Evaluation of the Impact of Transmission Line Unbalance in the Distance Protection

S. I. A Souza, F. A. Moreira

***Abstract*— The majority of short-circuit analysis methods make use of the symmetrical components technique when evaluating the condition of the system during a fault. This way, the transmission lines are commonly considered ideally transposed. Factors such as untransposed conductors, tower geometry and the presence of multiple conductors result in an unbalance due to the distance among the conductors being different along the line. The simplifications considered in short-circuit conventional analysis may result in significant errors when determining the fault current when an untransposed or actually transposed transmission line is considered as ideally transposed. The purpose of this paper is to evaluate the behavior of the distance protection system, since the error in measuring the fault current due to the previously mentioned simplifications have a direct influence in the measurement performed by a distance relay.**

***Keywords:* Symmetrical components, distance protection, transmission line, ATP, MATLAB**

I. Introduction

ELETRIC energy transmission lines are the most vulnerable components in an electric power system. The transmission lines are submitted to the most adverse weather conditions and external factors, resulting in about 80% of the faults being originated in them [1]. Therefore, studies related to protection systems and short-circuit analysis are necessary to assure the continuity of the energy distribution service.

The protection of transmission lines is primarily performed by distance relays that measure, through a phasor estimation algorithm, the impedance of the relay from the substation to the point where the fault occurs. The protection setting is adjusted taking into account the transmission line positive sequence impedance. However, the symmetrical components method can only be applied if the line is considered perfectly balanced. For this situation to be valid, it is necessary to assume that the transmission lines are ideally transposed. If the transmission lines are not transposed, their protection may become quite complicated [2].

This work evaluates the behavior of the distance protection system in three different cases: an actually transposed transmission line, an ideally transposed transmission line, and an untransposed transmission line.

The paper is divided as follows. In section 2 the basic theory about transmission line transposition and distance relays are presented. In section 3, the methodology is presented focusing on the computational tools used and the transmission line analyzed. In section 4, the results and analysis of the simulations are presented, while in section 5 the conclusions of this work are stated.

II. Theoretical Background

A. Balanced Transmission Lines

The impedance matrix of a three-phase transmission line may be written according to (1), so that the elements in the main diagonal are the self impedances of the line and the elements outside the main diagonal are the mutual impedances among the phases.

$$[Zabc] = \begin{bmatrix} Zaa & Zab & Zac \\ Zba & Zbb & Zbc \\ Zca & Zcb & Zcc \end{bmatrix} \tag{1}$$

The [Zabc] matrix will always be symmetric, that is, the mutual impedance Zij will always be equal to the mutual impedance Zji. However, the impedance matrix may only be considered balanced if all elements in the main diagonal are equal among them and all elements outside the main diagonal are also equal among them, according to (2).

$$[Zabc] = \begin{bmatrix} Zs & Zm & Zm \\ Zm & Zs & Zm \\ Zm & Zm & Zs \end{bmatrix} \tag{2}$$

where Z_s and Z_m are the values of the self and mutual impedances, respectively.

B. Transmission Line Transposition

If an actual transmission line is to be considered as approximately balanced, the concept of phase transposition is used. The purpose is that each phase occupies each of the three possible positions on the tower for the same distance. Fig. 1 shows a transposition scheme of three sections for a three-phase transmission line.

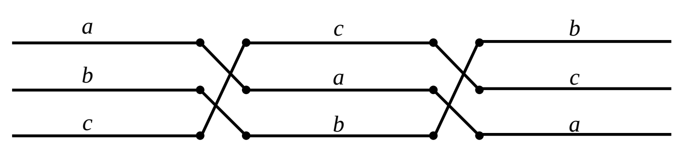

Fig. 1. Transposition scheme for a three-phase transmission line.

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The usual procedure to derive the impedance matrix of a transposed transmission line is to calculate an average of the impedance values for each transposition section, as shown in (3).

$$[Zabc] = \frac{1}{3}\left[\begin{bmatrix} Zaa & Zab & Zac \\ Zba & Zbb & Zbc \\ Zca & Zcb & Zcc \end{bmatrix} + \begin{bmatrix} Zcc & Zca & Zcb \\ Zac & Zaa & Zab \\ Zbc & Zba & Zbb \end{bmatrix} + \begin{bmatrix} Zbb & Zbc & Zba \\ Zcb & Zcc & Zca \\ Zab & Zac & Zaa \end{bmatrix}\right] \quad (3)$$

Therefore, it is possible to obtain a matrix as shown in (2) and to consider the line as approximately balanced.

In practice, it is quite difficult to exactly apply a transposition scheme as shown in Fig. 1, and thus, there will be a difference between the ideal and actual transpositions.

C. *Distance Relays*

Transmission line protection is normally performed by distance relays that measure the impedance from the substation where the relay is installed to the point on the line where the fault occurs, comparing it with the positive sequence impedance of the line. This impedance depends only on the line parameters, being common to all types of faults. Through an estimate of the voltage and current phasors, the impedance measured by the relay is obtained. Generally, if the impedance measured by the relay is smaller than the pre-defined line impedance, a fault is detected and the relay sends a tripping signal to the circuit breaker [3].

There are ten possible types of faults associated to a three-phase system: three single-phase, three double-phase, three double-phase to ground and one three-phase. In order for the transmission line to be protected against all possible types of faults, at least one of the six impedance units (three phase units and three ground units) of the relay should operate.

Due to inaccuracies in the measurement of the distance and in the estimation of the line impedance, which is generally not measured but actually obtained through calculations, it is not common in practice to have a reaching of 100% of the length of the line. In other words, the reaching point of a distance relay cannot be accurately determined [4]. Therefore, the distance relays are adjusted to work with protection zones, normally three. If the fault occurs in the first zone, the relay operates instantaneously. Meanwhile, in the second and third zones, a delay in the operation of the relay is allowed, so that, another relay may operate in its first zone.

With the development of digital technology, the main aspects of distance protection could be implemented in digital relays, which became extremely fast and reliable, calculating phasors even when signals are corrupted by the DC component due to exponential decay, transients provoked by capacitive voltage transformers, and non-linearities generated by current transformers saturated core among other interferences [5].

In this work, a traditional phasor estimation algorithm, the one-cycle Fourier algorithm, was used. In this algorithm, the discrete Fourier transform is applied to one cycle of voltage and current signals samples.

III. Simulation Methodology

A. *Computational Tools Used*

Currently, the computational tools mostly used for transients simulation in electrical power systems are the EMTP ("Electromagnetic Transients Program") type of programs, particularly the ATP ("Alternative Transients Program").

The electric parameters of the transmission lines studied in this project were calculated using the Line Constants routine of the ATP program at 60 Hz [6]. Using the ATP, three types of faults (single-phase, double-phase to ground, and three-phase) were applied to the line, changing the distance between the relay and the fault location. This process was performed considering an untransposed line, a line ideally transposed, and an actually transposed line that will be presented shortly.

The results obtained through the ATP program were stored in a databank in order to be used as input data to the MATLAB program. Using MATLAB, the one-cycle Fourier phasor estimation algorithm was implemented in order to filter the ATP output data, therefore obtaining the voltage and current phasors. This way, the impedance as seen by the relay is obtained even when the line analyzed is untransposed or not ideally transposed. Thus, it is possible to compare the path in the R-X plane as seen by the relay for the cases of an ideally transposed, actually transposed, and untransposed line.

B. *Electric Network Studied*

The power system shown in Fig. 2 represents the base model that was implemented in ATP. The system is composed by four buses and one source. The nominal voltage is 230 kV and the line length is 678.9 km. The CCVT and the CT were installed at bus PA200, and were represented in the simulations following the model proposed in [7]. The source impedance Zs was represented by lumped parameters while the line impedance was represented by distributed parameters throughout the extension of the line.

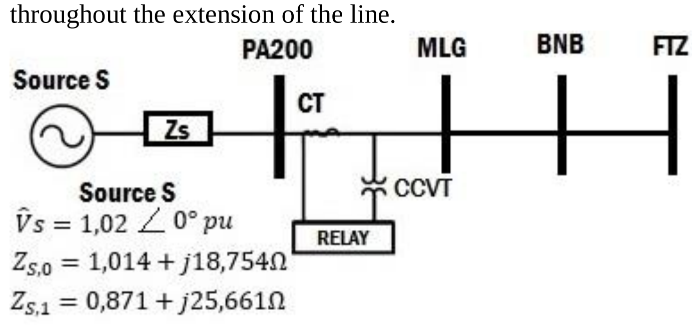

Fig. 2. Electric network implemented.

In all simulations, a fault incidence angle of 90º, with reference to the voltage in phase A, has been considered.

The reaching of the first protection zone of the relay has been set to 85% of the line impedance between buses PA200 and MLG. For the second zone, the relay has been set to 150% of the line impedance between buses PA200 and MLG, and for the third zone, the relay has been set to 100% of the line impedance between buses PA200 and MLG plus an additional 180% of the line impedance between buses MLG and BNB.

C. Transmission Line Analyzed

The line analyzed in this work is an expanded bundle double-circuit transmission line. The nominal voltage is 230 kV. Fig. 3 illustrates the conductor's configuration of one of the circuits, where a very asymmetric configuration can be noticed. For simplicity, it has been decided to consider the line as if it were a single circuit line, exactly as shown in Fig. 3. In future work, results obtained for the double circuit line will be presented. The configuration shown in Fig. 3 is used between the cities of Paulo Afonso and Fortaleza, in Brazil, as analyzed in [8]. Two conductors per phase and one ground wire are used. The height of the conductors and the ground wire shown in Fig. 3 are the average height. The longitudinal and shunt parameters of the transmission line were calculated at 60 Hz and considering a ground resistivity of 1000 Ω.m.

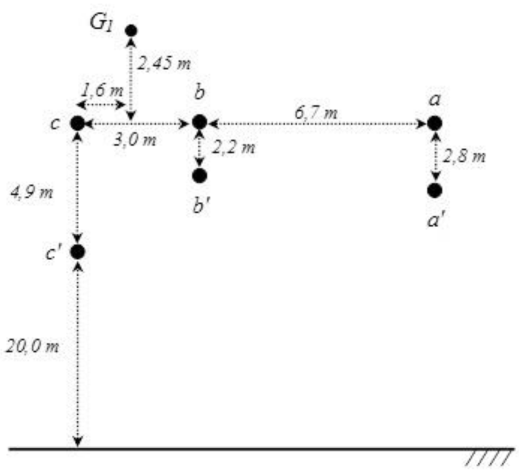

Fig. 3. Conductors geometry

The transmission line presents three sections along the buses of Paulo Afonso (PA200), Milagres (MLG), Banabuiu (BNB), and Fortaleza (FTZ). The length of each section and the line transposition scheme are presented in Fig. 4.

In the analysis that will be presented, only the relay at bus PA200 is considered, since this relay should protect all the line until close to FTZ, according to the protection zones.

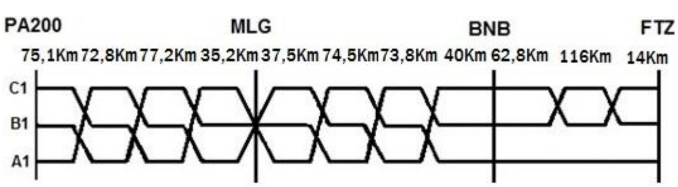

Fig. 4. Actual transposition scheme for the transmission line between Paulo Afonso and Fortaleza.

IV. Results and Simulation Analysis

The faults were applied at every 25 km, along the line for the three suggested situations: untransposed, ideally transposed, and actually transposed lines, according to the transposition sections shown in Fig. 4.

The R-X diagram illustrates the impedance path as seen by the relay for each situation previously mentioned. The closer to the relay bus the fault is applied, the smaller are the differences in the path for the two types of transpositions considered (ideal and actual) and for the case without transposition. Initially only solid faults are considered. However a comparison with a non-solid fault scenario is presented in the end of this section. Some significant situations for different types of faults will now be presented.

A. Single-Phase Fault Applied in Phase A

1) Location of the fault: 250 km from bus PA200

Fig. 5 shows the impedance path as seen by the relay Zag for the untransposed line, ideally transposed line, and actually transposed line, respectively. The fault is applied at a distance of 250 km from PA200.

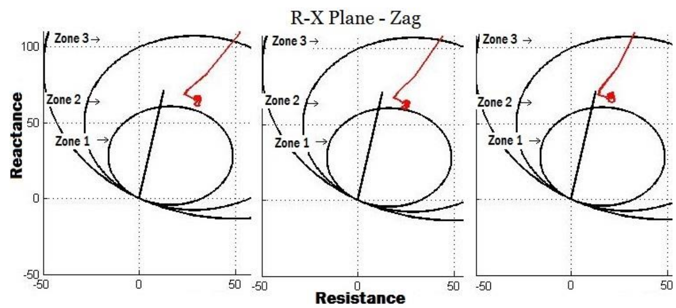

Fig. 5. R-X diagram for the Z_{ag} unit for the cases without transposition, with ideal transposition, and with actual transposition, respectively.

It is possible to verify a subtle difference in the R-X diagram among the three possible scenarios. However, in the case of an ideally transposed line, the impedance path has reached closer to the first protection zone than in the other two cases. In fact, there may exist a specific fault location where, in the ideally transposed case, the impedance path falls inside the relay´s first protection zone whereas in the other two scenarios, the impedance path falls inside the second protection zone only. In this situation, the error is significant since the relay operates instantaneously in its first protection zone while in the other protection zones there is a delay so that another relay may detect the fault in its first zone.

2) Aplication of the fault along the line

The magnitude and phase of the impedance Z_{ag} in steady state, after the fault has occurred, were used in order to plot the percent error, with the values obtained for the ideally transposed case serving as reference when compared to the other two possibilities. The fault was applied at every 25 km in the line shown in Fig. 4 up to 425 km. Figs. 6 and 7 show the results obtained for the magnitude and phase respectively when a single-phase fault is applied.

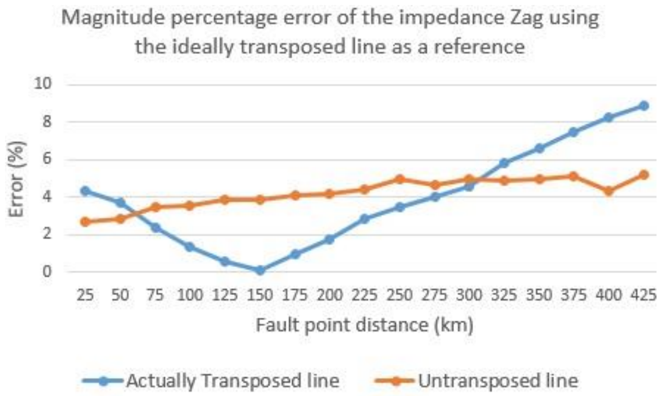

Fig. 6. Z_{ag} magnitude error in steady-state having as reference the values obtained considering the line ideally transposed.

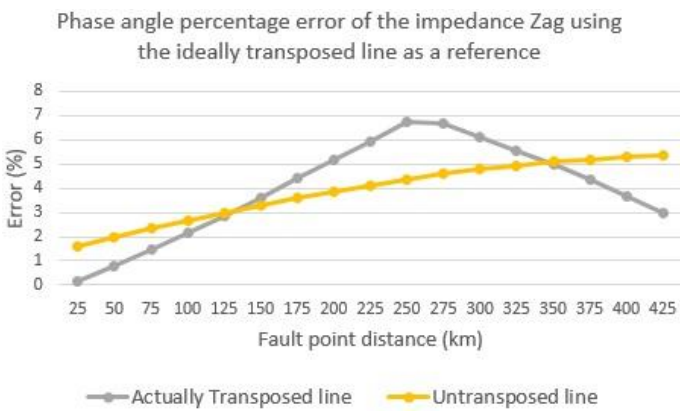

Fig. 7. Z_{ag} phase error in steady-state having as reference the values obtained considering the line ideally transposed.

Figs. 6 and 7 show that the behavior of the untransposed line is more constant than the behavior of the actually transposed line when compared to an ideally transposed line. This condition is verified both in the magnitude and phase of Zag.

Fig. 6 shows that the actually transposed line presents the maximum error in the magnitude of Zag when compared to the untransposed line (always having as reference the ideally transposed line). However, for distances varying from 75 to 300 km, the untranposed line presents a larger error in the magnitude of Zag.

Fig. 7 shows that the error in the phase of the Zag impedance keeps growing up to 250 km for the actually transposed line and then starts to decrease. In the untransposed case the error always increases with the increase in the line length. Once again the maximum and minimum peak errors are found in the actually transposed line.

B. *Double-Phase to Ground Fault Applied in Phases A and B*

In the case of a double-phase to ground fault, involving phases A and B, three impedance units of the relay should identify the fault. In this situation, the impedance units are: Zag, Zbg, and Zab.

1) *Fault location: 250 km from bus PA200*

The R-X diagrams shown in Figs. 8 and 9 show the impedance path for the ground and phase impedances, respectively, as seen by the relay.

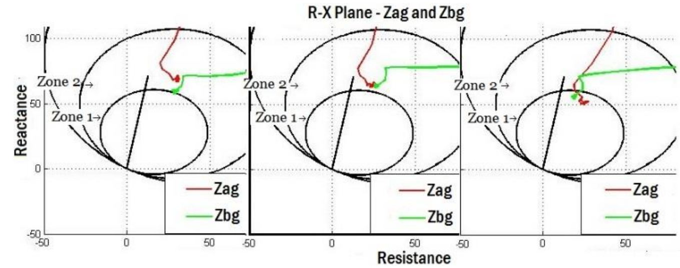

Fig. 8. R-X diagram for the Z_{ag} and Z_{bg} units for the cases without transposition, with ideal transposition and with actual transposition, respectively.

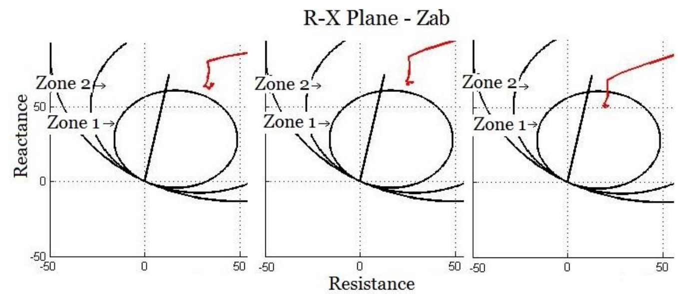

Fig. 9. R-X diagram for the Z_{ab} unit for the cases without transposition, with ideal transposition and with actual transposition, respectively.

It is possible to visualize that when a double-phase to ground fault occurs, the type of line transposition adopted interferes in the relay operation. When the actual transposition is considered, the three impedance units would lead the relay to operate in its first protection zone. This would result in an overreaching of the relay in the actual transposition scenario, since 250 km from bus PA200 is in the second protection zone of the relay.

2) *Aplication of the fault along the line*

Figs. 10 and 11 show the percent error in the magnitude and phase for the ground unit Zag, respectively, having as reference the case of ideal transposition.

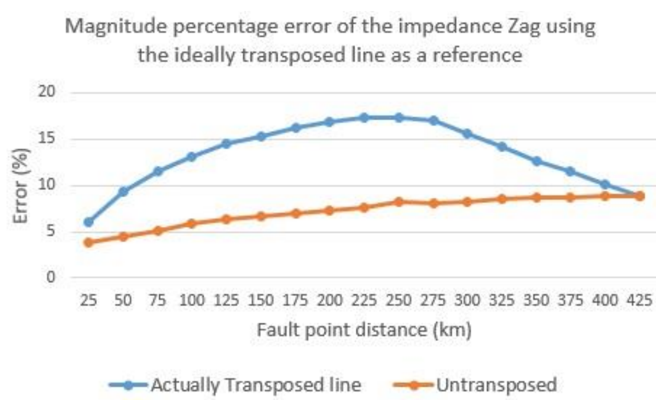

Fig. 10. Z_{ag} magnitude error in steady-state having as reference the values obtained considering the line ideally transposed.

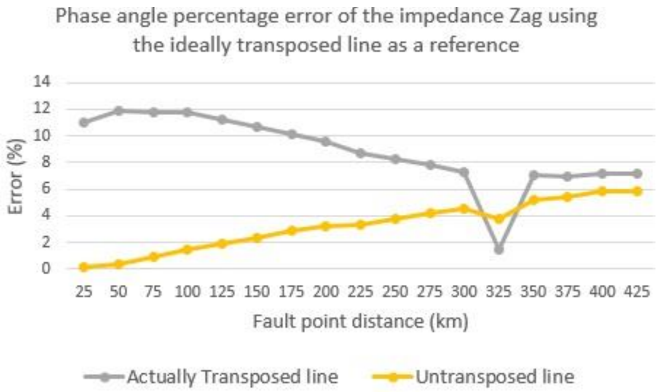

Fig. 11. Z_{ag} phase error in steady-state having as reference the values obtained considering the line ideally transposed.

Figs. 10 and 11 clearly show a relative error larger for the actually transposed line than for the untransposed line. In fact, the definition of relative error is restricted to the comparison of values. Therefore, the actually transposed line differs more from the ideally transposed line than the untransposed line does.

In this case, it should be stated that, although the difference is larger in the actually transposed line, the value of the Zag magnitude in this situation was always lower than the same value for the ideally transposed line, as shown in Fig. 12. This implies in a larger possibility of relay overreaching along the actually transposed line than in the cases of an ideally transposed and an untransposed line.

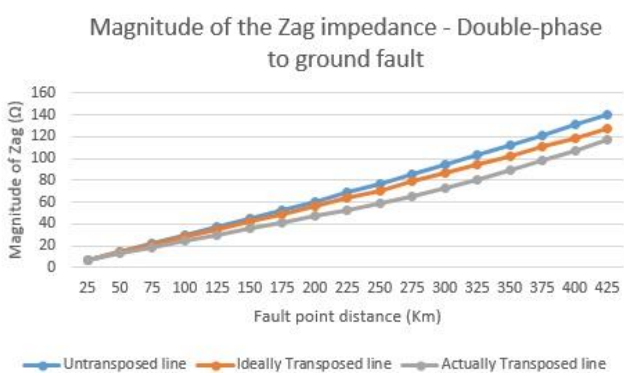

Fig. 12. Z_{ag} magnitude in steady-state for the three possible transposition schemes.

C. Three-Phase Fault

1) Fault location: 250 km from bus PA200

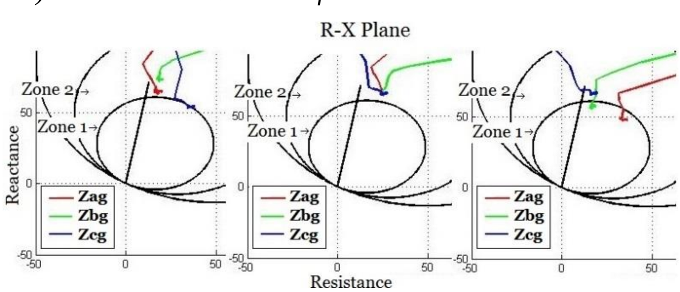

Fig. 13. R-X diagram for the Z_{ag}, Z_{bg}, and Z_{cg} units considering the cases without transposition, with ideal transposition, and with actual transposition, respectively.

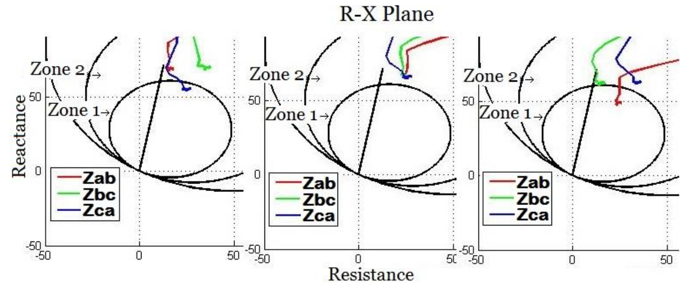

Fig. 14. R-X diagram for the Z_{ab}, Z_{bc}, and Z_{ca} units considering the cases without transposition, with ideal transposition, and with actual transposition, respectively.

Fig. 13 shows the behavior of the ground units for a three-phase fault, whereas Fig. 14 shows the behavior for the phase units.

Once again an overreaching scenario can be observed when the actually transposed or the untransposed lines are considered. It is verified that if a three-phase fault occurs, the relay for the ideally transposed line operates in its second protection zone, as expected. However, for the untransposed line, unit Zca leads the relay to operate in its first protection zone. Finally, the relay in the actually transposed line also operates in its first protection zone, having three impedance units with paths inside it (Zag, Zbg, and Zab).

It is important to state that the results are being presented for a distance of 250 km from bus PA200 because it is an important location in respect to the operation of the protection system, since the transposition schemes differ in connection to the protection zone where the relay should operate.

2) Aplication of the fault along the line

When applying the three-phase fault along the line shown in Fig. 4, considering the three transposition schemes, the errors in magnitude and phase in steady-state were calculated for units Zag and Zab, having as reference the values obtained for the ideally transposed line.

Figs. 15, 16, 17, and 18 show the percent error in magnitude and phase for impedances Zag and Zab, respectively.

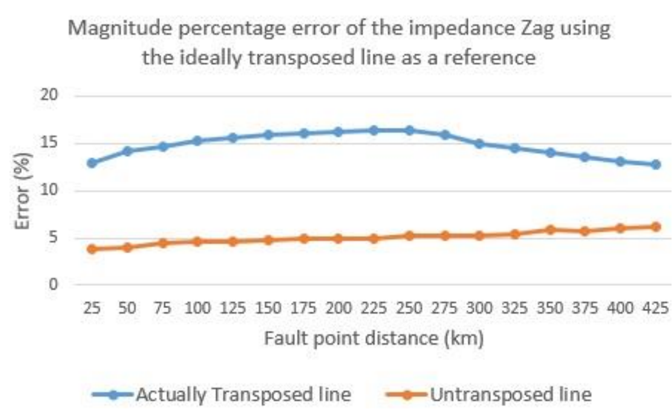

Fig. 15. Z_{ag} magnitude error in steady-state having as reference the values obtained considering the line ideally transposed.

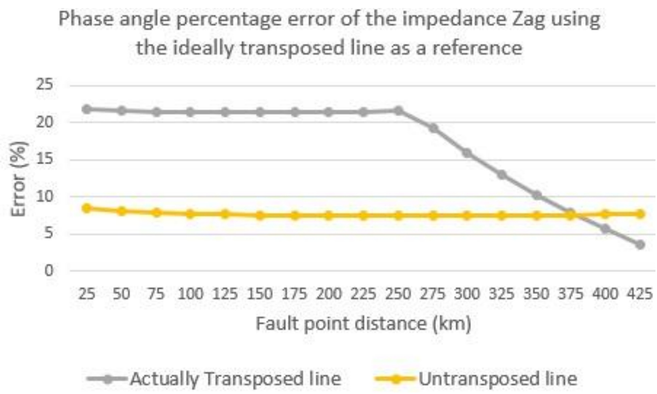

Fig. 16. Z_{ag} phase error in steady-state having as reference the values obtained considering the line ideally transposed.

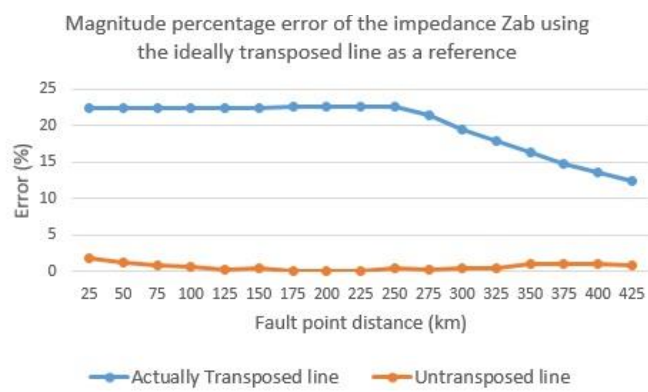

Fig. 17. Z_{ab} magnitude error in steady-state having as reference the values obtained considering the line ideally transposed.

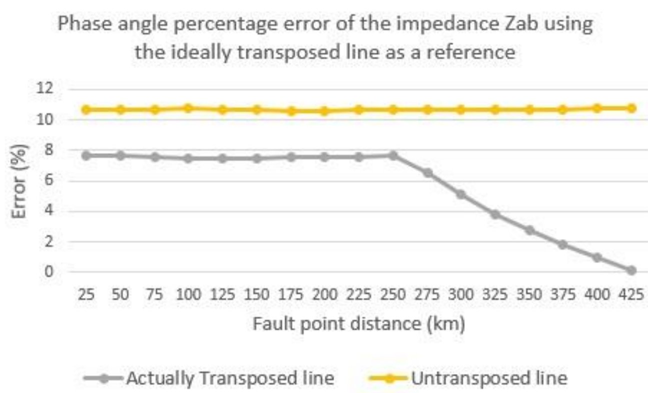

Fig. 18. Z_{ab} phase error in steady-state having as reference the values obtained considering the line ideally transposed.

Analyzing the three-phase fault situation, it is possible to observe a decrease in percent errors, starting at 250 km. In Fig. 4 the point corresponding to 250 km is located in the fourth transposition section, which is exactly the section where the transposition cycle is completed. When the fault is applied in the end of a complete transposition cycle, the relative error in the magnitude of the fault current decreases [9], and this reflects in the impedance seen by the relay.

D. Non-Solid Fault Scenario

With the purpose of observing the behavior of the distance relay in a more realistic fault situation, a fault resistance of 20 Ω was used and the results were compared with those obtained in the previous scenarios.

Fig. 19 shows the R-X diagrams for the relay units for the cases without transposition, with ideal transposition, and with actual transposition, when applying a single-phase fault in phase A. Figs. 20 and 21 show the same R-X diagrams when considering a double-phase to ground in phases A and B, and when considering a three-phase fault, respectively.

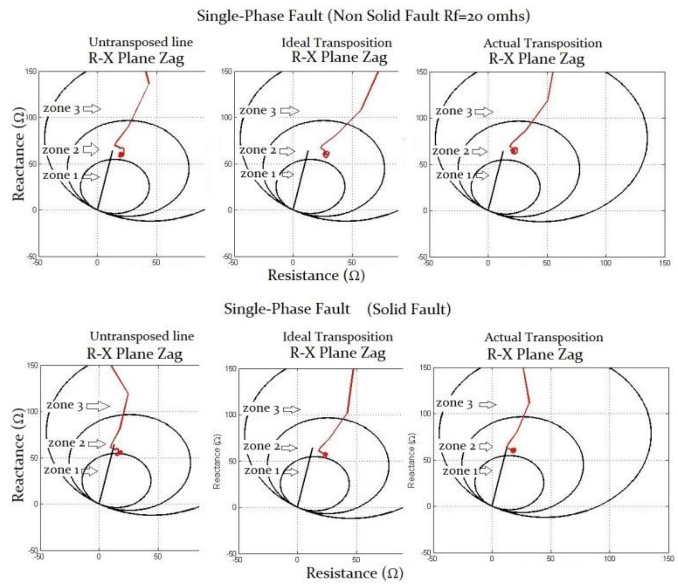

Fig. 19. Influence of considering a non-solid single-phase fault through a 20 Ω fault resistance when compared to a solid single-phase fault.

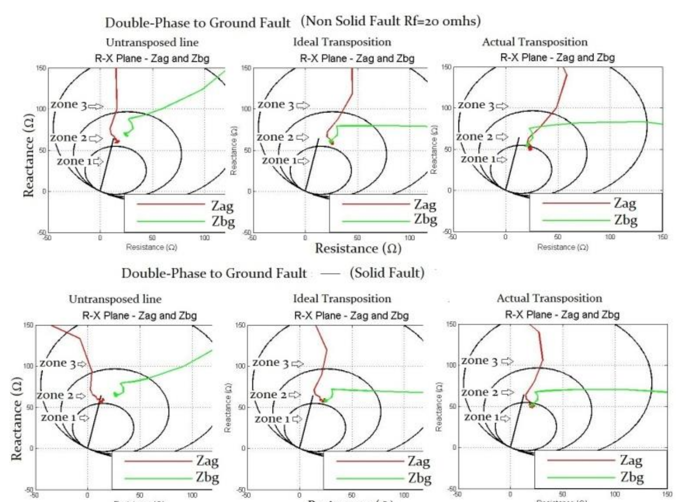

Fig. 20. Influence of considering a non-solid double-phase to ground fault through a 20 Ω fault resistance when compared to a solid double-phase to ground fault.

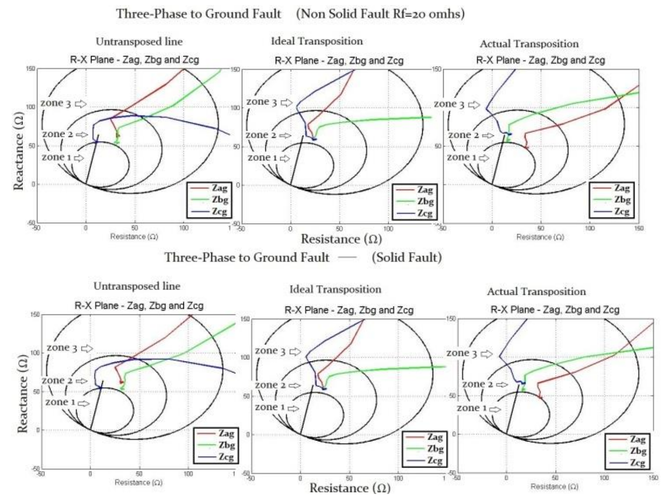

Fig. 21. Influence of considering a non-solid three-phase through a 20 Ω fault resistance when compared to a solid three-phase fault.

By analyzing Figs. 19, 20, and 21, it is possible to verify that there are differences in the impedance paths of the relay units when non-solid faults are considered when compared to the situations where solid faults are applied. However, there are no significant differences in the steady-state impedances seen by the relays.

V. Conclusions

When a fault occurs, the distance relay compares the measured impedance in the fault condition with the positive sequence impedance of the transmission line. The line is considered perfectly balanced and ideally transposed.

The simulation results presented in this paper show the error when treating untransposed or actually transposed transmission lines as ideally transposed. In general there may exist in the line, a location where the measurement of the impedance as seen by the relay under a fault condition may result in the anticipated or delayed relay operation.

The results also show that, in general, when a transposition cycle is completed, the errors in magnitude and phase of the impedances in steady-state for the actually transposed line, having as reference the ideally transposed line, tend to decrease.

A comparison was performed when considering non-solid faults with solid ones. The results obtained show that while there are differences in the impedance paths of the relay units, there are no significant differences in the steady-state impedances seen by the relays.

As already mentioned, for future work the authors intend to analyze the double-circuit transmission line between the substations of Paulo Afonso and Fortaleza, in Brazil. Also the effect of transposition on the homopolar compensation should be an interesting topic to consider especially in the case of double-circuit transmission lines.

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