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Influence of Infeed Current and Double Circuit Transmission Lines in Distance Protection

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Abstract: Detailed analysis of influence of infeed current and double circuit transmission lines in distance relays is presented in this work. In addition, is investigate the teleprotection scheme that allows the rapid and accurate fault extinction best suited for the system addressed with these complex topologies. The modeling stages of the test system and coordination studies of protection were carried out in commercial software designed to simulate protection studies of power electrical systems, where multiple fault scenarios have been applied, considering influence of infeed current and double circuit transmission lines separately. The results revealed the presence of inaccuracies in the apparent impedance measurements, which should be considered when planning distance protection zones in complex power grid topologies. Furthermore, permissive overreach transfer trip teleprotection scheme proved to be more efficient in relation to the directional comparison blocking teleprotection scheme, since the former lead more accurate and faster faults extinction for the scenarios under study.

Keywords: protection relay, teleprotection, interoperability, mutual inductance, infeed current.

1. INTRODUCTION

The transmission system is the part of the electrical power system (EPS) responsible for the transport of electricity from power plants to main consumers and has been assuming extremely complex configurations, with several interconnections covering wide geographical areas. In this context, two options of transmission line (TL) configurations commonly used in EPS are included:

i. The option for double circuit transmission line (DCTL), which is due not only to the constant growth of load, but also to the restrictions to obtain new land strips that suit the passage of TL. However, DCTL can also act as a source of electromagnetic interference in several ways, such as the induction of voltages and currents in the parallel conductors neighboring the other TL, which are directly influenced by the magnetic coupling of the conductors (Picardi, 2012).
ii. The TL option that has leads used to establish intermediate load connections or reinforce the system due to low voltages, this configuration is known as multiterminal lines. However, when generators are installed between the fault point and the interconnect relay, voltage drop occurs caused by the injection of intermediate currents, this typical effect on multiterminal lines is called the infeed effect (NERC, 2006).

If a fault in an important TL is not identified and removed as quickly as possible, it could lead to widespread damage in the power system. To prevent the damage from spreading to the healthy parts of the power system, protective relays need to detect the faults (Nam, 2007). The protection of these transmission lines is performed mainly by distance relays, which are based on indirect measurement of the distance from fault location by computing the reactive impedance of the positive-sequence of a TL segment between the relay and the fault location (Ziegler, 2006; Silva, 2009). It is noteworthy that the TL configurations addressed, negatively influence the performance of distance protection, since the faults are not located correctly.

Despite their advantages (Gers, 2004), the distance relays have the following limitations:

- Selectivity issues: the first zone of the distance relay does not cover 100% of the TL length. Thus, some portion of the TL is protected by a second zone (Anderson, 1999).
- The apparent fault impedance from the relay's perspective may be altered as mutual coupling between parallel TL (or DCTL) and infeed currents from intermediate sources of feed (Silva, 2009). As a result, the adjustments of the zones can be impaired.

To mitigate such problems, specialists have been proposed several strategies. In Pazoki (2014), a conventional distance relay was modeled in a real-time simulator and studies were carried out observing the effect of the infeed current in 1st and 2nd zones of the mho comparator. Among the restrictions of this work, highlighted as intrinsic inaccuracies, such as relay modeling and absence of observation of the quadrilateral comparator without distance relation, commonly used both for phase and ground protection.

In Patten (2018), TL performance with long taps was analyzed, based on real examples, using CAPE software and some factors affecting the apparent impedance were highlighted, such as: i) tap length, ii) tap location along the TL and iii) source impedance ratio (SIR). The authors did not use any distance protection comparator in the studies, that is, they performed the activities with distance relays in a generic way, which is a major limitation of this work.

In Zeng (2011), the influence of the mutual inductance intensity, the difference between the energy source on both sides, the location of the fault and other related factors were considered. Among the limitations of this work, the intrinsic inaccuracies to the analytical development of this complex problem stand out, culminating in values that approached those obtained with the simulator in real time, but still generated divergence in decimal places in the measured impedance value, which can cause imprecision in the performance of the protection system.

In Al-Mahrooqi (2017), the influence of parallel TL on distance protection was studied, seeking to recommend the strategic configuration of the distance protection of the power grid. Among the limitations of this work, we highlight the intrinsic inaccuracies in the modeling of the relay and also in the use of an artificial TL.

The analysis of the state of art indicates that protecting TL with complex topologies, such as parallel TL or with intermediate sources, is a current and important problem. Although some studies consider the use of teleprotection schemes for LT with these topologies, which consists of establishing a channel communication between the relays, in order to allow the interconnection of the trip schemes, exchanging information about the logical states of the relays, few works evaluate which is the best scheme for the system under analysis. This work is inserted in this context and presents not only the use of a teleprotection scheme, but also a study to identify the most appropriate teleprotection scheme that allows the quick and accurate extinction of faults, considering a system with parallel TL and intermediate sources.

The permissive overreaching transfer trip (POTT) and directional comparison blocking (DCB) schemes were used, since the POTT scheme is commonly used in LT protection and together with the DCB scheme they have a lower merit value (ratio between the weighted average of the fault release times for detectable faults and the area total of resistive faults detectable by the scheme) in relation to the other teleprotection schemes, offering a better performance (Schweitzer, 1998).

This paper is organized as follows: In Sections 2 and 3 the fundamentals of distance protection and teleprotections are presented, respectively. Section 4 describes the materials and methods used in this study. Section 5 presents and discusses the results. Finally, Section 6 is devoted to the conclusions of this work.

2. DISTANCE PROTECTION

Distance relay is currently the most used device for the protection of TL, due to its simplicity of parameterization (adjust and coordination) as well as its economic viability (Silva, 2009). These devices determine the impedance between its position and a fault localization by using voltage and current measurements by instrumentation transformers. The impedance is proportional to the conductor length, i.e. the distance between the relay and the fault (Guajardo, 2017).

Conventional distance relays are designed to protect simple models of TL, in which a single-phase fault leads to proportional impedance measured by relay and the distance between the relay and the fault location. The impedance can be determined by using the conventional compensation method for the zero-sequence current. Mathematically, the apparent impedance of phase A, considering fault impedance is computed as (Hu, 2002):

$$\mathrm{Z}_{\mathrm{measured(phase-A)}} = \frac{\mathrm{V}_{\mathrm{sfA}}}{\mathrm{I}_{\mathrm{sfA}} + (\mathrm{K}_0 \times \mathrm{I}_{\mathrm{sf0}})} = \mathrm{mZ}_{\mathrm{L1}}, \tag{1}$$

$$\mathrm{K}_0 = \frac{\mathrm{Z}_{\mathrm{L0}} - \mathrm{Z}_{\mathrm{L1}}}{\mathrm{Z}_{\mathrm{L1}}}, \tag{2}$$

where: K_0 is the compensation factor of zero-sequence; Z_{L0} and Z_{L1} are the zero and positive-sequence TL impedances, respectively; V_{sfA} and I_{sfA} are the fase voltage and phase current after the fault in the relay location, respectively; m is the distance per unit between the distance relay and the fault location; and I_{sf0} is the after-fault zero-sequence current in the relay location.

A distance relay should operate when the apparent impedance is into its operational characteristic, which consists of a geometric shape in the R-X plane, which the abscissa axis represents the resistance R and the ordinate axis represents the reactance X (Ziegler, 2006; Anderson, 1999).

Typically, the 1st protection zone does not have intentional delay in its operation and its range of impedance usually is within 80% to 85% of the TL impedance. The safety margin of 15% to 20% of the unprotected TL section comes from due to uncertainties, such as intrinsic errors from instrument transformers, which can lead the relays to overreach or underreach (the measured impedance value is less or greater than the real value the actual value, respectively), which causes improper operation of the relay (Cook, 1985).

The 2nd protection zone should cover 100% of the line protected by the 1st zone, more between 20% and 50% of the smallest line that emanate from its remote terminal. Typically, its operation is delayed from an order time of 200 ms to 500 ms. Finally, the adjustment range of coverage the 3rd zone is established such way that it's possible to identify faults from the relay's position until the end of the electrically longer adjacent TL, causing an overreach of the 2nd zones from the others TL. The operating time of the 3rd zone must be greater than the operation time of the 1st and 2nd zones of adjacent TL and usually, this value is established around 1 second (Anderson, 1999; Gonçalves, 2007).

2.1 Effect of coupling between parallel TL

Usage of parallel TL has advantages, since a single transmission tower can support two, hence optimizing physical space. Because of the mutual coupling resulting from the interaction of the magnetic flux produced by each circuit, usually, the positive and negative-sequence currents present small values, however, the zero-sequence currents can present high values (Santos, 2017; Lukach, 2014).

To evaluate the effect of coupling between parallel TL, considering the circuit of a parallel TL showed in Fig. 1. The apparent impedance measured in phase A, disregarding the fault impedance, is computed by (Hu, 2002):

$$\mathrm{Z_{measured(phase-A)}} = \frac{\mathrm{V_{afA}}}{\mathrm{I_{afA}} + (\mathrm{K_0} \times \mathrm{I_{af0}})} = \mathrm{mZ_{ab1}} + \mathrm{Z_{ab1}}, \quad (3)$$

$$\mathrm{V_{afA}} = \mathrm{mZ_{ab1}} \times \left(\mathrm{I_{afA}} + (\mathrm{K_0} \times \mathrm{I_{af0}})\right) + (\mathrm{mZ_{m0}} \times \mathrm{IP_{af0}}), \quad (4)$$

$$\delta = \frac{\mathrm{m}\left(\frac{\mathrm{Z_{m0}}}{\mathrm{Z_{ab1}}}\right) \times \mathrm{IP_{af0}}}{\mathrm{I_{afA}} + (\mathrm{K_0} \times \mathrm{I_{af0}})}. \quad (5)$$

Where: Z_{m0} is the zero-sequence of mutual coupling; IP_{af0} is the zero-sequence current of the parallel TL; and δ is the error in per unit.

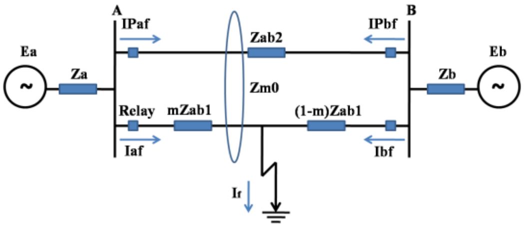

Fig. 1 Typical parallel TL circuit (adapted from Hu (2002).

There are embedded inaccuracies in the calculation of the apparent impedance measured by the conventional distance relay. These inaccuracies can lead to the overreach or underreach, depending on the relative direction of zero-sequence current of the parallel TL, IP_{af0} versus the compensated current $I_{\mathrm{afA}} + (K_0 \times I_{\mathrm{af0}})$. If they are in opposite directions, the relay will overreach, otherwise, the relay will underreach (Hu, 2002).

2.2 Infeed Effect

This effect occurs when an intermediate current source is inserted between the relay and the fault. To illustrate, consider the circuit of Fig. 2, in which a fault occurs at point F of the TL with three terminal sources (Horowitz, 2014).

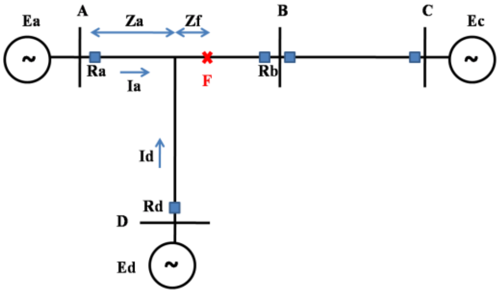

Fig. 2 Infeed effect in the settings of the relay distance zones (adapted from Horowitz (2014)).

Considering the relay R_{a}, the voltage at bar A is related to the current in bar A by the equation (Horowitz, 2014):

$$\mathrm{E_A} = \mathrm{Z_a I_a} + \mathrm{Z_f}(\mathrm{I_a} + \mathrm{I_d}), \quad (6)$$

and the apparent impedance seen by the relay R_{a}:

$$\mathrm{Z_{apparent(R_a)}} = \frac{\mathrm{E_A}}{\mathrm{I_a}} = \mathrm{Z_a} + \mathrm{Z_f}\left(1 + \frac{\mathrm{I_d}}{\mathrm{I_a}}\right). \quad (7)$$

From Fig. 2 can be observed that the tree sources contribute to the fault current. The current I_{d}, which corresponds to the contribution to the tap's fault, is referred to as infeed current if it's approximately in phase with I_{a}, otherwise, it's named outfeed current. If increase occurs (infeed) or reduction (outfeed) of the fault impedance measured by the relay, overreach or underreach of relay can occur, respectively (Horowitz, 2014; Cook, 1985).

3. TELEPROTECTION SCHEMES

As previously presented, in conventional protection systems, distance relays do not fully protect TL in 1st zone. Besides, it's observed that in about 40% of line, complete extinction of fault is delayed by second zone delay (Anderson, 1999). To work around this situation, the teleprotection schemes are employed. Briefly, teleprotection schemes are defined by standard, as three types: direct shot, permissive shot (or of transfer); and block. The distinction between these schemes depends on some factors, such as: reliability, number of terminals and the distance between them, number of required channels, cost, as well as selection among the links available for usage (Silva, 2009).

The main purpose of the teleprotection scheme is to perform data sharing and analysis between the relays in order to determine a fault location. This makes it possible to accelerate the decision-making process of the relay, both in the blockade against external faults and in the extinction of faults (Guerrero, 2011).

In practice, there are several teleprotection schemes, which are defined according to the characteristic of their impedance zone used for starting the transmission of the triggering or blocking trip signal. The standard IEC 60834-1 indicates the use of three parameters to analyze the performance of the schemes: reliability, security and latency (Dolezilek, 2014). All schemes have advantages and disadvantages over the others, thus, the search for balance of better among of better the three is necessary for satisfactory performance.

In this work, the operating time of POTT and DCB schemes were evaluated in a commercial software. These schemes were chosen because they are safe and reliable, respectively, indispensable requirements, especially for TL with complex topologies.

3.1 The POTT scheme

This scheme uses the 2nd zone timed element to send a permissive trip signal to the relay on the TL remote terminal. The relay in remote terminal, in turn, will give the opening command to the circuit breaker, if it receives the permissive trip signal and its element of 2nd zone has detected the lack (Silva, 2009). ECHO logic may also be used to transmit the trip signal if the circuit breaker is pre-opened (Guerrero, 2011).

3.2 The DCB scheme

In this scheme, the trigger command of the overreach unit has a time delay associated with the waiting period upon receipt of the blocking signal. This time interval, typically 1 to 2 cycles, is called a coordination time, *T*, which shall be calculated to compensate the signal propagation channel times and adds a safety margin. If the blocking signal does not arrive within *T*, the trigger command from the overreach unit will be released (Guerrero, 2011). However, this actuation is only permitted if the relay does not receive a blocking signal from the 3rd of the overreach unit on the remote terminal (Silva, 2009)

4. MATERIALS AND METHODS

To evaluate teleprotection scheme that will allow the most accurate and rapid extinction of faults in configurations with parallel TL or with intermediate sources, it was adopted the distance relay model SEL-311C of Schweitzer Company. The methodology applied is presented in the flowchart of Fig. 3.

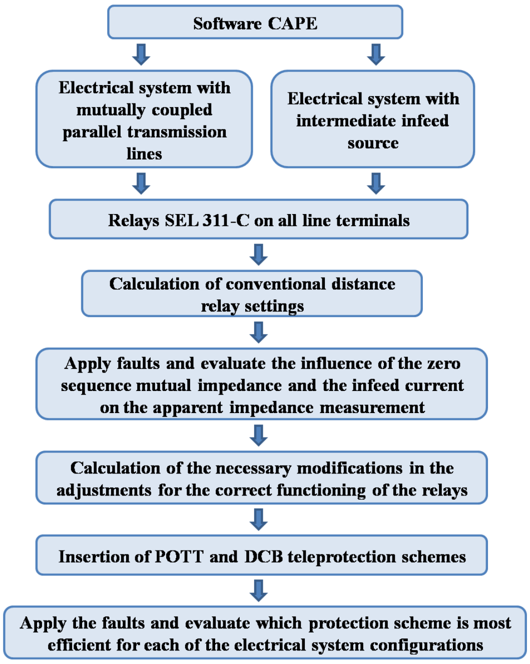

Fig. 3 Adopted methodology.

The modeling stages of the test system and coordination studies of protection were carried out in the Computer Aided Protection Engineering (CAPE^{TM}), commercial software designed to simulate protection studies of power electrical systems.

The test system adopted was based on the system proposed by (IEEE, 2004) and consists of (Fig. 4): four 72.42 km, 230 kV TL, of which two are parallel TL (TL1 and TL2) and two are simple TL (TL3 and TL4); current transformers (CT) and potential (PT), with ratios of 400 and 2000, respectively; three Thévenin equivalent (S1, S2 and S3) proposed by Lopes (2014); distance relays adjusted according to relay SEL-311C settings (SELINC, 2019). All the parameters used in the modeling of the test system were provided by (IEEE, 2004). For the test system in question, the distance relay was applied as primary / rearguard protection for all LT.

The delay and pickup time adjustments of the POTT and DCB schemes are shown in Table 1, which were computed following the SEL-311C relay configuration schedule.

In the study, three modes of operation of the test system were evaluated:

- No mutual impedance influence of zero- sequence and no infeed current, that is, separated parallel TL in single-circuit tower and intermediate source S3 disconnected;
- Mutual impedance influence of zero-sequence, but no infeed current, that is, close parallel TL in parallel towers and intermediate source S3 disconnected;
- Infeed current influence, that is, separated parallel TL in simple circuit towers and intermediate source S3 connected.

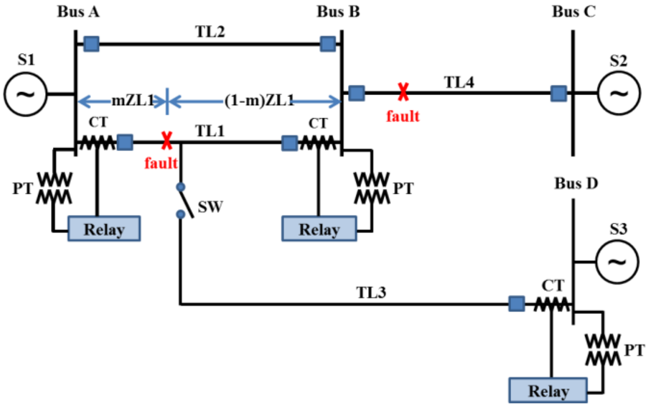

Fig. 4 Test system (adapted from IEEE (2004)).

Table 1. POTT and DCB schemes delay and pickup time settings.

Teleprotection	Transmission channel delay time (cycles)	Channel delay time for echo (cycles)	Operation time for coordination (cycles)
POTT	0.5	2	-
DCB	0.5	-	1

In this work is important to say, the outfeed effect was not approached, since this would require a change in the configuration of the test system, that is, remove the intermediate source and insert a load in its place.

5. RESULTS AND ANALYSIS

By applying faults in TL1 and TL4, as shown in Table 2, the apparent fault impedances measured by the distance relays were analyzed.

Table 2. Case study.

Cases	Fault type	Transmission line	Fault location	Fault impedance
I	AT	TL1	19% of bar A	$Zf = 0\ \Omega$
			80% of bar A	
		TL4	20% of bar B	
II	ABT	TL1	19% of bar A	$Zf = 0\ \Omega$
			80% of bar A	
		TL4	20% of bar B	
III	AB	TL1	19% of bar A	$Zf = 0\ \Omega$
			80% of bar A	
		TL4	20% of bar B	
IV	ABC	TL1	19% of bar A	$Zf = 0\ \Omega$
			80% of bar A	
		TL4	20% of bar B	

In order to evaluate only the effects of the infeed currents and the coupling between parallel TL, fault impedance was disregarded in this study, since this parameter can also cause errors in the measurement of conventional distance relays (Silva, 2009).

For parallel TL with zero-sequence mutual impedance, only case I presented on Table 2 was considered, since the effect of the zero-sequence current is present only in single-phase-to-ground faults.

Only case I was analyzed in detail, the other are discriminated against in table 4. Also are presented the modifications made in coverage of 2nd zone, aiming to maintain the selectivity, since changes in the 1st zone can cause overreach if the factors causing errors are removed from the system.

5.1 Case I: Mutual impedance and no teleprotection scheme

A. Fault location at 19% of bar A (TL1), $Z_f = 0\ \Omega$:

- Apparent impedance is $6.61\underline{/83.12^\circ}\ \Omega$, identified by relay distance function;
- The 1st zone of ground (red quadrilateral) was triggered by the fault and actuated in 0.017 s;
- If 1st zone fails, the 2nd zone of ground (green quadrilateral) is triggered by the fault and actuated in 0.417 s;
- The 3rd zone of ground (blue quadrilateral) was not sensitized, since it has been configured in reverse direction.

B. Fault located at 80% of bar A (TL1), $Z_f = 0\ \Omega$:

- Apparent impedance is $32.84\underline{/82.45^\circ}\ \Omega$, identified by relay distance function;
- The fault did not trigger the 1st zone of ground, since its location is out of the reach of 80% of TL;
- The 2nd zone of ground (green quadrilateral) was triggered by the fault and actuated in 0.417 s;
- The 3rd zone of ground (blue quadrilateral) was not triggered, since it has been configured in reverse direction.

C. Fault located at 20% of bar B (TL4), $Z_f = 0\ \Omega$:

- Apparent impedance is $60.74\underline{/82.14^\circ}\ \Omega$, identified by the relay distance function;
- The fault did not trigger the 1st zone of ground since its location is out of the reach of 80% of TL;
- The 2nd zone of ground (green quadrilateral) was not triggered, since its location is out of reach of 120% of TL;
- The 3rd zone of ground (blue quadrilateral) was not triggered, since it has been configured in reverse direction.

The location of the apparent fault impedances identified by the relay, represented by "x" in the quadrilateral characteristics is shown in Fig. 5.

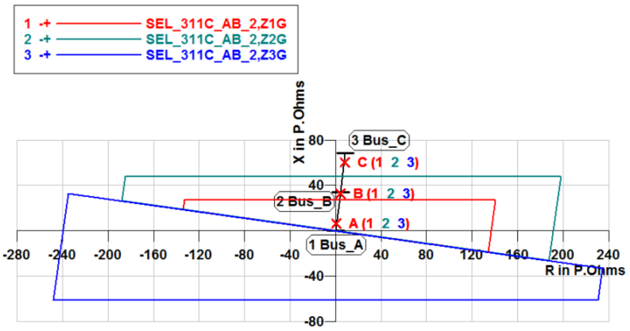

Fig. 5 R-X diagram of the quadrilateral characteristic from the perspective of the relay installed in bar A of Case I (with mutual impedance and without teleprotection).

It is observed that in the system with mutual impedance and no teleprotection scheme the distance relay did not operate correctly because it does not identify the fault in the correct location of its occurrence. Thus, in order to the relay to detect all faults applied and to maintain selectivity, it's necessary to adjust the second zone. Comparing the measurements with theorical values for case I - C (fault located at 20% of bus B and $Z_f = 0\ \Omega$):

$$Z_{\text{apparent\_measured}(120\%)} = 60.74\underline{/82.14^\circ}\ \Omega,$$

$$Z_{\text{apparent}(120\%)} = 1.2 \text{ x } 34.485\underline{/82.89^\circ}\ \Omega = 41.38\underline{/82.89^\circ}\ \Omega.$$

These values demonstrate that an underreach has occurred because with this range adjustment, the relay detects only faults with apparent impedance bellow $Z_{\text{apparent}(120\%)}$, since the $Z_{\text{apparent\_measured}(120\%)}$ is greater than $Z_{\text{apparent}(120\%)}$. Therefore, the range required for the relay to detect fault at about 120% of bus A, with TL with mutual impedance is obtained as follows:

$$m = \frac{Z_{\text{apparent\_measured}(120\%)}}{Z_{L1}} = 1.76,$$

$$\text{Reach}_{Z2} = \text{m x}100\% = 176\%.$$

In this configuration, all distant faults of bar A between 0 and 120% will be reached by the 2nd zone. If the system is modified, this adjustment should be reviewed. As shown in Fig. 6, after adjusting the range of the 2nd zone, the distance relay detects the faults applied without underreach in the 2nd zone.

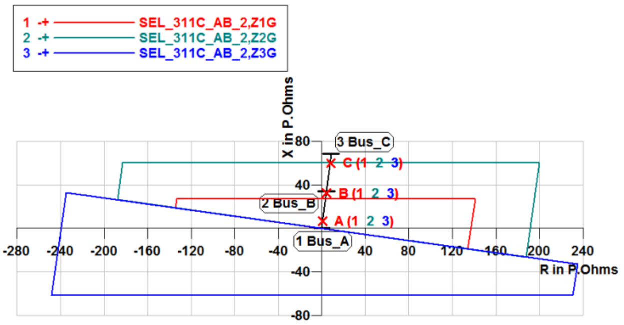

Fig. 6 R-X diagram of the quadrilateral characteristic from the perspective of the relay installed in bar A of Case I (with mutual impedance and without teleprotection), with range correction.

5.2 Case I: Current infeed and no teleprotection scheme

A. Fault located at 19% of bar A (TL1), $Z_f = 0\ \Omega$:

- Apparent impedance is $6.56\underline{/82.85^\circ}\ \Omega$, identified by relay distance function;
- The 1st zone of ground (red quadrilateral) was triggered by the fault and actuated in 0.017 s;
- If 1st zone fails, the 2nd zone of ground (green quadrilateral) is triggered by the fault and actuated in 0.417 s;
- The 3rd zone of ground (blue quadrilateral) was not triggered since it has been configured in reverse direction.

B. Fault located at 80% of bar A (TL1), $Z_f = 0\ \Omega$:

- Apparent impedance is $37.73\underline{/80.05^\circ}\ \Omega$, identified by relay distance function;
- The fault did not trigger the 1st zone of ground since its location is out of the reach of 80% of TL;
- The 2nd zone of ground (green quadrilateral) was triggered and actuated in 0.417 s;
- The 3rd zone ground (blue quadrilateral) was not triggered since it has been configured in reverse direction.

C. Fault located at 20% of bar B (TL4), $Z_f = 0\ \Omega$:

- Apparent impedance is $74.77\underline{/78.14^\circ}\ \Omega$, identified by relay distance function;
- The fault did not trigger the 1st zone of ground since its location is out of the reach of 80% of TL;
- The 2nd zone of ground (green quadrilateral) was not triggered, since its location is out of reach of 120% of TL;
- The 3rd zone of ground (blue quadrilateral) was not triggered since it has been configured in reverse direction.

The location of the apparent fault impedances identified by the relay, represented by "x" in the quadrilateral characteristics is shown in Fig. 7.

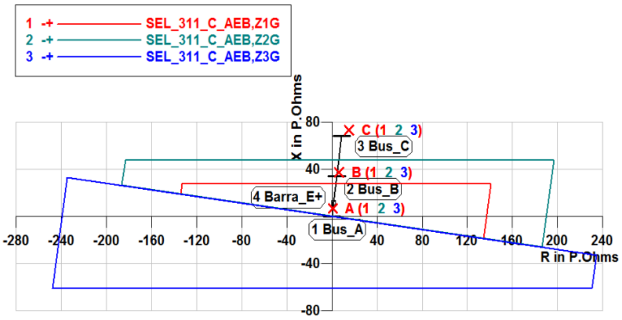

Fig. 7 R-X diagram of the quadrilateral characteristic from the perspective of the relay installed in bar A of Case I (with current infeed and without teleprotection).

It is observed that in the system with infeed current and no protection scheme, the relay did not operate correctly, because it does not identify the fault in the correct location of its occurrence. Thus, in order to the relay to see all faults applied and to maintain selectivity, it's necessary to adjust the second zone. In the case I-C (fault located at 20% of bus B and $Z_f = 0\ \Omega$):

$$\mathrm{Z}_{\mathrm{apparent\_measured(120\%)}} = 74.77\underline{/78.14^\circ}\ \Omega,$$

$$\mathrm{Z}_{\mathrm{apparent(120\%)}} = 1.2 \text{ x } 34.485\underline{/82.89^\circ}\ \Omega = 41.38\underline{/82.89^\circ}\ \Omega.$$

These values demonstrate that an underreach has occurred because with this range adjustment, the relay detects only faults with apparent impedance bellow $Z_{\mathrm{apparent(120\%)}}$, since the $Z_{\mathrm{apparent\_measured(120\%)}}$ is greater than $Z_{\mathrm{apparent(120\%)}}$. Therefore, the range required for the relay to detect fault at about 120% of bus A, with TL with infeed current is obtained as follows:

$$\mathrm{m} = \frac{\mathrm{Z}_{\mathrm{apparent\_measured(120\%)}}}{\mathrm{Z}_{\mathrm{L1}}} = 2.17,$$

$$\mathrm{Reach}_{Z2} = m \times 100\% = 217\%.$$

In this configuration, all distant faults of bar A between 0 and 120% will be reached by the 2nd zone. If the system is modified, this adjustment should be reviewed. As shown in Fig. 8, after adjusting the range of the 2nd zone, the distance relay sees the faults applied without underreach in the 2nd zone.

The errors inserted in the apparent impedance values are a consequence of mutual impedance and infeed current, since: i) the faults applied at the limits of the 1st zone were detected in the 2nd zone; ii) the faults applied within the limits of the 2nd zone are not detected.

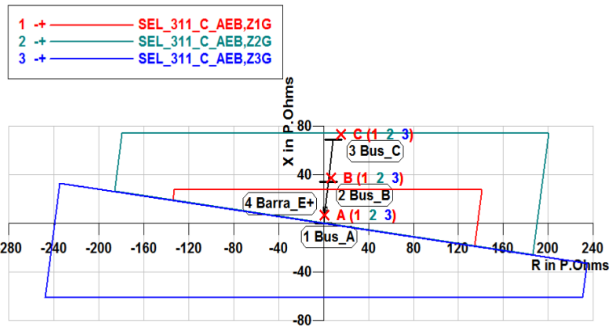

Fig. 8 R-X diagram of the quadrilateral characteristic from the perspective of the relay installed in bar A of Case I (with infeed effect and no teleprotection scheme), with range correction.

Once the adjustments were made, faults applied to the 2nd zone boundary were identified correctly. Therefore, one of the problems was circumvented, however, faults located in a percentage in LT1 remain not quickly eliminated, as this is a characteristic limitation of distance relays.

To work around this problem, teleprotection schemes have been applied. A summary of the results is presented in Tables 3 and 4.

Table 3. Comparative analysis of protection system with and without teleprotection in circuits with TL with mutual inductance.

Case	Without Teleprotection				POTT(P)				DCB(D)			
	Sub_A		Sub_B		Sub_A		Sub_B		Sub_A		Sub_B	
	T(s)	Zone	T(s)	Zone	T(s)	Zone	T(s)	Zone	T(s)	Zone	T(s)	Zone
I	0.017	Z1	0.417	Z2	0.074	Z1/P	0.074	P	0.074	Z1/D	0.074	D
	0.417	Z2	0.017	Z1	0.082	P	0.074	Z1/P	0.091	D	0.074	Z1/D
	0.417	Z2	1.017	Z3	0.474	Z4	-	-	0.474	Z4	-	-

Table 4. Comparative analysis of protection system with and without teleprotection in circuits with TL with infeed effect.

Case	Without Teleprotection				POTT(P)				DCB(D)			
	Sub_A		Sub_B		Sub_A		Sub_B		Sub_A		Sub_B	
	T(s)	Zone	T(s)	Zone	T(s)	Zone	T(s)	Zone	T(s)	Zone	T(s)	Zone
I	0.017	Z1	0.417	Z2	0.074	Z1/P	0.082	P	0.074	Z1/D	0.091	D
	0.417	Z2	0.017	Z1	0.082	P	0.074	Z1/P	0.091	D	0.074	Z1/D
	0.417	Z2	1.017	Z3	0.474	Z4	-	-	0.474	Z4	-	-
II	0.017	Z1	0.417	Z2	0.071	Z1/P	0.079	P	0.071	Z1/D	0.087	D
	0.417	Z2	0.017	Z1	0.079	P	0.071	Z1/P	0.087	D	0.071	Z1/D
	0.417	Z2	1.017	Z3	0.471	Z4	-	-	0.471	Z4	-	-
III	0.017	Z1	0.417	Z2	0.071	Z1/P	0.079	P	0.071	Z1/D	0.087	D
	0.417	Z2	0.017	Z1	0.079	P	0.071	Z1/P	0.087	D	0.071	Z1/D
	0.417	Z2	1.017	Z3	0.471	Z4	-	-	0.471	Z4	-	-
IV	0.017	Z1	0.417	Z2	0.071	Z1/P	0.079	P	0.071	Z1/D	0.087	D
	0.417	Z2	0.017	Z1	0.079	P	0.071	Z1/P	0.087	D	0.071	Z1/D
	0.417	Z2	1.017	Z3	0.471	Z4	-	-	0.471	Z4	-	-

The detailed analysis of the results presented in Tables 3 and 4 showed the following:

- System without teleprotection schemes: The faults were not extinguished at both terminals as fast as with teleprotection scheme, since the relays installed in bars A and B identified faults in different zones, which in turn are timed: the 1st zone after 0.017 s, the 2nd zone after 0.417 s and the 3rd zone, after 1.017 s. Thus, the complete extinction of the fault, that is, by both terminals, happened in the interval between 0.4 s and 0.6 s, if the zone 1 (relay of bus A) and zone 2 (bus relay B) or zone 2 (bus A relay) and zone 3 (bus relay B) respectively are sensitized;

- System with POTT scheme: The faults within the protected TL were correctly identified and their extinction by both terminals occurred between 0.0 and 0.008 s interval. In cases related to faults located in the adjacent TL, the POTT scheme was not sensitized, since the teleprotection scheme aims to protect only the TL in which the relays are installed. Thus, only a 4th zone (set as the 2nd conventional zone) of the relay installed at bus A was sensitized with a time delay of 0.417 s.

- System with DCB scheme: The faults within the protected TL were correctly identified and their extinction by both terminals occurred with an interval between 0.0 and 0.017 s. In cases related to faults located in the adjacent TL, the DCB scheme was not triggered, since the teleprotection scheme aims to protect only the TL in which the relays are installed. Thus, only a 4th zone (set as the 2nd conventional zone) of the relay installed in bus A was sensitized with a time delay of 0.417 s.

Finally, after equipping the relays installed on buses A and B with the POTT and DCB protection schemes, the following were found:

- Increased effectiveness of the protection system and stability of the EPS, since in case of fault, teleprotection schemes help to quickly isolate the section of the system under defective, in order to avoid large black-out areas;

- In the cases of faults located in the protected TL, the POTT scheme was more efficient than the DCB scheme, because it promoted the faster extinction of the fault, that is, with less delay or with equal extinction time for the relays of both bars.

5. CONCLUSIONS

The study carried out in this work showed the importance of the studies related to the protection of transmission lines, especially when using teleprotection schemes with distance relays, which demonstrates the relevance of this topic. Making use of specific simulation software for protection studies of electrical power systems, a test system was modeled considering infeed effect from intermediate sources and mutual coupling between parallel transmission lines. In the modeled system, two teleprotection schemes were compared under the same circumstances.

From the measured apparent impedance, it was proved that the mutual impedance and the infeed current are source of errors in the measurement of this parameter, which compromises the performance of the distance relays. In order to address these errors, adjustments were made in the coverage ranges of the installed relays, and new fault simulations were performed. As consequence, it was observed that even with the new adjustments, the performance of the relays continued to be compromised.

In order to correct this problem, POTT and DCB teleprotection schemes were inserted separately, which resulted in more accurate and rapid extinction of faults in all situations analyzed. At the end, it was found that: i) DCB scheme promoted complete extinction of the fault, with a shorter time delay than the system without teleprotection; ii) POTT scheme promoted complete extinction of faults without time delay or with a shorter time delay than the system with DCB scheme.

It was concluded that for the evaluated cases, the POTT teleprotection scheme was considered the most efficient, for both configurations contemplating parallel lines and infeed currents.

The study conducted in this paper aggregates to the improvement of power grid's reliability in terms of power outages. It also sets a foundation for studies regarding complex power systems, such as the ones use in the one this work. Finally, the paper reviews the advantages of POTT scheme over systems without any sort of teleprotection schemes.

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