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Single Phase and Resonance Fault Analysis in Highly Resistive Grounding Power Systems in Underground Mining

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Abstract

The modeling and simulation of an underground mining power system with high-resistance grounding (tens of ohms) considering the distributed capacitance of the conductors is presented. The influence of grounding methods on fault currents in single-phase failure scenarios is verified. Voltage and current behavior are evaluated against single-phase failure events in both faulted, and non-faulted branches together with the evaluation of the incidence of protection coordination. The presence of line-to-line voltages in the non-faulted phases during fault events was evidenced. Finally, the frequency response of the network is obtained, from which the non-linear load connection constraints are established as speed inverters and soft-starters of typical use in mining

Keywords: Distributed capacitance, resonance frequency, longwall mining, grounding, sag.

INTRODUCTION

The mining industry plays an important role in the energy and economical sector in Colombia, where coal has a significant participation in the energy matrix and is exploited on small and large scale. Such operation is carried out in two modalities: Open-pit and underground. In the case of underground mining there are great research opportunities focused on trying to diminish the technological gap in the safety in the different stages of the productive process. Within the most relevant aspects is the safety link-up of these systems with electric energy and technical factors that require these environments [1] [2].

The particularities of power systems in mining lie in the operating organization, since there are systems with large radial structures with loads of more than 15000 HP (11190 kW). Because these operating systems are considered confined spaces with reduced ventilation and with the tendency to accumulate explosive gases [3], very wet spaces and great dust exposure, the instruments and equipment that are introduced into the process must comply with strict standards under normative restrictions. Mining equipment, in general, is mobile and motorized, and is powered through portable cables which must be part of an elaborate grounding system [4].

The operating voltage level in underground mines has been constantly growing in the last 15 years, from 1000 V AC up to 14400 V Ac. This increase in voltage has meant a growth close to 200% in production. The incorporation of these voltages is limited to the transport of electric power since it must be done with shielded cables with ethylene propylene rubber (EPR) insulation to guarantee the safety of the process. These cables require a rigorous insulation system and generate a significant level of capacitance in the order of 110 pF/ft. This capacitance, over long distances, causes a significant charge of currents during a grounding failure. Moreover, this capacitance, combined with an inadequate grounding design, makes the system experience undesirable characteristics, such as high failure currents which affect the useful life of the equipment and generate high risk scenarios such as susceptibility to the presence of electric arcs [5].

In this sense, it is necessary to consider the application of grounding methods by resistive impedances in the electric systems in mining because of the limitation of the fault current is necessary [6]. However, the inclusion of an impedance between a neutral point and the grounding of the systems has effects on the voltage and current behavior in the system before scenarios of single-phase failures [7]. Furthermore, it is necessary to consider the high capacitance of the cables which will have effects over the resonance of the systems and will affect the system's selectivity [5].

Section II presents the modeling of the case study of an electrical system. Then, sections III and IV evaluate the influence of the grounding methods and it presents the high resistance method. Sections V and VI expose the effects of voltage and current in the non-failed branches of the systems before a single-phase failure. Finally, section VI discusses the analysis of the frequency response and the identification of critical frequencies.

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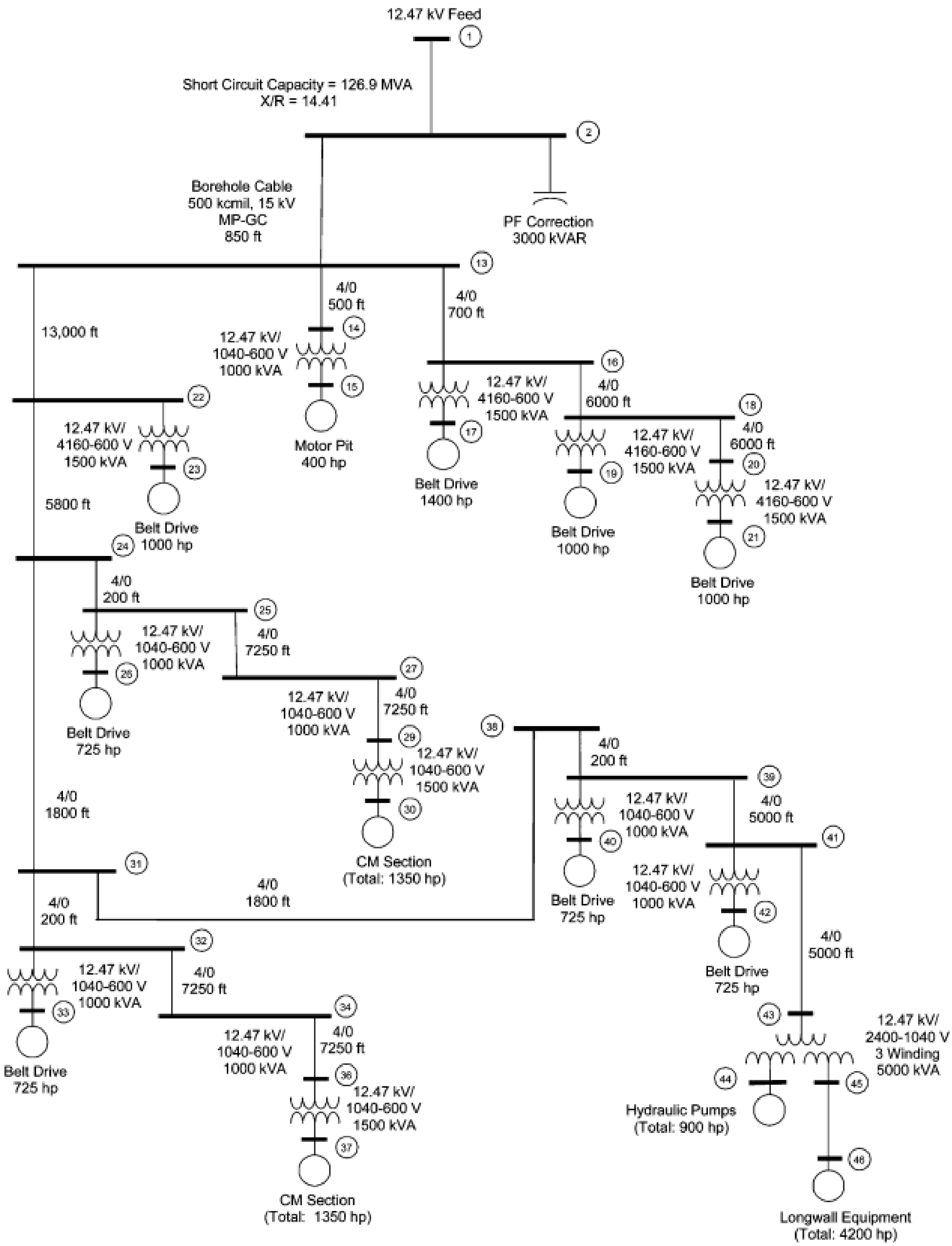

Figure 1. Electrical Power System-Underground Mining [8].

DESCRIPTION OF THE SYSTEM

The case study of evaluation of voltage fluctuations and resonance analysis consist of an electrical power system used in Longwall mining which is represented in [8]. This consists in a radial network fed with a voltage of 12.47kV taking care of the most significant loads whose total value is of 15500 HP. This load corresponds to conveyor belts, electrical pumps, and other power equipment. The single-line diagram is shown in figure 1.

The insulated conductors used in the electrical installation correspond to 500 kcmil caliber for the principal feeder and a 4/0 AWD caliber for the derived branches, which transmit power to the three-phase loads (motors) of the system which has local transformers which deliver power at a level between 600 and 1040 V.

*A. Modeling of the mining electrical system *

From the single-line diagram of the system, a modeling of the electrical components of the systems was made corresponding to the network equivalency, transformer, loads (motors) and conductors. The calculation of the parameters of each component was performed with the procedure as follows:

- *Network Equivalency*

From the short-circuit power of the system (S_{cc}), the X/R ratio (Reactance-Resistance) and the network voltage (V_{LL}), the equivalent is calculated according to equation (1)

$$Z = \frac{(V_{LL})^2}{S_{cc}} \tag{1}$$

Considering the X/R ratio of the system and the impedance triangle given by equation (2), the resistance parameters and network inductance are calculated.

$$Z = \sqrt{R^2 + X^2} \tag{2}$$

The values obtained for the resistance and inductance of the network are 84.9 mΩ and 3.24 mH, respectively.

- *Transformers*

The power of each transformer, the X/R ratio, and the impedance percentage are considered; the real impedance (Z) of the system is calculated using equation (3).

$$Z = (z\,\%) * \frac{(V_{LL})^2}{S_{transf}} \tag{3}$$

Where S_{transf} is the power of the transformer. With the results of (3) and by the X/R ratio and relationship (2), the transformer parameters are obtained. Assuming an X/R ratio of 4 and an impedance percentage of 5%, the results shown in table I are obtained for the respective power required.

Table I. Transformer parameters.

Power (kVA)	R (Ω)	L (mH)
1000	1.885	20
1500	1.257	13.3
5500	0.343	3.64

- *Motors*

In the calculation of the motor parameters, electrical power, efficiency, and power factor are considered. These are obtained with reference to the primary of the transformers (12.47kV). These calculations consider the relationships given by equation (4).

$$P_{elec} = \frac{P_{mec}}{\eta} \qquad P_{elec}\,(W) = \frac{1}{746} * P_{elec}(hp)$$

$$R = \frac{(V_{LL})^2}{3P_{elec}} \tag{4}$$

- *Conductors*

The parameters of the conductors are obtained from the manufacturer's data for the case of the resistance and inductance by unit length. In the case of capacitance, it is recurred to equation (5).

$$C = \frac{7.35\varepsilon}{log_{10}\left(1 + \frac{2t}{d}\right)} \left[\frac{pF}{ft}\right] \tag{5}$$

Where

Ɛ: Dielectric constant of the insulation;

T: Thickness of the conductor's insulation;

D: Lower diameter of the insulation;

Considering the data of the conductors with EPR insulation with dielectric constant of 3.2 and the data of the dimensions by the manufacturer, the parameters of the conductors in question are defined; these are calculated with units of the International System of Units (SI) and are presented in table II.

Table II. Conductor parameters.

Caliber of the conductor	Resistance (Ω/m)	Inductance (mH/m)	Capacitance (uF/m)
500 kcmil	88.58e-6	101.5e-6	498.69e-6
4/0 AWG	206.69e-6	114.8e-6	358.92e-6

The calculation procedure is done for the entire system and the implementation is done in ATPDraw. Figure 2 illustrates the structure of one the branch circuits of the system.

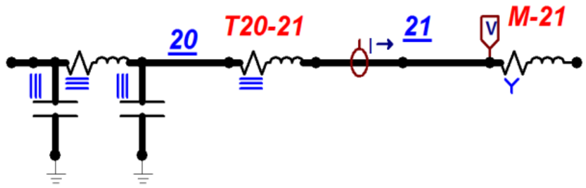

Figure 2. Branch Modeling – ATPDraw.

Figure 2 shows the Pi model of the conductor. Next, the equivalent transformed is observed. Finally, the modeled motor is shown as a three-phase load star connected.

CHARACTERIZATION OF THE GROUNDING METHOD

Because of the implied safety characteristics of having electrical equipment in confined spaces, all implemented systems are required to have a high security. In the case of underground mining systems, the fault current, electric arc, electric chock, and mechanical oscillation control is required. With these considerations in underground mining, a ground connection of high resistance is required. This grounding method is established by the insertion of a resistance between the neutral and the ground. The objective of the grounding method is to limit the fault current to the ground, which implies a reduction of the associated costs in the protection of the system in addition to improving the safety [9]. However, this method implies a compromise between the systems without a grounding connection and with solid grounding, because a flaw in the design implies that the system experiences characteristics of ungrounded systems [10].

To characterize the fault currents of the test circuit of figure 1, a free grounding fault was made between the line 13-14. The fault time is fixed at 2 ms after initializing the simulation to compare the pre-fault results. The fault is repeated for different resistance values of grounding. Figure 3 shows the obtained result for different values of grounding resistance, varying from 0.5 Ω to 100 Ω. The results show that as the grounding resistance increases, the fault current is reduced in magnitude without a variation of in phase.

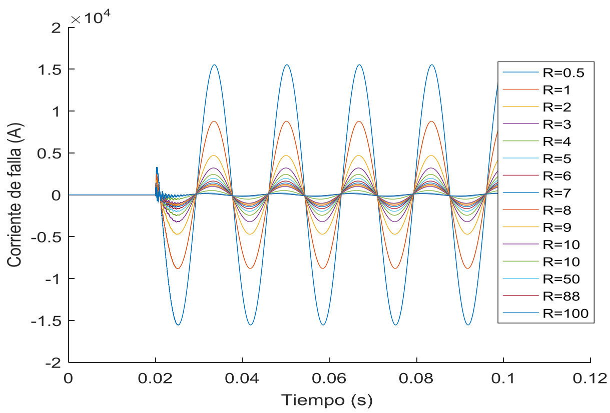

Figure 3. Fault currents in time

To make a better characterization of the fault current with respect to the grounding resistance, a graph is shown in figure 4 is made. There, the values of the RMS fault current are shown for different values of resistance, which were taken from the graphs of each of the current waves in figure 3. The tendency shown by the graph determines that for values close to zero in the grounding resistance, the values of the fault current increase considerably. This is because the system behaves as a system directly connected to the ground.

The problems associated for having elevated currents have led to research which seeks to mitigate this phenomenon because the high currents in mining pose a potential danger for safety. In [9] a grounding methodology is proposed for underground mining systems where, in addition to verifying the fault current, an emphasis in the distributed capacitance of the system and its effects on grounding is made.

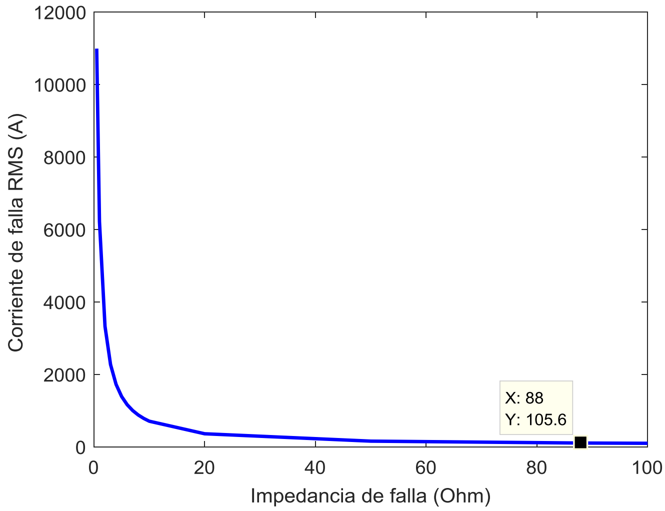

Figure 4. Relation between resistance versus fault current

HIGHLY RESISTIVE GROUNDING METHOD

The high-resistance grounding method is required in underground mining because it limits the quantity of dissipated energy and controls the elevation of potential on the phases during failure [11-12]; a high-resistance grounding system is defined as a system in which $R_0 \leq X_c$, where R_0 is the zero-sequence resistance by phase of the system and Xc is the distributed capacitive reactance of the system.

In the practical mining systems, the zero-sequence resistance is dominated by the grounding resistance since a high resistance grounded system requires $R_N \leq \frac{1}{3}X_c$, where R_N is the value of grounding resistance. In the cases where the high resistance grounding definition is not met, that means that $R_N > \frac{1}{3}Xc$ flows with more current through the distributed capacitance of the system than through the ground resistance, and the system begins to acquire the characteristics of a systems without a ground connection [12], [13].

The recommended value for the resistance must be selected in such a way that it satisfies equation 6.

$$R_N = \frac{|X_{c0}|}{3(S)} \qquad (6)$$

Where $|X_{c0}|$ is the magnitud of the reactve capacitance distributed by phase of the system and S is a safety factor to allow for the expansion of the shielded cables of the system.

The selection of the safety value is discussed in [10]. In general, a value of 1.25 is selected.

The capacitive reactance is determined by the length of the shielded cables of the system. According to figure 1, there are 259.08 m of cable with a caliber of 500kcmil MP-GC and 22920.96 m of cable with a caliber of 4/0 MP-GC. Using the data from table 1, the capacitance and reactance are estimated using the following calculation:

$$C = (259.08 * 498.69 \times 10^{-6}) + (22920.96 * 358.92 \times 10^{-6})$$

$$C = 8.36\ \mu F$$

$$|X_{c0}| = \left|\frac{-1}{\omega C}\right| = \frac{-1}{2\pi * 60 * 8.36 \times 10^{-6}} = 317.3\ \Omega$$

With a safety factor of 1.20, the resistance is given by:

$$R_N = \frac{317.3}{3(1.20)} \approx 88\ \Omega$$

A. Verification of the grounding method

One of the objectives of the grounding method consist in limiting the fault current. According to the results obtained in figure 1, as the grounding resistance increases, there is a decrease in the fault current [14]. The theoretical estimation of the fault current can be calculated using equation 7.

$$I_F \approx \frac{V_{LL}}{\sqrt{3} \times \left[\frac{1}{\mathrm{R_N}} + \frac{1}{\frac{jX_{C0}}{3}}\right]^{-1}} \qquad (7)$$

The current of the grounding resistance can be estimated using equation 8.

$$|I_N| = \frac{V_{LN}}{R_N} \qquad (8)$$

Applying equations 7 and 8 to find the fault current and the grounding resistance of the circuit of figure 1, we obtain:

$$I_F \approx \frac{12470}{\sqrt{3} \times \left[\frac{1}{88} + \frac{1}{\frac{j317.3}{3}}\right]^{-1}} \approx 106.4\ A$$

$$|I_N| = \frac{12470}{\sqrt{3} * 88} = 82\ A$$

To validate the theoretical results, a simulation of the model in ATPdraw is made by making a fault-free grounding in the line 13-14. The obtained results are shown in figure 5. A post-fault analysis is made with purpose of eliminating possible numerical noise that may be present at the moment of failure. A peak value of 149.2 A for the fault current and a peak value of 113A for the ground current is obtained. Converting these values into RMS, similar values are obtained for the equations; thus, validating the model developed for such implementation.

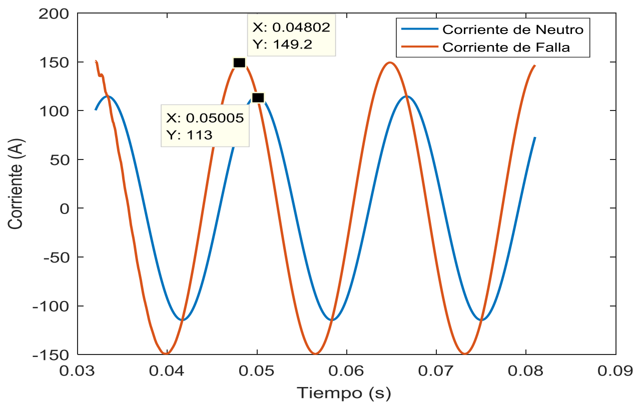

Figure 5. Neutral and fault currents

VOLTAGE FLUCTUATIONS

The implementation of a grounding method through an impedance offers advantages in terms of limiting the fault current in an electrical system, which reduces the risk of the presence of an electric arc and affectation of equipment and people [6]. Nevertheless, is it necessary to consider the implications for fault events that have an impedance between the neutral points and the ground points of the system. Since the electrical installations in mining require limiting the fault current, it is convenient to evaluate the effects on the voltage during the single-phase failure scenario.

To evidence the effects of the grounding method, the behavior of the voltage of the electrical system is verified with the presence and absence of the impedance of the grounding considering single-phase failure [15-16].

B. System directly grounded.

In the first case, a single-phase fault is simulated in the 13-14 conductor. Voltages are registered in the PCC, which correspond to node 2. Figure 6 shows the voltage behavior obtained in the time domain.

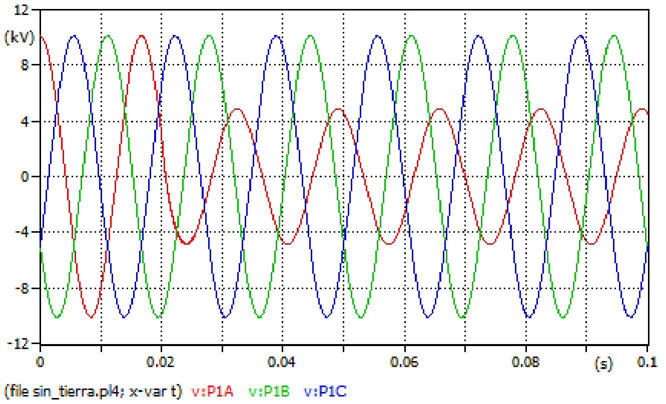

Figure 6. Voltages in the PCC before a single-phase failure 13-14 directly grounded.

A reduction in voltage in the fault phase and a minimal affectation in non-faulted the phases is observed. However, to observe the behavior of the phase angle, the respective voltage phasors are obtained and are shown in figure 7.

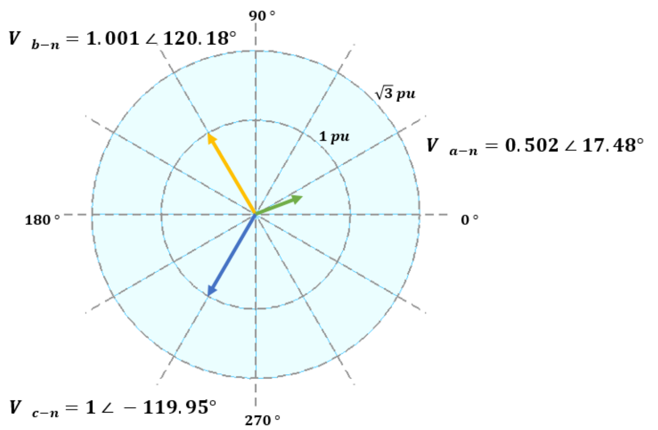

Figure 7. Voltage phasors in the PCC – single-phase fault 13-14 directly grounded

Figure 7 clearly shows the non-affectation in the voltage phasors in both magnitude and angle in the non-faulted phases while the faulted phase shows a reduction in both magnitude and a variation in the phase angle. Thus, it is concluded that a single-phase fault does not affect the voltages in the non-faulted phases with he directly grounded grounding method.

C. Grounded system by resistive impedance

On the other hand, the grounding method with purely resistive impedance is implemented with the suggested value in the high resistance method evaluated in section IV; such value corresponds to 88 Ω. The results of the voltage in the temporal regime are shown in figure 8.

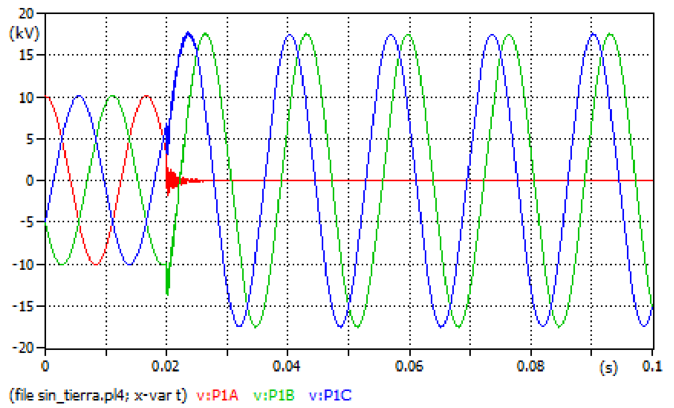

Figure 8. Voltages in the PCC before a single-phase fault 13-14 with impedance of resistive grounding of 88 Ω.

In this case, it is observed an affectation in the voltage of the three phases getting a sag to zero in the faulted phase and a swell in the non-faulted phases. The voltage behavior in the frequency domain is shown in figure 9.

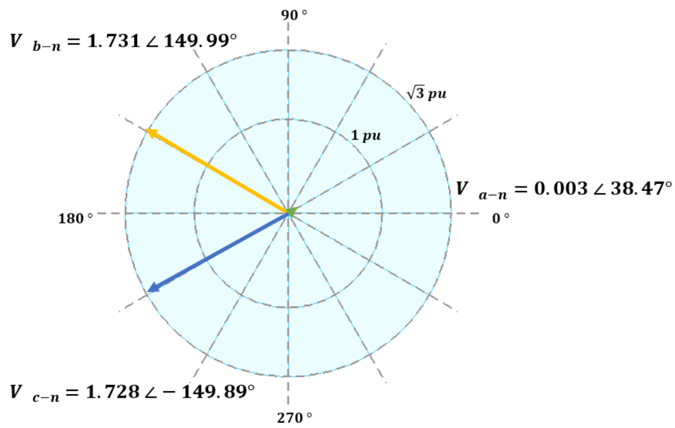

Figure 9. Voltage phasor in the PCC- single-phase fault 13-14 with resistive grounding of 88 Ω.

According to the results, it can be shown that the grounding method, in addition of presenting effects over the fault current, also has an influence on the non-faulted phases where voltage increases until reaching the line-to-line value of the system and presents an approximation among the voltage phasors. This phenomenon generates risky situations since the voltage equipment suffers a voltage swell of significant levels to failure events in the adjacent circuits.

Simulations with single-phase faults were made in different parts of the system and it was found that, in most cases, the phasors presented magnitudes close to the line-to-line voltage with reduced phase jumps. For the case of the faulted phase, the depth depended on the impedance between the fault point and the PCC, having a larger reduction in the fault points near the PCC [6]. On the other hand, it was observed that the magnitude of the impedance of the resistive grounding has little influence on the behavior of the voltages.

INFLUENCE OF THE CAPACITANCE IN THE NON-FAULTED BRANCHES.

To verify the influence of the distributed capacitance of the cables in the non-faulted branches, the system is modeled ignoring the capacitance of the cables. A fault is made, and its influence is verified on the behavior of the current in the non-faulted branches. Similarly, it is done considering the nominal capacitance of the conductors. This procedure was made in different lines, obtaining, as a result, that the influence of the capacitance in the cables creates a transitory state, which elevates the current in the lines. Moreover, in the post-fault state, the currents in the lines present a fluctuation in their magnitude. As an example, figure 10 shows the result of the line currents obtained in the branch 13-22. For a fault in 13-14, the figure shows a reduction in the line c current and a transitory state that augments the magnitude of the currents in lines b and c.

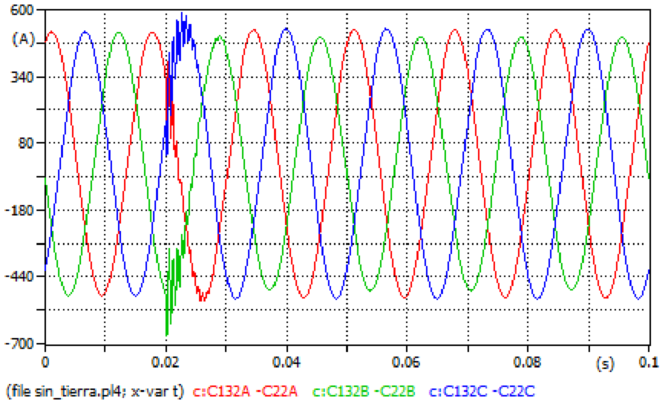

Figure 10. Currents in line 13-22

FRECUENCY RESPONSE OF THE SYSTEM

The electrical system applied in mining has a high capacitive component associated with the distributed capacitance of the shielded components commonly used. Considering the capacitive effect along with the inductive component of the loads, which in most cases corresponds to induction motors, the system eventually may present conditions of resonance [11].

For this reason, it results adequate to make a study of the frequency response that allows to identify the critical frequencies of resonance of the electrical system [17]. This way, it is possible to establish non-linear load connection restrictions as frequency inverters which may contain harmonics of critical frequencies in which case filtering of such harmonic is needed.

To identify the resonance frequencies, a frequency sweep of the is made by connecting a source of current in the different branch circuits of the systems. The results of the frequency sweep are shown in figure 11.

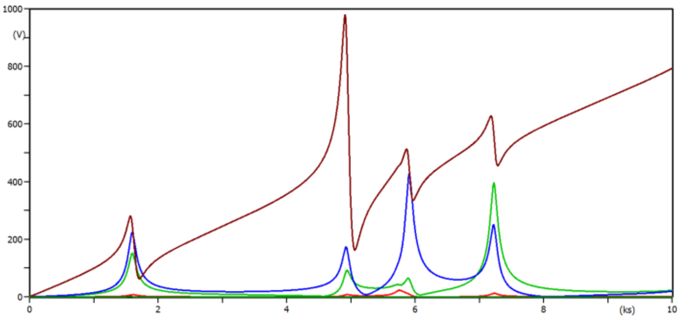

Figure 11. Frequency response of the electrical system.

From figure 11, the critical frequencies corresponding to 1581, 4916, 5981 y 7206 Hz are obtained. However, these frequencies correspond to the harmonics of order 26, 81, 99 y 120. Because the resonant frequencies correspond to the harmonics of high orders, it is concluded that system has no restrictions on the non-linear load connections whether it is 6, 12, or more pulses.

CONCLUSIONS

- As evidenced by the introduction, a grounding method in long-cut mining circuits limits the fault current, which reduces the risk of generating electric arcs or sparks in case of electrical failure that may risk the integrity of equipment and people. Because of the technical and safety restrictions present in the mining electrical installations, it is necessary to implement this grounding method.
- The grounding method favors the limitation of fault current. However, it results convenient to consider the voltage behavior during the fault events since the inclusion of an impedance between the neutral point and the ground originates the presence of voltages of line-to-line magnitude in each of the non-faulted phases as evidenced by the performed simulations. For this reason, it is recommended to consider the inclusion of voltage regulation and surge suppression devices in the electrical systems applied in mining.
- According to the simulations performed, the behavior of the voltage during the single-phase faults, as observed, results slightly influenced both by the capacitances, and the grounding resistance magnitude, because, when varying these parameters, the response is similar except for values of reduced resistance where the system tends to behave as directly grounded.
- To guarantee the good design of the high-resistance grounding method, the distributed capacitance of the entire system must be considered. This phenomenon is markedly seen in underground mining where the usage of shielded cables augments the capacitance. The poor design of this type of systems can lead the faulted system to

experience characteristics of a system without grounding.

- Analyzing the influence of the capacitance in the single-phase fault, it can be evidenced that the current in the non-faulted branches is altered by the capacitance, establishing a transient after the occurring fault where it augments the magnitude of the current in the lines that are not failing. After the transient, there is a fluctuation in the magnitudes of currents. These characteristics must be considered in the protections because this type of phenomena can cause a selectivity loss.

- Because the applied electrical system in mining includes a capacitive component associated with the distributed capacitance and has a significant inductive component related with highly inductive charges, it results convenient to evaluate the frequency response in the frequency of the system. However, according to the obtained results, the resonant frequencies correspond to high order harmonics, a reason for which it can be concluded that the system has no restrictions to incorporate non-linear loads of 6, 12, or more pulses since their associated harmonics do not represent a risk by resonance in the presence of voltage peaks.

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