Transient Overvoltages due to Intermittent-Ground Faults in an Industrial Power System Grounded by a Resistance connected to the Secondary of a Grounding Transformer

R. S. Ferreira, H. H. Favoreto

***Abstract*— In high-voltage industrial electrical power systems it is common to ground the neutral of the generators by high resistance to control the ground-fault currents. Grounding resistors are sized so that transient overvoltages remain at controlled amplitudes, and, for this, it is considered as a basic criterion to set the resistive component of the ground-fault current greater than or equal to the total capacitive current. Although this criterion is widespread in the literature, when the resistor is connected to the secondary of a grounding transformer this criterion can be different. Normally, the works found in the literature does not consider the transformer parameters, however, for large industrial power systems which have a high capacitive current, the transformer parameters need to be considered, hence a new criterion to keep the overvoltages at safe levels must be investigated. Thus, in this work, it is proposed a transient model to study intermittent-ground faults in a typical industrial power system. Furthermore, many simulations are performed to investigate which parameters affect the overvoltages when the grounding transformer parameters are considered.**

***Keywords*: Intermittent-Ground Fault, Industrial Power System, Grounding System.**

I. Introduction

It is a consensus that the operation of power electrical systems with generator neutral points ungrounded can lead to overvoltages in case of intermittent ground faults [1]-[8]. Due to these overvoltages, industrial power systems do not operate isolated and the use of resistance at the neutrals of generators is a very common practice. One possibility is to connect the resistor to the secondary of a grounding transformer which allows the usage of a resistor with limited size.

As a design criterion, for high-resistance grounded systems, it is considered that, during the fault, the resistive current must be greater than or equal to the total capacitive current. For large power systems the ground-fault currents have increased due to the increase of the number of capacitive components, such as surge capacitors connected to the terminals of rotating machines. Thus, a challenge of the electrical design is to ensure that the total ground-fault current does not damage the magnetic core sheets of rotating electrical machines in the event of an internal ground fault [9][10].

In this context, when a grounding transformer is used, their parameters, such as, impedance, X/R ratio and rated power, can be chosen to reduce the total grounding-fault current by cancelling part of the capacitive current with the inductive characteristic of the transformer winding. However, the criterion of keeping the resistive current greater than the total capacitive current needs to be revaluated, since it is validated when a pure resistor is considered or when the grounding transformer parameters are neglected [11]-[14]. Furthermore, it is not common to find works in the literature that show computer simulation models which obtain overvoltages that appear due to intermittent-ground faults, especially, in industrial power systems. Usually, the analyses are done only for an equivalent system, that is, the detailed modelling of all the components (grounding resistor and transformer) in a grounding system is not presented.

Therefore, in this work, it is proposed a transient model to study intermittent-ground faults in a typical industrial power system and to use this model to investigate which parameters affect the overvoltages when the grounding transformer parameters are considered.

II. Theoretical Background

A. *Grounding resistor at the secondary of a transformer*

In high-voltage industrial power systems the neutrals of the generators are not kept ungrounded since high overvoltages can appear in case of intermittent-ground faults. For rated voltages greater than 10 kV is common to use a resistor connected to the secondary of a grounding transformer to reduce the size of the resistor due to the lower rated voltage based on the transformer secondary voltage. Fig. 1 shows the scheme of this type of grounding for a 13.8 kV generator.

Based on Fig. 1, Fig. 2 shows the equivalent electrical model for a grounding transformer with the resistor. In this case, the neutral current is controlled by the parameters from both, resistor, and grounding transformer.

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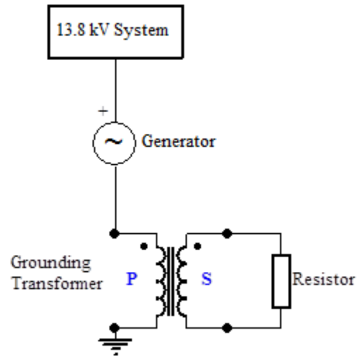

Fig. 1. Generator grounded by a resistor connected to the secondary of a transformer.

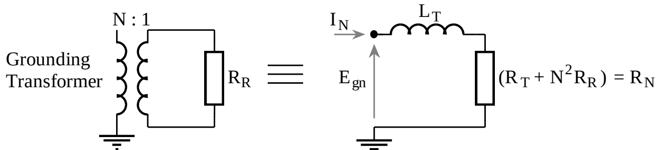

Fig. 2. Equivalent model of grounding transformer with resistor.

where, E_{gn} is the generator line-to-neutral voltage; N is the voltage ratio of the grounding transformer; I_N is the neutral current; L_T is the total leakage inductance of the grounding transformer and; R_N is the resistance of the grounding transformer (R_T) plus the resistance of the grounding resistor referred to the primary side of the grounding transformer (N^2R_R). The parameters of the grounding transformer (R_T and L_T) are related to both sides, primary and secondary, already referred to the primary side.

In case of a ground-fault, Fig. 3 shows a scheme of the currents flowing at the system and Fig. 4 shows an equivalent circuit to calculate the current components:

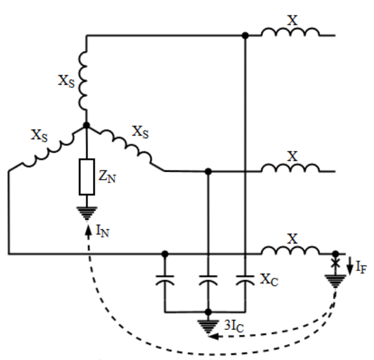

Fig. 3. Simple representation for a ground fault.

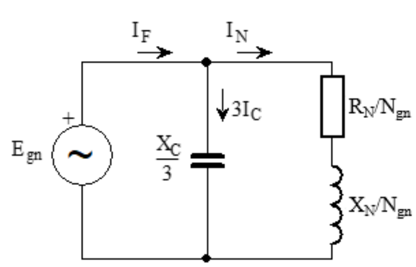

Fig. 4. Equivalent circuit representation for a ground fault considering N_{gn} generators in operation.

where, X_C is the capacitive reactance related to the total phase-to-ground capacitance; I_F is the total ground-fault current; R_N is the equivalent resistance; X_N is the leakage reactance of the grounding transformer; X is the reactance of the cables and X_S is the reactance of the generators.

In high-impedance grounded system, which is the case of this paper, the neutral current is mainly defined by the grounding components, because the neutral impedance is much greater than the system impedance (cables and generators). Therefore, the impact of the cables and generators parameters on the total ground-fault current is minimum, and this simplification is considered valid to analyse the total current analytically.

In this sense, based on circuit presented in Fig. 4, which neglects the reactances of the cables and generators, the total ground-fault current can be calculated by:

$$\vec{I}_F = \vec{I}_N + 3\vec{I}_C \;\; \rightarrow \;\; \vec{I}_F = \vec{I}_R + \vec{I}_L + 3\vec{I}_C \tag{1}$$

$$\vec{I}_F = E_{gn} \cdot N_{gn} \left(\frac{R_N}{R_N^2 + X_N^2} + \frac{-jX_N}{R_N^2 + X_N^2} \right) + E_{gn} \frac{j3}{X_C} \tag{2}$$

where N_{gn} is the number of generators in operation.

As can be seen by Eq. 2, the total ground-fault current (I_F) has resistive, inductive and capacitive components. Moreover, I_F is controlled by the resistor but also by the transformer parameters (L_T and R_T). In fact, the transformer has a positive impact on the system because it reduces the total ground-fault current due the inductance of the windings that cancels a portion of the capacitive current.

In the literature, the parameters of the grounding transformer are neglected [11]-[14], which is valid when the transformer impedance is much lower than the resistor, however for large industrial power systems, which have large capacitive currents, the grounding transformer can be optimized to reduce the total ground-fault current and its parameters need to be considered. Table 1 presents the main parameters of a typical grounding transformer used in offshore platform applications, which in practice, define the resistance and inductance, hence the resistive and inductive current components of the neutral current.

Table 1: Typical parameters of grounding transformer.

Parameter	Value
Primary Voltage [V]	13800
Secondary Voltage [V]	240
Rated Power [kVA]	50
Impedance [%]	5
X/R	2

In spite of the grounding transformer parameters can be chosen to reduce the total ground-fault, the possible transient overvoltages in case of an intermittent-ground fault shall be verified.

B. *Transient Overvoltages*

Ungrounded power systems are no longer used in industrial systems due to the possibility of occurrence of high transient voltage in case of intermittent-ground faults. To understand this transient overvoltage due to intermittent-ground faults in a simple way, Beeman [2] presents the didactic schematic, as shown in Fig. 5.

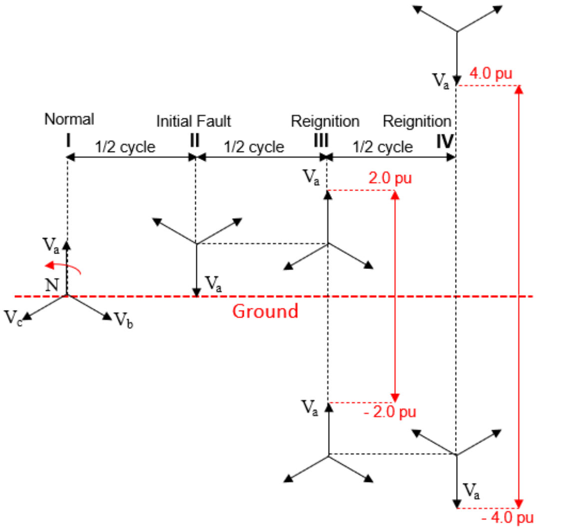

Fig. 5. Voltage escalation scheme [2].

Fig. 5 shows four different instants (from I to IV) of a system with the neutral isolated operating under intermittent ground faults. The voltage phasors in phases “a”, “b” and “c” rotate at synchronous speed and at the initial instant “I”, in normal condition, the neutral point (N) remains constant and coincides with the ground potential. Considering that at instant “II”, when the voltage in phase “a” is at its negative peak, a fault to ground occurs in phase “a”, then the neutral point of the three voltages is shifted, the voltage in phase “a” goes to zero and the voltages to ground of phases “b” and “c” increase by square root of 3. If the short circuit is not bolted, that is, it contains a small space (or gap) between the energized part and the ground, when the current passes through zero the fault is extinguished. After another half cycle, at instant “III”, the voltage in phase “a” reaches 2 pu in relation to the ground potential (considering 1 pu as the peak phase-to-neutral voltage). If by this time the fault has not been eliminated, that is, there is still a small gap between phase “a” and earth, when passing through a new voltage peak, a reignition occurs and, therefore, the phasor of phase “a” is inverted by 180º, when its amplitude reaches -2 pu in relation to the phase-to-ground voltage. When passing through zero again, the fault is extinguished, and the previous step is repeated. When reaching instant “IV”, in the event of a new reignition, the voltage in phase “a” already reaches 4 pu and in the other phases the amplitude is even higher. Note, therefore, the voltage scalation after these three faults (initial fault plus 2 reignitions). The voltage peaks are much larger than the rated one and, in addition, there is a “dc” component associated with the waveforms.

Therefore, if reignition occurs at the maximum value of the transient voltage (as shown in this illustrative case), the phase-to-ground voltage can reach 5 pu in less than 2 cycles. This premise of considering the reignition at the peak voltage is a conservative way to achieve the worst overvoltage in a smaller number of reignitions. In practice, the reignitions tend to occur before the voltage achieves the peak, however, even considering that these reignitions do not occur at the peak, the maximum amplitude of overvoltage will be also reached if more reignitions are considered.

In fact, according to [12], in real power systems totally ungrounded systems do not exist, since three-voltage inductive voltage transformers are used the system is grounded by their impedances and the protection equipment resistances connected at their secondaries also help to limit the transient overvoltage in such a way that few cases of overvoltage indeed, exists. Even though, in rare situations voltage escalation can occur, and IEEE C62.92.2 [11] presents a curve which shows the overvoltage as a function of the ratio between the capacitive reactance of the system (X_{CG}, relative to the capacitance of the three phases) and the grounding resistance of the neutral (R_N). According to the curve, the greater the ratio, that is, the greater the capacitances of the system in relation to the neutral resistance, the greater the transient overvoltage, and for a ratio of around 0.1, transient voltages from 4 to 5 times the rated phase-to-ground voltage may occur. Additionally, if the ratio is greater than or equal to 1, which means neutral resistance equal to the total capacitance, overvoltage is maintained at approximately 2.6 pu, which represents less than 75% of the withstand voltage test value of rotating machines [15].

The criterion of keeping the neutral resistance less than the total capacitive impedance, in other words, the resistive current greater than the total capacitive component ($I_R \geq 3I_C$), is well stablished for high-resistance grounded systems, and in this case the grounding transformer has not significant influence. However, for large industrial power systems which have a high capacitive current component, grounding transformer parameters need to be considered, hence a new criterion has to be investigated to control the overvoltages in case of intermittent-ground faults.

III. Transient Model

To study the influence of the grounding transformer in the transient overvoltage a simulation model of a typical industrial system for simulating intermittent-ground faults is proposed in this section. The system under analysis can be seen in Fig. 6.

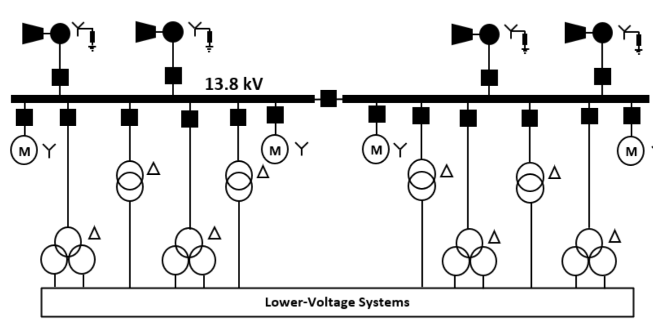

Fig. 6. Electrical system under analysis.

As can be seen in Fig. 6, the electrical system is composed of four main turbogenerators directly connected in the main switchgear, in 13.8 kV, and all of them are grounded by a resistor connected to the secondary of a grounding transformer. In the main switchgear there are several loads, which are motors and power transformers. Motors are star isolated connected and power transformers have always the primary connected in delta, which means that only the sources (generators) are grounded, and the grounding of the 13.8 kV system is segregated from the other lower-voltage systems, hence they can be disregarded by the transient model.

The choices of the models shall consider that the electromagnetic transients persist for some milliseconds and in this specific case zero sequence components are the focus. Therefore, the models can be substantially simpler than those used, for example, in electro-mechanical stability studies, especially for the rotating machines.

In addition, due to the high frequency characteristics of the electromagnetic transients and the nature of the events studies (single-phase fault to ground), it is necessary to consider the capacitances involved in the circuit, which are due to the surge capacitors and the stray capacitances of electrical equipment windings. The surge capacitances are installed at the rotating machines terminal boxes to reduce the overvoltages in the stator windings by increasing the rise time of an eventual transient surge that arrives at the machine line-end coils. The surge capacitors are chosen according to the rated voltage of the machine and for the voltage levels under consideration (13.8 kV) a value of 0.25 µF is used [2][16].

The simulations are performed in Alternative Transient Program (ATP) [17] and in the following subsections a quick explanation about the models used are presented.

A. *Generators*

A scheme of the model used for each generator can be seen in Fig. 7.

Each generator is modelled by an ideal and constant voltage source behind the zero-sequence impedance, that is, the zero-sequence reactance (x_o) and stator resistance (r_o). The mutual coupling of the generator's windings has not been considered, since, normally, these mutual values are not easily known and in high-impedance grounding systems the neutral impedance is much greater than the impedance of the generators.

The generator model considers that the voltage regulator does not respond as fast as the electromagnetic transient occurs. Moreover, the rotor is completely neglected due to the higher time constants of the mechanical system when compared with the electrical ones.

In the neutral of each generator a grounding component is placed, which has been modelled, by a resistance in series with an inductance as presented in Fig. 2. This model does not consider the grounding transformer capacitance and saturation, since they do not have significant influence on the transient overvoltages, because the capacitance of the grounding transformer is much less than those of other components and during a fault the grounding transformers will not operate under considerable saturation, because they are designed to have primary voltage equal to line-to-line voltage, as indicated in Table 1, and in a ground fault line-to-ground voltage will appear.

Finally, the capacitances, surge capacitors and typical stray capacitances of the windings have been considered according to [18].

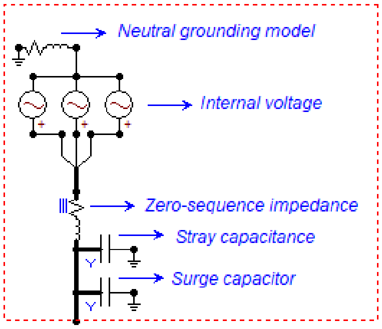

Fig. 7. Generator model.

B. *Motors*

Considering that the motors operate with an isolated neutral as indicated in Fig. 6, they were modelled only by the surge capacitances and stray capacitances of the stator windings as shown in Fig. 8, since the stator windings has no significant influence on the results.

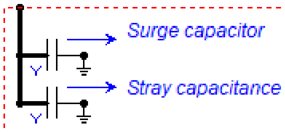

Fig. 8: Motor model.

The surge capacitors of 0.25 µF has been considered, and the parasitic capacitances were obtained based on factory acceptance test results and, when not available, typical values indicated in [18] were used.

C. *Power Transformers*

Power transformers are delta connected at the primary side as can be seen in Fig. 6. Therefore, no zero-impedance circuit has influence on the 13.8 kV grounding system. Thus, the model considers only the primary capacitance to ground of the transformer, as shown in Fig. 9. The stray capacitances of the power transformers have been considered according to [19].

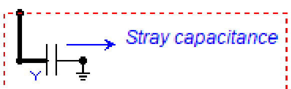

Fig. 9: Power transformer model.

D. *Cable*

To consider the high-frequency phenomena, the cables have been considered according to the Clarke model in ATP [17], which takes the travelling wave characteristic into account. The main parameters are the per unit length resistance, inductance and capacitance for positive and zero sequences, and the length as well. It is important to highlight that this model uses Clarke's transformation matrix, which decouples the three-phase cable into modes with constant surge impedance and travel time. However, this simple model has been chosen as a premise since the system used in this paper is an offshore platform with the ground return current done by the metallic structure of the vessel.

E. *Intermittent-Ground Fault*

In order to model the intermittent phase-to-ground short circuit, the scheme of Fig. 10 was considered. In the scheme the number of switches in parallel represents the quantity of subsequent ground faults contemplated and, therefore, in this case two faults were considered. This model is based on [3][20] and considers that once the arc ignition appears it is modelled by an ideal switch (electrical resistance equal do zero) and the quenching happens at the next zero high-frequency current (natural interruption).

Furthermore, a typical value a resistance in series with as inductance have been considered as the impedance of the fault, since this is the worst case for the overvoltages [2] and represents, for example an internal fault in motor. The values used in the simulations are $R_F = 1\,\Omega$ and $L_F = 5$ mH.

Still considering the scheme in Fig. 10, the phase-to-ground short circuit is initiated when the voltage in the faulted phase reaches the peak, then the first switch closes. Once initiated, the short circuit is extinguished when the ground fault current crosses zero (natural interruption) and therefore the first switch opens and clears the fault. Then, the short circuit starts again when the next peak (positive or negative) of the same faulted phase is reached, simulating a reignition. This process can be repeated several times, however, for this work only two subsequent faults were considered, as they proved to be enough to obtain the worst results.

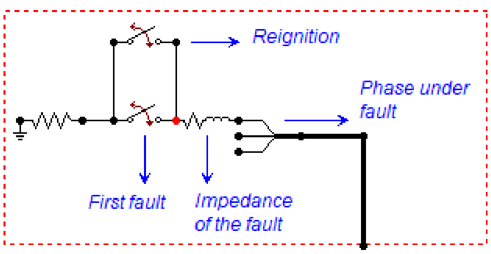

Fig. 10. Intermittent-ground fault model

The complete power system modelled and the parameters of the main components are presented in Appendix A.

F. *Comprehensive simulation results*

For a better understanding of the model, some comprehensive simulations have been performed considering the generators grounded by a pure resistor, since it is the case well-known and considered by the literature.

Simulations have been performed considering a single permanent fault and after an intermittent-ground fault. Some waveforms were presented to verify if the results are coherent.

The resistance of each generator is calculated to limit the neutral current at 24 A, which is enough to keep the total resistive current ($24 \times 4 = 96$ A) greater than the capacitive current (87 A). This capacitive current is related to the total capacitance of the system.

Fig. 11 shows the waveform of the ground-fault current with a permanent short-circuit in 13.8 kV panel. According to the figure, the ground-fault current has transient and steady state components, both of which depend on the equivalent zero sequence parameters. In the same figure, the steady-state interval of total ground-fault current waveform is shown, in which the peak value of 182 A is verified and refers to the vectorial sum of resistive component and the capacitive component.

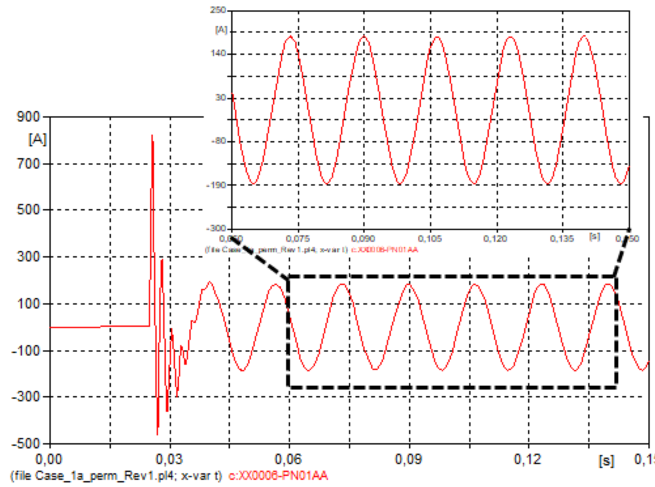

Fig. 11. Total current in a permanent-ground fault.

Regarding the voltages at main switchgear, according to Fig. 12, results are as expected, that is, the voltage at the phase under fault reduces to a value given by the product of the neutral current and the resistance of the grounding resistor, and the voltage at the non-faulted phases increases by square root of three.

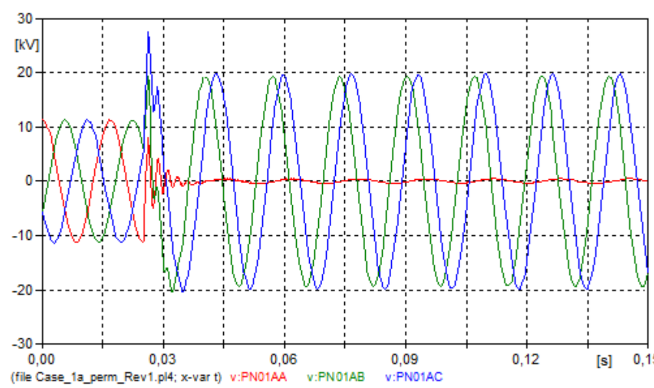

Fig. 12.: Voltages in main switchgear in a permanent ground fault.

In the case of an intermittent-ground fault, as can be seen in Fig. 13, once initiated, the short-circuit is eliminated when the current crosses the first zero. Subsequently, the fault is reignited when the voltage on the faulted phase crosses the maximum. This intermittence between fault elimination and reignition generates multiple transients that lead to high overvoltage values as indicated before.

In order to check the influence of the grounding resistor, simulations have been performed for many values of resistance. Fig. 14 shows the overvoltages obtained for many values of neutral resistance, including when the system operates ungrounded ($I_r/3I_C = 0$).

According to the results, the peak values are ranged from 2 to 4.5 pu, being the worse results when the ratio between the resistive and the total capacitive currents is lower, which shows the advantage of operating the system grounded and to follow the criteria of $I_r \geq 3I_C$.

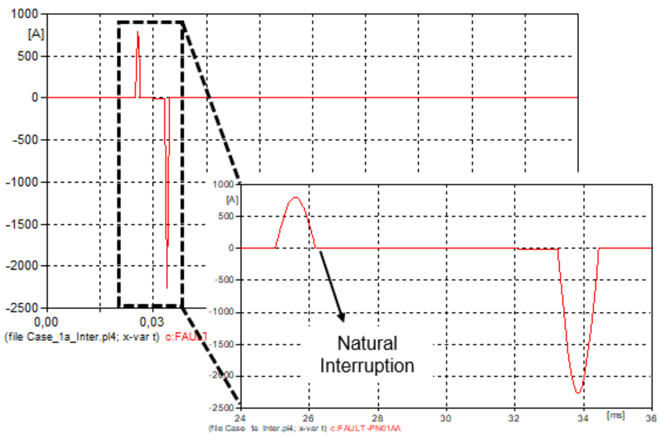

Fig. 13. Total current in an intermittent-ground fault.

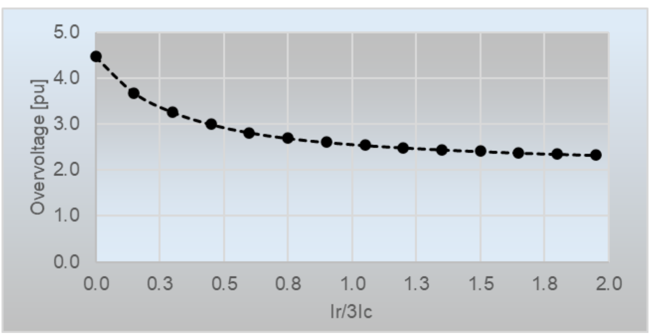

Fig. 14.: Overvoltage as a function of the ratio $I_r/3I_C$.

In addition, Fig. 15 and Fig. 16 show the waveforms of the voltages when the system operates ungrounded and with the grounded resistor set at 24 A in each neutral, respectively.

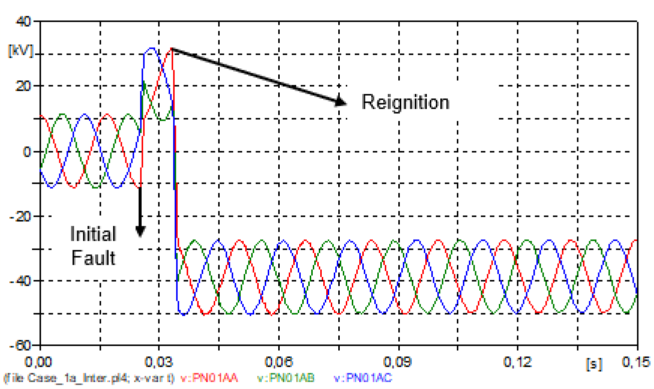

Fig. 15: Overvoltage when the system operates ungrounded.

According to the previous waveforms, the behaviour is different depending on whether the system is grounded or not. Overvoltage always occurs when the fault starts, however it ends quickly for cases which the grounding resistor is present. For the ungrounded system, the ground (reference voltage) is shifted with each new fault, resulting in voltage escalation and, consequently, in overvoltage. In addition to the high amplitude of the voltages in the three phases, the overvoltages have a significant "dc" component, which imposes difficulties for the correct measurement by potential transformers for fault elimination. Additionally, for both cases, grounded and ungrounded, the peak values are reached very quickly after the fault has occurred, that is, without the possibility of protection actuation.

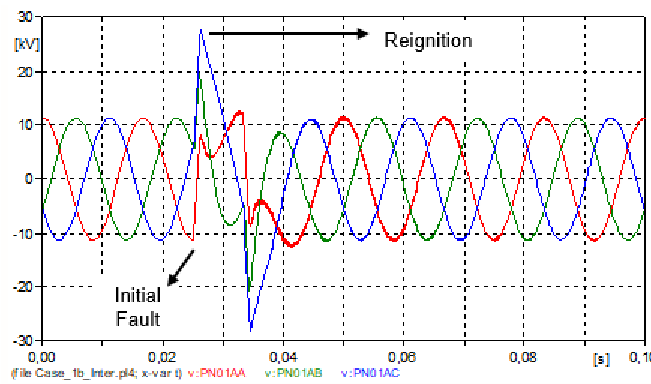

Fig. 16: Overvoltage when the system operates grounded and $I_r \geq 3I_C$.

Based on the results of curve shown in Fig. 14, the overvoltage obtained by the simulation model follow the behaviour indicated by IEEE C62.92.2 [11]. Therefore, the model can be considered suitable to study the overvoltage when a grounding transformer is used.

IV. GROUNDING SYSTEM SPECIFICATION

In this section many simulations are performed to verify the parameters which guide the transient overvoltage when the grounding transformer is used. The main objective is to define the criteria which shall be met to control the overvoltage in case of intermittent-ground faults. As explained before, the literature does not consider the grounding transformer parameters, however, as shown in the previous section they are important to control the total ground-fault current in systems which have a high capacitive current.

When a pure grounding resistor is used, the overvoltage is controlled by the ratio $I_r/3I_C$ (as shown in the last section), that is, to keep the overvoltage at safe levels, the resistive component of the current must be greater than the total capacitive current. In other words, the resistance of the resistor shall be less than the total capacitive impedance of the system. In a case where a grounding transformer is used, there is no reference in how the parameters affect the overvoltage. Therefore, in this section three different cases are considered to study which ratio controls the overvoltage:

1) Case 1: $I_r/3I_C$;
2) Case 2: $I_r/(3I_C - I_L)$;
3) Case 3: $I_n/3I_C$.

For all simulations the electrical system is not changed, therefore, the total capacitive current is kept constant ($3I_C = 87$ A). To change the abovementioned ratios, the equivalent grounding resistance and inductance must be adjusted to achieve the required variations. For the first two cases, the resistive component current must change for each neutral current and for the last case the neutral current is altered for each resistive current considered.

A. Case 1: $I_r/3I_C$

In this case, simulations are performed by changing the resistive component of the grounding current for different total neutral currents (60 A, 40 A and 20 A). For each simulation, the equivalent resistance and inductance of the grounding components are calculated to achieve the required resistive current component for each total neutral current. Fig. 17 shows the variation of the overvoltage as a function of the ratio $I_r/3I_C$. For a total neutral current of 20 A, due to the capacitive current being fixed, only, lower values of $I_r/3I_C$ are possible to be simulated.

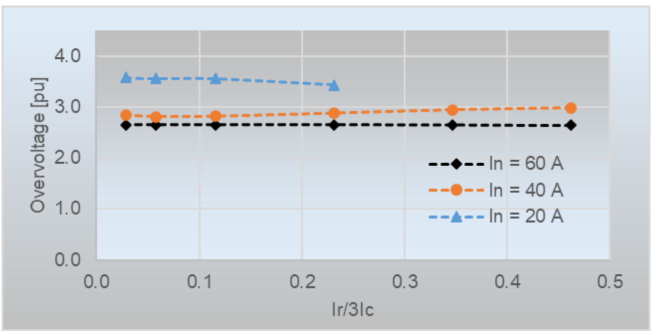

Fig. 17. Overvoltage as a function of $I_r/3I_C$.

As can be seen in Fig. 17, the ratio $I_r/3I_C$ does not have significant influence on the overvoltages, however for lower values of total neutral currents higher values of overvoltages has been observed.

B. Case 2: $I_r/(3I_C - I_L)$

Other simulations have been performed to verify the influence of the ratio between the resistive component and the equivalent reactive component. The same simulations of the previous case have been considered, however, in this case the ratio $I_r/(3I_C - I_L)$ is calculated for each required resistive current component. Results are presented in Fig. 18, and as for the previous case, for neutral current of 5 A, due to the capacitive current being fixed, only, lower values of $I_r/(3I_C - I_L)$ are possible to be simulated.

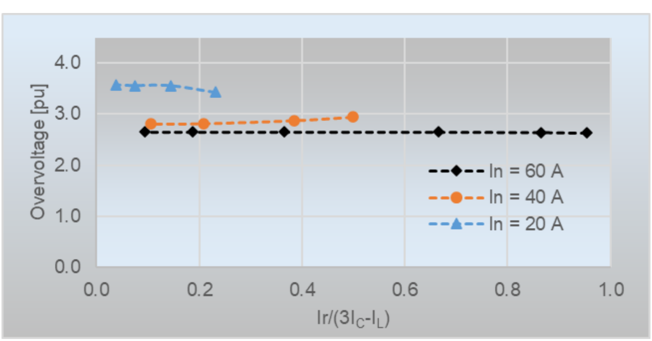

Fig. 18. Overvoltage as a function of $I_r/(3I_C - I_L)$.

According to the results indicated in Fig. 18, the $I_r/(3I_C\text{-}I_L)$ ratio does not have much influence on the overvoltages for all neutral currents simulated. In addition, as observed in the previous case, the neutral current affects the overvoltages.

C. Case 3: $I_n/3I_C$

In this last case, the ratio between the neutral current and the total capacitive current has been analysed. Simulations have been done for different $I_r/3I_C$ values (0.06, 0.12 and 0.46) for neutral currents from 10 A to 104 A. In this case, the resistive current component has been kept constant for each set of neutral currents considered, which is achieved by changing the equivalent resistance and inductance of the grounding components. Fig. 19 shows the results obtained.

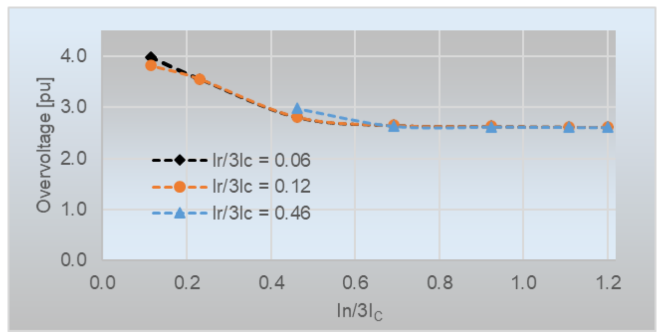

Fig. 19. Overvoltage as a function of $I_N/3I_C$.

In this case, as can be seen in Fig. 19, the overvoltages are greater for lower values $I_n/3I_C$. The behaviour of the curves is similar to that presented in [11] and in the last section of this paper. In addition, with these results it is possible to conclude that the reasons why the neutral current has affected the overvoltage in the previous two cases is that when the neutral current is reduced, the ratio $I_n/3I_C$ also reduces hence, greater values of overvoltages are observed.

Therefore, the criteria to specify the grounding system (grounding resistor and grounding transformer) is to keep the neutral current greater than or equal to the total capacitive current. This conclusion is different from when it is used a pure resistor, since in that case the ratio $I_r/3I_C$ controls the overvoltage instead of the ratio $I_n/3I_C$. If the ratio $I_r/3I_C$ is also considered as a criterion when a grounding transformer is used, the overvoltages will be controlled, however the neutral current will be greater than the necessary, hence the total ground-fault current will be also greater. Therefore, with this new criterion the total ground-fault current can be also optimized.

V. Conclusions

In this paper a model to study transient overvoltages due to intermittent-ground faults have been developed and presented in detail. The model is then used in an industrial power system to identify which parameters define the amplitude of the overvoltages in situations where a resistor is used at the secondary of a grounding transformer. In the literature, this transformer is neglected, and the analyses only considers the resistors, however, as also shown in this paper, the grounding transformer has a huge importance to limit the total-ground fault current.

Simulations have been done studying the influence of three main ratios: resistive component per total capacitive current; resistive component per total equivalent reactive current and neutral current per total capacitive component. According to the results, it can be concluded that the criteria to specify the grounding system (grounding resistor and grounding transformer) is to keep the neutral current greater than or equal to the total capacitive current. By respecting this criterion, the parameters of the grounding transformer (such as, impedance, X/R ratio and rated power) can be optimized to keep the possible overvoltages at safe levels.

VI. References

[1] L. A. F. Valle, “The use of the computer program ATP for studying electrical transients in industrial power systems”, International Conference on Power System Transients, Lisboa, 1995.

[2] D, Beeman, Industrial Power Systems Handbook, McGraw-Hill, New York, 1955.

[3] D. Braun and G. S. Koeppl, "Intermittent Line-to-Ground Faults in Generator Stator Windings and Consequences on Neutral Grounding," in *IEEE Transactions on Power Delivery*, vol. 25, no. 2, pp. 876-881, April 2010.

[4] N. El-Sherif and S. P. Kennedy, "A design guide to neutral grounding of industrial power systems," *2017 Petroleum and Chemical Industry Technical Conference (PCIC)*, 2017, pp. 151-162.

[5] J. Garcia, E. Robles, R. Campuzano and O. del Razo, "Series resonant overvoltages due to the neutral grounding scheme used in petrochemical power systems," *2008 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America*, 2008, pp. 1-6.

[6] Protection against Transient Overvoltages Caused by Intermittent Earth Faults in Unearthed Marine Power Distribution Networks," *2022 IEEE International Conference on Power Systems Technology (POWERCON)*, 2022, pp. 1-6.

[7] IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems," in IEEE Std 142-2007, vol., no., pp.1-225, 30 Nov. 2007.

[8] F. J. Angelini and D. D. Shipp, "Characteristics of different power systems neutral grounding techniques: fact and fiction," *[Proceedings] IEEE 1991 Annual Textile, Fiber and Film Industry Technical Conference*, 1991, pp. 8/1-810.

[9] D. Shipp *et al*., "Switching Transient Analysis and Specifications for Practical Hybrid High-Resistance Grounded Generator Applications—An IEEE/IAS Working Group Report #2," in *IEEE Transactions on Industry Applications*, vol. 48, no. 1, pp. 236-244, Jan.-Feb. 2012.

[10] G. Zhang, L. Gui, X. Wang, Q. Zhang, Y. He and C. Liu, "Experimental Study on Single-Phase Grounding Fault Safety Current of Large Generators," 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 2018, pp. 1-6.

[11] IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems, Part II--Synchronous Generator Systems," in IEEE Std C62.92.2-2017, vol., no., pp.1-38, 19 May 2017.

[12] D. Reimert, Protective Relaying for Power Generation Systems. 1st Edition, CRC Press, 2006.

[13] J. L., Blackburn, T. J., Domin, Protective Relaying – Principles and Applications. 4th Edition, Boca Raton, FL, CRC Press, 2014.

[14] Electric Transmission and Distribution Reference Book, 4th edition, East Pittsburgh, PA: Westinghouse Electric Corporation, 1964.

[15] IEC 60034-1:2010 Rotating electrical machines-Part 1: Rating and performance-Edition 12.0, International Electrotechnical Committee.

[16] R. L. Doughty and F. P. Heredos, “Cost-effective motor surge capability,” in IEEE Transactions on Industry Applications, vol. 33, no. 1, pp. 167-176, Jan.-Feb. 1997.

[17] ATP Instruction Manual – Rule Book.

[18] D. S. Baker, "Charging Current Data for Guesswork-Free Design of High-Resistance Grounded Systems," in IEEE Transactions on Industry Applications, vol. IA-15, no. 2, pp. 136-140, March 1979.

[19] IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (Brown Book)," in IEEE Std 399-1997, vol., no., pp.1-488, 31 Aug. 1998.

[20] M. S. Banjanin and M. S. Savić, "Experimental Registration and Numerical Simulation of the Transient Overvoltages Caused by Single Phase Intermittent Arc Earth Fault in 35 kV Network With Isolated Neutral," in *IEEE Transactions on Power Delivery*, vol. 37, no. 3, pp. 1795-1802, June 2022.