ATP-EMTP investigation of detection of fault position with respect to the compensating bank in series compensated line by determining the contents of dc components in phase currents

Jan Izykowski, Piotr Mazniewski Eugeniusz Rosolowski, Przemyslaw Balcerek, Marek Fulczyk

Abstract-- **This paper presents an analysis of possibility of detection of a fault position with respect to the compensating bank in a series compensating transmission line. The algorithm designed for this purpose is based on determining the contents of dc components in the distance relay input currents. Fuzzy logic technique is applied for making the decision whether a fault is in front of the compensating bank or behind it. The delivered algorithm has been tested and evaluated with use of the fault data obtained from versatile ATP-EMTP simulations of faults in the test power network containing the 400 kV, 300 km transmission line, compensated with the aid of the compensating bank installed at midpoint. The sample results of the evaluation are reported and discussed.**

Keywords: ATP-EMTP, power transmission line, series compensation, fault simulation, digital measurement, fuzzy logic distance protective relay.

I. INTRODUCTION

INCREASED transmittable power, improved power system stability, reduced transmission losses, enhanced voltage control and flexible power flow control are the reasons behind installing Series Capacitors (SCs) on long transmission lines. The environmental concerns stand for that too.

Both, capacitors of fixed value (FSC – Fixed Series Capacitors) and of controlled value (TCSC – Thyristor Controlled Series Capacitors) are installed in series compensated lines. This paper deals with distance protection issues for a line compensated with a three-phase bank of series capacitors (SCs) installed at the line midpoint (Fig. 1). SCs are equipped with their overvoltage protection devices: typically Metal Oxide Varistors (MOVs). Each MOV is in turn protected from overheating with aid of the thermal protection (TP), which eventually sparks the respective Air-Gap, in order to by-pass its MOV.

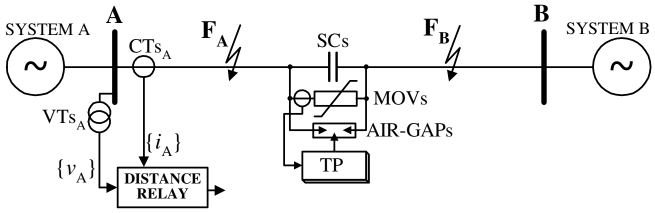

Fig. 1. Schematic diagram of series compensated line for considering distance protection: F_A – fault in front of SCs/MOVs, F_B – fault behind SCs/MOVs.

The compensating bank when installed in a line, creates, however, certain problems for its protective relays and fault locators. In the case a series compensated line suffers a fault behind the SCs as seen from the relaying point (fault F_B in Fig. 1), a fault loop measured by a distance relay contains depending on a type of fault, one (L-G faults) or even two (inter-phase faults) systems of SCs and MOVs. As a consequence, the operating conditions for protective relays become unfavorable and include such phenomena as voltage and/or current inversion, subharmonic oscillations, high frequency oscillations due to MOVs.

The most important singularity of series compensated lines as objects to be protected, lays, however, in the fact that the positive sequence impedance measured by traditional distance relays is no longer an indicator of the distance to a fault. The SC and its MOV affect both the apparent reactance and resistance seen by the relay

The aforementioned problems with protective relaying for series compensated lines are being extensively explored as a series of studies have been performed by relay vendors and utilities. Protection of networks with series compensated lines is considered as one of the most difficult tasks. There is still much room for developing efficient protective relaying for such networks. The approach presented in this paper is one of the attempts for realizing that.

II. MEASUREMENT OF FAULT LOOP IMPEDANCE IN SERIES COMPENSATED LINE

Two hypothetical places of faults (F_A and F_B) are indicated in Fig. 1. In the case of fault F_A (fault in front of the compensating bank) the measurement of fault loop impedance, performed by a distance relay from the substation A (Fig. 2) is analogous as for the traditional uncompensated line. In this case a fault resistance influences the measurement of the fault

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loop impedance (as shown in Fig. 2). This impedance ($\underline{Z}_{A\_p}$) consists of:

- $d\underline{Z}_{1L}$ – positive-sequence impedance of the line section between the relaying point A and the fault point F (d denotes the per unit distance between these points),
- $\underline{R}_F^{\#}$ – complex impedance which represents the fault path resistance seen from the relaying point .

Note: in Fig. 2, and also in Fig. 3 for the fault behind SCs&MOVs, the complex impedance $\underline{R}_F^{\#}$ is drawn as the pure resistance twisted clockwise, i.e. by a certain angle from the range $[\,0 \div (-90^{\circ})\,]$. However, it can remain untwisted (if there is no pre-fault power flow at all) or twisted counter-clockwise (by a certain angle from the range $[\,0 \div 90^{\circ}\,]$).

Measurement of fault loop impedance for the case of fault FB (fault behind the compensating bank), performed by a distance relay from the substation A (Fig. 2), differs from the case of fault F_A. The fault loop impedance ($\underline{Z}_{A\_p}$) consists of:

- $d\underline{Z}_{1L}$ – positive-sequence impedance of the line section between the relaying point A and the fault point F (d denotes the per unit distance between these points),
- $\underline{R}_F^{\#}$ – complex impedance which represents the fault path resistance seen from the relaying point,
- ($R_{SC\&MOV}$–j$X_{SC\&MOV}$) – impedance of the R–C character, which represents presence of the compensating bank in the fault loop.

Impedance which represents the compensating bank in the fault loop is not fixed, but depends on the current flowing through the bank [13].

Presence of the compensating bank in the fault loop drastically influences the fault loop impedance measurement. As a result of that, certain shortening of the distance protection reach for the first zone may happen, if special countermeasures are not undertaken.

The voltage drop on the compensating device can be estimated on basis of current supplying the distance relay. Such procedure of estimation of voltage drop was introduced in [14].

Also, the presence of the compensating bank in the fault loop can be reflected with use of the fundamental frequency equivalent introduced in [13].

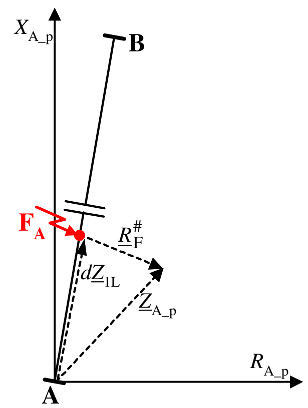


Fig 2. Measurement of fault loop impedance for the case of fault F_A occurring in front of SCs&MOVs.

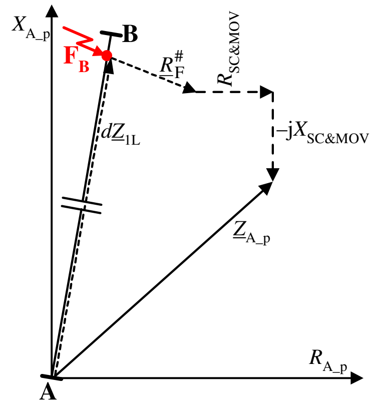


Fig 3. Measurement of fault loop impedance for the case of fault F_B occurring behind SCs&MOVs.

In order to counteract the negative influence of presence of the compensating bank in the fault loop for faults occurring behind the bank the position of the fault with respect to the bank, in terms whether in front or behind it, has to be recognised. The compensation for the compensating bank has to be applied only for faults occurring behind the compensating bank.

This paper presents the algorithm for detecting the fault position. For this purpose filtration the dc component is applied and the fuzzy logic technique is utilised for the reasoning.

III. Idea Fuzzy Logic Algorithm of Detection of Fault Position – Fundamental Principles

The concept of Fuzzy Logic (FL) was conceived by Lotfi Zadeh as way of processing data by allowing partial set membership rather than crisp set membership or non-membership. FL offers several unique features that make it a particularly good choice for many problems.

It classic logic is based at on two represented values the most often by 0 and 1 or truth and falseness. Border between them is definite unambiguously and invariable.

Fuzzy logic introduces value between standard 0 and 1 and fuzzification of the borders between them isw giving the possibility of appearing the values from between this compartment.

Schematic diagram of the proposed fuzzy logic algorithm is presented in Fig. 4.

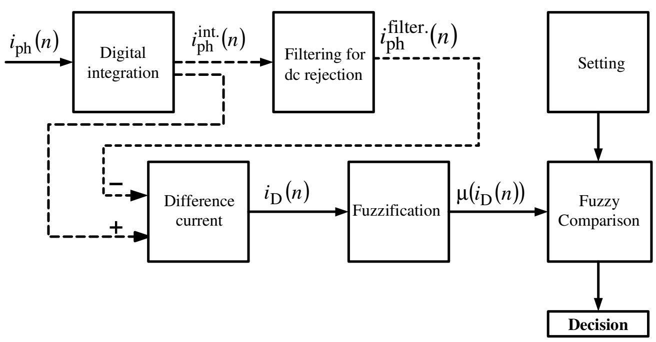


Fig. 4. Schematic diagram of fuzzy logic based detection of fault position.

First, digital integration of phase currents is performed with the aid of the trapezoidal principle as follows:

$$i_{\mathrm{ph}}^{\mathrm{int.}}(n) = i_{\mathrm{ph}}^{\mathrm{int.}}(n-1) + \frac{T_{\mathrm{s}}}{2}\left(i_{\mathrm{ph}}(n) + i_{\mathrm{ph}}(n-1)\right) \tag{1}$$

where:
n – index denoting the current sample of the processed current,
T_{s} – sampling period.

Next, filtration for dc rejection [8] is applied according to:

$$i_{\mathrm{ph}}^{\mathrm{filter.}}(n) = \frac{i_{\mathrm{ph}}^{\mathrm{filter.}}(n) + i_{\mathrm{ph}}^{\mathrm{filter.}}(n-\mathrm{N})}{2} - \frac{1}{\mathrm{N}}\sum_{k=0}^{\mathrm{N}-1} i_{\mathrm{ph}}^{\mathrm{filter.}}(n-k) \tag{2}$$

where:
N – number of samples in the single fundamental frequency cycle.

Then, the difference current is calculated:

$$i_{\mathrm{D}}(n) = i_{\mathrm{ph}}^{\mathrm{int.}}(n) - i_{\mathrm{ph}}^{\mathrm{filter.}}(n) \tag{3}$$

The calculated samples of the difference currents undergo fuzzification. For this purpose the set of five consecutive samples (Fig. 5a) are considered for determining the membership function in the shape of the triangle (Fig. 5b). The points of this triangle are determined with the minimum, average and maximum values of the difference current (Fig. 5b).

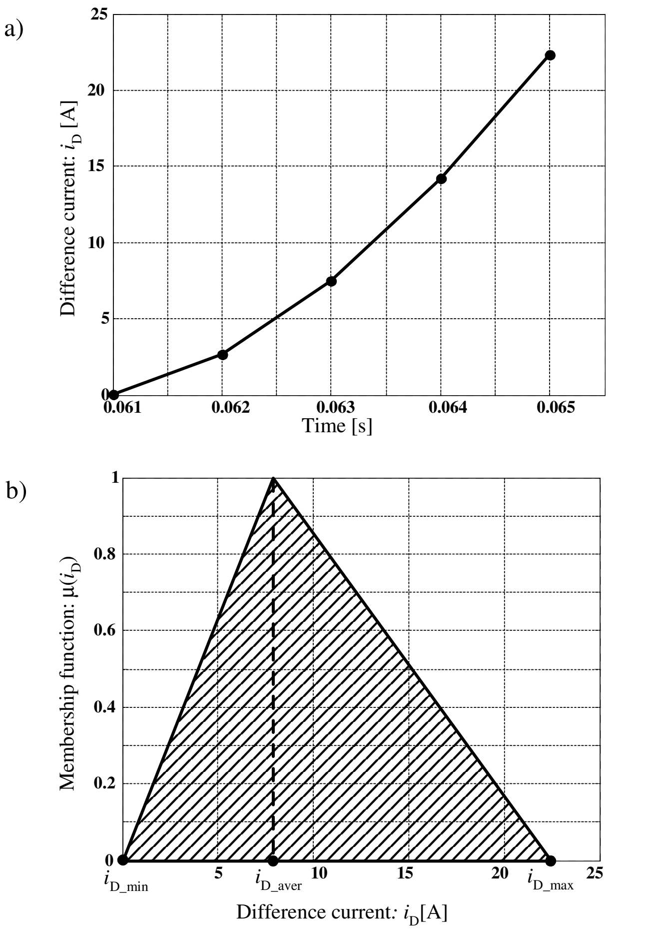


Fig 5. Fuzzification principle: a) difference current, b) membership function of difference.

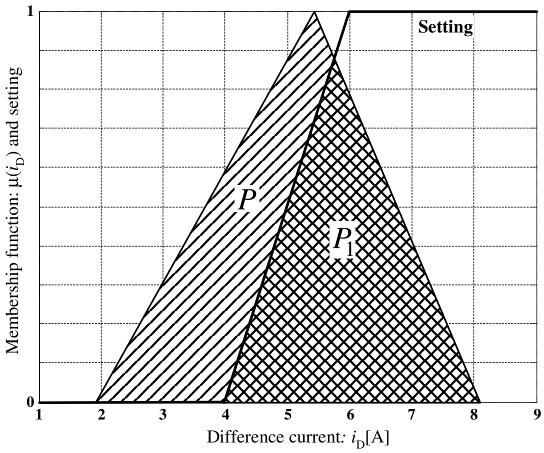


Fig. 6. Illustration of fuzzy comparison.

The setting applied in the comparison was determined arbitrary, for each fault type separately.

Making the decision on the fault position is a result of the fuzzy comparison determined with the following relationship:

$$W = \frac{P_1}{P} \tag{4}$$

where:
P – area determined by the membership function $\mu(i_{\mathrm{D}})$,
P_1 – the area obtained from P by limiting it with the applied setting (Fig. 6).

If the ratio (4) exceeds the specified threshold, the decision is taken that the fault is in front of the compensating bank.

IV. Simulation and Tests Conducted in ATP-EMTP and Matlab Programs

The presented algorithm for detecting the position of the fault with respect to the compensating bank, in terms whether a fault occurred in front or behind the bank, has been tested and evaluated with the fault data obtained from versatile ATP-EMTP [4] simulations of faults in the test power network. Basic parameters are gathered in Table I.

The test power network contains the 400 kV, 300 km transmission line, compensated with a three-phase bank of series capacitors installed at mid-line. The compensation rate of 70% was assumed. MOVs installed in parallel to series capacitors were modelled as nonlinear resistors defined with the analytical characteristic and its parameters as given in Table 1. The thermal protection (TP in Fig. 1) preventing the MOV from overheating was modelled as the component integrating the accumulated energy. After exceeding the set threshold for energy, the sparking of the associated air-gap undergoes, and the MOV becomes shunted. It has been checked that in the considered application, i.e. the application related to high-speed protective relaying, the air-gap sparking does not take place prior to detecting a fault position. Thus, the thermal protection does not influence the algorithm.

The model includes the Capacitive Voltage Transformers (CVTs) and the Current Transformers (CTs). The analogue filters with 350 Hz cut-off frequency were also included. The sampling frequency of 1000 Hz was applied.

TABLE I. BASIC PARAMETERS OF THE TEST TRANSMISSION NETWORK

Equivalent system at terminal A (φ=0°)	$\underline{Z}_{1SA}$	(0.656+j7.5) Ω
	$\underline{Z}_{0SA}$	(1.167+j11.25) Ω
Equivalent system at terminal B (φ= ±15°)	$\underline{Z}_{1SB}$	(1.31+j15) Ω
	$\underline{Z}_{0SB}$	(2.33+j26.6) Ω
Line AB	$\underline{Z}_{1L}^{'}$	(0.028+j0.315) Ω/km
	$\underline{Z}_{0L}^{'}$	(0.275+j1.027) Ω/km
	$C_{1L}^{'}$	13.0 nF/km
	$C_{0L}^{'}$	8.5 nF/km
Series compensation	Series capacitors	0.70 X_{1L}
	Position of the compensating bank	0.5 p.u.
MOV characteristic: $i_{MOV} = P\left(\frac{V_V}{V_{REF}}\right)^q$	P	1 kA
	V_{REF}	150 kV
	q	23
Line length		300 km
System voltage		400 kV

Faults with different specifications occurring in front and behind the compensating bank have been modelled. The following parameters have been altered:

- distance to fault,
- fault resistance: for faults L–E and L–L–E resistance from the range $(0.1 \div 50)$ Ω and for faults L–L, L–L–L (L–L–L–E) from the range $(0.1 \div 5)$ Ω has been set,
- point on the waveform at which fault has been applied: 0º and 90º.

In the equivalent systems behind the line terminals A, B, the equivalent impedances were altered (in Table 1 the basic values are given). The angle of EMFs at the end A was set as φ=0° (the cosine wave with zero phase shift in the phase a), while for the end B: –15º÷15º.

The presented algorithm (schematic diagram in Fig. 4) for detecting the fault position has been reflected in MATLAB environment [9].

The example 1, for which the results are presented in Fig. 7, is for the fault F_A (occurring in front of the compensating bank) with the following specifications – fault distance: d=0.15 p.u., fault resistance R_F=10 Ω.

The example 2, for which the results are presented in Fig. 8, is for the fault F_B (occurring behind the compensating bank) with the following specifications – fault distance: d=0.85 p.u., fault resistance R_F=10 Ω.

The presented examples (Fig. 7–8) illustrate effectiveness of the proposed detection algorithm. The detailed evaluation results are gathered in Table II.

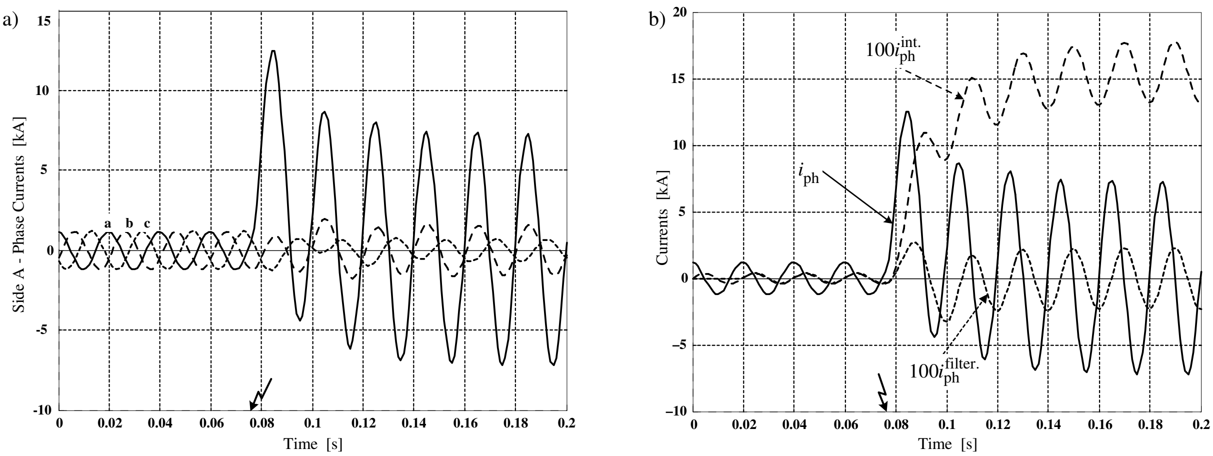


Fig. 7. Example 1 – fault in front of SCs&MOVs (fault F_A): a) phases currents, b) signals of fuzzy logic based detection of fault position.

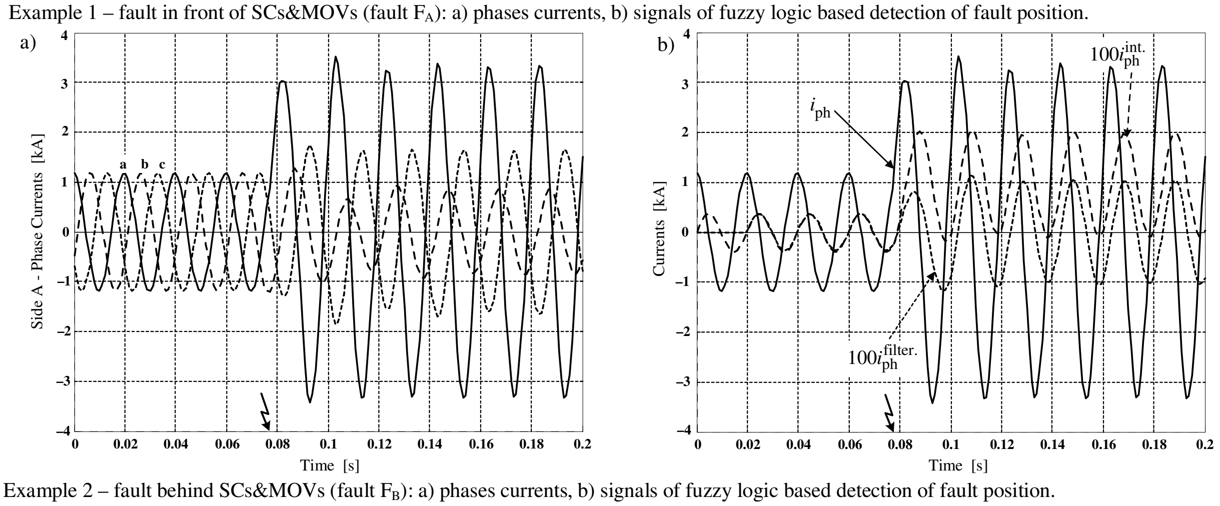


Fig. 8. Example 2 – fault behind SCs&MOVs (fault F_B): a) phases currents, b) signals of fuzzy logic based detection of fault position.

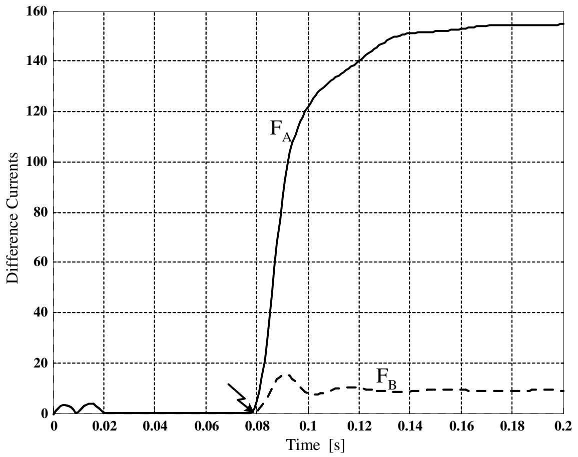


Fig. 9. The signal of dc components in phase currents: a) fault position in front of compensating bank (F_A), b) fault position behind compensating bank (F_B).

In Fig. 7a the phase currents are shown. Since this is the fault occurring in front of the compensating bank, the current from the faulted phase 'a' contains a considerable dc component. This current, together with the signals from the presented fault position detecting algorithm are visualised in Fig. 7b. As a result of integrating the faulted phase current one obtains the signal: $i_{\text{ph}}^{\text{int.}}$ in which the dc component is highly magnified. In turn, filtering the faulted phase current with the digital algorithm (2) results in effective rejection of the dc. component. The fundamental frequency components in the signals $i_{\text{ph}}^{\text{int.}}$, $i_{\text{ph}}^{\text{filter.}}$ are in phase and have identical magnitudes. Therefore, their difference i_D (3) contains only the magnified dc component (as the curve FA in Fig. 9).

In contrast, for the example 2 (fault occurring behind the compensating bank) the faulted phase current is contaminated with the subharmonic oscillations. As a result, the difference current i_D (3) contains much lower dc component (as the curve FB in Fig. 9).

The samples of difference current i_D from the fault interval undergo fuzzification (Fig. 4) and then the fuzzy comparison. The setting applied in this comparison was determined arbitrary for each fault type. In further investigations, the self-adjusting fuzzy settings will be applied.

For each fault type (phase-to-earth, phase-to-phase, double phase-to-earth and three phase faults) 2550 cases were applied in evaluation of the fault position detecting algorithm. All faults occurring behind the compensating bank (fault FB) were successfully detected (100% efficiency). In turn, the faults occurring in front of the compensating bank (fault FA) were correctly recognised with the efficiency of around 85%. This is a result of initial assumption that a fault is behind the bank, and this can be changed to opposite type (fault in front of the compensating bank) only if the fuzzy comparison yields a decision that this is fault with considerable contents of dc component – thus a fault in front of the compensating bank.

In some fault cases with unfavourable point on the wave of fault inception and/or high fault resistance the dc component may be very low (or even not present) and very quickly decaying for faults in front of the bank. This justifies why the 100% efficiency is not achieved for detecting faults occurring in front of the compensating bank. However, the efficiency rate of the order of 85% is considered as relatively high. Also the approach from [10] was not 100% efficient.

Average time of the fault position detection is around 20 ms. In order to get higher speed of detection, the other filtering digital algorithm, as for example applying the half-cycle dc rejection can be applied.

TABLE II. EFFICIENCY OF DETECTION OF FAULTS F_A, F_B

Fault type	Number of fault cases	Detection of fault F_A [%]	Detection of fault F_B [%]	Average time of detection [ms]
Phase-to-earth	2550	83	100	20
Phase-to-phase	2550	88	100	18
Double phase-to- earth	2550	85	100	21
Three phase	2550	88	100	18
F_A – fault in front of SCs/MOVs F_B – fault behind SCs/MOVs				

V. CONCLUSIONS

The paper presents the algorithm aimed at determination of the fault position with respect to the compensating device. The decision with respect to the fault position, i.e. whether a fault occurred in front of the bank or behind it, is highly required for design of the adaptive distance relay. Knowledge of the position of a fault, allows to make the distance relay adaptable to presence of the compensating bank in the fault loop. In case of faults occurring behind the compensating device there is a need for reflecting of presence of SC&MOV (or SCs&MOVs in the case of inter-phase faults) in the fault loop considered by the distance relay. For this purpose the differential equation or fundamental frequency equivalenting approaches, known from the numerous references, can be applied. By reflecting the presence of SCs&MOVs in the fault loop, in the case of faults occurring behind them, the quality of distance protection can be substantially improved. In particular, one can avoid shortening of the reach for the high speed first zone.

The presented algorithm for detecting the position of the fault with respect to the compensating device is based on exploring the contents of dc components in the protective relay input currents. The decision with respect to the fault position is made using fuzzy logic reasoning. The decision is made with determining the difference current which is a measure of dc contents in processed phase currents.

The delivered algorithm has been tested and evaluated with the fault data obtained from versatile ATP-EMTP simulations of faults in the test power network containing the 400 kV, 300 km transmission line. Different specifications of faults and pre-fault power flows have been considered in the evaluation study. In total, above 10 thousands of fault cases were utilised in the analysis.

Application of fuzzy logic appeared as the tool which allowed to obtain efficient detection of the fault place. The faults occurring behind SCs&MOVs have been detected perfectly correct (100%). In turn, faults occurring in front of SCs&MOVs were identified in around 90% efficiency. Some fault cases with very low dc contents were not detected as occurring in front of the compensating bank. However, even so, in majority of unidentified faults in front of the bank, it has been checked that the distance relay operates correctly and the fault loop impedance enters the relay impedance characteristic.

In future research on the issue of detecting the fault position in series compensated line, it is expected that a multi-criteria algorithm will be developed, hoping to obtained completely correct identification of the fault position.

VI. References

[1] B. Bachmann, D. Novosel, D. Hart, Y. Hu and M. M. Saha, "Application of articial neural networks for sereies compenstaed line protection," *in Proc. of the International Conference on Inteligent Systems Aplications to Power Systems*, Orlando, FL, pp. 68–73, Jan. 28–Feb. 02, 1996.

[2] CICGRE SC-34 WG-04, *Application guide on protection of complex transmission network configurations*, CIGRE materials, August 1990.

[3] P. K. Dash, S. R. Samantaray and G. Panda, "Fault classification and section identification of an using support vector machine," *IEEE Trans. on Power Del.*, vol. 22, no. 1, pp. 67–73, Jan. 2007.

[4] H. W. Dommel, *Electro-Magnetic Transients Program*, BPA, Portland, Oregon, 1986.

[5] A. A. Girigis, A. A. Sallam and A. K. El-Din, "An adaptive protection scheme for advanced series compensated (ASC) transmission lines," *IEEE Trans. on Power Del.,* vol. 13, no. 2, pp. 414–420, Apr. 1998.

[6] F. Ghassemi, J. Goodarzi and A. T. Johns, "Method for eliminating the effect of MOV operation on digital distance relays when used in series compensated lines," *in Proc. of the Universities Power Engineering Conference*, Manchester, UK, Sept. 10-12, 1997.

[7] J. A. S. B. Jayasinghe, R. K. Aggarwal, A. T. Johns and Z. Q. Bo, "A novel nonunit protection for series compensated EHV transmission lines based on fault generated high frequency voltage signals," *IEEE Trans. on Power Del.*, vol. 13, no. 2, pp. 405–413, Apr. 1998.

[8] A. Magdziarz and Z. Zagan, "Elimination of dc component from the input signals of power system control and protection devices," *Electrotechnical Review*, No 1, 2005.

[9] MATLAB, *High-Performance Numeric Computation and Visualization Software. External Interface Guide*, The Mathworks, Inc., January 1993.

[10] D. Novosel, A. Phadke, M. M. Saha and S. Lindahl, "Problems and solutions for microprocessor protection of series compensated lines," *in Proc. of Sixth International Conference on Developments in Power System Protection*, Nottingham, UK, Conference Publication No. 434, IEE 1997, pp. 18-23, 25–27 March 1997.

[11] W. Rebizant, A. Wiszniewski and L. Schiel, "Acceleration of transformer differential protection with instantaneous criteria," *in Proc. Advanced Power System Automation and Protection*, Jeju, Korea, Apr 24–27, 2007.

[12] E. Rosolowski, J. Izykowski and B. Kasztenny, "A new half – cycle adaptive chasor estymator immune to the decaying dc component for digital protective relaying," *in Proc. of North America Power Systems (NAPS) Conference*, University of Waterloo, Canada, October 23–24, 2000.

[13] E. Rosolowski, J. Izykowski, B. Kasztenny and M. M. Saha, "A new Accurate Fault Algorithm for Series Compensated Lines," *IEEE Trans. on Power Del.*, vol. 14, no. 3, pp. 789–795, Jan. 1999.

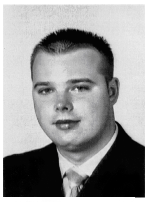
[14] E. Rosolowski, J. Izykowski, B. Kasztenny and M. M. Saha, "First zone algorithm for protection of series compensated lines," *IEEE Trans. on Power Del.*, vol. 16, no. 2, pp. 67–73, Apr. 2001.

[15] A. Wiszniewski and B. Kasztenny, "A multi–criteria differential transformer relay based on fuzzy logic," *IEEE Trans. on Power Del.*, vol. 10, no. 4, pp. 1786–1793, Oct. 1995.

[16] Q. Y. Xuan, Y. H. Song, A. T. Johns, R. Morgan and D. Williams, "Performance of an adaptive protection scheme for series compensated EHV transmission systems using neural networks," *Electric Power System Research*, vol. 36, no. 1, pp. 57–66, Jan. 1996.

VII. Biographies

Jan Izykowski (M'97, SM'04) received his M.Sc., Ph.D. and D.Sc. degrees from the Faculty of Electrical Engineering of Wroclaw University of Technology (WrUT) in 1973, 1976 and in 2001, respectively. In 1973 he joined Institute of Electrical Engineering of the WrUT. Presently he is an Associate Professor and Director of this Institute. His research interests are in power system simulation, power system protection and control, and fault location.



Piotr Mazniewski was born in Poland in 1982. He received his M.Sc. degree from the Faculty of Electrical Engineering of Wroclaw University of Technology (WrUT) in 2006. At present he is PhD student at the Institute of Electrical Engineering of the WrUT His research interests are in power system protection, and FACTS systems.

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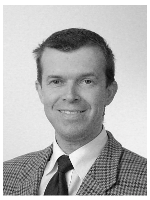
Przemyslaw Balcerek received his M.Sc. and Ph.D degrees in Electrical Engineering from the Wroclaw University of Technology in 2000, 2004 respectively. Fault location, instrument transformers and ATP-EMTP simulation of power system transients are in the scope of his research interests. Presently he is in ABB Corporate Research Center in Krakow/Poland as a research scientist.



Marek Fulczyk (M'04) received the M.Sc. and Ph.D. degree in Electrical Engineering from the Wroclaw University of Technology/Poland in 1993 and 1997, respectively. In 1997 he joined ABB as a research scientist. Now he is a group leader of Electrical & Engineering Systems at ABB Corporate Research in Krakow/Poland. His fields of interests include power system protection, power system/voltage stability, and simulations of phenomena in power systems.