

INFLUENCE OF THE ZERO SEQUENCE MUTUAL IMPEDANCE TO THE DISTANCE PROTECTION

Ionuț Ciprian BORĂSCU¹, Sergiu Stelian ILIESCU²

In terms of operating regimes and safety of the power system, the occurrence of a circuit breaker has been and will be the most important solutions to avoid interruptions in the power supply.

From the point of view of protection, changing network topolog by building a new power outlet circuit mainly on the same tower, may cause mutual inductive coupling of the current path and measurement errors for distance protection.

Starting from the measured impedance and errors in different 110 kV double circuit configurations, the paper analyzes the influence of the mutual coupling to the measured impedance in a 110 kV double overhead line configuration, taking also into account the variation of earth resistivity, fault location, rotor angle and fault resistance.

Keywords: distance protection, mutual coupling, topology

1. Introduction

Parameter measurements of 110 kV overhead lines have shown that in the case of 110 kV double circuit transmission line the mutual zero sequence impedance will always be present, regardless of the number of configurations or the number of transpositions. Also, for 110 kV overhead lines that have different voltage levels and that are on the same tower or paralleled along the same direction, the zero sequence mutual impedance exists [1].

In order to achieve correct short-circuit scenarios in the transient programs, the mutually coupled lines must be modelled in accordance with the following technical data: types and dimensions of the poles, length, resistance and radius of the active conductor, resistance and the radius of the protective conductor, all double circuit sections in order to determine the begin and the end of the mutual coupling.

In 110 kV network the fault measuring is more secure with distance protection than the overcurrent protection. However, depending on the trip characteristic the distance protection has some fault impedance measuring issues, namely [2, 3]:

¹ PhD student, Department of Automatic Control and Industrial Informatics, University POLITEHNICA of Bucharest, Romania, e-mail: borascu.ciprian@yahoo.com

² Prof., Department of Automatic Control and Industrial Informatics, University POLITEHNICA of Bucharest, Romania, e-mail: iliescu@shiva.pub.ro

- MHO characteristic:
 - There is an impedance measurement error due to the fault resistance. These errors are usually larger than the polygon feature;
 - limited arc resistance;
 - mutual coupling between parallel transmission circuits;
- Polygon characteristic:
 - Phase to earth measuring loop is affected by measurement errors of currents and voltages when the resistance is greater than the set reactance;
 - Phase to earth measuring loop are influenced by the unbalances of the power system (unequal sources and angles of the 110 kV overhead lines, cables);
 - Mutual coupling between parallel transmission circuits;

2. Positive and negative sequence impedance

Distance protection measurement algorithms require the positive sequence impedances and zero sequence impedances. Because the transmission line has passive and bilateral properties, the positive sequence (R-S-T) voltages produce the same voltage drops as negative sequence (R-T-S) voltages [4]. Theoretically, this means that the positive and negative sequence impedances are the same, provided that the line is transposed. In reality, errors can occur because of unbalances of the lines.

For any configuration of the conductors of a 110 kV double circuit line (r, s, t, r', s', t') the matrix of impedances, $Z_{rst''}$, is expressed as follows:

$$Z_{rst''} = \begin{bmatrix} Z_{rr} & Z_{rs} & Z_{tr} & Z_{rr'} & Z_{rs'} & Z_{t'r'} \\ Z_{rs} & Z_{ss} & Z_{st} & Z_{sr'} & Z_{ss'} & Z_{st'} \\ Z_{tr} & Z_{st} & Z_{ss} & Z_{sr'} & Z_{s't} & Z_{tt'} \\ Z_{rr'} & Z_{r's} & Z_{sr'} & Z_{r'r'} & Z_{r's'} & Z_{t'r'} \\ Z_{rs'} & Z_{ss'} & Z_{s't} & Z_{r's'} & Z_{s's'} & Z_{s't'} \\ Z_{t'r'} & Z_{st'} & Z_{tt'} & Z_{t'r'} & Z_{s't'} & Z_{t't'} \end{bmatrix} \quad (1)$$

Considering the matrix of impedances, the voltage drop along the 110 kV parallel line with length „1”, it is:

$$[\Delta U_{rst''}] = [Z_{rst''}] [I_{rst''}] I \quad (2)$$

Where:

- $\Delta U_{rst''}$ is the voltage drop along the 110 kV parallel line;

- $Z_{rst''}$ is the matrix of impedances;

- $I_{rst''}$ are the phase currents;

Based on symmetric matrix components, the equation (2) becomes:

$$Z_{012''} = \begin{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} & 0 & \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} & 0 \\ 0 & \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} & 0 & \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \\ \end{bmatrix} \begin{bmatrix} Z_{rst'} \end{bmatrix} \begin{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} & 0 & \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} & 0 \\ 0 & \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} & 0 & \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \\ \end{bmatrix} \quad (3)$$

When determining the phase position of 110 kV double circuit lines, studies are performed in order to obtain the lowest coefficients of unbalance and the smallest direct sequence impedance [5]. The results of the studies show that mutual impedance is the same for every configuration. The transposition of a double circuit line involves, from a physical point of view, rearranging of phases in the same configuration (fig. 1.).

In the case of double circuit overhead transmission lines mutual coupling in the positive and negative sequence systems can be neglected (for transposed 110 kV lines mutual impedance is less than 3% of the rated self impedance and for 110 kV not transposed lines is below 5% of the rated self impedance). This means that in case of load and short-circuit (without earth) conditions, the lines can be considered independent [6].

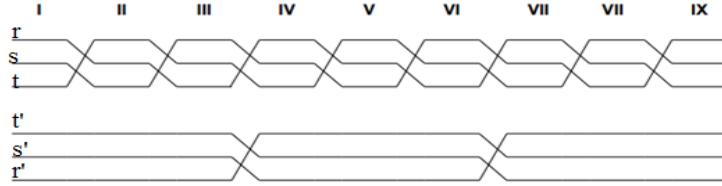


Fig.1. Transposed double circuit line.

In case that could be calculated the impedance matrix $Z_{012''}$, it would represent the sum of impedances in symmetrical components of each segment, namely:

$$Z_{012''} = \left(\sum_{i=1}^{IX} Z_{012''i} \right) \frac{1}{9} = \begin{bmatrix} Z_{00} & 0 & 0 & Z_{00m} & 0 & 0 \\ 0 & Z_{11} & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_{22} & 0 & 0 & 0 \\ Z_{00m} & 0 & 0 & Z_{00'} & 0 & 0 \\ 0 & 0 & 0 & 0 & Z_{11'} & 0 \\ 0 & 0 & 0 & 0 & 0 & Z_{22'} \end{bmatrix} \quad (4)$$

The goal of transposition of a line is to remove the mutual terms from the impedance matrix. Equation (4) shows that even in the case of a fully transposed line, the mutual zero sequence impedance would not be zero.

3. Zero sequence and mutual impedance

The zero sequence current from the parallel circuit induces a voltage in fault loop and changes the short-circuit voltage at the relay location. Therefore, results measuring errors that are determined by the system configuration.

The mutual impedance (Z_{12}) between two parallel conductors or groups of conductors [1] with a common earth return is:

$$Z_{12} = 0.987 \times f \times 10^{-3} + j \times 2.894 \times f \times 10^{-3} \times \log \frac{De}{GMR} \text{ ohm/km} \quad (5)$$

The zero sequence mutual impedance (Z_{0M}) is:

$$Z_{0M} = 3 \times Z_{12} = 0.148 + j \times 0.4340 \times \log \frac{De}{GMD} \text{ ohm/km} \quad (6)$$

Where:

- GMD is the geometrical mean distance;
- GMR is the geometric mean radius of a conductor (or a group of conductors);
- De is the equivalent depth of earth return: $De = 658.368 \cdot \sqrt{\frac{\rho}{f}}$ (meters), where ρ the earth resistivity in meter-ohms and f is the frequency. The values for various soils are presented in Table 1 [1].

Also, the zero sequence impedance of parallel lines is determined by the following equation:

$$Z_{0P} = \frac{1}{2} \times (Z_0 + Z_{0M}) \quad (7)$$

Where:

- Z_0 is the zero sequence impedance of the line;
- Z_{0P} is the zero sequence impedance of parallel lines;

Table 1

Values for various soils

Soil	ρ ($\Omega \cdot \text{m}$)	De at 50 Hz (meters)	Log De
Damp earth	100	931.073	2.969
Dry earth	1000	2944	3.469
Seawater	1	93.107	1.969
Pure slate	10^7	$2.944 \cdot 10^5$	5.469
Sandstone	10^9	$2.944 \cdot 10^6$	6.469

The influence of the zero sequence mutual impedance can be as high as about 70% of the zero sequence self impedance when the parallel lines are

mounted on the same tower [7]. Therefore, in short circuit studies the positive and negative mutual sequence impedance can be neglected and the zero sequence mutual impedance must be considered.

Mutual impedance represents a logarithmic relationship and therefore the slowly decrease with increasing distance between the lines is notable. Even if the distance between the lines is notable, mutuality still persists.

The most common single phase short-circuits appear in one of the next configurations [8]:

1. Single phase short-circuit on one circuit of a double overhead line that is fed from two sources (fig. 2a);
2. Single phase short-circuit at the opposite end, circuit breaker disconnected (fig. 2b);
3. Single phase short-circuit at the opposite end, the other line grounded at both ends (fig. 2c);
4. Single phase short-circuit at the opposite end (fig. 2d);

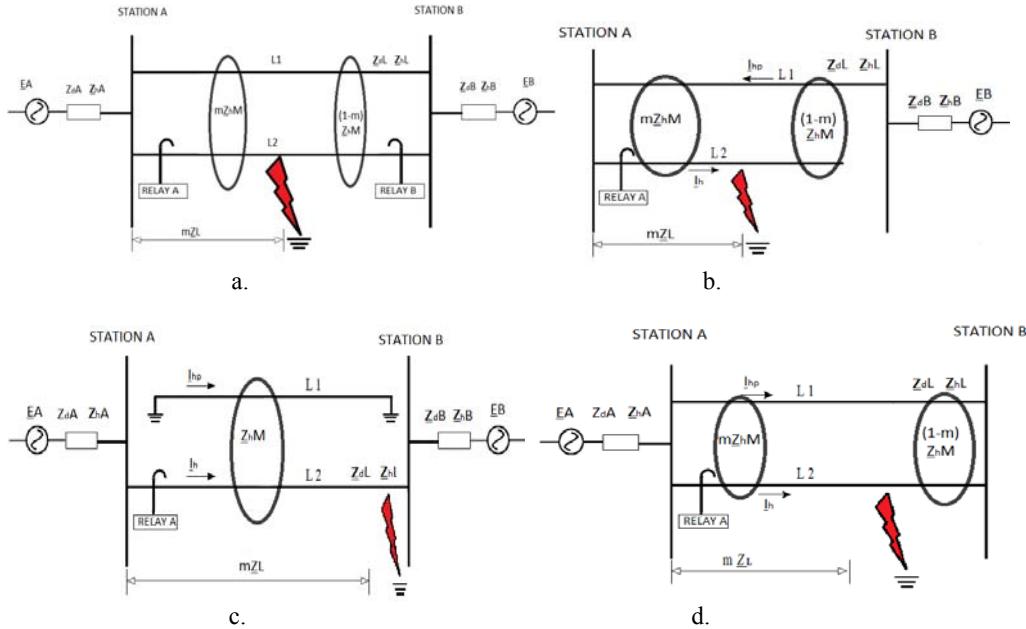


Fig.2. Double overhead lines configurations and the mutual influence.

- a. Single phase shortcircuit on one circuit of a double overhead line that is fed from two sources.
- b. Single phase shortcircuit at the opposite end, circuit breaker disconnected.
- c. Single phase shortcircuit at the opposite end, the other line grounded at both ends.
- d. Single phase shortcircuit at the opposite end.

When a single phase short-circuit appears on one circuit (fig.2a), measuring error occurs due to the fact that the parallel line earth current induces a voltage into the fault-loop.

Considering a phase short-circuit on phase a, the classic impedance measured is:

$$Z_{measured} = \frac{V_a}{I_a + k_0 \times I_h} \quad (8)$$

Where:

V_a = the phase to earth voltage applied to the relay;

I_a = the phase to earth current applied to the relay;

k_0 = earth compensation factor - $k_0 = \frac{Z_0 - Z_d}{3 \times Z_d}$;

I_h = earth current;

Z_d = positive sequence impedance of the line;

Due to the parallel line, the phase to earth voltage applied to the relay is:

$$V_a = Z_d \times I_a + \frac{Z_0 - Z_d}{3 \times Z_d} \times I_h \times Z_d + \frac{Z_{0M}}{3 \times Z_d} \times I_{hp} \times Z_d \quad (9)$$

Where:

I_{hp} = earth current from parallel line;

Considering the equations (8), (9), the impedance measured by the relay becomes:

$$Z_{measured} = Z_d \times \left(1 + \frac{k_{0M} \times I_{hp}}{I_a + k_0 \times I_h} \right) \quad (10)$$

Where:

k_{0M} = mutual coupling factor - $k_{0M} = \frac{Z_{0M}}{3 \times Z_d}$;

$\frac{k_{0M} \times I_{hp}}{I_a + k_0 \times I_h}$ = error that increases with the parallel line earth current in relation with the relay current $I_a + k_0 \times I_h$;

The relay underreaches when I_a , I_h , I_{hp} are in phase. Overreach occurs when I_{hp} and I_a/I_h have opposite signs.

From equation (10) and considering $I_a = I_h = I_{hp}$, we get the error:

$$\Delta Z = \frac{k_{0M}}{1 + k_0} \times Z_d = 15.3\% \text{ of } Z_d \quad (11)$$

where $k_{0M}=0.25$ and $k_0=0.63$.

In case of the single phase short-circuit at the end of a parallel line, one breaker open (fig.2b), $I_a = I_h = -I_{hp}$ and the error is:

$$\Delta Z = -\frac{k_{0M}}{I+k_0} \times Z_d = -15.3\% \text{ of } Z_d \quad (12)$$

For short-circuits at the opposite end, the other line grounded at both ends (fig.2c), ΔZ has the following expression:

$$\Delta Z = -Z_d \times \frac{k_{0M} \times \frac{Z_{0M}}{Z_0}}{I+k_0} = -10\% \text{ of } Z_d \quad (13)$$

where $k_{0M}=0.4$ and $k_0=0.7$

4. Case study

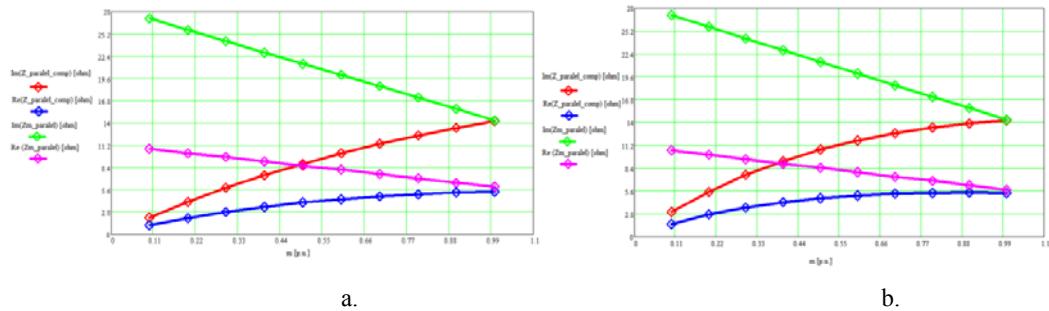
Considering single phase short-circuits on one circuit of a 110 kV double overhead line that is fed from one source (fig.2d.). The impedances of the source and the line length are:

$Z_{Sh}=4+j*6$ [ohm] – zero sequence impedance of the source;

$Z_{Sd}=2+j*3$ [ohm] – positive sequence impedance of the source;

Positive sequence impedance, zero sequence impedance and the zero sequence mutual impedance of the line are determined considering the Sn 110252.5.3.B.R pole, ALOL 185/32 mm² conductor and different earth resistivities.

The calculations were made in Mathcad considering different scenarios (fig.3, fig.4, fig.5, fig.6, fig.7, fig.8).



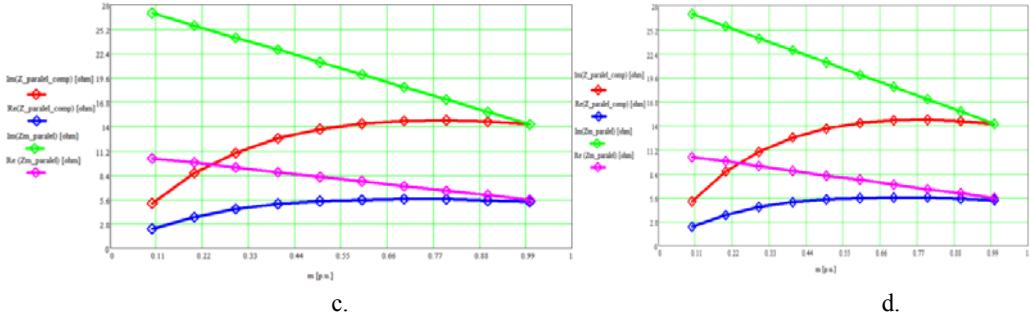


Fig.3.Variation of compensating and measured impedances by the relay from the healthy circuit, according to the place of shortcircuit.

- a. $L=34$ km, $m=0.1, 0.2..1$, $R_{\text{fault}}=0$ ohm, $\rho=10^9$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i0}$ V.
- b. $L=34$ km, $m=0.1, 0.2..1$, $R_{\text{fault}}=0$ ohm, $\rho=1000$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i0}$ V.
- c. $L=34$ km, $m=0.1, 0.2..1$, $R_{\text{fault}}=0$ ohm, $\rho=1$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i0}$ V.
- d. $L=34$ km, $m=0.1, 0.2..1$, $R_{\text{fault}}=0$ ohm, $\rho=1$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i22}$ V.

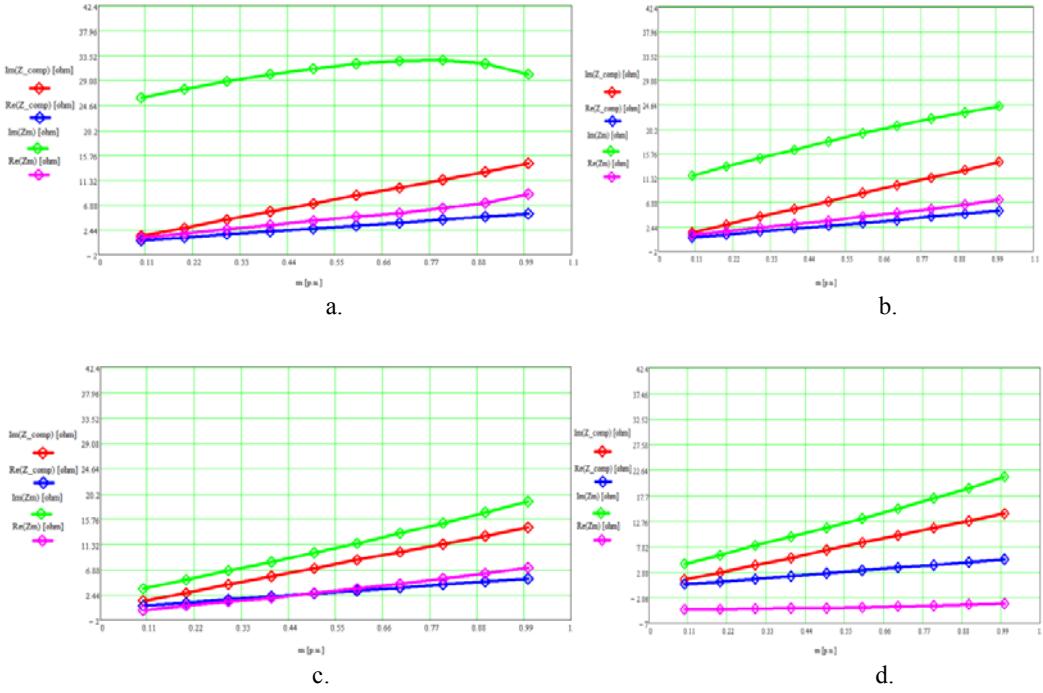


Fig.4.Variation of compensating and measured impedances by the relay from the affected circuit, according to the place of short-circuit.

- a. $L=34$ km, $m=0.1, 0.2..1$, $R_{\text{fault}}=0$ ohm, $\rho=10^9$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i0}$ V.
- b. $L=34$ km, $m=0.1, 0.2..1$, $R_{\text{fault}}=0$ ohm, $\rho=1000$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i0}$ V.
- c. $L=34$ km, $m=0.1, 0.2..1$, $R_{\text{fault}}=0$ ohm, $\rho=1$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i0}$ V.
- d. $L=34$ km, $m=0.1, 0.2..1$, $R_{\text{fault}}=0$ ohm, $\rho=1$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i22}$ V.

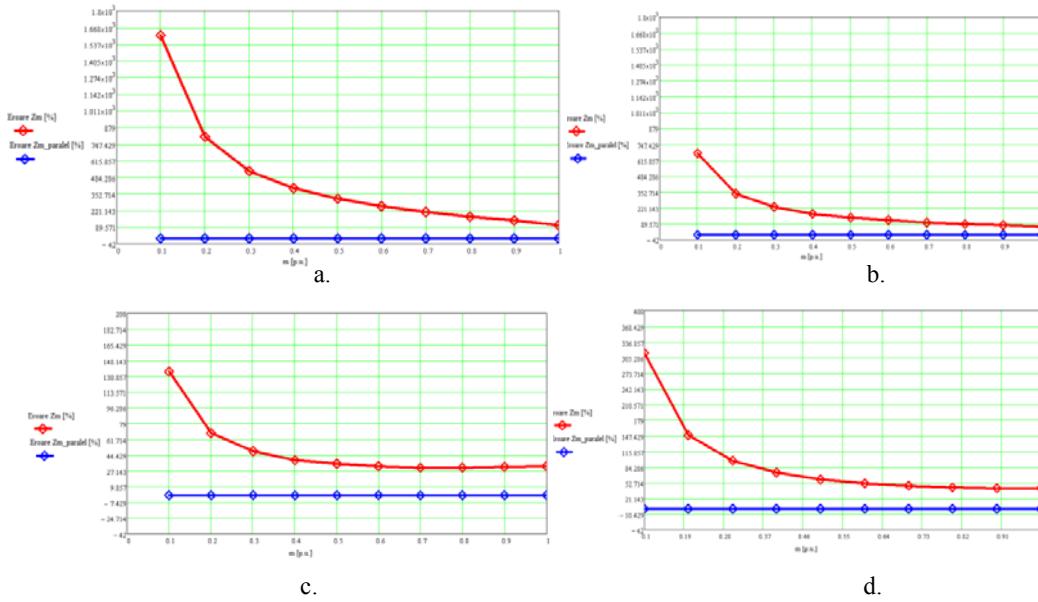


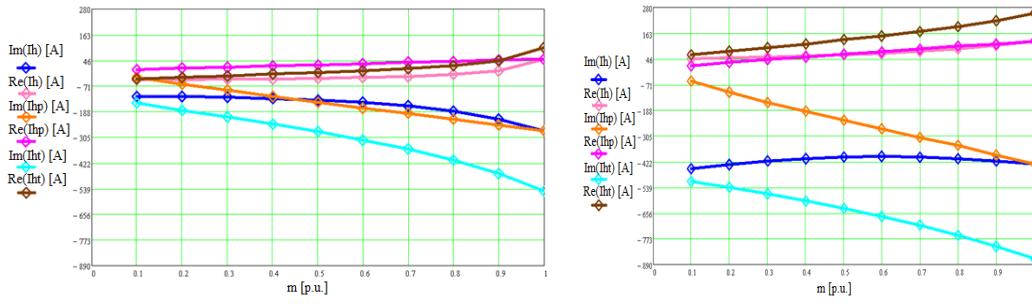
Fig.5. Measurement errors of both relays according to the place of short-circuit.

a. $L=34 \text{ km}$, $m=0.1, 0.2, \dots, 1$, $R_{\text{fault}}=0 \text{ ohm}$, $\rho=10^9 \text{ ohm}\cdot\text{m}$, $U_n=110000/\sqrt{3} \text{ V}$, $EA=U_n \cdot e^{1i0} \text{ V}$.

b. $L=34 \text{ km}$, $m=0.1, 0.2, \dots, 1$, $R_{\text{fault}}=0 \text{ ohm}$, $\rho=1000 \text{ ohm}\cdot\text{m}$, $U_n=110000/\sqrt{3} \text{ V}$, $EA=U_n \cdot e^{1i(0)} \text{ V}$.

c. $L=34 \text{ km}$, $m=0.1, 0.2, \dots, 1$, $R_{\text{fault}}=0 \text{ ohm}$, $\rho=1 \text{ ohm}\cdot\text{m}$, $U_n=110000/\sqrt{3} \text{ V}$, $EA=U_n \cdot e^{1i0} \text{ V}$.

d. $L=34 \text{ km}$, $m=0.1, 0.2, \dots, 1$, $R_{\text{fault}}=0 \text{ ohm}$, $\rho=1 \text{ ohm}\cdot\text{m}$, $U_n=110000/\sqrt{3} \text{ V}$, $EA=U_n \cdot e^{1i22} \text{ V}$.



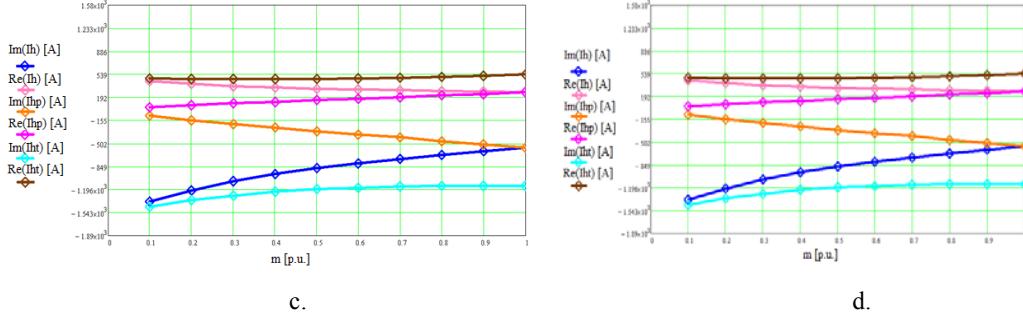


Fig.6. Variations of the earth currents according to the place of short-circuit.

a. $L=34$ km, $m=0.1, 0.2..1$, $R\text{defect}=0$ ohm, $\rho=10^9$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i0}$ V.
 b. $L=34$ km, $m=0.1, 0.2..1$, $R\text{defect}=0$ ohm, $\rho=1000$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i0}$ V.
 c. $L=34$ km, $m=0.1, 0.2..1$, $R\text{defect}=0$ ohm, $\rho=1$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i0}$ V.
 d. $L=34$ km, $m=0.1, 0.2..1$, $R\text{defect}=0$ ohm, $\rho=1$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i22}$ V.

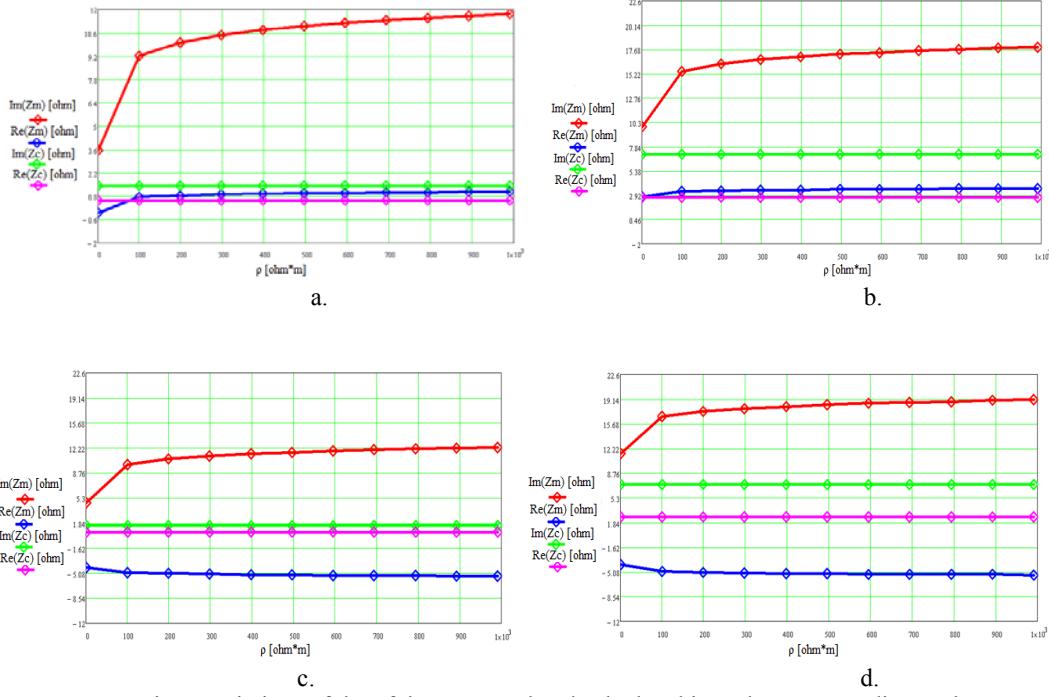


Fig.7. Variations of the measured and calculated impedances according to the resistivity.

a. $L=34$ km, $m=0.1$, $R\text{defect}=0$ ohm, $\rho=1,100..1000$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i0}$ V.
 b. $L=34$ km, $m=0.5$, $R\text{defect}=0$ ohm, $\rho=1,100..1000$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i0}$ V.
 c. $L=34$ km, $m=0.1$, $R\text{defect}=0$ ohm, $\rho=1,100..1000$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i22}$ V.
 d. $L=34$ km, $m=0.5$, $R\text{defect}=0$ ohm, $\rho=1,100..1000$ ohm·m, $U_n=110000/\sqrt{3}$ V, $EA=U_n \cdot e^{1i22}$ V.

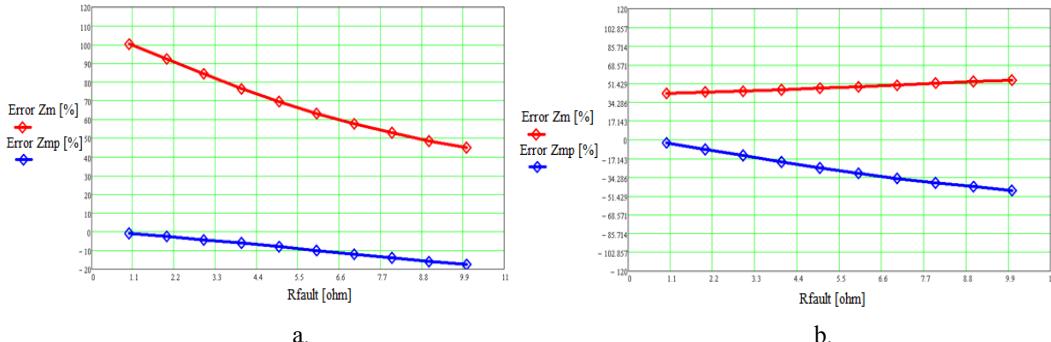


Fig.8.Measurement errors of both relays according to the fault resistance.

a . $L=34$ km, $m=0.5$, $R_{defect}=0.1,0.2..1$ ohm, $\rho=100$ ohm·m, $U_n=110000/\sqrt{3}$ V, $E_A=U_n \cdot e^{1i0}$ V.
 b . $L=34$ km, $m=1.5$, $R_{defect}=0.1,0.2..1$ ohm, $\rho=100$ ohm·m, $U_n=110000/\sqrt{3}$ V, $E_A=U_n \cdot e^{1i0}$ V.

5. Conclusions

Phase arrangement and transposition allow smaller natural unbalance in the transmission lines, but do not eliminate the zero-sequence mutual impedance between the parallel lines.

Since in protection studies a number of factors are neglected, the paper is proposing to simulate the influence of the mutual coupling to the measured impedance in 110 kV double overhead line configuration. The variation of earth resistivity, fault location, rotor angle and fault resistance are also taken into account.

In a 110 kV double circuit configuration which is connected to a common bus bar, if a single phase to earth fault occurs on one of the two circuits, zero sequence current in the other circuit may cause a greater underreaching of the protection at one end of the faulted circuit than it causes overreaching at the other end. Measurement error of the impedance, as results from the study, decrease as the fault is far from the relay location. Also, if the resistivity increases, the impedance measured by the distance protection increase as well.

In order to compensate the influence of the zero sequence current from the parallel circuit, one solution is to connect the ground current from the parallel line to the ground input CT of the CT bank. In other relays, the algorithm for eliminating the mutual compensation is based on the ratio of neutral current of the parallel line to the neutral current of the protective line (I_{MUTUAL}/IN) [9, 10, 11, 12].

At the moment, in 110 kV network, the mutual coupling is not considered because the distance protection from healthy line will underreach. However, the influence of the mutual coupling is reduced by determining the appropriate settings for relays.

This type of example presented in the article, helps protection engineers to take the best decisions for minimizing the effect of the mutual coupling. Also, the study reveals that the mutual coupling must be included in the development of a protection scheme.

The work of this paper can contribute to develop new adaptive algorithms for underreach correction in the basic distance relaying schemes, without considering the residual current from the parallel circuit.

Acknowledgement

This work was co-funded by the European Social Fund through the Operational Programme Human Resources Development 2007-2013 (Contract number POSDRU/159/1.5/S/132395).

R E F E R E N C E S

- [1]. *J. Lewis Blackburn*, Symmetrical Components for Power Systems Engineering, Marcel Dekker, 1993.
- [2]. *E.O. Schweitzer, Normann Fisher* -SEL, A fresh look at limits to the sensitivity of line protection, 65th Annual Georgia Tech Protective Relaying Conference, Atlanta, Georgia, May 11-13, 2011.
- [3]. *Felicia Lazăr, M. Eremia*, Numerical Protections Impact on the Secure Operation of Electric Power Systems, U.P.B. Sci. Bull., Series C, Vol. 75, Iss. 4, 2013.
- [4]. *R. E. Fehr*, Sequence Impedances of Transmission Lines, May 2004.
- [5]. *F. Calero*, Mutual Impedance in Parallel Lines-Protective Relaying and Fault Location Considerations, Schweitzer Engineering Laboratories, Inc., 2008.
- [6]. *G. Ziegler*, Numerical Distance Protection, Siemens, Third Edition, 2008.
- [7]. *Working Group 04 of Study Committee 34 (Protection)*, APPLICATION GUIDE ON PROTECTION OF COMPLEX TRANSMISSION NETWORK CONFIGURATIONS, Cigre, November 1991.
- [8]. *A. Vasilevici, S. Gal, F. Balasiu, T. Fagarasan*, Implementarea echipamentelor digitale de protecție și comandă pentru rețele electrice, Editura Tehnică, 1998.
- [9]. *D. Mihoc, S. S. Iliescu, Ioana Făgărășan, Onița Calotă, G. Tărănu, O. Stan*, Protecții prin releu clasice și numerice, Editura Printech, 2008.
- [10]. *A. Apostolov (OMICRON electronics), D. Tholomier (AREVA T&D Automation), S. Sambasivan (AREVA T&D Automation), S. Richards (AREVA T&D Automation)*, Protection of Double Circuit Transmission Lines, 2007.
- [11]. *** D60 – Line distance relay, Instruction manual, 2002.
- [12]. *** P543 – Current differential protection relays, Technical manual, 16 march 2009.