# MAGNETIC INDUCED CURRENTS AND VOLTAGES IN DE-ENERGIZED CONDUCTORS BY THE HV TRANSMISSION O/H LINES UNDER NORMAL AND SHORT-CIRCUIT CONDITIONS

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*Abstract* – **Due to an intense necessity of performing erection and maintenance works on the overhead electric lines with a track parallel to working overhead electric lines it becomes more and more imperative to determine as exactly as possible the currents and voltages to be induced in the overhead line conductors undergoing the induction. Applying the IEEE 524-2003 standard for calculating the induced measures will not solve the problem correctly, which asks for stating another algorithm for this purpose.**
***Keywords:*** electric shock, grounding, magnetic induction, overhead transmission lines, touch voltage.

## 1. INTRODUCTION

The problem of adopting the most adequate technology for stretching the conductors of a new circuit or performing repairing works on an existing circuit, under the influences of another electric circuit or of another overhead electric transmission line or even of several overhead electric transmission lines, following a track parallel to that of the circuit under discussion is a necessity derived from applying some adequate norms of security during working in such conditions, when the apparition of some currents and/or voltages relatively high is foreseen in the induced circuit on which they are working.

In the conductors of the circuit to be erected or repaired currents and voltages are induced by the electromagnetic coupling cuplajul that is created within the multi-conductor system made up of the active and passive conductors of the inducing circuits, as well as of the conductors to be put in.

## 2. ELECTROCUTION RISK

Working near voltage can lead to receiving dangerous electric shocks by the working staff, shocks that can be disagreeable or even lethal. It must be mentioned that working on the conductors of an de-energized circuit (induced) lying nearby another circuit belonging to another line under voltage (inductor), in normal work conditions of the inductor circuit and especially in case a short-circuit appears in it, the current flows through the body of the worker at any direct touch of the induced conductor or at any indirect one, through the equipment, becoming dangerous, leading even to physiological effects.

As mentioned in Std 524-2003 [1] the maximum bearable current is of 9 mA, for normal work conditions on the energized circuit and several values may be taken into consideration in the case of a short-circuit, considering Dalziel's equations [1, 2]. Also, the idea of suggesting a shock energy limit at 12.5 J, in the case of a short-circuit, proposed [3], can be considered useful, too.

In these conditions it is very easy to find some values for the shock current or energy, having a direct effect on the worker's body, thus making a comparison to the known limits, if the touch voltage is known.

## 3. CONSIDERATIONS TO THE ALGORITHM FOR CALCULATING THE MAGNETIC INDUCTION ACCORDING TO STD 524- 2003

The algorithm is based on the relations between voltages, impedances and currents making use of Carson's relations to calculate their own and the mutual impedances.

These are some initial simplifying hypotheses considering the conductors de-energized and the protecting ones grounded in more than one point, which does not hold true for a real resistance of the ground [3]. This resistance can differ in different points of poles or short-circuitors placement.

There is a limitation of the algorithm that does not allow simulating a system with more than three inducting phases, three induced phases and four protection conductors.

In the case of the magnetic induction there cannot be determined the currents and respectively the cross voltages in the case of the panels with unequal openings or with poles and/or shortcircuitors with different grounding resistances.

There is no way to model the situation of the monophasal shortcircuit on the inducting line in the case of the magnetic induction, the case that leads to far higher values of the induced measures.

## 4. THE PROPOSED ALGORITHMS

### A. Description of the multi-conductor system

Being considered a multi-conductor system, representing an overhead inducting transmission electric line equipped with *3N* phases, *Ncp* one or two protecting conductors (to enable modeling any type of transmission electric line) and an induced conductor, the most un-convenient case, by neglecting the influence of other de-energized conductors, which, if existing, would play a screening role, reducing the induction of the line at work.

The section of the circuit where works on de-energized phases (conductors) are done is considered to contain *Nd* spans. No limit for *Nd*.

The currents through the energized phases (conductors) are considered constant and can be done as normal operating conditions or as a short-circuit case of one of the inducting circuits. In the latter case one phase is considered charged with current and the other two without, the mono short circuit case being the worst one in such cases of magnetic induction.

The de-energized phases (conductors) of the section in case are not electrically connected to the corresponding ones of the adjacent sections.

All the *Ns* towers are grounded, the resistances to ground getting different values if the case. All the induced conductors are connected to ground by the same resistance.

All the *Nd* spans may get different lengths.

The resistivity of the ground may vary along the line route and can be taken into consideration as a constant value for each span.

### B. Calculation of the touch voltage at each tower location of the section in case B.

Un inducting electric line is taken into consideration having *Nd* openings, *Ns*=*Nd*+1 poles, *3N* inducting phases, *Ncp* conductors of protection and an induced conductor.

In elaborating the calculation algorithm there have been taken into account the following hypotheses:

- The currents in the phases of the inducting line under normal functioning mode are constant all along the section of the parallelism under discussion;
- in case of short-circuit on the inducting line, its place will be away from the line of parallelism, a more disadvantaging situation, as the currents in the protecting conductors are minimum and constant along the line;
- *Nd* - number of openings of the induced circuit (*Ns=Nd+1* poles);
- $I_k$ - loop current "k" in A;
- $E_k$ - t.e.m. corresponding to the electric induction according to the "k" opening of the induced circuit, in V;
- $[l_k]$ - vector of *Nd* openings considered (span length), in m;.
- $Z_{k;k+}1$ – the circuit own liniar impedance of the induced circuit corresponding to the "k", opening in Ω;
- $R_{pk}$ – resistance to the ground of the "k" pole , in Ω.

Applying Kirchoff's theorem II to the loops of this circuit results in:

$$E_1 = (R_{p1} + Z_{12} + R_{p2})I_1 - R_{p2}I_2$$
$$E_2 = (R_{p2} + Z_{23} + R_{p3})I_2 - R_{p2}I_1 - R_{p3}I_3$$
…………………………………………………
$$E_k = (R_{pk} + Z_{k,k+1} + R_{pk+1})I_k - R_{pk}I_{k-1} - R_{pk+1}I_{k+1}$$
…………………………………………………
$$E_n = (R_{pn} + Z_{n,n+1} + R_{pn+1})I_n - R_{pn}I_{n-1} \qquad (1)$$

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$$[I_k] = [Z^*]^{-1}[E_k] \qquad (2)$$

Where:

$[I_k]$ – vertical vector matrix of the n loop currents.

$[E_k]$ – vertical vector matrix of the n induced electromagnetic voltages;

$[Z^*]$ –*Nd* x *Nd* matrix of the total impedances, that can be calculated as follows:

- for $i = jZ^*_{ii} = Z_{i,i+1}+R_{pi}+R_{pi+1}$
- for $i < j\text{-}1 \quad Z^*_{ij} = Z^*_{ji} = 0$ (3)
- for $i = j\text{-}1 \quad Z^*_{ij} = Z^*_{ji} = -R_{pi+1}$

Voltage drops on each pole (on the grounding impedance) can be calculated by applying Ohm's law, thus:

$$\begin{bmatrix} U_1 \\ U_2 \\ U_k \\ U_n \\ U_{n+1} \end{bmatrix} = [R] \times \begin{bmatrix} I_1 \\ I_2 \\ I_k \\ I_n \end{bmatrix} \qquad (4)$$

Where:

$U_k$ - voltage dropon "k" pole

$[R]$ - matrix *Ns x Nd* of the resistances to grounding and it is calculated as follows:

for $i = j \quad R_{ij} = R_{pi}$
for $i < j \quad R_{ij} = 0$
for $i > j+1 \quad R_{ij} = 0$
for $i = j+1 \quad R_{ij} = -R_{pi}$ (5)

$[I_k]$ - vertical vector matrix of the *Nd* loop currents.

By introducing the relation *(2)* in *(4)* it is obtained:

$$[U_k] = [R] \times [Z^*]^{-1}[E_k] \qquad (6)$$

To determine the voltages $U_k$ $(k \in [1 \div n+1])$ there must be calculated their own impedances $Z_{k,k+1}$ and the electromotor induced voltages $E_k$. For their own impedances Pollaczek's relation can be easily used for the line own impedance corresponding to a line corresponding to an overhead conductor [6]:

$$Z_0 = R_0 + \frac{\mu_0 \omega}{8} + j\frac{\mu_0 \omega}{2\pi}\left(\ln\frac{\delta}{r_0} + \frac{\mu_r}{4}\right) \text{ in } \Omega/\text{m}; \quad (7)$$

Where:
$R_0$ - resistance in c.a. of the induced conductor in Ω/m;
ω - pulsating c.a. *(2πf=100π)* in $\sec^{-1}$;
$\mu_0$ - absolute permeability of void - $4\pi x10^{-7}$ H/m
$\mu_r$ - relative permeability of the conductor material ($\mu_r$=1 forOl-Al,)
δ - deepening the effective depth of penetrating into the ground of the c.a. earth in m;

$$\delta = \frac{1{,}85}{\sqrt{\mu_0 \frac{\omega}{\rho}}} \quad (8)$$

$$Z_{k,k+1} = L_k \times Z_0 \quad \text{in } \Omega \quad (9)$$

Where: $L_k$ - opening length of the widening opening k, in m

Electromotor induced voltage in each opening is calculated by the relation:

$$E_k = l_k \sum_{m=1}^{3N+2} Z_{m0} \cdot I_m^{*} \quad \text{in V} \quad (10)$$

Where:
$Z_{m0}$ - mutual impedance between the conductor "m" and the induced conductor, in Ω/m;
$I_m^{*}$ - current in conductor "m", in A;
For active conductors, these currents are known, but for the protecting conductors they must be determined.

$$I_{3N+1}^{*} = -\frac{\sum_{m=1}^{3N}\left(Z_{3N+2}Z_{m,3N+1} - Z_{3N+1,3N+2}Z_{m,3N+2}\right)I_m^{*}}{Z_{3N+1}Z_{3N+2} - Z_{3N+1,3N+2}^2} \quad (11)$$

$$I_{3N+2}^{*} = -\frac{\sum_{m=1}^{3N}\left(Z_{3N+1}Z_{m,3N+2} - Z_{3N+1,3N+2}Z_{m,3N+1}\right)I_m^{*}}{Z_{3N+1}Z_{3N+2} - Z_{3N+1,3N+2}^2} \quad (12)$$

Where:
$Z_{3N+1}$, $Z_{3N+2}$ - are the specific line impedances of the protecting conductors and they are calculated by the relation *(9)* introducing the characteristics of the respective conductors (Ω/m);
$Z_{m,3N+1}$, $Z_{m,3N+2}$, $Z_{3N+1,3N+2}$ – are the mutual line impedances between the conductor "m" and the protection conductors, respectively between the two protection conductors (Ω/m).
To calculate the mutual impedances, Pollaczek's relation referring to the cases of interaction between two parallel overhead conductors returning to through the ground can be applied: [4]

$$Z_{i;j} = \frac{\mu_0 \omega}{8} + j\frac{\mu_0 \omega}{2\pi}\ln\frac{\delta}{d_{ij}} \quad \text{; in } \Omega/\text{m} \quad (13)$$

Where: $d_{ij}$ - distance between conductors "i" and "j".

The touching voltage is considered the voltage to the ground of the conductor in the contact point to the pole or the body of the worker; this is modeled by a grounding resistance of the pole.

**C. Software**

Based on the algorithm and the logic diagram, the software was developed using Mathlab - version 6.5. The size of the software is 7.37 kB and can be easily worked on normal computers. This software, as it may be understood from the Appendix, is made up of a main body.

## 5. RESULTS FOR THE CASE OF 400 KV SIMPLE AND DOUBLE CIRCUIT LINE

The algorithm and the soft have been first applied to determine the voltages induced in the conductor of a circuit, being set in place or on which works were being carried on, placed at a distance *D* from the axis of the inducting line, as exemplified in Fig. 1. by a cross view in the simple circuit 400 kV line.

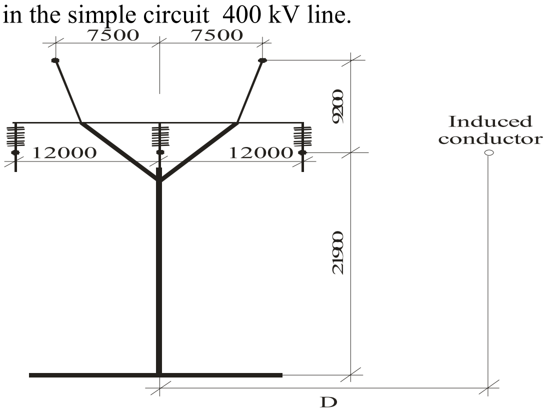


Fig. 1. Cross view of the simple circuit 400kV line

The line is equipped by two protection conductors and one circuit with conductors in phase. The protection conductor taken into consideration was Ol 95, and the active conductors were of the AlOlN 450/75 type. The current traveling through the inductor circuit, under normal conditions, has been considered of a 1000A value. Under short-circuit conditions (of a mono-phase type) on one of the circuits of the inductor line, through the affected circuit null currents are taken into consideration for the unaffected phases and 1000A through the short-circuited phase.
In the panel considered the inter-poles openings are identical, of 350 m. The grounding resistances were considered as 2, respectively 5 ohms, and the resistivity to the ground of 50, respectively 200 ohms.
For thet conductor of an overhead electri line parallel to another overhead inducting electric line, calculations

were made for its voltages at the end of the considered section, the results being presented as a function of the distance from the axis of the inducting line and the induced conductor, according to the number of openings of the induced section, the grounding resistances of the short-circuitors and the resistivity of the ground, for the normal functioning conditions of the inducting line. The diagrama are shown Fig. 2. Fig. 3.

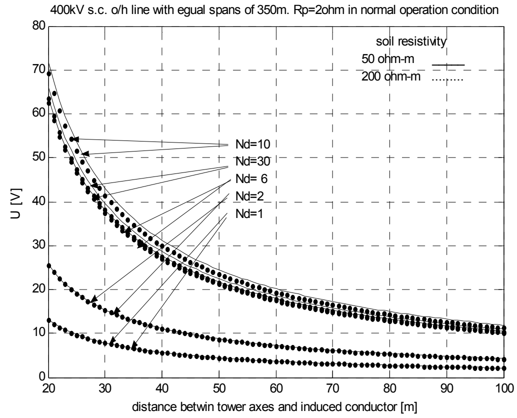


Fig. 2. 400 kV s.c. o/h line with equal spans of 350 m each and 2 ohms grounding resistances in normal operation condition

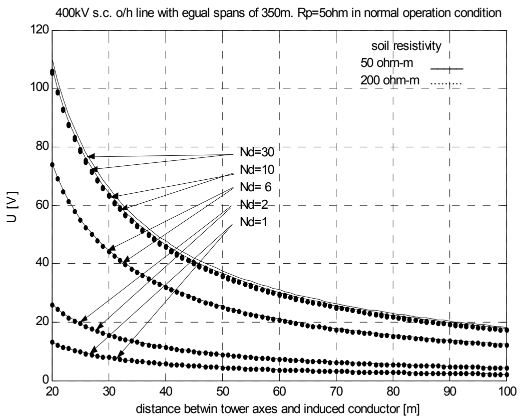


Fig. 3. 400 kV s.c. o/h line with equal spans of 350 m each and 5 ohms grounding resistances in normal operation conditions

In Fig. 4-5 the results of the algorithm working are shown as diagrams in mono-phase short-circuit conditions on the inductor line.

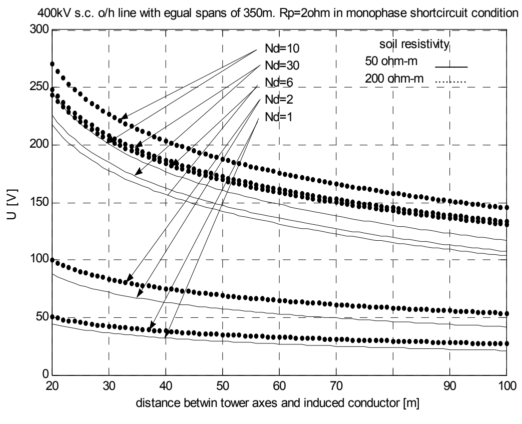


Fig. 4. 400 kV s.c. o/h line with equal spans of 350 m each and 2 ohms grounding resistances in mono-phase short-circuit condition

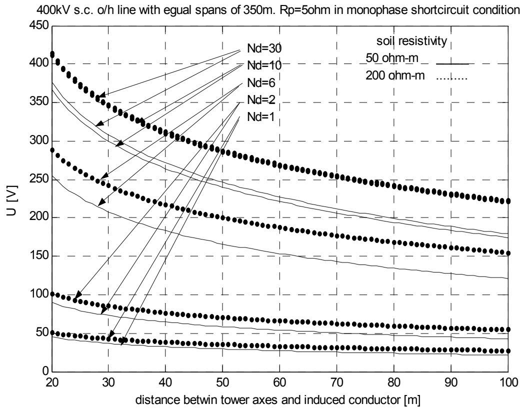


Fig. 5. 400 kV s.c. o/h line with equal spans of 350 m each and 2 ohms grounding resistances in mono-phase short-circuit conditions

The algorithm and the soft have been applied in a second stage for determining induced voltages in one circuit conductor, during its setting up or on which work was going on, placed at a distance *D* from the axis of the inductor line, as shown in Fig. 6. as a cross section of the double circuit 400 kV line.

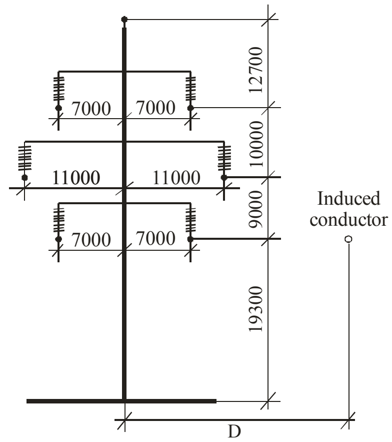


Fig. 6. Cross section of the double circuit 400kV line.

The line is equipped with the same type of conductors as in the case of the simple circuit 400 kV line, the calculations being made in the same conditions met in the anterior stage.

The diagrams of the touching voltages are shown in Fig. 7. Fig. 8, Fig. 9, Fig. 10.

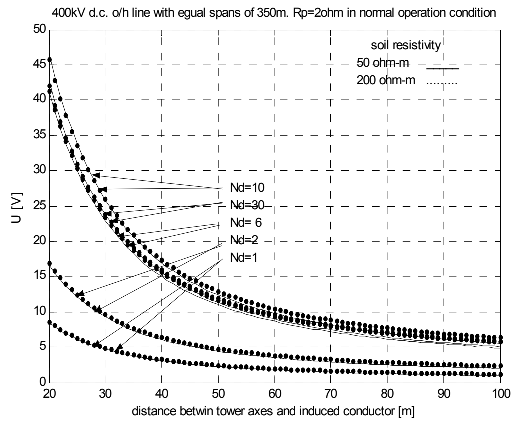


Fig. 7. 400 kV s.c. o/h line with equal spans of 350 m each and 2 ohms grounding resistances in normal operation condition

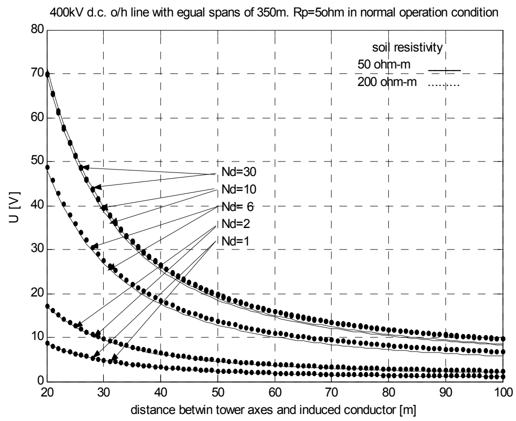


Fig. 8. 400 kV s.c. o/h line with equal spans of 350 m each and 5 ohms grounding resistances in normal operation condition

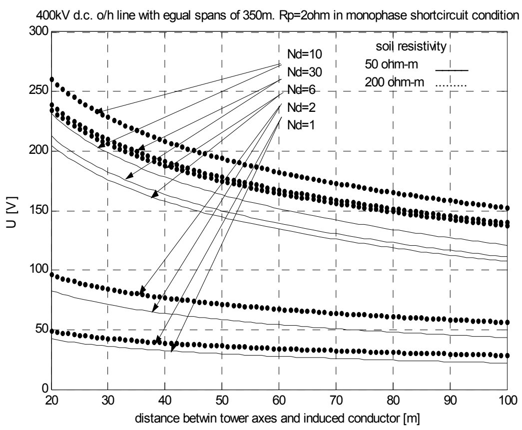


Fig. 9. 400 kV d.c. o/h line with equal spans of 350 m each and 2 ohms grounding resistances in mono-phase short-circuit condition

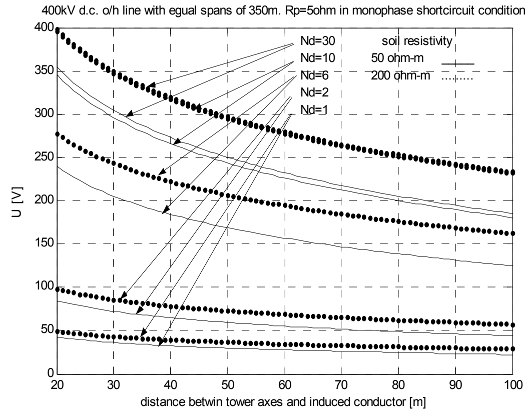


Fig.10. 400 kV d.c. o/h line with equal spans of 350 m each and 5 ohms grounding resistances in mono-phase short-circuit condition

From the analysis of all the figures the following conclusions can be drawn:

- From the analysis of figures (2, 3, 7 and 8) it can be stated that the highest voltages met are by far lower to the one of 125V provided by STAS 2612-87 standard, for any of the hyupotheses taken into consideration and analyzed.
- The values found on the ordinate in figures (4, 5, 9 and 10) should be multiplied by the ratio between the effective current of the mono-phase short-circuit and 1000 A and these values should finally be compared to the maximum admissible values. Thus it can be derived that the maximum admissible values may be usually surpassed at the ends of the considered section in the condition of some short distances between the inductor circuit and the induced circuit, in the case of high resistance groundings of the short-circuitors and especially in the case of a larger number of openings of the section. At the same time, it can also be noticed that for a smaller number of openings (1-3) the voltage fits the ceiling of 250 V. By increasing the distance of the induced conductor from the axis of the inductor line (D) to 25-30 m for grounding resistances rezistențe of 2 Ω the voltages thus calculated fit the ceiling of 250 V, standardized according to STAS 2612-87.

## 6. THE COMPARISON BETWEEN THE CALCULATED AND MEASURED RESULTS IN A SPECIFIC REAL CASE

There have been considered the following measurements made in Canada, at Ontario Hydro, on the double circuit 230 kV lines Pickering GS-Cherrywood TS [8]. Initially, there had been erected and were functional in the area only two lines 1 and 4, afterwards, between 1978-1979 two more lines of the same type being set up with a parallel track, between the two existing and working lines.

The active conductors used are AlOl with the 84/19 component, a diameter of 2.2 inches and a linear weight of 3.9 lb/ft and the protection conductors are also of the AlOl type with a component of 26/7, the diameter of 0.858 inches and a linear weight of 0.655 lb/ft.

Measurements of the magnetic inductionwere performed on the same circuit of the line Nr. 3, in the year 1979, on a section of 1.44 miles. Ther results were: an induced eletromotor voltage of 100 V and a current of 16 A through the conductor. By applying the calculation algorithm for the magnetic induction proposed by IEEE an induced electromotor voltage 288,8 V resulted, and by applying the specific algorithm , an electromotor voltage of 199.1 V. The IEEE algorithm cannot determine the current directly, but the specific algorithm resulted in 19.3 A.

The maximum current through the active conductors of the lines is 1.450A.

Initially measurements were performed before the building started for the two lines in the middle, three circuits being energized and an exterior one being cut off. On this circuit measurements were performed, resulting, for the superior phase, after cutting off the short-circuits of grounding in the terminal stations, that through this conductor a current of 160 A (4,2 miles between the stations, on the electric track) had traveled.

By applying the calculation algorithm for the magnetic induction there resulted a value of 230.2 A, which can be explained by the fact that in calculating there was considered the maximum charge of the lines, which is not correct. At a charge of 66 % there results a current of 153A.

Measurements of the magnetic induction were performed in the year 1979 on the nr 3 (T1) line being erected on the circuit nearest to line 4, functioning, as well as line, on a section of 1.44 miles. There resulted: an induced electromotor voltage of 100 V and a current of 16 A through the conductor. By applying the calculation algorithm for the magnetic induction an electromotor voltage of 199.1 and a current of 19,3 A resulted.

From the point of view of the magnetic induction, the first measurement confirmed the calculation made by applying the specific algorithm that, considering the induced electromotor voltage, leads to results very near the field measured ones. The same conclusion holds true for the second field measurement.

## 7. CONCLUSIONS

Having in view the necessity of erection and maintenance works to be done at the multi-circuit transmission overhead lines with energized circuits, applying technologies with multi-grounding protective connections, probably at each tower, but at least at the two ends of the considered section, the calculation of the correct touch voltages at each point, where the workers may be in direct contact with the de-energized but induced conductor, for the optimum worker protection, cannot be neglected and all the field and electrical elements have to be modeled for the most accurate results.

The proposed algorithm and its software solve this matter.

The existent Annexes L and N of the IEEE Std 524 may be further used for the case of induction in the circuit of a line but only in the case of the single grounding methodology.

## 8. REFEENCES


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