Detection of Fault Position with Respect to the Compensating Bank in Series Compensated Line by Measurement of Phase Shift for Distance Relay Input Currents

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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 change of phase shift for 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 algorithm has been tested and evaluated with use of the fault data obtained from versatile ATP-EMTP simulations of faults in the test network containing the 400 kV, 300 km transmission line, compensated with the aid of the compensating bank installed at mid-line. The sample results of the evaluation are reported and discussed.**

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 [2]. 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 fixed series capacitors (SCs) installed at mid-line (Fig. 1). SCs are equipped with their overvoltage protection devices: typically Metal Oxide Varistors (MOVs). Each MOV is in turn protected from overheating with the aid of the thermal protection (TP), which eventually sparks the respective Air-Gap, in order to by-pass its MOV.

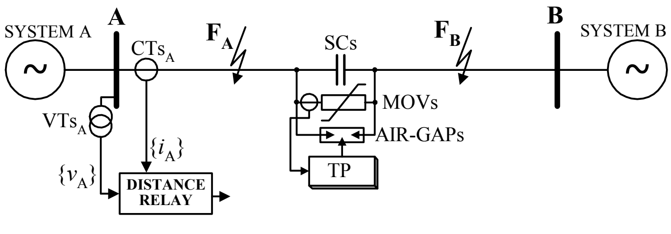

Figure 1. Schematic diagram of series compensated line for protection study: F_A – fault in front of SCs/MOVs, F_B – fault behind SCs/MOVs.

The compensating bank when installed in a line creates, however, certain problems for its protective relays and fault locators. If 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 (for single phase faults) or even two (for inter–phase faults) systems of SCs and MOVs. As a consequence, the operating conditions for protective relays become unfavourable and include such phenomena as voltage and/or current inversion, subharmonic oscillations, high frequency oscillations due to MOVs [2]. The most important peculiarity of a series compensated line as the object to be protected, lays, however, in the fact that the positive sequence impedance measured by a traditional distance relay is no longer an indicator of the distance to a fault. The SC and its MOV affect both, the steady state and transient conditions of the distance relay measurements.

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 [1], [3], [11].

In this paper a new criterion of qualification of a fault place with respect to the compensating bank is introduced. It is based on measuring the change of a phase shift of input currents of a distance relay.

II. Fuzzy Logic Based Algorithm for Detecting Fault Position With Respect to Compensating Bank

The concept of fuzzy logic was conceived by Lotfi Zadeh as a way of processing data by allowing a partial set membership rather than a crisp set membership or non-membership. It offers several unique features that make it a particularly good choice for many problems [6], [9].

A classic logic is based on two values, the most often represented by 0 and 1, or truth and falsehood. A border between them is definite unambiguously and invariable. Fuzzy logic introduces values between the standard 0 and 1 and fuzzification of the borders between them, giving the possibility of appearing the values between these values.

Schematic diagram of the proposed fuzzy logic algorithm is presented in Fig. 2.

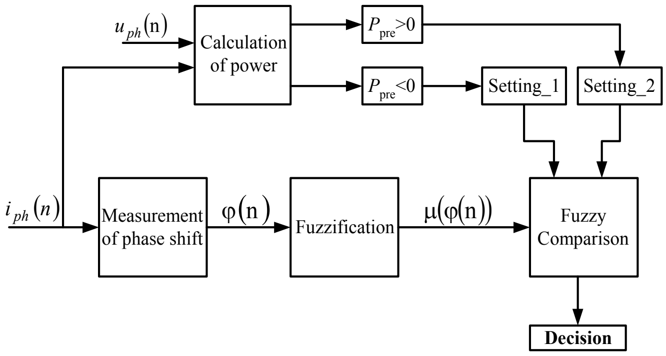

Figure 2. Schematic diagram of fuzzy logic based detection of fault position.

First, digital measurement of phase shift for phase currents is performed [8]:

$$\varphi(n) = \text{atan}\left[\frac{\text{imag}(i_{ph}(n))}{\text{real}(i_{ph}(n))}\right] \quad (1)$$

where:

n – index denoting the current sample of the processed phase current.

From pre-fault voltages and currents, an active power is calculated [8]:

$$P_{pre}(n) = 0.5[u_{1C}(n)\cdot i_{1C}(n) + u_{1S}(n)\cdot i_{1S}(n)] \quad (2)$$

where:

u_{1C}(n), i_{1C}(n), u_{1S}(n), i_{1S}(n) – voltages and currents after full-cycle Furrier filtering (a pair of sine and cosine filters).

The calculated pre-fault power is used for detecting a power flow direction. Appropriate setting is applied according to the detected direction.

The calculated samples of the phase shift undergo fuzzification. For this purpose the set of five consecutive samples are taken for determining the membership function in the shape of the triangle. The points of this triangle are determined with the minimum, average and maximum values of the phase shift.

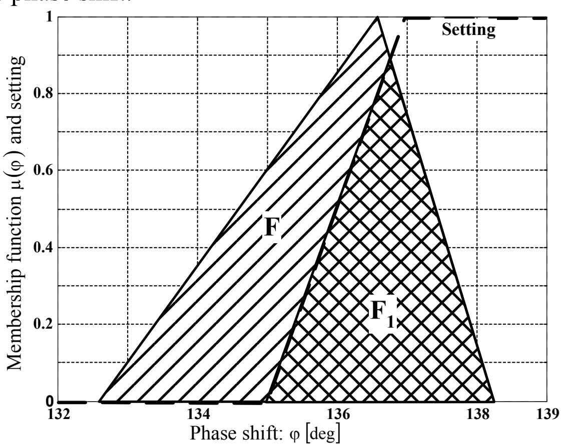

Figure. 3. Illustration of fuzzy comparison.

The setting applied in the fuzzy comparison (Fig. 3) was determined arbitrary, for each fault type separately. In further investigations, the self-adjusting fuzzy settings will be applied

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

$$W = \frac{F_1}{F} \quad (3)$$

where:

F – area below the membership function $\mu(\varphi)$,

F_1 – area obtained from F by limiting it with the applied setting (Fig. 3).

If the ratio (3) exceeds the specified threshold, the decision is taken that a fault is in front of the compensating bank; otherwise a fault is classified as behind the bank.

III. Simulations and Testing Conducted With Use of MATLAB and ATP-EMTP

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 network (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 I. 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 for 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.

Faults, occurring in front and behind the compensating bank, of different specifications have been modelled:

- distance to fault – 17 values: 30, 40, 45, 50, 60, 90, 120, 149, 151, 180, 210, 240, 250, 255, 260, 270, 290 [km],
- fault resistance:
  for faults L–E and L–L–E – 5 values: 0.1, 5, 10, 25, 50 [Ω],
  for faults L–L, L–L–L (L–L–L–E) – 5 values: 0.1, 0.5, 1, 2, 5 [Ω],
- point on the wave at which the fault is applied – 10 cases: by changing the angle from 0° (at zero crossing) up to 90° (at maximum),
- 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 – 4 cases: –20°, –15°, 15°, 20°.

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

The presented algorithm for detecting the fault position (as in Fig. 2) has been reflected in MATLAB [5] environment. The sample obtained results are shown in Fig. 4–Fig. 5.

The example 1, for which the relay input currents are presented in Fig. 6, is for the fault F_A (occurring in front of the compensating bank) with the following specifications – fault distance: d=0.2 p.u., fault resistance: R_F=5 Ω.

The example 2, for which the relay input currents are presented in Fig. 7, is for the fault F_B (occurring behind the compensating bank) with the following specifications – fault distance: d=0.8 p.u., fault resistance: R_F=5 Ω.

The presented sample results illustrate effectiveness of the proposed detection algorithm. The results of the overall evaluation are gathered in Table II.

TABLE II
EFFICIENCY OF DETECTION OF FAULTS F_A, F_B

Fault type	Number of fault cases	Detection of faults F_A [%]	Detection of faults F_B [%]	Average time of detection [ms]
Phase-to-phase	10200	100	100	16
Double phase-to- earth	10200	100	100	17
Three phase	10200	100	100	15

F_A – fault in front of SCs/MOVs
F_B – fault behind SCs/MOVs

In Fig. 6 (Example 1) the phase currents under a–b fault occurring in front of the compensating bank are shown. DC components are present in the currents from the faulted phases. The phase shift is as the one presented by the curve F_A in Fig. 4.

In contrast, for the example 2 (fault occurring behind the compensating bank) the currents from the faulted phases are contaminated with the subharmonic oscillations (Fig. 7). The phase shift is as the one presented by the curve F_B in Fig. 4.

In Fig. 5 the decision signal for the example 1 is shown. The decision that this is a fault in front of the compensating bank (fault F_A) is reached after 16 ms from the fault inception.

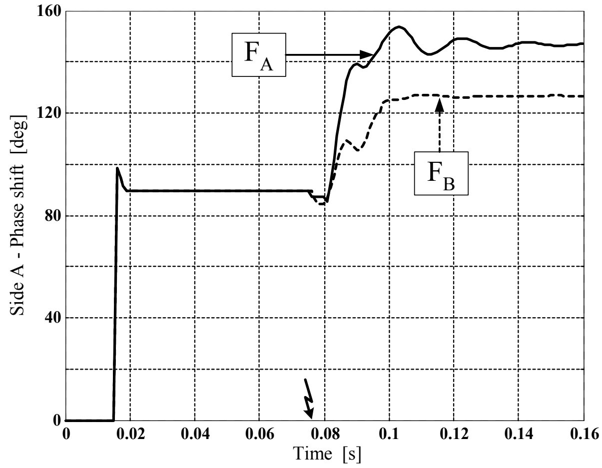

Figure 4. Typical shapes of phase shift: a) fault position in front of compensating bank (F_A), b) fault position behind compensating bank (F_B).

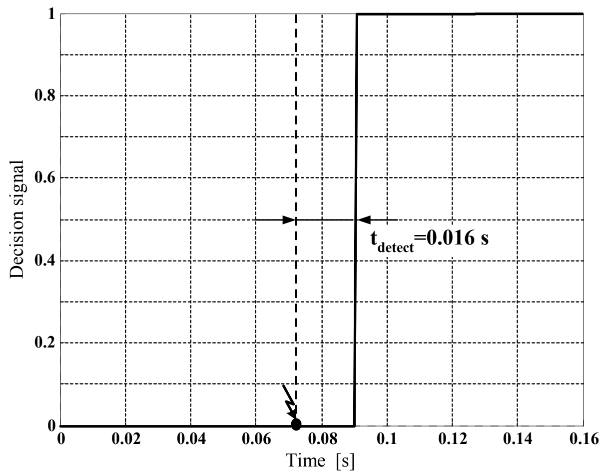

Figure 5. Example 1 – making a decision with utilizing the relationship (3).

For each fault type (phase-to-phase, double phase-to-earth and three phase faults) 30 600 cases were applied in evaluation of the fault position detecting algorithm.

All faults occurring in front of the compensating bank (fault FA) and occurring behind the compensating bank (fault FB) were successfully detected (100% efficiency). This concerns only inter-phase faults since in the case of single phase faults the recognition of fault position appeared as unreliable and thus these results are not shown here.

Average time of the fault position detection is around 16 ms. In order to get higher speed of detection, the other filtering digital algorithm, as for example applying the half-cycle dc rejection [8] can be applied.

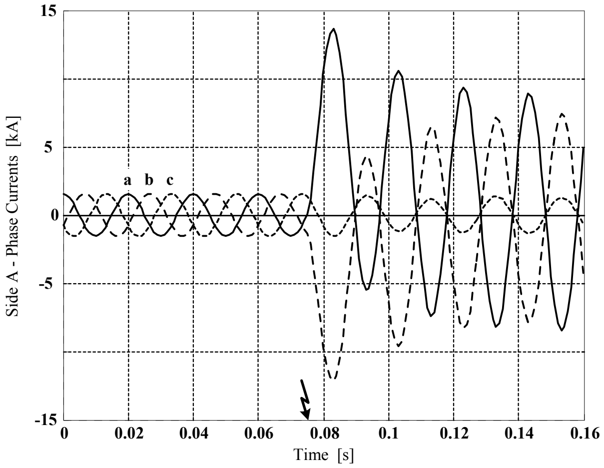

Figure 6. Example 1 – currents for fault in front of SCs&MOVs (fault F_A).

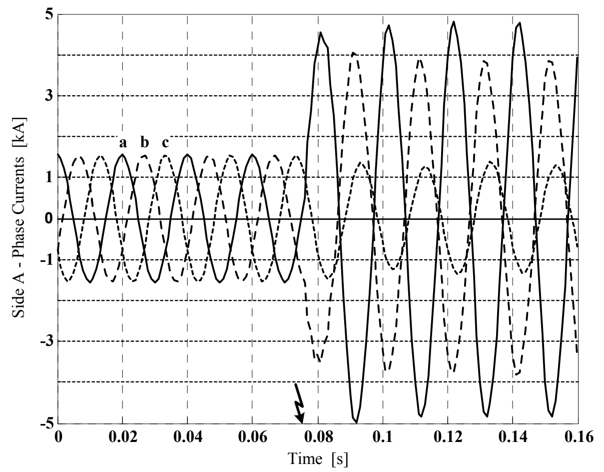

Figure 7. Example 2 – currents for fault behind SCs&MOVs (fault F_B).

IV. Conclusion

This paper presents the algorithm aimed at recognising 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 fault position allows making the distance relay adaptable to presence of the compensating bank in the fault loop. There is a need for reflecting the presence of SC&MOV (or SCs&MOVs in the case of inter-phase faults) in the fault loop, considered by the distance relay under faults occurring behind the compensating bank. 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 (for 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 change of the phase shift for the protective relay input currents. The decision with respect to the fault position is made using fuzzy logic reasoning.

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 with the 400 kV, 300 km transmission line. Different specifications of faults and pre-fault power flows (in total, above 30 thousand cases) have been considered in the evaluation study.

Application of fuzzy logic appeared as the tool which allowed obtaining efficient detection of the fault place. Inter-phase faults occurring behind and in front of SCs&MOVs have been detected perfectly correct (100%).

It is expected that in future research on the issue of detecting the faulted section of the series compensated line, a multi-criteria algorithm will be developed. It seems that only multi-criteria approach can assure completely correct recognition of the fault position, for very wide range of specifications of faults and the transmission network parameters. This is so also since the position of single phase-to earth faults is not well recognised with the presented algorithm.

V. References

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