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A More Accurate Algorithm And Software To Calculate The Magnetic Induced Voltages In Multiconductor Systems.

George A. Florea, *Senior Member, IEEE*, Stelian I. A. Gal, Laurențiu Lipan, Elena Mateescu, Nicolae Chiosa

Abstract **— Because of the necessity to perform maintenance on one of the circuits of the high and very high tension double circuit lines that have one of the circuits operational, a case that lately becomes more frequent, the calculation of the currents and induced tensions in the circuit's conductors that is under induction is required to establish safety working conditions.**

This paper does not intend to modify the standardized established limits for touching tensions in normal conditions or short circuit of the inductor conductor, but proposes a mathematical model and the associated software that will give more precise results than those resulting from applying the methodology and software from IEEE Std. 524-2003 annexes.

Index terms **- energized conductors, grounding, impedances, magnetic induction, overhead transmission lines, resistance to ground, touch voltage .**

I. INTRODUCTION

THE most adequate technology applying to string the conductors of a new circuit or to perform some maintenance works on an existing de-energized circuit, under electric and magnetic induction of the other energized circuit conductors, implies the knowledge of the currents and/or voltages induced in the de-energized conductors, their magnitudes having to be taken into account for protecting the working personnel.

In this paper only the magnetic induction is taken into consideration, being the most dangerous one in case of conductor stringing or of works at different towers of the same section, in the same time, when grounding the de-energized conductors at least at both ends of the section is necessary.

The annexes L and N of the IEEE Std 524- 2003[1] contain an algorithm and the relevant software to calculate the magnetic induced voltage, but unfortunately, first of all there are some simplifying hypotheses affecting the result accuracy, second, the impossibility to take into account the case of a short circuit on one of the energized circuits, and third, it cannot be applied to the described situation of the multi-grounding protection, but only to the single grounding protection, which can be used only for insulated works at one tower of that section.

The developed algorithm and the subsequent software model with high accuracy all the geometrical and electrical elements of the multi-conductor system over its entire length, not only over the section in case.

II. CONSIDERATIONS ON THE MAGNETIC INDUCTION CALCULATION ALGORITHM AS PER STD 524- 2003

The algorithm is based on the matrix relations between the voltages, impedances and currents, using Carson relations for the self and mutual impedance calculation.

There is an initial simplifying hypothesis considering no voltages on the de-energized conductors and shield wires if connected to ground in more than one point, which is not true in the case of real grounding resistance [3]. These resistances can be different for different locations of the towers or of the protective grounding sets.

There is a limitation of the algorithm that can take into account only three inductive phases, three induced phases and four shield wires and no short circuit case of the inductive circuit.

The algorithm calculates the open loop voltages per length unit of the de-energized conductors (phases) which can be useful in the case of single grounding of the induced conductor (phase) in that section.

It is not possible to model the real spans of the section with possible different grounding resistances of the towers and/or grounding sets.

III. THE PROPOSED ALGORITHM

A. *Multi-conductor system description*

The considered multi-conductor system, representing the multi-circuit electric overhead line, is composed by I inductive phases and J induced conductors, including all the shield wires and the de-energized phases (conductors). There are no limits for I and J.

The section where works on de-energized phases (conductors) are performed is considered to contain N spans and on its left and right side are other M spans. There is no limit for M and N.

The currents through the energized phases (conductors) are considered constant and can be used in normal operating condition or in short-circuit case of one of the inducting circuit. In this latest case one phase is considered loaded 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 towers are grounded, the resistances to ground

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having different values if the case. All the induced conductors are connected to ground by the same resistance.

All the 2M+N spans may get different lengths.

The resistance of the soil 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

There are 2M+N spans, 2M+N+1towers, I inducting phases and J induced phases and shield wires.

Applying the Kirchoff II theorem in the matrix form to all the (2M+N) spans for all the J loops of each span there are used for self and mutual impedances the Carson[1] or Polaczeck [4] relations.

The following hypotheses have been considered in elaborating the calculation algorithm [5]:

- in case of a short circuit in the inducting line, its location is away from the parallelism zone, which is a more disadvantageous situation because the currents in the protection conductors are minimal and practically constant all along the line;
- $[I_0]$ – the vector of the *I* inducting currents, in the active conductors, in A;
- $[R]$ – vector of *2M+N+1* elements representing the resistance to ground of the *2M+N+1* towers, in Ω;
- $[a]$ – vector of *2M+N* spans considered (span length), in m;.
- $z_{\bar{j}\bar{j}}$ is j conductor's self line impedance;
- $z_{i\bar{j}}$ isthe mutual line impedance between the active conductor *i* and the passive conductor $\bar{j}$.

$$[J_k] = -[Z_{j^*k}]^{-1}[E_j] \tag{1}$$

where:

$[J_k]$ – is the vertical vector matrix of the *2M+N* loop passive currents;

[Ej]– is the vertical vector matrix of the electromotive voltages induced by the currents in the active conductor into every opening of the passive conductor;

$$E_j = a(j^*)\sum_{i=1}^{I} z_{i\bar{j}} I_o(i) \tag{2}$$

where:

$z_{i\bar{j}}$ - is the mutual line impedance between the active conductor *i* and the passive conductor $\bar{j}$;

$[Z_{j^*k}]$ – is the square matrix of all impedances, that can be calculated as :

if k = j

$$Z_{j^*k} = z_{\bar{j}\bar{j}} a(j^*) + R_{j^*} + R_{j^*+1} \tag{3}$$

where:

$z_{\bar{j}\bar{j}}$ is the conductor's self line impedance $\bar{j}$

if k ≠ j

$$\begin{gathered} Z_{j^*k} = 0, for \quad |j^* - k^*| \geq 2 \\ Z_{j^*k} = R_{k^*} + R_{k^*+1} + z_{\bar{j}\bar{k}} a(k^*), for \quad j^* = k^* \end{gathered} \tag{4}$$

where:

$z_{\bar{j}\bar{k}}$ is the mutual impedance between the passive conductors $\bar{j}$ and $\bar{k}$

$$Z_{j^*k} = -R_{k^*}, for \quad |j^* - k^*| = 1, if \quad j^* > k^* \tag{5}$$

$$Z_{j^*k} = -R_{k^*+1}, for \quad |j^* - k^*| = 1, if \quad j^* < k^*$$

$$\begin{gathered} j \in [1; (2M+N)J] \\ k \in [1; (2M+N)J] \end{gathered} \tag{6}$$

$$j^* = \begin{cases} 1 + Integer\left(\dfrac{j}{J}\right), for & j \neq Multiplu(J) \\ \dfrac{j}{J}, for & j = Multiplu(J) \end{cases} \tag{7}$$

$$\bar{j} = \begin{cases} rest\left(\dfrac{j}{J}\right), for & j \neq Multiplu(J) \\ J, for & j = Multiplu(J) \end{cases} \tag{8}$$

$$k^* = \begin{cases} 1 + Integer\left(\dfrac{k}{J}\right), for & k \neq Multiplu(J) \\ \dfrac{k}{J}, for & k = Multiplu(J) \end{cases} \tag{9}$$

$$\bar{k} = \begin{cases} rest\left(\dfrac{k}{J}\right), for & k \neq Multiplu(J) \\ J, for & k = Multiplu(J) \end{cases} \tag{10}$$

The touch voltage at each tower position across the grounding impedance can be calculated by applying Ohm's law, thus:

$$U_m = \begin{cases} R_m\left[\displaystyle\sum_{k=(m-1)J+1}^{mJ} J_k - \sum_{k=(m-2)J+1}^{(m-1)J} J_k\right], for\ m \in (1, 2M+N+1) \\ R_m \displaystyle\sum_{k=1}^{J} J_k, for \quad m = 1 \\ -R_m \displaystyle\sum_{k=(2M+N-1)J+1}^{(2M+N)J} J_k, for \quad m = 2M+N+1 \end{cases} \tag{11}$$

where:

U_m is the touch voltage at the tower "m" position, *m=2M+N+1*.

The touch voltage at each tower position across the grounding impedance can be calculated by applying Ohm's law, thus:

The touch voltage is considered the voltage to ground of the conductor at the point of connection to the tower or to the worker's body; in the latest case a much higher resistance to ground has to be taken into account [1].

C. Software

Based on the algorithm and the logic diagram described in Appendix, the software was developed using Matlab - version 6.5. The software has a size of 7.37 kB and can be easily run on normal computers. This software is composed by a main body and two auxiliary procedures.

IV. Results for the Case of 220 kV Double Circuit Line

In a first stage, the algorithm and the software were applied for calculating the induced voltages in the lower phase of a 220 kV double circuit line with the other circuit under normal and short circuit operation.

The transversal geometry of the line is drawn in Fig. 1.

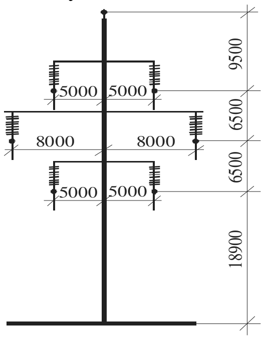

Fig. 1. The transversal geometry of the line

The line is equipped with a shield wire and single phase conductors. The shield wire is a steel conductor of 95 sq. mm cross section and the conductors are of ACSR type with 450/75 sq. mm. cross section. The currents of the inducting circuit are considered conventionally as loaded with 1000 A in the normal operating condition. In short circuit condition (monophase type), a conventional current of 1000 A flows through the lower phase of the inducting circuit, and the other two phases are not loaded.

Calculations were performed for the reference section (N spans) with N from 1 to 30. The spans were identical of 350 m each. The other 2M spans are of 350 m each, too. The grounding resistances are of 2, 5 and 10 ohms, respectively, the soil resistances being of 30, 50 and 100 ohm, respectively. M was considered 5 (spans).

The diagrams of the touching voltages are plotted in Fig. 2, Fig. 3, Fig. 4 and Fig. 5.

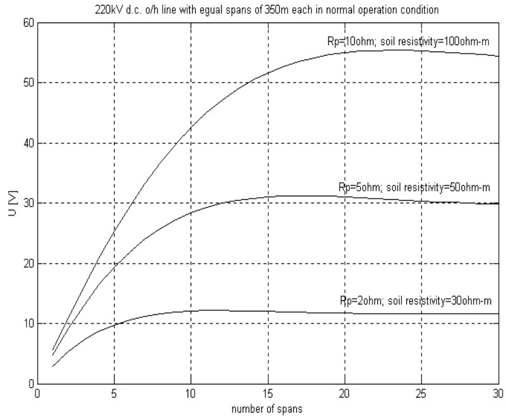

Fig. 2. 220 kV d.c. o/h line with equal spans of 350 m each in normal operation condition

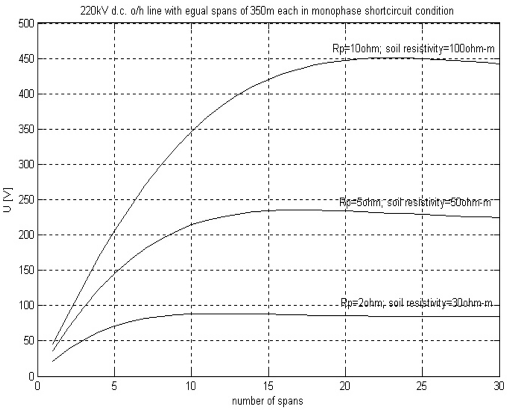

Fig. 3. 220 kV d.c. o/h line with equal spans of 350 m each in monophase shortcircuit condition

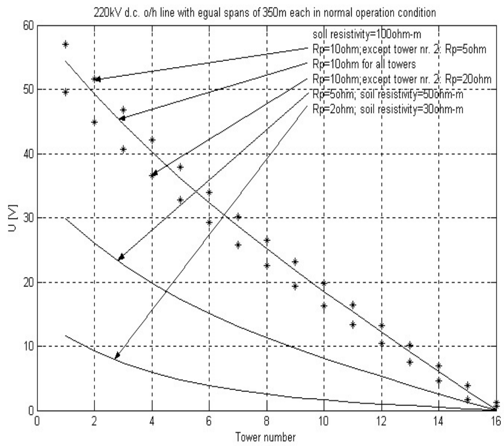

Fig. 4. 220 kV d.c. o/h line with equal spans of 350 m each in normal operation condition

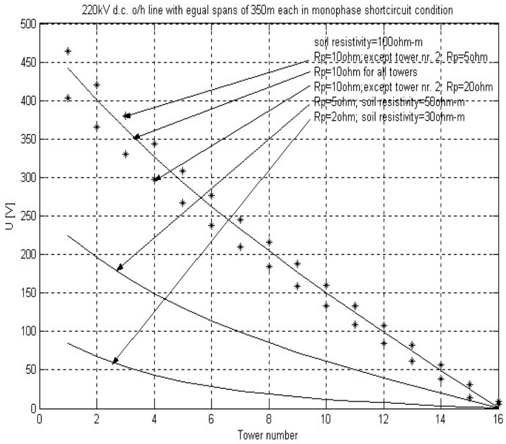

Fig. 5. 220 kV d.c. o/h line with equal spans of 350 m each in monophase short circuit condition

It results that the touch voltage at the ends of the section are the maximum one for each case, but the a/m situation is an ideal one, in practice the spans and the tower resistance being different. Therefore a situation with different lengths of spans and different resistances to ground of the towers was calculated and the results show that the length of the span is not so important if differences exist, but the differences in tower resistances are important. In Fig.4 and 5, the values of the touch voltages in the case of higher or lower resistances to ground of the tower no.2 than that of the other by a factor of 1.5 are presented. In some cases, the touch voltage at the end of the section cannot be more than the highest one, if high differences between the tower resistances to ground are met.

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

Measurements under normal operating conditions were performed in January 2006, April 2006 and May 2007 in Timisoara district (Romania) on three different sections of the 220 kV double circuit Timisoara – Sacalaz – Arad (2 sections, one with 3 spans and one with 5 spans) and Resita - Timisoara (1 section with 5 sections). The lines were disconnected and after performing the connection to ground of the induced circuit lower phase at all of the locations in the considered section, the other circuit was reconnected.

The transversal geometry of the line is the same as the one described in Fig.1.

The resistances to ground of the earthings had different values, ranging from 1.25 to 7.8 ohms.

The spans had different lengths, ranging from 168 to 340 meters.

The soil resistances were different too, ranging from 14 to 120 ohm.

The inducting currents had the amplitudes between 65 and 430 A.

The currents at each tower location on the connection to ground of the grounded phase were measured and all results showed a good agreement with the calculated ones. The discrepancies are minor and may be described as caused by the impossibility to have correct values of the towers grounding resistances, since the towers were connected to ground by the natural resistance of the foundations paralleling to the auxiliary galvanized steel grounding.

First case – January 2005 – Measurements done on 220 kV double circuit line Timisoara- Scalaz- Arad, towers no. 17- 20.

The resistances to ground of the connections were: 2.055, respectively 1.8, 3.07 and 2.08 ohms.

The spans had the lengths of: 234, 345, 678 and 450 m.

The soil resistivity was 31 ohmm.

The inducting currents had the amplitude of 65 A.

The induced currents calculation results are: 0.768, 0.32, 0.378 and 0.72 A

The measured values are: 0.665, 0.246, 0.229 and 0.618 A.

Second case – April 2006 - Measurements done on 220 kV double circuit line Timisoara- Sacalaz- Arad, towers no. 20-25.

The resistances to ground of the connections were: 5.92, 2.37, 2.08, 6.50, 1.27, 7.80 ohms.

The spans had the lengths of: 330, 315, 340, 291, 168 m.

The soil resistivity was 37 ohmm.

The inducting currents had the amplitude of 430 A.

The induced currents calculation results are: 12.23, 4.558, 1.104, 1.863, 5.959, 10.449 A

The measured values are: 12.21, 2.67, 0.725, 1.46, 4.15, 12.91A.

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Third case – May 2007 - Measurements done on 220 kV double circuit line Resita- Timisoara, towers no. 65- 70.

The resistances to ground of the connections were: 4.46, 6.37, 2.60, 2.425, 2.386, 1.03 ohms.

The spans had the lengths of: 252, 298, 279, 321, 296 m.

The soil resistivity was different along the section its value varying from 14.45 to 118.87 ohmm.

The inducting currents had the amplitude of 4418.76 A.

The induced currents calculation results are: 3.31, 2.11, 0.76, 0.57, 2.02, 3.42 A

The measured values are: 2.59, 1.34, 0.85, 0.55, 0.77, 4.45 A.

There are some differences between the calculated and the measured values , the maximum ones not exceeding 20 %. This error can be explained by the inequal resistanec to ground of the connections, the ununiformity of the soil resistivity and of course due to the considered approximation of the electric and geometric parameters of the line beyond the measured section.

VI. 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, can not be neglected.

The proposed algorithm and its software solve this matter.

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

VII. APPENDIX

ACKNOWLEDGEMENTS

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IX. BIOGRAPHIES

George Alexandru Florea (M'2001,SM'2002) was born in Bucharest, Romania, on October, 1, 1947 and received a Dipl. in Electric Power Engineering in 1970 and a Doctor's degree in High Voltage Engineering in 1985, both from University Politehnica Bucharest, Romania. His employment experience includes the Institute of Power Studies and Design, Bucharest, Romelectro Foreign Trade Company, Bucharest, Tehnorob Ltd, Bucharest, Power & Lighting Thnorob S. A., Bucharest. His special fields of interest include the design of powerlines, surge propagation on transmission and distribution lines, electromagnetic field of electric network effect on biological systems and live-line maintenance methods.

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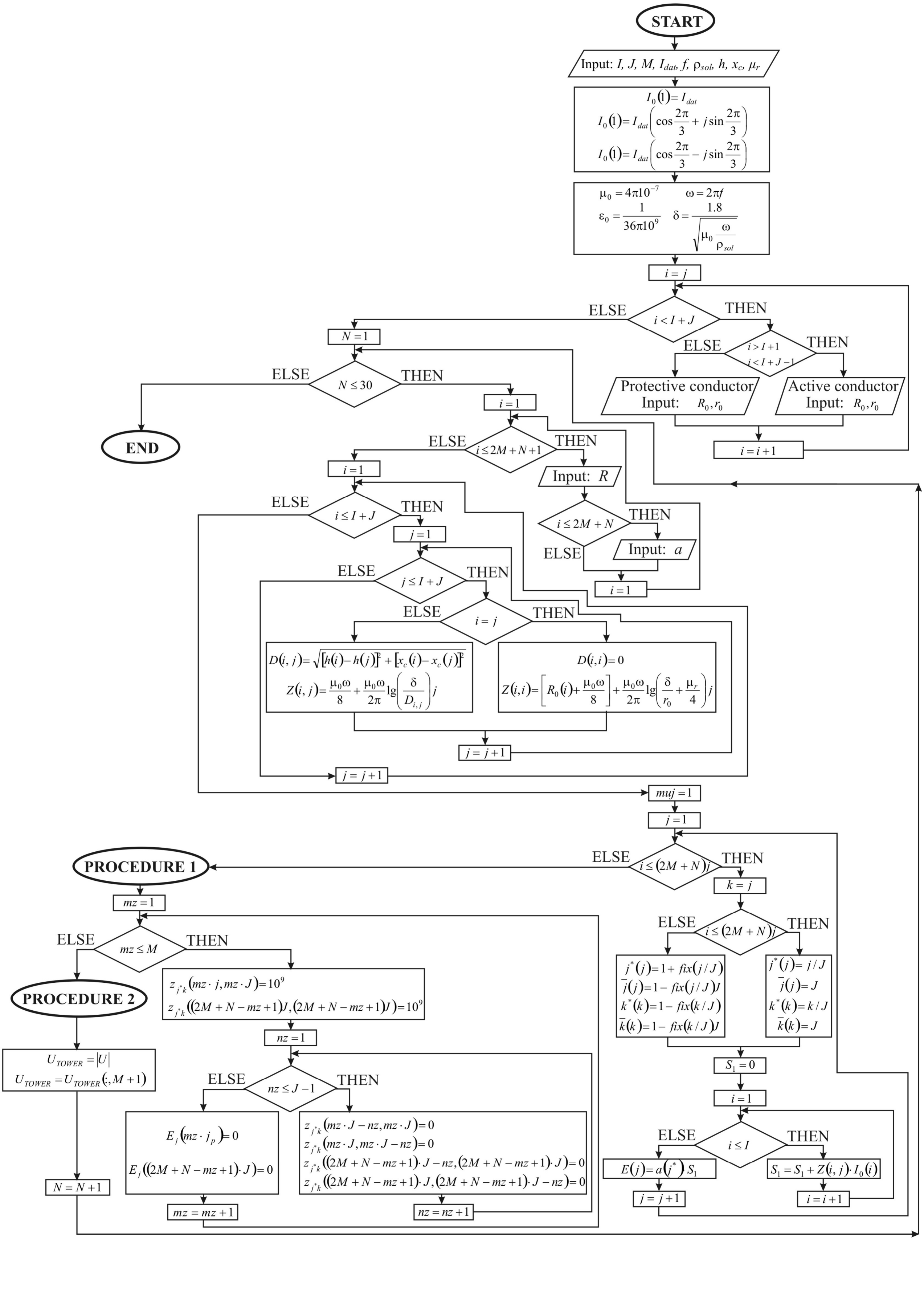
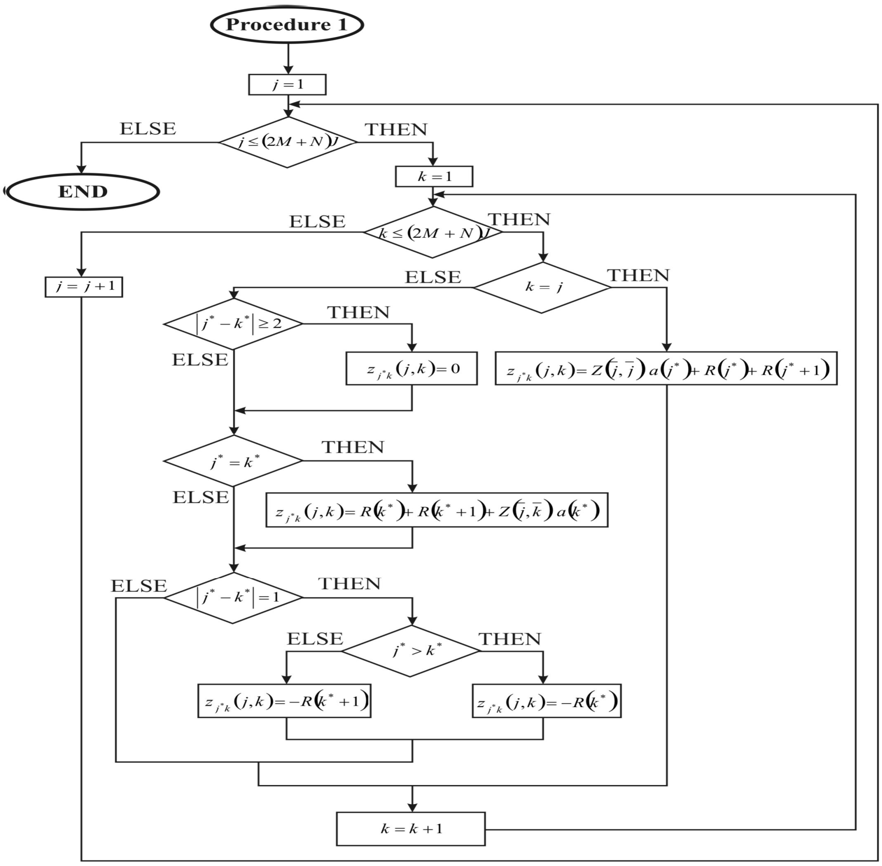
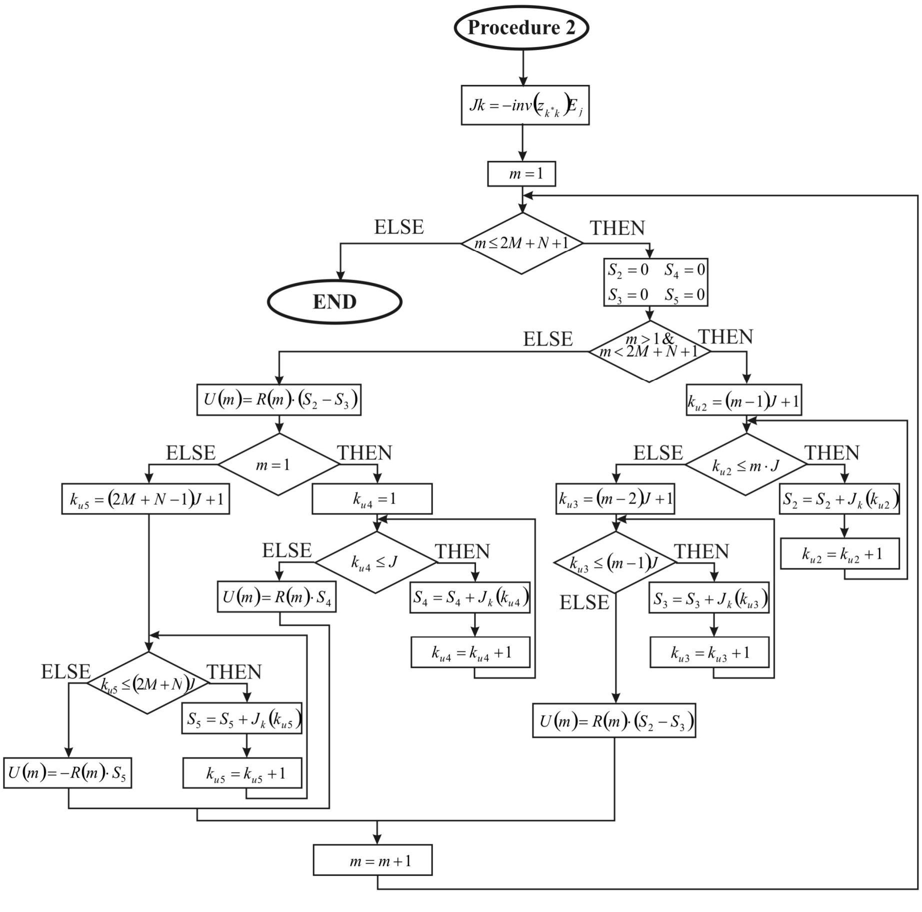
Nicolae Chiosa was born in Gorj, Romania, on February, 16, and received a Dipl. in Electric Power Engineering in 1990 from Institute Politehnica "Traian Vuia" Timisoara, Romania. and a Doctor's Engineering Dipl. in 2006, from Politehnica University , Timisoara. His employment experience includes the FRE Timisoara, STD Timisoara, Romania National Power Grid Company "Transelectrica"- S.A. - Timisoara. His special fields of interest include relay protection and transformer susbstation monitoring.

X. APPENDIX – THE LOGIC DIAGRAM.




Procedure 1
$j = 1$
$j \le (2M+N)J$
ELSE
THEN
END
$k = 1$
$k \le (2M+N)J$
ELSE
THEN
$j = j + 1$
$k = j$
ELSE
THEN
$|j^* - k^*| \ge 2$
THEN
ELSE
$z_{j^*k}(j,k) = 0$
$z_{j^*k}(j,k) = Z(\bar{j},\bar{j})\, a(j^*) + R(j^*) + R(j^*+1)$
$j^* = k^*$
THEN
ELSE
$z_{j^*k}(j,k) = R(k^*) + R(k^*+1) + Z(\bar{j},\bar{k})\, a(k^*)$
ELSE
$|j^* - k^*| = 1$
THEN
ELSE
$j^* > k^*$
THEN
$z_{j^*k}(j,k) = -R(k^*+1)$
$z_{j^*k}(j,k) = -R(k^*)$
$k = k + 1$


Procedure 2
$Jk = -inv(z_{k^*k})E_j$
$m = 1$
ELSE
$m \le 2M+N+1$
THEN
END
$S_2 = 0 \quad S_4 = 0$
$S_3 = 0 \quad S_5 = 0$
ELSE
$m > 1$ & $m < 2M+N+1$
THEN
$U(m) = R(m) \cdot (S_2 - S_3)$
$k_{u2} = (m-1)J + 1$
ELSE
$m = 1$
THEN
ELSE
$k_{u2} \le m \cdot J$
THEN
$k_{u5} = (2M+N-1)J + 1$
$k_{u4} = 1$
$k_{u3} = (m-2)J + 1$
$S_2 = S_2 + J_k(k_{u2})$
ELSE
$k_{u4} \le J$
THEN
$k_{u3} \le (m-1)J$
THEN
$k_{u2} = k_{u2} + 1$
$U(m) = R(m) \cdot S_4$
$S_4 = S_4 + J_k(k_{u4})$
ELSE
$S_3 = S_3 + J_k(k_{u3})$
$k_{u4} = k_{u4} + 1$
$k_{u3} = k_{u3} + 1$
ELSE
$k_{u5} \le (2M+N)J$
THEN
$S_5 = S_5 + J_k(k_{u5})$
$U(m) = R(m) \cdot (S_2 - S_3)$
$U(m) = -R(m) \cdot S_5$
$k_{u5} = k_{u5} + 1$
$m = m + 1$