

CAPACITIVE INDUCED VOLTAGES IN PARALLEL TRANSMISSION LINES

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The circuits of double-circuit transmission lines or two different lines with a common parallel path, influence each other by capacitive and inductive coupling, both if one of them operate normally or in a fault regime. The paper present a simply algorithm to be followed in order to assess the permanent capacitive induced voltages in a victim circuit. Numerical values of induced voltages are determined for a 220 kV double-circuit line and also for a 110 kV line nearby one of 400 kV.

Keywords: transmission line, line parameters, capacitive coupling

1. Introduction

The issue of induced voltages caused by overhead transmission lines in operation, in different structures located in their vicinity, such as other power lines or telecommunications lines, running parallel on longer or shorter distances or in moving or stationary vehicles, fences, irrigation systems, metal pipes disposed above ground or underground etc., has been studied in many papers [1–5]. Influences occurring between circuits having the same or different rated voltages and disposed on the same tower have been also studied, [6, 7]. Circuit or field approaches have been used, consisting in analytical relations or computer codes which can solve the problem numerically.

Different assumptions have been applied, each of them neglecting some of the multitude of influence parameters. In many cases, when the requirements stipulated by technical prescriptions are not very specific, the designers ask frequently for simple calculation procedures in order to adopt the right decision regarding the safe operation of the power line in the presence of others, once the insulation distances have been respected.

The issue is important from the following points of view:

- to ensure the safety of personnel which works at one of the parallel lines when the other one is just been energized (as a result of willing switching operations or imposed by fault condition); the same problem occurs when working on a line circuit and the other one is in operation;
- to assess the changes in the line parameter values of parallel power lines and their effect on the voltage symmetry in normal operation conditions;

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- to ensure the proper adjustments of relay protections of the circuits disposed on common towers.

In normal or fault operation conditions, in the line placed nearby or in the circuit disposed on the same tower capacitive and inductive couplings occur. Their separated or combined effect has undesirable influences on the “victim” line.

Capacitive coupling occurs between adjacent circuits because of time-varying potential differences between them and consequently because of displacement current.

The paper deals with the interaction between two parallel lines having different rated voltages (high and low) and the inter-influence problem which occurs between the circuits disposed on the same tower, trying to find the simplest way to solve it and to identify the adequate way to compute the line parameters.

Because will be analyzed only cases where common length paths of circuits that interact are substantially shorter comparing with wavelength of signal, the propagation phenomena do not occur and consequently it's not necessary to apply the transmission line theory.

2. Theoretical considerations

The capacitive coupling causes transversal voltages between juxtaposed circuits in parallel paths. As the quasistatic approximation stands for low frequencies such as the power frequency, induced voltages can be calculated with an acceptable error applying the electrostatics analytical methods based on the geometry of the power line and the conductors' potentials or their electrical charges.

In the first step were calculated self and mutual Maxwell's potential coefficient of multi-conductor system under consideration, both in the case of multi-circuit lines or distinct lines with parallel paths. The diagonal elements of the potential coefficient (per unit length) matrix were calculated using relations:

$$p_{ii} = \frac{1}{2\pi\epsilon_0} \ln \frac{2h_i}{r_i}, \quad (1)$$

where h_i is the suspension height of conductor “ i ” above the ground, r_i – the real or equivalent radius of conductor and ϵ_0 – the permittivity of free space. Regarding the average height of conductor above ground, which is considered constant, it can be used either the value (commonly used in the Romanian references),

$$h_i = h_{\text{tower}} - (2/3) \cdot s, \quad (2)$$

or the value resulting from:

$$h_i = h_{\text{min}} + (1/3) \cdot s, \quad (3)$$

h_{tower} being the suspension height of conductor at the tower, h_{\min} – the minimum suspension height of conductor versus the soil, at the half span, in the condition when the conductor describe a parabola shape between towers (span width up to 500 m), and s – the conductor sag.

In the case of bundled conductors, instead of real radius r_i shall be used the equivalent radius, calculated by relation:

$$r_{eq,i} = R \sqrt[n]{\frac{nr_i}{R}}, \quad (4)$$

where R is the radius of the bundle, n – the number of conductors which compose a bundle and r_i – the radius of a single conductor in the bundle structure of a phase. The mutual potential coefficients (the off-diagonal elements of specific matrix) were calculated using the relation:

$$p_{ij} = \frac{1}{2\pi\epsilon_0} \ln \frac{D_{ij}}{d_{ij}}, \quad (5)$$

where d_{ij} is the distance between conductors i and j , and D_{ij} – the distance between the real conductor i and the image of the conductor j , image disposed under the ground level at a distance h_j (according the method of image charges). Also it is evident the equality: $p_{ij} = p_{ji}$.

The Maxwell's potential coefficient matrix can be also calculated using the relation:

$$[p] = \epsilon_0 \mu_0 [L]^{-1}, \quad (6)$$

if inductance matrix is known.

It should be mentioned that dedicated subroutines exists, either in Matlab (power_lineparam) and also in EMTP (Line Constants) which can compute overhead specific line's parameters, when input data are adequate introduced.

Parameters determined by the above relations, called "geometric parameters", are valid by accepting the hypothesis of perfect conductor (zero resistivity) ground.

The finite value of the ground conductivity (lossy ground assumption) alters only the resistance and inductance values of the line conductors which are also sensitive to the frequency of the signal and could be affected by the skin effect. Referring to this last point it should be mentioned that for power frequency and in the case of a solid conductor, its resistance is higher with a few percentages compared with DC case, while inductance is smaller (than in the DC case), also with few percentages.

The potentials of conductors can be calculated using matrix relation:

$$[V] = [p] \cdot [q], \quad (7)$$

$[V]$ and $[q]$ being vectors having $1 \times m$ dimension (m – the number of conductors which compose the system, taking into consideration also the ground wires if they

exist), the potential coefficients matrix, $[p]$, being a square matrix with $m \times m$ dimension. If the conductors' potentials are known, their electrical charges can be calculated using the following matrix relation:

$$[q] = [\gamma] \cdot [V], \quad (8)$$

where $[\gamma]$ is the matrix of coefficients of electrostatic induction, $[\gamma] = [p]^{-1}$ the properties of those matrix elements being: $\gamma_{ij} = \gamma_{ji} < 0$, and $\gamma_{ii} > 0$ (the same properties which characterize the elements of potential coefficient matrix, regarding diagonal and non-diagonal terms).

The case when the electrostatic induced voltages are highest, in the conductors of a circuit disposed nearby another one in operation, is when the "victim" circuit is open (the conductors are insulated from the ground, the line being disconnected at both ends). Knowing the particular situations of the conductors regarding theirs applied potentials or theirs surface charges, it is possible to calculate the unknown quantities. It is well known that the conductors connected to ground take null potentials, while the induced charges in those conductors, by an operating circuit disposed in neighborhood are non-zero. And also, if an insulated conductor is under the influence of other ones which are energized, then its electrical charge is zero but its potential is non-zero.

Let's now consider a double-circuit line which has one ground wire and has only one circuit energized and the other one insulated. The system has 7 conductors, 3 of them energized (belonging to the active circuit, denoted by 1, 2 and 3), one conductor is at zero potential – the ground wire (denoted by 4) and the remaining conductors (denoted by 5, 6, 7) have null electrical charge. The matrices equation will be:

$$[q_1 \ q_2 \ q_3 \ q_4 \ 0 \ 0 \ 0]^T = [\gamma] \cdot [V_1 \ V_2 \ V_3 \ 0 \ V_5 \ V_6 \ V_7]^T, \quad (9)$$

the exponent T standing for transposed.

The voltages V_5 , V_6 , V_7 being unknown, their values can be calculated using the last three equations from the system above. The first of the three mentioned equations is:

$$0 = \gamma_{51}V_1 + \gamma_{52}V_2 + \gamma_{53}V_3 + \gamma_{54} \cdot 0 + \gamma_{55}V_5 + \gamma_{56}V_6 + \gamma_{57}V_7, \quad (10)$$

this one and the following two equations could be written into the following form, when the unknown quantities are passed in the left side:

$$\begin{aligned} \gamma_{55}V_5 + \gamma_{56}V_6 + \gamma_{57}V_7 &= -\gamma_{51}V_1 - \gamma_{52}V_2 - \gamma_{53}V_3 \\ \gamma_{65}V_5 + \gamma_{66}V_6 + \gamma_{67}V_7 &= -\gamma_{61}V_1 - \gamma_{62}V_2 - \gamma_{63}V_3 \\ \gamma_{75}V_5 + \gamma_{76}V_6 + \gamma_{77}V_7 &= -\gamma_{71}V_1 - \gamma_{72}V_2 - \gamma_{73}V_3 \end{aligned} \quad (11)$$

Arranging the equation system (into a matrix form), the unknown quantities shall be calculated with the relation:

$$\begin{bmatrix} \underline{V}_5 \\ \underline{V}_6 \\ \underline{V}_7 \end{bmatrix} = - \begin{bmatrix} \gamma_{55} & \gamma_{56} & \gamma_{57} \\ \gamma_{65} & \gamma_{66} & \gamma_{67} \\ \gamma_{75} & \gamma_{76} & \gamma_{77} \end{bmatrix}^{-1} \cdot \begin{bmatrix} \gamma_{51} & \gamma_{52} & \gamma_{53} \\ \gamma_{61} & \gamma_{62} & \gamma_{63} \\ \gamma_{71} & \gamma_{72} & \gamma_{73} \end{bmatrix} \cdot \begin{bmatrix} \underline{V}_1 \\ \underline{V}_2 \\ \underline{V}_3 \end{bmatrix} \quad (12)$$

Generalizing, the relation (12) could be written as:

$$[\underline{V}_{\text{unknown}}] = -[\gamma_{\text{uu}}]^{-1} [\gamma_{\text{uk}}] [\underline{V}_{\text{known}}], \quad (13)$$

where the vector $[\underline{V}_{\text{unknown}}]$ contains the unknown voltages, $[\gamma_{\text{uu}}]$ is the square matrix which contains the coefficients of electrostatic induction only between the conductors of the “victim” circuit, and $[\gamma_{\text{uk}}]$ – the matrix which contains the coefficients of electrostatic induction between the conductors of the victim circuit and those of the disturbance source; the vector $[\underline{V}_{\text{known}}]$ contains the known voltages. The equations matrix (13) could be also applied if the number of conductors with known voltages, as example, m , (which is the dimension of vector $[\underline{V}_{\text{known}}]$) differ by the number of unknown voltages (as example, n), the only condition being that $n \leq m$. In this case the matrix $[\gamma_{\text{uu}}]$ is a square matrix with dimensions $n \times n$ and the matrix $[\gamma_{\text{uk}}]$ has dimensions $m \times n$. The presence of ground wires connected to the earth (having 0 potential) do not influence the values of induced voltages in the victim circuit by means of this coupling mechanism.

The previous relation shows that the product of the two matrices whose terms are the coefficients of electrostatic induction, is dimensionless (the measuring unit for $[\gamma_{\text{uu}}]^{-1}$ is [m/F] and for $[\gamma_{\text{uk}}]$ is [F/m], the last, as for capacitances per unit length). As result, the values of induced voltages by capacitive coupling between the two circuits not depend of the parallel length between them. The same conclusion can be found in [8].

An explanation may be the following: when the parallel length of the lines or circuits increases, the equivalent capacitance increases as well. In terms of electro-kinetics, the displacement current injected in the overall capacity increases (the total reactance decreases) but the charges carried per unit time will now be distributed over a larger capacity so that the voltage between the two armatures do not increase proportional to the length of the circuit. If the induced voltage level is not dependent to the parallelism length between lines, the effect of induced charges depend strongly of this length. If a conductor of the victim line is connected to the ground, directly or through a resistance, the discharge current (due to the stored energy) will be strictly proportional to the parallel length.

More precautions (during short circuiting stage in order to ensure the working zone) must be taken in this case, as example, before live working on the non-energized line or circuit that are close and parallel, on a long distance, with an energized circuit.

On the other hand, measurements performed on a 220 kV double-circuit line, reported in [9], exhibit a dependence of the induced voltage with the

interaction length of the two circuits but, however, from the presented data it appears that this dependence is weak.

3. Numerical results

Calculations were made for the following cases: 220 kV double-circuit line, figure 1 (two types of towers) and parallel lines 400 kV with 110 kV. The 220 kV and 400 kV transmission lines are equipped with ACSR 450/75 mm², but the 400 kV line is equipped with 2 conductors per phase, with a distance between them of 400 mm.

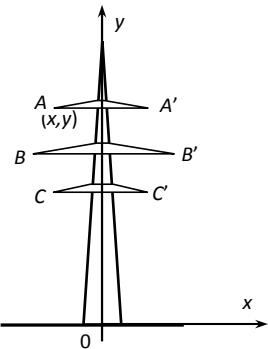


Fig.1. Geometrical coordinates of 220 kV double circuit line, at the tower.

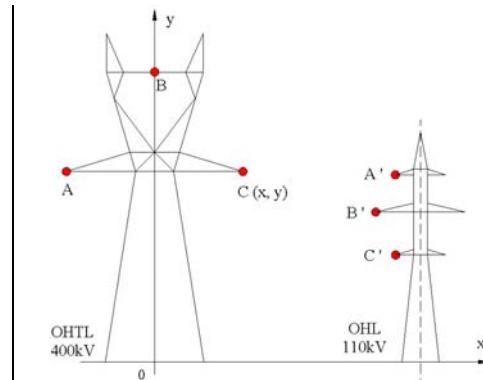


Fig. 2. Geometrical coordinates of the couple 400 kV line parallel with a 110 kV line.

The 110 kV line is equipped with ACSR 185/32 mm² conductors. The insulators string lengths and conductors' sags are known and typical for such lines. The suspension strings positions in Cartesian coordinates, and also the resulting values of capacitive induced voltages are indicated in Table 1. For the double-circuit 220 kV lines the coordinates are given with reference to the vertical axis of the tower, while for the coupling between the 400 kV and 110 kV lines the reference is the vertical axis of the 400 kV line (Figure 2).

The transposition of phases for the inductor line (or circuit) has no effect on the induced voltages in the nearby circuit, i.e. the same r.m.s. value of the voltage is induced in the phases of the "victim" line, as long as the conductors' positions remain unchanged. Regarding the capacitive coupling between the circuits of the 220 kV double-circuit line, as it can be observed, the maximum value of the capacitive induced voltage appears on the phase located in the upper position on the tower, in both analyzed cases, and the minimum values on the phases disposed in the middle or the lowest position.

The minimum horizontal distances between the closest phases (inductor-induced) in the case of the double-circuit 220 kV lines were 9.5 m and 10 m respectively, and in the case of 400 kV and 110 kV parallel lines was 8.15 m.

Table 1

Geometrical characteristic of lines and the values of capacitive induced voltage in parallel circuit

Double circuit OHTL 220 kV, tower type SN 220201						
	Source of disturbance			Victim of disturbance		
Phase coordinates (*)	A	B	C	A'	B'	C'
x [m] →	-5	-8	-5	5	8	5
y [m] →	35	28.5	22	35	28.5	22
Capacitive induced voltage [kV] ∠ phase angle°	in normal operation conditions of circuit A,B,C →			11.04∠156.7°	3.30∠155.7°	2.34∠311.0°
	in conditions of single-phase fault ($V_A=0$), other two phases operating normally →			11.37∠22.6°	7.84∠10.0°	9.26∠349°
Double circuit OHTL 220 kV, tower type SN 220205						
	Source of disturbance			Victim of disturbance		
Phase coordinates (*)	A	B	C	A'	B'	C'
x [m] →	-4.5	-8	-5	4.5	8	5
y [m] →	37	30.5	24	37	30.5	24
Capacitive induced voltage [kV] ∠ phase angle°	in normal operation conditions of circuit A,B,C →			11.48∠158.9°	2.69∠162.0°	4.19∠313.7°
	in conditions of single-phase fault ($V_A=0$), other two phases operating normally →			13.54∠17.8°	9.81∠4.7°	13.06∠346.6°
Parallel 400 kV OHTL (tower type ICR+6 400170) with 110 kV line (tower type ICn 110231)						
	Source of disturbance (OHTL 400 kV)			Victim of disturbance (OHL 110 kV)		
Phase coordinates (*)	A	B	C	A'	B'	C'
x [m] →	-7.75	0	7.75	17.54	15.90	17.44
y [m] →	27	38.5	27	25.4	21.2	17.00
Capacitive induced voltage [kV] ∠ phase angle°	in normal operation conditions of circuit A,B,C →			15.18∠323.2°	13.67∠311.9°	6.92∠312.2°
	in conditions of single-phase fault ($V_A=0$), other two phases operating normally →			27.18∠340.5°	22.75∠333.4°	12.79∠333.6°

(* at the suspension point of insulator string.

4. Conclusions

Relative high values of the induced voltage (several kV or more) occur due to capacitive coupling when one of the circuits is disconnected and isolated from ground, while the parallel circuit disposed on same tower (or the parallel line located at reduced distance) remains energized. The induced voltages forms an unbalanced three-phase system. In particular cases, such as in example with the coupling between 400 kV and 110 kV lines, this three-phase system appear to be closer to a zero sequence system.

Not only the induced voltages are a concern for operational personnel but also the currents injected by means of capacitances between the conductors of the source of disturbance and those of the victim. The magnitude of those currents depend, of course, on the parallel length of circuits. As example, in the case of 220 kV double circuit overhead lines, above presented, the most exposed phase conductor of victim circuit receives a capacitive current of about 36 mA/km. As a mention, a general case was discussed, neglecting the possibility to transpose the phase conductors in order to symmetrize line parameters.

The paper presents a simple way for estimating capacitive induced voltages, in steady state, in the circuits disposed on the same tower or running nearby parallel with an energized line and offers some numerical results in order to estimate the magnitude of these voltages.

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