DISTANCE PROTECTION OF DOUBLE–CIRCUIT TRANSMISSION LINES WITH COMPENSATION FOR THE REACTANCE EFFECT UNDER STANDARD AVAILABILITY OF MEASUREMENTS

Jan Izykowski Marcin Bozek
e-mail: jan.izykowski@pwr.wroc.pl *e-mail: marcin.bozek@pwr.wroc.pl*
Wroclaw University of Technology, Institute of Electrical Power Engineering
Wroclaw, Poland

Key words: Double–circuit transmission line, distance protection, fault, reactance effect, compensation

ABSTRACT

In this study, the negative impact of the reactance effect on operation of a distance relay in double–circuit line is presented and discussed. An adaptive procedure, based on simplified fault location algorithm for compensation for the reactance effect is proposed. The procedure uses standard availability of measurements from one end and calculates the shift vector, which is used for changing the position of the characteristic of a distance relay on *R–X* plane. The procedure has been tested using EMTP current and voltage signals.

I. INTRODUCTION

The principle of distance relaying is well known and is based on comparing the measured fault loop impedance with a characteristic of a distance relay on the impedance plane. This rule may prove not to be adequate in case of the presence of a fault resistance [1]. The fault resistance and pre-fault power flow may cause the relay not to trip at all or may lead to mal-operation [2, 3].

To compensate for the negative influence of the reactance effect, adaptive procedures may be used in a decision block. This paper introduces an adaptive algorithm for compensating for the fault resistance, which uses simplified fault location procedure and measurements from one end. The procedure calculates components of the shift vector ($\Delta\underline{Z}$) on–line, according to measured fault loop voltage and current. Therefore, the relay characteristic position on *R–X* plane is not constant, but varies according to shift vector value.

II. REACTANCE EFFECT AND MUTUAL COUPLING

Faults occurring in power lines may be divided into two groups:
– faults without the presence of fault resistance;
– faults with the presence of fault resistance.

Since fault resistance is an unknown and random value, it is not possible to create a characteristic that would provide proper operation of the relay in any case. The influence of fault resistance on distance relay operation is therefore essential, because combined effect of the fault resistance itself combined with pre-fault power flow may lead to delayed operation or maloperation. In case of parallel lines, mutual coupling has to be taken into account and additional component has to be added to an equation describing fault loop current. Therefore, zero sequence current from the healthy line has to be provided to compensate for the mutual coupling effect [6]. The zero sequence current can be provided as a relay input signal in case of complete (phase voltages and currents from faulted line and phase currents from healthy line) or standard (phase voltages and currents from faulted line and zero sequence current from healthy line) availability of signals.

The adaptive procedure described in the next section utilizes standard availability of signals. Figure 1 depicts standard availability of signals as well as the transmission system.

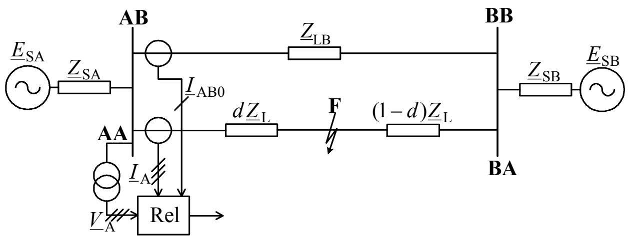

Figure 1. Transmission system used for analysis

III. BASICS OF THE ADAPTIVE PROCEDURE

One of the main qualities of digital distance relays that are in use nowadays is the easiness of applying decision algorithms. Therefore, it is possible to implement adaptive procedures to standard decision algorithms to make the relay more attuned to system conditions.

The procedure described in this paper is based on generalized fault loop model [5], which is stated as

$$\underline{V}_{\mathrm{Ap}} - d\underline{Z}_{1\mathrm{L}}\underline{I}_{\mathrm{Ap}} - R_{\mathrm{F}}\underline{I}_{\mathrm{F}} = 0 \quad (1)$$

where

$\underline{V}_{\mathrm{Ap}} = \underline{a}_1\underline{V}_{\mathrm{A1}} + \underline{a}_2\underline{V}_{\mathrm{A2}} + \underline{a}_0\underline{V}_{\mathrm{A0}}$ – fault loop voltage,

$\underline{I}_{\mathrm{Ap}} = \underline{a}_1\underline{I}_{\mathrm{AA1}} + \underline{a}_2\underline{I}_{\mathrm{AA2}} + \underline{a}_0\dfrac{\underline{Z}_{0\mathrm{L}}}{\underline{Z}_{1\mathrm{L}}}\underline{I}_{\mathrm{AA0}} + \underline{a}_0\dfrac{\underline{Z}_{0\mathrm{m}}}{\underline{Z}_{1\mathrm{L}}}\underline{I}_{\mathrm{AB0}}$ – fault loop current,

$\underline{I}_{\mathrm{F}} = \underline{a}_{\mathrm{F1}}\underline{I}_{\mathrm{F1}} + \underline{a}_{\mathrm{F2}}\underline{I}_{\mathrm{F2}} + \underline{a}_{\mathrm{F0}}\underline{I}_{\mathrm{F0}}$ - total fault current.

Coefficients $\underline{a}_{\mathrm{i}}$ determine fault loop signals and depend on fault type. Table 1 shows the values of these coefficients according to fault type.

Table 1. Coefficients $\underline{a}_{\mathrm{i}}$ for determining fault loop signals

Fault type	$\underline{a}_1$	$\underline{a}_2$	$\underline{a}_0$
a–g	1	1	1
b–g	$\underline{a}^2$	$\underline{a}$	1
c–g	$\underline{a}$	$\underline{a}^2$	1
a–b a–b–g a–b–c a–b–c–g	$1-\underline{a}^2$	$1-\underline{a}$	0
b–c b–c–g	$\underline{a}^2-\underline{a}$	$\underline{a}-\underline{a}^2$	0
c–a c–a–g	$\underline{a}-1$	$\underline{a}^2-1$	0
$\underline{a} = \exp(\mathrm{j}2\pi/3)$			

To determine voltage drop across the fault resistance, one needs to establish weighting coefficients ($\underline{a}_{\mathrm{Fi}}$). These coefficients can be derived from the symmetrical components theory and boundary conditions for particular fault type. It is possible to exclude one of the coefficients, i.e. $\underline{a}_{\mathrm{F0}}$ to eliminate zero sequence impedance, often considered as an unreliable value. The values of the weighting coefficients used for further calculations have been gathered in Table 2.

The shift vector $\Delta\underline{Z}$ comprises of two components: resistive and reactive and can be written as $\Delta\underline{Z} = \Delta R + \mathrm{j}\Delta X$. The MHO characteristic with a boundary of the first zone set to 85% (s = 0.85 p.u.) of the protected line length is described by the following inequality,

$$\left(R_{\mathrm{AP}} - 0.5sR_{1\mathrm{L}}\right)^2 + \left(X_{\mathrm{Ap}} - 0.5sX_{1\mathrm{L}}\right)^2 \le \left(0.5s\left|\underline{Z}_{1\mathrm{L}}\right|\right)^2 \quad (2)$$

where:

R_{Ap} – resistance measured by the relay,

X_{Ap} – reactance measured by the relay,

$R_{1\mathrm{L}}$ – positive sequence resistance of the protected line,

$X_{1\mathrm{L}}$ – positive sequence reactance of the protected line,

$\underline{Z}_{1\mathrm{L}}$ – positive sequence impedance of the protected line.

This inequality may be modified by adding the components of $\Delta\underline{Z}$ vector. Therefore, one can obtain adaptive MHO characteristic, stated as follows

$$\begin{aligned}&\left(R_{\mathrm{Ap}} - \left(0.5sR_{1\mathrm{L}} + \Delta R\right)\right)^2 \\ &+ \left(X_{\mathrm{Ap}} - \left(0.5sX_{1\mathrm{L}} + \Delta X\right)\right)^2 \le \left(0.5s\left|\underline{Z}_{1\mathrm{L}}\right|\right)^2\end{aligned} \quad (3)$$

ΔR and ΔX denote the shift of the relay characteristic. If these values are known in particular case and for certain transmission network state, it is possible to make the relay invulnerable to random disturbances.

Table 2. Different sets of weighting coefficients $\underline{a}_{\mathrm{F}i}$

Fault type	Set I		Set II		Set III	
	$\underline{a}_{\mathrm{F1}}$	$\underline{a}_{\mathrm{F2}}$	$\underline{a}_{\mathrm{F1}}$	$\underline{a}_{\mathrm{F2}}$	$\underline{a}_{\mathrm{F1}}$	$\underline{a}_{\mathrm{F2}}$
a–g	0	3	3	0	1.5	1.5
b–g	0	$3\underline{a}$	$3\underline{a}^2$	0	$1.5\,\underline{a}^2$	$1.5\,\underline{a}$
c–g	0	$3\underline{a}^2$	$3\underline{a}$	0	$1.5\,\underline{a}$	$1.5\,\underline{a}^2$
a–b	0	$1-\underline{a}$	$1-\underline{a}^2$	0	$\dfrac{1-\underline{a}^2}{2}$	$\dfrac{1-\underline{a}}{2}$
b–c	0	$\underline{a}-\underline{a}^2$	$\underline{a}^2-\underline{a}$	0	$\dfrac{\underline{a}^2-\underline{a}}{2}$	$\dfrac{\underline{a}-\underline{a}^2}{2}$
c–a	0	$\underline{a}^2-1$	$\underline{a}-1$	0	$\dfrac{\underline{a}-1}{2}$	$\dfrac{\underline{a}^2-1}{2}$
a–b–g	$1-\underline{a}^2$	$1-\underline{a}$	$1-\underline{a}^2$	$1-\underline{a}$	$1-\underline{a}^2$	$1-\underline{a}$
b–c–g	$\underline{a}^2-\underline{a}$	$\underline{a}-\underline{a}^2$	$\underline{a}^2-\underline{a}$	$\underline{a}-\underline{a}^2$	$\underline{a}^2-\underline{a}$	$\underline{a}-\underline{a}^2$
c–a–g	$\underline{a}-1$	$\underline{a}^2-1$	$\underline{a}-1$	$\underline{a}^2-1$	$\underline{a}-1$	$\underline{a}^2-1$
a–b–c a–b–c–g	$1-\underline{a}^2$	0	$1-\underline{a}^2$	0	$1-\underline{a}^2$	0

IV. DERIVATION OF SHIFT VECTOR $\Delta\underline{Z}$

From the equation (1) one obtains

$$\begin{aligned}&\underline{Z}_{\mathrm{Ap}} - d\underline{Z}_{1\mathrm{L}} - R_{\mathrm{F}}\frac{\underline{I}_{\mathrm{F}}}{\underline{I}_{\mathrm{Ap}}} = 0 \\ &\Delta\underline{Z} = \Delta R + \mathrm{j}\Delta X = \frac{\underline{I}_{\mathrm{F}}}{\underline{I}_{\mathrm{Ap}}}\end{aligned} \quad (4)$$

Choosing the weighting coefficients set where $a_{\mathrm{F0}} = 0$, equation (1) may be written down in an expanded form as follows

$$\underline{V}_{\mathrm{Ap}} - d\underline{Z}_{\mathrm{1L}}\underline{I}_{\mathrm{Ap}} - R_{\mathrm{F}}\left(\underline{a}_{\mathrm{F1}}\underline{I}_{\mathrm{F1}} + \underline{a}_{\mathrm{F2}}\underline{I}_{\mathrm{F2}}\right) = 0 \qquad (5)$$

Unknown values $\underline{I}_{\mathrm{F1}}$ and $\underline{I}_{\mathrm{F2}}$ can be derived from equivalent circuit diagrams for positive and negative sequence [5]. The equations resulting from the equivalent circuit diagrams are as follows

$$\underline{I}_{\mathrm{F1}} = \frac{\Delta\underline{I}_{\mathrm{A1}}}{\underline{k}_{\mathrm{F}}} \qquad \underline{I}_{\mathrm{F2}} = \frac{\underline{I}_{\mathrm{A2}}}{\underline{k}_{\mathrm{F}}} \qquad (6)$$

where $\Delta\underline{I}_{\mathrm{A1}}$ is the incremental positive sequence current, $\underline{I}_{\mathrm{A2}}$ is the negative sequence current, $\underline{k}_{\mathrm{F}}$ is the current distribution factor (identical for the positive and negative sequences).

The current distribution factor depends on parallel lines configuration and for the considered transmission network (Figure 1) takes the form

$$\underline{k}_{\mathrm{F}} = \frac{\underline{K}_1 d + \underline{L}_1}{\underline{M}_1} \qquad (7)$$

where

$$\underline{K}_1 = -\underline{Z}_{\mathrm{1L}}\left(\underline{Z}_{\mathrm{1sA}} + \underline{Z}_{\mathrm{1sB}} + \underline{Z}_{\mathrm{1LB}}\right)$$
$$\underline{L}_1 = \underline{Z}_{\mathrm{1L}}\left(\underline{Z}_{\mathrm{1sA}} + \underline{Z}_{\mathrm{1sB}} + \underline{Z}_{\mathrm{1LB}}\right) + \underline{Z}_{\mathrm{1LB}}\underline{Z}_{\mathrm{1sB}}$$
$$\underline{M}_1 = \underline{Z}_{\mathrm{1L}}\underline{Z}_{\mathrm{1LB}} + \underline{Z}_{\mathrm{1L}}\left(\underline{Z}_{\mathrm{1sA}} + \underline{Z}_{\mathrm{1sB}}\right) + \underline{Z}_{\mathrm{1LB}}\left(\underline{Z}_{\mathrm{1sA}} + \underline{Z}_{\mathrm{1sB}}\right)$$

The current distribution factor is a function of an unknown distance to fault (d, [p.u.]) and an unmeasurable in case of one end measurements value of $\underline{Z}_{\mathrm{1sB}}$. However, it will be further shown that it is not necessary to determine the value of $\underline{k}_{\mathrm{F}}$.

Total fault current from (4)–(5) may now be rewritten as $\underline{I}_{\mathrm{F}} = \dfrac{\underline{a}_{\mathrm{F1}}\Delta\underline{I}_{\mathrm{A1}} + \underline{a}_{\mathrm{F2}}\underline{I}_{\mathrm{A2}}}{\underline{k}_{\mathrm{F}}}$ and therefore

$$\underline{V}_{\mathrm{Ap}} - d\underline{Z}_{\mathrm{1L}}\underline{I}_{\mathrm{Ap}} - R_{\mathrm{F}}\frac{\underline{a}_{\mathrm{F1}}\Delta\underline{I}_{\mathrm{A1}} + \underline{a}_{\mathrm{F2}}\underline{I}_{\mathrm{A2}}}{\underline{k}_{\mathrm{F}}} = 0 \qquad (8)$$

The current distribution factor is a complex number and it may be presented as $\underline{k}_{\mathrm{F}} = k_{\mathrm{F}}\,\mathrm{e}^{\mathrm{j}\gamma} = k_{\mathrm{F}}\left(\cos\gamma + \mathrm{j}\sin\gamma\right)$. Substituting $\underline{k}_{\mathrm{F}}$ into equation (8) and dividing it by $\underline{I}_{\mathrm{Ap}}$ one obtains

$$\underline{Z}_{\mathrm{Ap}} - d\underline{Z}_{\mathrm{1L}} - \frac{R_{\mathrm{F}}}{k_{\mathrm{F}}}\underline{N}_{12}e^{-\mathrm{j}\gamma} = 0 \qquad (9)$$

Resolving $\underline{N}_{12}$ into real and imaginary part, the equation (9) takes the form

$$\underline{Z}_{\mathrm{Ap}} - d\underline{Z}_{\mathrm{1L}} - \frac{R_{\mathrm{F}}}{k_{\mathrm{F}}}\left(G_{12}^{\mathrm{real}} + \mathrm{j}G_{12}^{\mathrm{imag}}\right) = 0 \qquad (10)$$

where

$$G_{12}^{\mathrm{real}} = N_{12}^{\mathrm{real}}\cos\gamma + N_{12}^{\mathrm{imag}}\sin\gamma$$
$$G_{12}^{\mathrm{imag}} = N_{12}^{\mathrm{imag}}\cos\gamma + N_{12}^{\mathrm{real}}\sin\gamma$$

Comparing equation (4) with equation (10) one gets the ratio of ΔR to ΔX

$$\frac{\Delta R}{\Delta X} = \frac{G_{12}^{\mathrm{real}}}{G_{12}^{\mathrm{imag}}} = \frac{N_{12}^{\mathrm{real}}\cos\gamma + N_{12}^{\mathrm{imag}}\sin\gamma}{N_{12}^{\mathrm{imag}}\cos\gamma + N_{12}^{\mathrm{real}}\sin\gamma} \qquad (11)$$

Assuming that $\gamma=0$ (it is justified, because in real transmission networks the angle γ is close to zero (Figure 2) and rarely exceeds 10^{o} [2]), a simplified form of equation (11) is obtained.

$$\frac{\Delta R}{\Delta X} = \frac{N_{12}^{\mathrm{real}}}{N_{12}^{\mathrm{imag}}} \qquad (12)$$

From equation (4) and (12) one may derive the components of the shift vector, which are as follows

$$\Delta R = \frac{N_{12}^{\mathrm{real}}\left(R_{\mathrm{P}}X_{\mathrm{1L}} - X_{\mathrm{P}}R_{\mathrm{1L}}\right)}{N_{12}^{\mathrm{real}}X_{\mathrm{1L}} - N_{12}^{\mathrm{imag}}R_{\mathrm{1L}}} \qquad (13)$$

$$\Delta X = \frac{N_{12}^{\mathrm{imag}}\left(R_{\mathrm{P}}X_{\mathrm{1L}} - X_{\mathrm{P}}R_{\mathrm{1L}}\right)}{N_{12}^{\mathrm{real}}X_{\mathrm{1L}} - N_{12}^{\mathrm{imag}}R_{\mathrm{1L}}} \qquad (14)$$

where $\underline{N}_{12} = \dfrac{\underline{a}_{\mathrm{F1}}\Delta\underline{I}_{\mathrm{A1}} + \underline{a}_{\mathrm{F2}}\underline{I}_{\mathrm{A2}}}{\underline{I}_{\mathrm{Ap}}}$.

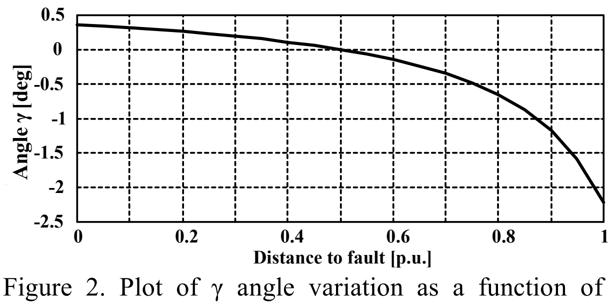

Figure 2. Plot of γ angle variation as a function of a distance to fault

IV. RESULTS AND DISCUSSION

The proposed procedure has been thoroughly tested using signals taken from ATP-EMTP [7] simulations. The modelled transmission system comprised of 400 kV transmission line and two equivalent sources. The parameters of the system have been gathered in Table 3. Presented simulation results include line–to–ground faults only, as these faults stand for approximately 70% of all faults in transmission and distribution lines. Various fault locations and fault resistances ranging from 0.1 Ω up to 20 Ω have been modelled to determine the accuracy of the proposed procedure

Table 3. Parameters of the modelled transmission system

System element	Parameter	
Line A Line B	Length l	150 km
	$\underline{Z}'_{1L}$	(0.0276 + j0.315) Ω/km
	$\underline{Z}'_{0L}$	(0.275 + j1.0265) Ω/km
	$\underline{C}'_{1L}$	13 nF/km
	$\underline{C}'_{0L}$	8.5 nF/km
	$\underline{Z}'_{0m}$	(0.20 + j0.628) Ω/km
Equivalent system A	$\underline{Z}_{1SA}$	(2.615+ j14.829) Ω
	$\underline{Z}_{0SA}$	(4.637 + j26.297) Ω
	Voltage phase	–30°
Equivalent system B	$\underline{Z}_{1SB}$	$\underline{Z}_{1SB} = \underline{Z}_{1SA}$
	$\underline{Z}_{0SB}$	$\underline{Z}_{0SB} = \underline{Z}_{0SA}$
	Voltage phase	0°

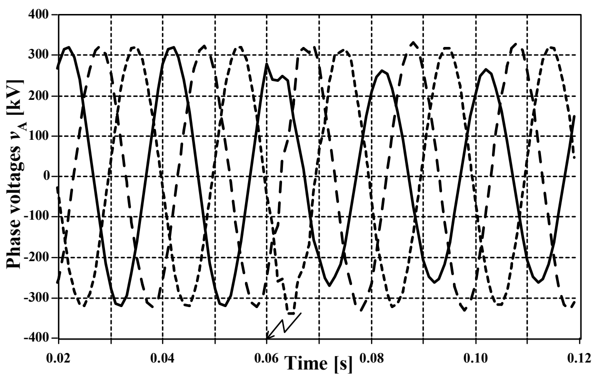

Figure 3. Phase voltages at the relaying point – faulted line

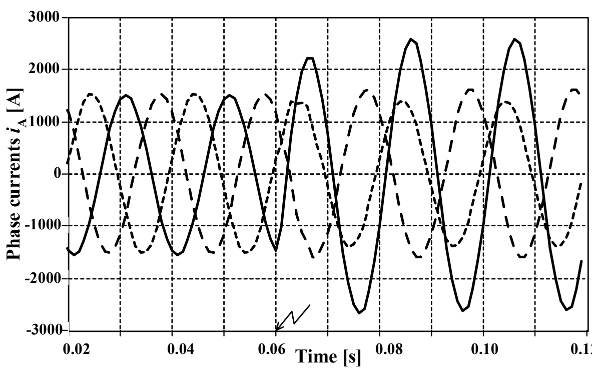

Figure 4. Phase currents at the relaying point – faulted line

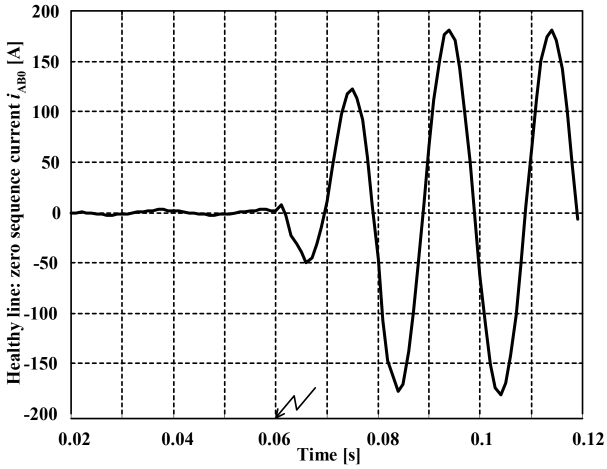

Figure 5. Zero sequence current from the healthy circuit (i_{AB0})

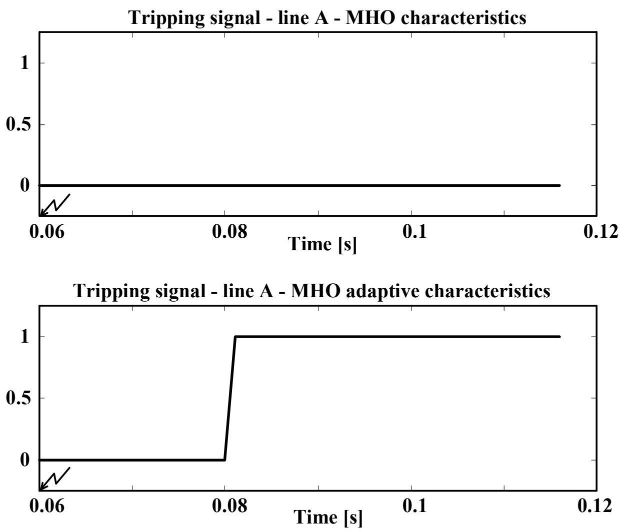

Figure 6. Conventional relay tripping signal and adaptive relay tripping signal

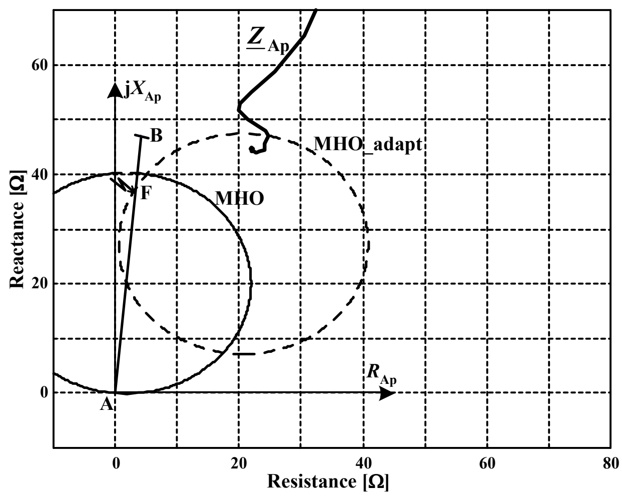

Figure 7. Conventional (solid) and adaptive (dotted) distance relay characteristics and measured impedance trajectory

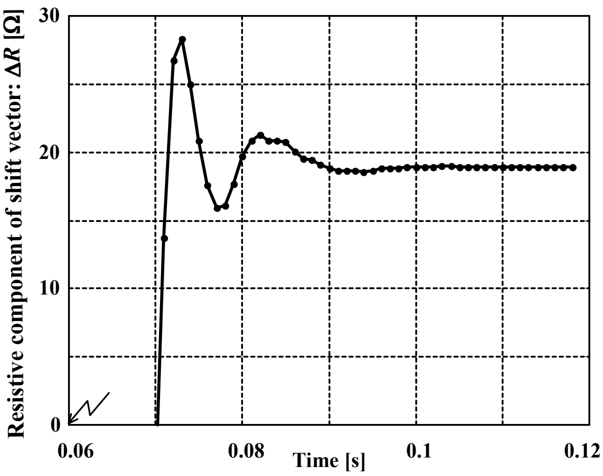

Figure 8. ΔR calculated samples

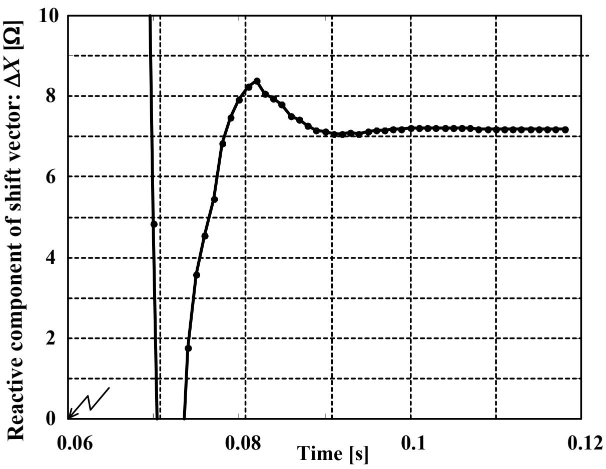

Figure 9. ΔX calculated samples

The input voltages and currents for an example shown above were measured during simulations of a–g fault at a distance $d = 0.8$ [p.u] with fault resistance $R_F = 10\ \Omega$.

V. CONCLUSION

This paper introduces an adaptive procedure that allows moving the relay characteristic on *R–X* plane, according to on-line calculated value of the shift vector. Therefore, it is possible to compensate for the negative influence of the reactance effect. Additionally, the procedure speeds up taking a tripping decision.

The components of the shift vector are functions of locally measured quantities, line parameters and fault type. Thus the equations determining these components are simple in form and do not require sophisticated calculation methods. Moreover, it is not necessary to provide data from the remote end of the protected line and source impedance values, which makes the procedure easy to implement in a digital distance protection device.

ATP–EMTP simulations proved that incorporating the presented adaptive procedure enhances operation of a distance relay, making the relay practically invulnerable to reactance effect.

REFERENCES

1. J. Izykowski, E. Rosolowski, M. M. Saha, Postfault analysis of operation of distance protective relays of power transmission lines. IEEE Transactions on Power Delivery, Vol. 22, No. 1, pp. 74-81, 2007.
2. A. Wiszniewski, Accurate fault impedance locating algorithm, IEE Proceedings, Vol. 130, Pt. C, No. 6, pp. 311-315, 1983.
3. L. Eriksson, M. M. Saha, G. D. Rockefeller, An accurate fault locator with compensation for apparent reactance in the fault resistance resulting from remote-end infeed, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, No.2, pp. 424-436, 1985.
4. Y. Liao, S. Elangovan, Digital distance relaying algorithm for first zone protection for parallel transmission lines, IEE Proceedings: Generation, Transmission and Distribution, Vol. 145, No. 5, pp. 531-536, 1998.
5. J. Izykowski, E. Rosolowski, M. M. Saha, Locating faults in parallel transmission lines under availability of complete measurements at one end, IEE Proceedings: Generation, Transmission and Distribution, Vol. 151, No. 2, pp. 268-273, 2004.
6. Yi Hu, D. Novosel, M. M. Saha, V. Leitloff, An adaptive scheme for parallel-line distance protection, IEEE Transactions on Power Delivery, Vol. 17, No. 1, pp. 105-110, 2002.
7. H. Dommel, ElectroMagnetic Transient Program. BPA, Portland, Oregon, 1986.

ACKNOWLEDGMENT

This work was supported in part by the Ministry of Science and Higher Education of Poland under Grant N511 008 32/1688.