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The Electromagnetic Transients in Compensated High Voltage Power Lines

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Abstract

This paper addresses the simulation of the transients developed in high voltage lines, which are initiated by lightning discharges. The analysis allows for compensated and uncompensated lines. Both the individual and simultaneous series inductive and shunt capacitive compensation types can be dealt with. The sizes and locations of the compensating elements are included in the analysis. Numerous studies on the transient concentrated stresses across these elements and the related protection concerns have been carried out in recent years. With the use of sophisticated computer programs, like the well-known Electromagnetic Transient Program (EMTP), it is possible to assess and mitigate eventually excessive transient voltages and currents by using high power varistors and arresters. The derived mathematical model includes simultaneous partial differential equations governing the current and voltage along the line as functions of the location and time subject to appropriate initial and boundary conditions. A Mathematica approach is adopted in order to get the current and voltage in the Laplace s-domain followed by their numerical inversion to the time-domain. The model and computer code are validated via discussing the results of special cases of known exact solutions.

Keywords: Electromagnetic, transients, simulation, high voltage lines, towers, series, parallel, compensation, differential equations, *mathematica*, numerical laplace inversion

INTRODUCTION

The maximum power transmission capability of transmission lines can be increased through the use of series compensating capacitors [1-7, 14]. The achievable improvement depends greatly on the size and location. Reference [8–10, 12] presents a procedure 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 corresponding 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 arresters and high power varistors [8]. Sometimes, this is accompanied by a considerable computation burden in terms of the required memory and long execution time. Most practicing engineers, however, need more affordable and user-friendly procedures and techniques for identifying, estimating and mitigating the adverse effects related to the transient analysis of compensated high voltage power lines. This paper is a step in that direction [11–13].

THE METHOD OF ANALYSIS

Figure 1 illustrates the compensated line under study. It has a time delay or wave propagation time

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of T seconds, or equivalently, a total length of 3×10^8 meters. It is terminated by a general s-domain load impedance Z_{load}= kx.Z_o, where Z_o is the line's impedance and kx is a factor, 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 time-step voltage source of the time expression: $e(t) = 1000.u[t]$,

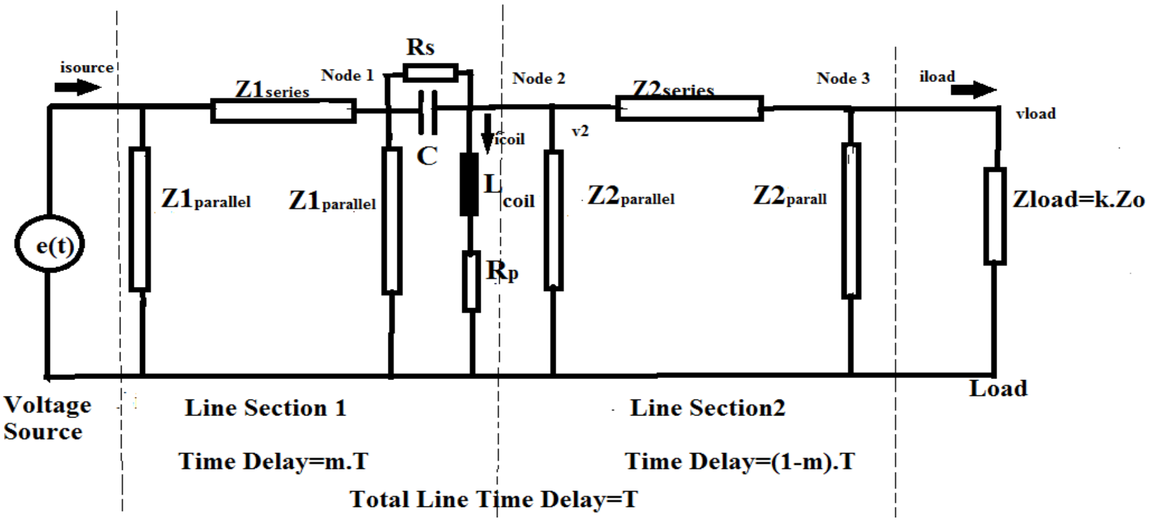

Figure 1. The assumed equivalent circuit representing a loaded long transmission line with a series compensating capacitor C and a parallel compensating coil L controlled by the two auxiliary resistorsRs and Rp, respectively.

where $u[t]$ is the usual unit – step function. The study analyzes the schematic Laplace-domain equivalent circuit depicted in Figure 1 for a long lossless power line having the total time.

The compensating elements are located at a point dividing the entire long line with the ratio *m:(1-m)*. The corresponding delay times of the two resulting sections are, therefore [*m.T*] and [*(1-m).T*], respectively. The equivalent series and parallel circuit elements appearing in Figure 1 can be easily expressed in terms of the surge impedance Z_o , *T*, *m* in addition to the operator *s*, [1-7]. The capacitor *C* and inductor *L* represent the series sand parallel compensating elements.

According to [1-3], the generalized circuit constants of the line section on the left-hand side are:
$A = D = \cosh[m.T.s]$
$B = Zo \sinh[m.T.s]$
$C = \sinh[m.T.s]/Zo$

Where *Zo* and *T* are the line's surge impedance and 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 on the right hand side are:
$A = D = \cosh[(1-m).T.s]$
$B = Zo \sinh[(1-m).T.s]$
$C = \sinh[(1-m).T.s]/Zo$

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 required value of the concentrated series capacitor *C* in order to achieve a

ks per unit compensation of the total line inductive reactance is

$$C = \frac{1}{(ks.\omega^2.l.length)}$$

Type equation here. Farad

Where $l, length$ are the inductance per unit length and the line 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

$$\omega L = 2kp/(\omega.c.length)$$

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. Table.1 showing Compensation type with Rs and Rp* They can be selected either zero or infinity according to the following table:

Table 1. Compensation type with Rs and Rp

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 *Zinput[s]* seen by the source of the voltage *vsource [s].* Accordingly, the expression of the source current is

$$isource[s] = vsource[s] / Zinput[s]$$

It will then be possible to derive the s-domain expressions of all other voltages and currents.

They could then be numerically inverted into the time domain using one of the available algorithms. As an example algorithm, the following *Mathematica* statement indicates how to numerically invert and plot the Laplace expression of the voltage *v1[s],* expressed as a function of the Laplace operator *s*, over the time range $0 \leq t \leq$ tend.

```
F = v1[s] // N;
approx[n_] := Block[{k = n}, ((-1)^k/k!)*(k/t)^(k + 1) (D[F, {s, k}] /. s □ k/t)]
Plot[{approx[15]} //
Evaluate, {t, 0, tend},
PlotLegends -> {n == 15}, ImageSize -> 300, PlotRange -> All,
GridLines -> Automatic, Frame -> True, Frame □ True, FrameLabel □ {Seconds, v1 },
PlotStyle□{Thickness[0.016]}]
```

SAMPLE RESULTS

The following section deals with the application of the suggested mathematical model and the associated *Mathematica* program to a 50-Hz, 40-km lossless transmission line which is loaded by 50% of its surge impedance, i.e. about 200Ω.It has a delay time T= 133 μs. The values of the inductance and capacitance per unit length are l=1.346×10^-6 H/m and c=8.55×10^-12F/m, respectively. The per unit series and parallel total compensation parameters are *kseries*=0.75 and *kparallel*=0.75. Accordingly, the compensating series capacitance C and parallel inductance L appearing in the equivalent circuit are 22.24H and 251 μF, respectively.

It is further assumed that m=0.75, i.e. both compensators are connected at a point 10-km far from the source.

The results will be displayed over the time range between zero and 4.5ms. This guarantees that the solution will approach the final steady-state conditions.

The source voltage *e(t)* is assumed a 1000-V 1.2/50μs voltage surge described by the following double-exponential time function

$$e(t) = 1037.\,(\mathrm{Exp}[-t * 10^6/68.5] - \mathrm{Exp}[-t * 10^6/0.405])$$

Where t is the time in microsec. It is illustrated by the following plot in Figure 2 over the time range $0 < t < 1ms$.

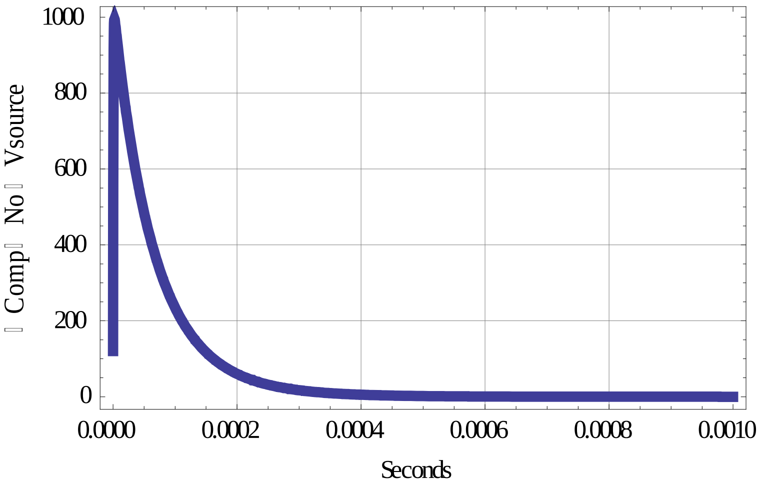

Figure 2. The assumed source voltage *esource(t)*.

The x-axis gives the time in sec,

Case Study A: Inductive & Capacitive Compensated Line

According to the previously mentioned Table 1., the values of the two auxiliary resistances are: *Rs*= Infinity and *Rp*=zero, respectively. The loading parameter is *k*=0.5;

(i.e. $Z_{load=}Z_o$ /2 =200Ω).

The line's pure resistive surge impedance is

$$\text{Zo}= \sqrt{\frac{l}{c}} = 396.8\ \text{Ohm}$$

The parallel inductance required for a complete compensation of the line capacitance is $L = \text{kparallel}/(\omega^2 \text{c length})$ =22.24H,

The series capacitance required for a complete compensation of the line inductance is C=(kseries $\omega^2 l$ length) =0.000251F.

The separation between the compensating elements and the source terminal, in per unit of the total length, is *m*=0.75 per unit. This corresponds to a distance of 30-km.

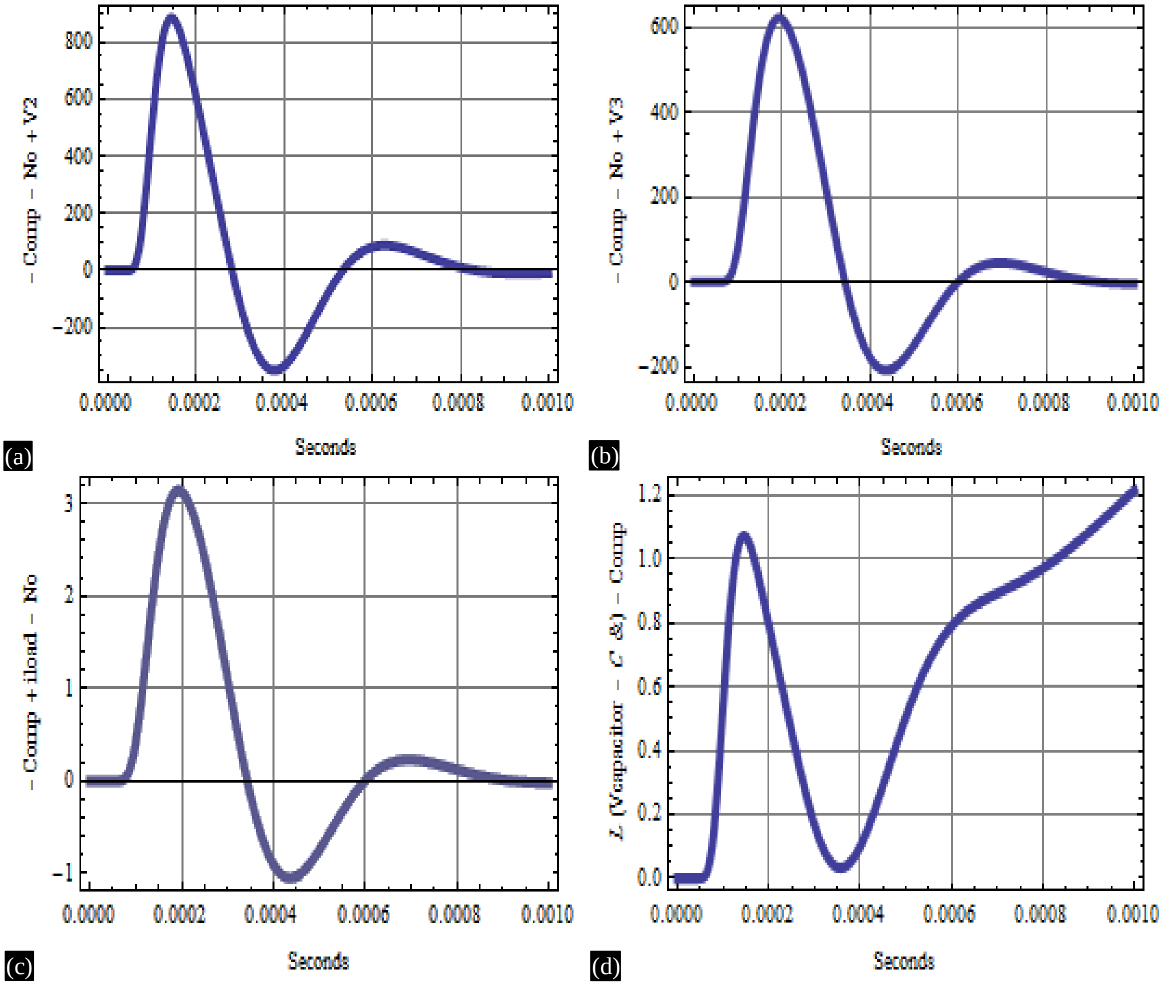

Figure 3. Results of the Compensated Case Study A, (a) voltage at Node 2, (b) voltage at Node 3, (c) (c) the load current, (d) the voltage across the capacitor.

Figure 3 depicts a part of the results pertaining to the inductive/capacitive compensated case. It shows the voltages at the two nodes Node 2 and Node 3 as well as the load current, respectively. The waveforms of both node voltages are similar. Their peak values in the positive direction occur at a time point *t*=0.2 ms, while the negative peaks occur at *t*=0.45 ms. He positive peak values appearing at the two nodes are about 900V and 620 V for Nodes 2 and 3, respectively. Plot 3-(c) illustrates the load current. It indicates a maximum value of about 3.2A and validates the maximum load voltage of around 620V. Figure 3-(d) shows the relatively small voltage across the capacitor. It indicates maximum and minimum values at the time points of 250 and 350 µsec second, respectively.

CASE STUDY B

Capacitive-Compensated Line

This case addresses the situation if only the line's series inductance is compensated. The per unit level of compensation is again *kseries*=0.75. The transient voltage at Node 2 is almost identical to that of the previous uncompensated case, whereas the peak transient voltage at Node 3 is about 610 V, slightly less than that of the simultaneous inductive and capacitive compensation case. The load current is displayed in Figure 4-(c). It exhibits a maximum positive transient value of approximately 3.2 A. This is very close to that of the compensated line. The transient coil current is illustrated by the plot 4-(d) and shows a relatively small peak value of about 75 mA at the time point *t*=260µsec. Results of the Capacitive-Compensated Case Study have been shown in Figure 4 a, b, c, d.

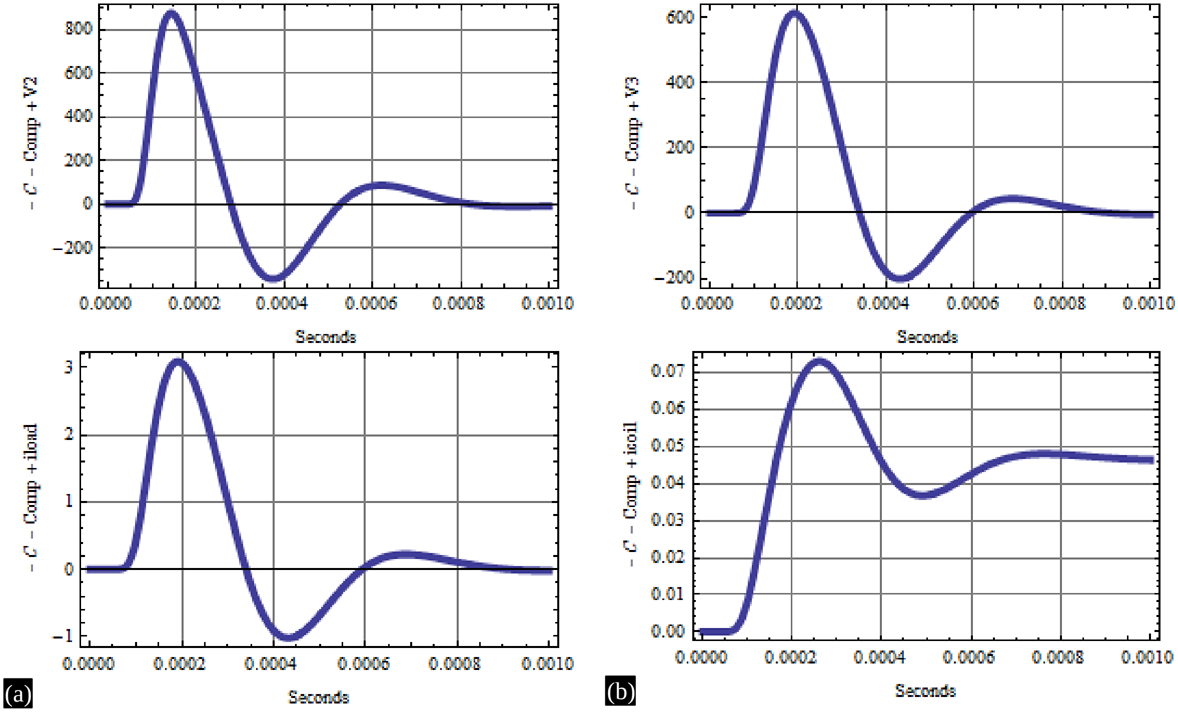

Figure 4. Results of the Capacitive-Compensated Case Study, (a) voltage at Node 2, (b) voltage at Node 3, (c) load current, (d) the coil current

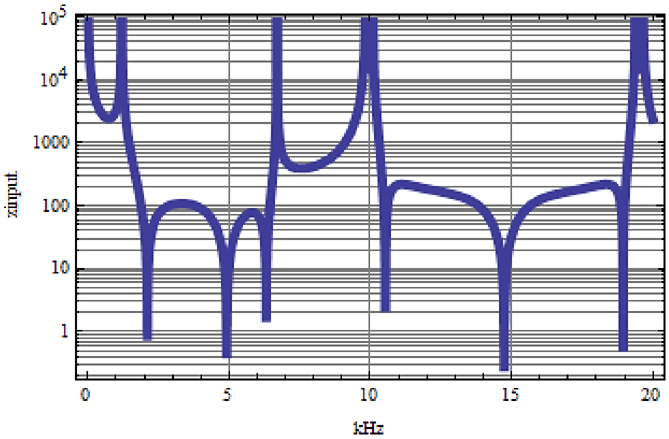

Figure 5. The Magnitude of the Line's Input Impedance as seen by the source as a function of frequency.

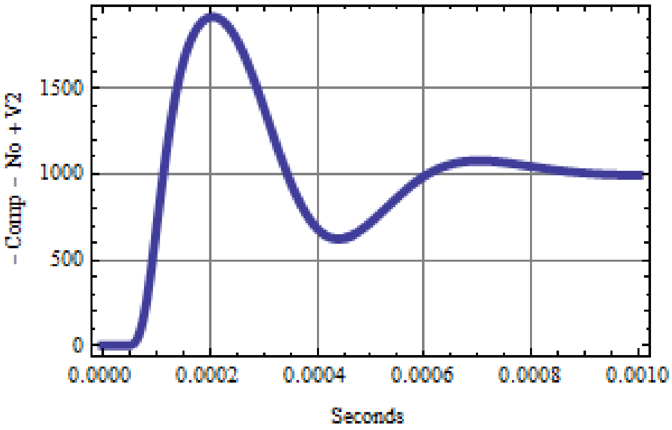

Figure 6. The Transient Response of the Voltage at Node 2.

For completeness, the plot depicted in Figure 5 illustrates the dependence of the input impedance on the Frequency. It shows a number of series and parallel resonance frequencies, at which the impedance exhibits minimum and maximum values, respectively. It is observed that the first resonance frequency is about 2 kHz. As shown in Figure 6, this is in a good agreement with the time response of the voltage *v2* at Node 2 (computed for a 1000-V step source voltage *e (t)).*

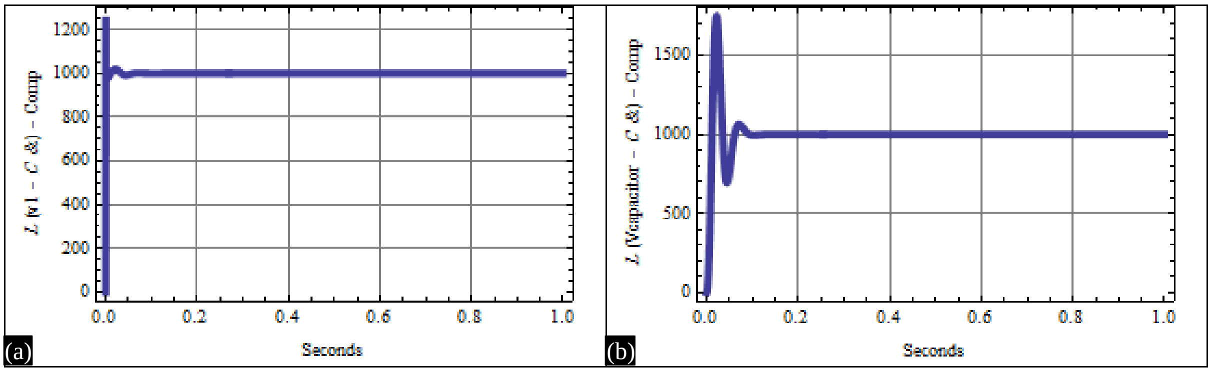

Figure 7. The Voltages at Node 1 and across the Capacitor over The Time Range between *t*=0 and 1 second, (a) The Voltage transient at Node 1 over the Time Range between *t*=0 and 1 second, (b) The Capacitor Voltage transient over The Time Range between *t*=0 and *t*=1 second

In order to validate the mathematical model and the computer code, a run was done for the above-mentioned CASE STUDY A addressing the simultaneous inductively- and capacitively- compensated Line due to a 1000-V step source voltage. In this special case, a simple DC analysis yields zero final values for all voltages and currents except the voltages at Node 1 (*v1)* and across the capacitor (*vcapacitor*). Their expected values are both 1000 Volts. This is in complete agreement with the two plots depicted in Figure 7.

CONCLUSIONS

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 transient voltages and currents along the line. The code yields also the voltage across the series capacitor and or 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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