



Ingeniería Energética

ISSN: 1815-5901

Instituto Superior Politécnico José A. Echeverría.Cujae

Espinosa Domínguez, Julio; Perez Baluja, Osmel; Gabriela de la Cruz  
Conte, Amada; Sigas Martínez, Carlos; Breffe, Orlys Ernesto Torres  
Zero sequence impedance behavior in power transformers. Analysis of special cases  
Ingeniería Energética, vol. XLV, núm. 1, 2024, Enero-Abril, pp. 64-74  
Instituto Superior Politécnico José A. Echeverría.Cujae

Disponible en: <https://www.redalyc.org/articulo.oa?id=329177474007>

- Cómo citar el artículo
- Número completo
- Más información del artículo
- Página de la revista en redalyc.org

UAEH  redalyc.org

Sistema de Información Científica Redalyc  
Red de Revistas Científicas de América Latina y el Caribe, España y Portugal  
Proyecto académico sin fines de lucro, desarrollado bajo la iniciativa de acceso  
abierto

# Zero sequence impedance behavior in power transformers. Analysis of special cases

## *Comportamiento de la Impedancia de secuencia cero en transformadores de potencia. Análisis de casos especiales*

Julio Espinosa Domínguez<sup>I,\*</sup>, Osmel Perez Baluja<sup>I</sup>, Amada Gabriela de la Cruz Conte<sup>II</sup>, Carlos Sigas Martínez<sup>II</sup>, Orly Ernesto Torres Breffe<sup>II</sup>

<sup>I</sup>Transilvania University of Brasov, Brasov, Romania

<sup>II</sup>Universidad Tecnológica de La Habana, La Habana, Cuba

\*Corresponding author: [julio.dominguez@unitbv.ro](mailto:julio.dominguez@unitbv.ro)

Received: noviembre 10, 2023

Approved: January 10, 2024

Este documento posee una [licencia Creative Commons Reconocimiento-No Comercial 4.0 internacional](https://creativecommons.org/licenses/by-nc/4.0/)



### ABSTRACT/RESUMEN

Sequence networks make it possible to represent the elements of an electrical network during unbalanced faults, according to Fortescue's theorem presented in 1918. In the case of three-phase transformers, the equivalent sequence networks depend on the connection group of the windings and the connection of the neutral to the ground. This paper carries out a detailed study of zero-sequence networks in power transformers, using mathematical simulation to analyze two special cases, unknown to some electrical protection specialists, in which the zero-sequence impedance can cause significant changes in short-circuit currents. The results have been obtained using theoretical and empirical methods, which have made it possible to demonstrate that transformers can behave as sources of short-circuit contribution in the presence of shunt lines. At the same time, the zero-sequence impedance is different depending on the design of the ferromagnetic core for the same connection group.

**Keywords:** connection groups; single-phase short-circuit; transformer; zero-sequence impedance; zero-sequence network.

*Las redes de secuencia permiten representar los elementos de una red eléctrica ante la presencia de fallas desbalanceadas, según el teorema de Fortescue presentado en el año 1918. En el caso de los transformadores trifásicos, las redes equivalentes de secuencia dependerán de la conexión de los devanados y de la conexión del neutro con respecto a tierra. El propósito de este trabajo es la realización de un estudio detallado de las redes de secuencia cero en los transformadores de potencia, donde por medio de la simulación matemática se analizaron dos casos especiales desconocidos por algunos especialistas en protecciones eléctricas en los cuales la impedancia de secuencia cero puede realizar cambios significativos en las corrientes de cortocircuito. Los resultados fueron obtenidos con el empleo de los métodos teóricos y empíricos que permitieron demostrar que los transformadores pueden comportarse como fuentes de aporte al cortocircuito en presencia de líneas con derivación; mientras que, en dependencia del diseño del núcleo ferromagnético, la impedancia homopolar es diferente para un mismo grupo de conexión.*

**Palabras clave:** cortocircuito monofásico; grupos de conexión; impedancia de secuencia cero; red de secuencia cero; transformador.

### INTRODUCTION

The method of symmetrical components presented by Fortescue in 1918 allows the analysis of unbalanced networks in a simplified way. This theorem shows that to solve an unbalanced system of  $n$ -related phasors,  $n$  systems of balanced phasors called symmetrical components can be used [1, 2]. The application of this method to an unbalanced three-phase system is reduced to the decomposition into a sum of three phasor systems (symmetrical components); two balanced systems of positive and negative sequence in conjunction with one homopolar system (zero-sequence) in which the phasors are of equal magnitude and phase [1, 2].

How to cite this article:

Julio Espinosa Domínguez, y otros. Zero sequence impedance behavior in power transformers. Analysis of special cases.

*Ingeniería Energética*. 2024. 45 (1), enero-abril. ISSN: 1815-5901.

Journal site: <https://rie.cujae.edu.cu/index.php/RIE/index>

The representation of the different three-phase elements that make up the power system (generators, transformers, transmission lines, and loads) to asymmetrical faults can go expressed in three equivalent circuits in response to each of the components of the short-circuit current. Therefore, this idea allows us to understand that the sequence networks are nothing more than the connection of the sequence circuits individually, according to the connections between the electrical system elements [1–3]. Towards analyzing the sequence networks, the impedances of the elements of the system to be analyzed are required. In the case of the positive and negative sequence impedances of the linear and symmetrical elements these are considered to be the same; except in the case of rotating machines where the impedances are different for each sequence. However, zero sequence impedances vary based on the element being represented according to [1–3].

In the case of power transformers, the positive and negative sequence impedances are the same, unlike the zero-sequence impedance, which may differ slightly in value. The variations in the values of positive, negative, and zero sequence impedances in power transformers are primarily influenced by the type of transformer core. This is because the zero-sequence flux paths can differ, resulting in variations in the zero-sequence impedance [2–4]. Although these impedance differences are generally negligible, they are considered while representing the positive, negative, and zero sequence impedances in power transformers. This simplification allows for a more straight forward representation of the impedances [2, 3].

The zero sequence impedance values in transformers play an important role in calculating asymmetric short circuit currents when a ground fault occurs. However, it is also crucial to consider the connection group. The grounding of the windings is extremely important because, in short circuit calculations it may mean taking or not taking into account the zero-sequence impedance. Furthermore, their configuration allows us to characterize the behavior in the face of overvoltages or overcurrents that may occur in the power system in the event of asymmetrical faults, such as in generation plants where the objective is to reduce the magnitude of the short-circuit current given the generators. Given these characteristics, special cases may arise in power systems where the zero-sequence impedance of the transformers behaves differently for different faults [2, 3].

A detailed study of zero-sequence networks in power transformers is the main objective of this paper, where two special cases in which zero-sequence impedance produces important changes in asymmetrical short-circuit currents are analyzed by mathematical simulation. The paper is divided into four sections, organized as follows. After the Introduction, the Materials and Methods section presents the main features of the case studies together with a theoretical characterization of the different phenomena. The Results and Discussion section provides the reader with the main results of the mathematical simulation. The last section gives the basic Conclusions of the work.

## MATERIALS AND METHODS

To carry out this paper, it was necessary to review the existing studies in search of theoretical knowledge about zero-sequence networks in power transformers. The theoretical-analytical-synthetic method was used, in addition to modeling, to verify the existing theory concerning the proposed case studies. The empirical method was used using mathematical simulation of the phenomena using Matlab software.

### Zero sequence networks in power transformers

According to [2, 3], the sequence equivalent circuits in power transformers depend on the connections of the primary and secondary windings. Depending on the wye or delta connection, the configurations of the zero-sequence networks and the phase shift in the positive and negative sequence circuits can be determined. It is important to clarify that if the small magnetizing core current is neglected, this results in no current flowing on the primary side of the transformer unless current flows in the secondary. Furthermore, the primary current is determined by the secondary current through the transformation ratio. Based on this theory, the authors of the references [2, 5, 6], present the five most commonly used zero sequence connections and circuits of two-winding transformers in short-circuit analysis (figure 1).

In figure 1, we can see that in a winding without a return or neutral (as in the case of a delta and wye winding with an isolated neutral), the sum of the phase currents is zero. Similarly, the symmetrical components that will be present will be those of positive and negative sequence, while in the case of zero sequence, this will not be present [3, 5, 7]. If the neutral is grounded in the windings, phase currents with zero-sequence components can flow through this system. This behavior is typical of grounded wye connections, where the zero-sequence current component is one-third of the current flowing in the neutral because the zero-sequence components are in phase and have the same amplitude in all three phases [5, 7, 8].

| No | Symbols | Zero-Sequence equivalent circuit |
|----|---------|----------------------------------|
| 1  |         |                                  |
| 2  |         |                                  |
| 3  |         |                                  |
| 4  |         |                                  |
| 5  |         |                                  |

Fig. 1. Zero-sequence equivalent circuits for three-phase two-winding transformers - author's elaboration from [2]

#### Influence of the core on the zero-sequence impedance of transformers

The zero-sequence networks explained in the previous section are the most commonly used for short-circuit calculations. However, as mentioned above, the zero sequence impedance also depends on the type of core in the transformer, although in practice the zero sequence impedance is often taken to be equal to the positive and negative sequence impedances. Taking the impedances of different sequences equal is not always an accurate method, this can lead to considerable errors in short-circuit calculations because the geometry of the cores influences the zero sequence fluxes ( $\phi_0$ ) and hence the value of the zero sequence impedance.

Transformer cores can be classified in two main ways; three-limb core and five-limb core type. Depending on the core type, the zero sequence flux behaves differently in the presence of asymmetrical faults because the flux behavior depends on the geometry and connection of the windings [9–11]. In the case of a transformer with a three-limb core, the representation of the zero-sequence circuits in figure 1, is invalid due to the non-existence of a return path for the zero-sequence flux inside the magnetic core as shown in figure 2. The occurrence of this phenomenon is because zero-sequence flows that are in phase need to find a path to cancel out. The only way they find is to pass through the oil, air, and transformer tank [5, 9–11].

Figure 2b), shows how the zero sequence flux closes outside the iron core; this behavior represents a high reluctance which results in a lower zero sequence impedance. This zero sequence impedance is obtained from laboratory tests and typical values based on IEC 60076-8 of 1997 are given in table 1, [10].

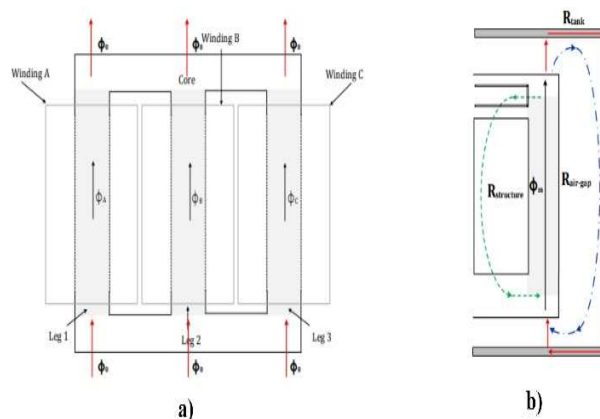


Fig.2.a) Core structure of 3-limb core transformer, b) Flux paths of 3-limb core transformer[10]

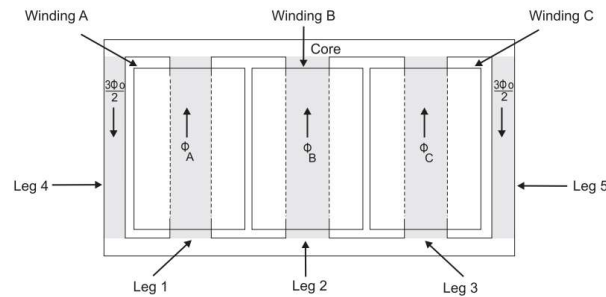
**Table 1.** Typical zero sequence impedance values for two-winding transformers with different cores according to IEC 60076-8 standard

| Impedance %    |     |                              |              |                              |                |
|----------------|-----|------------------------------|--------------|------------------------------|----------------|
| Winding symbol |     | Excited winding, 3-limb core |              | Excited winding, 5-limb core |                |
| (1)            | (2) | (1)                          | (2)          | (1)                          | (2)            |
| YN             | Y   | $\approx 50$                 | -            | $\approx 10^4$               | -              |
| Y              | YN  | -                            | $\approx 60$ | -                            | $\approx 10^4$ |
| YN             | YN  | $a_1 Z_{12}$                 | $a_2 Z_{12}$ | $Z_{12}$                     | $Z_{12}$       |
| YN             | D   | $a_1 Z_{12}$                 | -            | $Z_{12}$                     | -              |
| D              | YN  | -                            | $a_2 Z_{12}$ | -                            | $Z_{12}$       |

Note:  $Z_{12}$  is short-circuit positive-sequence impedance.

$a_1$  and  $a_2$  are multiplying factors in the range:  $0.8 < a_1 < a_2 < 1$ .

In a five-limb core transformer, the zero-sequence flux behavior is different because the unwound outer columns allow the flux to return, and thus the flux can be canceled (figure 3). Zero sequence flux cancellation in the columns results in lower zero sequence reluctance and high magnetizing impedance [5, 9–11].



**Fig. 3.** Schematic of five-legged core-type transformer magnetic paths [9]

The differences in the behavior of the zero sequence fluxes shown in figures 2 and 3, allow us to understand that there are notable differences in the zero sequence impedance, therefore, if they are not taken into account in the short-circuit calculations, this leads to significant errors in the values of the currents. Because of this, it has become necessary to search for methods to find the real values of the zero-sequence impedances [12].

According to the reference [11], the IEC 60076-8 standard provides a zero sequence impedance circuit in correspondence with the design of the magnetic core of the transformer (figure 4). Figure 4 a), shows the mathematical model of the five-limb core, where  $Z_0$  represents the zero-sequence leakage impedance provided by the manufacturer. Moreover, figure 4 b), shows the three-limb core model, where  $Z_m$  represents the magnetizing impedance, while the zero-sequence leakage impedance ( $Z_0$ ) is divided into  $Z_A$  and  $Z_B$ .



**Fig. 4.** General series and shunt switch models for the zero-sequence circuit of two-winding transformer, **a)** Five-limb core, **b)** Three-limb core [11]

The use of switches (SW1, SW2, SW3, and SW4) in figure 4, allows the zero sequence impedances to be represented according to the different winding connections. In the case of the grounded wye connection, two switches were used in series (SW1 and SW2), while in the case of the delta connection, two shunt switches were used (SW3 and SW4). These configurations allow the zero-sequence impedance equivalent circuits to be designed according to the connection of the windings (figure 5), [11].

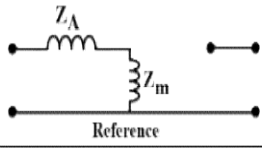
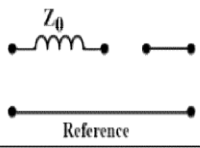
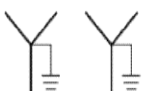
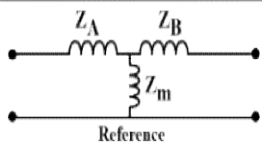
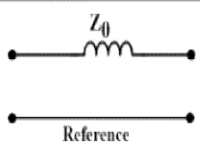
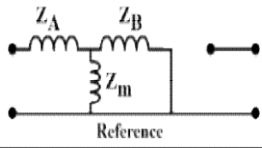
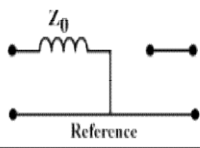
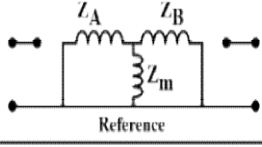
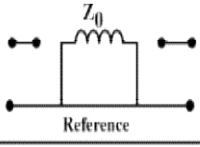
| No | Symbols                                                                           | Zero sequence equivalent circuit                                                  |                                                                                    |
|----|-----------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
|    |                                                                                   | Three-limb core transformer                                                       | Five-limb core transformer                                                         |
| 1  |  |  |  |
| 2  |  |  |  |
| 3  |  |  |  |
| 4  |  |  |  |

Fig. 5. Zero-sequence equivalent circuit according to winding connections - author's elaboration from [11]

The equivalent circuits shown in the figure above reflect the importance of knowing the type of three-phase transformer core in short-circuit studies for the occurrence of asymmetrical faults. In the case of zero-sequence networks in a five-limb cores transformer, these are the same as those shown in figure 1, while in the case of a three-limb cores transformer, the behavior is completely different. These considerations call for the attention of specialists in the field of short-circuit studies before the implementation of electrical protection systems in networks, due to the possible occurrence of peculiar phenomena such as those that will be dealt with in the following sections.

#### Case study 1: The transformer as a short-circuit source

For many specialists and technicians involved in the settings of electrical protection, it is very difficult to understand that under very peculiar circumstances the transformer can behave as a short-circuit source due to its zero-sequence impedance. This case is part of the concept of the infeed effect that can manifest itself in shunted transmission line and affect the impedance measurement in the distance protection, which can bring problems to the stability of the power system [13–17].

The infeed effect is one of the many phenomena that affect the operation of distance protection, which can not be used as the main protection on transmission lines [14, 18–20]. In the case of transformers that can be left in no load conditions on shunt lines, the intermediate source phenomenon manifests itself only in the occurrence of single-phase and two-phase ground faults. This phenomenon causes uncertainty among technicians and specialists, who may not take it into account and make significant errors in the protection settings.

To analyze the phenomenon of the intermediate source in shunted lines, we will use the diagrams in figure 6, where we can see an equivalent of the power system with a shunted transmission line, while on bus 2 of the shunt is connected a transformer  $Yg\Delta$  that is not connected to the load. The absence of the connected load allows us to disregard the pre-fault state in the transformer, and therefore the observation of the phenomenon will be more effective.

The occurrence of a single-phase or two-phase short-circuit to ground causes the short-circuit current  $I_{SC}$  to present a contribution not only from the equivalent system ( $I_S$ ) but also from the unloaded transformer ( $I_T$ ), figure 6 b). This behavior is irregular because it only occurs in asymmetrical faults involving ground, in comparison with the other faults where the phenomenon is non-existent. The behavior of the short-circuit currents can be analyzed in detail in the sequence circuits of a single-phase fault on bus 3. See figure 6 c).

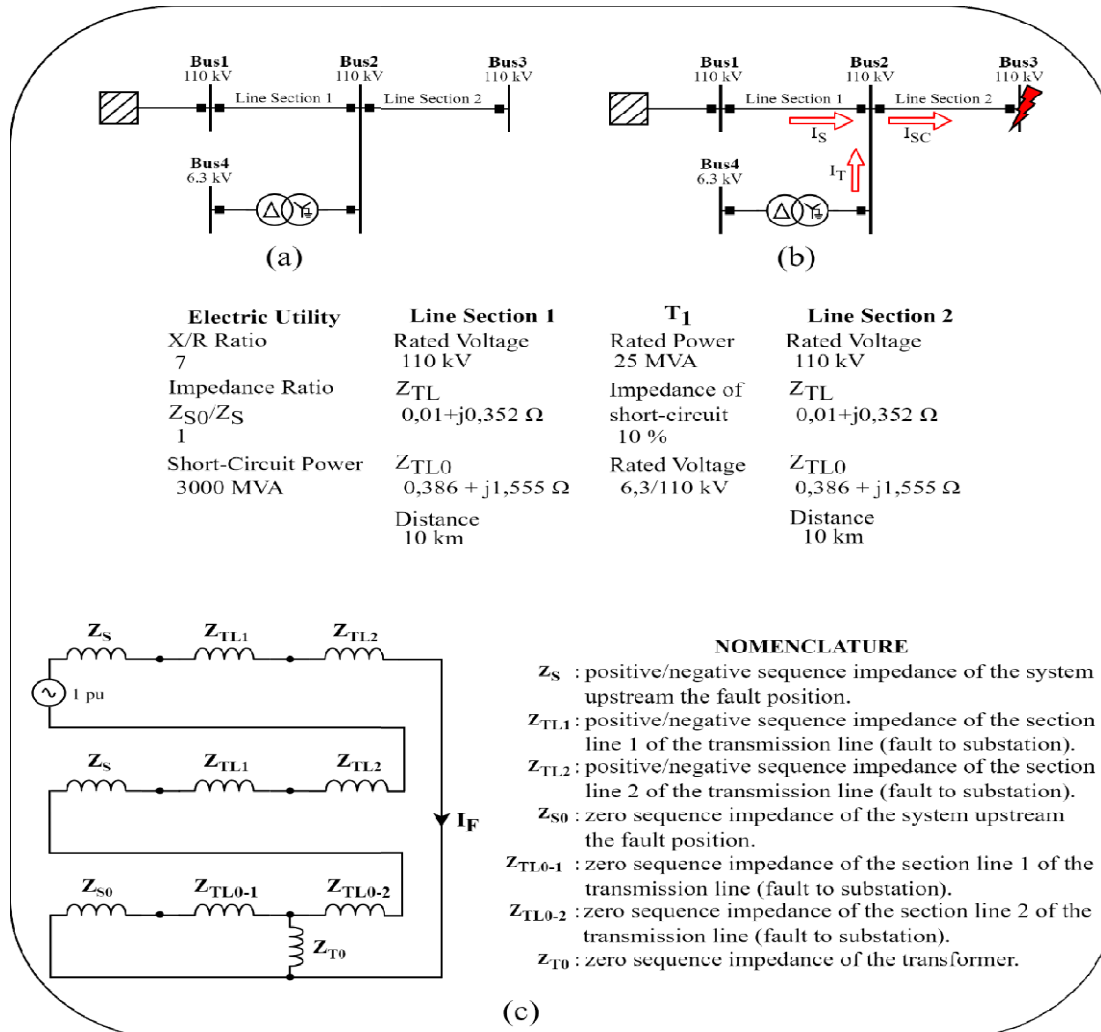


Fig. 6. Case 1 Diagrams, a) Diagram of lines in shunt with a transformer, b) Current paths to the short-circuit on bus 3, c) Sequence networks for a single-phase ground fault on bus 3

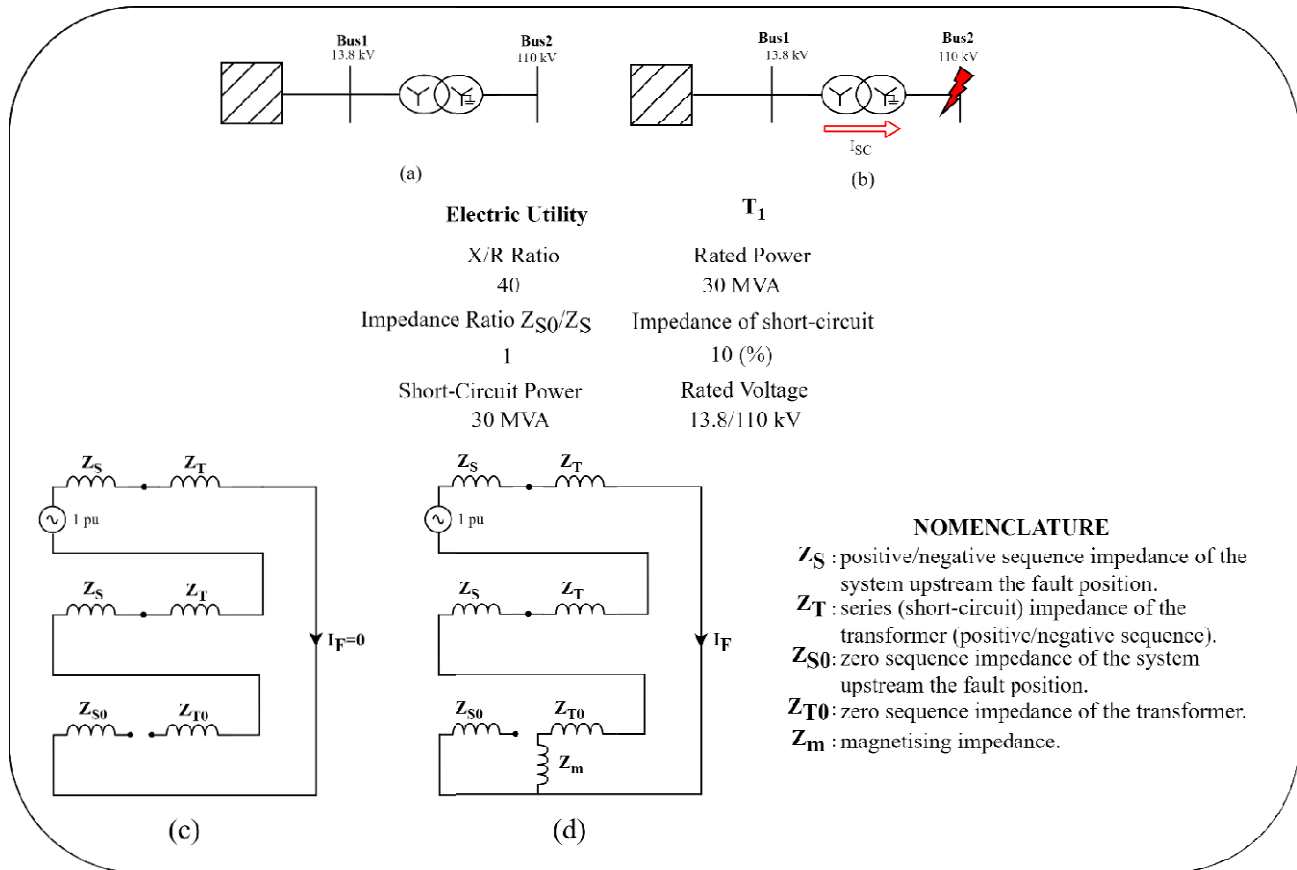
The analysis of the sequence networks in figure 6 c), shows that the transformer appears only in the zero-sequence diagram, which means that the zero-sequence impedance is responsible for the  $I_T$  current. This phenomenon reveals that the transformer's contribution to the fault is zero-sequence; demonstrating that for two-phase and three-phase short circuits the transformer will not behave as a short-circuit source.

#### Case study 2: Transformer YYg at single-phase to ground faults

One of the uncommon connection groups in the analysis of asymmetrical ground faults is the YYg connection of the three-phase two-winding transformer. This connection group did not represent any interest for the specialists in electrical protection because the zero-sequence network was reduced to the equivalent circuit of figure 1, where the zero-sequence impedance did not participate in the ground fault.

At present, with this connection important care must be taken because the zero sequence network does not always behave as in figure 1, due to the type of transformer core. If the YYg transformer core is a five-limb core the zero sequence impedance can be neglected in the analysis of single-phase to ground faults, whereas in the case of a three-limb core, the zero sequence impedance cannot be neglected.

Figure 7, consisting of an equivalent power system in series with a transformer T1, will serve as an example for the explanation of the phenomenon. In conjunction with figure 7 a) and b), figure 7 c) and d), also shows the behavior of the sequence circuits in different types of cores in the event of a single-phase short-circuit to ground on bus 2.



**Fig.7.** Case 2 Diagrams, **a)** Equivalent system in series with a transformer with connection group YYg, **b)** Direction of the short-circuit current in the event of a single-phase fault on bus 2, **c)** sequence network for a five-limb core transformer in the event of a single-phase short-circuit on bus 2, **d)** sequence network for a three-limb core transformer in the event of a single-phase short-circuit on bus 2

The analysis of figure 7, allows us to understand that the sequence networks are different depending on the transformer core. The occurrence of a single phase to ground fault on the grounded wye side can have a zero sequence current contribution and therefore an overcurrent protection could be used in the neutral of the transformer. Moreover, the differences in the behavior of zero sequence impedances in the presence of single-phase ground faults in YYg transformers draw the attention of protection specialists to the need for knowledge of the type of core to be able to correctly adjust the protection devices.

## RESULTS AND DISCUSSION

To validate the phenomena explained above, simulations were carried out using MATLAB (mathematical software with academic licence number 41037228). The representation of the scenarios was made using the real values exposed in case studies 1 and 2, where the events of the different short circuits validate the issues raised in the Materials and Methods section.

### Case study 1

The results of the simulations for case study 1 are shown in figure 8, where the plots of voltage, short-circuit current, transformer short-circuit current contribution and transformer zero-sequence current are shown. The simulations were carried out for four types of faults where single-phase and two-phase ground faults being the most significant.

Figure 8, shows that the transformer does not contribute to the zero-sequence current for three-phase and two-phase faults, demonstrating that this phenomenon occurs only for faults involving zero-sequence current. The contribution of the transformer to the short-circuit current is a special case of the infeed effect, showing that the transformer can behave as a short-circuit source in the presence of shunt lines.

### Case study 2

Figure 9 a) and b), show the results of case study 2, showing the transformer voltage, short-circuit current, and zero sequence current plots. The simulations were realized for single-phase ground faults to analyze the behavior of three-phase transformers with two windings but with different cores.

The figure 9 a), shows how, in the event of a single-phase short-circuit to ground, the transformer with a five-limb type core, the zero sequence current contribution is almost negligible, which means that the current at the short-circuit point is zero. This behavior is because the zero-sequence flux is cancelled at the transformer core and therefore the zero-sequence network can be represented as in figure 1.

In the case of figure 9 b), the response of the transformer to the occurrence of a single-phase short-circuit to ground is different from that of figure 9 a), because the three-limb core transformer brings zero-sequence current to the fault. This phenomenon demonstrates that short-circuit studies must take into account the type of transformer core which can influence the value of the single-phase short-circuit current to ground, and also opens up the possibility of applications near generating sets where single-phase ground faults can be detected by installing an overcurrent relay in the neutral of a YYg transformer with a three-limb core.

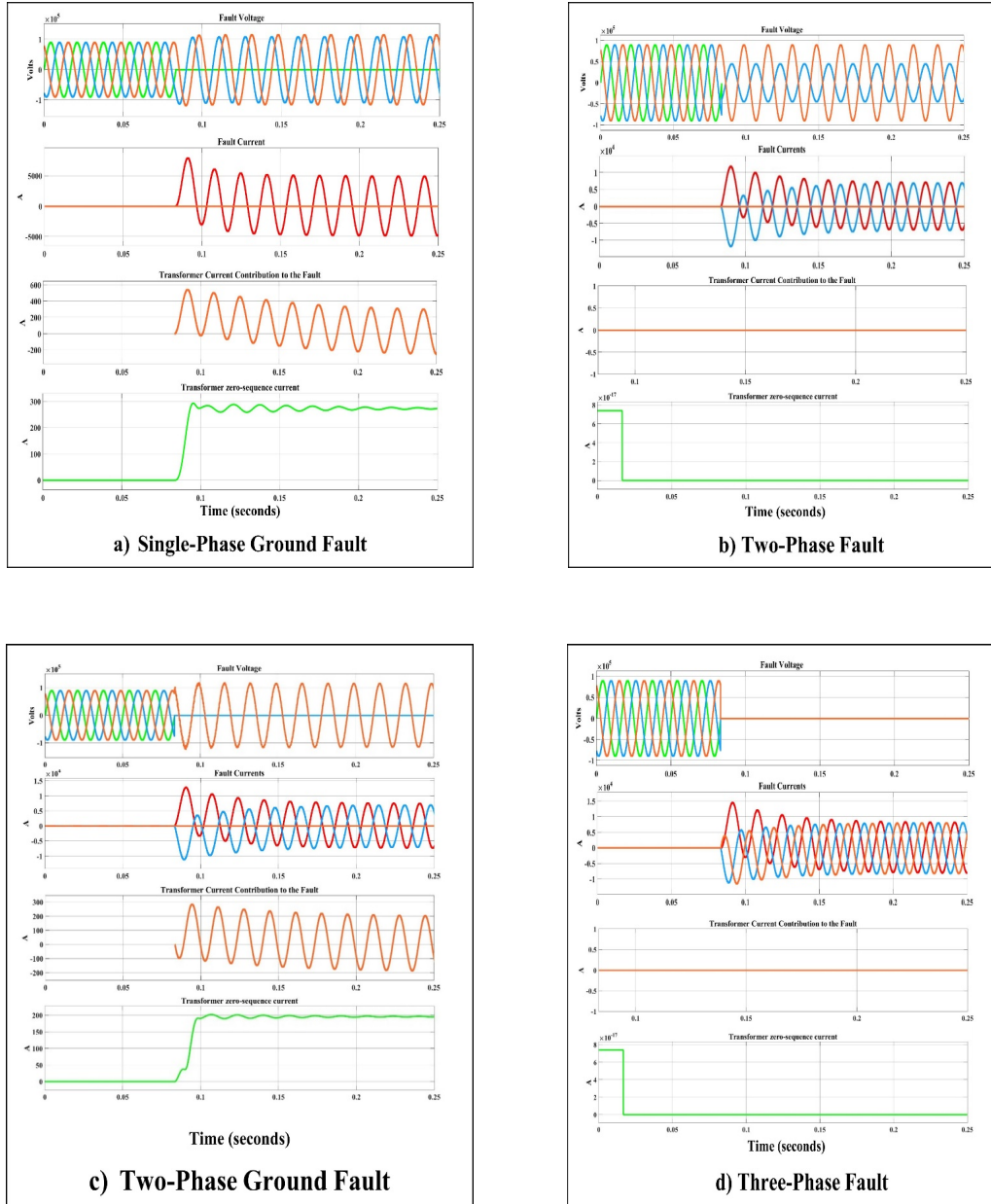
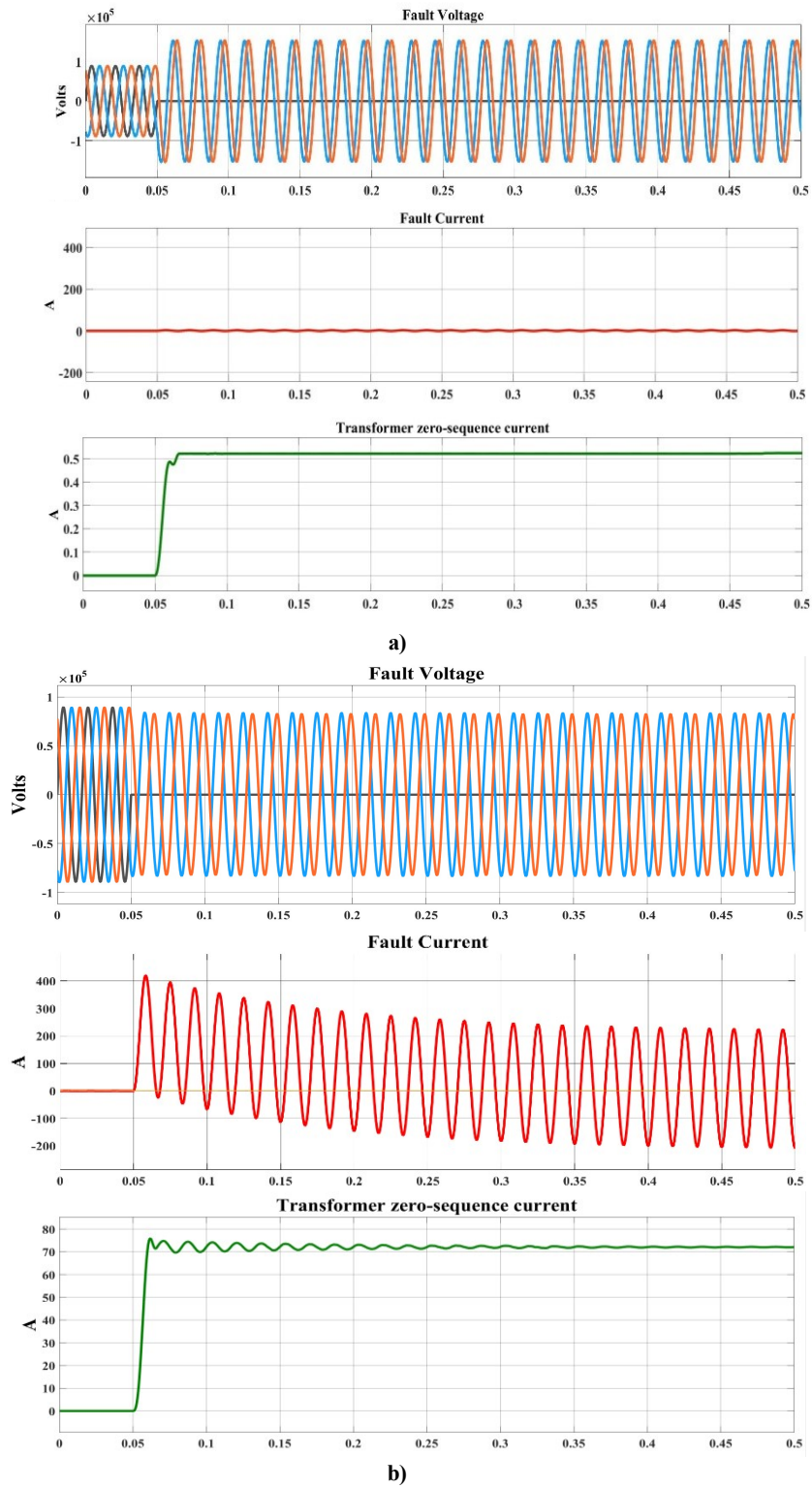


Fig. 8. Transformer behavior in the event of various faults in the presence of shunt lines



**Fig. 9.** Results case 2, **a)** Behavior of the five-limb core transformer in the event of single-phase ground faults, **b)** Behavior of the three-limb core transformer in the event of single-phase ground faults

## CONCLUSIONS

The analysis of the zero-sequence impedance in three-phase transformers depends on the connection group and the type of core. In the case of transformers with five-limbed cores, the zero-sequence impedance network behaves according to the traditional method found in the classical literature, while in the case of a transformer with a three-limbed core, the zero-sequence network behaves differently due to the influence of the magnetizing impedance and the zero-sequence flux that does not cancel in the outer columns of the core.

Moreover, the phenomenon of the transformer as a short-circuit source is a special case of the infeed effect that can occur in shunted transmission line. This case can only be understood by analyzing the zero-sequence impedance network of the transformer, since it only manifests itself for asymmetrical short-circuits in the presence of ground, whereas this phenomenon does not occur for three-phase and two-phase faults.

The YYg connection of a three-phase transformer can be used to detect ground faults if the transformer core is of the three-limb type, unlike the case of the five-limb core, which does not allow the fault to be detected because the zero-sequence impedance network is open and does not allow the zero-sequence current to flow. This peculiar phenomenon must be analyzed in detail by electrical protection specialists who, in some circuits, must take into account the structure of the transformer core, not only the connection group, in order to make the correct settings of the protection devices.

## REFERENCES

- [1] Fortescue CL. "Method of Symmetrical Co-Ordinates Applied to the Solution of Polyphase Networks". Trans Am Inst Electr Eng. 1918; vol. 37, n. 2, p. 1027–1140. ISSN 2330-9431. [Consulted January 3, 2023]. Available at: [https://ia600708.us.archive.org/view\\_archive.php?archive=/28/items/crossref-pre-1923-scholarly-works/10.1109%252Fpaiee.1917.6591996.zip&file=10.1109%252Fpaiee.1918.6594104.pdf](https://ia600708.us.archive.org/view_archive.php?archive=/28/items/crossref-pre-1923-scholarly-works/10.1109%252Fpaiee.1917.6591996.zip&file=10.1109%252Fpaiee.1918.6594104.pdf)
- [2] Grainger JJ, Stevenson WD. "Análisis de sistemas de potencia". McGraw-Hill, 2000. ISBN 9-789701-009086. [Consulted January 3, 2023]. Available at: <https://catedras.facet.unt.edu.ar/sep/wp-content/uploads/sites/20/2020/03/An%C3%A1lisis-de-Sistemas-de-Potencia-Grainger-Stevenson.pdf>
- [3] Blackburn JL, Domin TJ. "Protective Relaying: Principles and Applications". CRC Press, 2006, ed. 3rd. ISBN 978-1-57444-716-3. [Consulted January 3, 2023]. Available at: [https://bank.engzenon.com/tmp/56122028-4370-460a-8d96-485ec0feb99b/565727cc-1bdc-4894-803e-4beac0feb99b/J\\_Lewis\\_Blackburn\\_Thomas\\_J\\_Domin\\_Protective\\_RELAYING.pdf](https://bank.engzenon.com/tmp/56122028-4370-460a-8d96-485ec0feb99b/565727cc-1bdc-4894-803e-4beac0feb99b/J_Lewis_Blackburn_Thomas_J_Domin_Protective_RELAYING.pdf)
- [4] Winders J. "Power Transformers: Principles and Applications". CRC Press, 2002. ISBN 0-8247-0766-4. [Consulted January 3, 2023]. Available at: [https://api.pageplace.de/preview/DT0400.9780203910474\\_A23567183/preview-9780203910474\\_A23567183.pdf](https://api.pageplace.de/preview/DT0400.9780203910474_A23567183/preview-9780203910474_A23567183.pdf)
- [5] Al Juboori MAA, Alrawe MAA, Younus YM. "The Impact of the Power Transformer Connections on the Flow of Zero Sequence Current". Al-Rafidain Eng J AREJ. March 2023; vol. 28, n. 1, p. 219–229. ISSN 2220-1270. [Consulted April 3, 2023]. Available at: [https://rengi.mosuljournals.com/article\\_177758.html](https://rengi.mosuljournals.com/article_177758.html)
- [6] Yalçın F, Yildirim Y. "A Study of Symmetrical and Unsymmetrical Short Circuit Fault Analyses in Power Systems". Sak Univ J Sci. 2019; vol. 23, n. 5, p. 879–895. ISSN 2147-835X. [Consulted January 3, 2023]. Available at: <https://dergipark.org.tr/tr/download/article-file/723523>
- [7] Cho N, Yoon M, Choi S. "Impact of Transformer Topology on Short-Circuit Analysis in Distribution Systems with Inverter-Based Distributed Generations". Sustainability 2022; vol. 14, n. 15, e9781. ISSN 2071-1050. [Consulted January 3, 2023]. Available at: <https://www.mdpi.com/2071-1050/14/15/9781>
- [8] Suárez LP, et al. "Disparos incorrectos de las protecciones eléctricas de parques fotovoltaicos conectados al Sistema Eléctrico de Cuba". Ing Energética. May-August 2023; vol. 44, n. 2, p. 1–10. ISSN 1815-5901. [Consulted September 3, 2023]. Available at: <http://scielo.sld.cu/pdf/rie/v44n2/1815-5901-rie-44-02-71.pdf>
- [9] Wang J, Lascu R. "Zero sequence circuit of three-legged core type transformers". In: 2009 62nd Annual Conference for Protective Relay Engineers. 2009, p. 188–213. ISBN 978-1-4244-4182-2. [Consulted January 3, 2023]. Available at: <https://ieeexplore.ieee.org/document/4982513?denied=>
- [10] Song JS, et al. "A Study on Zero Sequence Impedance of 3-limb Core Transformer". In: 2019 IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia). 2019, p. 559–564. ISBN 978-1-5386-7434-5. [Consulted January 3, 2023]. Available at: <https://ieeexplore.ieee.org/document/8716026?denied=>
- [11] Cho N, Wendha B, Yoo J. "Analysis of reverse fault current regarding the impact of transformer core types on the two most common winding connections of distributed energy resources in distribution systems". Int J Electr Power Energy Syst. January 1, 2024; vol. 155, part. B, e109548. ISSN 0142-0615. [Consulted January 5, 2024]. Available at: <https://www.sciencedirect.com/science/article/pii/S0142061523006051>

- [12] Zhang M, Fang J, Wang H, et al. Efficient Zero-Sequence Impedance Measurement in Autotransformers Using Low-Voltage Excitation. Appl Sci. January 1, 2024; vol. 14,n. 1, e215. ISSN 2078-2489. [Consulted January 5, 2024]. Available at: <https://www.mdpi.com/2076-3417/14/1/215>
- [13] Nikolaidis VC, et al. “Investigating Particularities of Infeed and Fault Resistance Effect on Distance Relays Protecting Radial Distribution Feeders With DG”. IEEE Access. 2018; vol. 6: p. 11301–11312. ISSN2169-3536. [Consulted January 3, 2023]. Available at:<https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8286903>
- [14] Pérez Baluja O, Torres Breffe OE. “Protección de distancia en las líneas con derivación”. CienciAméricaRevDivulg Científica Univ Tecnológica Indoamérica. 2020; vol. 9,n. 4, p. 67–74. ISSN 1390-9592. [Consulted January 3, 2023]. Available at:<https://cienciameerica.edu.ec/index.php/uti/article/view/345/657>
- [15] Hariri F, Crow M. “New Infeed Correction Methods for Distance Protection in Distribution Systems”. Energies. 2021; vol. 14, n. 15, e4652. ISSN 1996-1073. [Consulted January 3, 2023]. Available at:<https://www.mdpi.com/1996-1073/14/15/4652>
- [16] Jagtap PS, Thakre MP. “Effect of Infeed Current and Fault Resistance on Distance Protection for Teed-Feed line”. In: 2020 IEEE First International Conference on Smart Technologies for Power, Energy and Control (STPEC). 2020, p. 1–6. ISBN 978-1-7281-8873-7. [Consulted January 3, 2023]. Available at:<https://ieeexplore.ieee.org/document/9297799?denied=>
- [17] Yoldas YB, Yumurtacı R. “Improvement of Distance Protection with SVM on PV-Fed Transmission Lines in Infeed Conditions”. Energies.January 2023; vol. 16, n. 6,e2587. ISSN 1996-1073. [Consulted March 5, 2023]. Available at:<https://www.mdpi.com/1996-1073/16/6/2587>
- [18] Baluja OP, et al. “Efecto de inductancia mutua en protecciones de lineas paralelas de transmisión. Defecto de sus soluciones”. Ing Energética. 2020; vol. 41, n. 2,p. 1–9. ISSN 1815-5901.[Consulted January 3, 2023]. Available at:[http://scielo.sld.cu/scielo.php?pid=S1815-59012020000200004&script=sci\\_abstract](http://scielo.sld.cu/scielo.php?pid=S1815-59012020000200004&script=sci_abstract)
- [19] Baluja OP, et al. “Las Oscilaciones de Potencia y sus retos a las protecciones de distancia en Cuba: Power Swing challengestodistanceprotectionsin Cuba”. Ing Energética. 2022; vol. 43. n. 2,p. 9. ISSN 1815-5901. [Consulted January 3, 2023]. Available at:[http://scielo.sld.cu/scielo.php?script=sci\\_arttext&pid=S1815-59012022000200129](http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S1815-59012022000200129)
- [20] PérezBaluja O, et al. “La protección de distancia y las condiciones de prefalla”. Ing Energética. 2019; vol. 40,n. 2, p. 103–111. ISSN 1815-5901. [Consulted January 3, 2023]. Available at:[http://scielo.sld.cu/scielo.php?script=sci\\_arttext&pid=S1815-59012019000200103](http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S1815-59012019000200103)

## CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

## CONTRIBUTION OF THE AUTHORS

**Julio Espinosa Domínguez:** <https://orcid.org/0000-0003-0696-5009>

Research design, and data collection. He participated in the analysis of the results, drafting of the article, and final approval of the article.

**Osmel Perez Baluja:** <https://orcid.org/0000-0003-1857-9594>

He participated in the analysis of the results, drafting, and final approval of the article.

**Amada Gabriela de la Cruz Conte:** <https://orcid.org/0009-0003-4505-7545>

She participated in the analysis of the results, drafting, and final approval of the article.

**Carlos Sigas Martínez:** <https://orcid.org/0009-0004-1120-9528>

He participated in the analysis of the results, drafting, and final approval of the article.

**Orlys Ernesto Torres Breffe:** <https://orcid.org/0000-0001-7781-2611>

Research design, and data collection. He participated in the analysis of the results, drafting of the article, and final approval of the article.