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DIFFERENTIAL PROTECTION WITH BETTER STABILIZATION FOR EXTERNAL FAULTS

This paper presents a new differential protection scheme for transmission lines with application of fuzzy signal processing and support of phase comparison criterion. Traditional differential relays may have problems with proper classification of external faults with CT saturation. Better protection stabilization for such cases is obtained with support of fuzzy signal processing. In proposed solution the input signals as well as the standard percentage characteristic are fuzzified. The performance of presented fuzzy protection scheme has been tested with the signals generated with use of EMTP-ATP program and compared to the traditional solution.

1. INTRODUCTION

Current differential protection is one of the first relays that were developed and put into service. Its main advantage is reliable and fast detection of internal faults. Therefore, it is used to protection of various elements in power systems, i.e. power transformers, generators, busbars and transmission lines. The zone of action of differential relay embraces only protected object, which means that differential relay should trip for internal faults only and restrain for all external disturbances. This is the main requirement differential protection must meet.

The basic operating principle of current differential criterion (in accordance with the Kirchhoff's current law) is to compare currents flowing into the object with the currents flowing out of the object at the other end(-s) [1]. Generally in standard solution the current differential signal is calculated according to following formula [2]:

$$I_d = | \underline{i}_1 + \underline{i}_2 + \ldots + \underline{i}_k | \tag{1}$$

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where: $\underline{i}_1, \ldots, \underline{i}_k$ –secondary current phasors (from CTs) measured at k-terminals, I_d – amplitude of differential current.

The value of differential current amplitude for internal faults is much greater than zero, while for external faults and normal operation of protection object should be negligible. This case is purely theoretical. In practice, the value of differential current amplitude may also be greater than zero for external faults which may lead to protection maloperation. This situation is caused by CT errors which are due to high value of fault current amplitude or/and decaying DC components in fault currents. To improve the selectivity of protection operation for external faults with CTs saturation the restraint current (4) and stabilized characteristic is used. Fig. 1 presents the typical two-segment stabilized characteristic which can be described by (2) and (3) [2]. The first section of this characteristic (k_1) is responsible for detecting of internal faults (especially via high resistance). However, the second part of characteristic (k_2) is used to improve protection stability for external faults with CT saturation [2]. In standard solution the trajectory of differential/bias currents is tracked with respect to the relay characteristic to determine whether or not to trip the transmission line. The tripping command is initiated if:

$$|I_d| \geq I_{op} = k_1 \cdot |I_{st}| + I_{d0} \quad \text{for} \quad |I_{st}| \leq I_{s2} \tag{2}$$

$$|I_d| \geq I_{op} = k_2 \cdot |I_{st}| - (k_2 - k_1) \cdot I_{s2} + I_{d0} \quad \text{for} \quad |I_{st}| \geq I_{s2} \tag{3}$$

$$I_{st} = \sum_{j=1}^{k} |\, \underline{i}_j \,| \tag{4}$$

where: I_{st} – amplitude of restraint current, I_{d0} – minimum pick-up level of the protection, I_{s2} – the threshold value determines which part of characteristic k_1 or k_2 is used, k_1 – the lower percentage restraint setting, k_2 – the higher percentage restraint setting.

Generally, CT errors due to saturation should be compensated for by conventional stabilized characteristic with adequate slope setting. However, when there is a mismatch in CTs' load or they have non-identical magnetizing characteristics or/and residual flux, a possibility still exists that one of the CTs may saturate and not the other, which may lead to protection malfunction.

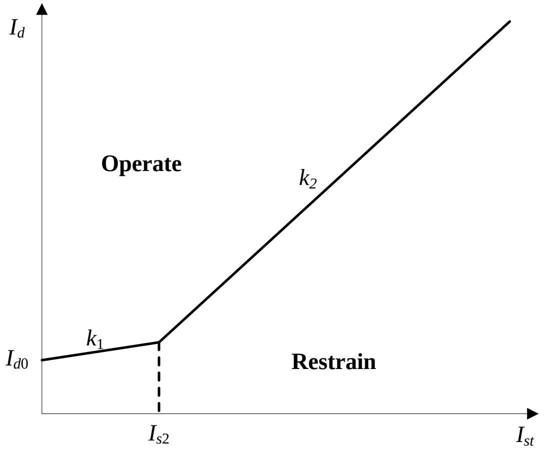

Fig. 1. Stabilized characteristic of the current differential relay

Several approaches may be found in the literature, that according to the authors, should improve performance of the line differential relays. The solution presented in [1] is based on the so called phaselets (“partial” Fourier signals) and variable window Fourier transform as well as variance-based measurement confidence calculation that is used for dynamical adaptation of the relay percentage restraint, which should bring improvement in sensitivity. The other idea described in [4] makes use of adaptive time-dependent restraint coefficients that define the shape of percentage differential curve. A method based on zero-sequence component for detection of current transformer saturation is proposed in [9]. In order to better improve stabilization of the differential protection harmonics of differential current may be used (e.g. second and/or fifth) [5] or a method which identifies CTs saturation (i.e. employing second or third derivative of secondary current) [6]. Since also the cited solutions do not guarantee proper operation of the relay for all fault cases, new protection ideas are still needed to fulfill the gap, especially if the CT saturation evoked errors are concerned.

Therefore, there is a need for an improved algorithm for protecting transmission lines with better stabilization for external faults cases, yet with maintained sensitivity and operation speed for internal faults requiring prompt tripping. Therefore, the authors of this paper focused on the development of the new algorithm (described in section II) that improves the performance of differential protection for external faults with CTs saturation.

2. STABILIZATION SCHEME FOR DIFFERENTIAL PROTECTION

Classical (Boolean) logic based on the concept of truth/falsity cannot effectively cope with the many ambiguities that arise during operation of the power system. Therefore, fuzzy logic is increasingly being used in decision-making, whereas the criteria signals are described by membership functions. The use of fuzzy logic increases the confidence of the decision-making within an area of uncertainty, since the fuzzy logic can deal better (as compared to Boolean logic) with suspense and missing data. In addition, inferencing with multiple objectives in such systems is a natural way of processing information – it is therefore utterly possible to use numerous criteria in parallel.

Fig. 2 presents the structure of the new fuzzy protection. The main idea of action relies on fuzzification of differential current I_d that is further compared with fuzzy setting obtained on the basis of the stabilized characteristic (Fig. 1). Additionally, the criterion of phase difference is introduced, value of which affects the degree of fuzzifiness of fuzzy setting. Below the various blocks of scheme from Fig. 2 are described in detail.

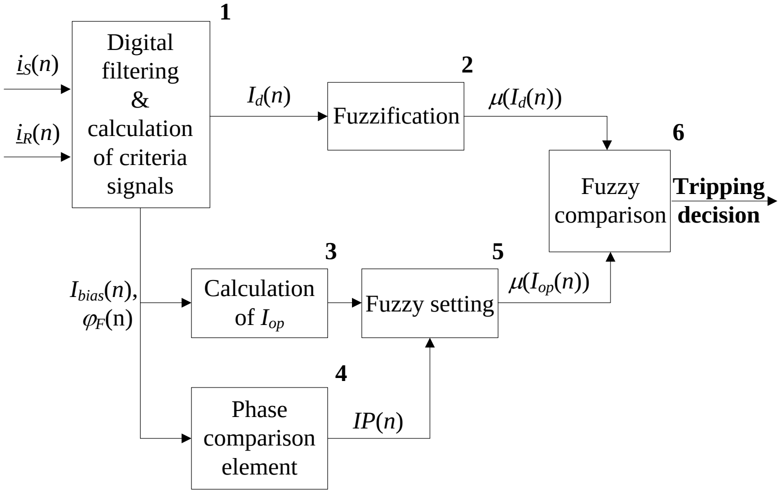

Fig. 2. Block scheme of the fuzzy adaptive differential protection of transmission line

Digital filtering and calculation of criteria signals (block 1) – here the main criteria signals (differential current I_d (3), bias current I_{bias} (3) and phase difference φ_F) are calculated with use of full cycle Fourier filters. The variable φ_F can be expressed by the formula based on negative sequence currents from both line terminals:

$$\varphi_F = 180^{\circ} - \left| \arg \frac{\underline{i}_{2S}}{\underline{i}_{2R}} \right| \tag{5}$$

which is well suited for effective discrimination of asymmetrical faults [7].

Unfortunately, the negative sequence current cannot provide identification of three-phase faults. Therefore, for symmetrical faults the phase difference φ_F is calculated on the basis of positive sequence current as follows:

$$\varphi_F = 180^{\circ} - \left| \arg \frac{\underline{i}_{1S}}{\underline{i}_{1R}} \right| . \tag{6}$$

A three-phase fault is detected using overcurrent element tracking the level of restraint currents in all phases.

Symmetrical components of the signals can be calculated according to the well known matrix formula:

$$\begin{bmatrix} \underline{i}_{0S(R)} \\ \underline{i}_{1S(R)} \\ \underline{i}_{2S(R)} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} \underline{i}_{L1S(R)} \\ \underline{i}_{L2S(R)} \\ \underline{i}_{L3S(R)} \end{bmatrix} , \tag{7}$$

where: $a=\exp(j2\pi/3)$, $i_{0S(R)}$, $i_{1S(R)}$, $i_{2S(R)}$ – zero, positive, negative sequence currents at the S and R ends, $i_{L1S(R)}$, $i_{L2S(R)}$, $i_{L3S(R)}$ – phase currents at the S and R ends of the line.

Measuring of phase difference is initiated when the differential current is greater than or equal to I_{d0} in any phase.

Fuzzification (block 2) – magnitude of differential current (3) is fuzzified, which means that triangular membership functions is formed by using minimum I_{min}, average I_{av} and maximum I_{max} values of differential current (it was assumed that these values were calculated for a quarter of fundamental frequency cycle):

$$I_{\min}(n) = \min_{k=0 \div (N/4)-1} \{ I_d \; (n-k) \} \tag{8}$$

$$I_{av}\,(n) = \frac{1}{N/4} \sum_{k=0}^{(N/4)-1} I_d \,(n-k) \tag{9}$$

$$I_{\max}(n) = \max_{k=0 \div (N/4)-1} \{ I_d \; (n-k) \} \tag{10}$$

here: N – number of samples per cycle of the fundamental harmonic (here N=20).

An example of how the fuzzification of differential current proceeds is shown in Fig. 3. Based on five samples of magnitude of differential current (Fig. 3(a)) the adequate values are calculated according to equations (8), (9) and (10). Next, the triangle membership function is formed as shown in Fig. 3(b).

Calculation of I_{op} (block 3) – the value of operation current is calculated according to equations (2) and (3) – based on restraint current I_{st}.

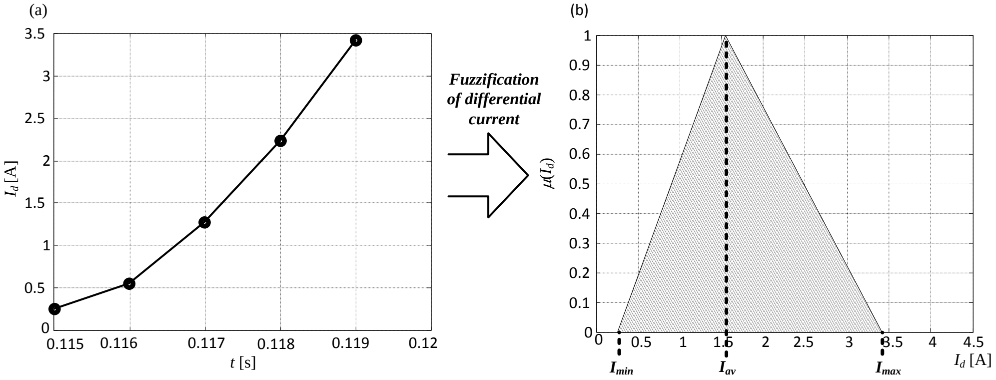

Fig. 3. Fuzzification of differential current:(a) magnitude of differential current, (b) fuzzy differential current

Phase comparison element (block 4) – here the calculated phase difference, (5) or (6), is compared with the operation characteristic (see Fig. 4(b)). The adequate threshold values of the characteristic have been set according to the statistical information gained through analysis of generated simulation signals. One can see (Fig. 4(a)) that basing on this criterion signal it is possible to define two regions: operation and restraint. The output value *IP* from phase comparison element influences fuzzification of the operation current. If the output value is close to 1.0 it indicates an external fault. Otherwise (internal fault cases) the output is close to 0.

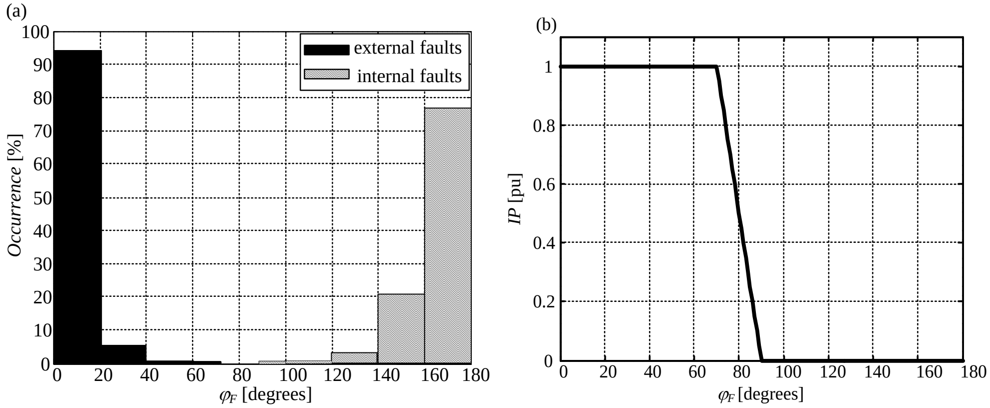

Fig. 4. Statistical information (a) and operation characteristic (b) for phase difference

Fuzzy setting (block 5) – based on the actual value of operation current and information from phase comparison block the fuzzy setting is formed as it is illustrated in Fig. 5(a). The parameters δ_1 and δ_2 determine the shape of membership function of fuzzy setting, being calculated according to:

$$\delta_1 = IP\cdot I_{st} + 0.1 \qquad \delta_2 = 1.5\cdot IP\cdot I_{st} + 0.3 \tag{11}$$

The values of parameters in (10) are small (δ_1=0.1 and δ_2=0.3) for *IP*=0 (this value indicates internal fault) which means that membership function is slightly fuzzy. When *IP*=1 (this value indicates external fault) both parametres are high and the membership function of fuzzy setting is quite broad.

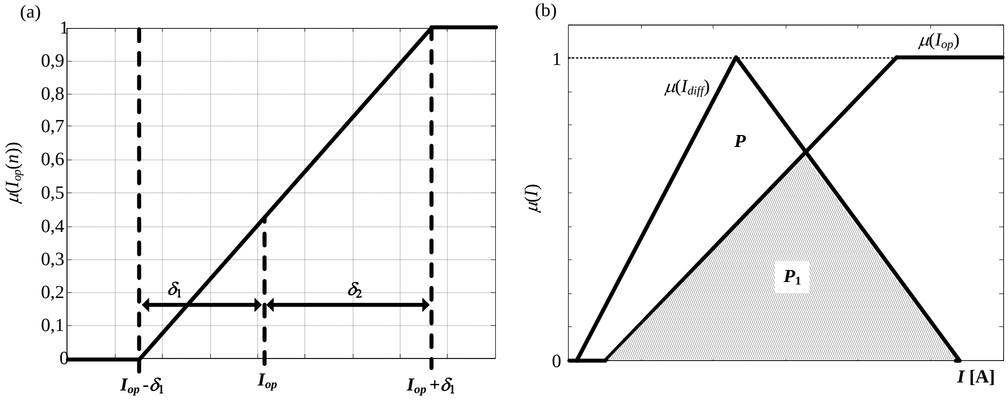

Fig. 5. Formation of fuzzy setting (a) and fuzzy comparison illustration (b)

Fuzzy comparison (block 6) – in this block both membership functions fuzzy differential current $\mu(I_d)$ and fuzzy setting $\mu(I_{op})$ are compared with each other (Fig. 5(b)). The value of fuzzy comparison is determined by:

$$P_d = \frac{\int \min[\mu(I_d),\mu(I_{op})]dI}{\int \mu(I_d)\,dI} = \frac{P}{P_1} \tag{12}$$

where *P* - the area under the membership function of differential current $\mu(I_\mathrm{d})$ and P_1 - surface area (hatched) under both the fuzzy setting $\mu(I_\mathrm{op})$ and $\mu(I_\mathrm{d})$, [8].

The final decision to trip a protected transmission line is taken when the value of index P_d is greater than threshold 0.7.

Below testing results of two different types of protection versions (standard differential relay [2] and fuzzy adaptive scheme proposed) are presented.

3. TESTING OF DEVELOPED FUZZY PROTECTION SCHEME

The tests were performed on the ATP-EMTP model as shown in Fig. 6. It consists of two 5P30 20VA 1000/1A CTs which were modeled using the TYPE-96 pseudo-nonlinear element [3]. In this model there is a possibility to set the residual flux in the CT core, which is very important for studying CT saturation effects [9]. It was assumed that CT_A is the reference CT (never saturated) and CT_B is the saturable CT.

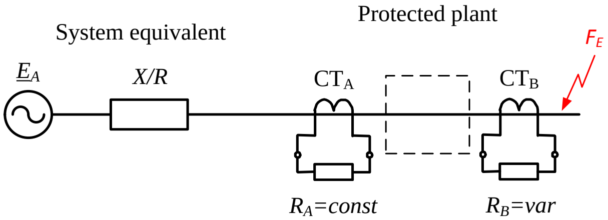

Fig. 6. ATP-EMTP test model

The adequate value of the CT knee voltage can be calculated according to the following equation [5]:

$$V_k > K \cdot I_s \cdot \left(1 + \frac{X}{R}\right) \cdot Z \tag{13}$$

where: I_s – nominal secondary current, K – multiples of secondary current (fault level), system X/R ratio, Z – current transformer burden.

In some cases (for high value X/R ratio and fault level), the fulfilment of this condition is impossible (very high value of knee voltage) because it would imply the CT with large core diameter, which is uneconomical. Therefore, it is important that differential protection works properly even when the CTs saturate.

This test was to prove that the new method is more immune to CT saturation than the standard relay. In the test the following parameters that affect the saturation of CT were being changed:

- system X/R ratio ($X/R = 10 \div 120$),
- multiples of secondary current ($K = 5 \div 35$),
- burden of CT_B ($R_B = 1 \div 25\Omega$),
- point on wave (maximum current offset).
- residual flux in the CT core (0 or ±0.7 of saturation flux).

The testing results proved that the proposed scheme is stable for external faults (zero percent of incorrect operation). Contrary, the standard protection failed for a few percent of external fault cases. Figs. 7-8 present an extreme example generated for the following parameters assumed: K = 35, RB=25 Ω, X/R = 120. As one can see the CTB gets deeply saturated, especially in phase L1 (Fig. 7(a)) and the standard protection based on the stabilized characteristic with fixed settings maloperates, since the differential-restraining trajectory (phase L1) enters the tripping zone (Fig. 7(b)), thus the trip command is sent to the circuit breakers (Fig. 8(c)). For this case the phase comparison element output was high (Fig. 8(a)) since the value of calculated phase difference was low (not greater than 40 degrees), which implies an external fault. The response of the phase comparison element affected the shape of fuzzy setting membership function, which became much broader. As one can see the proposed algorithm remained fully stable here, without issuing false tripping command (Fig. 8(d)).

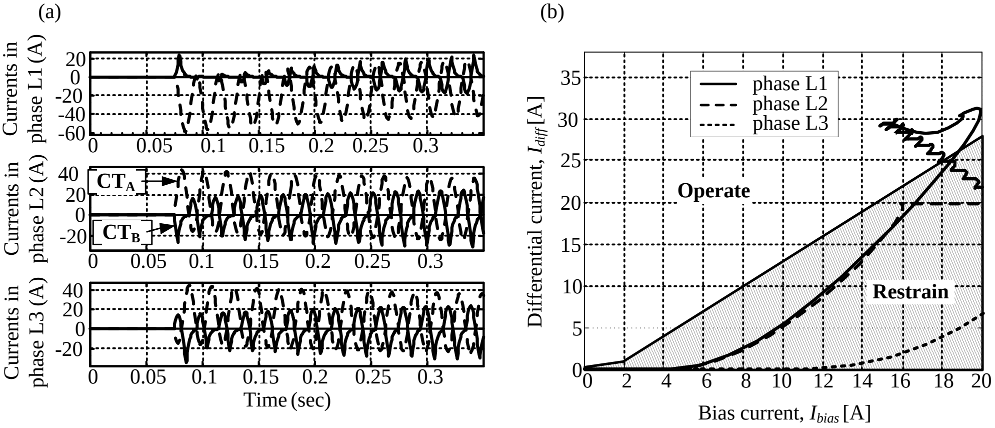

Fig. 7. Testing example: (a) line terminal current waveshapes, (b) protection stabilized characteristic and I_d-I_{st} trajectory

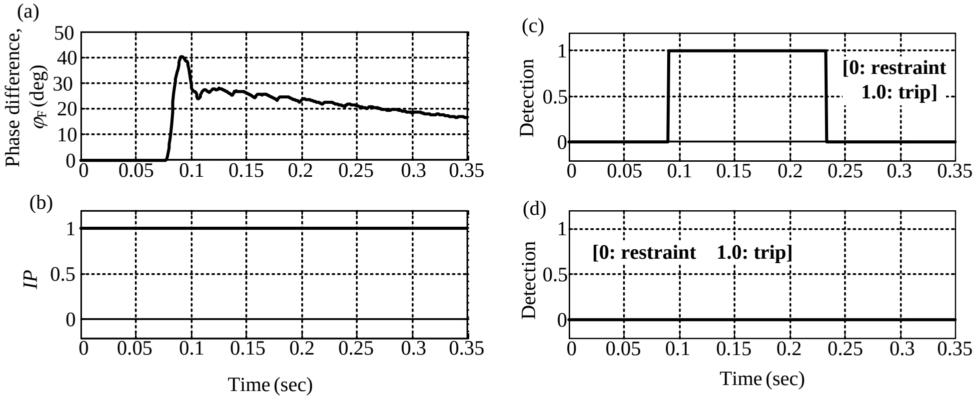

Fig. 8. Testing example: (a) calculated phase difference φ_F, (b) phase comparison element response, (c) standard differential protection response, (d) fuzzy differential protection response

4. CONCLUSIONS

The solution for improvement of the line differential protection operation for external fault cases with possible CT saturation is described in the paper. For better stabilization under external faults a method employing fuzzy signal processing and phase comparison element is proposed to be used. The tests performed prove that the developed algorithm remains stable for external faults under all conditions, including heavily saturated current transformers. This method can also be used for protection of other power system elements, e.g. busbars or generators.

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ZABEZPIECZENIE RÓŻNICOWE Z LEPSZĄ STABILIZACJĄ DLA ZWARĆ ZEWNĘTRZNYCH

W artykule zaprezentowano nowe zabezpieczenie różnicowe, w którym zastosowano rozmyte przetwarzanie sygnałów oraz dodatkowe kryterium porównawczo-fazowe. Proponowane zabezpieczenie jest bardziej odporne na zwarcia zewnętrzne z nasyceniem przekładników prądowych, co potwierdziły przeprowadzone testy. Proponowany algorytm testowany był na sygnałach pochodzących z symulacji w EMTP-ATP, a wyniki porównano ze standardowym przekaźnikiem różnicowym.