Adaptive distance protection for 110 kV double circuit transmission line

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Abstract: This article approaches the precision of the distance protection relay under earth fault shortcircuits with large resistance on one circuit of a 110 kV double circuit configuration line. Using adaptive trip logic, the reliability and selectivity of the classic distance protection algorithm from a 110 kV double circuit transmission line are improved. In the typical distance protection algorithm to be immune to the influence of the zero sequence mutual impedance and to the high fault resistance, the tilt angle α is calculated and used for changing the position of the fault impedance on the R-X plane. Using only local signals, two current distribution factors are used to calculate the zero sequence current of the healthy parallel circuit and the zero-sequence fault current. In case that the currents of the parallel circuit can be injected into the distance protection relay, the tilt angle α can be estimated with only one current distribution factor. Comprehensive phase to earth shortcircuits with high fault resistance are simulated on one circuit of a 110 kV double configuration transmission line. The shortcircuit scenarios confirm that the distance protection determines an instantaneous trip of the 110 kV circuit breaker of the faulted line, even in the presence of single-phase faults with fault resistance of 50 ohms.

Keywords: adaptive algorithms, error correction, fault detection, protection, resistance.

1. INTRODUCTION

In order to ensure optimal conditions for evacuation of the power produced by wind turbines and photovoltaics, and to avoid limitations of power imposed by the dispatcher, the common solution is to build 110 kV double circuit overhead lines. Despite numerical technology progress in the field of relay protection (Majid Sanaye-Pasand et al., 2011) the basic distance scheme protection still remains a solution for 110 kV double circuit configurations.

In order to compute the impedance between the relay location and the fault location, on the dedicated binary inputs of a digital distance protection are connected current and voltage circuits. Based on current and voltage vectors the faulted loops and the unfaulted loops are evaluated continuously. The apparent impedances in all the loops are computed in the distance protection relay and compared with the polygonal/ MHO characteristics, in order to trip or not. Because the unfaulted loops always have a larger voltage than the faulted loops, the apparent impedance in the unfaulted loops are usually outside the trip zone.

The trip conditions of the circuit breaker are met when the fault impedance is in the limits of the phase – phase or phase to earth impedance characteristics of the distance protection (Marcin Bozek et al., 2008). Changes in operating regimes, load curve and power generation should not lead to distance protection trip. Also, depending on the operating regime the distance protection must be sufficiently selective and sensitive to all types of shortcircuits, regardless of SIR (source impedance ratio). In practice, the setting group of distance protection is set strictly to the system operating conditions that occur where the relay is located. Besides the system conditions, there are other factors that influence the accuracy of the impedance between the relay location and fault location, such as: fault resistance, mutual influence, power swings, errors generated by the current and voltage transformers, relay measuring inputs, protection algorithms, inaccuracies of the zero sequence and positive sequence impedances of the circuits (A.G. Jongepier et al., 1994).

Generally, the distance protection algorithms employed are designed and optimized for the single transmission line, without considering the zero sequence mutual impedance (J.Upendar et al., 2010). For a single-phase-to-ground fault in a 110 kV single circuit line, the voltage at the relay location is determined by the positive and zero sequence impedance. In the case of a 110 kV double circuit line, the earth current of the parallel line induces a voltage in the fault loop, which can cause a measuring error in the estimated impedance (Yi Hu et al., 2000). The mutual coupling includes positive, negative and zero sequence symmetrical components. The positive and negative sequence coupling represents 3% to 7% of the self -impedance and can not be taken into consideration in the shortcircuit studies (I.C. Borascu, et al., 2015). Hence, the zero sequence mutual coupling it has the major impact on the accuracy of the fault locator, and it will produce underreach (measurement of an impedance which is much higher than the real one) at importing end, or overreach (measurement of an impedance which is much smaller than the real one) at exporting end. (M.M. Eissa et al., 2001). In addition to the mutual coupling effects, the value of the fault resistance causes a negative effect on the distance protection in case of close-in faults and remote end faults (Yong-Jin Ahn et al., 2001). Voltage memory techniques determine the direction of all types of faults, based on the pre-fault voltage from the local bus for a period of up to 2 seconds after the occurrence of shortcircuit (W.D. Breingan et al., 1979). For single phase faults or phase – phase faults close to the remote bus, the measurement precision of the local distance protection can be improved by algorithms that receive the fault information from all the relays of the transmission line (I. Dumitrache et al., 2008).

In order to prevent non-selective trips of the local circuit breaker, due to the impedance difference induced by the reactance effect, the distance protection scheme submitted in this paper uses the tilt angle of an impedance deviation vector produced by two points on the polygon characteristic (Yo ng-Jin Ahn et al., 2001). One point constitutes the apparent impedance of the fault loop and the other point constitutes the fault location on the double circuit transmission line.

2. EFFECT OF FAULT RESISTANCE

In 110 kV network the distance protection permanent computes all the six fault loops. Also, the resistance and the reactance calculated values are updated each sample and compared with the polygon characteristic. An accurate apparent impedance measurement during earth fault occurrence is mandatory because false measurement might cause false tripping. The relay used to protect short transmission line tends to underreach even under shortcircuit condition with small fault resistance. Also, when a fault occurs just outside the zone, the apparent impedance Z_{app} can be in the trip zone – overreach. To compensate for the negative influence of the reactance effect adaptive procedures may be used in a decision block (E. Tanyi et al., 2011). This adaptive distance scheme proposes a tilt angle (Fig. 1), α, which is influenced by the fault type, fault location, fault resistance and load (Yong-Jin Ahn et al., 2001; Zhang Zhizhe et al., 1991; A. Wiszniewski et al., 2008).

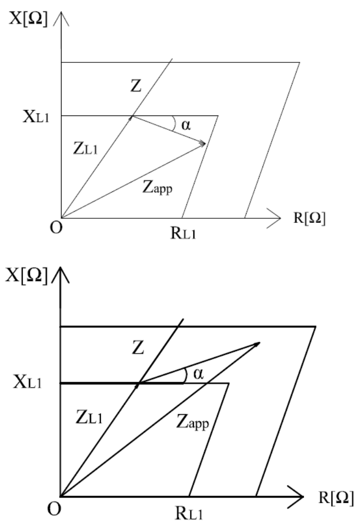

Fig.1. Apparent impedance deviation.

From the apparent impedance Z_{app} (Fig.2) and the argument α of the deviation vector, can be determined the point X'.

$$X' = X_{app} \pm R_{app} \times \tan\alpha \quad (1)$$

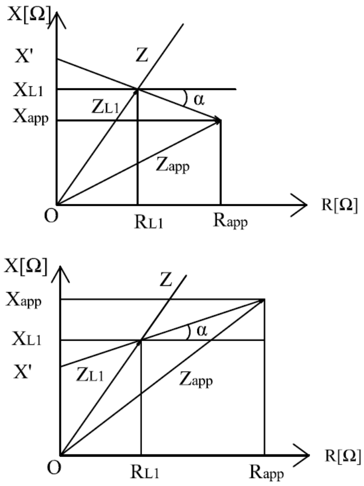

Fig. 2. Correction of impedance.

The actual line impedance to a fault, is expressed as follows:

$$X_{L1} = \frac{X}{R} \times \frac{X'}{\frac{X}{R} - \frac{(X_{app} - X')}{R_{app}}}$$
$$R_{L1} = \frac{X'}{\frac{X}{R} - \frac{(X_{app} - X')}{R_{app}}} \quad (2)$$

where,

R_{app} - apparent resistance [Ω];

X_{app} - apparent reactance [Ω] ;

X - line reactance [Ω/km] ;

R - line resistance [Ω/km] ;

R_{L1} - positive sequence resistance to a fault [Ω] ;

X_{L1} - positive sequence reactance to a fault [Ω] ;

3. IMPEDANCE CORRECTION ALGORITHM FOR DOUBLE CIRCUIT CONFIGURATION

The asymmetry and geometry of double circuit transmission line represent an important source of errors for the distance protection relay. In order to eliminate the mutual impedances from the impedance matrix of the double circuit configuration, the position of the phases is rearranged in the same physical setup (I.C. Borascu et al., 2015).

The impedance matrix of a transposed double circuit line is (Fernando Calero, 2007):

$$Z_{abc}=\begin{vmatrix} Z_s & Z_p & Z_p & Z_m & Z_m & Z_m \\ Z_p & Z_s & Z_p & Z_m & Z_m & Z_m \\ Z_p & Z_p & Z_s & Z_m & Z_m & Z_m \\ Z_m & Z_m & Z_m & Z_s & Z_p & Z_p \\ Z_m & Z_m & Z_m & Z_p & Z_s & Z_p \\ Z_m & Z_m & Z_m & Z_p & Z_p & Z_s \end{vmatrix} \quad (3)$$

where,

Z_{abc} - the impedance matrix of the line;

Z_s - the self-impedance of a phase per unit length;

Z_p - the mutual impedance between two phases of the same circuit per unit length;

Z_m - the mutual impedance between two phases of different circuits per unit length;

The matrix impedance with symmetrical components is:

$$Z_{012}=\begin{vmatrix} Z_0 & 0 & 0 & Z_{m0} & 0 & 0 \\ 0 & Z_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_1 & 0 & 0 & 0 \\ Z_{m0} & 0 & 0 & Z_0 & 0 & 0 \\ 0 & 0 & 0 & 0 & Z_1 & 0 \\ 0 & 0 & 0 & 0 & 0 & Z_1 \end{vmatrix} \quad (4)$$

Z_{012} - the symmetrical component impedance matrix per unit length;

Z_0, Z_1 - the zero and positive sequence impedance of one circuit of the line per unit length;

Z_{m0} - the zero sequence mutual coupling impedance of the line per unit length;

Despite major efforts are made to transpose a double circuit line, in reality, the zero sequence mutual impedance is not zero (I.C. Borascu et al., 2015).

A single phase to earth shortcircuit model in a simple two-terminal parallel transmission line that is fed from two sources is represented in Fig. 3. Also, the prefault model of the two-terminal parallel transmission line that is fed from two sources is represented in Fig. 4.

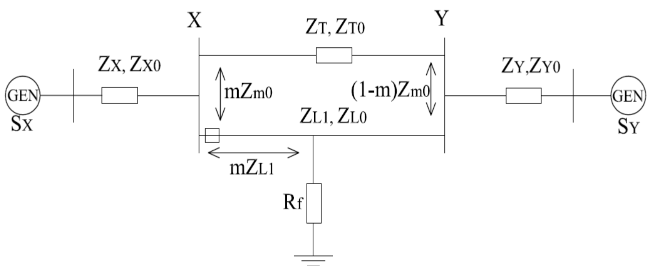

Fig. 3. Single phase to ground fault model.

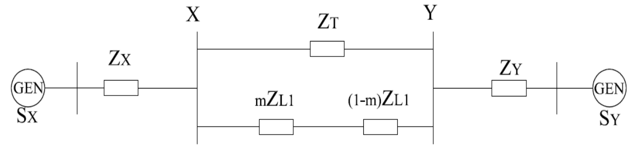

Fig. 4. Prefault model.

The voltage at the relay location, U_{Xa}, is determined as follows:

$$U_{Xa}=Z_{L1}\times\left(I_{Xa}+\frac{Z_{L0}-Z_{L1}}{Z_{L1}}\times I_{X0}+\frac{Z_{m0}}{Z_{L1}}\times I_{T0}\right)+R_f\times I_f \quad (5)$$

The apparent impedance Z_{app} can be defined as

$$Z_{app}=\frac{U_{app}}{I_{app}} \quad (6)$$

where,

$$U_{app}=U_{Xa}$$

$$I_{app}=I_{Xa}+\frac{Z_{L0}-Z_{L1}}{Z_{L1}}\times I_{X0}+\frac{Z_{m0}}{Z_{L1}}\times I_{T0}$$

From (5) and (6), the equation for apparent impedance can be expressed as

$$Z_{app}=Z_{L1}+R_f\times\frac{3\times I_{f0}}{I_{Xa}+\frac{Z_{L0}-Z_{L1}}{Z_{L1}}\times I_{X0}+\frac{Z_{m0}}{Z_{L1}}\times I_{T0}}$$

$$Z_{app}=Z_{L1}+R_f\times\left|\frac{3\times I_{f0}}{I_{Xa}+\frac{Z_{L0}-Z_{L1}}{Z_{L1}}\times I_{X0}+\frac{Z_{m0}}{Z_{L1}}\times I_{T0}}\right|\times e^{j\times\alpha} \quad (7)$$

where,

U_{Xa} = phase voltage at the local end of faulted circuit [V];

I_{Xa} = phase current at the local end of faulted circuit [A];

I_{f0} =zero sequence fault current [A];

I_{X0} = zero sequence current at the local end of faulted circuit [A];

I_{T0} = zero sequence current at healthy circuit [A];

m = fractional fault distance from local end [p.u.];

Z_{L0} = faulted circuit zero sequence impedance [Ω];

Z_{L1} = faulted circuit positive sequence impedance [Ω];

Z_{T0} = healthy circuit zero sequence impedance [Ω];

R_f = fault resistance [Ω];

Equation 7 shows that the impedance deviation influence the proper operation of the distance protection.

3.1 The residual current of the parallel line calculated by the relay

In this case, using only the local end signals of the faulted line, the zero sequence current of the parallel circuit that is unaffected by the shortcircuit, I_{T0}, and the total zero sequence fault current, I_{f0}, can be evaluated (Yong-Jin Ahn et al., 2001; Yong-Jin Ahn et al., 2000). I_{T0} and I_{f0} can be expressed by the local end residual current of the faulted circuit, I_{S0}, respectively by the current distribution factors CDF_{T0} and CDF_{f0}.

To estimate the fault current at a shortcircuit point, the zero sequence current distribution factor, CDF_{f0}, must be calculated as the ratio of the residual current at the local end of the faulted circuit to the residual fault current at the fault point (I.C. Borascu et al., 2015).

Using Kirchhoff's laws to each parallel circuit of Fig. 5, it can be deduced the following equation:

$$\begin{aligned}&(Z_{X0}+m\times Z_{L0})\times I_{X0}-[Z_{Y0}+(1-m)\times Z_{L0}]\times I_{Y0}+(Z_{X0}+Z_{Y0}+Z_{m0})\times I_{T0}=0\\&(Z_{X0}+m\times Z_{m0})\times I_{X0}-[Z_{Y0}+(1-m)\times Z_{m0}]\times I_{Y0}+(Z_{X0}+Z_{Y0}+Z_{T0})\times I_{T0}=0\end{aligned} \quad (8)$$

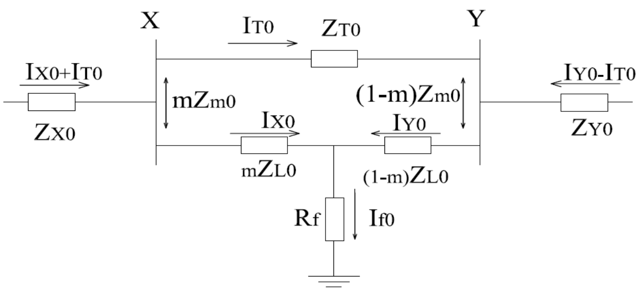

Fig. 5. Zero sequence impedance diagram after a fault.

Considering that the zero-sequence fault current, I_{f0}, is the sum of I_{X0} and I_{Y0}, the current distribution factor CDF_{f0} can be determined as follows:

$$CDF_{f0}=\frac{I_{X0}}{I_{f0}}=\frac{I_{X0}}{I_{X0}+I_{Y0}}=\frac{m\times B_{f0}+C_{f0}}{A_{f0}} \quad (9)$$

where,

$$\begin{aligned}&A_{f0}=(Z_{L0}-Z_{m0})\times(Z_{X0}+Z_{Y0}+Z_{m0})+(Z_{T0}-Z_{m0})\times(Z_{L0}+Z_{Y0}+Z_{X0})\\&B_{f0}=(Z_{m0}-Z_{L0})\times(Z_{X0}+Z_{Y0}+Z_{m0})-(Z_{T0}-Z_{m0})\times Z_{L0}\\&C_{f0}=(Z_{L0}-Z_{m0})\times(Z_{X0}+Z_{Y0}+Z_{m0})+(Z_{T0}-Z_{m0})\times(Z_{L0}+Z_{Y0})\end{aligned}$$

Z_{X0} = zero sequence impedance for source SX;

Z_{Y0} = zero sequence impedance for source SY;

I_{Y0} = zero sequence current from remote source at the faulted circuit;

Removing from the equation (8) the residual current from source Y, I_{Y0}, it can be computed the current distribution factor CDF_{T0} as the ratio of the zero sequence current at the local end of the faulted circuit to the zero sequence current from the healthy circuit.

$$CDF_{T0}=\frac{I_{X0}}{I_{T0}}=\frac{m\times A_{T0}+B_{T0}}{m\times C_{T0}+D_{T0}} \quad (10)$$

where,

$$\begin{aligned}&A_{T0}=(Z_{m0}-Z_{L0})\times(Z_{X0}+Z_{Y0}+Z_{m0})-(Z_{T0}-Z_{m0})\times Z_{L0}\\&B_{T0}=(Z_{L0}-Z_{m0})\times(Z_{X0}+Z_{Y0}+Z_{m0})+(Z_{T0}-Z_{m0})\times(Z_{L0}+Z_{Y0})\\&C_{T0}=(Z_{L0}-Z_{m0})\times(Z_{X0}+Z_{Y0})\\&D_{T0}=(Z_{m0}-Z_{L0})\times Z_{X0}\end{aligned}$$

The expression of the argument α in equation (7), can be expressed as:

$$\begin{aligned}&\alpha=\mathrm{Arg}\left(\frac{I_{f0}}{I_{Xa}+\frac{Z_{L0}-Z_{L1}}{Z_{L1}}\times I_{X0}+\frac{Z_{m0}}{Z_{L1}}\times\frac{I_{X0}}{CDF_{T0}}}\right)\\&\alpha=\mathrm{Arg}\left(\frac{I_{X0}}{I_{Xa}+\frac{Z_{L0}-Z_{L1}}{Z_{L1}}\times I_{X0}+\frac{Z_{m0}}{Z_{L1}}\times\frac{I_{X0}}{CDF_{T0}}}\right)+\mathrm{Arg}\left(\frac{1}{CDF_{f0}}\right)\end{aligned} \quad (11)$$

3.2 The residual current of the parallel line injected into a relay

The producers of numerical relays allow zero sequence current from the healthy line to be connected to the measuring input of the relay, in case of complete (phase voltage and currents from faulted line and phase currents from healthy line) or standard (phase voltage and currents from faulted line and zero sequence current from healthy line) availability of signals (Jan Izykowski *et.al.*, 2008; Yi Hu *et.al.*, 2002). If the digital relay has sufficient binary inputs, the zero sequence current from the parallel circuit can be injected into relay, and the tilt angle α, can be evaluated as:

$$\begin{aligned}&\alpha=\mathrm{Arg}\left(\frac{I_{f0}}{I_{Xa}+\frac{Z_{L0}-Z_{L1}}{Z_{L1}}\times I_{X0}+\frac{Z_{m0}}{Z_{L1}}\times I_{T0}}\right)\\&\alpha=\mathrm{Arg}\left(\frac{I_{X0}}{I_{Xa}+\frac{Z_{L0}-Z_{L1}}{Z_{L1}}\times I_{X0}+\frac{Z_{m0}}{Z_{L1}}\times I_{T0}}\right)+\mathrm{Arg}\left(\frac{1}{CDF_{f0}}\right)\end{aligned} \quad (12)$$

4. DISTANCE PROTECTION ALGORITHM

4.1 The residual current of the parallel line calculated by the relay

The distance protection algorithm is represented in Fig. 6. In order to determine the apparent impedance, the current distribution factor, CDF_{T0}, is computed after setting the initial value of the zone 1 of the distance protection to 80% of the line impedance. This value is not selected to cover the line impedance because in reality there are errors generated, among others, by the voltage and current transformer, line parameters and relays.

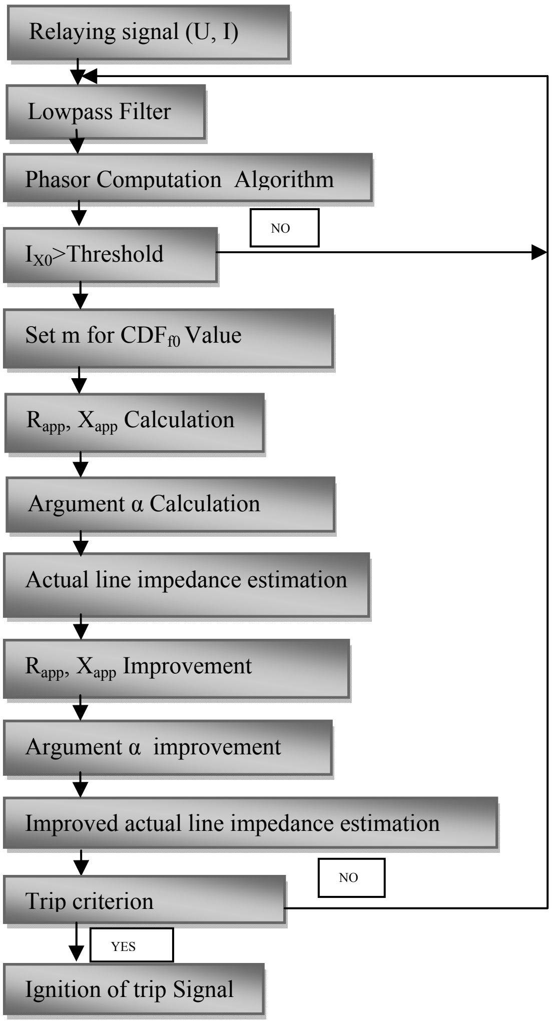

Fig. 6. Flow chart of the distance protection algorithm.

In the next step, it is calculated the apparent impedance and the value of the line impedance to a fault is approximated (Yong-Jin Ahn et al., 2001). Considering that the line impedance was estimated taking into account the type and dimensions of the poles, electrical characteristics of the active conductors, electrical characteristics of the OPGW (optical ground wire) and the line length, the error is reduced by the new apparent impedance estimated with the evaluated fault distance at the previous step. Taking into account this new apparent impedance, the line impedance to a fault is evaluated again.

In order to evaluate a line impedance which is much closer to reality, this process can be performed several times.

4.2 The residual current of the parallel line injected into a relay

Fig.7 shows the steps of the distance protection algorithm for single phase to ground faults.

Unlike the first case algorithm, the fault distance in the second case is obtained from the apparent impedance. Also, it is not necessary to set the fault distance value previously.

Based on the apparent fault distance it is calculated the CDF_{f0}.

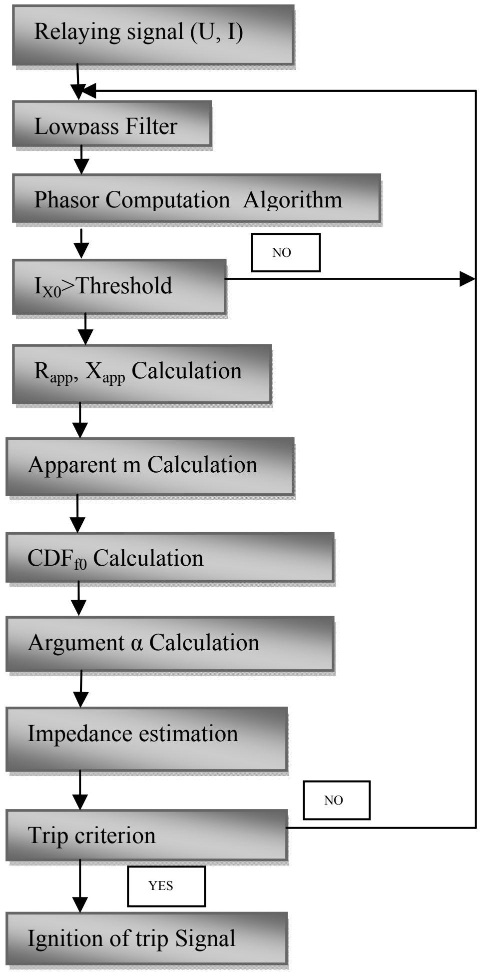

Fig. 7. Flow chart of the distance protection algorithm.

5. CASE STUDY

In order to emphasize the efficacy of the proposed algorithm, single phase to earth shortcircuits on one circuit of a 110 kV double circuit overhead line were simulated in Mathcad.

In Table 1 are provided the test cases, considering the zone 1 trip conditions including up to 80 % of the total line length.

The electrical parameters of the sources and lines are shown in Table 2.

Table 1. Test Cases.

Type of shortcircuit	Single phase to ground fault	
	No correction	Correction
Fault distance [km]	+2.4 (zone 1) +16 (zone 1) +24 (zone 1) +32.4 (zone 2)	+2.4 (zone1) +16 (zone 1) +24 (zone 1) +32.4 (zone 2)
Fault resistance [Ω]	0 50	0 50

Table 2. Parameters of the Sources and Lines.

Parameters		Positive sequence impedance	Zero sequence impedance [Ω]	
			Self	Mutual
Source [Ω]	SX	0.582+j5.822	2.219+j14.313	-
	SY	0.635+j6.351	2.495+j13.603	-
Line 1 (2) [Ω/km]		0.098+j0.381	0.298+j1.329	0.200+j0.881

The results of the single phase to ground faults, without correction of the apparent impedance, are presented in Table 3 in the case of the faults that occur at 2.4, 16, 24 and 32.4 km, with and without fault resistance of 50 Ω. Some results are showing that the relay does not operate (underreach).

Table 4 shows the results of the single phase to ground faults with correction of the apparent impedance. As a result, the tripping time is improved. The resistance and the reactance estimated by the algorithm are shown in Table 5 and 6.

The errors are presented in Fig. 8, 9. For forward faults, the maximum error is about 60% despite fault resistance of 50 Ω.

Overall, this impedance correction algorithm makes the proposed distance algorithm to improve the accuracy of the distance protection.

Table 3. Trip Decision Results (No Correction).

Fault location [km]	Fault resistance [Ω]	Distance algorithm 1	Distance algorithm 2
+2.4 (zone 1)	0	No Trip	No Trip
	50	No Trip	No Trip
+16 (zone 1)	0	Trip	Trip
	50	No Trip	No Trip
+24 (zone 1)	0	Trip	Trip
	50	No Trip	No Trip
+32.4 (zone 2)	0	No Trip	No Trip
	50	No Trip	No Trip

Table 4. Trip Decision Results (With Correction).

Fault location [km]	Fault resistance [Ω]	Distance algorithm 1	Distance algorithm 2
+2.4 (zone 1)	0	No Trip	No Trip
	50	No Trip	No Trip
+16 (zone 1)	0	Trip	Trip
	50	Trip	Trip
+24 (zone 1)	0	Trip	Trip
	50	Trip	Trip
+32.4 (zone 2)	0	No Trip	No Trip
	50	No Trip	No Trip

Table 5. Resistance Estimation.

Fault location [km]	Fault resistance [Ω]	Actual value [Ω]	Distance algorithm 1	Distance algorithm 2
+2.4 (zone 1)	0	0.235	0.235	0.235
	50		0.378	0.304
+16 (zone 1)	0	1.570	1.570	1.570
	50		1.813	1.686
+24(zone 1)	0	2.356	2.356	2.356
	50		2.806	2.719
+32.4(zone 2)	0	3.180	3.180	3.180
	50		3.499	3.078

Table 6. Reactance Estimation.

Fault location [km]	Fault resistance [Ω]	Actual value [Ω]	Distance algorithm 1	Distance algorithm 2
+2.4 (zone 1)	0	0.915	0.915	0.915
	50		1.470	1.182
+16 (zone 1)	0	6.100	6.100	6.100
	50		7.044	6.550
+24(zone 1)	0	9.151	9.151	9.151
	50		10.900	10.562
+32.4(zone 2)	0	12.354	12.354	12.354
	50		13.592	11.956

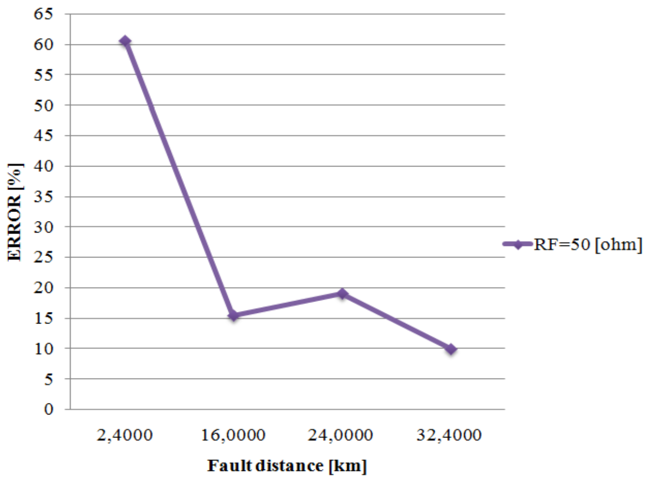

Fig. 8. Case 1 -Impedance estimation error.

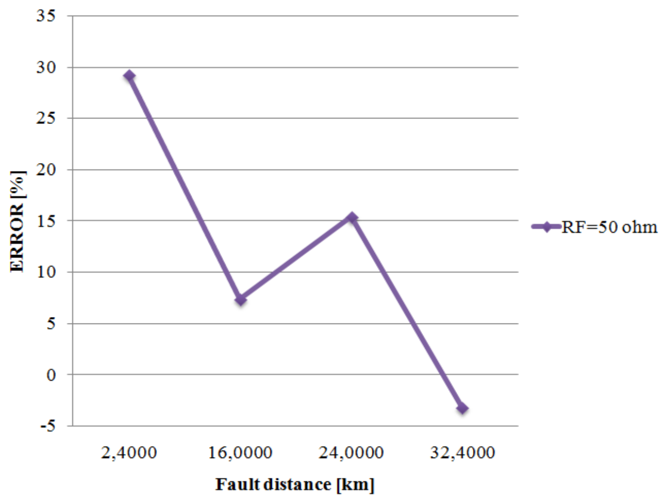

Fig. 9. Case 2 -Impedance estimation error.

6. CONCLUSIONS

The precision of distance protection from double-circuit lines is affected by the zero sequence mutual impedance and fault resistance. Through earth faults with the parallel line operation, the impedance estimated by the fault locator of the relay will be incorrect, due to the zero sequence mutual coupling. Also, the power system state and the geometry of the line are an important source of errors.

An accurate numerical distance protection algorithm immune to the reactance effect is approached in the paper. The algorithm uses only the local end information from current and voltage transformers, and can be performed in digital distance protections from 110 kV double transmission lines.

In the logic, the deviation angle α is calculated and used for modification of the position of the fault impedance in the quadrilateral characteristic. If the ground current of the parallel line can be connected to the measuring input of the distance protection, the argument α can be evaluated with only one current distribution factor. Also, the zero sequence current of the parallel line and the zero sequence fault current can be calculated with only two current distribution factors.

Several phase to earth shortcircuits scenarious with 50 ohm fault resistance were simulated on one circuit of a 110 kV double circuit line. In case that the residual current is calculated the maximum error is up to 60%. The error is up to 30% in case that the residual current is injected into the relay. The highest error was determined for single phase to earth faults behind the distance protection and also close to relay location.

The results of the study indicate that the proposed logic can speed up the relay operation for clearance of the close-in as well as the high-impedance faults. Furthermore, it can ensure higher security compared to the conventional nonadaptive decision logic, for the single phase faults at the 110 kV double circuit transmission line boundary.

The adaptive method presented in the paper is autonomous, meaning that the influence of fault resistance and the zero sequence mutual impedance is neglected. Another advantage of this algorithm is that it does not require fault information from the remote relays, nor the source impedance value.

Using this distance protection scheme in 110 kV double circuit transmission network, the operability of the distance protection relay can be enhance and the phenomena of overreach and underreach can be avoided. Also, the protection coordination and the selectivity of the whole electric power system can be improved.

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