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Novel Laplace-domain Approach to the Electromagnetic Transients in Compensated High Voltage Power Lines

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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. Applying the relations governing cascaded two-port networks, the resulting branch currents and node voltages will be obtained as functions of the location of the compensating elements, the line's data as well as the Laplace operators. An efficient Mathematica code based on the Hosono algorithm is used for their numerical inversion in order to get the corresponding results in the time domain. The model and computer code are validated via discussing the results of their application to several case studies with solutions available elsewhere.

Keywords: Electromagnetic, transients, simulation, high voltage lines, series, parallel, compensation, *Mathematica*, two-port networks, numerical Laplace inversion. Hosono algorithm, validation, parameter study

INTRODUCTION

The maximum power limit of transmission lines can be effectively increased through the use of series compensating capacitors [1–7]. The achievable improvement depends largely on several parameters such as their size and location. References [8–12] present procedures for identifying the parameters' optimal values based primarily on economic considerations such as the compensated line's optimal total cost including that of the compensating capacitor. Shunt coils at selected points along a transmission line can be important tools for controlling its voltage profile. 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 possible concentrated transient stresses in 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 possible excessive transient voltages and currents, such as investigating the deployment of high power varistors, [8]. The related analyses can demand a considerable computation burden in terms of the required memory and long execution times. Most practicing engineers, however, need more affordable and user-friendly procedures and techniques for this purpose. The information presented in this paper is a step foreward in this direction.

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METHOD OF ANALYSIS

Figure 1 illustrates the investigated compensated line. 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 operators.

The transients are assumed initiated either by an ideal step- or double-exponential voltage source denoted v_{sourve} . 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*] seconds, respectively.

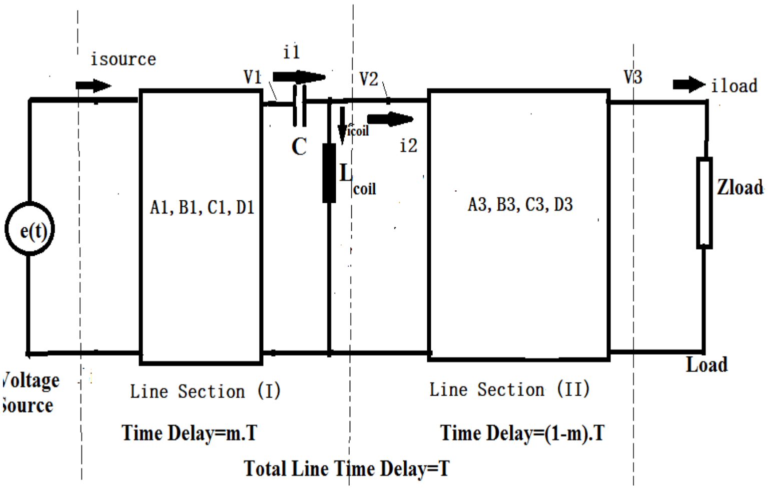


Figure 1. The assumed equivalent circuit representing a loaded long transmission line with a series compensating capacitor C and a parallel compensating coil L_{coil},respectively.

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

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

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

$C1 = sinh[[m.T.s\}/Zo$

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

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

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

$C3 = sinh[[(1-m).T.s\}/Zo$

Where *ind* and *length* are the inductance per unit length and the line’s

It can be derived that in order to achieve a $\mathrm{k}_{\mathrm{shunt}}$ power frequency per unit compensation level of the total line’s capacitive admittance, the required inductance of the concentrated shunt coil is

$L_{\ coil} = 2kshunt/(\omega.c.length)$ Henries.

Similarly, the required value of the concentrated series capacitor *C*, required for achieving a per unit compensation $kseries$ of the total line’s inductive reactance at the power angular frequency ω is the

$$\mathrm{C} = \frac{1}{(k \ shunt.\omega^2.ind.length)}$$

The circuit illustrated in Figure 1 can simulate either the series or parallel (or both) compensation types.

Referring to the same circuit, the following seven simultaneous algebraic equation s-domain equations can be easily derived:

$e(s) = A1.v1(s) + B1.i1(s)$
$and\ isource(s) = C1.v1(s) + D1.i1(s)$
$v2(s)=v1(s)-i1(s)/(s.C).$
$i1(s)=i2(s)+v2(s)/(s.L_{coil}).$
$v2(s)=A3.v3(s)+B3.iload(s)$
$I2=C3.v3(s)+D3.iload(s)$
$V3(s)=Zload.iload(s)$

They could be solved using *Mathematica* 14.0 software. The results are seven rather lengthy analytical closed-form expressions for the seven unknowns (*v1,i1, isource, v2, i2, v3 and iload).*

By definition, the ratio [*e(s)/isource(s)*] is the line's input impedance denoted as *Zinput(s).* Substituting $s=j2000\ \pi.kHz$ yields the corresponding complex impedance expression in terms of the frequency in *kHz,* with $j = \sqrt{-1}$.

SAMPLE RESULTS

The magnitude, real part, imaginary part and the phase angle (in degrees, multiplied by 10) of a sample compensated transmission line are depicted in Figure 2. The following data were assumed:

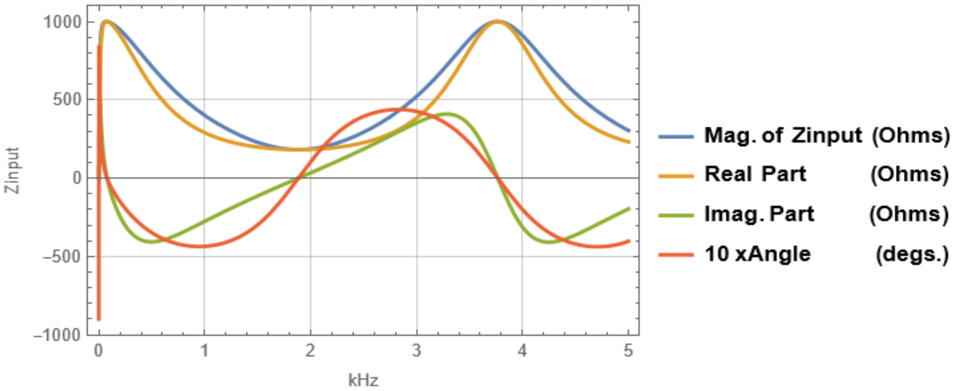


Figure 2. The frequency characteristics of the compensated line over the frequency range(0-5kHz).

l=1.414×10^{-6} H/m
c=7.79×10^{-12} F/m
f=50 Hz
length=40000 m
m=0.5
kseries=0.5
kshunt=0.5
zo=Sqrt[l/c]=426 Ohm
zload=1000 Ohm
ω=314 rad./sec

The lowest two resonance frequencies at about 2.1 and 3.5kHz can be recognized. They are determined by the zero-crossings of the impedance angle or its imaginary part. The imaginary part is seen to change between -400 and +400 Ohms, respectively. The impedance angle varies between -45 (capacitive) and 45 degrees (inductive).

The corresponding curve in Figure 3 illustrates the root-locus parametric plot of the compensated line's input impedance over the frequency range (0-5kHz).

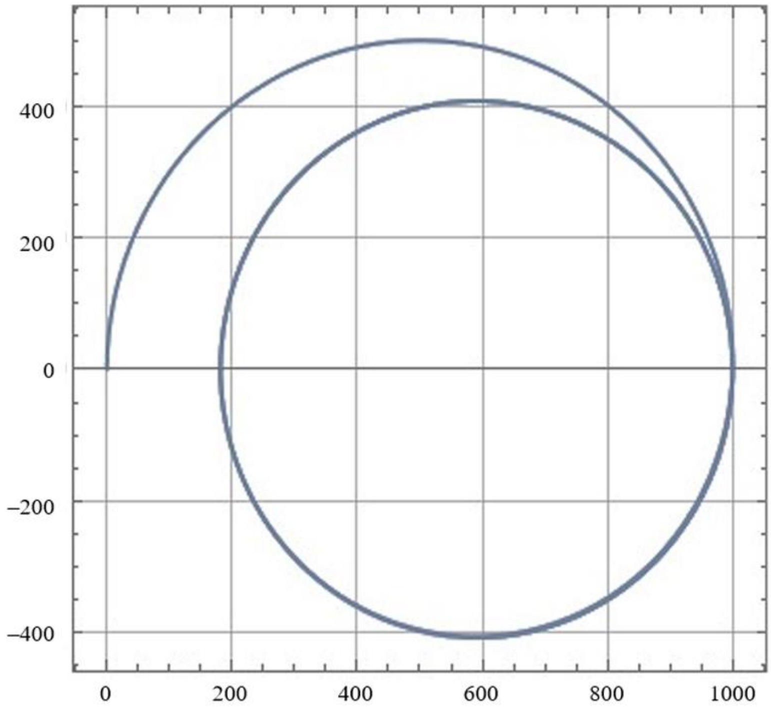


Figure 3. The root-locus parametric plot of the compensated line’s input impedance over the frequency range (0-5kHz):

x-axis: The Real Part (Ohms)
y-axis: The Imaginary Part (Ohms)

The following section deals with the transient response of the compensated line. As one of the popular algorithms for finding the inverse Laplace transform, a *Mathematica* short code and the corresponding output plot are given below indicate how to numerically invert and plot the function $f(s) = (1/s^2)$ based on Hosono’s algorithm [14]. This will be applied to determine the transient response of the currents *isource* , *iload, i2* and *i1*. The results are depictd in Figure 4. The plots cover the time range from zero to 0.5ms Immediately after switching the source, the value of the source current (2.35A) is in a good agreement with the expected value 1000V/Zo, where Zo is the line’s surge impedance 426 Ohms. It will later increase sharply to reach an approximate peak close to 5A after about 267 micro-seconds, i.e. double the line’s delay time. This is due to the negative current’s wave reflection at the almost short-circuited load terminals. The plots further indicate that the two currents i*load* and *i2* are almost identical.

The *Mathematica* Numerical Laplace Inversion Based on Hosono’s Algorithm,[14]

```
f[s_]:= (1/s^2);
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 = 0.001; tmin = 0; nn = 100; 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[ f[s[mm, ii]]]], {ii, 1, 29}] +
Sum[N[(-1)^(l1 + 29) × amn[l1]×Im[ f[s[mm, (l1 + 29)]]]], {l1, 1, 6}])×
(E^5)/t[mm]), {mm, 1, nn}]
ListPlot[%]
```

For more details, References [13,14] should be consulted.

Figure 4. The Transients in a 40-km, compensated line with a load impedance of 1 Ohm, due to a 1000 V step source voltage and the following data:

m=0.5; (i.e. the compensating elements are placed at the midpoint of the line's midpoint)
kseries=0.5; (i.e. the series compensation level at 50-Hz is 50%)
kshunt=0.5; (i.e. the shunt compensation level at 50-Hz is 50%)
zo=426 Ohm
zload=1000 Ohm;
$v_{source}(t) = 1042(e^{-2.469\times10^{6t}} \text{-} e^{-14598.5t})$

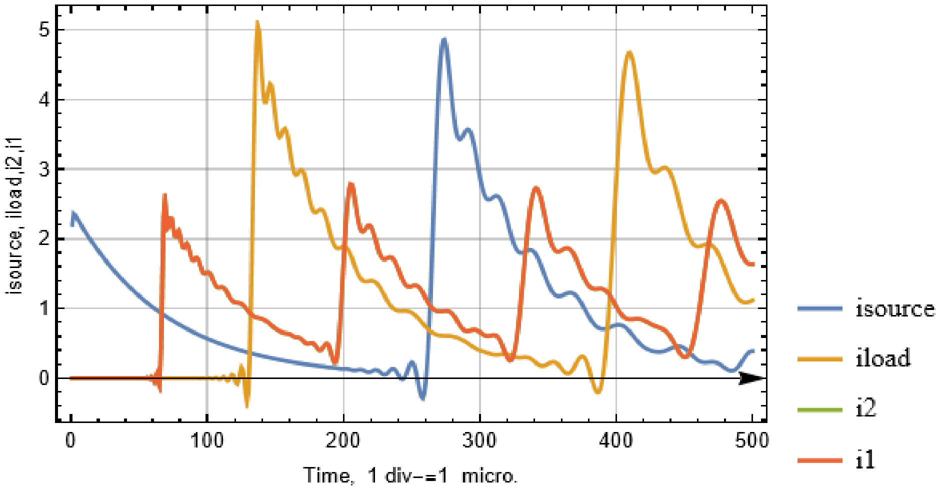


Figure 4. The transient response of the currents *isource, iload, i2* and *i1* during the first 500 microsec due to a 1000-V double-exponential voltage source. The load line is terminated by a pure resistive 1-Ohm load impedance.

The computed voltage transients for *vsource, vload, v2 and v1* are shown in Figure 5 during the first 1ms. It is seen that the voltage *v1* at Node 1, which is 20-km far from the source (because of the assumed value of *m*=0.5) starts to deviate from the initial value zero only after approximately 68 microsec. This is the expected delay of the left line section.

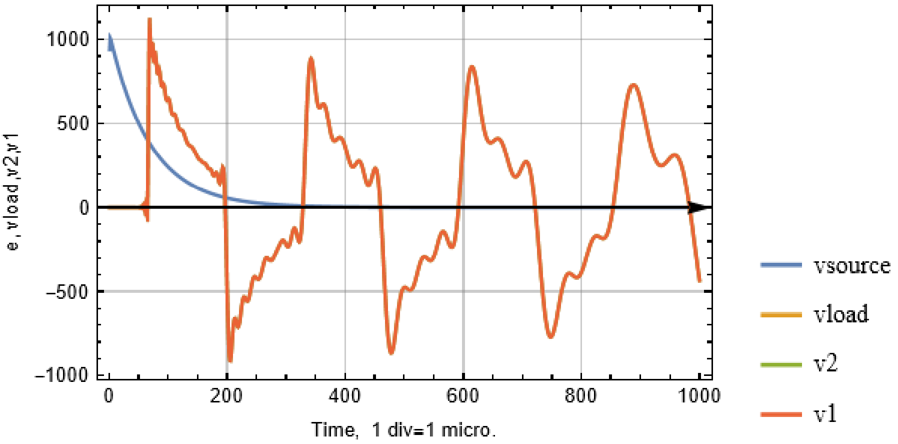


Figure 5. The transient response of the voltages *vsource, vload, v2 and v1* during the first 1000 microsec. due to the 1000-V double-exponential voltage source. The load line is terminated by a 1-Ohm load resistance

The transient response of the network currents *isource* , *iload*, *i2* and *i1* during the first 500 microsec. Resulting from a 1000-V step voltage source *vsource*=1000 u(t) is shown in Figure 6.

The initial source current as well as the time point at which the different wave reflections take place agree with the well-known Bewley's travelling wave techniques.

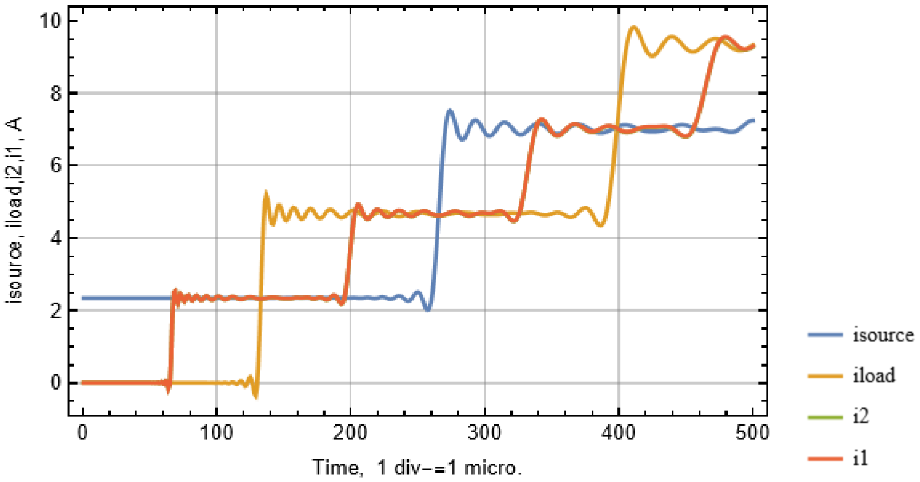
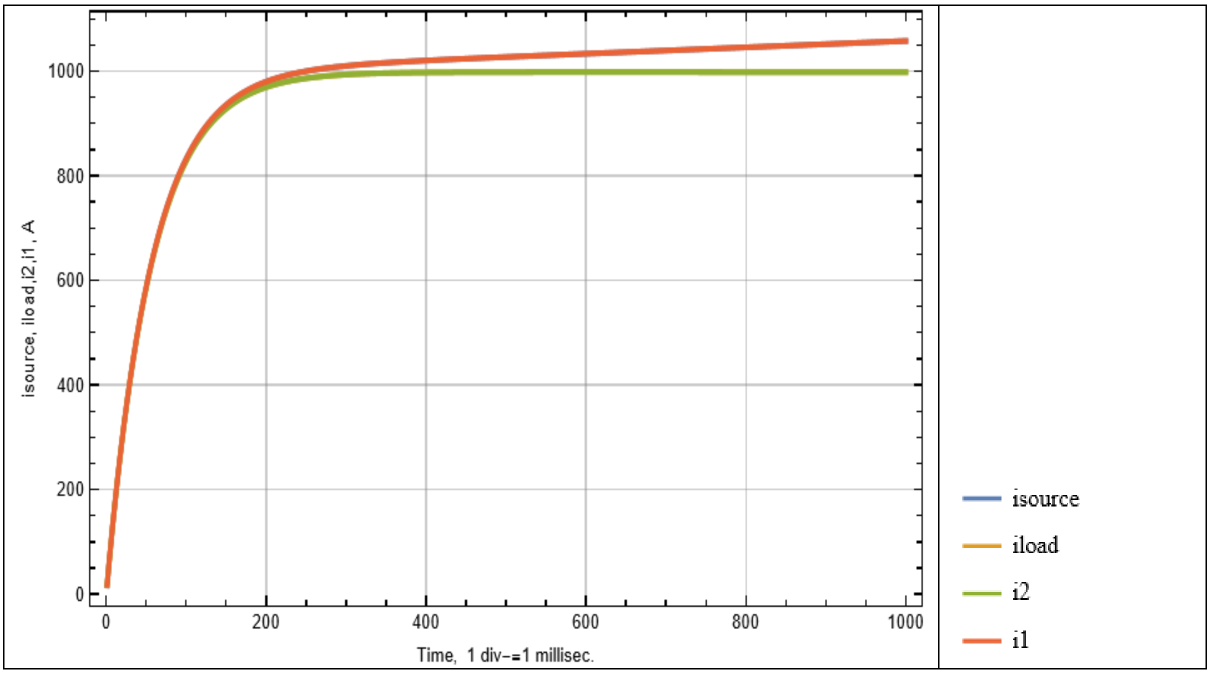


Figure 6. The transient response of the currents *isource, iload, i2* and *i1* during the first 500 microsec due to a 1000-V step voltage source. The line is terminated by a 1-Ohm load resistance.



zload=1 ohm

Figure 7. The transient response of the currents *isource, iload, i2* and *i1* during the first one second due to a 1000-V step voltage source. The line is terminated by a 1-Ohm load resistance.

It is observed from Figure 7 that the four currents *isource, iload, i2* and *i1* are very close and similar to the response of a series R-L circuit of a time constant of approximately 100 msec. Their final steady-state value is 1A, as anticipated.

CONCLUSIONS

A new Laplace-domain model for analyzing the electromagnetic transients and the frequency characteristics of compensated power lines is presented. It can deal with both the inductive and capacitive compensation types either individually or simultaneously. The suggested approach considers the line's circuit parameters, its loading condition as well as the location and size of the compensating elements. A corresponding *Mathematica* program is developed and applied to several case studies. The results illustrate the various transient voltages and currents along the line and the current through the shunt compensating coil. They include also information on the line's impedance frequency characteristics such as the resonance frequencies and how they are impacted by the line's data and the compensation parameters. Several computer runs were carried out to validate the presented results. The presented procedure is simple, accurate, direct and user-friendly. It can serve as a helpful effective educational and training tool for the graduate and undergraduate power engineering students and practicing engineers.

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