Modeling intermittent earth faults (2023)

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***Abstract*— With the increasing importance given to the quality of the energy supplied by the grid operators, in the last few decades there's been growing attention given to the study of intermittent earth faults and its consequences. Selectively detecting these types of faults, allows for the elimination of the fault, which in turn leads to a better voltage wave quality, and prevents the faults from becoming permanent, which causes more severe damages to the grid components. In this paper are presented and compared three methodologies for the study of intermittent single line to ground faults and their application through a case study. Intermittent faults in networks with three different neutral grounding systems are also analyzed and their properties documented. The methodology that got the best results for all the studied cases was Methodology C: Direct EMTP Solution.**

***Index Terms*—Intermittent Single Line to Ground Fault, Neutral Grounding System, Symmetrical Sequence Components, EMTP.**

I. INTRODUCTION

Conventional protections are typically designed to detect faults that persist far beyond the transient they originate and can be detected in the steady state. The fault current and voltages, in steady state, comprise only the fundamental frequency component (50Hz), resulting in simple sinusoidal characteristics. Intermittent faults in time, on the other hand, have the inherent complexity of manifesting and extinguishing repeatedly, and the duration of each occurrence being short. Thus, it is necessary to analyze voltages and currents both in the steady state and in the transient state, which makes their detection harder, compared to permanent faults. So, for protections to be sensitive to intermittent faults, it is necessary to consider the transient state and consider its short duration.

It is important to detect and eliminate intermittent faults in the network because, although they typically do not cause damage to network equipment, repeated disturbances in the voltage decrease the voltage wave quality, which may cause outages of loads that are more sensitive to these disturbances. Additionally, intermittent faults can evolve into permanent faults, so their detection and early extinction are essential to avoid permanent and more severe damage to equipment.

In the last decades, the attention given to the study of intermittent faults has been increasing as the importance of a better quality of service by network operators is increasingly being recognized.

In terms of state-of-the-art modeling of intermittent faults, the theory developed is based on the method of symmetrical components [1] [2] [3] [4] [5], frequently used in the study of permanent faults. The theoretical models are validated with the aid of an electromagnetic transient program, such as the EMTP, which is used in this work. Sometimes real data obtained from records of intermittent faults is also used for model validation. From the established models, are deduced principles or properties that allow for the development of protections against intermittent faults. In the literature, some methods of detection of intermittent faults have already been proposed.

In this paper, the focus will be the modeling of intermittent faults in order to promote a theoretical basis that allows the development of future detection or location algorithms. With this goal, methodologies for modeling earth faults, single-phase and intermittent, are studied. The methodologies are applied to faults in networks with three different neutral grounding systems. The three systems, unearthed, high impedance and resonant (or compensated) are neutral grounding systems whose connection to earth is not solid. For these regimes, the fault current is low and intermittent faults are more likely to occur.

II. BACKGROUND

A. Arc Intermittence

An electric arc in the air, results from the disruption of the dielectric between two conductors, due to a high electric field, and originates a short circuit in the system, being a single-phase fault if the arc is found between one of the phases and the ground. The permanence or intermittency of the fault, in this case, is therefore related to the arc's stability over time.

To study the stability of the electric arc in time, consider the circuit in Fig.1. A Thevenin equivalent generator with voltage V_{Th}, the Thevenin impedance of the circuit Z_{Th} and the arc between the fault point (F) and ground, characterized by its voltage V and current I, are represented.

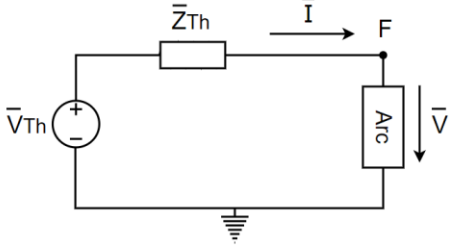

Fig.1. Electric Arc equivalent circuit: *Thevenin equivalent generator,* Thevenin equivalent impedance, and Arc. Adapted from [6].

From Fig.1:

$$V(I) = V_{Th} - Z_{Th} I \tag{1}$$

Assuming that the arc has length l, and dividing (1) by l, we obtain the magnitude of the electric field in the arc E as a function of the current, (2). E_0 is the average maximum magnitude of the electric field in the arc, when the current is null.

$$E(I) = E_0 - \frac{Z_{Th}}{l} I \qquad (2)$$

Equation (2), with Z_{Th} fixed, describes a straight line. The intersection of that line with the characteristic of the electric arc represented in Fig.2 [6], satisfies the principle of energy equilibrium of Elenbaas-Heller and (2). At point P and Q there is an electric arc, but only at point P is the arc stable, therefore resilient to disturbances. For point Q, an increase in current translates into a translation to P, while a decrease in current leads to self-extinction of the arc. So, the stability increases the further point P is from point T, that is, for higher current values, [6].

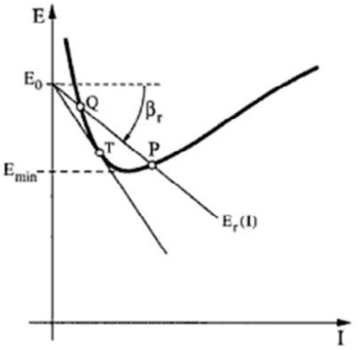

Fig.2. E(I) Characteristic of an arc, schematically, and resistor lines. Extracted from [6]

In neutral grounding systems with a non-solid connection to ground, the Thevenin impedance assumes sufficiently high values (steeper slope) so that the intersection of the straight line with the characteristic, Fig.2, is close to the point T, that is, the arc is unstable and likely to extinguish naturally due to small variations in the Thevenin impedance.

B. Single Phase to ground Fault Calculation

The calculation of the short circuit is based on the method of symmetrical components, which is a direct result of the Fortescue modal transformation, in which three uncoupled components are considered: the positive, the negative and the zero-sequence. Each of them is a single-phase system and analyzed as such.

The Fortescue transform is used as the relationship between the phase magnitudes and their symmetrical components.

In addition to the Fortescue transform, the Superposition Theorem was also considered, which establishes that the fault current will be the sum of the current before the fault occurs, pre-fault (pf), with the current resulting from the fault, over-imposed current (Δ). And the same is true for the circuit voltages.

During a single-phase fault in phase A, the over-imposed component of the current in phase B and C is null, (3). And the voltage in phase A, (4), depends on the fault resistance, R_f, which during this work will always be considered null, value for which the fault current is maximum.

$$\bar{I}_{\Delta_a} \neq \bar{I}_{\Delta_b} = \bar{I}_{\Delta_c} = 0 \qquad (3)$$

$$\bar{V}_a = \bar{V}_{pf_a} + \bar{V}_{\Delta_a} = R_f \, \bar{I}_{\Delta_a} \qquad (4)$$

From equation (3) the symmetric current components are necessarily equal, (5). Consequently, the fault current, $\bar{I}_f$, in phase A, is the sum of the three symmetric current components, and is also the triple of each one of them, (6).

$$\bar{I}_{\Delta_0} = \bar{I}_{\Delta_1} = \bar{I}_{\Delta_2} = \frac{\bar{V}_{pd}}{\bar{Z}_0+\bar{Z}_1+\bar{Z}_2} \qquad (5)$$

$$\bar{I}_f = \bar{I}_{\Delta_a} = 3\,\bar{I}_{\Delta_0} \qquad (6)$$

Based on (5) the equivalent circuit of a single-phase to ground fault is created, in which the three sequence components of the system are in series, Fig.3. The F point is the fault point, and point N is the transformer’s neutral.

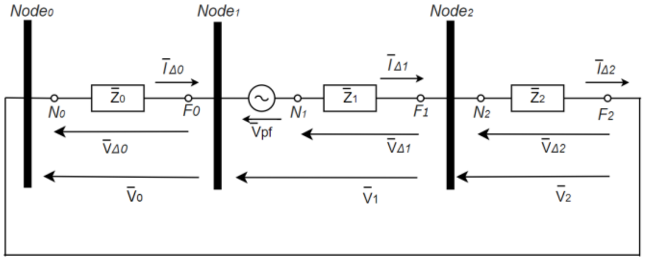

Fig.3. Equivalent Circuit of a Single-Phase-to-Ground Fault in Symmetrical Components.

III. METHODOLOGIES

A. Methodology A – Sequence Components Analytical Solution

In the equivalent circuit for the single-phase to ground fault in symmetrical components, Fig. 3, the impedances, and admittances of the network elements relevant to the calculation are considered. The elements are, the generator, the transformer and the line, or lines of the system. To calculate the voltages and current during the fault, it is also necessary to adapt the equivalent circuits according to the different neutral grounding systems.

In this methodology, the longitudinal impedances and transverse admittances of the lines are considered as constant lumped parameters, calculated at a frequency of 50Hz.

The circuit in Fig. 3, is only correct when a short circuit occurs in one of the phases. This phenomenon can be translated by a switch that closes at t = 0, simulating the onset of a single-phase fault. It is always necessary to pay attention to the initial conditions of the system. The equations deduced from the simplified circuit are then studied in Matlab.

This methodology has an analytical limitation for systems beyond the second order, so to overcome this limitation, methodology B is used.

B. Methodology B – Sequence Components EMTP Solution

For this methodology, the simplified equivalent circuit for the fault in symmetrical components, the circuit introduced in methodology A, is modeled in the EMTP, using all the same elements and parameters.

This methodology is used to study the permanent and intermittent fault, for that the previously mentioned switch, which simulates the permanent fault, is adapted to simulate the intermittence.

C. Methodology C – Direct EMTP Solution

In methodology C, the faults are simulated in the electromagnetic transient program, through the creation of a case study network, using the program's own models and considering the network elements due parameters. It is a more practical method that allows for good results to be obtained due to the robustness of the EMTP models.

IV. CASE STUDY

A. Electrical Grid – Analyzed Networks

The networks considered as a case study, Fig. 4, are composed of a generator, a transformer, and one line, in the case of network 1, and 16 lines, in the case of network 2. It is intended to simulate the single-phase fault at the end of line 16, L16, that is, on bus 15, B15, for both networks. Network 2 has a total of 150 km of lines and 15 buses. Two networks were used to allow firstly the study of a network with only one line, for simplicity purposes, and secondly, a bigger network allows for the study of not only a more realistic network but also the study of the consequences of increasing the network size.

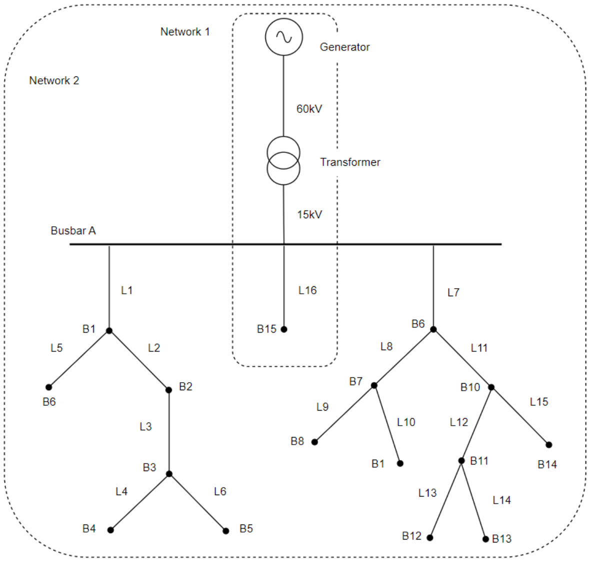

Fig.4. Electric Grid – Analyzed Networks. Network 1 with Line 16. Network 2, all the lines, L1-L16.

B. Fault Intermittence

The times between occurrences, in intermittent faults, do not have fixed values, they are random due to the random nature of the timing of the phenomena involved. In the bibliographic study, values between 0.02s and 0.2s are found [1], [2].

In this paper, a controlled switch is used to simulate the intermittent faults. It changes position with a predefined periodicity, which does not actually happen in real intermittent faults, but the important thing is not the exact time between faults but modeling the successive instances regardless of the time interval between them. Like this, it is possible to test the onset and extinction of each occurrence and study the behavior of the currents and voltages in these circumstances.

Intermittent faults were simulated in EMTP, in methodologies B and C, through the switch controlled by an input signal. A sinusoidal signal was created with a signal generator and fed to a comparator that transforms it into a square wave, Fig.5. The switch closes when it receives the maximum value of the square wave and opens otherwise. Changing the signal frequency and duty-cycle of the square wave the switch is controlled.

The values chosen for the duration of the switch being open and closed were 40ms and 4.5ms, respectively, which results in a frequency of approximately 22.5Hz for the signal created by the signal generator.

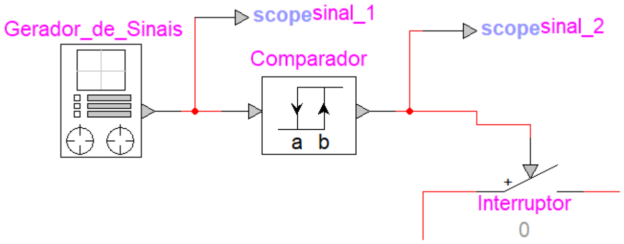

Fig.5. Controlled Switch used to simulate Fault Intermittence. EMTP.

V. ISOLATED NEUTRAL

In this regime, the neutral is not directly connected to ground, but the network remains "connected" to ground through the capacitive effect between the line and ground. When a single-phase fault occurs on phase A, for example, its voltage drops to zero, assuming that the fault resistance is null, and its current increases. In the healthy phases, overvoltage occurs, and the neutral voltage becomes equal to the pre-fault voltage of a healthy phase.

The already established equivalent circuit for the single-phase fault in symmetrical components, Fig.3, was adapted to the isolated neutral system, Fig.6. The difference is that there is no zero-sequence current circulation in the secondary windings of the transformer, due to the Δ-type connection. To represent the components of network 1, the impedances of the equivalent generator $\overline{Z}_G$, transformer $\overline{Z}_T$, power line $\overline{Z}_L$, and the capacity of line C, are considered. Resulting in the circuit in Fig.6.

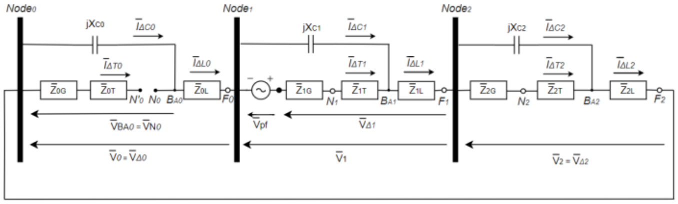

Fig. 6. Equivalent Circuit for the Single-phase-to-Ground Fault in Symmetrical Components for the Isolated Neutral System.

The susceptance of the positive and negative sequence components is much greater than the respective impedances of the transformer and generator, so being in parallel they will henceforward be neglected.

A. Methodology A - Isolated Neutral

With the circuit in Fig.6 defined, its transient and steady state was analyzed. For this, the circuit was simplified by adding the various impedances correspondent to each of the symmetrical components, (7) and (8), as represented in Fig.7(i).

$$\bar{Z}_0 = \bar{Z}_{L_0} \tag{7}$$

$$\bar{Z}_1 = \bar{Z}_2 = \bar{Z}_{G_1} + \bar{Z}_{T_1} + \bar{Z}_{L_1} \tag{8}$$

The resistive components are added together, obtaining R, and the inductive components, obtaining L, resulting in a series RLC circuit represented in Fig.7(ii). In which, C is the zero-sequence capacitance of the line since the others (positive and negative sequence) were neglected.

$$R = R_{L_0} + 2\left(R_{G_1} + R_{T_1} + R_{L_1}\right) \tag{9}$$

$$L = L_{L_0} + 2\left(L_{G_1} + L_{T_1} + L_{L_1}\right) \tag{10}$$

$$C = C_0 \tag{11}$$

Note that in Fig.7, the current $i(t)$ is equals any of the current components since they are all equal. Consequently, the fault current in phase A is three times the current for the simplified circuit, (6).

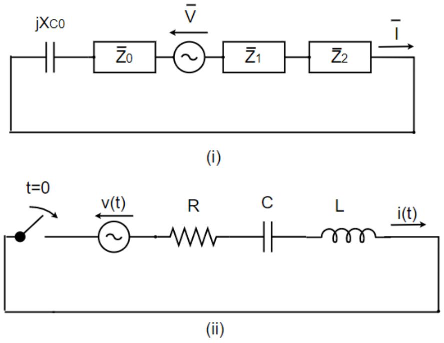

Fig.7. Simplified Equivalent Circuit for the Single-phase-to-ground fault in Symmetrical Components with Isolated Neutral System: (i) Impedance Symmetrical Components of the network elements. (ii) Equivalent Parameters R, L and C.

The current shape of $i(t)$, can be described as the sum of two parcels, one is the natural response, which is an intrinsic characteristic of the system, $i_n(t)$, defined by the components of the system, and the other is the forced response, $i_f(t)$, determined extrinsically, that is, by the voltage source.

$$i(t) = i_n(t) + i_f(t) \tag{12}$$

Considering:

$$i_n(t) = I_l\, e^{-\beta t}\, sin(\omega_n\, t + \alpha) \tag{13}$$

$$i_f(t) = I_f\, sin(\omega t + \phi_i) \tag{14}$$

Where I_l and I_f are the amplitude values of the natural and forced current responses, respectively, and ω_n is the natural frequency of the system, distinct from the angular frequency ω corresponding to 50 Hz. The angles α and ϕ_i refer to the value of the currents at the beginning of the fault and β to the damping coefficient.

Equation (15) was deduced and is detailed in the dissertation original document. In which V_M is the maximum value of the pre-fault voltage.

$$i(t) = \frac{V_M}{\sqrt{R^2 + (\,\omega L - \frac{1}{\omega C})^2}}\left(-\frac{sin(\phi_i)}{sin(\alpha)}e^{-\beta t} sin(\omega_n t + \alpha) + sin(\omega t + \phi_i)\right) \tag{15}$$

The symmetrical voltage components were also deduced from the circuit in Fig.6 and are represented in Fig.10.

$$v_1(t) = v_{pd}(t) + L_1\frac{di(t)}{dt} + R_1 i(t) \tag{16}$$

$$v_2(t) = L_2\frac{di(t)}{dt} + R_2 i(t) \tag{17}$$

$$v_0(t) = \frac{1}{C_0}\int_0^t i(t)\,dt + L_0\frac{di(t)}{dt} + R_0 i(t) \tag{18}$$

Since $i(t)$ is the sum of the natural and forced responses, the voltages being calculated as a function of the current also have two distinct parts. The natural and forced responses oscillate at different frequencies, the natural frequency of the system, ω_n, and the industrial frequency, ω, respectively.

B. Methodology B - Isolated Neutral

Based on Fig.6, the equivalent circuit of the single-phase

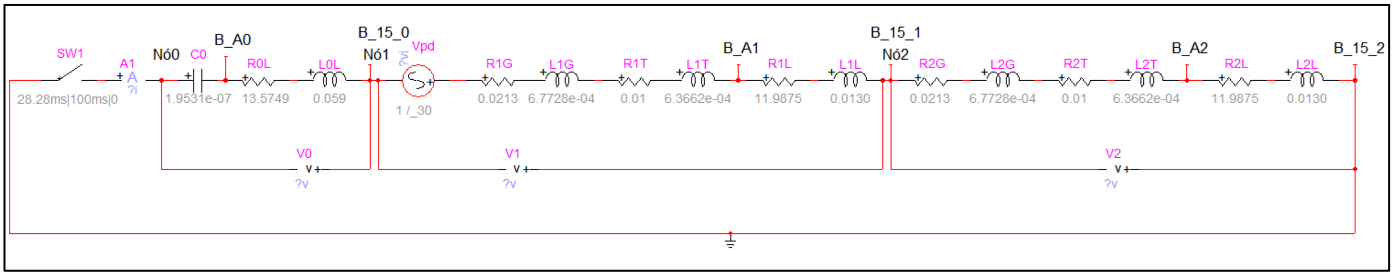

Fig.8. Implemented Circuit for the Single-phase-to-Ground Fault in Symmetrical Components for the Isolated Neutral System. (G)- Generator, (T)- Transformer, (L)- Line – EMTP.

fault in symmetrical components was constructed in EMTP, Fig.8. In the circuit are defined the positions of busbar A, $B_{A_{012}}$, and busbar 15, $B_{15_{012}}$, as well as the nodes between the symmetrical components.

The results obtained for the fault current with methodology A and B are identical, as can be seen in Fig.8, which means that equation (15) is in accordance with the circuit in Fig.8 and with the calculations performed in EMTP.

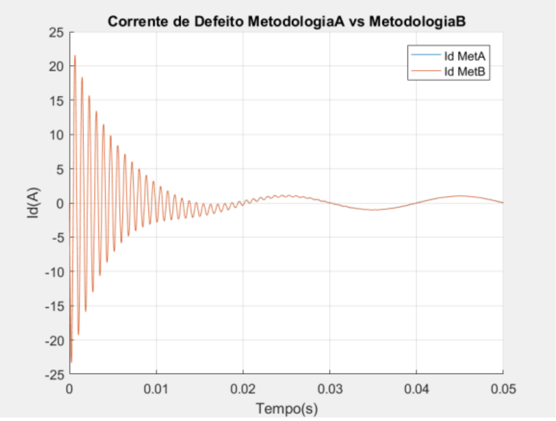

Fig.9. Fault Current, Methodology A and Methodology B. – Network 1- 1/β = 4.7ms, $f_n =$ 1257Hz. Max Value 23.29A, Steady-state amplitude 1.01A. Matlab.

It is possible to observe in Fig.10 that in steady state the positive and zero-sequence voltages are in phase opposition with the same amplitude, which results in the negative sequence voltage being null. This may be relevant for the development of an algorithm as a basis for protection against permanent single-phase faults, in an isolated neutral system.

Once the fault characteristics for network 1 were obtained, the network 2 was studied. The other lines were added to the circuit in Fig.8 to be able to understand their influence on the fault state. The fault continued to be simulated at the end of line 16, but the diagram representing the symmetrical components needed to be changed. The components already considered in Fig.8 remained unchanged. What was added were the symmetrical components of the new lines, line 1 through 15.

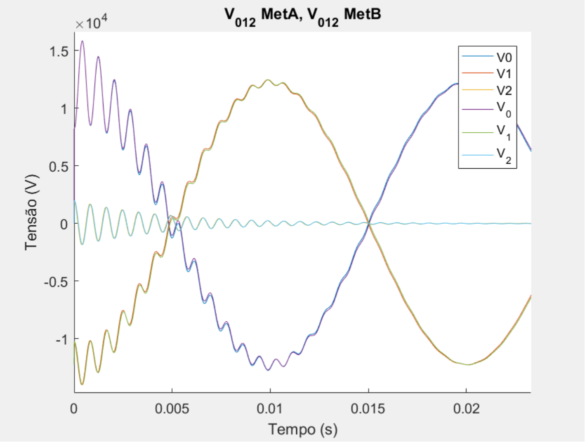

Fig.10. Comparison of Symmetrical Voltage Components obtained with Methodology A and Methodology B at the fault point. Network 1.

Each of the lines was represented through its zero-sequence capacity, in parallel with that of line 16, because of the currents seen from the fault point. Considering for each line only the zero-sequence capacity is a good approximation, because the zero-sequence capacity determines the capacitive current of the line, which in the case of the new lines is the most relevant in terms of the impact they have on the fault current in phase A, of line 16.

By adding new lines to the network, where previously only line 16 was considered, the network capacity naturally increased, which lead to an increase in the fault current. With the increase of the network, the natural frequency of the system decreased, and the damping coefficient remained unchanged. This fact is interesting as it allows us to conclude that for the isolated neutral, a protection whose algorithm intends to detect single-phase-to-ground faults and is sensitive to the transient, has the same time interval to act in networks of different sizes. This is because the duration of the transient state does not change with the increase in the size of the network capacity.

So far, a single fault has been described and modeled, simulated by closing the switch. To simulate the intermittence, the switch must be controlled to change its position according to the predefined times. Therefore, the controlled switch, already introduced, was used instead of the simple switch, used until this point.

Fig. 12 shows the fault current for an intermittent fault and the faulty phase voltage at the fault point, obtained with methodology B (in red). Observing the relationship between the two signals, it is possible to perceive two concepts.

Firstly, the higher the phase voltage at the time the fault occurs, the higher the maximum current value at that occurrence. This is due to the initial conditions defining the behavior of the current's natural response and consequently the transient state.

Secondly, after each instance, the phase voltage has an offset, which can be equated to the line zero-sequence capacitor voltage. This voltage influences the neutral voltage, and consequently the voltages of the two healthy phases. The voltage on the zero-sequence capacitor is zero at the beginning of the first fault, but for the following occurrences it is not. The fact that it is constant between faults is due to the opening of the switch. When a new fault occurs, the capacitor voltage varies, but between faults it is constant.

C. Methodology C - Isolated Neutral

To apply methodology C, the circuit corresponding to network 1 was created and the results of the permanent single-line-to-ground fault were compared with those previously obtained. Afterwards, network 2, shown in Fig.11, was created.

The parameters of the generator, transformer and lines have identical values in terms of symmetrical components, in relation to those used in methodology B, Fig.8.

For the lines, the CP (Constant Parameters) type was chosen, as in methodology B, and the electrical parameters of the lines were calculated with the EMTP, inserting its physical characteristics in the “line data” model. The lines were also divided into three parts of equal length and transposed to simulate three-phase symmetry. A present difference is the fact that the parameters used in methodology A and B are concentrated, while those of methodology C are distributed.

The time at which the switch closes in methodology B and C is the same, and was calculated so that the fault current peak is as high as possible, as in methodology A.

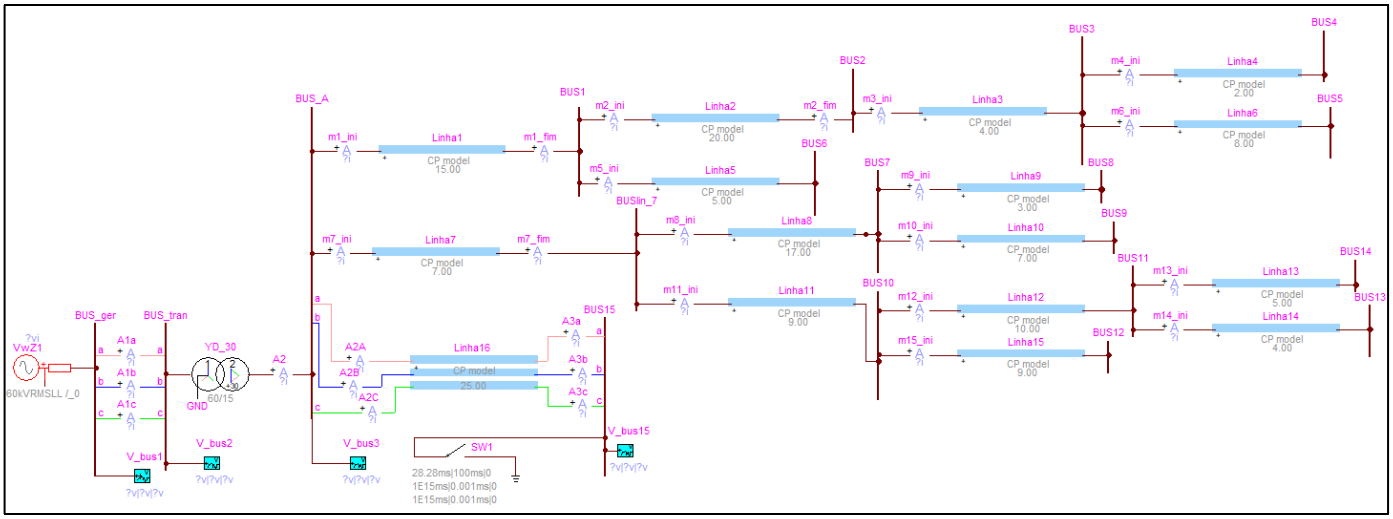

Fig.11. Network 2 - Methodology C - EMTP.

After simulating the system in Fig.11, the fault current was obtained and other frequencies were present, in addition to the natural and industrial frequencies, Fig.12. This is because the phenomena of wave propagation and reflection on the line’s end are now present.

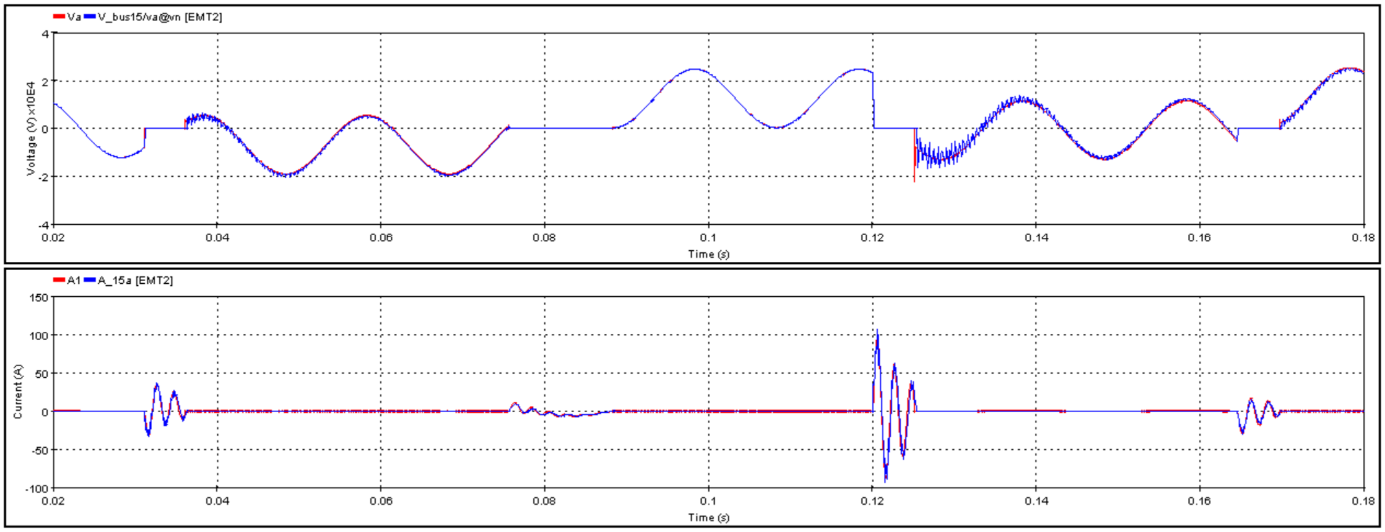

Fig.12. Top: Phase-A Voltage, Methodology B (Red) and Methodology C (Blue) on Bus 15, Fault Point. Bottom: Intermittent Fault Current, Methodology B (Red) and Methodology C (Blue) – EMTP.

VI. HIGH IMPEDANCE NEUTRAL

In this grounding system, a high impedance is connected between the neutral of the transformers and ground, with the aim of limiting the value of the fault current. Alternatively, an artificial neutral is established through the use of a zigzag transformer.

To simulate the high impedance neutral system, a zigzag transformer will be used as an artificial neutral. The zigzag transformer has the property of being an open circuit in the positive and negative sequence networks and an impedance limiting the neutral current in the zero-sequence network, positioned between neutral and ground.

The zero-sequence component of the zig-zag transformer was considered as a simple inductance in parallel with the zero-sequence capacity of the line, as represented in Fig.13.

The only difference in terms of components in this neutral system, compared to the isolated neutral, is the inductance between neutral and ground. But this novelty also changes the previous simplification of the previous equivalent circuit of symmetrical components, Fig.7.

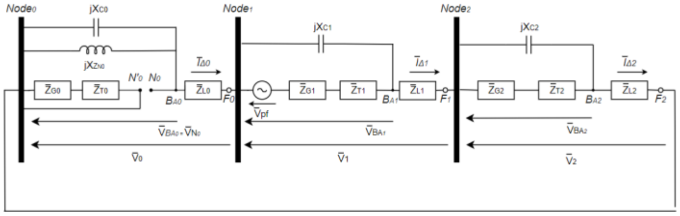

Fig.13. Equivalent Circuit for the Single-Phase-to-Ground Fault in Symmetrical Components for the High Impedance Neutral System.

The obtained simplified circuit for the impedance neutral, Fig.14, is of the 3rd order, due to the existence of two coils and a capacitor. As previously stated, this fact is a limitation for methodology A.

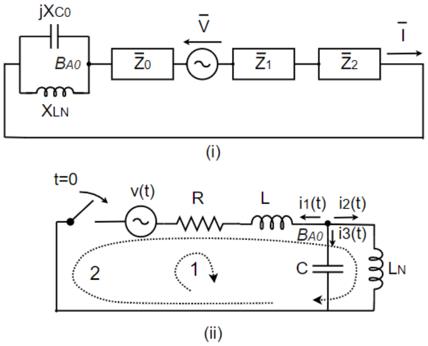

Fig.14. Simplified Equivalent Circuit for the Single-Phase-to-Ground Fault in Symmetrical Components for the High Impedance Neutral System.

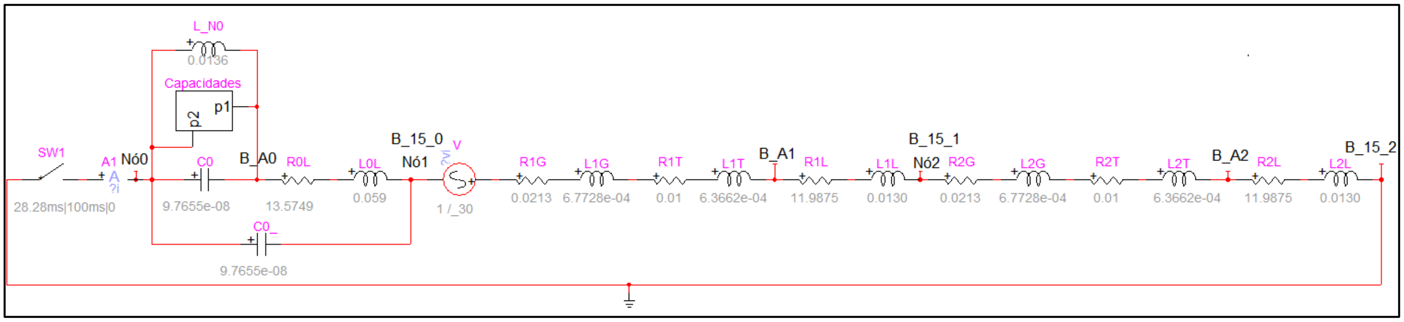

Fig.15. Implemented Circuit for the Single-Phase-to-Ground Fault in Symmetrical Components for the High Impedance Neutral System – Network 2 - Methodology B - EMTP.

Note: The symmetrical current components calculated based on the scheme from Fig.14 are:

$$\bar{I}_{0_f} = \bar{I}_{1_f} = \bar{I}_{2_f} = \frac{\bar{V}_{pf}}{(\bar{X}_{C_0}//\bar{X}_{L_N})+\bar{Z}_0+2\bar{Z}_1} \quad (19)$$

The same analysis was performed for the permanent fault in network 1 and 2, which was performed for the isolated neutral system.

To simulate network 2, the zero-sequence capacities of the multiple lines are added, as was done for the isolated neutral system. The neutral inductance is in parallel with the set of capacitors, Fig.15.

The fault current has, in steady state, a magnitude significantly higher than the value obtained with the isolated neutral system, which depends on the chosen zigzag transformer, naturally. But it is important to note that with the High Impedance neutral system, the magnitude of the single-phase fault current is always higher than that of the isolated neutral system, in steady state.

The zigzag transformer inductance limits the fault current. This phenomenon is due to the value of the susceptance being much higher than that of the inductance, and to the fact that they are

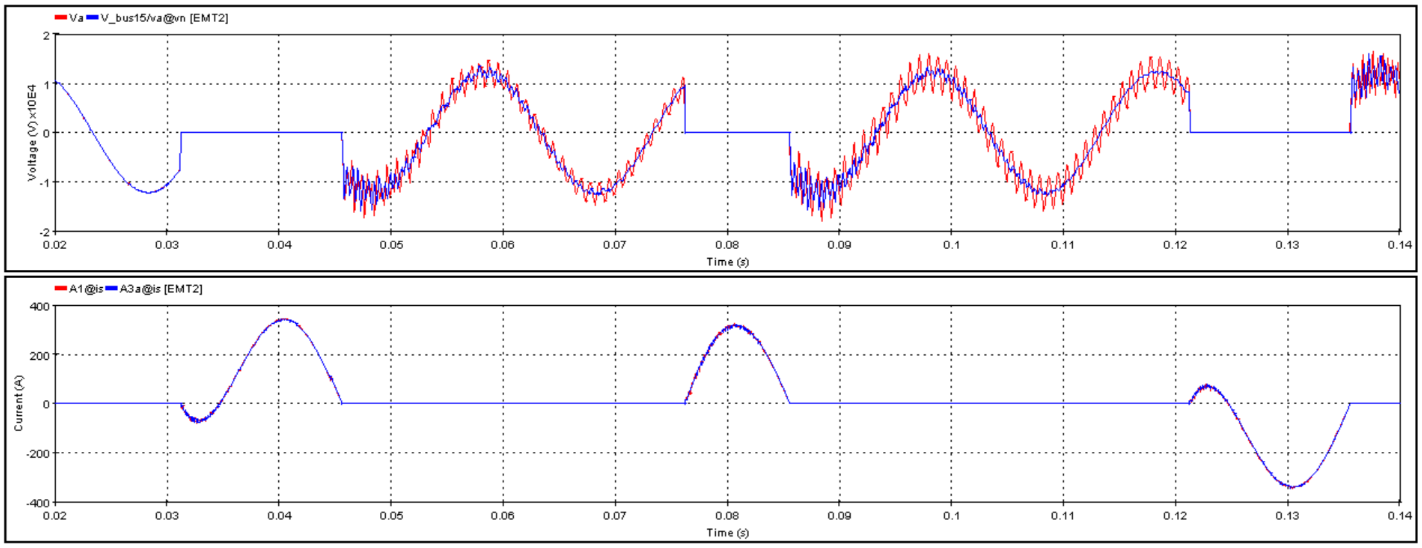

Fig.16. Top: Phase-A Voltage, Methodology B (Red) and Methodology C (Blue) on Bus 15, Fault Point. Bottom: Intermittent Fault Current - Methodology B (Red) and Methodology C (Blue) – High Impedance Neutral System. - EMTP.

in parallel, see Fig.13. Therefore, the fault current obtained for networks 1 or 2 was practically the same.

With the onset and extinction times of the intermittent fault, identical to those used for the isolated neutral, the characteristic of the voltage in the faulted phase and the fault current shown in Fig.16 were obtained (Methodology B in Red).

An interesting property is the visible undamped oscillations in the A-phase voltage at the fault point. These are due to the energy oscillation between the zero-sequence line capacitance and the zigzag transformer inductance. And since losses in the zigzag transformer were not considered, the oscillations do not extinguish.

Note that the extinction of the fault always occurs when the current crosses zero, this is due to the impossibility of an immediate variation of the current which would require an infinite voltage.

Regarding methodology C, the intermittent fault was simulated, obtaining the characteristics of the voltage in phase A, on busbar 15 and the fault current, Fig.16 (in blue).

The currents resulting from the two methodologies are practically identical. However, for the voltages it is possible to see that the oscillations do not dampen in methodology B (as previously mentioned), but dampen in methodology C. This is due to the EMTP considering losses in the zigzag transformer (0.01[Ω]).

VII. RESONANT NEUTRAL

With a resonant or compensated neutral grounding system a Peterson Coil (Lp) is used, which is connected between the transformer's neutral and the ground, with the aim of canceling the fault current through an inductive component in opposition to the otherwise predominantly capacitive fault current.

The equivalent circuit for the single-phase-to-ground fault in symmetrical components for this neutral system is shown in Fig.17.

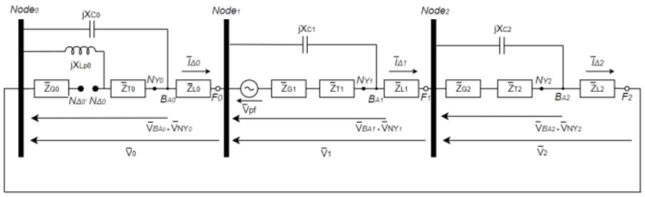

Fig.17. Equivalent Circuit for the Single-Phase-to-Ground Fault in Symmetrical Components for the Resonant Neutral System.

For this neutral system, the transformer phase connections are of the ΔYn type, so there is zero-sequence current in the transformer's secondary windings during the phase-to-ground short circuit. So, comparing with the equivalent circuit for the impedance neutral, Fig.13, we now have the neutral inductance in series with the zero-sequence impedance of the transformer.

Based on the circuit of Fig.17, to compensate the capacitive component of the fault current, it is necessary that the Peterson coil be sized so that:

$$L_P = \frac{\frac{1}{\omega C_0} - \omega L_{0T}}{3\omega} \tag{17}$$

Note that in equation (17), the factor 3 is related to the fact that the Peterson coil is common to all three phases.

Regarding the transient analysis, we proceed as in the other neutral grounding systems, by simplifying the equivalent circuit of Fig.17, originated the circuit of Fig.18.

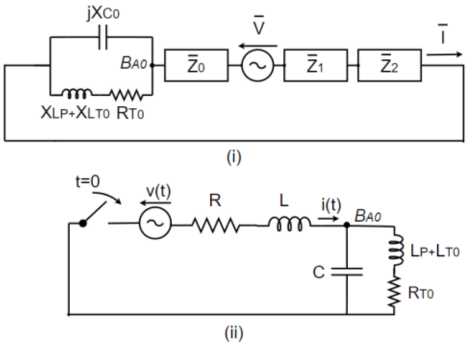

Fig.18. Simplified Equivalent Circuit for the Single-Phase-to-Ground Fault in Symmetrical Components for the Resonant Neutral System.

As it was the case for the High Impedance neutral system, the simplified circuit for this neutral system is of order 3, due to the existence of two coils and a capacitor. Therefore, to continue the analysis, methodology B was applied.

For Network 1, the Peterson coil was considered in the EMTP circuit, and the remaining parameters were unchanged. The fault current in steady state was null, for the reasons already mentioned, and in the transient, the system response is of the damped periodic type, similar to the one obtained for the isolated neutral, the difference being that the current's forced response for this case is null.

For Network 2, Fig.19, the network capacitance increased, relative to network 1, and a smaller neutral inductance was required to compensate the fault current. Taking equation (17) into account, an increase in capacitance causes the value needed for the Peterson coil to be smaller. This considered, the permanent fault current was null, which means that the adjustment to the Peterson coil produced the desired effect. The natural response current, on the other hand, increased due to the increase in capacitance, with the natural frequency being smaller than in network 1, as for the previous damped periodic type response (isolated neutral).

For the intermittent fault with methodology B, the fault current shown in Fig.20 was obtained, as well as the voltage in the corresponding phase. The same properties obtained for the intermittent fault with the isolated neutral are visible, except in relation to the offset that was present in Fig.12. This is because, in this case the zero-sequence voltage is not constant, it is in fact oscillating due to the alternation of energy between the line and the Peterson coil at 50Hz (due to the value chosen for the Peterson Coil). The zero-sequence voltage is in phase

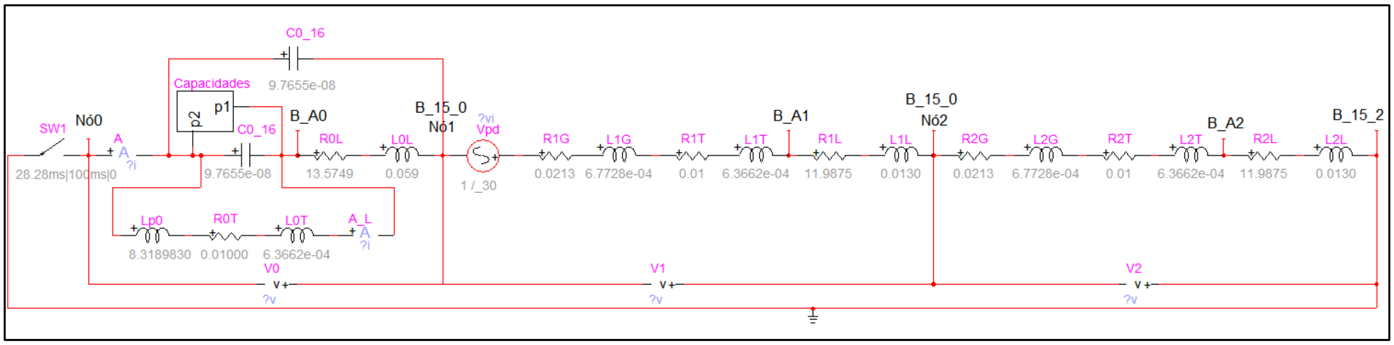

Fig.19. Implemented Circuit for the Single-Phase-to-Ground Fault in Symmetrical Components for the Resonant Neutral System – Network 2 - Methodology B - EMTP.

opposition relative to the positive sequence voltage, resulting in the phase voltage (the sum of the voltage components) being lower than the nominal phase voltage. This also happens with the impedance neutral system, Fig.16, the zero-sequence voltage can be seen, thru its higher frequency, overlaying the positive sequence voltage (50Hz).

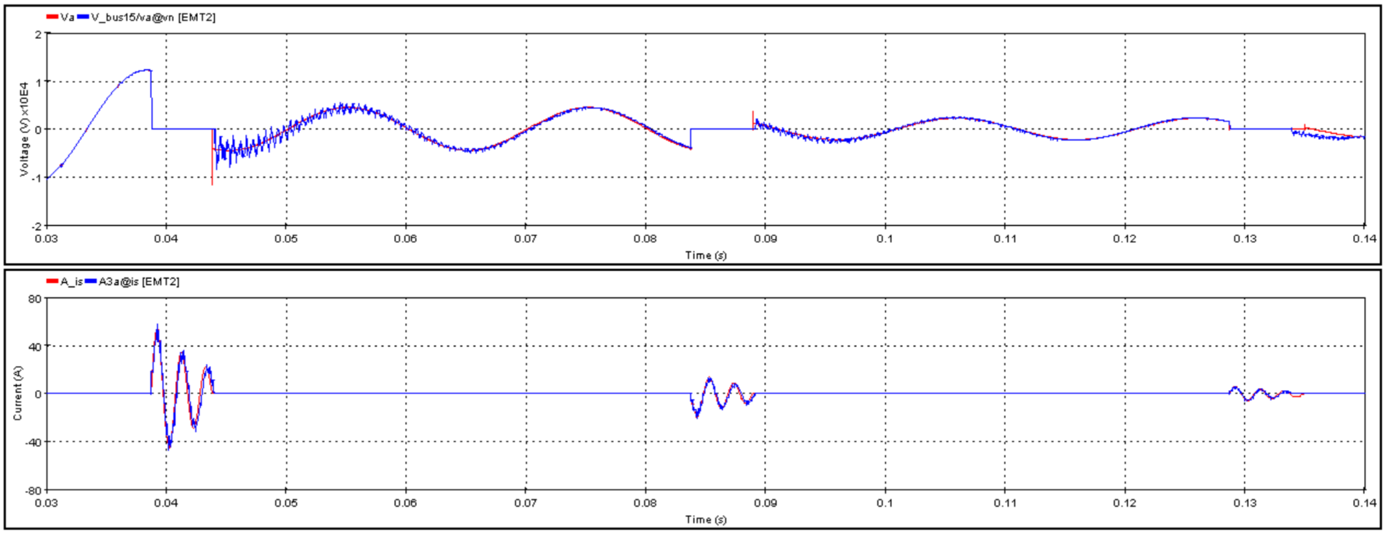

Fig.20. Top: Phase-A Voltage on Busbar 15, Fault Point, Network 2. Bottom: Intermittent Fault Current, Network 2. Resonant Neutral System - Methodology B (red) and C (blue)- EMTP.

With methodology C, the intermittent fault was obtained, Fig.20 (in blue), and it is possible to verify once again that the higher the voltage at the moment the fault occurs, the greater the fault current peak for that occurrence. The A-phase voltage (Methodology B) does not show the same high frequency oscillations observed with the C methodology, this is because the phenomena of wave propagation and reflection on the line's end. Furthermore, the two methodologies are congruent with each other, including the interesting fact that the A-phase voltage between faults decreases over the successive occurrences. This phenomenon is due to the presence of a zero-sequence voltage between faults, which results from the trapped energy that oscillates between the zero-sequence capacitor and the Peterson coil (see Fig.18) at a frequency of 50 Hz. As the present resistance is small, it does not dissipate energy before the next fault. Therefore, for each successive occurrence, there is a higher homopolar voltage and, as a consequence, an increasingly smaller pre-fault and peak voltages in phase A.

VIII. CONCLUSION

In this article were presented three methodologies for the study of intermittent faults, which were applied to three case studies, each having a different neutral grounding system. The main takeaways for these methodologies are: Methodology A, "Sequence Components Analytical Solution", is only valid for systems up to the second order. Methodology B, "Sequence Components EMTP Solution", can be applied to systems of any order, but does not consider high order frequencies resulting from wave propagation and reflection phenomena. Methodology C, "Direct EMTP Solution", is applicable for both steady-state and transient-state and takes into account wave propagation and reflection phenomena.

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