Improvement of resistive reach of distance protection through a power flow-based adaptive parameterization

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Abstract – **An adaptive operational logic scheme considering the effect of pre-fault load is introduced for distance protection applications to improve the coverage against high fault resistance. This adaptive scheme is based in assigning an enhanced set of protection parameters to distance relays, subject to the terminal pre-fault power flow condition. The apparent impedance seen by the relay is determined by a straightforward method based on the nodal matrix representation of the power system. The proposed algorithm for determining the apparent impedance locus has been simulated in a real power system against three phase, double phase and single phase faults and results has been compared with most commonly used distance algorithm; Fourier, Walsh and DEA distance algorithms. The practical usefulness of the coordination through the proposed adaptive parameterization is shown by the enhanced sensitivity achieved, which increase up to 47% the coverage of conventional settings against resistive faults.**

Keywords: distance protection, apparent impedance locus, R-X diagram, logical operation, resistive faults.

1. Introduction

Latest distance protection algorithms seek time performance improvements and sensitivity increase to detect all types of possible faults that may occur in the protected line. Adaptive algorithms improve in this sense the coverage of the distance protection against different types of faults in the electric network [1]-[4]. However, to implement these algorithms in existing electrical substations (E/S) involves in most cases a considerable economic cost both to buy new protective relays neither change the firmware of existing ones.

This study develops an adaptive parameterization for distance protection based on the effect of prefault power flow in the apparent impedance locus. This adaptive application is integrated through a flexible operational logic to be implemented in many protection schemes currently used in E/S.

The coordination of distance protection relays considering the prefault power flow gives a better appreciation of the apparent impedance locus seen by relay against faults in a multiterminal network. In some cases where load flow has been neglected, the relay system will perform properly until a contingency situation arises and causes an incorrect relay operation attributable to the effects of load flow [5],[6].

To mitigate the adverse effects of pre-fault power flow, settings criteria are presented for performing a selective coordination. These settings maximize the protection coverage by increasing the sensitivity for fault resistance in the protected line. The application restrictions over selectivity between protection zones of the distance relay are obtained by an algorithm that has been developed in order to analyze the performance of distance protection against three phase, double phase to earth and single phase to earth faults considering the pre-fault power flow and fault resistance expected in the protected line. This algorithm is based in the method of nodal matrix presented in [7],[8] and its results have been compared with Fourier , Walsh [9],[10] and DEA (Differential Equation Algorithm) [9],[11] distance algorithm.

Conventionally, the protection parameters of distance relays have common values for both local and remote terminals of the protected line [5],[12]. However, through this adaptive parameterization each terminal has a different resistive reach depending on the direction of the line power flow, increasing the resistive faults coverage that could not be detected with conventional methods of distance coordination.

2. Apparent impedance locus considering power flow in multiterminal networks

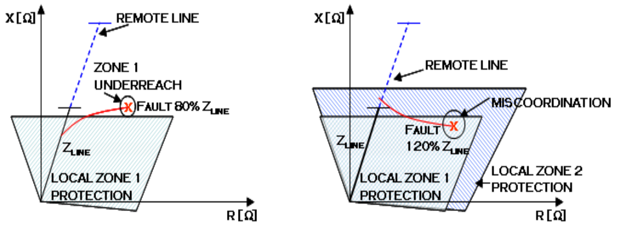
To simulate the effect of prefault power flow and fault resistance in the apparent impedance locus seen by the relay it is important to consider a series of equivalences in a multiterminal network.

A. Effect of power flow in the protected line

Following fault inception, the apparent impedance seen by the relay can be denoted as a function of the pre-fault impedance and the impedance up to the fault. This demonstrates that load impedance influences the impedance seen by the relay measuring elements during a system fault condition.

The literature [5]-[8],[13] consider that the locus of the apparent impedance describe a circle if all parameters are kept fixed except the fault resistance. Summarizing the above consideration of pre-fault power flow the effect of importing power at the relay location is to cause an increase in the apparent impedance presented to the faulted relay, and result in further underreaching of the protection.

An export power case causes an overreaching tendency of the protection. As shown if Fig. 1, this effect of power flow lead to miscoordination between protection zones at a local relay and selectivity losses with the remote terminal distance relays.



(a) (b)

Fig. 1. Apparent impedance locus seen by the relay. (a) importing power, underreach of zone 1, (b) exporting power, miccordination between protection zones.

A method to determine the apparent impedance seen by the relay is by expressing the relay signals in terms of the healthy system signals from a solution of the equivalent circuit representing the fault. However, this method involves the use of complex coefficients to establish relations between healthy and faulty signals. To avoid complexity in the impedance calculation, a straightforward method based in nodal matrix manipulation is introduced into the algorithm.

This method inherently considers the pre-fault load conditions, and gives the total fault current and voltage at a relay location. Therefore, with the nodal matrix representation of the electric network under study, the apparent impedance seen by the relay in each bus can be determine for any pre-fault condition and for an expected set of fault resistance.

The apparent impedance during a fault, considering the prefault power flow [8], is determined as follows

$$Z_R = m \cdot Z_l^+ + K_x \cdot R_f \qquad (1)$$

where Z_R is the apparent impedance seen by the distance relay, m is the distance to fault in per unit of protected line length, Z_l^+ is the positive sequence impedance of the protected line, R_f represents the fault resistance and K_x is a multiplication factor whose value varies depending on the type of fault and the distance to fault. For a three phase fault, K_x is determined as follows

$$K_{3\varphi} = \frac{Z_{rr}^+ + (m-1)\cdot Z_{pr}^+ - m\cdot Z_{qr}^+}{(Z_{rr}^+ + R_f)\cdot\left[\dfrac{N\cdot(1-m)}{(1-m)\cdot N + m}\right] - (1-m)\cdot(Z_{pr}^+ + R_f)} \qquad (2)$$

for 0<m<1

being $K_{3\varphi}$ the multiplication factor for three phase faults, Z^+ the nodal impedance matrix deduced for the electrical system under study and its subscripts p, q, r denotes the local terminal, remote terminal and point of fault in protected line, respectively. N is the prefault power flow indicator and is calculated as follows

$$N = \frac{E_p}{E_q} \qquad (3)$$

where E_p and E_q are the local and remote voltage respectively.

For $m=0$, $K_{3\varphi}$ is determined as

$$K_{3\varphi} = \frac{Z_l^+}{(Z_l^+ + ZI_{qp}^+ + R_f) - \dfrac{(ZI_{pp}^+ + R_f)}{N}} \qquad (4)$$

and, for $m=1$, $K_{3\varphi}$ is deduced as follows

$$K_{3\varphi} = \frac{Z_l^+}{N * (ZI_{qq}^+ + R_f) - (ZI_{pq}^+ + R_f)} \qquad (5)$$

being ZI^+ the simplified nodal impedance matrix once m fit the minimum or maximum value to avoid mathematical indetermination.

In double phase faults, $K_{2\varphi}$ *is* determined:

- for 0 < m < 1 as

$$K_{2\phi} = \frac{Z_{rr}^+ - Z_{pr}^+ + \left(\dfrac{m}{1-m}\right)*(Z_{rr}^+ - Z_{qr}^+)}{[m*(N-1)+1]*2*Z_{rr}^+ - 2*Z_{pr}^+ + m*(N-1)*R_f} \qquad (6)$$

- for m = 1 as

$$K_{2\phi} = \frac{Z_l^+}{N*(2*ZI_{qq}^+) - ZI_{pq}^+ - ZI_{qp}^+ + (N-1)*R_f} \qquad (7)$$

- and for m = 0 as

$$K_{2\phi} = \frac{Z_l^+}{\left|\dfrac{N-1}{N} - 1\right| * (2*ZI_{pp}^+) + 2*ZI_{pq}^+ + \left|\dfrac{N-1}{N}\right| * R_f} \qquad (8)$$

In single line to ground faults, $K_{1\varphi}$ *is* determined:

- for 0 < m < 1 as

$$K_{1\phi} = \frac{m*Z_l^+}{\left[\dfrac{m*(N-1)}{N-m*(N-1)}+1\right]*(2*Z_{rr}^+ + Z_{rr}^0) - 2*Z_{pr}^+ - Z_{pr}^0 + 3*\left[\dfrac{m*(N-1)}{N-m*(N-1)}+1\right]*R_f} \qquad (9)$$

- for m = 0 as

$$K_{1\phi} = \frac{3*Z_l^+}{\left[\dfrac{(N-1)}{N}-1\right]*(2*ZI_{pp}^+ + ZI_{pp}^0) + 2*ZI_{qp}^+ + ZI_{qp}^0 + Z_l^0 + 6*Z_l^+ * \left[\dfrac{(N-1)}{N}\right]*R_f} \qquad (10)$$

- and for m = 0 as

$$K_{1\phi} = \frac{3*Z_l^+}{N*(2*ZI_{qq}^+ + ZI_{qq}^0) - 2*ZI_{pq}^+ - ZI_{pq}^0 + 3*(N-1)*R_f} \qquad (11)$$

B. Algorithm for determining the apparent impedance locus

The effect of the power flow in the apparent impedance locus seen by relays has been analyzed by an algorithm developed in MATLAB [14] and based in the nodal matrix method described above. The operation sequence of the algorithm can be briefly described as follows:

- Charge of database from Excel to main routine in Matlab. The database must include principles aspect of the network under study such as: from bus, to bus, line impedance, source impedance, load impedance, status, etc.
- For different distance to fault, m, create the new row and column in the admittance matrix. The connection

of this new "fictitious" bus will be m*Z_{LINE} with the relay position bus and (1-m)* Z_{LINE} with the remote bus.
- Calculate the bus impedance matrix for positive sequence, [Z^+], and zero sequence [Z^0].
- Determine the apparent impedance, Z_R, for three phase, double phase to earth and single phase to earth faults, varying power flow, *N*, and fault resistance, R_f. In this loop the limits of power flow are represented by a voltage array containing the maximum and minimum value of E_p and E_q.
- Graphical and numerical output to established restrictions for selective coordination.

Fig. 2 shows the flowchart of the algorithm for determining the apparent impedance seen by the relay by the procedure described above.

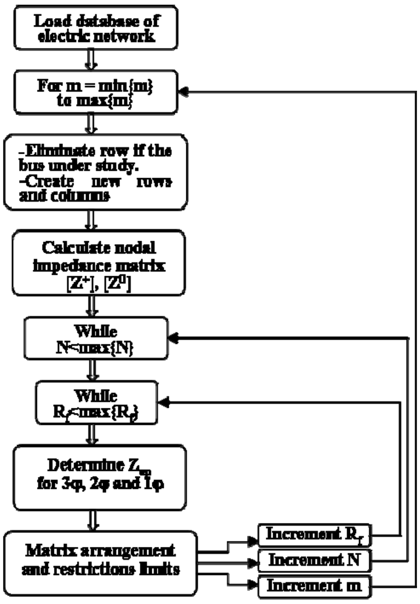


Fig. 2. Algorithm flowchart for determining apparent impedance.

3. Settings criteria for protection parameter considering power flow effect

The protection parameters setting are performed to fit the restrictions outlined in the algorithm. Thus, settings criteria are presented to mitigate the power flow effect for both scenarios exporting and importing power.

A. Setting criteria for exporting power

In Mho protection characteristic, a slightly improvement of resistive reach can be perform by adjusting the characteristic angle, φ_c, to a different angle of the protected line, θ_L. Thus, it can be the same setting for both exporting and importing power condition. In order to keep the same reactive reach, correction factor is applied to characteristic magnitude as a function of the φ_c as follows

$$|Z_{C1}| = k.|Z_l^+|.\frac{1}{\cos(\theta_l - \varphi_C)} \qquad (12)$$

where $|Z_{c1}|$ is the characteristic magnitude of zone 1 of the Mho with the reactive correction factor, *k* is the portion of setting for each protection zone and $|Z^+_l|$ the positive sequence of the protected line. Fig 3. shows the Mho characteristic adjustment with a resistive reach improvement.

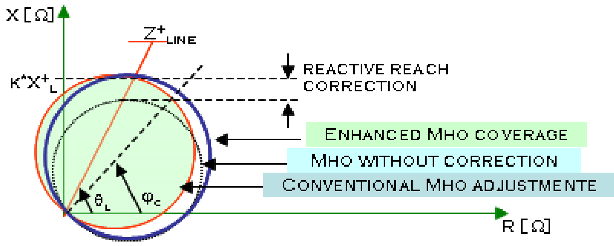


Fig. 3. Mho characteristic setting for importing and exporting terminal.

Otherwise, resistive reach of protection zones in quadrilateral characteristic are limited to the curvature of the apparent impedance locus plotted for a three phase fault at a desired reactive reach, i.e. 1.05*$X_{zone\ 1}$. The latter locus can be set as the restriction to adjust the reflection angle *M* of this protection characteristic, which for the example assume can be formulated as follows

$$M = 180^\circ + \operatorname{atan}\left(\frac{X_1 - X_{1\_90\%}}{R_{1\_codo} - R_1}\right) \qquad (13)$$

where X_1 and R_1 are the reactance and resistive reach of zone 1, respectively. $X_{1\_90\%}$ is the reactance reach at 90% of the protected line, R_{1_codo} is the resistive value that fit with the knee of the reactance reach with the impedance locus for a three phase fault at 90% of the protected line

Fig. 4 describes the setting of protection parameter related to a quadrilateral characteristic for exporting terminal.

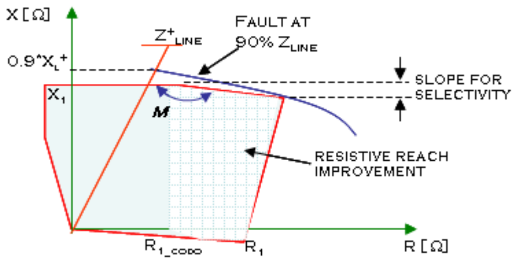


Fig. 4. Settings for exporting terminal with quadrilateral characteristic.

B. Setting criteria for importing power

The settings assigned to the terminals importing power will enable the distance protection to increase the coverage of faults resistance in the protected line, as shown in Fig. 5. This improvement is achieved mostly in quadrilateral characteristics considering the following restriction to maintain selectivity with remote terminals. Fig. 5 describes the settings for distance protection in terminals importing power.

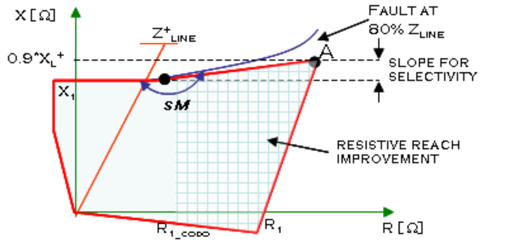


Fig. 5. Settings for importing terminal with quadrilateral characteristic..

The resistive reach is set proportionally with the reactance reach without overlap widely the protection zone that follows. To achieve a greater coverage of resistance fault, the slope of the characteristic must be the vector $\overline{OA}$, shown in Fig. 5, formed by the knee of the apparent impedance locus for three phase fault to the real part of the apparent impedance for the maximum fault resistance.

$$\begin{cases} R_1 \le \begin{cases} \mathrm{Re}\left\{Z_{ap\,3\varphi}^{X_1}\right\}\ a\ R_F = R_{FMAX} \\ 3 * X_1 \end{cases} \\ X_{CUADRI} \le 0.95 * X_L \end{cases} \qquad (14)$$

4. Integration of the adaptive parameterization to distance protection schemes

Adaptive parameterization is integrated through a flexible operational logic function that continuously monitors the direction of power flow. This application determines the protection parameters that shall be set at each terminal of the protected line in each instance of time.

Therefore, it is important that protection relays in E/S admit at least two groups of settings. Each group of setting is prepared by the criteria of exporting or importing power terminal.

The activation of each group depends on a logic input from a directional power relay (32), which switched to the proper setting group according to the power flow in each instance of time. The function 32 is already incorporated in most multifunction relays; nonetheless, it can be assigned to a logical input of the distance relay controlled by an external power direction relay.

Fig. 6 shows the operational logic scheme to implement an adaptive parameterization in E/S in case where carrier channels are available.

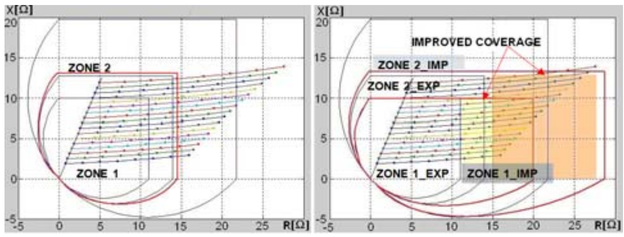
Note that the directionality of power is provided by an internal function or an external contact followed by an intentional delay, RI, to ensure its implementation under steady state conditions.

The condition of power flow enables the selection of a group of settings to improve the fault resistance coverage. Thus, the importing terminal will provide more sensitivity against fault resistance in the protected line, keying trip permission to the exporting terminal for a simultaneous operation in both terminals.

In this study, the exporting power bus is treated as a weak terminal in comparison with the importing power bus. Therefore, high resistance faults will not be detected by impedance measurement units in the exporting terminal but with the weak terminal algorithm. Faults in weak terminal are detected by including an undervoltage phase relay (27P), overvoltage neutral relay (59N) and overcurrent neutral relay (50N) [15].

The trip decision in exporting terminals is achieved once confirmed both trip permission from the remote terminal and the activation of weak terminal algorithm. Overreach units (SB) are implemented as pilot scheme if carrier channel is available. Otherwise, the distance protection is set to underreach units (SA).

Fig. 7 shows the difference between the conventional and the adaptive parameterization settings for zone 1 and 2. The terminal with import criteria settings covers a wider range of fault resistance.



(a) (b)

Fig. 7. Comparison between distance protection zones with (a) conventional settings and (b) adaptive parameterization. Blue lines denote exporting terminals and red lines denote importing terminals.

5. Power system simulation

The practical usefulness of the coordination through adaptive parameterization is shown in a case of study of a 69 kV multiterminal power system.

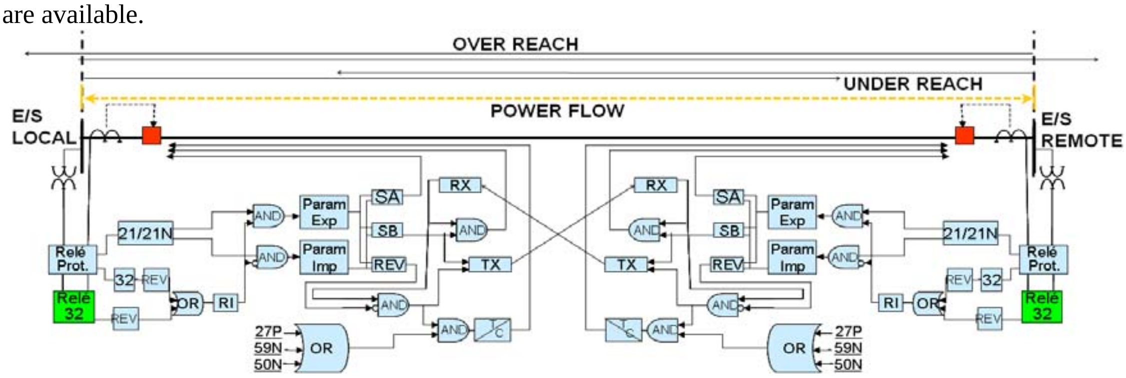


Fig. 6. Operational logic to integrate adaptive parameterization in distance protection schemes.

This electric network is shown in Fig. 8 and is based in 20 E/S and 21 transmission lines with different source to line impedance relation (SIR) related to a petroleum company in Venezuela.

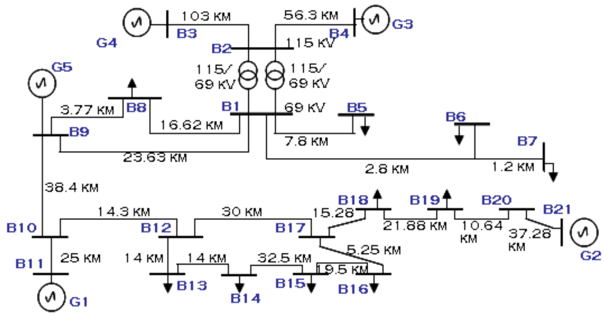


Fig. 8. Electrical power systems considered for the study.

The apparent impedance seen by each distance relay position obtained from the presented program is compared by conventional distance algorithm. These algorithms are DFFT (Discrete Fast Fourier Transform), Walsh and DEA developed in PSCAD [16]. The simulations are based in a set of faults for different inception angle (0º, 30º, 60º, 90º), load, and a fault resistance up to 55 ohm.

Figs. 9 and 10 show the comparison of the reactance reach obtained by the nodal matrix method, Fourier, Walsh and DEA algorithm for single phase to ground faults at 50% of line B18-B19 of the study case, importing and exporting power, respectively.

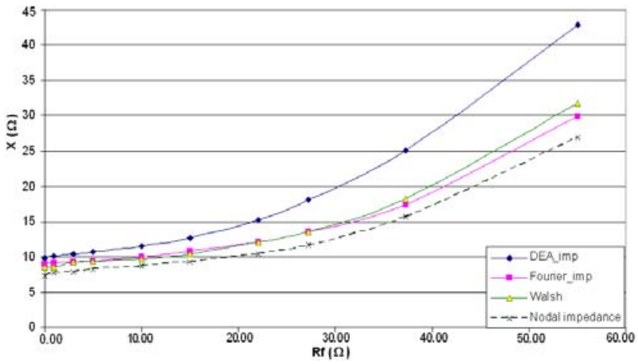


Fig. 9. Reactance reach determined by the nodal matrix method, Fourier, Walsh and DEA algorithm for single phase to ground faults at 50% of line B18-B19 of the study case, importing power.

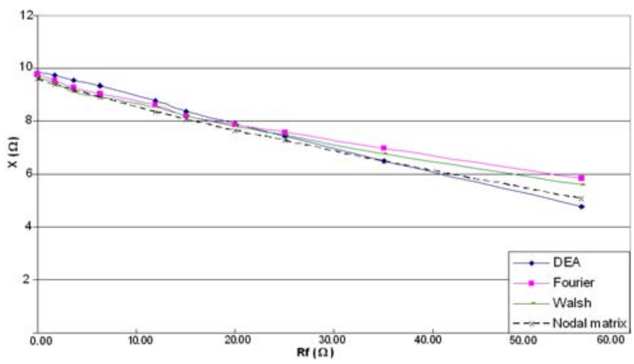


Fig. 10. Reactance reach determined by the nodal matrix method, Fourier, Walsh and DEA algorithm for single phase to ground faults at 50% of line B18-B19 of the study case, exporting power.

Summarizing the results obtained from the comparison it is concluded that the present program based in nodal matrix is quiet approximate to the performance of commonly used distance protection algorithm.

In Table I is represented the error of the apparent impedance determined by the nodal matrix method in relation with the apparent impedance seen by a relay that implements Fourier, Walsh or DEA distance algorithm, for exporting and importing terminals.

TABLE I

APPARENT IMPEDANCE ERROR OF NODAL MATRIX IN COMPARISON WITH FOURIER, WALSH AND DEA DISTANCE ALGORTIHMS FOR IMPORTING AND EXPORTING TERMINAL.

m	R_f [Ω]	Importing			Exporting		
		Walsh	DEA	DFFT	Walsh	DEA	DFFT
25%	0.001	-9.8%	-19.4%	-12.4%	-0.4%	-1.3%	-0.9%
	5	-7.9%	-16.8%	-7.9%	0.0%	-2.7%	-0.8%
	10	-6.3%	-18.3%	-8.1%	-1.3%	-2.8%	-1.7%
	20	-8.9%	-25.4%	-8.9%	-1.2%	-1.9%	-1.6%
	35	-9.1%	-32.9%	-6.1%	-2.5%	-0.1%	-4.2%
50%	0.001	-17.8%	-35.3%	-22.5%	-0.73%	-2.37%	-1.67%
	5	-14.4%	-30.5%	-14.4%	0.00%	-4.92%	-1.46%
	10	-11.5%	-33.3%	-14.6%	-2.40%	-5.03%	-3.11%
	20	-16.1%	-46.2%	-16.1%	-2.10%	-3.51%	-2.97%
	35	-16.6%	-59.9%	-11.0%	-4.48%	-0.18%	-7.56%
75%	0.001	-20.5%	-40.5%	-25.9%	-0.8%	-2.7%	-1.9%
	5	-16.6%	-35.1%	-16.6%	0.0%	-5.7%	-1.7%
	10	-13.2%	-38.3%	-16.8%	-2.8%	-5.8%	-3.6%
	20	-18.6%	-53.1%	-18.6%	-2.4%	-4.0%	-3.4%
	35	-19.0%	-68.9%	-12.7%	-5.1%	-0.2%	-8.7%

Errors are magnified in importing condition; however for exporting terminals, the errors presented are much closer to distance algorithms, being this latter condition the restriction limit to avoid miscoordination between protection zones. Moreover, note that errors sign always indicate that the apparent impedance determined by the nodal matrix method is under the values estimated by distance algorithm. Thus, restriction limits and parameters settings will have implicit a security margin that makes the algorithm more conservator.

In Table II is shown the resistive coverage improvement resulted from applying the adaptive parameterization shown in Fig. 6 to the study case. Simulations have been performed for transmission lines with different SIR. The sensitivity increase against resistive faults is compared with the actual settings of distance devices installed in E/S of the study case.

TABLE II

APPARENT IMPEDANCE ERROR OF NODAL MATRIX IN COMPARISON WITH FOURIER, WALSH AND DEA DISTANCE ALGORTIHMS FOR IMPORTING AND EXPORTING TERMINAL

Line	SIR	R_F reach improvement	Sensitivity increase
B9-B10	0.505	11.3 Ω	**9%**
B10-B11	0.922	8.9 Ω	34%
B10-B12	1.41	8.5 Ω	**47%**
B12-B17	0.902	9.3 Ω	28%
B12-B14	0.69	10.1 Ω	14%

The results obtained for short and medium line length show an improvement up to 47% in the coverage of the distance relay compared with conventional settings (existing settings in E/S of the study case).

4. Conclusions

The application of adaptive parameterization proposed in this study achieved a significant improvement in the coverage of protective relays against fault through resistance. This improvement is more appreciable for short and medium transmission lines.

The nodal matrix algorithm represents a straightforward method for determining the restriction limits for protection coordination with a reduced margin error between commonly used distance algorithm as Fourier, Walsh and DEA algorithm.

The criteria for allowing selective coordination between distance protection zones are more suitable for quadrilateral characteristic and mitigate in a higher grade the adverse effect of power flow over the apparent impedance locus. Additionally, the operational logic described allows the simultaneous clearing of faults in the protected line.

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