Z_{\text{input}} = \frac{\text{Atotal.Zload+Btotal}}{\text{Ctotal.Zload+Dtotal}}$$

Accordingly, the expression of the source current is

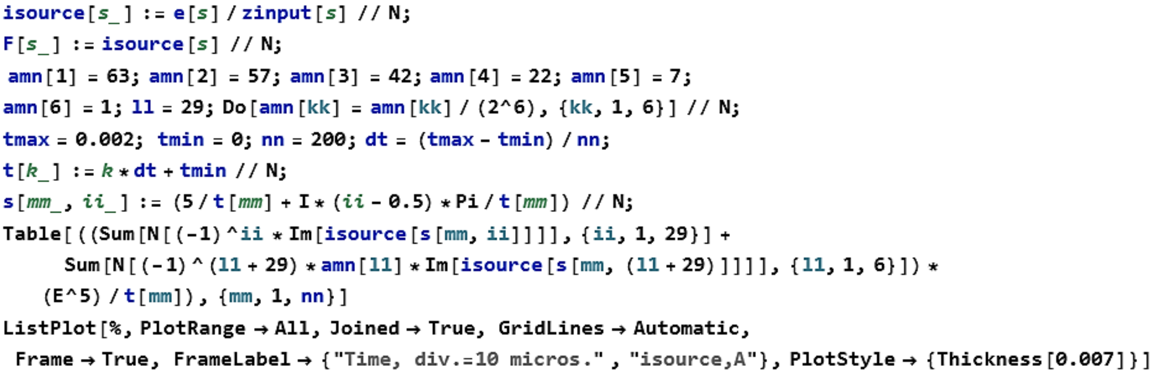
$$isource(s) = \frac{e(s)}{\text{Zinput}(s)}$$

e(s) denotes the Laplace expression for the source voltage e(t). It is assumed (1000/s) in this study. Applying matrix algebra, the s-domain expressions of the other voltages and currents can be easily derived.

They could then be numerically inverted into the time domain using one of the available algorithms.

The Numerical Laplace Inversion Based on Hosono's Algorithm shown in Figure 2. As an example algorithm, the Mathematica statement given below and the corresponding output plots depicted in the two figures Figure. 3 and Figure.4 indicate how to numerically invert and plot the Laplace expression of the current $i_{\text{source}}[s]$, expressed as a function of the Laplace operator s. The plots cover the time ranges of 2 and 20 milliseconds, respectively.

Immediately after switching the source, the value of the source current (2.35A) agrees with the expected value 1000V/Z_0. It drops sharply to about 0.5A after approximately 267 micro-seconds which is double the line's delay time. As expected, the source current's final value of 2 A will flow through the parallel connection of the load impedance zo and the shunt resistance Rp of the coil's shunt branch, 1000 Ohms each.



```
isource[s_] := e[s] / zinput[s] // N;
F[s_] := isource[s] // N;
 amn[1] = 63; amn[2] = 57; amn[3] = 42; amn[4] = 22; amn[5] = 7;
amn[6] = 1; ll = 29; Do[amn[kk] = amn[kk] / (2^6), {kk, 1, 6}] // N;
tmax = 0.002;  tmin = 0; nn = 200; dt = (tmax - tmin) / nn;
t[k_] := k * dt + tmin // N;
s[mm_, ii_] := (5 / t[mm] + I * (ii - 0.5) * Pi / t[mm]) // N;
Table[((Sum[N[(-1)^ii * Im[isource[s[mm, ii]]]], {ii, 1, 29}] +
      Sum[N[(-1)^(l1 + 29) * amn[l1] * Im[isource[s[mm, (l1 + 29)]]]], {l1, 1, 6}]) *
    (E^5) / t[mm]), {mm, 1, nn}]
ListPlot[%, PlotRange → All, Joined → True, GridLines → Automatic,
 Frame → True, FrameLabel → {"Time, div.=10 micros." , "isource,A"}, PlotStyle → {Thickness[0.007]}]
```

Figure 2. Numerical Laplace inversion

For more details, Reference [13] should be consulted.

Sample Results

The input data of this case study are as follows:

- l=1.414*10^{-6} H/m; (line's inductance/unit length)
- c=7.79*10^{-12} F/m; (line's capacitance/unit length)
- m=0.5; (The length of the line's left section in perunit)
- zload= 1000 Ohms;
- omega=314 c/s;
- Light speed=3*10^{8} m/s;
- length=40000 m;
- kshunt=0.1 ; (total shunt compensation in per unit)
- kseries=0.1 ; (total series compensation in per unit)

- zo=Sqrt[l/c] (the line's surge impedance)
- T=length/speed (the line's time delay, seconds)
- Rs= 0.1 Ohm;
- Rp= 1000 Ohm
- $C=1/(k_{series}*omega^2*l*T*speed)$
- $L=k_{shunt}/(omega^2*c*T*speed)$

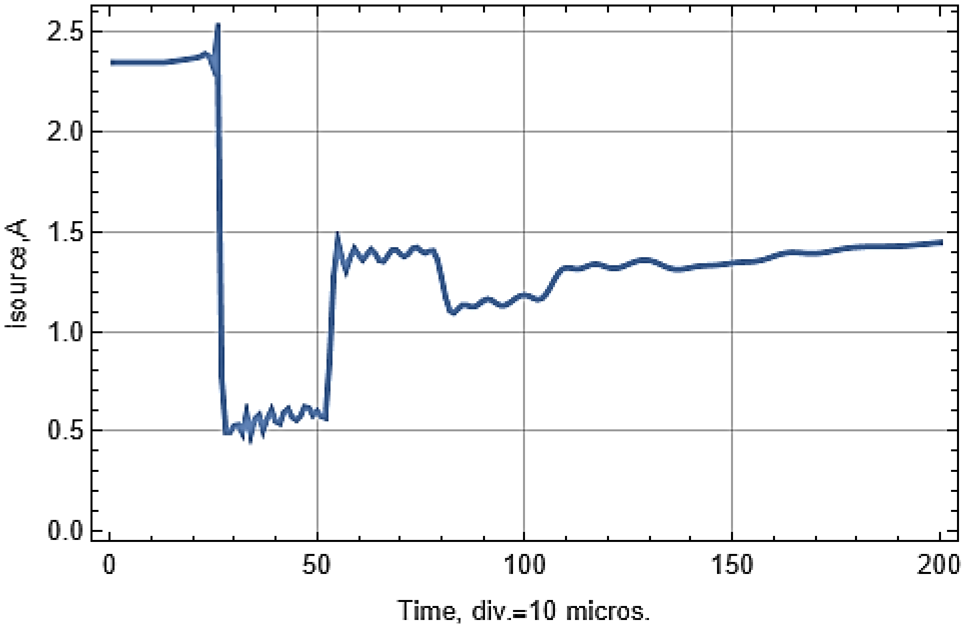


Figure 3. The source current during the time range 0-2ms

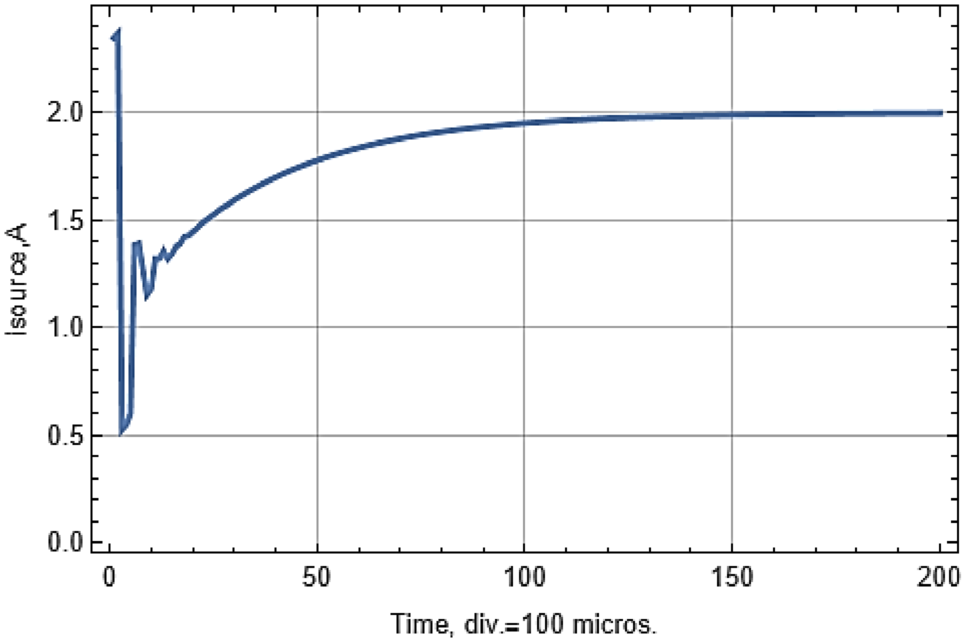


Figure 4. The source current during the time range 0-20ms

The response of the load current is illustrated in Figure 4 over the time range $0 \leq t \leq 2500$ microseconds. It indicates that the load current starts to deviate from its initial zero value only after about 135 microsec, which is the time delay of the 40-km line. The steady-state load current assumes the expected value of 1A.

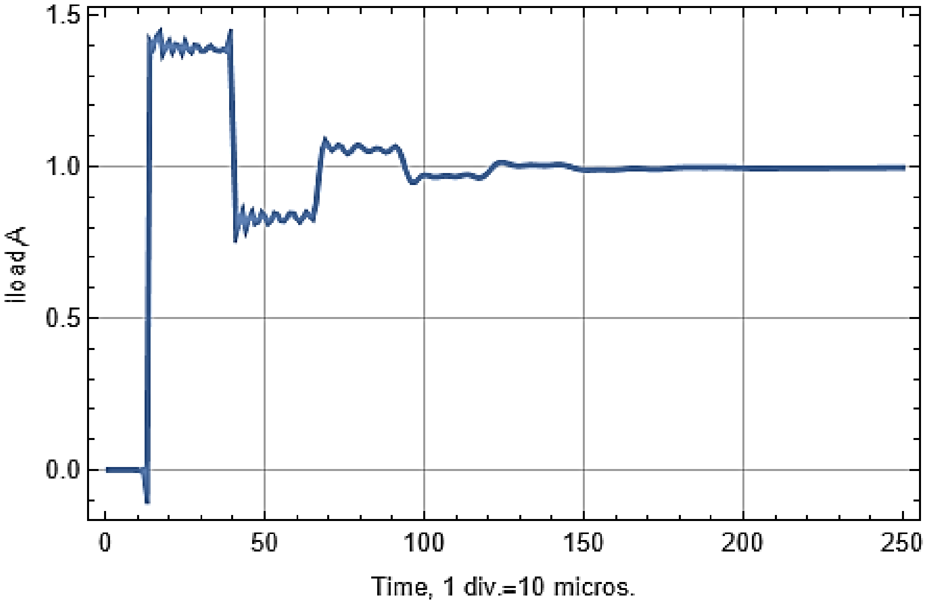


Figure 4. The load current

The current through the shunt compensating coil is shown in Figure. 5. It resembles the transient current of a simple series L/R circuit. As the plot indicates a time constant which is very close to L/rp.

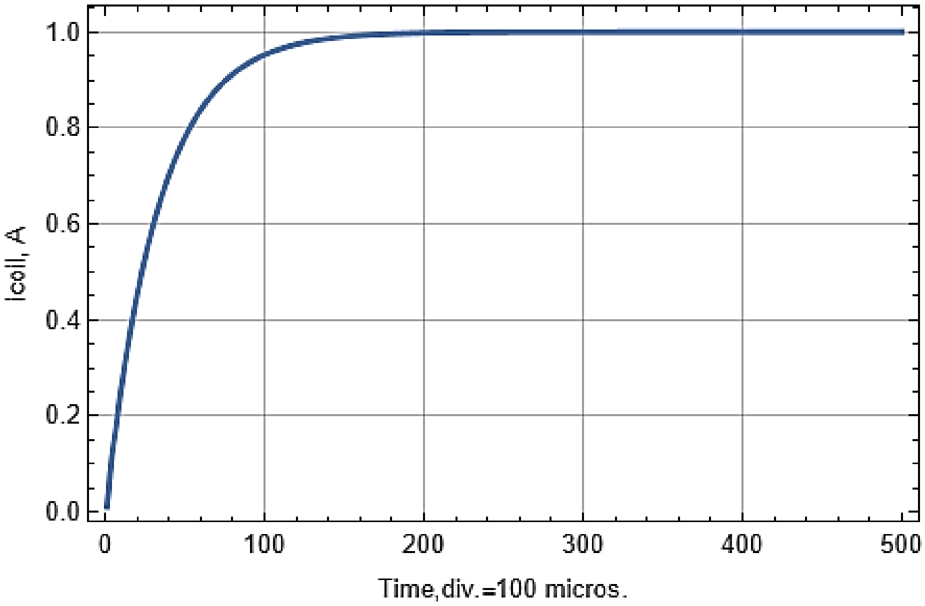


Figure 5. The coil current

The plots displayed in Figure. 6 show the frequency characteristics of the input impedance of the compensated line b over the frequency range from zero to 8-kHz.They are obtained by substituting s=I(2000π) radians/s in the above-mentioned impedance expression $z_{input}[s]$. It exhibits a group of series and parallel resonance frequencies of approximately 0, 2, 3.7, 5.5, etc., respectively. The impedance magnitude, as well as its real part oscillate between maximum and minimum values of approximately 1000 and 200 Ohm, respectively. On the other hand, the imaginary part varies between the two extreme values +400 and -400 Ohms. The curve illustrates zero impedance phase angles at the above-mentioned resonance frequencies. This information is validated by the polar parametric plot depicted in Figure.7. The pure real 500-Ohm impedance value agrees with the simple DC analysis of the equivalent circuit of Figure 1.

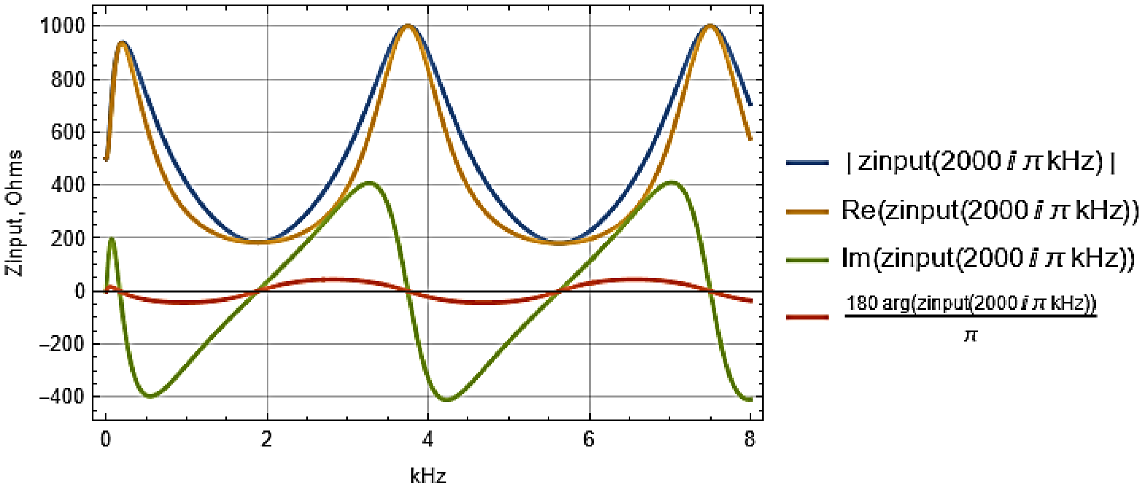


Figure 6. The magnitude, real and imaginary parts of the input impedance as functions of the frequency.

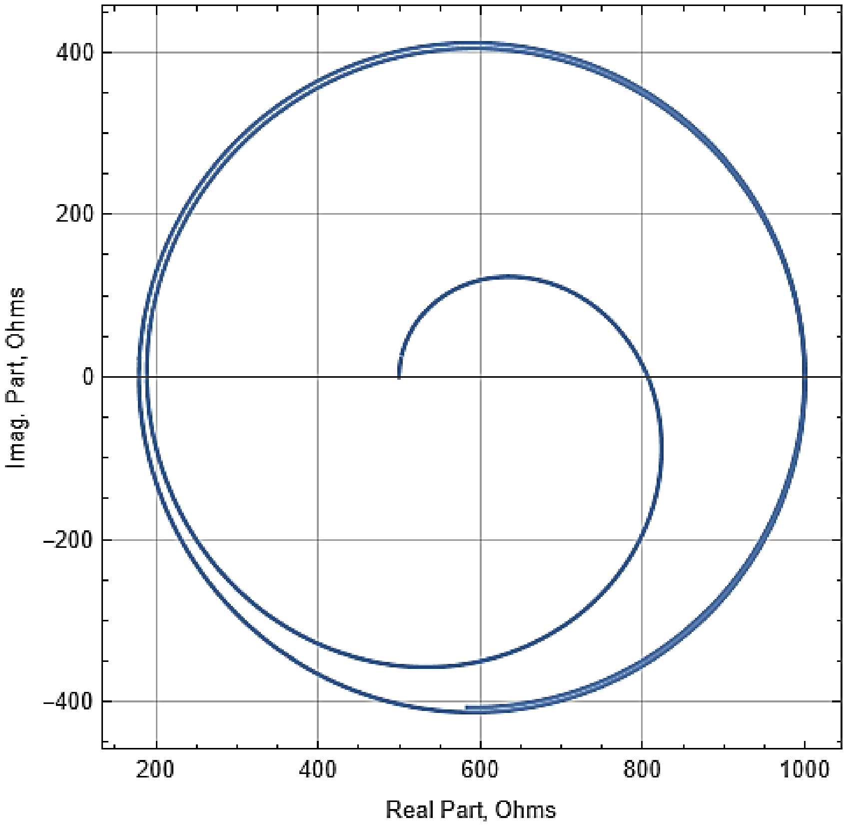


Figure 7. Root locus plot of Z_{input} over the frequency range $0 \leq \text{kHz} \leq 8$ kHz

In power systems, electromagnetic transients are brief, abrupt variations in voltage and current brought on by faults, switching activities, or lightning strikes. These transients can be especially noticeable in compensated power lines, which control reactive power and improve transmission capacity using components like shunt reactors and series capacitors. Power systems stability and dependability depend on our capacity to comprehend and mitigate these transients. Conventionally, assumptions and oversimplified models have been used in the analysis of electromagnetic transients in compensated power lines. However, more advanced techniques are required due to the growing complexity of contemporary electricity systems. This paper introduces sophisticated modelling methods and real-time simulation tools for a reexamined understanding of electromagnetic transients in compensated power lines.

Advanced Methods of Modelling

Compensated power lines require sophisticated modelling techniques that capture the dynamic behaviour of the system components in order to analyse electromagnetic transients effectively. This includes intricate models of protective devices, transmission lines, shunt reactors, and series capacitors. We can create a more accurate simulation of the power system by adding these components to the surroundings. Using the Electromagnetic Transients Programme (EMTP) software, which enables accurate simulation of transient phenomena, is one useful strategy. The nonlinear properties of compensating devices and how they interact with the rest of the power system can be modelled by EMTP. It can also mimic how various fault events and switching activities affect compensated lines' transient responsiveness.

CONCLUSION

A Laplace-domain model for analyzing the electromagnetic transients in compensated power lines is presented. It can deal with both the inductive and or capacitive compensation types either individually or simultaneously. It takes into account the line's circuit parameters, its loading condition as well the location and size of the compensating elements. A corresponding Mathematica program is developed and applied to several case studies. The results include the various transient voltages and currents along the line, such as the current through the compensating shunt coil. The procedure is simple, direct and user-friendly. Several computer runs were done in order to validate the presented results.

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