Determination of the Induced Voltages by 220 kV Electric Overhead Power Lines Working in Parallel and Narrow Routes. Measurements on the Ground and Mathematical Model

FLAVIUS DAN SURIANU
Electrical Power Engineering Department
"Politehnica" University of Timisoara
300223 Timisoara, Bd. V. Parvan, Nr. 2, Timis
ROMANIA
flavius.surianu@et.upt.ro

Abstract: - The paper presents the measurements that the author has done in the South - West area of Romania for the 220 kV double circuit overhead power lines having a passive circuit and an active one. It also describes a mathematical simulation for determining the induced voltages by the active circuit into the disconnected one. The measurements are compared with those obtained through calculations in order to validate the mathematical model, becoming a useful tool for professionals in electric high voltage overhead power lines.

Key-words: electromagnetic interference, high voltage, induced voltage, electric capacity, mutual inductivity.

1 Introduction

Electromagnetic fields of low frequency (50 Hz) created by the overhead power transport and distribution lines affect good working and service of all electrical equipments placed nearby, and they could also produce some unwanted effects on the biological organisms located in that area. The electro-magnetic disturbance field interferences produce two different types of influences on all the objects located in that area (including the nearby electric lines), namely:

- *Electric influences* produced by capacitive connections (couplings) between the phase conductors of the three phase overhead power lines and the nearby objects or electrical lines;
- *Magnetic influences* realized by inductive couplings between the loops of the parallel and adjacent circuits formed by the conductors and the earth.

All these influences are physically reflected on the voltage levels induced by the capacitive or inductive connections in the electrical nearby circuits, on the electric field intensity or potential from the earth, and on the value of the magnetic induction in different points, located near the power mains.

Knowing, as accurate as possible, these electro-magnetic parameters, especially those of the voltages induced in a capacitive, respectively magnetic way, is necessary in order to search for methods and techniques that will be able to reduce the unwanted effects and to increase the protection of the working staff.

- *Measuring on the ground* the electro-magnetic parameters by using specialized equipment. This method is very important to establish some relative values, and could be used as a real reference for all the other methods. But it has some disadvantages related to the limited opportunities of realizing physically the various operating regimes in real conditions of exploitation, to the emergence of relatively great measuring errors, and to the impossibility of measuring overhead high voltage electrical lines in any locations in the vicinity of the power lines;
- *Experimental determinations* in high voltage specialized laboratories, using physical models able to simulate the real situation. This method allows, theoretically, the realization of all service regimes, but, even if it is intuitive from the physical point of view, it is restrictive from the point of view of being extended to all power line dimensions of any type and it is also affected by errors due to specific laboratory conditions;
- *Mathematical modeling* of electro-magnetic interferences, which, by using modern and fast computing software, allows the numerical determination of all the parameters of the power line, in any point located nearby and for any service regime. This method, although fast, simple and generally efficient, could not be valid and sure unless the results it offers are comparable

to those obtained by at least one of the two experimental methods described above.

Taking into account the advantages of mathematical modeling and the necessity of the experimental validation of these models, this paper presents a comparison between the author's results obtained by measuring on the ground the voltages induced electrically and magnetically on the passive circuit of the double circuit overhead lines of 220 kV from area Banat - România and those obtained by using a specific software application.

2 Measuring on the ground the induced voltages

All the measurements carried out on the double circuit 220 kV overhead power lines, area Banat - Romania, during the autumn of 2006 had, as a unique task, the determination of the electromagnetic stress level that appears on a disconnected circuit when, in parallel, there is a second circuit operating in a normal regime. Such a situation is frequently met in the operation of high voltage overhead power lines with double circuit when one of the circuits has to be passivated in order to perform the revision or repair works. In this case, immediately after disconnection, in the passivated ground insulated circuit, voltages induced by electrical coupling occur on each phase, and when the earthing and short-circuit devices close down, the voltages induced by capacitive coupling are canceled, but there occur voltages induced by inductive coupling, forcing the emergence of induced currents in loops formed by each of the three phases of the passivated circuit and earth. Taking into account both types of disturbances affecting the passivated power circuit, at first the measurements concerned the voltages induced by capacitive coupling in each of the 3 phases, and then the voltages induced by inductive coupling in the 3 loops of the passive circuit connected to earth through short-circuit devices, at one of the ends.

In order to determine practically the voltages induced by the two types of electromagnetic couplings, the following procedures have been used:

a) If the three phase circuit conductors of the interrupted line are not connected to the earth by short-circuit devices, in this way being isolated from ground, the interrupted phase conductors will have a much smaller potential than the active phase conductor potentials existing nearby. In this case, between the active phase conductors and those of the passivated one, electric couplings will occur, the conductors having the role of fittings of huge condensers having the air as a dielectric medium. Depending on the intensity of the electric coupling (dependent on the distances between conductors and the length of the portion of parallelism between the lines) the interrupted circuit phase conductor potentials will depend on earth potential. A possible measurement of these potentials (voltages induced by capacitive coupling) is shown in Fig. 1.

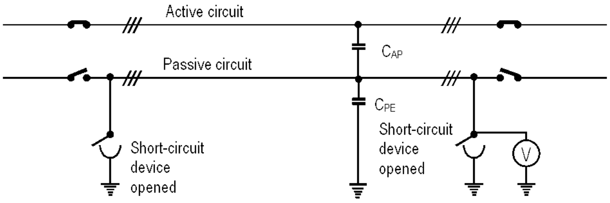


Fig. 1. The measurement of the voltage induced through capacitive coupling in the passive circuit of a double circuit high voltage overhead power line

b) If discontinued three phased circuit conductors are linked to the earth at both ends, by short-circuit devices, there are three loops formed, in which intense electromagnetic fields of the currents of the active line will induce electromotive voltages (EMV) forcing the closure of the induced currents, the coupling being a magnetic one (Fig. 2).

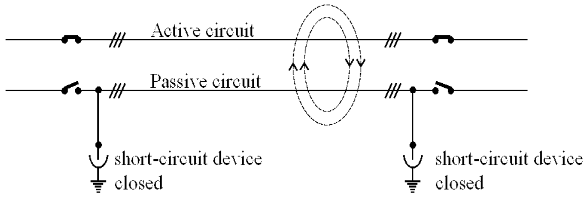


Fig. 2. Magnetic coupling between the active circuit and the passivated one of a double circuit high voltage overhead power line

In this case, in order to measure the electromotive voltages (EMV) induced in the passivated circuit phases the short-circuit devices from one end of the line have to be opened and a voltmeter should be set, as seen in Fig. 3.

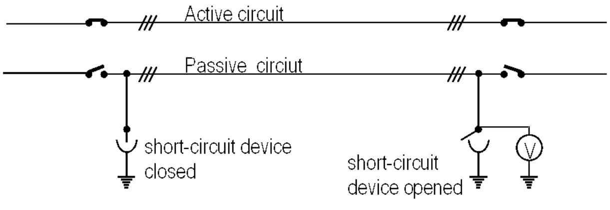


Fig. 3. The measurement of the EMV induced trough inductive coupling in the passivated circuit of a double circuit high voltage overhead power line

In the area of Banat - Romania, which includes 4 counties, there are several 220 kV overhead electric power lines that work in parallel on double circuit pole structure on portions of different lengths, loading different consumers. Depending on the load of these lines, in the case of the disconnection of a circuit, voltages induced by electrical and magnetical coupling will occur in the disconnected circuit, these voltages having to be known. The most unfavorable cases will be those in which the active circuit, remained in service, is long and supplies large power consumers. Fig. 4 shows the configuration of overhead electric power lines of 220 kV from area Banat - Romania.

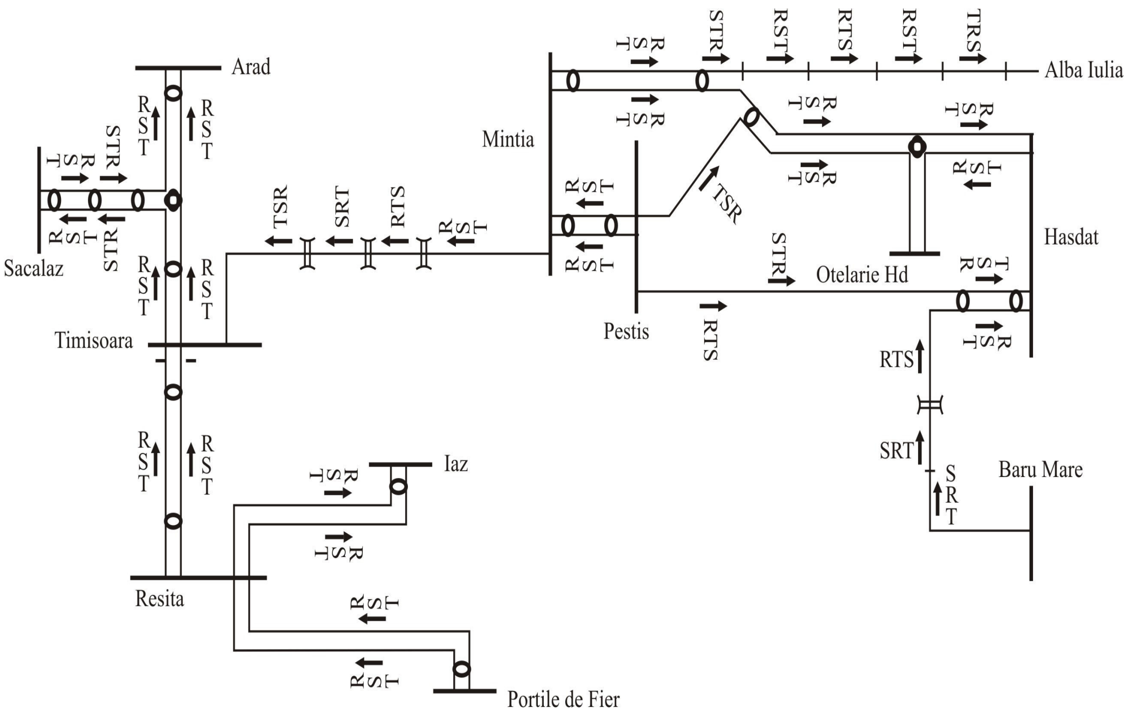


Fig. 4. The diagram of 220 kV overhead electric power lines from county Banat - Romania

Taking into account the fact that the support poles of most of the lines are of the same configuration, as in Table 1, the main geometrical data for different types of supporting poles used for double circuit 220 kV lines are given, these data corresponding to the general geometric distances shown in Fig. 5.

Table 1. The size of the support poles for 220 kV overhead electric power lines whith double circuit

No.	Pole 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

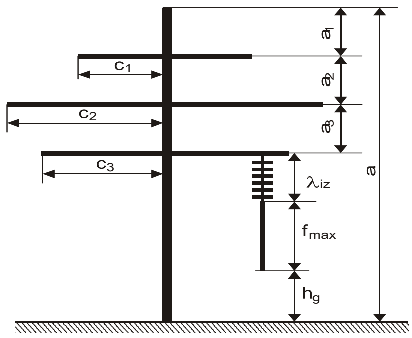


Fig. 5. The diagram of the geometry of a support pole

The active phase conductors of lines are of Steel-Aluminium type with standard sections of 400 mm^2 or 450 mm^2, this being specified for each electric line.

In order to carry out the measurements of induced voltages, there has been used a program of measurements with well defined steps, to protect the working staff from exposure to high voltages. This program has included all the necessary steps to be taken when working in high voltage exposure conditions. It was divided into the following steps:

a) *The initial state of the overhead high voltage double circuit line is specified, indicating exactly the situation of the two circuits of the line, namely:*
- circuit A – loading operating conditions;
- circuit B – taken off from service and being in the state of earthing at both ends by short-circuit devices.

b) *For each measurement the following protection conditions have to be followed:*
1. The leader of the team is equipped with overalls, electro-isolated high-voltage boots, protective helmet, electro-isolated high-voltage gloves;
2. The change of the field measurement of the measuring device is performed only after disconnecting the measuring circuit by removing the electric isolating bar under the measured circuit;
3. The reading of the measuring device is performed from a remote site, by an operator specifically equipped;
4. During the measurement, the cables of the measuring device will be placed at a distance from the operator.

c) *The measurement of the voltages induced in the passivated circuit conductors is performed using the following procedure:*
1. The cable associated with the electrostatic voltmeter should be earthed and then it should be connected to the mass of the device;
2. One end of the active cable has to be connected to the measuring terminal of the electrostatic voltmeter;
3. The other end of the active cable should be connected to the electric insulating switch rod;
4. The short-circuit devices of the passivated circuit of the electric line have to be opened at both ends, to measure the voltages induced by electrical coupling, respectively at the end of the line where measurements of voltages induced by magnetic coupling are taking place;
5. The induced voltages are successively measured, on the three phases of the passivated circuit. They are measured through reaching the connections of the phase short-circuit devices with the switch rod.

In order to measure the capacitive induced voltages, there has been used an electrostatic voltmeter with field measuring range between 1 kV and 30 kV. For inductive voltages, there have been used two voltmeters of 1 kV maximum measuring field, connected in series. The induced voltages are successively measured on the 3 phases of the passivated circuit.

Based on the electrical network scheme, shown in Fig. 4, there have been established the substations in which the measurements have been done, based on the number of 220 kV double circuit departure lines. These substations are:
- Hasdat – with links to Mintia, Pestis and Baru Mare;
- Sacalaz – with links to Arad and Timisoara;
- Resita – with links to Iaz, Timisoara and Portile de Fier;
- Mintia – with links to Alba Iulia, Hasdat and Pestis;
- Otelarie – with links to Pestis and Hasdat.

The results of the measurements performed through the two methods are presented, synthetically, in Tables 2 and 3.

Table 2. Voltages induced through capacitive coupling in 220 kV electric lines with circuit 2, passivated

Overhead electric line	**Circ. 1 [km]**	**Circ. 2 [km]**	**Active circuit voltage**	**Capacitive induced voltage measured in passivated circuit**		
			U [kV]	**U_R [kV]**	**U_S [kV]**	**U_T [kV]**
Mintia-Hasdat	49.876	25.455	237.5	8.87	2.7	4.4
Pestis - Otelarie max. charege	25.455	11.249	236.9	12.7	20.2	18.3
Pestis - Otelarie	25.455	11.249	236.9	12.7	20.2	12.3
Baru M-Hasdat	16.688	43.897	225	1.9	3.35	2.35
Otelarie-Hasdat	25.455	7.422	236.8	19.4	23.4	18.2
PdF-Resita	116.550	116.550	228 225 232	10.4	3.6	5.1
Mintia-Pestis	18.675	18.675	237	8.9	4.42	6.25
Resita-Iaz	30.730	30.730	226.5	3.03	7.94	5.9
Resita-Timisoara	72.867	72.867	234	11.1	3.7	5.4
Timisoara-Sacalaz	53.719	24.620	230 235 225	6.55	5.82	5.41
Sacalaz-Arad	53.719	55.173	230 235 225	8.2	2.8	4.2

Table 3. Voltages induced through inductive coupling in 220 kV electric lines with circuit 2, passivated

Overhead electric line	Circ. 1 [km]	Circ. 2 [km]	Activ circuit voltage	Active circuit current	Magnetically induced voltage measured in passivated circuit			Active and reactive power flow and initial phase difference voltage - currents			
			U [kV]	I [A]	U_R [V]	U_S [V]	U_T [V]	P [MW]	Q [MVAR]	cos φ	φ [rad]
Mintia-Hasdat	49.876	25.455	237.5	265.75	320	21	120	107	22	0.9795	0.2028
Pestis - Otelarie max. charge	25.455	11.249	236.9	156.9	68	10.2	39	50	40	0.781	0.6745
Pestis-Otelarie	25.455	11.249	236.9	74.826	34	10.2	18.5	24.9	17.9	0.812	0.6232
Baru M-Hasdat	16.688	43.897	225	181.68	120	26	122	5	5	0.707	0.7855
Otelarie-Hasdat	25.455	7.422	236.8	92.542	11	4.3	13.2	28.5	25	0.7518	0.72
PdF-Resita	116.550	116.550	228 225 232	440 480 460	1400	400	1440	182	7.354	0.98	0.2003
Mintia-Peştiş	18.675	18.675	237	71.77	63.6	13	42	29	5	0.985	0.1734
Resita-Iaz	30.730	30.730	226.5	14.54	20.8	3.6	17	0	5.7	0	1.57
Resita-Timisoara	72.867	72.867	234	497.03	1020	400	940	200	22	0.988	0.155
Timisoara-Sacalaz	53.719	24.620	230 235 225	212 237 218	180	71	1260	50	10.15	0.98	0.2003
Sacalaz-Arad	53.719	55.173	230 235 225	212 237 218	310	80	270	50	10.15	0.98	0.2003

The length of parallelism between the active line and passive line influences the value of the induced voltage regardless the type of electromagnetic coupling. To follow this phenomenon, the curves of the induced voltages have been raised depending on the parallel portion lengths. The resulting curves are shown in Fig. 6 and Fig. 7.

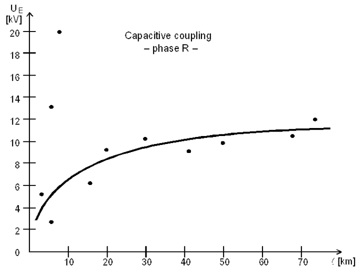


Fig. 6. The variation of the voltage induced through capacitive coupling depending on the length of the parallelism with double circuit 220 kV electric power lines having a passivated circuit

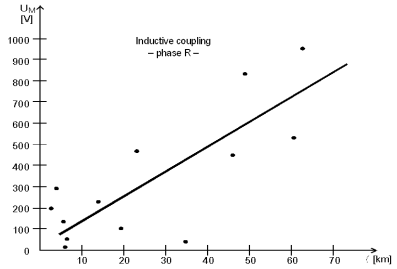


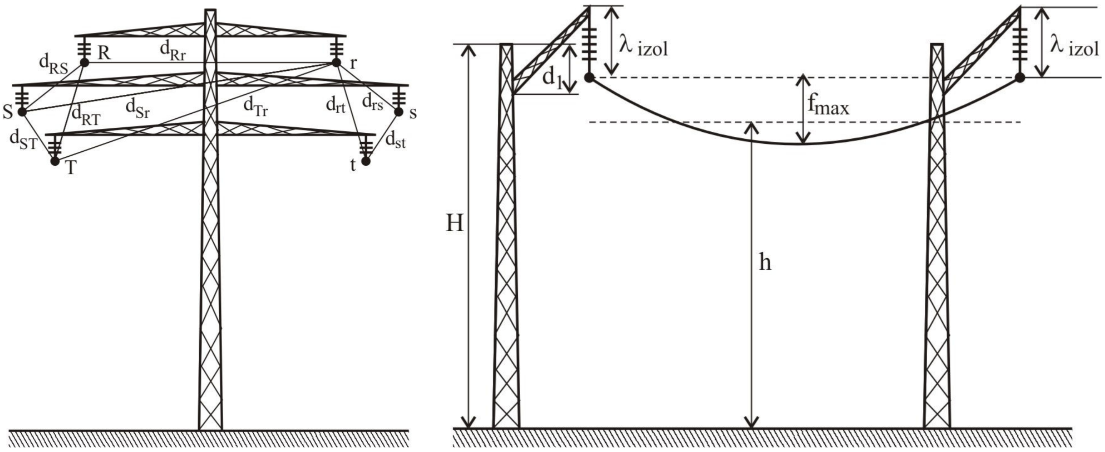
Fig. 7. The variation of the voltage induced through inductive coupling depending on the length of the parallelism with double circuit 220 kV electric power lines having a passivated circuit

Analyzing Fig. 6 and 7, we observe that on small distances of parallelism, up to about 20 km, the length of the line has a small influence on the induced voltages. On these distances, a number of other causes are more powerful in influencing the value of the induced voltage, regardless the way in which the electromagnetic interference between the active circuit and passivated one is done. At greater lengths, over 20 km, the value of the voltage induced through electrical coupling (capacitive) and the magnetic coupling have got an increasing linear trend depending on the parallelism distance length.

3 Mathematical models for determining the induced voltages

The advantage of the measurements on the ground made possible the existence of a database for mathematical modeling, because the results obtained by it can be checked by comparison with the real ones. This was the basis of designing mathematical models, by trying to imitate as accurately as possible, the physical phenomena that happen in nature. Considering that at low frequencies, couplings between sources and victims of EMI can be separated by different experiments, in electrical couplings and magnetic couplings, the mathematical modeling will take into account this observation that leads to two different models, one for the electric phenomena and another one for the magnetic phenomena.

Regardless the type of electromagnetic coupling, the values of induced voltages depend on the geometry of electrical lines, and on the loads transported through them. Therefore, mathematical models have to include, in a first stage, the geometric calculation of the power line poles with double circuit and also the determination of capacities and mutual inductivities between the conductors of double circuit electric power lines. The calculation of geometrical parameters of a line pole for double circuit overhead electric power line taking into account both the distances between the conductors of the double circuit and the distances between the conductors and their images from the ground, and the maximum arrow made by the conductors of the line in a standard, horizontal opening, as shown in Fig. 8, a and b, is done as following:



a) *b)*

Fig. 8. Determination of the geometric parameters of a high voltage overhead power line with double circuit. a) Geometric pole parameters. b) Determination of the average height of the conductors above the ground

a) The average distance between the conductors and the return path through earth is obtained taking into account the earth resistivity, using the following relation:

$$D_{CP} = 550\sqrt{\frac{\rho}{f}}, \qquad (1)$$

where ρ - the earth resistivity and f - line voltage frequency.

b) Average heights of the line conductors above the ground level result from:

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

c) Vertical and horizontal distances of active conductors for each type of pole given in Table 1, are determined by the following relations:

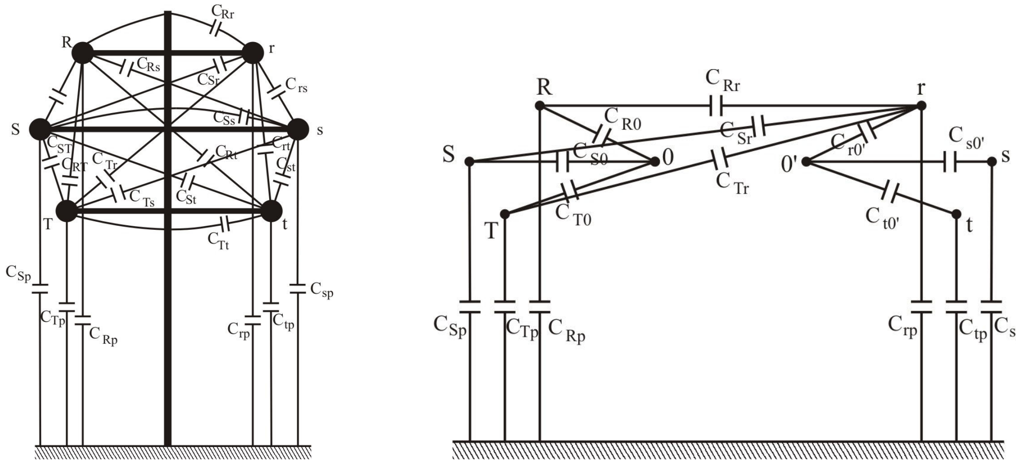
$$\begin{gathered} d_{RS} = d_{rs} = \sqrt{h_1^2 + \left(d_2 - d_1\right)^2} \\ d_{ST} = d_{st} = \sqrt{h_2^2 + \left(d_2 - d_3\right)^2} \\ d_{RT} = d_{rt} = \sqrt{\left(h_1 + h_2\right)^2 + \left(d_3 - d_1\right)^2} \end{gathered} \qquad (3)$$

d) The distances between the conductors of the two circuits of the electric line with double circuit result from the following relations:

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

3.1 Mathematical modeling of the electric coupling

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



a) b)

Fig. 9. System of capacities formed between the active circuit (RST) and the passive circuit (RST) for the electric line with double circuit.
a) The capacities formed between the two circuits; b) Equivalent capacities for a phase of the passivated circuit

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

- for the partial capacities between phases:

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

- for the partial capacities between phases and ground:

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

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

By transforming the capacities of the triangle connected phases (Fig. 9, a) in equivalent capacities connected in star (Fig. 9, b), the null potentials of the two star connections are equal with the null potential of earth and thus the phase capacities are put in parallel with the phase capacities related to the ground, resulting in the electrostatic equivalent scheme represented in Fig. 10.

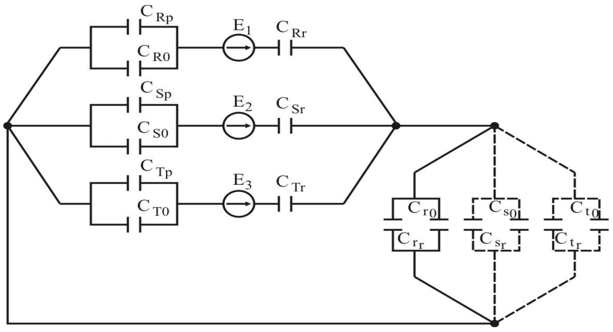


Fig. 10. The electric scheme of the capacitive coupling between the two circuits of the electric line

This electric scheme represents a complex set of circuits having only condensers as passive elements and solving such a type of problem involves the use of Kirchhoff's theorems either to determine the electric charges of the condensers, or to determine the voltages at which these condensers are charged. In this particular case, we do not know either the electric charges of the condensers or the voltages with they are charged. Therefore, to solve the problem, we have to make some analogies between electric networks containing only condensers and electric networks containing only resistors. Thus, if the relations for drop U are written between the condenser fittings of capacity C and charged with charge Q and drop U at the terminals of a resistor of resistance R run by a current intensity I, there follows:

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

This allows the establishment of the following correspondences: value $\frac{1}{C}$ is similar to the value R and value Q is similar to value I and because voltage U has to have the same sense in both cases, the sense of the current I must correspond to the sense of the electrostatic field between the condenser fittings, as in Fig. 11.

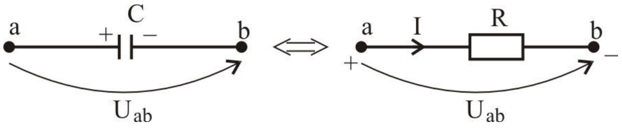


Fig. 11. The correspondence between the analogous values in electrostatics and electrokinetics theories

Based on the analogies between the values in electrostatics and electrokinetics theories, the equivalent electrokinetic scheme has been built, as presented in Fig. 12.

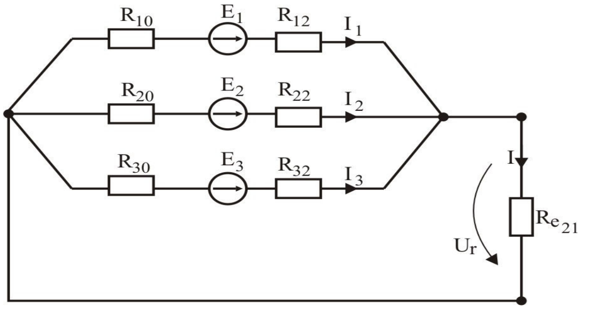


Fig. 12. The analogous electrokinetic scheme of the capacitive coupling for a phase of the passivated circuit

In order to determine the voltages induced by capacitive coupling, the Kirchhoff's theorems could be applied in the case of the analogous electrokinetic scheme from Fig. 12. Thus the following system of equations (7) is resulting, where currents of edge circuits are unknown:

$$E_1 - E_2 = (R_{10} + R_{12}) \cdot I_1 - (R_{20} + R_{22}) \cdot I_2$$

$$E_2 - E_3 = (R_{20} + R_{22}) \cdot I_2 - (R_{30} + R_{32}) \cdot I_3$$

$$E_3 = (R_{30} + R_{32}) \cdot I_3 + R_e \cdot I \qquad (7)$$

$$I_1 + I_2 + I_3 = I$$

Solving the system of equations (7) and considering the analogies $I \equiv Q$ and $R_{ei} \equiv \dfrac{1}{C_{i0} + C_{ip}}$, there results the value of induced capacitive voltage in each of the three conductors of the passivated circuit of the line with double circuit, i.e.:

$U_{fi} = R_{ei} \cdot I_i$, respectively

$$U_{fi} = \frac{Q_i}{C_{i0} + C_{ip}} \qquad (8)$$

Observations:

1. The analogies between electrostatic and electrokinetic values are correct and valid only for circuits in DC (direct current). But in this case, the analyzed circuits are in alternative current (AC) because the sources of voltage E_1, E_2 and E_3 are alternatively sinusoidal having the following expressions:

   $$E_1 = \sqrt{2} \cdot U_{fR} \sin(\omega \cdot t + \phi)$$

   $$E_2 = \sqrt{2} \cdot U_{fS} \sin\left(\omega \cdot t + \phi - \frac{2 \cdot \pi}{3}\right) \qquad (9)$$

   $$E_3 = \sqrt{2} \cdot U_{fT} \sin\left(\omega \cdot t + \phi - \frac{4 \cdot \pi}{3}\right)$$

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

   Because the analogies should be valid in this case too, it is necessary to consider time as a constant value. But time, t = const. represents exactly the moment of measurement of the voltages capacitively induced for each phase of the passivated circuit of the analyzed electric line. In order to determine the moment of measurement, there has been considered a period of the sinusoidal wave voltage, that, at frequency f = 50 Hz has the duration T = 0.02 seconds. Period, T, of the sinusoidal wave has been divided into 100 discreet and constant time intervals of $\Delta t = 0.0002$ seconds, and thus by discreeted the time, the varying values of AC circuits have been converted into constant values on the intervals Δt_k, $k = 1...100$, for which the analogies considered become valid. Knowing through measurements, the capacitively induced voltages in the conductors of the passivated circuit of the electric line, by assigning 2-3 values to time intervals, Δt, and using a computing program developed in MATHCAD 11 to solve the equations (7), from relations (8), there result the calculated values of the capacitive induced voltages. These values are given in Table 4, compared with the measured ones. The values measured and those obtained by calculation are very close, this demonstrating the validity of the adopted mathematical model.
2. The mathematical model presented above also allows the determination of the maximum value of the capacitive voltage induced in each phase of the passivated circuit of the line, by assigning discrete values to time intervals around the maximum of the sinusoidal function of the inductive voltage.
3. For each phase of the passivated circuit, a different value of the discreet time has been adopted because the measurements were performed for each phase separately.

Table 4. Comparison between the measured and calculated capacitively induced voltages

Overhead electric line	**Circ. 1 [km]**	**Circ. 2 [km]**	**Activ circuit voltage**	**Capacitively induced voltage measured in passivated circuit**			**Capacitively induced voltage calculated in passivated circuit**		
			U [kV]	**U_R [kV]**	**U_S [kV]**	**U_T [kV]**	**U_r [kV]**	**U_s [kV]**	**U_t [kV]**
Mintia-Hasdat	49.876	25.455	237.5	8.87	2.7	4.4	**8.823**	**2.755**	**4.415**
Pestis.-Otelarie max. charge	25.455	11.249	236.9	12.7	20.2	18.3	**12.643**	**20.324**	**12.278**
Pestis-Otelarie	25.455	11.249	236.9	12.7	20.2	12.3	**12.726**	**20.324**	**12.278**
Baru M-Hasdat	16.688	43.897	225	1.9	3.35	2.35	**1.845**	**3.419**	**2.427**
Otelarie-Hasdat	25.455	7.422	236.8	19.4	23.4	18.2	**19.433**	**23.259**	**17.906**
PdF-Resita	116.55	116.55	228 225 232	10.4	3.6	5.1	**10.422**	**3.619**	**4.948**
Mintia-Pestis	18.675	18.675	237	8.9	4.42	6.25	**9.076**	**4.573**	**6.278**
Resita-Iaz	30.730	30.730	226.5	3.03	7.94	5.9	**3.154**	**7.998**	**5.876**
Resita-Timisoara	72.867	72.867	234	11.1	3.7	5.4	**11.221**	**3.768**	**4.798**
Timisoara-Sacalaz	53.719	24.620	230 235 225	6.55	5.82	5.41	**6.582**	**5.865**	**5.452**
Sacalaz-Arad	53.719	55.173	230 235 225	8.2	2.8	4.2	**8.206**	**2.845**	**4.210**

3.2 Mathematical modeling of the magnetic coupling

Inductive coupling is generated by electric currents varying in time which pass through the conductors of the active circuit of the electric line with double circuit whose variable electric and magnetic fields induce electromotive voltages (EMV) in the conductors of the passivated circuit. The mathematical expression of the currents from the active circuit conductors is 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 difference of phase between voltages and currents of the active circuit and it is known because the powers P and Q with which the active circuit is charged are known, according to Table 2.

In the network model, the magnetic coupling can be represented by mutual inductivities between the conductors of the two circuits whose general expression is:

$$M_{12}=\frac{\mu_0}{4\pi}\int_0^l\frac{dl_1dl_2}{\sqrt{\left(l_1-l_2\right)^2+d_{12}^2}} \tag{11}$$

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

After developing the square root in series and neglecting the terms of higher rank, the relation (11) becomes:

$$M_{ik}=\frac{\mu_0}{2\pi}\cdot l\cdot\ln\left(\frac{D_{cp}}{d_{ik}}\right), \tag{12}$$

where $i\in\left(R,S,T\right)$, respectively $k\in\left(r,s,t\right)$.

But because the electromotive voltage (EMV) induced in each of the three conductors of the passivated circuit represents the contribution of all the three inductive magnetic fields generated by variable currents of the active circuit, the mathematical expression for each phase of the passivated circuit is:

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

The calculating algorithm, presented, above has been the basis of a computing program in MATHCAD 11, with which there have been determined analytically the voltages induced by magnetic coupling in the passivated circuits of the electric lines of 220 kV double circuit-Banat area of Romania. In Table 5, the analytical results are presented compared with those measured on the ground.

Observation: Taking into account φ, the difference of phase between voltage and current, through which the loading of the inductive circuit is expressed indirectly has required that the representation of the current be done through momentary values instead of effective ones. This fact has led to the appearance of an additional supplementary value, that is time, t. But time, t, is the moment of measurement and that is why there has been required the digitization of a period T = 0.02 seconds into 100 intervals $\Delta t = 0.0002$ seconds, each of them thus searching for the moment when the measuring of each phase of the passivated circuit has been realized.

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

Overhead electric line	**Circ. 1 [km]**	**Circ. 2 [km]**	**Active circuit voltage**	**Active circuit current**	**Magnetically induced voltage measured in the passivated circuit**			**Magnetically induced voltage calculated in the passivated circuit**		
			U [kV]	**I [A]**	**U_R [V]**	**U_S [V]**	**U_T [V]**	**Ur [V]**	**Us [V]**	**Ut [V]**
Mintia-Hasdat	49.876	25.455	237.5	265.75	320	21	120	**317.193**	**21.014**	**120.452**
Peşt.-Oțelarie. max. charge	25.455	11.249	236.9	156.9	68	10.2	39	**67.888**	**10.365**	**39.073**
Pestis-Otelarie	25.455	11.249	236.9	74.826	34	10.2	18.5	**33.415**	**7.18**	**18.808**
Baru M-Hasdat	16.688	43.897	225	181.68	120	26	122	**120.222**	**25.88**	**120.363**
Otelarie-Hasdat	25.455	7.422	236.8	92.542	11	4.3	13.2	**11.279**	**4.28**	**13.584**
PdF-Resita	116.55	116.55	228 225 232	440 480 460	1400	400	1440	**1401**	**404.28**	**1444**
Mintia-Pestis	18.675	18.675	237	71.77	63.6	13	42	**62.844**	**13.182**	**42.529**
Resita - Iaz	30.730	30.730	226.5	14.54	20.8	3.6	17	**20.862**	**3.671**	**17.091**
Resita -Timisoara	72.867	72.867	234	497.03	1020	400	940	**1021**	**357.93**	**941.014**
Timisoara-Sacalaz	53.719	24.620	230 235 225	212 237 218	180	71	1260	**181.052**	**71.05**	**1261**
Sacalaz-Arad	53.719	55.173	230 235 225	212 237 218	310	80	270	**311.44**	**81.009**	**270.174**

Following, comparatively, the measured values of voltages induced by magnetic coupling with those determined by calculation, we observe that they are almost the same. This shows a good mathematical approximation of the physical phenomena that lead to the magnetic coupling between conductors.

4 Conclusion

4.1. Both in capacitive coupling (electric) and inductive coupling (magnetic), between the conductors of the active circuit and those of the passivated one of a high voltage overhead electric line with double circuit, we observe, both through measurements on the ground and mathematical modeling, that the middle phase of the passivated circuit has got the lowest induced voltage, for most of the lines. This is explained for capacitive coupling through the longest distance between the phases of the active circuit and the middle phase of the passivated circuit. In the case of inductive coupling, the effect is due to the vector addition of the inductive magnetic fields intensity.

4.2. In the case of lines where the transposition of phases do not take place, the voltage induced by inductive coupling is the largest on the top phase. This is explained because loop conductor - earth has got the largest surface.

4.3. All voltages induced by capacitive coupling have got very large values, which are dangerous for the operating staff. By earthing, the lines are discharged of this high electric potential but voltages induced by inductive (magnetic) coupling occur and they are, themselves, large enough to be dangerous. Therefore, we consider that in the case of circuits galvanically separated from earth, special protection conditions are required for the working staff.

4.4. If earth loops are closed, the voltages induced by magnetic coupling can force currents of large values, that are very dangerous for the operating personnel.

4.5. In addition to several other factors, (including the atmosphere state) that influence the value of voltages induced, an important factor is the length of parallelism distances between the active line and the passivated ones. For lengths of more than 20 km, the value of induced voltages increases, practically, linearly with the length of the parallelism distance.

4.6. Mathematical models developed to simulate the phenomena of electric and magnetic coupling between the conductors of circuits of overhead high-voltage electric line with double circuit lead to results which are very close to those obtained by direct measurements on the ground, in real working situations. This turns mathematical models into useful tools for studying the phenomena of electromagnetic interference (EMI) at low frequency in case of overhead electric lines when operating on parallel and narrow paths.

References:

[1] X1. Author, Title of the Paper, *International Journal of Science and Technology*, Vol.X, No.X, 200X, pp. XXX-XXX.

[2] X2. Author, *Title of the Book*, Publishing House, 200X.

[1] Surianu F.D., Compatibilitate Electromagnetica. Aplicații în Sistemele Electroenergetice. Editura Orizonturi Universitare Timisoara, 2006, ISBN 973-638-244-3, ISBN 978-973-638-244-4; (in Romanian languege);

[2] Surianu F.D., An apparatus for signalizing the induced currents in the disconnected circuits of double circuit h.v. overhead lines, Scientific Bull. of UPT, Serie Energetics, Tom 50(64), Fasc.1-2, Nov., 2007, pp. 615-620, ISSN 1582-7194;

[3] Surianu F.D., Masurarea tensiunilor induse in LEA 220 kV d.c. si pe portiuni de paralelism cu LEA 110 kV, contract de cercetare, Timisoara, 2006; (in Romanian language);

[4] Munteanu C., Topa V., Muresan T., Costin A.M., Electromagnetic Interferences between HV Power Lines and RBS Antennas Mounted on HV Tower, Proceedings of the 6th International Symposium on Electromagnetic Compatibility, EMC Europe, 2009, Eindhoven, Holland, pp. 878-881;

[5] TTU-T and CIGRE, Protection Measure for Radio Base Stations Sited on Power Line Towers, Recommendation K 57, 2003.

[6] Sanchez Santiago A.J., Yuste A..J., Menoz Expozito J.E., Garcia Galan S., A Balanced Scheduler for Grid Computing, Proceedings of the 8th WSEAS International Conference on Simulation, Modelling and Optimization (SMO ’08), Santander, Calabria, Spain, September 23-25, 2008, pp. 59-64 ISSN 1790-2769, ISBN 978-960-474-007-9.

[7] Kenedy Aliila Greyson, Anant Oonsivilai, Identifying Critical Measurements in Power System Network, Proceedings of The 8th WSEAS International Conference on Electric Power Systems, High Voltage, Electric Machines (POWER ’08), Venice, Italy, 21-23 November, 2008, pp. 61-66, ISSN 1790-5117, ISBN 978-960-474-026-0.

[8] Isaramongkolrak A., Kulworawanichpong T., Pao-La-Or P., Influence of an Overhead Ground Wire on Electric Fields Around the HV Power Transmission, Proceedings of The 8th WSEAS International Conference on Electric Power Systems, High Voltage, Electric Machines (POWER ’08), Venice, Italy, 21-23 November, 2008, pp. 128-132, ISSN 1790-5117, ISBN 978-960-474-026-0.