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Novel Approach to Validate the Behavior of Current Flows in Power Systems with High Impedance Grounding Methods

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Abstract: This study studies the direction of fault current flow in power systems with the High Impedance Grounding method (HRG). The direction of the current was validated by two methods, the first was to process the signals over time, applying the Fourier transformation to determine the magnitude and phase of each of the signals. The second method analyzes the system in symmetrical components, determining the equations of voltages and currents. The two methods are represented in data diagrams to analyze and compare the results in detail. Finally, it clarifies the confusion that exists in the literature about the direction of the fault current, the appropriate interpretation mode can better adjust the parameters of the programming of the direction of the current. In addition, a way of graphing the limits is proposed to allow a real representation of the currents of the electrical system.

INTRODUCTION

Associated with high ground fault currents in industrial systems result in risks to both people and equipment.

Events such as the electric arc and its associated effects are linked to the magnitude of the ground fault current for this reason, industries such as mining, petrochemicals, refineries, food processors and paper have adopted the method of high impedance grounding either by resistance (HRG) or inductance, in order to reduce the magnitude of the fault current and thus mitigate possible risks[1].

A high impedance system is defined as one in which during a phase-to-ground fault event, the current flow through the grounding method is equal to or slightly greater than the capacitive current of the system[2]. This condition is achieved by inserting resistors and/or inductors between the neutral point and ground, their design must be in accordance with the distributed capacitance of the system.

The Petersen coil is a special case of high impedance grounding, the inductive reactance is made nominally equal to the capacitive reactance of the system, so that, when a ground fault occurs the two currents are annulled approaching a near zero fault current[3]. The difficulty of this method lies in accurately determining the distributed capacitance of the system[4].

The implementation of high impedance systems as a neutral grounding method in industrial systems is increasingly frequent due to the benefits described in[2]. The safety in operation is a determining factor for the use of this type of systems, the reduction of fires, mergers of equipment and electric shocks to people are some benefits. In operational terms, the system reduces stress in circuits that carry fault currents, avoids service interruptions in the event of the first ground fault, controls transient overvoltages and decreases the probability of arcing.

The use of this type of systems was limited by the detection of faults in the system, limiting the fault current makes detection difficult with conventional methods. With the proliferation of ground fault protection relays with more sensitive microprocessors capable of detecting very low ground fault currents[5] as well as the continuous monitoring of the grounding impedance, led to an increase in the application of this type of systems in the industry[6].

Conventional ground fault current detection systems use magnitude as the main operating parameter. Currently, modern ground fault protection relays incorporate phasorial measurements and direction of current flow[7]. Therefore, it is important to study these parameters which must be clearly understood for proper programming of equipment and thus ensure proper performance of power systems.

This study seeks to validate the direction of fault current flow as well as the phasor diagrams associated with power systems with high impedance grounding methods. A theoretical analysis is performed using symmetrical components of the system and then a computational validation by signal processing. In the first part of the article a review of the concept of capacitive current is carried out, together with the study of the main phasorial diagrams reported in the literature. After developing two methods to validate the direction of the fault current, the first incorporating symmetrical components and the second makes use of signal processing.

MATERIALS AND METHODS

Conventionally in solidly grounded systems the fault current is given by the current circulating through the system neutral (In). However, in high impedance grounded systems the concept extends to the inclusion of capacitive current which brings a component to the fault current. This is because the systems are coupled to ground through the distributed capacitance of the system[8].

In a solidly grounded system the capacitive current of the system is very low compared to the fault current. However, by limiting the fault current by inserting a grounding method, the capacitive current of the system becomes relevant because the magnitude of this current is comparable to the current flowing by the grounding method, even higher on occasions where the design of the grounding method underestimates the capacitive reactance of the system.

Under normal operating conditions in a balanced power system, the sum of the capacitive currents is zero, therefore no current flows to Earth (Fig. 1). In the event of ground fault conditions, a capacitive current flow is presented by the non-faulted phases that are added with the current flowing by the grounding method, producing a total fault current whose direction is given by the vector sum of these two currents.

Background: There is some confusion in the literature about the actual direction of flow of the ground fault current as well as the phase diagram representing that current. In this section are reviewed some studies whose way of expressing current flows are different from each other. Based on the interpretation of the phase diagram, the adjustment of the directional relays will allow suitable protection of the system or otherwise, wrong operation.

Figure 2 is a replicate of[9] in which the author makes a representation of the capacitive and resistive current flows from the fault to the source. The phasorial representation of the system shows the capacitive currents (Ic and Ib) of the non-faulted phases in advance with their respective voltages, the resistive current is in phase with the faulted phase, while the ground fault current (IG) is given by the vectorial sum of these phasors. Taking as reference the resistive current (IR), it is determined that the fault current is in delay. This same representation is shown in[10-13].

Figure 3 is a replicate of[14] where the author makes a representation of the capacitive and resistive current flows from the source to the ground, the flow goes through the ground until it finds the point of failure where the sum of these currents is produced. The Earth fault current (IG) in the phasorial representation is given by the sum of the capacitive and resistive current. The direction of the resistive current is in the opposite direction to that of the faulted line voltage, so, the direction of the fault current is in advance with respect to the resistive current, opposite to the representation shown in Fig. 2.

Figure 4 is a replicate of[14], the researcher makes a consideration by industrial convention with respect to the flow of the capacitive current which proposes that the direction of this current is in opposite direction to the load current of the system, so, the flow is in the direction of failure to the source. One consideration is that the fault current (IGF) is in the opposite direction of the capacitive current, so, the vector sum is made with-IC. In this way, it has that the fault current is in advance with respect to the resistive current.

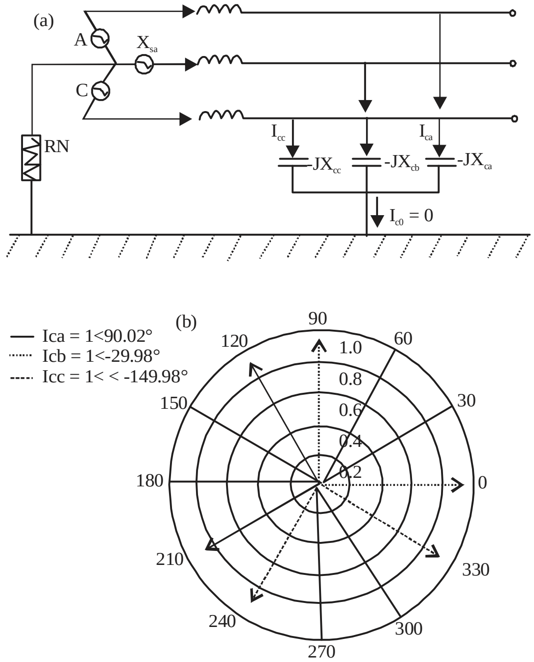

Fig. 1(a, b): (a) Balanced power system under normal operating conditions and (b) Phasorial system diagram

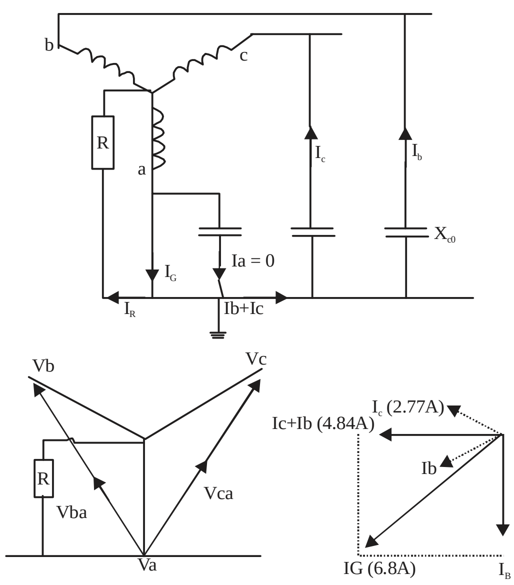

Fig. 2: Power system with HRG grounding and phasorial diagram

Figure 5 is a replicate of Weddy *et al*.[15], corresponding to a power system with Petersen coil grounding method, tuned to the capacitive reactance of the system, so that, the fault current is eliminated. The researcher proposes a phase-to-ground current flow, so that, the current flows to the fault point where the sum of the capacitive current and inductance is made. These

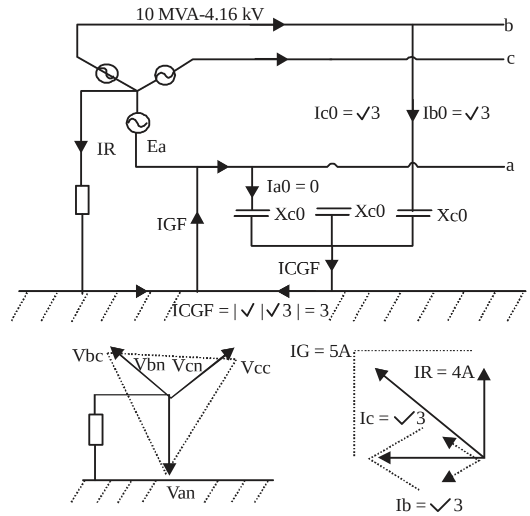

Fig. 3: Power system with HRG grounding and phasorial diagram

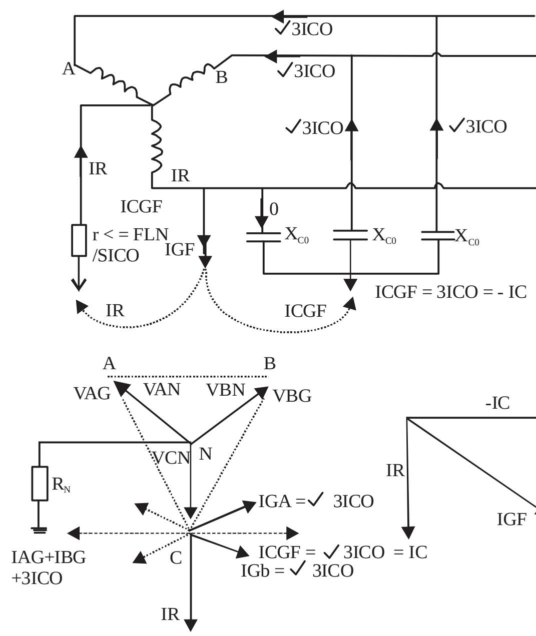

Fig. 4: Power system with HRG grounding and phasorial diagram

currents are by nature in opposite directions, resulting in the suppression of the fault current. In this case the phasor diagram shows a flow of capacitive current in the direction of the load current of the system.

Validation of current flow direction and phasorial diagrams: The test model to validate the direction of current flow was taken from Zhang[16] which characterizes a power system used in underground mining applications, the model recreates the distributed capacitance in the cables in feeder 3.

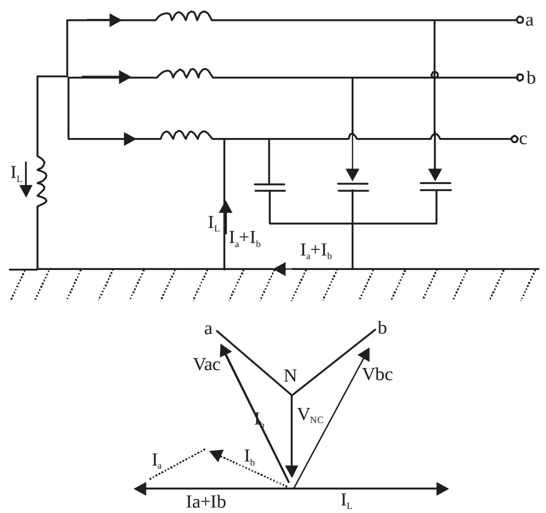

Fig. 5: Power system with Petersen coil grounding and phasorial diagram

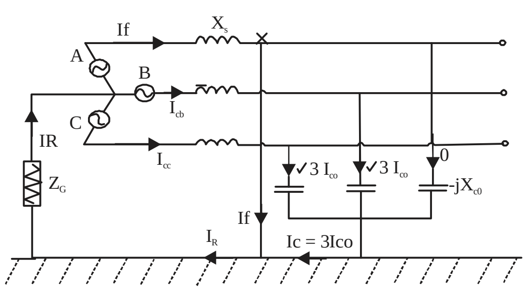

Fig. 6: Phase a faulted power system

The power system simulating a phase A fault is shown in Fig. 6. The current meters are located in the direction of the arrows which represent the direction of current flow. The grounding method will be replaced in each case by the resistance and inductance value. The values applied per phase are taken from Weedy *et al.*[15] are E_G = 12.47KV, C_Φ = 1.64 μF, L_Φ = 1.39 mF.

Two high impedance grounding methods are analyzed. The first with resistance and the second by inductance. Equation 1 describes the design condition for the grounding resistance of the neutral:

$$R_N = \frac{|X_c|}{3} \quad (1)$$

Where:
X_C = The capacitive reactance of the power system
R_N = The grounding resistor. This way it has

$$R_N = \frac{\left|\frac{1}{\omega C_\varphi}\right|}{3} = \frac{\left|\frac{1}{2*\pi*606164\mu F}\right|}{3} = 539.143\Omega$$

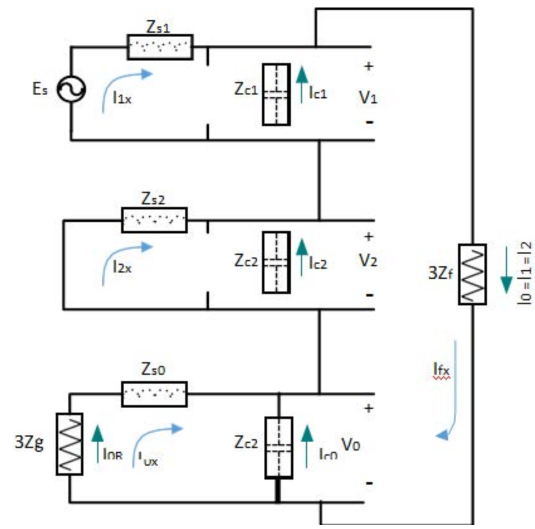

Fig. 7: Sequence diagram of power system in Fig. 6

To tune the Peterson coil as a grounding method in such a way that the fault current is eliminated, the current flowing by the grounding method must be equal to the capacitive current. This is obtained with Eq. 2. (Fig. 7)

$$L = \frac{\left|\frac{X_{c\varphi}}{3}\right|}{\omega} \quad (2)$$

With:

$$X_c = \frac{1}{\omega C_\varphi} = 1617.43\Omega$$

Therefore:

$$L = \frac{\left|\frac{1617.43}{3}\right|}{2*\pi*60} = 1.43 \text{ H}$$

Applying Kirchhoff's laws for the failure node it is obtained Eq. 3:

$$I_R = I_F + I_c \quad (3)$$

Symmetrical component method : In order to validate the behavior of the power system during ground fault conditions, the concept developed by Fortescue[17] is applied. The method known as symmetric components assumes that the entire circuit is asymmetric in such a way that it can be expressed in three symmetric systems, as shown in Fig. 7.

Using symmetrical components in the analysis of the direction of current flows, allows to validate this concept in a theoretical way, finding magnitudes and phases of voltage and current phasors which led to phasorial diagrams are compared with the results found by means of signal processing.

The system in Fig. 7 assigns a sub-index of 1 for the positive sequence variables, 2 for negative and 0 for zero. For this analysis no mutual effects between phases are considered, therefore, the values of capacitive and reactive impedance are equal in each sequence.

To find the sequence current and voltage values from Fig. 7 an analysis by the mesh current method is posed. In such a way that it allows the solution of Eq. 4:

$$A_x = b \Rightarrow x = A^{-1}b \tag{4}$$

Where the vector x represents the mesh currents:

$$x = \left[I_{1x}\ I_{2x}\ I_{0x}\ I_{fx}\right]^T$$

Matrix A is given by the impedances of each mesh:

$$A = \begin{bmatrix} z_{s1}+z_{ci} & 0 & 0 & -Z_{c1} \\ 0 & z_{s2}+z_{c2} & 0 & -Z_{c2} \\ 0 & 0 & 3Z_g+Z_{s0}+Z_{c0} & Z_{c0} \\ -z_{c1} & -z_{c2} & -Z_{c0} & Z_{c1}+Z_{c2}+Z_{c0}+3Z_f \end{bmatrix}$$

Finally, b represents the sources of the system in each of the meshes:

$$b = \left[E_s\ \ 0\ \ 0\ \ 0\right]^T$$

To find the sequence voltages and capacitive currents Eq. 5-7 are considered:

$$V_1 = \left(I_{1x}\text{-}I_{fx}\right)Z_{c1} = I_{c1}\,Z_{c1} \tag{5}$$

$$V_2 = \left(I_{2x}\text{-}I_{fx}\right)Z_{c2} = I_{c2}\,Z_{c2} \tag{6}$$

$$V_0 = \left(I_{0x}\text{-}I_{fx}\right)Z_{02} = I_{c0}\,Z_{c0} \tag{7}$$

The rotation operator α is defined as:

$$\alpha = -\frac{1}{2}+j\sqrt{\frac{3}{2}}$$

With the rotation operator α the direct transfer matrix is raised which allows the transformation between sequence and phase, both for voltages and currents as shown in Eq. 8:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} I_{ca} \\ I_{cb} \\ I_{cc} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} I_{c0} \\ I_{c1} \\ I_{c2} \end{bmatrix}$$

The numerical values are evaluated in the developed equations in such a way that it allows to find the values of magnitude and phase of each phasor with these values a representation is made in phasorial diagrams for the methods of grounding of resistance and inductance with Petersen coil.

Grounding resistance: The value of Z_g is made equal to and the algorithm developed for symmetric components is executed. Figure 8 shows the phasorial representation of the currents and voltages of the power system. It shows a capacitive current in the opposite direction to the fault current, in the same way it shows a fault-current phasor in advance with respect to the current flowing by the grounding (IR) method.

Grounding inductance: In this case Z_g is made equal to and the algorithm of symmetric components is executed. The results in the phasor diagram are shown in Fig. 9. Voltage magnitudes and capacitive currents increase to line-to-line values with a phase angle of 60° between their respective variables. In addition, the diagram shows the elimination of fault current due to the action of the Peterson coil.

Signal processing method: In the case of validation of the direction of the current flows of the power system in Fig. 6, it is necessary to perform time measurements of the currents and voltages using signal processing. For this purpose, the ATPDraw[18] circuit was implemented from where these signals are extracted, simulating fault events. The signals in time are exported to MATLAB where a Fast Fourier Transform (FFT) is applied, so that, the magnitude and phase values of each current and voltage can be quantified at the fundamental frequency. From these values the representation is made in a phasorial diagram[19]. This method also makes it possible to locate the direction of measurement of the CTs in order to obtain results in accordance with the method of symmetrical components (Fig. 8-10).

Grounding resistance: Measurements of capacitive, fault and resistive currents are taken from Fig. 6. In the studied case of high resistance Earthing method Z_G is taken with an equal value R_N.

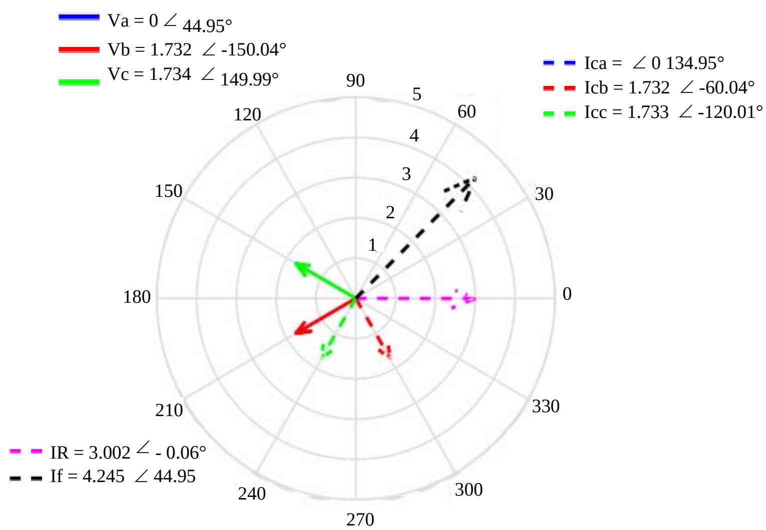

Fig. 8: Phasorial diagram of the power system with HRG grounding

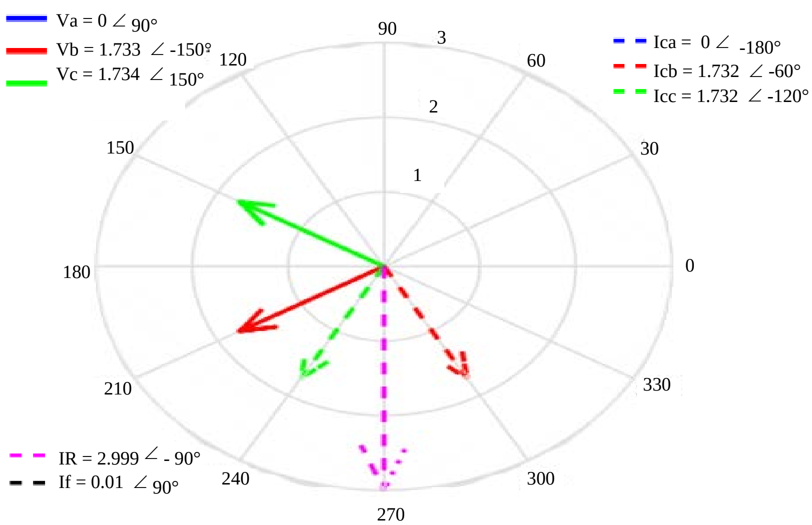

Fig. 9: Phasorial diagram of the power system, grounded by Petersen coil

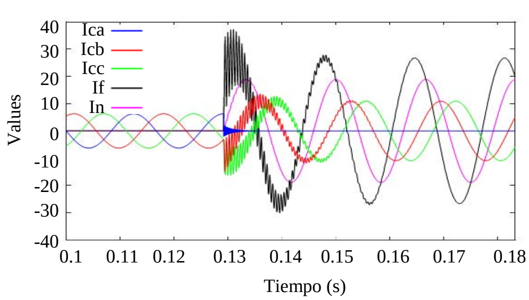

Fig. 10: Current signals from the power system with HRG grounding

An analysis of the time signals shown in Fig. 10 determines a phase jump in the capacitive currents, decreasing their phase angle to each other. The fault current is in advance with respect to the resistive current, furthermore it is determined that it is 180° out of phase with respect to the capacitive current. In terms of the literature consulted, the fault current is in the opposite direction to the capacitive current.

The phasorial representation in Fig. 11 validates the observations made in the signals in Fig. 10. The fault current is in advance with respect to the resistive current, in addition it is in inverse direction with the capacitive current ($3I_{C0}$). The phase angle between the resistive

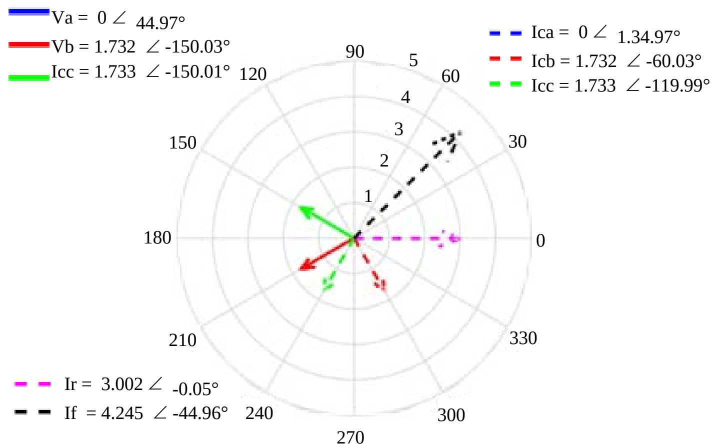

Fig. 11: Phasorial diagram of the power system with grounding HRG

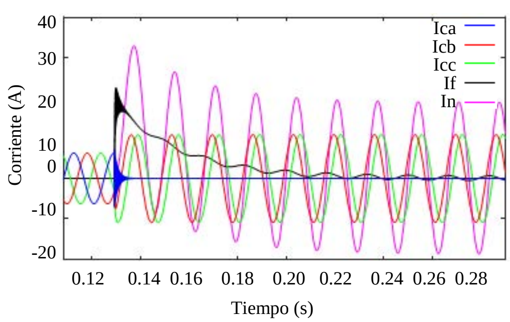

Fig. 12: Power system current signals, grounded by Petersen coil

current and the fault current is determined by the design of the grounding method, the representation shown in Fig. 11 has a phase angle of ≈45° corresponding to a design in which the resistive current is equal to the capacitive current.

The voltages in the faulted phases (B Y C) are converted to line voltages with a phase angle of 60° between them. Capacitive currents in non- faulted phases increase as do voltages by a factor of √3 from the pre-fault value, to 60° in between them and 90° in advance of their reference voltage.

Grounding inductance: Maintaining the orientation in the measurements in Fig. 6 and replacing Z_G with the inductance calculated for the Petersen coil obtains the current signals shown in Fig. 12. The fault current is eliminated due to the sum at the fault point of the capacitive and inductive currents. There is evidence of an increase in the magnitude of the capacitive fault currents as well as a phase jump decreasing their phase angle to each other. The inductive current presents an asymmetry that attenuates in 4 cycles of the signal, during that time a fault current is evident that is eliminated as the signals stabilize.

The processing algorithm is applied to the signals in Fig. 12. The values of amplitude, phase and direction correspond to those obtained using the symmetrical component method. The direction of the current flows is therefore, validated by the two proposed methods.

RESULTS AND DISCUSSION

The direction and phasorial representation of the currents of the power system in Fig. 6 is a matter of discussion. According to Roberts *et al*.[8] the idea was raised that the direction of the capacitive currents is inverted during the fault condition. Another reason for discussion is generated when it is stated that by industrial convention currents flow from point of failure to phase. Although, this statement allows a more conceptual representation of phasorial diagrams, they do not represent the true direction of current flows which creates confusion when setting relay direction and configuration parameters.

In this research it has been looked for a representation according to how the measurements are seen in a real system. To clarify the confusion generated by the representation of the signals both in time and in phasorial diagrams, shown in this article where the sum of the signals does not seem to be so clear to obtain the direction of the fault current. The analysis of Kirchhoff's currents shown in Eq. 3 is posed. Clearing the fault current is Eq. 9 (Fig. 13):

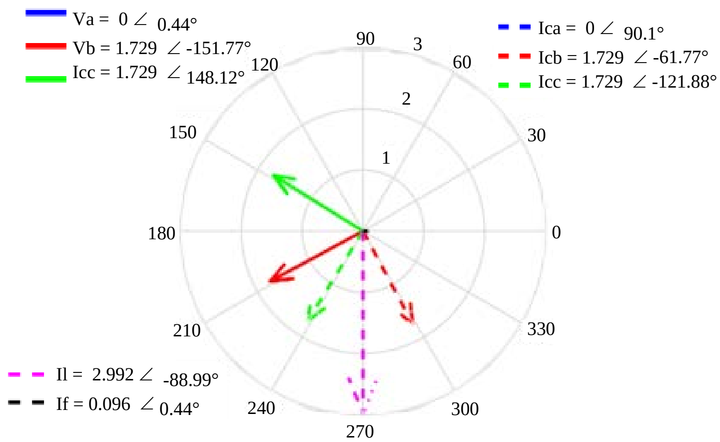

Fig. 13: Phasorial diagram of the power system, grounded by Petersen

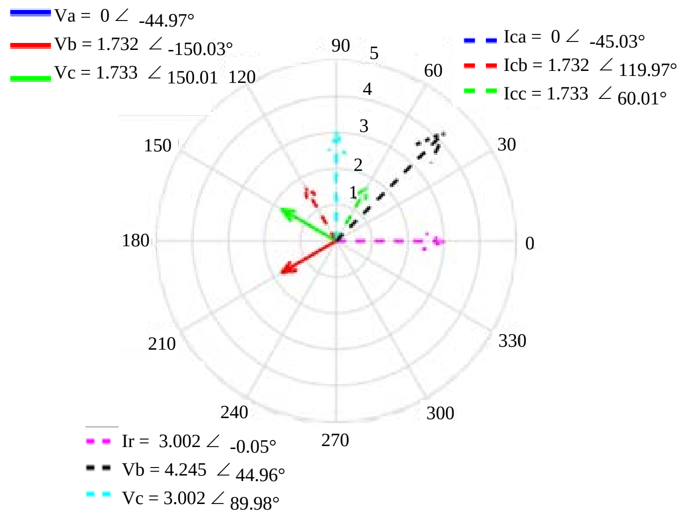

Fig. 14: Phasorial diagram of the power system with HRG grounding (applying Eq. 9)

$$I_F = I_R + (-I_C) \quad (9)$$

This equation represents how signals operate in the case of the time frame and vectors in the fasorial frame. It consists of taking the direction of the inverted capacitive current 180°. It should be made clear that this does not correspond to the true direction but serves as a conceptual basis for understanding the operation to be made to obtain the fault current in a theoretical way.

It should be mentioned that this work the fault current was obtained by measurement, this in order to obtain the true direction of this. In a real system is difficult to measure the fault current, for this reason it is important that with this disposition of meters the operation is performed. To find the fault current must be done according to Eq. 9.

A conceptual example of the phasorial mathematical operation according to Kirchhoff's laws is shown in Fig. 14 which corresponds to the method of resistance grounding. It might be thought that this is a more adequate representation than the one implemented in this work. However, the capacitive currents in this type of representation are delayed with their respective voltages which contradicts the circuit theory. Finally, we must clarify that this representation is shown as a conceptual basis for the mathematical operation to be performed in all the cases exposed in this research.

CONCLUSION

The direction of the capacitive current in phase-to-ground fault conditions is maintained in the direction of the load. Considering that this current is inverted in fault conditions is a concept that does not reflect the actual behavior of the currents and may cause confusion as shown in this article. Using the results shown in this study for proper programming of directional current relays results in better performance in the operation of the protections and thus, improves the safety conditions of the power system.

The results shown in this study are supported for systems that meet the definition of high impedance grounding. In the case of systems with grounding method by means of resistance, the fault current is kept in advance of the current flowing through the neutral or in phase in solidly grounded systems. In the case of Peterson coil systems, the magnitude and direction of the fault current depends on the tuning of the neutral grounding method. The phasorial representation used in this study describes the actual performance of current flows for this reason the authors consider this a valid representation for power systems and it is recommended to make use of this to avoid confusion in the literature.

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REFERENCES

01. Golzarfar, A., A.R. Sedighi and A. Asadi, 2015. Optimal placement and sizing of fault current limiter in a real network: A case study. Int. J. Eng., 28: 402-409.
02. Sottile, J., A. Tripathi and T. Novak, 2007. Best practices for implementing high-resistance grounding in mine power systems. Proceedings of the 2007 IEEE Industry Applications Annual Meeting, September 23-27, 2007, IEEE, New Orleans, Louisiana, pp: 1341-1347.
03. Paul, D., 2014. High-resistance grounded power-system equivalent circuit damage at the line-ground fault location-part I. IEEE. Trans. Ind. Appl., 50: 4179-4187.
04. Sumner, J.H., 2014. The theory and operation of Petersen coils. J. Inst. Electr. Eng. Part II. Power Eng., 94: 283-298.
05. Mazlumi, K. and S.M. Motlagh, 2014. A novel objective function for directional overcurrent relays coordination. Int. J. Eng. Trans. B. Appl., 28: 205-213.
06. Paul, D., 2015. High-resistance grounded power system. IEEE. Trans. Ind. Appl., 51: 5261-5269.
07. Paul, D., 2015. Phasor and directions of a bolted single-phase-ground fault current in a High-Resistance Grounded (HRG) power system. Proceedings of the 2016 IEEE/IAS 52nd Industrial and Commercial Power Systems Technical Conference (I&CPS), May 1-5, 2016, IEEE, Detroit, Michigan, pp: 1-7.
08. Roberts, J., H.J. Altuve and D. Hou, 2001. Review of ground fault protection methods for grounded ungrounded and compensated distribution systems. Proceedings of the 28th Annual Western Protective Relay Conference, October 23-25, 2001, Spokane, Washington, pp: 1-40.
09. Khan, S., S. Khan and G. Ahmed, 2007. Industrial Power Systems. CRC Press, New York, USA.,.
10. Das, J.C. and R.H. Osman, 2002. Grounding of AC and DC low-voltage and medium-voltage drive systems. IEEE. Trans. Ind. Appl., 34: 205-216.
11. Dunki-Jacobs, J.R., 2008. The reality of high-resistance grounding. IEEE. Trans. Ind. Appl., IA-13: 469-475.
12. Das, J.C., 2016. Selective high resistance grounding system for a cogeneration facility. Proceedings of the 2016 IEEE Pulp, Paper & Forest Industries Conference (PPFIC), June 19-23, 2016, IEEE, Austin, Texas, pp: 29-40.
13. Dunki-Jacobs, J.R., F.J. Shields and C.S. Pierre, 2007. Industrial Power System Grounding Design Handbook. Thomson-Shore, Michigan,.
14. Paul, D., 2017. Phasor diagram of a single-phase-ground fault current in a high-resistance grounded power system. Proceedings of the 2017 IEEE/IAS 53rd Conference on Industrial and Commercial Power Systems Technical Conference (I&CPS), May 6-11, 2017, IEEE, Niagara Falls, Canada, pp: 1-6.
15. Weedy, B.M., B.J. Cory, N. Jenkins, J.B. Ekanayake and G. Strbac, 2012. Electric Power Systems. John Wiley & Sons, Hoboken, New Jersey,.
16. Zhang, Y., 2014. Active current injection method for limiting ground fault current harmonics in underground coal mines. Ph.D. Thesis, University of Kentucky, Lexington, Kentucky.
17. Fortescue, C.L., 1918. Method of symmetrical co-ordinates applied to the solution of polyphase networks. Trans. Am. Inst. Electr. Eng., 37: 1027-1140.
18. Conceicao, E.N. and K.M. Silva, 2015. Modeling and Simulation of the Protection of distribution feeders in ATP. IEEE Latin Am. Trans., 13: 1392-1397.
19. Gonzalez, C., E. Vazquez and F. Sellschopp, 2015. Fault location diagnosis based on synchronized phasor measurements. IEEE. Latin Am. Trans., 13: 645-650.