Chapter 16

Experimental Determinations and Numerical Simulations of the Effects of Electromagnetic Interferences into the Overhead Power Lines with Double Circuit, Operating with a Disconnected Circuit

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Additional information is available at the end of the chapter

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1. Introduction

The goal of finding methods and ways of warning and protecting the operating personnel, who perform maintenance programs on high voltage overhead power lines with double circuit, operating with a disconnected circuit, requires accurate knowledge of the electric and magnetic coupling mechanism as well as the voltages induced by these types of coupling at low frequency (50-60 Hz).

The experiments performed over the last 60 years in specialized laboratories around the world showed that low-frequency electromagnetic fields (50 Hz) generated by the overhead power lines affect both the functioning of electrical devices and equipments in the neighborhood and the health of living organisms in the area.

The experimental researches have showed that electromagnetic interferences of disturbing electromagnetic fields created by high voltage overhead power lines manifests itself mainly by two types of influences on the objects in the area, including the neighboring power lines, namely:

- Electrical influences produced by capacitive couplings between the phase conductors of electric three-phase lines and objects or neighboring power lines;
- Magnetic influences realized through the inductive couplings between the loops formed by the conductors of the neighboring parallel electric circuits and the earth.

The two types of influences are expressed, physically, through the values of the voltages induced in the elements of the electric conductor placed near the high voltage active power lines [1].

The accurate knowledge of these induced voltages, both electrically and magnetically, is necessary for searching the ways of reducing the adverse effects that these voltages produce and especially for ensuring the protection of the operating staff [2].

In practice, there are several ways of determining the electromagnetic values of the interferences of the high voltage overhead power lines, namely:

- Measurements on the ground with specialized measuring instruments. This method has a special importance for establishing some relative values and therefore it can be considered as a reference for the other methods. But this method has disadvantages related to the very limited possibilities to achieve, physically, different operating regimes in the real conditions. This method can also lead to the occurrence of relatively large errors produced by the measuring instruments. We have to consider the impossible of taking measurements in all the points of the proximate area of the power lines.
- Experimental determinations in high voltage specialized laboratories, using physical models that simulate, on an appropriate scale, the real situations on the ground. The method allows, theoretically, of realizing any operating regime of the power lines, being intuitive in terms of physical phenomena, but it is affected by errors due to the specific laboratory conditions of the realization of the physical model because some conditions imposed by the physical parameters of the objective reality (temperature, pressure, humidity, dielectric rigidity of the atmosphere, electrical permittivity and magnetic permeability of the environment) are neglected or circumvented.
- Mathematical modeling of the electromagnetic interferences using some modern ultra fast computing software which allows of obtaining through calculation the values of the electromagnetic values for any power line, at any point in the space around it in any operating regime. Mathematical modeling, although quick and easy in apply, has an inconvenience, namely: it doesn't offer reliability unless the results it produces are comparable to those obtained by at least one of the other two experimental methods mentioned above.

It means that a realistic research requires, along with the advantages of mathematical modeling and numerical simulation of electromagnetic phenomena from the objective reality the necessity to validate them through experiments so that the mathematical models should be able to confer reliability on the instruments used for the accurate representation of the natural phenomena of electromagnetic interferences. Taking into account these observations, we are presenting, comparatively, the results obtained by the author through measurements on the ground of the voltages induced electrically and magnetically in the disconnected circuits of 220 kV power lines with double circuit, from the Banat area – Romania, with the results obtained through mathematical modeling and numerical simulation of the voltages induced through capacitive and inductive couplings in the measuring points of the respective power line conductors. The concordance of the mathematical simulation results with those determined experimentally allow of validating the mathematical models which become, therefore, useful tools for the professionals in electric power systems.

2. A practical method for measuring on the ground the voltages induced by the overhead power lines

In the case of high voltage overhead power lines with double circuit having one of the electrical circuits disconnected for maintenance or repair, the active electrical circuit will induce electromotive voltages and will force the electric currents induced in the disconnected electric circuit, threatening the technical staff working on the respective line [3-5,7].

Considering this phenomenon, between years 2006 - 2009, the author measured on the ground the voltages induced in the 220 kV power lines with double circuit from the Banat area - Romania. These measurements were aimed at determining the level of electromagnetic stress which appears in a disconnected circuit, when in parallel with it there is the second circuit which is operating in normal regime. Experimentally, there has been established that immediately after disconnecting the circuit, although it is disconnected and insulated from the earth, the voltages induced through electric (capacitive) coupling appear on each phase and at the moment when the short-circuit devices are closed, the voltages induced through electric coupling become null and voltages induced through magnetic (inductive) coupling appear and they force the appearance of currents induced in the loops formed by each of the three phases of the disconnected circuit and the earth.

Given the appearance of two types of disturbances affecting the disconnected power line, the measurements must firstly take into account the determination of the voltages induced through electric (capacitive) coupling on each of the three phases, and then, that of the voltages induced by magnetic (inductive) coupling in the three loops of the disconnected circuit and connected to the ground through short-circuit devices, at one of its ends.

There are several methods of determining the induced voltages, but we have opted for using classical measurement apparatuses accessible to everybody, namely an electrostatic voltmeter, with a scale of up to 30 kV, a common voltmeter with a scale up to 2.5 kV and Ditz pliers ammeter, which is sensitive enough.

For measuring the voltages induced electrically and magnetically by the active circuit into the power lines of the disconnected circuits, the following two methods have been adopted [6]:

a. If the three-phase circuit conductors of the disconnected lines are not grounded through short-circuit devices, thus they being insulated from the ground, the disconnected circuit conductors will have a much lower potential than the active circuit conductor placed in close proximity. In this case, between the active circuit conductors and the disconnected circuit conductors there will take place electric (capacitive) couplings, the conductors playing the role of armature of the huge condenser having the air as a dielectric medium. Depending on the intensity of the electric coupling (depending on the distance between the conductor and the length of parallel lines), the potentials of the disconnected circuit phases will change when compared with the ground potential. A possible measurement of these potentials (voltages induced through capacitive coupling) is shown in figure 1.

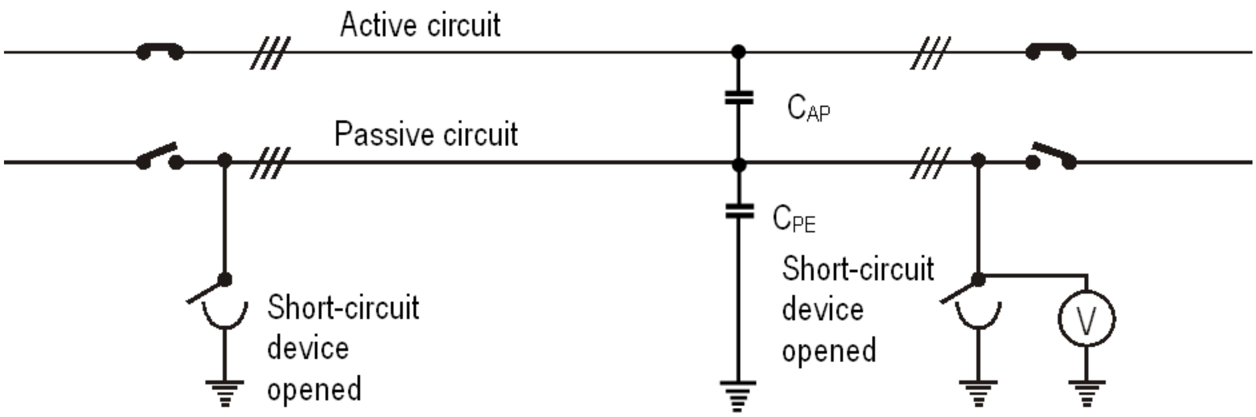

Figure 1. Measuring the voltages induced by the electric (capacitive) coupling in the disconnected circuit conductors of a high voltage overhead power line with double circuit.

b. If the disconnected three-phase circuit conductors are grounded at both ends through short-circuit devices, three loops are basically being formed, in which the intense electromagnetic fields of the load currents of the active circuit will induce electromotive voltages, forcing the closing of the induced currents, this coupling being magnetic (figure 2).

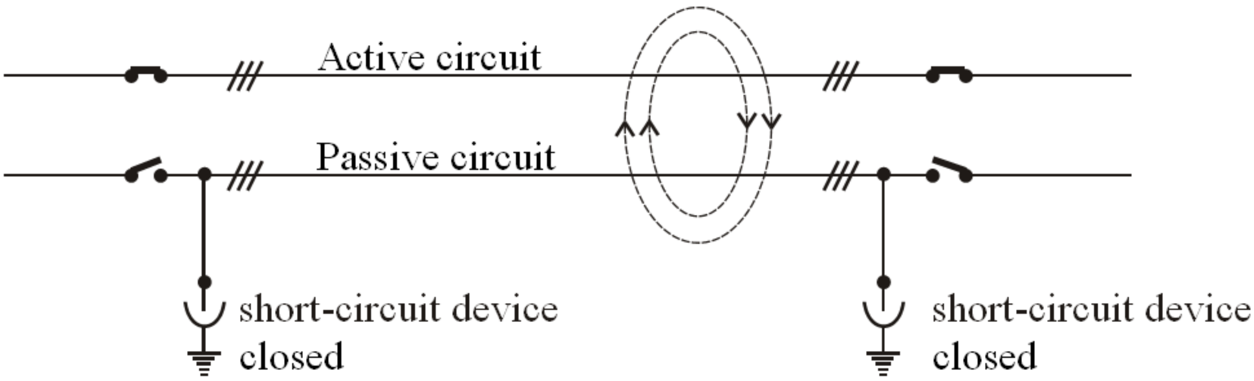

Figure 2. The magnetic coupling between the active circuit and the disconnected circuit of a high voltage overhead power line with double circuit.

In this situation, in order to measure the induced voltages in the three phases of the disconnected circuit, there need to be opened the short-circuit devices from one of the ends of the line and install a voltmeter, as shown in figure 3.

In the Banat area- Romania, which consists of four districts, there are several overhead lines of 220 kV, which operate in parallel on a structure of double circuit metal pillars, on different distances supplying many consumers of different types. Depending on the power transferred on these lines, if there is a disconnected circuit, there will appear voltages induced in the

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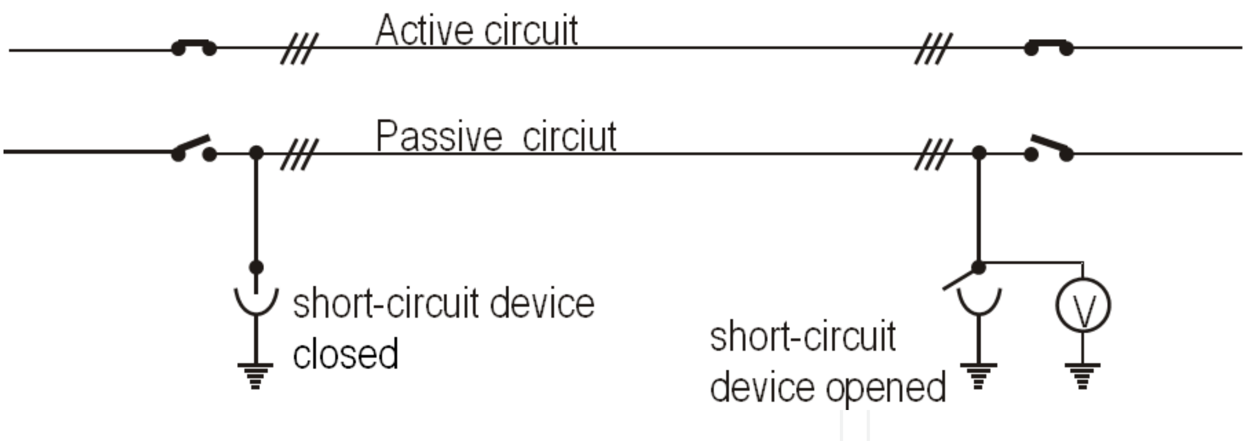

Figure 3. Measuring the voltages induced by the magnetic (inductive) coupling in the disconnected circuit of a high voltage overhead power line with double circuit.

disconnected circuit both through electric and magnetic coupling, and these voltages must be known. The worst cases are those in which the active circuit is very long and supplies consumers requiring high power consumption.

In figure 4 there is presented the configuration of 220 kV overhead power lines with double circuit, from the Banat area – Romania.

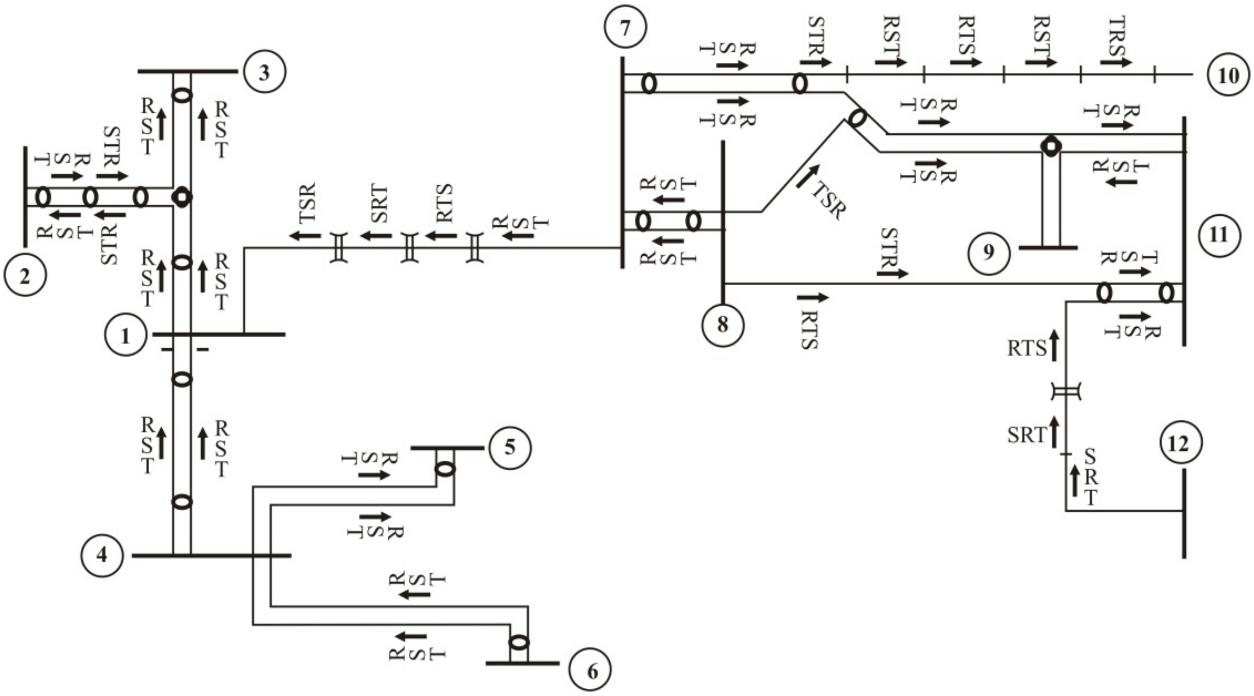

Figure 4. Configuration of 220 kV overhead power lines from the Banat area - Romania

Since the metal supporting pillars for most of the lines have the same configuration, in Table 1 there are given their main geometrical parameters corresponding to the generalized geometrical distances presented in figure 5.

Nr. crt.	Pillar type	H (m)	a1 (m)	h1(m)	h2 (m)	d1 (m)	d2 (m)	d3 (m)	λ_{iz} (m)	f_{max} (m)	h_g (m)
1	Sn 220.201	41,4	6,4	6,5	6,5	5,0	8,0	5,0	2,541	14,0	5,459
2	Sn 220.202	41,4	6,4	6,5	6,5	5,0	8,0	5,0	2,541	14,0	5,459
3	Sn 220.204	42,5	5,5	6,5	6,5	4,5	8,0	5,0	2,541	14,0	7,459
4	Sn 220.205	42,5	5,5	6,5	6,5	4,5	8,0	5,0	2,541	14,0	7,459
5	Ss 220.205	44,9	6,9	8,0	8,0	5,5	9,5	5,5	2,541	14,0	5,459
6	Ss 220.206	46,0	6,0	8,0	8,0	4,75	9,25	5,25	2,541	14,0	7,459

Table 1. The dimensions of the supporting pillars for 220 kV overhead power lines with double circuit.

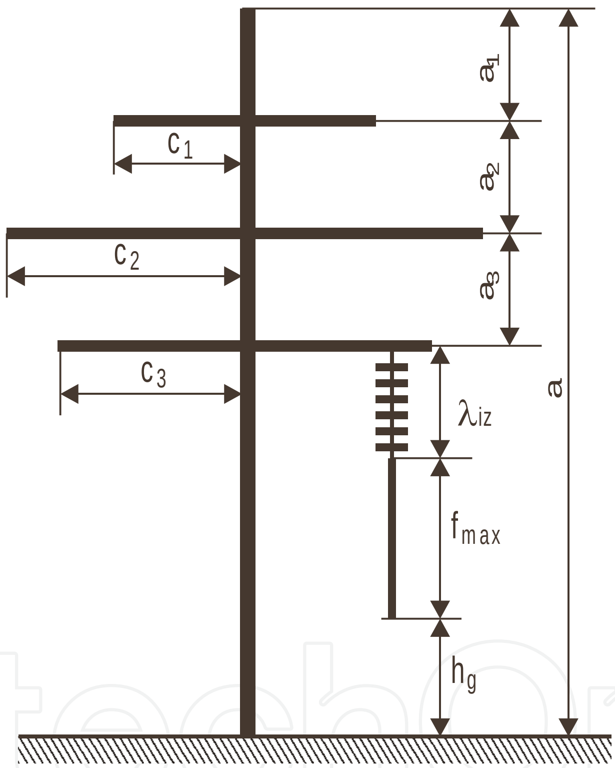

Figure 5. Schematic geometrical representation of a supporting pillar

The active conductors of the power lines are steel-aluminium with standard sections of 400 mm^2 or 450 mm^2, these being specified for each power line separately.

In order to perform measurements of the voltages induced there was previously required to establish the measuring program, with well defined steps, to be able to protect the operating staff against the exposure to the high voltage effects. This program has included all the

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necessary measures to be taken in case of working under voltage and it was spread out over the following steps:

a. Specification of the initial state of the overhead high voltage power line with double circuit, on which measurements are to be carried out, indicating the exact situation of the two circuits of the power lines, namely:

- Circuit A – set into operation;
- Circuit B – non- operating, grounded through short-circuit devices at both ends.

b. For each measurement, the following conditions of protection must be respected:

- The leader of the team must be equipped with overalls, high voltage electro-insulated boots, protective helmet and high voltage electro-insulated gloves.
- The modification of the measuring range of the apparatus is made only after disconnecting the measuring circuit by removing the electro-insulated rod from the circuit being measured;
- The reading of the measuring apparatus is done remotely by an operator equipped accordingly (work under high voltage).
- The cables of the measuring apparatus will be placed at a distance from the operator.

c. The measurement of the voltages induced through the two types of coupling into the conductors of the disconnected circuit is realized according to the following procedures:

- Connect to the ground the cable of the electrostatic voltmeter and then connect it to the grounding clamp of the apparatus;
- Connect one end of the active cable to the measuring clamp of the electrostatic voltmeter;
- Connect the other end of the active cable to the electro-insulated rod
- For measuring the voltages induced by electric coupling, the short-circuit devices of the disconnected circuit of the power lines have to be open at both ends and for measuring the voltage induced by magnetic coupling, the short-circuit devices of the disconnected circuit are opened only at the end where the measuring is performed.
- The voltages induced on the three-phase disconnected circuit are measured successively by touching, with the electro-insulated rod the connections of the phase conductors to the short-circuit devices.

Based on the diagram shown in Fig. 4, there have been determined sub stations in which the measures are performed, according to the number of the outputs of 220 kV lines, with double circuit:

- Substation 11 – with connections to substation 7, 8 and 12;
- Substation 2 - with connections to substation 3 and 1;
- Substation 4 - with connections to substation 5, 1 and 6;

- Substation 7 - with connections to substation 1, 8, 10 and 11;
- Substation 9 - with connections to substation 8 and 11.

The results of the measurements carried out according to the program described above are synthetically, presented in Table 2, for the voltages induced through electric (capacitive) coupling and in Table 3, for the voltages induced by the magnetic (inductive) coupling.

Overhead power line	Circuit A [km]	Circuit B [km]	Active circuit voltage	Voltage induced electrically (capacitive) measured in the disconnected circuit		
			U [kV]	U_R [kV]	U_S [kV]	U_T [kV]
7 - 11	49.876	25.455	237.5	8.87	2.7	4.4
8 - 9 maximum load	25.455	11.249	236.9	12.7	20.2	18.3
8 - 9	25.455	11.249	236.9	12.7	20.2	12.3
11 - 12	16.688	43.897	225	1.9	3.35	2.35
9 - 11	25.455	7.422	236.8	19.4	23.4	18.2
4 - 6	116..550	116..550	228 225 232	10.4	3.6	5.1
7 - 8	18.675	18.675	237	8.9	4.42	6.25
4 - 5	30.730	30.730	226.5	3.03	7.94	5.9
4 - 1	72.867	72.867	234	11.1	3.7	5.4
1 - 2	53.719	24.620	230 235 225	6.55	5.82	5.41
2 - 3	53.719	55.173	230 235 225	8.2	2.8	4.2

Table 2. The voltages induced through electric (capacitive) coupling in 220 kV overhead power lines, with double circuit, having circuit B disconnected.

Observing Table 2 and Table 3 there has been stated that:

- In the case of the lines where no phase transposition has been performed, the voltage induced through magnetic (inductive) coupling is the largest on the phase placed the highest from the ground;
- In the case of the middle phase, at most of the lines, the induced voltage is the lowest;

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Overhead power line	Length of A circuit [km]	Length of B circuit [km]	Active circuit voltage	Active circuit current	Magnetically induced voltage measured in the disconnected B circuit			Transferred power and voltage – current phase shift			
			U [kV]	I [A]	U_R [V]	U_S [V]	U_T [V]	P [MW]	Q [MVar]	cos φ	φ [rad]
7 - 11	49.876	25.455	237.5	265.75	320	21	120	107	22	0.9795	0.2028
8 - 9 maximum load	25.455	11.249	236.9	156.9	68	10.2	39	50	40	0.781	0.6745
8 - 9	25.455	11.249	236.9	74.826	34	10.2	18.5	24.9	17.9	0.812	0.6232
11 - 12	16.688	43.897	225	181.68	120	26	122	5	5	0.707	0.7855
9 - 11	25.455	7.422	236.8	92.542	11	4.3	13.2	28.5	25	0.7518	0.72
4 - 6	116.550	116.550	228 225 232	440 480 460	1400	400	1440	182	7.354	0.98	0.2003
7 - 8	18.675	18.675	237	71.77	63.6	13	42	29	5	0.985	0.1734
4 - 5	30.730	30.730	226.5	14.54	20.8	3.6	17	0	5.7	0	1.57
4 - 1	72.867	72.867	234	497.03	1020	400	940	200	22	0.988	0.155
1 - 2	53.719	24.620	230 235 225	212 237 218	180	71	1260	50	10.15	0.98	0.2003
2 - 3	53.719	55.173	230 235 225	212 237 218	310	80	270	50	10.15	0.98	0.2003

Table 3. Voltages induced through magnetic (inductive) coupling in 220 kV overhead power lines, with double circuit, with circuit B disconnected.

- All the voltages induced by capacitive coupling are very high and dangerous for the operating staff.
- The length of the parallel distance between the active line (inductor) and the disconnected one (armature) influences the values of the voltage induced, regardless of the type of electromagnetic coupling. To observe this phenomenon, there have been drawn the curves of the voltages induced, depending on the length of their parallel portions; there have been drawn curves for voltages induced both through electric (capacitive) coupling, U_E = f(l) and for magnetic (inductive) coupling, U_M = f(l). The resulted curves are shown in fig. 6 and fig. 7.

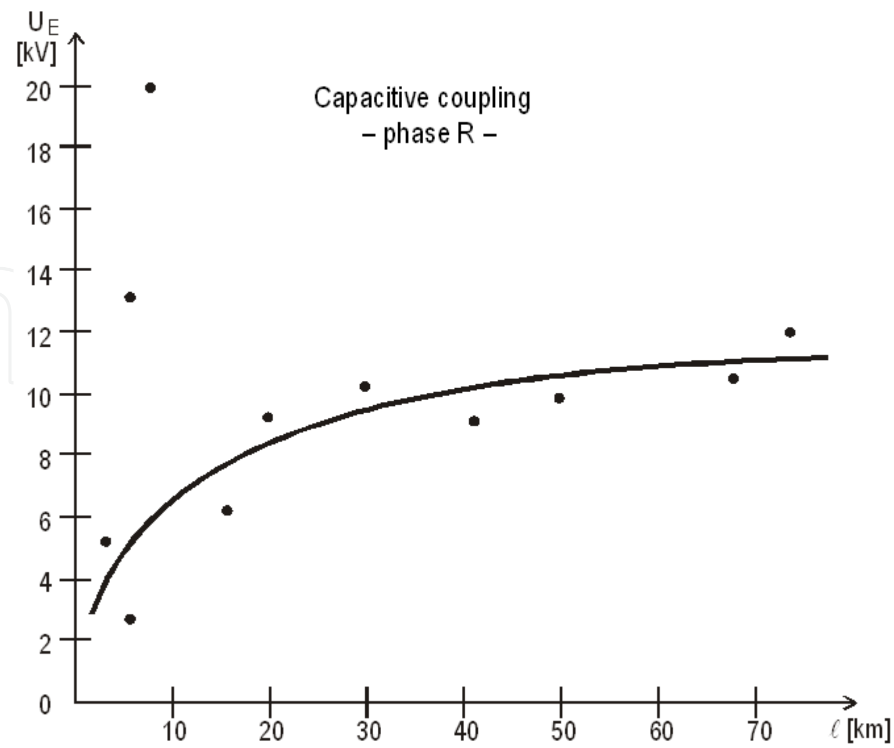

Figure 6. The variation of the voltages induced through capacitive coupling depending on the length of their parallel portions.

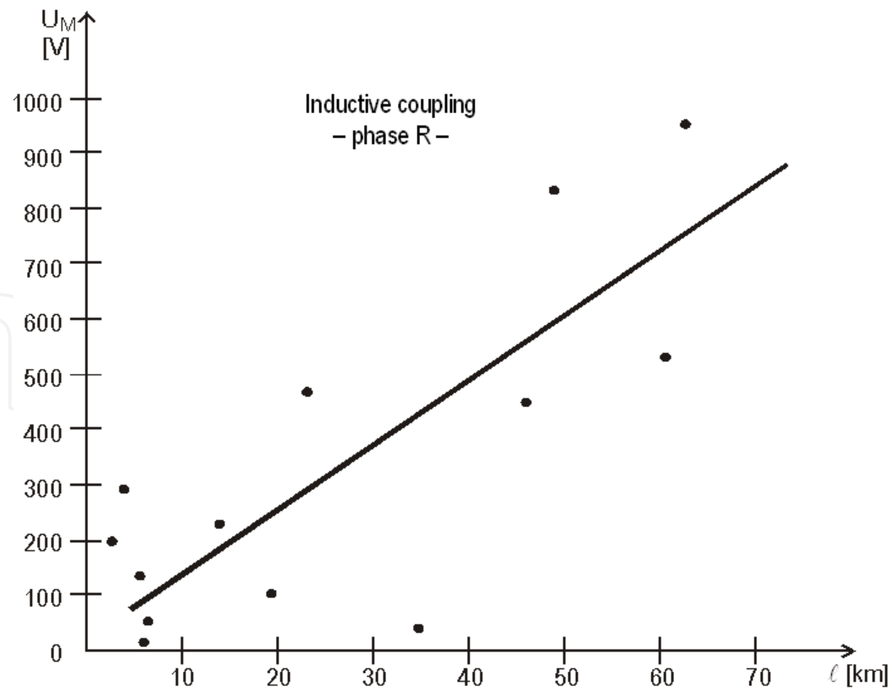

Figure 7. The variation of the voltages induced through inductive coupling depending on the length of their parallel portions.

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From the analysis of figures 6 and 7 there has been observed that on small distances, of up to about 20 km, where there is parallelism between the two electric circuits located on the same pillars of the double-circuit, the length influences very little the induced voltage. On these distances, a number of other causes are more important. At distances longer than 20 km, the value of the voltage induced by both the electric (capacitive) and magnetic (inductive) coupling has a linear increasing trend along with the increasing of the length of the parallel distance.

3. The mathematical models for determining the induced voltages

The data obtained from measurements on the ground represent an advantage for conceiving mathematical models, because the results obtained through mathematical modeling can be managed comparing with the real ones. This fact has lain at the basis of designing the mathematical models, trying to imitate, as realistically as possible, the physical phenomena that occur in nature.

It should also be mentioned that, at low frequencies, the couplings of the electromagnetic interferences between sources and victims can be separated, through different experiments, into electric couplings and magnetic couplings, respectively. Mathematical modeling should take into account this observation that leads to achieving, separately, two different models, one for electric and one for magnetic phenomena [8, 9].

But regardless of the type of electromagnetic coupling, the values of induced voltages are dependent on both the geometry of the power lines and the power running on these lines and therefore the mathematical models must include, primarily, the geometric calculation of the supporting pillars of the high voltage overhead power lines with double circuit and the determination of their capacities and, respectively, the mutual inductances between the conductors of the power line with double circuit. The geometric, electric and magnetic parameters represent equation coefficients through which there are determined the voltages induced electrically and magnetically in the conductors of the disconnected circuit of the high voltage power line with double circuit.

3.1. Determination of the geometric parameters of the supporting pillars of the high voltage overhead power lines with double circuit

The calculation of the geometrical parameters of the supporting pillars of the high voltage overhead power lines with double circuit must consider the distances between the conductors of the double circuit, the distances between conductors and their images in the earth and the maximum arrow formed by the conductors of the power line in a standard horizontal opening, as shown in Fig.8, a and b.

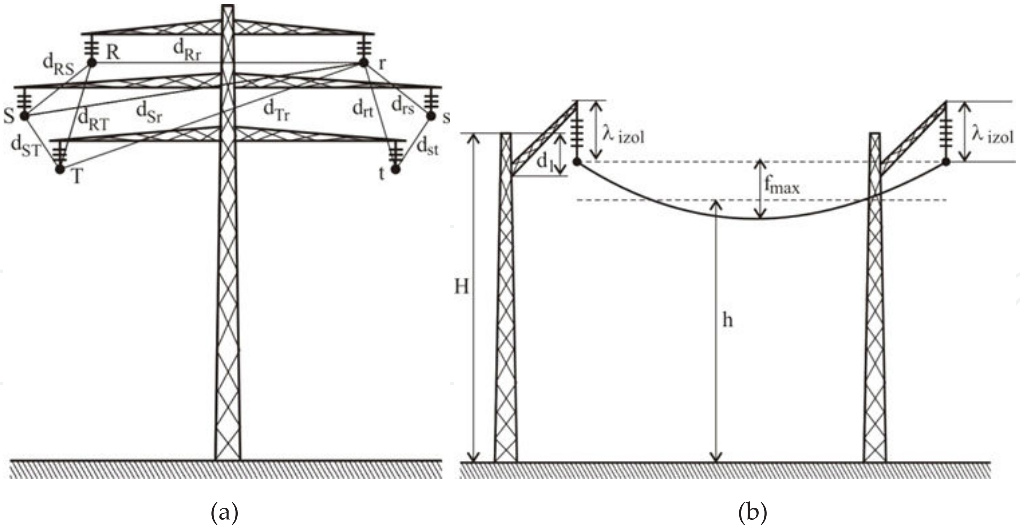

Figure 8. Explanation of the determination of the geometrical parameters of the high voltage overhead power lines with double circuit. a) The geometrical parameters of the pillar; b) Determination of the average height of the conductors from the ground.

The geometric calculation of the supporting pillar of the high voltage overhead power line with double circuit is made using the following algorithm:

a. The average distance between the conductors and the return path through the ground is obtained by taking into account the resistivity of the soil, with the expression:

$$D_{CP} = 550\sqrt{\frac{\rho}{f}} \tag{1}$$

where ρ - resistivity of the soil and f - the frequency of the power line voltage.

b. The average height of the power line conductor from the ground level results from:

$$h_k = H - a_1 - \lambda_{izk} - \frac{2}{3} f_{\max k} \tag{2}$$

c. The vertical and horizontal distances of the active conductors, for each type of pillar presented in table 1, are determined by the following expressions:

$$\begin{aligned} d_{RS} &= d_{rs} = \sqrt{h_1^2 + \left(d_2 - d_1\right)^2} \\ d_{ST} &= d_{st} = \sqrt{h_2^2 + \left(d_2 - d_3\right)^2} \\ d_{RT} &= d_{rt} = \sqrt{\left(h_1 + h_2\right)^2 + \left(d_3 - d_1\right)^2} \end{aligned} \tag{3}$$

d. The distances between the conductors of the two circuits of the power line with double circuit result from the following expressions:

$$\begin{aligned}
&d_{Rr} = 2d_1; \qquad d_{Ss} = 2d_2; \qquad d_{Tt} = 2d_3 \\
&d_{Sr} = d_{Rs} = \sqrt{h_1^2 + \left(2d_2 - d_1\right)^2} \\
&d_{Ts} = d_{St} = \sqrt{h_2^2 + \left(2d_2 - d_3\right)^2} \\
&d_{Tr} = d_{Rt} = \sqrt{\left(h_1 + h_2\right)^2 + \left(2d_3 - d_1\right)^2}
\end{aligned} \tag{4}$$

3.2. The mathematical modeling of the electric (capacitive) coupling

In the case of electric (capacitive) coupling, the high voltage overhead power line with double circuit represents a complex set of capacities which are formed due to the differences in potential both between the active circuit phases, because of the different values of the voltage phasers of the three-phases at any moment and between the potentials of the conductors of the active circuit and those of the disconnected circuit and that insulated from the earth. The assembly of capacities which are formed is shown in Fig. 9.

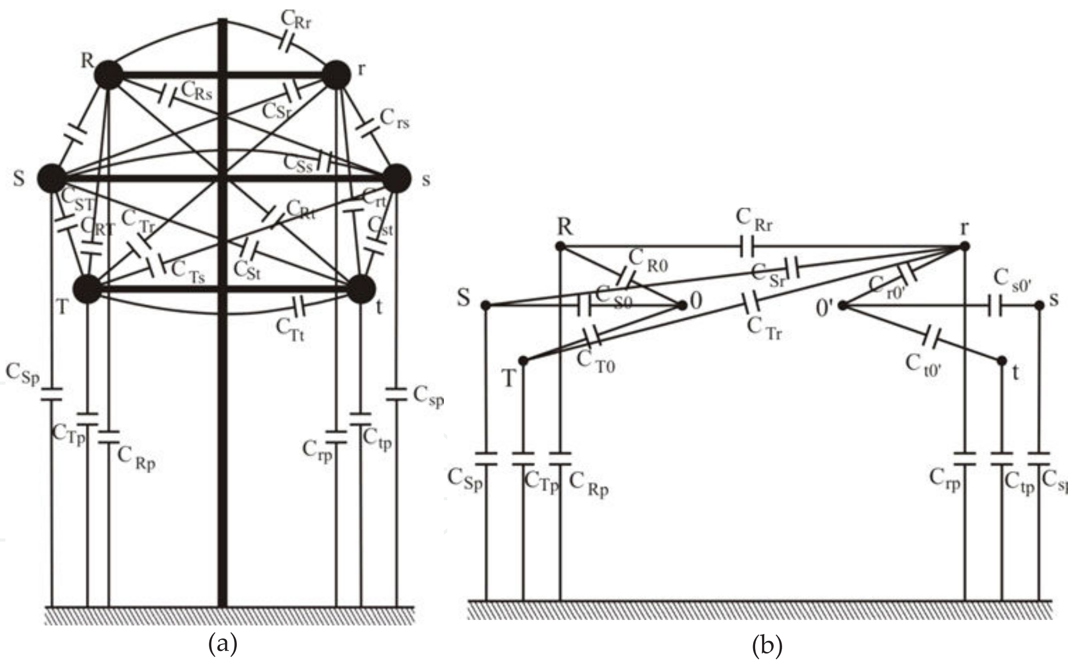

Figure 9. The set of capacities formed between the active circuit (RST) and the disconnected one (rst). a) Capacities formed between the two circuits; b) The equivalent capacities for a phase of the disconnected circuit.

The values of the partial capacities between phases and between the phases and the ground are calculated by the following expressions:

- For partial capacities between phases:

$$C_{ik} = \frac{2\pi\varepsilon_0 l}{\ln \frac{d_{ik}}{r_0}} \tag{5}$$

- For partial capacities between the phases and the ground:

$$C_{pi} = \frac{2\pi\varepsilon_0 l}{\ln\left(\frac{2h_i}{r_0}\right)} \tag{6}$$

where: l- is the length of power line, d_{ik}- the distances between the phase conductors, according to relations (3) and (4), and r_0- the radius of the phase conductor.

By transforming the phase capacities connected in delta connection (Fig. 9 a) into the equivalent capacities in Y-connection (Fig. 9 b), the null potential of the two Y-connections are equal with the null potential of the ground and thus the phase capacities are placed in parallel with the phase capacities versus the ground. There results the electrostatic equivalent scheme shown in Fig. 10:

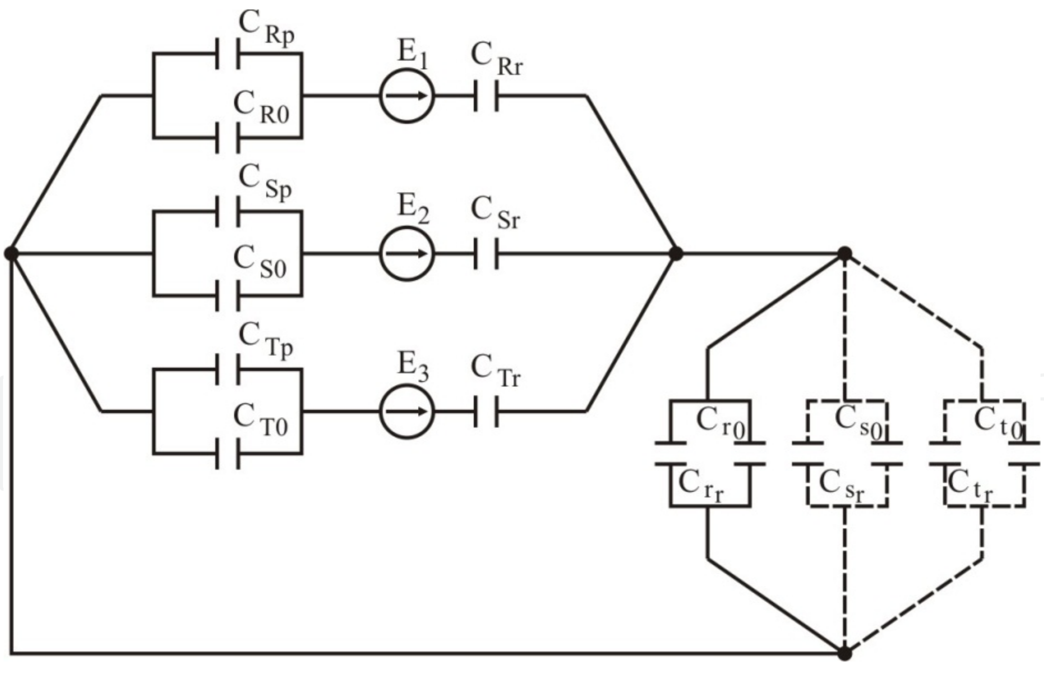

Figure 10. The electrical scheme of the capacitive coupling between the two circuits of the power line.

This electrical scheme represents a set of circuits having as passive elements only condensers, and solving of such a problem supposes using Kirchhoff's theorems either for determining the electric charge of the condensers or determining the voltages at which these condensers are

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being charged. But, in this particular case, there are known neither the electric charges of the condensers, nor the voltages at which these condensers are loading. In order to solve this complicated problem we have used analogies between the electric network, which contains only condensers and the electric network containing only resistors. Thus, if the relation for voltage drop, U, between the armatures of a condenser of capacitance C loaded with electric charge Q and voltage drop U, at the hubs of a resistor of resistance R run by currents of intensity I, there results:

$U = \frac{Q}{C}$, respectively: $U = R \cdot I$,

which allows of the establishment of the following correspondences: value $\frac{1}{C}$ is analogous to value R, and value Q is analogous to value I and, as to voltage U, in order to have the same sense in both cases, the sense of current I has to correspond to the sense of electrostatic field E between the condenser armatures, as shown in Fig.11.

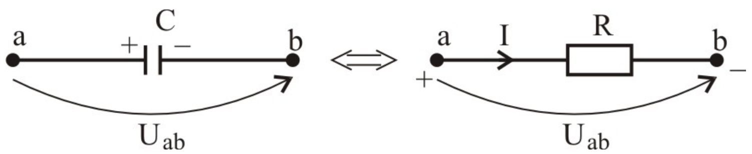

Figure 11. The correspondence between the analogous values of the theory of electrostatics and that of electro-kinetics.

Based on the analogies between the electrostatic and electro-kinetics values, there has been designed the equivalent electro-kinetics scheme, as shown in Fig. 12.

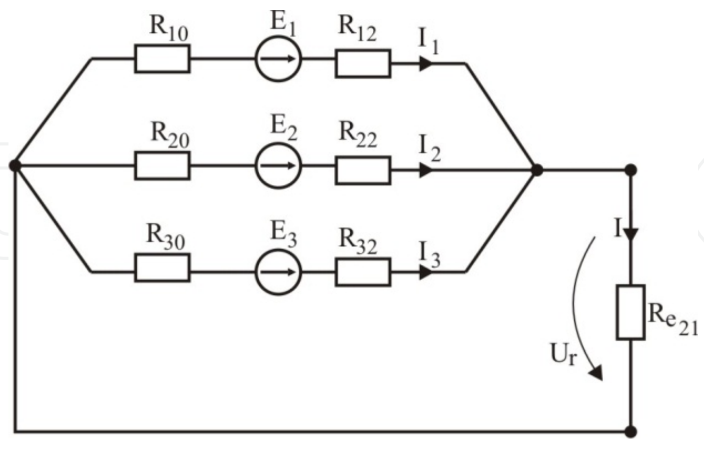

Figure 12. The analogous electro-kinetics scheme of the electric (capacitive) coupling for a phase of the disconnected circuit.

In order to determine the voltages induced through the electric (capacitive) coupling there can be applied the method of Kirchhoff's theorems in the case of the analogous electro-kinetics scheme in Fig. 12. The following system of equations result, where the currents of the edge circuits are unknown.

$$\begin{aligned} E_1 - E_2 &= \left(R_{10} + R_{12}\right)\cdot I_1 - \left(R_{20} + R_{22}\right)\cdot I_2 \\ E_2 - E_3 &= \left(R_{20} + R_{22}\right)\cdot I_2 - \left(R_{30} + R_{32}\right)\cdot I_3 \\ E_3 &= \left(R_{30} + R_{32}\right)\cdot I_3 + R_e \cdot I \\ I_1 + I_2 + I_3 &= I \end{aligned} \tag{7}$$

After solving system of equations (7), considering the analogies $I \equiv Q$ and $R_{ei} \equiv \dfrac{1}{C_{i0} + C_{ip}}$, there results the value of the voltage induced electrically in each of the three conductors of the disconnected circuit of the high voltage overhead power line with double circuit, namely:

$$U_{fi} = R_{ei} \cdot I_i, \text{ respectively } U_{fi} = \frac{Q_i}{C_{i0} + C_{ip}} \tag{8}$$

There should be mentioned that the analogies between electrostatic and electro-kinetics values are valid only in the case of d. c. circuits. But, in the present case, the analyzed circuits are in a. c. because voltage sources E_1, E_2 and E_3 are sinusoidal alternative voltages, having expressions:

$$\begin{aligned} E_1 &= \sqrt{2}\cdot U_{fR} \sin\left(\omega\cdot t + \phi\right) \\ E_2 &= \sqrt{2}\cdot U_{fS} \sin\left(\omega\cdot t + \phi - \frac{2\cdot\pi}{3}\right) \\ E_3 &= \sqrt{2}\cdot U_{fT} \sin\left(\omega\cdot t + \phi - \frac{4\cdot\pi}{3}\right) \end{aligned} \tag{9}$$

where $\omega = 2\cdot\pi\cdot f$ - is the angular frequency of the sinusoidal wave of the phase voltage and $\phi = 0$ is the initial phase difference, considered null because the relative positions of the voltage phasers versus the fixed reference axis of the phasers are not known.

For the analogies presented above be valid, "time" must to be considered a constant. But time, $t = const.$, represents the very moment of measuring the capacitive voltage induced for each phase of the disconnected circuit. Therefore it is necessary to know the measuring moment of the voltage induced for each of the three phases, separately. To determine the measuring moment there has been considered a period of the sinusoidal voltage wave, which at the frequency of $f = 50\ Hz$ has duration $T = 0.02$ seconds. Duration T, of the sinusoidal voltage wave has been divided into 100 discrete and constant time intervals, each $\Delta t = 0.0002$ seconds and thus, through the digitization of time, the variable values of the alternative current circuit have been transformed into constant values on small time intervals, Δt_k, where: $k = 1...100$, for which the analogies mentioned above become valid.

Knowing, by measuring the voltages induced electrically in the conductors of the disconnected circuit, if there are assigned 2 ÷ 3 time interval values, Δt_k, and if we use a calculation program realized in MATHCAD, from relations (9), there result immediately the calculation values of the voltages induced electrically (capacitive). These values are given in table 4, comparatively with the measured values. The measured values and those obtained through calculation are very close, this fact demonstrating the validity of the mathematical model developed and used for determining the voltages induced electrically in the circuits of the disconnected power lines.

Overhead power line	Circuit A [km]	Circuit B [km]	Active circuit voltage	Measured voltage induced electrically in the disconnected circuit			Calculated voltage induced electrically in the disconnected circuit		
			U [kV]	U_R [kV]	U_S [kV]	U_T [kV]	E_r [kV]	E_s [kV]	E_t [kV]
7 - 11	49.876	25.455	237.5	8.87	2.7	4.4	**8.823**	**2.755**	**4.415**
8 - 9 maximum load	25.455	11.249	236.9	12.7	20.2	18.3	**12.643**	**20.324**	**12.278**
8 - 9	25.455	11.249	236.9	12.7	20.2	12.3	**12.726**	**20.324**	**12.278**
11 - 12	16.688	43.897	225	1.9	3.35	2.35	**1.845**	**3.419**	**2.427**
9 - 11	25.455	7.422	236.8	19.4	23.4	18.2	**19.433**	**23.259**	**17.906**
4 - 6	116.550	116.550	228 225 232	10.4	3.6	5.1	**10.422**	**3.619**	**4.948**
7 - 8	18.675	18.675	237	8.9	4.42	6.25	**9.076**	**4.573**	**6.278**
4 - 5	30.730	30.730	226.5	3.03	7.94	5.9	**3.154**	**7.998**	**5.876**
4 - 1	72.867	72.867	234	11.1	3.7	5.4	**11.221**	**3.768**	**4.798**
1 - 2	53.719	24.620	230 235 225	6.55	5.82	5.41	**6.582**	**5.865**	**5.452**
2 - 3	53.719	55.173	230 235 225	8.2	2.8	4.2	**8.206**	**2.845**	**4.210**

Table 4. Comparison between the measured voltages induced electrically and the calculated ones.

The mathematical model presented above also allows of the determination of the maximum values of the voltages induced electrically in each of the phases of the disconnected circuit by assigning to "time" discrete values around the maximum of the sinusoidal function of the inductor voltage.

Another important observation is required, namely, that for each phase of the disconnected circuit there has been adopted a different value for the digitized time because the measurements have been made separately for each of the three phases of the respective circuit.

3.3. The mathematical modeling of the magnetic (inductive) coupling

The magnetic (inductive) coupling is generated by the electric currents varying in time running through the three conductors of the active circuit of the high voltage overhead power line with double circuit and creating variable magnetic fields which induce electromotive voltages in the conductors of the disconnected circuit. The mathematical expressions of the electric currents running through the conductors of the active circuit are given by relations (10), namely:

$$\begin{aligned} i_R &= \sqrt{2} \cdot I_{fR} \sin\left(\omega \cdot t + \varphi\right) \\ i_S &= \sqrt{2} \cdot I_{fS} \sin\left(\omega \cdot t + \varphi - \frac{2\pi}{3}\right) \\ i_T &= \sqrt{2} \cdot I_{fT} \sin\left(\omega \cdot t + \varphi - \frac{4\pi}{3}\right) \end{aligned} \tag{10}$$

where φ represents the phase shift between the voltages and the currents of the active circuit and the phase shift is known because powers *P* and *Q* which charge the active circuit are known. (Table 2).

In the mathematical model called "network model", the magnetic (inductive) coupling can be represented by the mutual inductance between the conductors of the two circuits having the general expression:

$$M_{12} = \frac{\mu_0}{4\pi} \int_0^l \frac{dl_1 dl_2}{\sqrt{\left(l_1 - l_2\right)^2 + d_{12}^2}} \tag{11}$$

where, $l_1$and l_2 are the lengths of two conductors in parallel and d_{12} is the distance between them.

After the expansion in series of the radical and neglecting the superior rank terms, relation (11) becomes:

$$M_{ik} = \frac{\mu_0}{2\pi} \cdot l \cdot \ln\left(\frac{D_{cp}}{d_{ik}}\right), \text{ where } i \in \left(R, S, T\right), \text{respectively } k \in \left(r, s, t\right) \tag{12}$$

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But, as the electromotive voltage induced in each of the three conductors of the disconnected circuit represents the contribution of all the three magnetic inductive fields generated by the variable currents of the active circuit, the mathematical expression for each phase of the disconnected circuit will be:

$$\begin{aligned} U_r &= -j \cdot \omega \cdot \left(i_R \cdot M_{Rr} + i_S \cdot M_{Sr} + i_T \cdot M_{Tr} \right) \\ U_s &= -j \cdot \omega \cdot \left(i_R \cdot M_{Rs} + i_S \cdot M_{Ss} + i_T \cdot M_{Ts} \right) \\ U_t &= -j \cdot \omega \cdot \left(i_R \cdot M_{Rt} + i_S \cdot M_{St} + i_T \cdot M_{Tt} \right) \end{aligned} \tag{13}$$

Overhead power line	**Circuit [km]A**	**Circuit [km]B**	**Active circuit voltage**	**Active circuit current**	**Measured voltage induced magnetically in the disconnected circuit**			**Calculated voltage induced magnetically in the disconnected circuit**		
			U [kV]	**I [A]**	**U_R [V]**	**U_S [V]**	**U_T [V]**	**Ur [V]**	**Us [V]**	**Ut [V]**
7 - 11	49.876	25.455	237.5	265.75	320	21	120	**317.193**	**21.014**	**120.452**
8 - 9 maximum load	25.455	11.249	236.9	156.9	68	10.2	39	**67.888**	**10.365**	**39.073**
8 - 9	25.455	11.249	236.9	74.826	34	10.2	18.5	**33.415**	**7.18**	**18.808**
11 - 12	16.688	43.897	225	181.68	120	26	122	**120.222**	**25.88**	**120.363**
9 - 11	25.455	7.422	236.8	92.542	11	4.3	13.2	**11.279**	**4.28**	**13.584**
4 - 6	116.550	116.550	228 225 232	440 480 460	1400	400	1440	**1401**	**404.28**	**1444**
7 - 8	18.675	18.675	237	71.77	63.6	13	42	**62.844**	**13.182**	**42.529**
4 - 5	30.730	30.730	226.5	14.54	20.8	3.6	17	**20.862**	**3.671**	**17.091**
4 - 1	72.867	72.867	234	497.03	1020	400	940	**1021**	**357.93**	**941.014**
1 - 2	53.719	24.620	230 235 225	212 237 218	180	71	1260	**181.052**	**71.05**	**1261**
2 - 3	53.719	55.173	230 235 225	212 237 218	310	80	270	**311.44**	**81.009**	**270.174**

Table 5. Comparison between the measured voltages induced by magnetic coupling and the calculated ones

This simple calculation algorithm has lain at the basis of designing the calculation program in MATHCAD, by means of which there were determined analytically, the voltages induced through magnetic (inductive) coupling in the disconnected circuits of 220 kV power lines with double circuit from the Banat area – Romania. The results are presented in Table 5, in comparison with the values of the voltages measured on the ground..

This case brings about an important observation. Considering phase shift φ, between voltages and currents, through which the charging with power of the inductor circuit is indirectly expressed, the mathematical model has required the representation of the currents through momentary values instead of effective ones. But this leads to an additional unknown, which is time, *t*, namely the measuring moment of the voltages induced for each phase. It means that this case also requires the digitization of period $T = 0.02$ seconds in 100 time intervals, $\Delta t_k = 0.0002$ seconds and the search of the moment in which the measurement of the voltage induced through magnetic coupling for each of the phases of the disconnected circuit was performed.

Comparing the measured values of the voltages induced through magnetic (inductive) coupling with the calculated ones there has been observed a very good concordance, which demonstrates an appropriate mathematical approach of the physical phenomena which lead to the magnetic (inductive) coupling between the conductors of the high voltage overhead power lines.

4. Conclusions

a. In all of the cases, the middle phase of the disconnected circuit of the high voltage overhead power lines with double circuit has got the lowest value for the voltage induced. It has been proved by both the measurements on the ground and the mathematical modeling. The explanation for the electric coupling lies in the longest distance between the phases of the active circuit and the middle phase of the disconnected circuit. As to the magnetic (inductive) coupling, the effect is due to the vector summation of the intensities of the inductor magnetic fields..

b. In the case of the power lines where the transposition of the phases has not been performed, the voltage induced through magnetic (inductive) coupling is the highest on the upper phase. This phenomenon is explained by the fact that the respective conductor – earth loop has the largest surface. This means that if all the protection conductors of each of the pillars were grounded there would be realized a large number of conductor – earth loops (equal with the number of openings) which would capture a part of the inductor magnetic flux, particularly that of the upper phase, thereby reducing the voltages induced through magnetic (inductive) coupling.

c. All the voltages induced through electric (capacitive) coupling have got very high values, which are dangerous for the operating staff. By being grounded, the power lines are discharged of this high potential, but there appear voltages induced through magnetic (inductive) coupling, they being high enough to be dangerous, too. Therefore, we consider that, in the case of circuits separated from the ground in a galvanic way, the operating staff have to obey the protection rules regarding working under high voltage.

d. If the grounding loops are closed at both ends through short-circuit devices, the voltages induced through magnetic (inductive) coupling can force high electric currents, which are very dangerous for the operating staff.

e. Besides a number of other factors (including weather) which influence the voltages induced electrically or magnetically, an important factor is the length of the portions of parallelism between the active line and the disconnected one. For lengths of parallelism greater than 20 km, the value of the voltages induced increases, practically, linearly with the length of the portion of parallelism, a phenomenon observed in figures 6 and 7.

f. The original mathematical models, designed to simulate the phenomena of electric and magnetic coupling between the conductors of the high voltage overhead power lines with double circuit lead to results very close to those obtained directly through measurements on the ground, in real operating circumstances. Therefore the mathematical models are useful instruments for studying the phenomena of electromagnetic interferences at low frequency in the case of power lines operating on parallel neighboring paths.

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