Modifying the Transient Overvoltages in Mixed Power Networks by Inserting Cable Sections

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***Summary*: The paper deals with the analysis of the electromagnetic transients in mixed power net--works. Special emphasis is made on assessing the effectiveness of using cable sections in reducing the transients in the power network components such as transformer substations. A distributed parameter modeling of the overhead lines, underground cables and transformer windings is applied in the Laplace domain. The simulation can handle the different time waveforms of the sources initiating the transients, the lengths of the cable sections as well as the transformers' neutral treatment. The direct analytical *s*-domain solution is numerically inverted in order to get the corresponding time domain results. The affecting parameters such as the line and cable surge impedances, the length of the cable section (or its time delay) and the transformer data, are investigated. A case involving multiple-pulse lightning surges is also addressed. The results of four case studies of known solutions are presented in order to validate the developed mathematical model and computer program.**

***Key Words*:**
Cable,
Overvoltage,
Transformer,
Neutral treatment,
Transient model,
Lightning,
Mixed power networks

1. INTRODUCTION

The analysis of the electromagnetic transients is crucial in the planning, design and operation of power networks [5,11,18]. The proper implementation of the insulation coordination and overvoltage protection will be primarily affected by the networks' topology; their characterizing parameters as well as the waveforms of the initiating input voltage and/or current. The latter can result from internal or external disturbances such as switching actions or lightning discharges, respectively. Moreover, the coordination will allow for a more effective protective measures and efficient utilization of the network resources. In references [1–18], considerable attention is given to the transients involving overhead lines and underground cables. One of the possible procedures for reducing the electromagnetic stresses on the power network components, such as transformer substations, is the insertion of relatively short cable sections between the supplying overhead lines and these components [3,7,9,12]. This can be augmented by the efficient connection of surge arresters to suitable network buses. Reference [6] reports, however, on possible excessive overvoltages due to the presence of cable sections. This was concluded from an experimental investigation on an 11000/230 V distribution transformer. The study [2] addresses the nature of the wave propagation modes along single-core coaxial cables. In [7], an investigation is presented on the effect of cable sections of different lengths and the presence of arresters on the transients within a 380-kV power network. The analysis is conducted using the PSCAD program [9], when the network is subjected to a 10-kA, 1.2/50 μs surge current wave. It was important to check whether the cable sections can lead to dangerous overvoltage stresses at the different cable junctions in excess of the network's basic insulation level (BIL) of 1425 kV. The references also hinted briefly to the rather theoretical and small possibility of several simultaneous lightning strikes hitting the network. In reference [3], the application of an alternative ATP-EMTP time-domain technique to the analysis of mixed 380-kV networks is demonstrated. The issues of possible dangerously high transient stresses in power transmission networks, including cables, due to multiple-pulse lightning strikes are discussed in [10,16]. Reference [16] gives a detailed analysis of that via the *s*-domain analysis followed by the numerical inverse Laplace transform.

The average practicing engineers, however, occasionally need fast and straightforward procedures capable of quickly estimating the expected transient stresses without resorting to the above-mentioned sophisticated programs. This paper is a step in that direction and tries to provide one of these procedures.

The main objectives of this paper are therefore:

1. To present direct analytical closed-form formulas for the transient stresses in a sample mixed power network. It can handle different cable section lengths and all types of the network's neutral connections.
2. To conduct several case studies in order to assess the impact of the different affecting parameters, such as the lengths of the cable section, the surge impedances of the cables and overhead lines, the system's neutral treatment and the time waveform of the sources initiating the transient stresses.
3. To investigate the effectiveness of using cable sections in controlling the transient stresses initiated by multiple-impulse lightning strikes.
4. To validate the proposed approach and computer program.

2. METHOD OF ANALYSIS

The *s*-domain equivalent circuit depicted in Fig. 1 describes a sample radial network composed of the cascade connection of an overhead line on the left, a cable section in the middle which is inserted in order to reduce the transient stresses as well as a transformer on the right. The transformer's neutral point is earthed via the general impedance given in the s-domain by: $Z_N = R_N + sL_N$. The values ($R_N = 0$, $L_N = 0$), ($R_N = 0$), ($L_N = 0$) and ($R_N or L_N = \infty$) represent the cases of: solid-earthing, inductive earthing, resistive earthing and isolated neutral, respectively. The equivalent circuit to the left results from Thevenin's theorem applied to the terminals at the Line/Cable junction. These terminals are also referred to as the (Cable's Sending End, SE). The voltage source 2E(s) is, therefore, the Laplace transform of twice the voltage initiating the transients. The impedance Z_{oL} and Z_{oC} are the surge impedances of both the long overhead line to the left and the cable section in the middle, respectively. The quantities $V_{J(s)}$, $I_{J(s)}$ are the voltage and current at the Cable/Transformer junction, whereas $V_{N(s)}$, $I_{N(s)}$ denote the corresponding values at the neutral point.

The transformer winding is described as an equivalent distributed parameter line of ground (shunt) capacitive admittance per unit length sC_g as well as an equivalent series impedance per unit length of $sL/(s^2LCs + 1)$. The parameters L, C_g, C_s are the winding's uniformly distributed inductance, ground capacitance and series inter-turn capacitance, respectively. The solution of the two simultaneous differential equations relating the voltage V and current I (with the distance along the winding as the independent variable x, ranging from x=0 at the cable/transformer junction to x=1 at the neutral point N), yields the following expression for the transformer's input impedance $Z_{Tinput}(s) = V_J(s)/I_J(s)$. It follows from dividing the expressions of the winding's voltage and current solutions at x=1 per unit (eq. 1; see below)

The next step is to solve the two following simultaneous equations resulting from applying Kirchhoff's voltage and current laws at the cable's sending and receiving ends, together with the cable's two-port relations:

$$V_{SE}(s) = \cosh(\tau s)\cdot V_J(s) + [Z_{oC}\sinh(\tau s)]\cdot[V_J(s)/Z_{Tinput}(s)] \quad (2)$$

$$[2E(s) - V_{SE}(s)]/Z_{oL} =$$
$$= [\sinh(\tau s)/Z_{oC}].V_J(s) + [V_J(s)/Z_{Tinput}(s)].\cosh(\tau s) \quad (3)$$

Where τ denotes the cable section's delay time, which is an indirect measure for its length.

The voltage solutions are: eq. 4, eq. 5 (see below)

$$Z_{Tinput}(s) = \frac{\sqrt{L}[\sqrt{C_g}(s^2LC_s+1)Z_N[e^{\frac{2s\sqrt{LC_g}}{\sqrt{s^2LC_s+1}}}+1] + \sqrt{L(s^2LC_s+1}[e^{\frac{2s\sqrt{LC_g}}{\sqrt{s^2LC_s+1}}}-1]]}{\sqrt{C_g(s^2LC_s+1)}[\sqrt{C_g}(s^2LC_s+1)Z_N[e^{\frac{2s\sqrt{LC_g}}{\sqrt{s^2LC_s+1}}}-1] + \sqrt{L(s^2LC_s+1}[e^{\frac{2s\sqrt{LC_g}}{\sqrt{s^2LC_s+1}}}+1]]} \quad (1)$$

$$V_{SE}(s) = \frac{2E(s)Z_{oC}[Z_{oC}\sinh(\tau s) + Z_{Tinput}(s)\cosh(\tau s)]}{\sinh(\tau s)[Z_{oC}^2 + Z_{oL}Z_{Tinput}(s)] + Z_{oC}[Z_{oL} + Z_{Tinput}(s)]\cosh(\tau s)} \quad (4)$$

$$V_J(s) = \frac{2E(s)Z_{oC}Z_{Tinput}(s)}{\sinh(\tau s)[Z_{oC}^2 + Z_{oL}Z_{Tinput}(s)] + Z_{oC}[Z_{oL} + Z_{Tinput}(s)]\cosh(\tau s)} \quad (5)$$

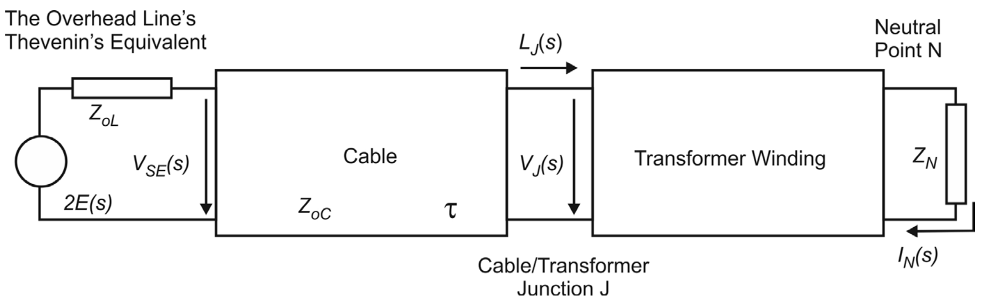


Fig. 1. The equivalent circuit of the considered radial power network.

$$I_{SE}(s) = \frac{2E(s)[Z_{oC}\cosh(\tau s) + Z_{Tinput}(s)\sinh(\tau s)]}{\sinh(\tau s)[Z_{oC}^2 + Z_{oL}Z_{Tinput}(s)] + Z_{oC}[Z_{oL} + Z_{Tinput}(s)]\cosh(\tau s)} \quad (6)$$

$$I_J(s) = \frac{2E(s)Z_{oC}}{\sinh(\tau s)[Z_{oC}^2 + Z_{oL}Z_{Tinput}(s)] + Z_{oC}[Z_{oL} + Z_{Tinput}(s)]\cosh(\tau s)} \quad (7)$$

from which the following current expressions can be derived: eq. 6, eq. 7 (see above).

The above s-domain expressions can be transformed in the time-domain through the application of one of the available numerical inverse Laplace-transform techniques, such as the Hosono's algorithm [4,8]. They have been successfully applied to analyze several problems, as reported in [1,13-15].

3. SAMPLE RESULTS

A sample 300-kV network is considered. In this study the two typical surge impedance values of Z_{oL} = 500 and 250 Ohms are assumed for single- or double-circuit overhead lines, respectively. Also, the two values 20 and 40 Ohms are substituted for the cable section surge impedance Z_{oC}. The following transformer's parameters are assumed: L = 450 μH, C_g = 10.5 nF and $C_s = C_g/10$.

The transients are initiated by the 1/12.5 μsec. double-exponential voltage source having a peak value of 1. It has the following equations in the time- and s-domains, respectively:

$$e(t) = 1.034[Exp(-\frac{1000000t}{16.8}) - Exp(-\frac{1000000t}{0.085})] \quad (8)$$

$$E(s) = \frac{1.21032\times10^7}{s^2 + 1.18242\times10^7 s + 7.0028\times10^{11}} \quad (9)$$

4. CONDITIONS WITHOUT CABLE SECTIONS

The two plots Fig. 2-(a) and Fig. 2-(b) depict the voltage transients across the transformer $v_J(t)$ for the two cases of single- and double-circuit overhead lines, respectively. Results for the three different transformer's neutral treatments (solid-earthing, isolated neutral and a 450 μH inductive earthing) are given. For reference, the waveform of the initiating voltage source $e(t)$ is also shown over the time range $0 \le t \le 75$ μsec. In both plots (a) and (b), the highest transformer transient voltage occurs in networks having isolated neutral at the time point t = 7.5 μsec. The corresponding voltage peaks are 1.31 and 1.65 per unit for the cases of single- and double-circuit overhead lines, respectively. Both cases of solid and inductive earthing exhibit almost the same value of the peak transient voltage, 0.80 per unit, after about 1.5 μsec. These voltage peaks are approximately 0.80 per unit for the case of single-circuit line and 1.16 per unit for the double circuit line. The superimposed high frequency oscillations occur at a frequency close to 200 kHz.

5. CONDITIONS WITH CABLE SECTIONS

The plots given in Fig. 3 describe the network transients after inserting a cable section having a delay time of 0.25 μsec. This corresponds to a cable length of about $75/\sqrt{\varepsilon_r}$ meters, where ε_r is the dielectric constant of the cable's insulating material. The reduced peak transient voltages due to the cable section, for the different neutral treatments, can be clearly recognized if the plots Fig. 2-(a) and Fig. 2-(b) are compared with the corresponding ones Fig. 3-(a) and Fig. 3-(b). For instance, with isolated neutral, the maximum instantaneous transformer voltage decreases from 1.31 per unit to 1.13 per unit with the cable section. With a solidly-earthed as well as inductively-earthed neutral, the maximum voltage also drops from 0.80 to about 0.50 per unit. With networks comprising double-circuit overhead lines, the reductions in the transformer's peak transient voltage are:

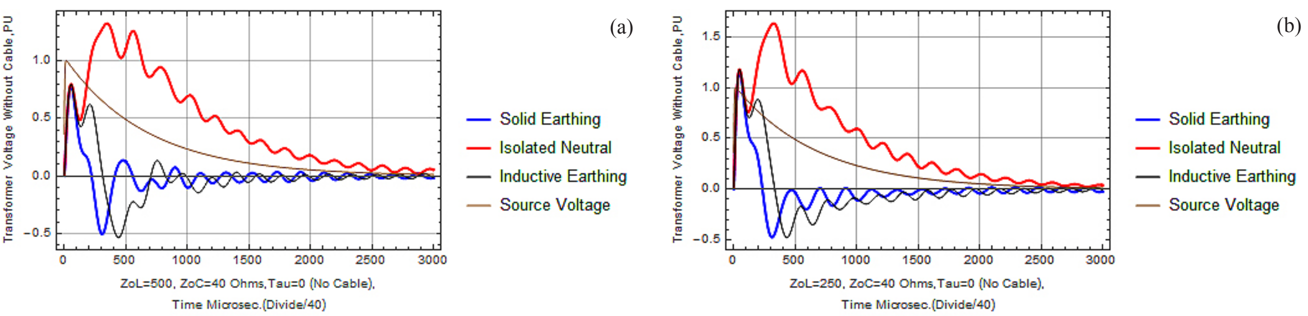
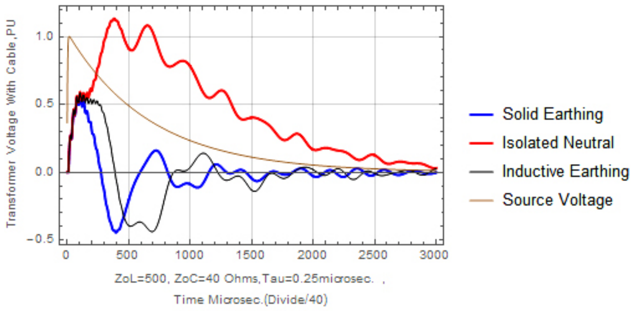
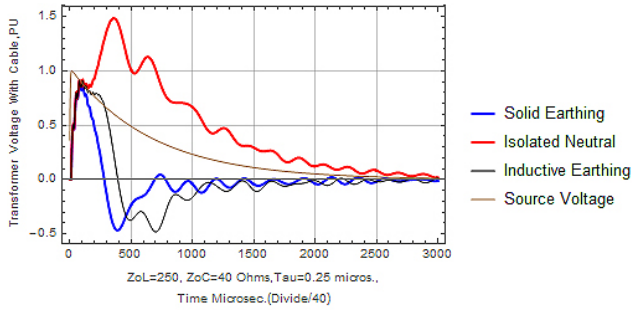


Fig. 2. The transient voltage across the transformer without any cable sections:
(a) Single-circuit transmission line with surge impedance 500 Ohms; (b) Double-circuit transmission line with surge impedance 250 Ohms.



(a) $Z_{oL} = 500\ \Omega$ & $Z_{oC} = 40\ \Omega$



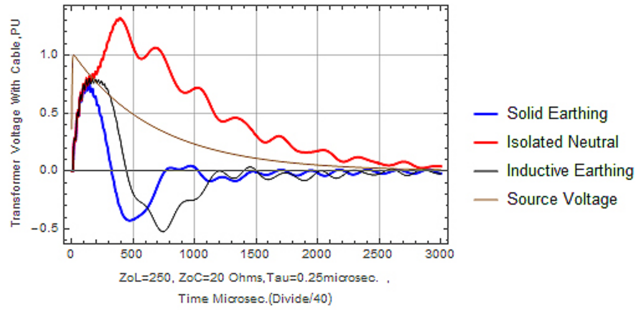
(b) $Z_{oL} = 250\ \Omega$ & $Z_{oC} = 40\ \Omega$

Fig. 3. The transient voltage across the transformer after inserting cable sections of time delay $\tau = 0.25$ µsec

(a) Single-circuit transmission line of surge impedance $Z_{oL} = 500\ \Omega$ & cable section of surge impedance $Z_{oC} = 40\ \Omega$

(b) Double-circuit transmission line of surge impedance $Z_{oL} = 250\ \Omega$ & cable section of surge impedance $Z_{oC} = 40\ \Omega$

(c) Double-circuit transmission line of surge impedance $Z_{oL} = 250\ \Omega$ & able section of surge impedance $Z_{oC} = 20\ \Omega$



(c) $Z_{oL} = 250\ \Omega$ & $Z_{oC} = 20\ \Omega$

from 1.65 to 1.50 per unit for the networks with isolated neutral and from 1.16 to 0.85 per unit for both cases of solid- and inductive-earthing.

1. Effect of The Cable Surge Impedance

The reduction in the transformer voltage stress is more pronounced if cables of smaller surge impedance Z_{oC} are used. This is observed by inspecting the two plots shown in Fig. 3-(b) for $Z_{oC} = 40\ \Omega$ and Fig. 3-(c) $Z_{oC} = 20\ \Omega$. Both describe the case of double-circuit lines. The reductions in the transformer's peak voltage are: from 1.50 to 1.35 per unit for the networks with isolated neutral and from 0.85 to 0.75 per unit for both cases of solid- and inductive-earthing, respectively.

The two plots in Fig. 4 illustrate the effect of the cable's surge impedance Z_{oC} on the voltage $v_J(t)$ and current $i_J(t)$ developed at the cable/transformer junction in a network with isolated neutral having a single-circuit overhead line of $Z_{oL} = 500\ \Omega$. The two values $Z_{oC} = 40\ \Omega$ and Fig. 3-(c) $Z_{oC} = 20\ \Omega$ are compared. The two corresponding voltage peaks are about 1.20 and 0.85 per unit in the cases of $Z_{oC} = 40\ \Omega$ and $Z_{oC} = 20\ \Omega$, respectively. The current plot Fig. 4-(b) indicates the two corresponding peak values of 0.0037 and 0.0025 A per 1 V of the surge source's $e(t)$ crest value. The two plots of Fig. 4 demonstrate the advantage of using cable sections of smaller surge impedance.

2. Effect of The Cable Length

Fig. 5 depicts the dependence of the magnitude of the transformer's peak voltage on the length of the cable section expressed by its time delay τ. The assumed surge impedances of the single-circuit overhead line and the cable sections are $Z_{oL} = 500\ \Omega$ and $40\ \Omega$, respectively. The results of solidly-, inductively-earthed as well as isolated neutral are illustrated. Eighteen plotting points, 0.10 µsec. apart, are used in order to construct each of the three indicated curves. The values for $\tau = 0$ (i.e. without cable sections) agree with the corresponding peak voltages indicated in Fig. 2-(a). It can be observed that cable sections of $\tau = 0.25$ µsec. can reduce the peak voltage developed across the transformer by about 50%, for all the three neutral treatments. It is further noticed that, for all cable lengths, the voltage peaks of solidly- or inductively-earthed cases are only about 60% of the corresponding values in networks with isolated neutral. This information can be helpful in assessing the economical considerations in the process of selecting the proper cable length.

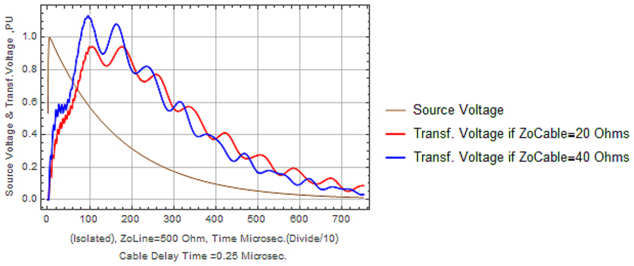
3. Response to Multiple-Pulse Lightning Surges [10,16]

This section describes the response of the above described networks to multiple-pulse lightning current surge. For convenience, its peak value is assumed 1 A. The number of the equidistant pulsed is n of duration T, each. Its time- and Laplace s-domain expressions are given by [16]:

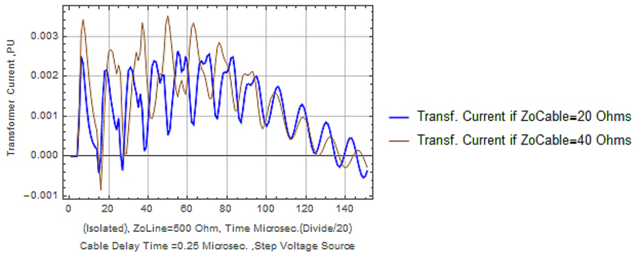
$$i_{surge}(t) = \sin^2\left(\frac{\pi t}{T}\right)[u(t) - u(t - nT)] \qquad (10)$$

$$I_{surge}(s) = 0.5\left[\frac{1}{s} - \frac{s}{s^2 + 1.57914\times 10^{12}}\right](1 - 2.71828^{-0.00004s}) \qquad (11)$$

In terms of Thevenin's theorem, the corresponding expression of $E(s)$ is $Z_{oL} \cdot I_{surge}(s)$.



(a) The junction voltage $v_J(t)$



(b) The junction current $i_J(t)$

Fig. 4. The transients at the cable/transformer junction with a cable section of $\tau = 0.25$ μsec. The network is of isolated neutral and includes a single-circuit line of $Z_{oL} = 500\ \Omega$. The two values of the cable surge impedance $Z_{oC} = 20\ \Omega$ and $40\ \Omega$ are considered
(a) The voltage $v_J(t)$ at the cable/transformer junction; (b) The junction current iJ(t)

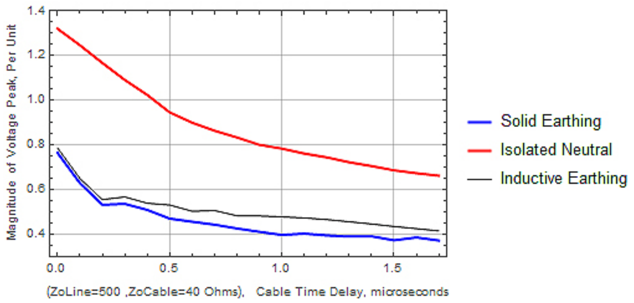


Fig. 5. Effect of the cable length on the peak value of the junction voltage for three conditions of neutral treatment

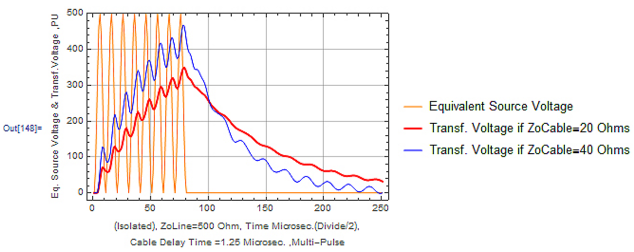
The plots of Fig. 6 give the transient response of a network of isolated neutral including a single-circuit line of $Z_{oL} = 500\ \Omega$ and a cable section of a delay time $\tau = 1.25$ μsec. According to above discussion, the peak value of the 8-pulse surge is 500 V. The pulse duration T is assumed 5 μsec. Two cable sections of $Z_{oC} = 20\ \Omega$ and $40\ \Omega$ are considered. In addition to the $e(t)$ of a total duration of 40 μsec., Fig. 6-(a) shows the voltage developed across the transformer, $v_J(t)$, for the two types of cables. They exhibit peak values of 340 V and 470 V for the cases of $Z_{oC} = 20\ \Omega$ and $Z_{oC} = 40\ \Omega$, respectively. For the same cable surge impedances, the peak current at the transformer's terminals can assume values close to 0.3 A and 0.6 A, respectively, as illustrated by the two plots 6-(b) and 6-(c). This demonstrates the superiority of using cable sections of low surge impedance.

4. Validation of the Computation Procedure

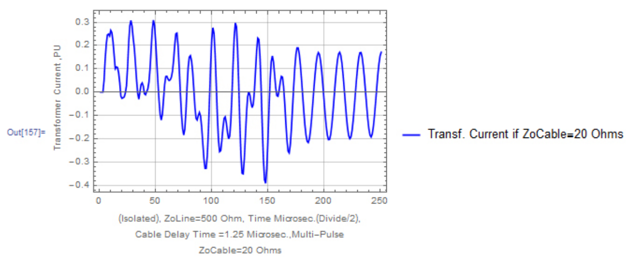
This section is devoted to checking the suggested model and the computer program used for generating the above results.

Case (i): Results With Cable Section, No Transformer

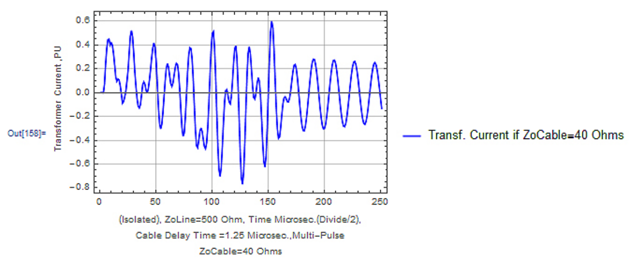
In this case, a cable of time delay 1 μsec. is assumed. The absence of the transformer is simulated by substituting $C_g = 0$, $C_s = 0$ and an infinitely large value for its inductance L. The results are depicted in Figs. 7-(a) and 7-(b) for the voltage and current at the line/cable junction, respectively. The source voltage $e(t)$ is assumed a step function of magnitude 1000 V, i.e. $E(s) = 1000/s$ in the Laplace-domain. The surge impedances Z_{oL}, Z_{oC} have the values 500 and 50 Ω, respectively. The plots agree exactly with both those resulting



(a) The transformer voltage $v_J(t)$

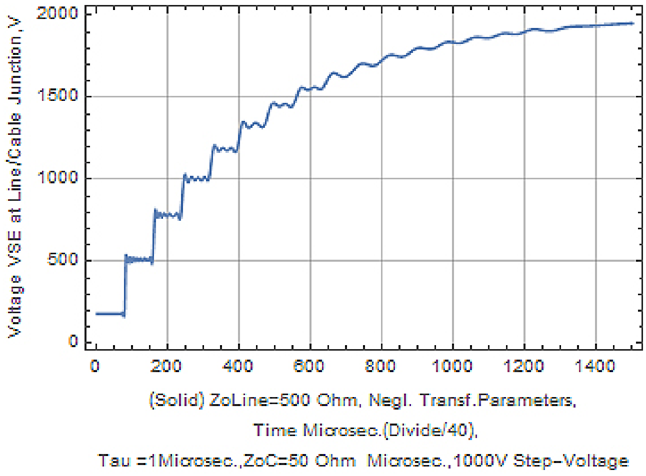


(b) The transformer junction current $i_J(t)$ for $Z_{oC} = 20\ \Omega$

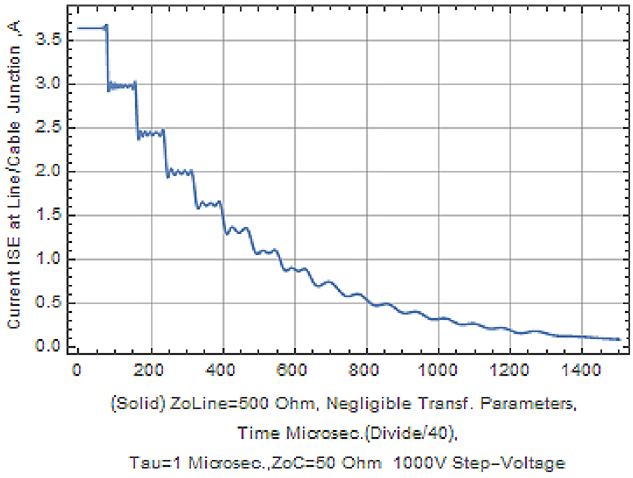


(c) The transformer junction current $i_J(t)$ for $Z_{oC} = 40\ \Omega$

Fig. 6. The transients at the cable/transformer junction due to an 8-pulse current lightning surge with a cable section of τ = 1.25 μsec. The network is of isolated neutral and includes a single-circuit line of $Z_{oL} = 500\ \Omega$. The two values $Z_{oC} = 20\ \Omega$ and $40\ \Omega$ are considered.
(a) The voltage $v_J(t)$ at the cable/transformer junction
(b), (c) The junction current $i_J(t)$



(a) The voltage at the line/cable junction, $v_{SE}(t)$



(b) The current at the Line/Cable junction, $i_{SE}(t)$

Fig. 7. Plots of the voltage $v_{SE}(t)$ and current $i_{SE}(t)$ at the line/cable junction due to a 1000 V step source voltage $e(t)$

from Bewely's lattice diagram [5]. The results are also in full agreement with those obtained from the numerical Laplace inversion of the exact voltage and current expressions in the s-domain. They can be obtained as:

$$V_{SE}(s) = \frac{(2000/s)}{500 + 50/\tanh(\tau s)} \qquad (12)$$

$$I_{SE}(s) = V_{SE}(s)/[50/\tanh(\tau s)] \qquad (13)$$

where 50/tanh(τs) is the cable's input impedance seen at the line/cable junction, at no load.

Case (ii): No Cable Sections, Inductive Earthing

In order to simulate the absence of any cable sections, a zero value for the time delay τ is assumed. It is further supposed that the transformer has zero circuit parameters L, C_g, C_s. This means a direct connection between the cable/transformer junction J and the transformer's neutral point. The neutral is inductively-earthed via a 450 µH Petersen coil. As expected, the obtained voltage and current results are exactly identical to those of an R/L series circuit with $R = Z_{oL}$ and L=450 µH. Moreover, the two voltages $v_J(t)$ and $v_{SE}(t)$ are equal. Similarly, $i_J(t) = i_{SE}(t)$.

Case (iii): No Cable Sections, Solid Earthing

In this case also, the cable delay time τ = 0. The capacitances (C_g, C_s) of the solidly-earthed transformer are assumed zero. Its inductance is substituted L=450 µH. The equivalent circuit of this special case is identical to that of the previous case (ii).

As expected, the results are also exactly the same.

Case (iv): Comparison with EMTP results available in Reference [17]

Fig. 8 depicts a sample 345-kV mixed power network analyzed in [17]. It comprises a 100-km overhead line which is hit in its midpoint by a 20-kA, 8/20 µsec. lightening surge current. The line is connected to a 500-kVA, 345/115-kV transformer via an XLPE underground cable. Several values of the cable length, and accordingly its time delay τ_C, are investigated. The data of a sample case are the values 500 and 33 Ω for the line's and cable's surge impedances, respectively. Each of the two 50-km line sections has τ_L of about 167 µsec. The reference applied the sophisticated Electromagnetic Transient Program EMTP based on lumped-parameter representation. Results pertinent to the transient voltage $v_J(t)$ at the cable/transformer junction are given.

The following plots illustrate the results of analyzing the same case study through the application of the here suggested simpler closed-form analytic solution. The s-domain equivalent circuit is given in Fig. 9.

It can be shown that the Laplace-domain expression of the voltage at cable/transformer junction is:

$$V_J(s) = A(s)/B(s) \qquad (14)$$

$$A(s) = 2I_{source}(s).R_i Z_{oC} Z_{oL} Z_{Tinput}(s).\cosh(\tau_L s) \qquad (15)$$

$$\begin{aligned} B(s) = {} & \sinh(\tau_C s).(\sinh(2\tau_L s)(2R_i Z_{oC}^2 + Z_{oL}^2 Z_{Tinput}(s)) + Z_{oL}(2R_i Z_{Tinput}(s) + Z_{oC}^2)\cosh(2\tau_L s) + \\ & Z_{oC}^2 Z_{oL}) + Z_{oC}\cosh(\tau_C s)((2R_i Z_{Tinput}(s) + Z_{oL}^2)\sinh(2\tau_L s) + Z_{oL}(2R_i + Z_{Tinput}(s))\cosh(2\tau_L s) + \\ & Z_{oL} Z_{Tinput}(s)) \end{aligned} \qquad (16)$$

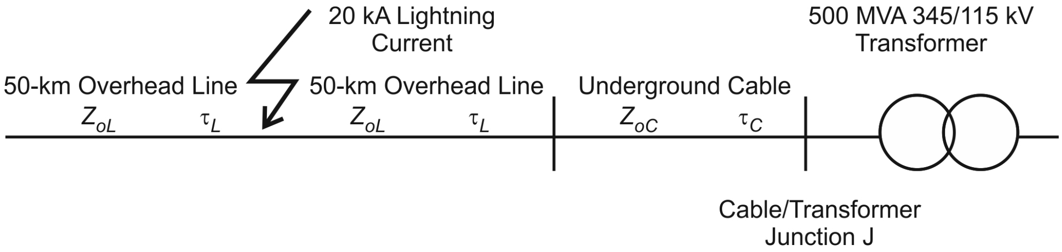


Fig. 8. One-line diagram of the sample network investigated in [17]

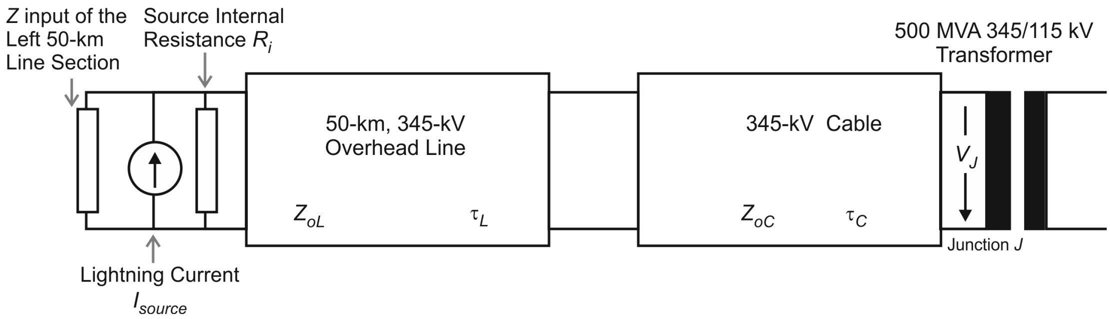
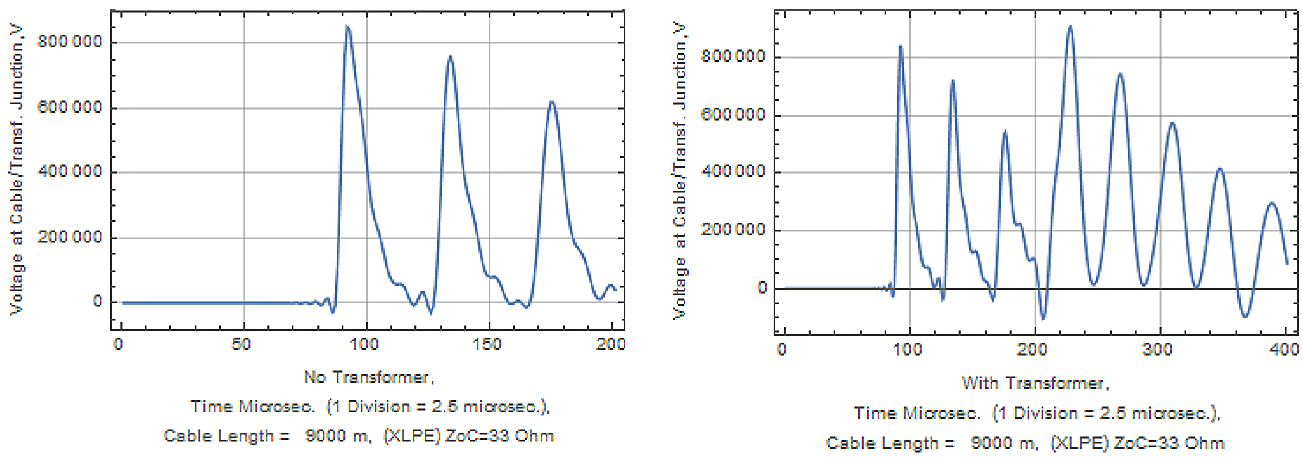


Fig. 9. The *s*-domain equivalent circuit of the network described in Fig. 8, derived according the here proposed procedure



(a) The voltage $v_J(t)$ at the cable/transformer junction, without the transformer

(b) The voltage $v_J(t)$ at the cable/transformer junction, with the transformer

Fig. 10. The results obtained from the Mathematica program according to the here proposed procedure

The transformer's input impedance, $Z_{Tinput}(s)$ is defined according to equation (1).

The time domain response, $v_J(t)$, can be obtained from numerical inverse Laplace inversion.

The two plots in Figs. 10-(a) and 10-(b) could be obtained for a 9000-m cable without and with the receiving-end transformer, respectively. The waveforms and peak values of the two plots are in good agreement with the corresponding ones given in [17].

6. SUMMARY AND CONCLUSIONS

1. The paper is a contribution to the electromagnetic transient analysis of mixed power networks with special emphasis on the use of cable sections to reduce the transient stresses in the power network components such as transformers.
2. A distributed parameter modeling of the lines, cables and transformers is applied in the Laplace domain. It can handle the different waveforms of the sources initiating the transients, the lengths of the cable sections as well as the transformers' neutral treatments. The direct analytical *s*-domain solution is numerically inverted in order to get the time domain results.
3. The transformer winding is described as an equivalent line with uniformly distributed inductance, ground capacitance and series inter-turn capacitance.
4. A 300-kV network is considered. Two typical surge impedance values of 500 and 250 Ω are assumed for single- or double-circuit lines, respectively. Also, the two values 20 and 40 Ω are considered for the cable surge

impedance. The transients are initiated by a 1/12.5 μsec. double-exponential voltage source having a base peak value of 1 V.

5. In the absence of cable sections, results indicate that the highest transformer transient voltage occurs in networks having isolated neutral. The voltage peaks are 1.31 and 1.65 per unit for the cases of single- and double-circuit lines, respectively.
6. Both cases of solid and inductive earthing exhibit almost the same value of the peak transient voltage, i.e, 0.80 per unit in the case of single-circuit line and 1.16 per unit with a double circuit line.
7. With isolated neutral, the maximum transformer voltage decreases by 13.7% after inserting a cable section with a delay time of 0.25 μsec. With a solidly- and inductively-earthed neutral, the maximum voltage drops by 37.5%.
8. In networks comprising double-circuit lines, the reductions in the transformer's peak transient voltage are: 9.1% for isolated neutral and 26.7% for solid- and inductive-earthing.
9. The reduction in the transformer voltage stress is more pronounced if cables of smaller surge impedance are used. In networks with double-circuit lines, the reductions in the transformer's peak voltage due to inserting cables of a surge impedance 20 instead of 40 Ω are 10% for isolated neutral and 11.8% for solid- and inductive-earthing, respectively.
10. In a network with isolated neutral and comprising a single-circuit overhead line, the transients for two values of the cable's surge impedances 40 and 20 Ω are compared. The voltage peaks are about 1.20 and 0.85 per unit, respectively. The two current peaks are 0.0037 and 0.0025 A per 1 V of the surge source's crest value.
11. Cable sections of a 0.25 μsec. delay time can reduce the peak voltage developed across the transformer by about 50%, for all the three neutral treatments.
12. For all cable lengths, the voltage peaks of solidly- or inductively-earthed cases are only about 60% of the corresponding values in networks with isolated neutral.
13. If the network with a single-circuit line is struck by an 8-pulse, 1 A repetitive surge current, peak transformer voltages of 340 and 470 V will be developed in the cases of 20 and 40 Ω cable surge impedances, respectively. The peak transformer currents are about 0.3 A and 0.6 A, again demonstrating the advantage of using cables of low surge impedance.
14. A section is presented for validating the suggested model and computer program. Four case studies of available solutions (either exact from direct circuit analysis followed by analytical inverse Laplace transform, or having comparable results in the literature obtained from applying the EMTP), are discussed.
15. Although the presented results are those initiated by single- or multiple-pulse voltage or current sources, the technique is equally applicable to cases involving other types of stimuli such as sinusoidal or step-function time waveforms.

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