



A Novel Fuzzy Theory-Based Differential Protection Scheme for Transmission Lines

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Abstract: Ever-increasing consumption of electrical energy has forced extension of power networks to large areas. This would raise reliability and stability problems of power networks. Hence, there is a serious need to work on protection arrangements and relays behavior for solving these problems. By suitable configuration of protection systems and using correct protection functions, negative effects of undesirable faults in power system will be decreased. In this paper, an algorithm is proposed to enhance the performance of differential relays based on the fuzzy logic systems. The algorithm is employed for the protection of short transmission lines against internal faults with/without resistance. By selecting the best stability characteristics based on fuzzy logic systems, the possibility of protection relays' malfunction will be negligible. In this algorithm, sensitivity, reliability and speed of the relay performance are preserved at suitable levels. Considerable external faults which can saturate current transformers (CTs) have been taken to account in this algorithm. This study purpose is to present an algorithm based on the fuzzy logic, which can select the best slopes for stability characteristics of a differential relay during various conditions. The presented algorithm performance has been analyzed by PSCAD/EMTDC software and compared to conventional methods. The results of fuzzy adaptive protection performance testing prove that the proposed algorithm remains fully immune to current transformer saturation during external faults. The other advantage of this algorithm bases on the fact that the scheme does not need to detect CT saturation, it processes the proposed criteria signals independently of the situation.

Keywords: Differential relay, internal faults, fuzzy logic, stability characteristics

1. Introduction

In the last four decades, the application of digital differential relays has been extended due to the advancements in digital technology. This type of relays is more flexible than electro-mechanical and static differential relays. In digital differential relays, the protection principles are digitally implemented. The existence of digital relays allows the utilization of more complicated and more efficient algorithms. In such relays, the required signals are sampled and processed using protection algorithms. The fuzzy logic is a particular and effective system which is able to use experimental information and numerical data. Its performance is based on "if – then" principles, which are obtained from experts' or field information. In recent years the application of protection algorithms has been a major research field in power system protection to increase the performance speed of differential relays in fault conditions. The main aim has been to enhance their security against non-fault events. However, the research have been extended to achieve more desirable protection schemes due to the difficulties and disadvantages of these algorithms. The current differential principle is the most powerful short-circuit protection method. Its principle has a very high capacity for both sensitivity and security. Also, differential protection is typically easy to apply because it does not require elaborate short-circuit studies and settings and coordination calculations. In its application to power lines, the principle is little or not affected by weak terminals, series compensation, changing short-circuit levels, current inversion, power swings, nonstandard short-circuit current sources, and many other issues

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relevant for protection techniques based on measurements from a single line terminal [1]. However, line current differential protection is no exception. Its challenges include the requirement of high sensitivity, current alignment issues, security under current transformer (CT) saturation, line charging current, limited bandwidth channels, channel impairments, and failure modes.

Throughout the history of power system protection, researchers have strived to enhance sensitivity and speed of protection relays without decreasing security. With the significant technological advances in wide-area measurement systems, for transmission system protection, current differential protection scheme outweighs alternatives like overcurrent and distance protection schemes. In 1983, Sun and Ray [2] published a seminal paper describing current differential relay system using fiber optics communication. An effective transmission rate of 55 samples per cycle at 60-Hz frequency was achieved in [2].

The inaccuracies in such a current differential protection scheme arise, primarily, due to the following reasons:

- effect of the distributed shunt capacitance current of the line is neglected;
- modelling inaccuracies with series-compensated transmission line;
- approximate delay equalization between local and remote end current;
- current transformer (CT) inaccuracies, in particular errors due to saturation of the core in the presence of decaying dc offset current [3].

This study tries to dynamically control the differential relay characteristics using the fuzzy logic system.

The first digital relay was introduced by Rockefeller [4] in the early 1970s. Logic performance has been used for fault detection, fault locating, and appropriate opening of the breakers. After that, most digital differential relays have benefited from the harmonic analysis algorithm of differential current using digital signal processing methods.

Differential relays are used in abundance for the protection of generators and transformers. Proliferation of differential relays in transmission lines is due to the communication technologies advancement [5,6]. In the 1980s, these progress lead to producing a differential relay, which works by digital current and is based on optic fiber or microwave communication in Japan [7]. Conventional current differential schemes employing GPS synchronized current measurements is discussed in [8]. If ultrahigh transmission system voltages are used (e.g., 765 kV and above), then line charging current component is significant. It causes a large variation in phase angle of the line current from one end to another. In traditional pilot wire schemes, relaying sensitivity will have to be compromised to prevent the mal-operation. Reference [9] proposes a current differential relay which uses distributed line model to consider line charging current. A time-domain protection solution based on integrated quantities is presented in [10]. The algorithm works by integrating time-domain measurements and generated signals in order to achieve stable quantities that are afterwards used for protection. The multiagent-based wide area current differential protection system is proposed in [11]. Reference [12] proposes the use of phasorlets for fast computation of phasors in distance and differential relaying. The paper on digital communication for relay protection [13] authored by working group H9 of IEEE Power System Relaying committee is an excellent reference to understand the implications and consequences of digital communication technologies on relaying.

Several studies with various algorithms have been carried out in the field of the distinction between transformer inrush current and faults inside/outside of the protected area. Wavelet transform (WT) is used as a powerful tool for disturbance signal analysis. Hossam et al. [14] used WT in different conditions to differentiate between the power transformer inrush current, faults inside /outside of protected area. Choosing the mother wavelet is a very important factor in the analysis results of the WT. One disadvantage of the proposed method is selecting the mother wavelet has not been analyzed. Furthermore, since the fourth level of wavelet transform was used in this method, this algorithm requires a large computational burden, hence, decreasing the performance speed of the relay. Subsequently, it is necessary to choose the mother wavelet and transformation level of the discrete wavelet with greater accuracy and evaluation. Despite these disadvantages, the proposed method is capable of distinguishing between internal faults and inrush current.

Fuzzy logic (FL) was first introduced by Lotfi Zadeh. His paper titled "Fuzzy Sets" [15] was published in a magazine that he was its editor-in-chief. Lotfi Zadeh changed his interests from precise engineering control to FL which brings the possibility of ambiguity and speciosity. He defined the "Principle of Incompatibility". According to this theory, when the complexity of a system goes beyond the determined limit, explicit and precise definition and performance meaning of that system will be impossible. Furthermore, Mohammadi et al. [16] utilized FL for FACTS devices optimal placement to minimize the losses in a distribution system. In the other research, Abasi et al. [17] investigated different parameters that affect the normal operation of a power system and result in abnormal faults. A new FL type method, named NSGAI, was used by Mazidi et al. [18] to find the optimal places of switching devices in distribution systems for decreasing the fault bad impacts on the network.

The proposed algorithm in [19] defin fuzzy logic for transformer protection. The transformer differential current defines membership functions in this procedure. Lower and upper predefined values have been presented for the accurate operation of the transformer protection. If the differential current value is less than the lower predefined value (I_1), then it is a normal operating condition. If the differential current value is greater than the upper predefined value (I_2), a fault has happened. For the differential current values between I_1 and I_2 , it indicates a non-confidence mode and reveals the percentage of fault probability.

The main contribution of this paper is proposing a new fuzzy logic inference algorithm for the protection of transmission lines. The proposed method represents benefits such as simplicity, adequate performance for different power system configurations (single and parallel, short, long transmission lines) without fuzzy inference parameter changing.

Furthermore, the proposed algorithm show suitable fault responses against different faults such as internal and internal with resistance, external and transformer energizing inrush compared to other conventional strategies.

The paper is structured as follows. Section 2 describes the differential protection method and fuzzy system. The proposed method is presented in Section 3. Software simulation of the proposed algorithm is given in Section 4 and, finally, Section 5 concludes the paper.

2. Differential protection and fuzzy logic

Differential protection forms unit protection and shows reliable and high selectivity protection for high voltage equipment such as generators, transformers and to name but a few are obtained based on comparison of electrical quantities at both ends of that equipment. A differential relay function zone contains the protected element only. According to this, differential relay only acts on internal faults and send the trip commands and show no reaction for the out of zone disturbances. Differential protection is a form of absolute selective protection. This kind of protection is based on current amplitudes and angles measuring on both sides of the protected area. This protection schematic is illustrated in fig. 1.

Fig. 2 shows the basic layout of the differential protection for the protected element. The current which is entering the protected area, I_{p1} , is changed to secondary current I_{s1} by current transformers (CT) #1, and output current from the protected area, I_{p2} , is changed to current I_{s2} by CT #2. CTR is the transformation ratio of the current transformer. Assuming the CTs to be ideal

$$\begin{cases} I_d = I_{s1} - I_{s2} \\ I_{p1} = I_{p2} \Rightarrow I_{p1} - I_{p2} = 0 \end{cases} \Rightarrow I_d = \frac{1}{CTR} * I_{p1} - \frac{1}{CTR} * I_{p2} = 0 \quad (1)$$

There is no notable differential current (I_d) under normal operation conditions. However, I_d will increase when a fault happens inside of the protection area. Thus, the increase of differential current is a sign of faults inside the protected area. Nevertheless, since this can happen due to series of other reasons except inside protection area faults, the presence of differential current is not a definite sign of inside the protection area faults. Fig. 3 shows a short circuit in the protected zone (point F1), where current I_{p1} is not equal to current I_{p2} . The difference in the power currents leads to a difference in secondary currents of the CTs as follows’.

$$\begin{cases} I_d = I_{s1} - I_{s2} \\ I_f = I_{p1} - I_{p2} \end{cases} \Rightarrow I_d = \frac{1}{CTR} * I_{p1} - \frac{1}{CTR} * I_{p2} = \frac{1}{CTR} * I_f \quad (2)$$

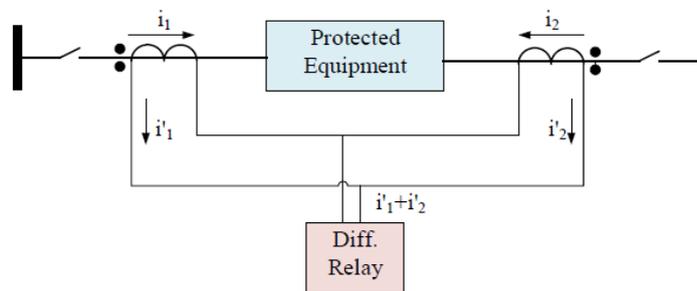


Fig.1- Differential protection scheme

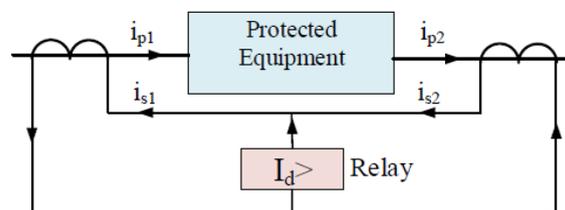


Fig.2- The initial scheme of differential protection of circulating current

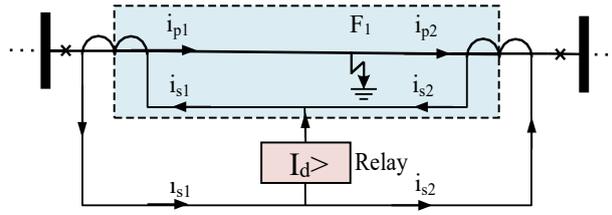


Fig. 3 - Fault in the protection zone

The stability characteristic of conventional differential relay is composed of two parts as shown in Fig. 4. Coefficient at the first section of slope (K_1) helps to discover faults inside the protection area, and coefficient at the second section of slope (K_2) is for helping the protection stability of faults out of protection area [20]. Trip order in normal protection is issued in two modes of (3) and (4) as below:

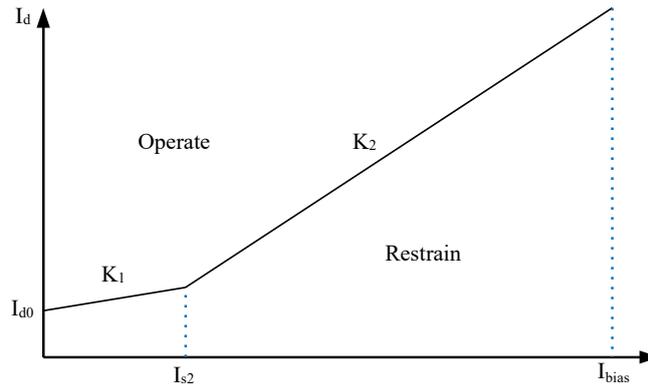


Fig. 4- The stability characteristics of conventional differential relay

In the case $I_{bias} < I_{s2}$

$$I_{bias} < I_{s2} : |I_d| > I_{op} = K_1 * |I_{bias}| + I_{d0} \tag{3}$$

In the case $|I_{bias}| > I_{s2}$

$$|I_{bias}| > I_{s2} : |I_d| > I_{op} = K_2 * |I_{bias}| - (K_2 - K_1)I_{s2} + I_{d0} \tag{4}$$

I_{bias} and I_d are bias current and differential current and obtained from (5) and (6), respectively:

$$I_d = |i_s + i_r| \tag{5}$$

$$I_{bias} = (|i_s| + |i_r|) \times 0.5 \tag{6}$$

where i_s, i_r are terminal currents, and I_{op} is the relay's performance threshold current.

The fuzzy logic is a particular and effective system which is able to use experimental information and numerical data. Its ability is based on "if-then" principles which are analyzed from expert's or field information. Fig. 5 shows the fuzzy block.

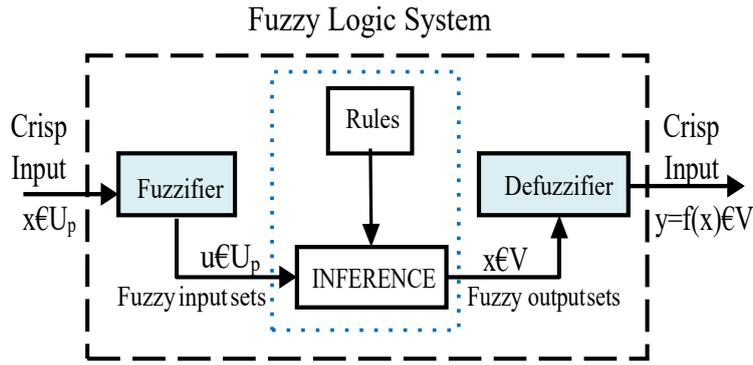


Fig. 5 - Fuzzy block

3. The proposed algorithm

Fig. 6 illustrates the proposed fuzzy differential protection plan structure. I_d and I_{bias} of block 1 are estimated by (5) and (6). Fundamental and some other harmonic components are gained using full cycle Fourier transform in this block. By online matching of terms of slope changes in one or both parts of K_1 and K_2 , relay characteristic, which is illustrated in Fig. 4, is suggested based on the conditions of a conventional power network. If an out of protection area fault occurs with CT saturation or transformer energizing, the maximum value must be fixed for characteristic slope. Otherwise, the characteristic slope will be fixed at lower value. It will particularly happen during ground faults with high resistance, to show the required sensitivity for internal faults.

Zero, positive and negative sequence currents related to block 3 of Fig. 6, are calculated based on the (7):

$$\begin{cases} \begin{bmatrix} i_{0s} \\ i_{1s} \\ i_{2s} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} i_{11s1} \\ i_{12s1} \\ i_{13s1} \end{bmatrix} \\ \begin{bmatrix} i_{0r} \\ i_{1r} \\ i_{2r} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} i_{11s2} \\ i_{12s2} \\ i_{13s2} \end{bmatrix} \end{cases} \quad (7)$$

In (7) $a = 1 < 120^\circ$, i_{0s} , i_{1s} and i_{2s} are sending end denotation of zero, negative and positive sequence currents, respectively, and i_{0r} , i_{1r} and i_{2r} are receiving end denotation of zero, positive and negative sequence currents, respectively. Mixing of negative and positive sequence currents in (8) and (9) has made another criterion.

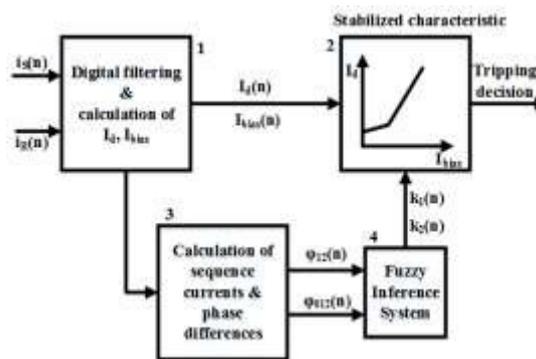


Fig. 6 - New Fuzzy differential protection structure

$$i_{12z} = (i_{2z} - K_{1g} i_{1z}) \quad (8)$$

$$i_{12R} = (i_{2R} - K_{1g} i_{1R}) \quad (9)$$

Next criterion value can be gained by mixing zero, negative and positive sequence currents in (10) and (11).

$$i_{012s} = K_{2p}i_{2s} + K_{1g}(i_{0s} + i_{1s}) \tag{10}$$

$$i_{012r} = K_{2p}i_{2r} + K_{1g}(i_{0R} + i_{1r}) \tag{11}$$

The inputs of “Fuzzy Inference System” block are angles φ_{012} and φ_{12} that are respectively obtained from (12) and (13), as follow:

$$\varphi_{12} = 180^\circ - |\arg(i_{12s} / i_{12r})| \tag{12}$$

$$\varphi_{012} = 180^\circ - |\arg(i_{012s} / i_{012r})| \tag{13}$$

Fig. 7 shows negative and positive sequence currents angles (φ_{12}) in case of external and internal faults. φ_{012} Also has a similar form.

The second harmonic order (h_2) of transformer current, i.e. I_{h2} , gives information about transformer energizing. If $I_{2h\delta} > 0.05I_n$ then $h_2 = 1$, otherwise $h_2 = 0$, which I_n indicates line load current. In case of discovering a disturbance, this term will be evaluated and investigated through all $N+1$ samples (N shows sampling window length).

If $h_2 = 1$ or $\{(I_{biasL1} > 1.5I_n \ \& \ I_{biasL2} > 1.5I_n \ \& \ I_{biasL3} > 1.5I_n)\}$ Then $K_{1g} = 6$, otherwise $K_{1g} = 0$.

If $h_2 = 0$ or $\{(I_{biasL1} > 1.5I_n \ \& \ I_{biasL2} > 1.5I_n \ \& \ I_{biasL3} > 1.5I_n)\}$

Then $k_{1g} = 6$, otherwise $k_{2g} = 0$.

I_{biasL} is line bias current. φ is the criterion angel and K_{1g} and K_{2p} are variables of the proposed algorithm [21, 22].

$I_{2h\delta L1}$, $I_{2h\delta L2}$, and $I_{2h\delta L3}$ are the first, second and third line second harmonic amplitudes, which are gained by (14):

$$I_{2h\delta} = I_{2h\delta L1} + I_{2h\delta L2} + I_{2h\delta L3} \tag{14}$$

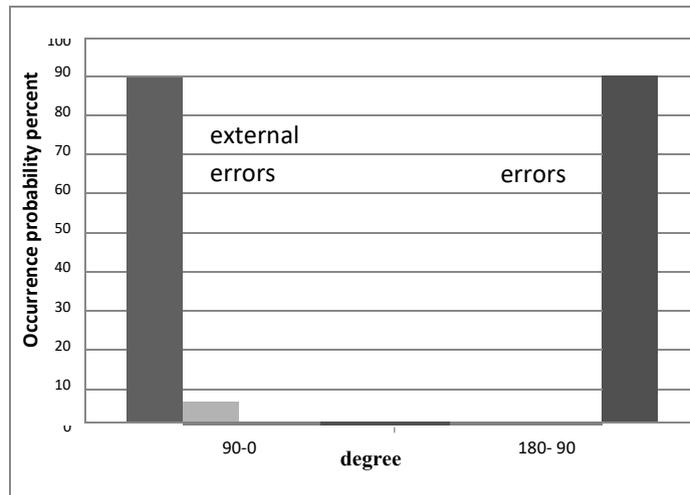


Fig.7 - Phase difference values of negative and positive sequence currents for in and out of area faults

$I_{2h\delta}$ is given through (15) in each phase.

$$I_{\delta} = |i_s - i_r| \tag{15}$$

Proper restricted impulse response filters can be produced by the second harmonic signals. It is notable from (8) and (9) that in the case of a symmetric fault or transformer inrush current, positive sequence current is decreased by a proper factor and negative sequence current contribution will get bold. Equations (10) and (11) are very similar to (8) and (9), except that they are combined with zero sequence current in order to improve the detection of ground faults. The block 3 outputs are considered as inputs for block 4 in Fig. 6. The fuzzy inference system of block 4, includes three parts [23-24].

Those part are: fuzzification, inference and changing fuzzy to numeric values, respectively. Block 4 detailed illustration is shown in Fig. 8. Fig. 8 illustrates that the inputs of FIS system which are numerical values will change to fuzzy variables (shown in Fig. 9) by defuzzification block using trapezoidal membership functions. Membership function of output variable is singleton type as shown in Fig. 10.

The rules of inference block of Fig. 8 are:

IF φ_{012} is "High" AND φ_{12} is "High" THEN y will be L

IF φ_{012} is "Low" AND φ_{12} is "High" OR φ_{012} is "High" AND φ_{12} is "Low" THEN y will be M .

IF φ_{012} is "Low" AND φ_{12} is "Low" THEN y will be H

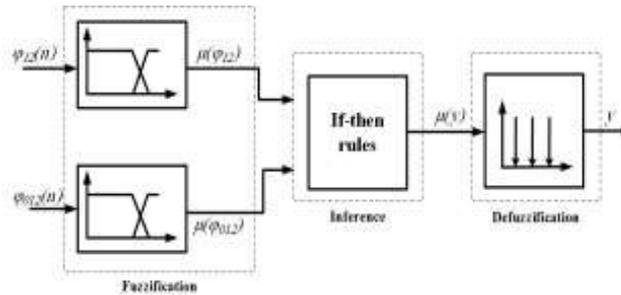


Fig. 8 - FIS (Fuzzy Inference System) for differential protection current setting

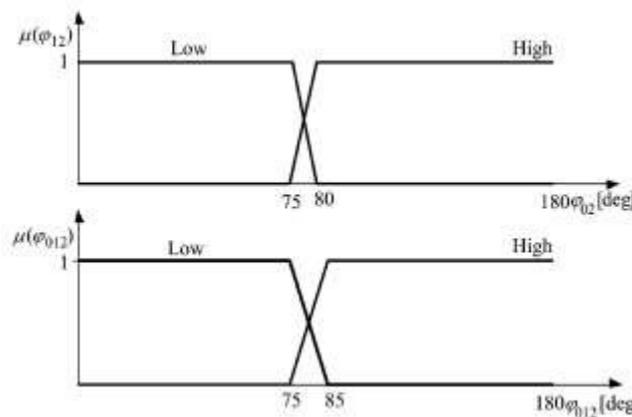


Fig. 9 - Fuzzy input membership functions variable

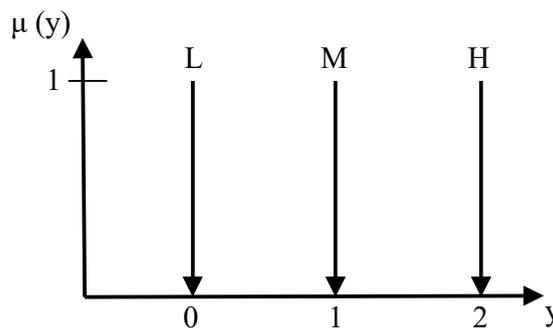


Fig. 10 - fuzzy output membership functions variable

Inference operation would be done by PROD-MAX method. The final fuzzy output will be transformed to truth values by the act of defuzzification, as mentioned previously. The method used for defuzzification is center of gravity method. The real output is obtained by (16).

$$y = (\mu_L y_L + \mu_M y_M + \mu_H y_H) / (\mu_L + \mu_M + \mu_H) \tag{16}$$

H, M and L values denotes high, medium and low values, respectively.

According to fuzzy inference block output values, both K_1 and K_2 settings, as the differential characteristics slopes, will be differ as follows.

If parameter y acquires from (16) is between 0 and 0.5, settings of K_1 and K_2 are (17):

$$K_1 = 0.3 + 0.03y \text{ and } K_2 = 1.2 + 0.3y \tag{17}$$

If parameter y obtained from (16) is between 0.5 and 1.5, K_1 and K_2 settings will be:

$$K_1 = 0.3 + 0.05y \text{ and } K_2 = 1.3 + 0.6y \tag{18}$$

If parameter y obtained from (16) is between 1.5 and 2, setting of K_1 and K_2 are:

$$K_1 = 0.3 + 0.4y \text{ and } K_2 = 1.5 + 0.8y \tag{19}$$

4. Simulation studies

Fig. 11 depicts the network considered for this study. It shows that the network has two power supplies. The power supply in the S side has a short circuit level of 32 GVA. Effective (rms) line-to-line voltage and frequency are 400 kV and is 50 Hz, respectively, while the power supply in the R side has the short circuit level of 4 GVA. The length of transmission line is 50 km, which is divided into two parts, and a fault (FL) occurs in the middle of the line. Two 350 MVA and 400/110 kV power transformers are embedded to supply a 350 MVA load with power factor of 0.9. One of the transformers is permanently connected to the network and another one is entered into the network after a specific time. The fuzzy block is also depicted in Fig. 12 (ϕ_{012} is equal to ϕ_{012} and ϕ_{12} is equal to ϕ_{12} , mentioned in section 3). In Fig. 13, the fuzzy rules mentioned in Section 3 are shown. A single-phase fault occurs at $t=4$ sec. Both sides line currents are shown in Figs. 12-14. Criterion signals, the output of fuzzy block, and switching in both conventional and the proposed algorithm are shown in Figs 14, 15 and Figs 16 and 17, respectively. In both cases, switching's are performed correctly.

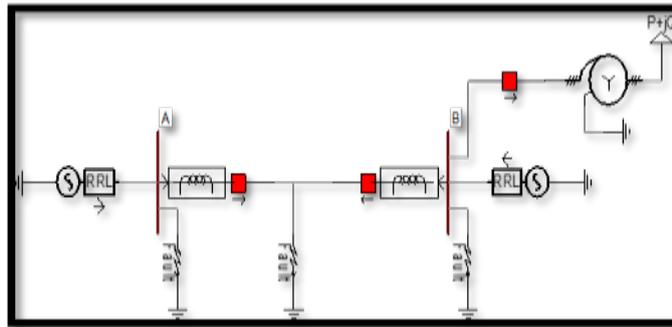


Fig. 11 - The test system for simulation studies

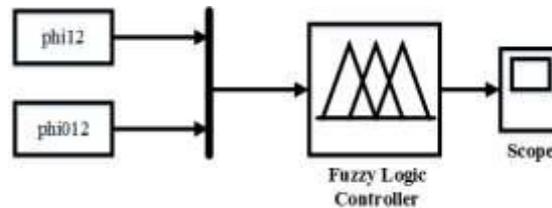


Fig. 12 - Fuzzy block

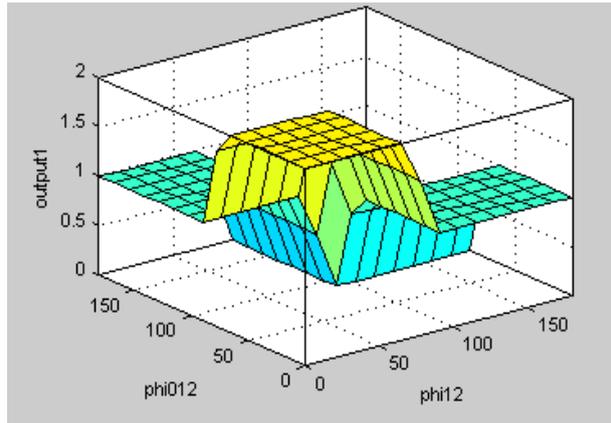


Fig. 13 - Fuzzy rules

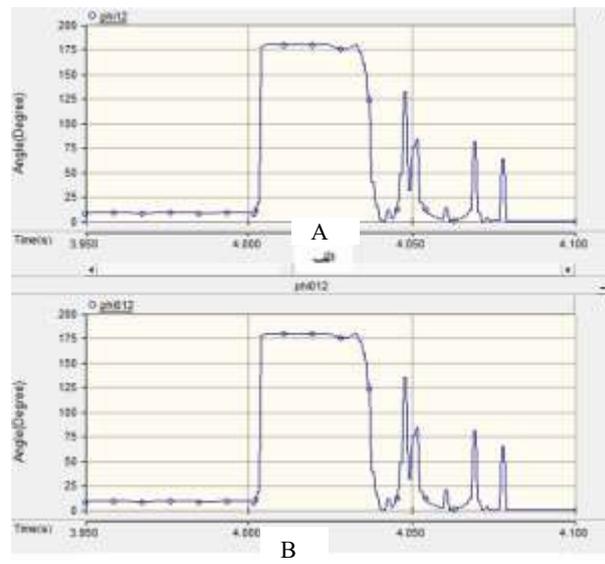


Fig. 14 - The calculated phase difference during an internal single-phase fault (a_g), A: ϕ_{12} B: ϕ_{012}

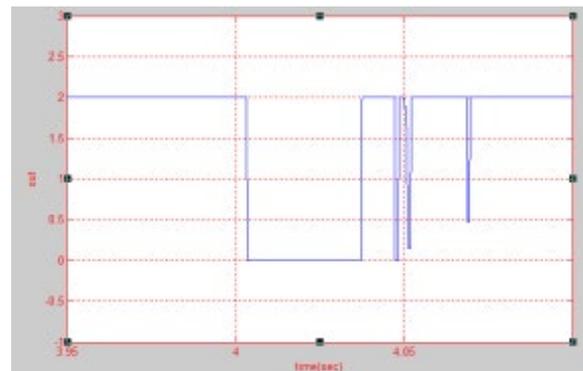


Fig. 15 - The output of fuzzy block

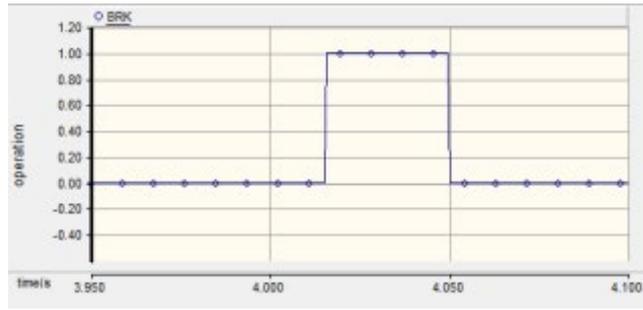


Fig. 16 - Switching with the conventional relay for an internal single-phase fault (a_g)

Criterion signals, the output of fuzzy block, switching of conventional relay, and switching of the proposed relay for internal single-phase fault (A_g) with resistance, are shown in Figs 18, 19, 20 and 21, respectively. In the case of an internal fault without resistance, there was not a considerable difference between switching. However, in the case of an internal fault with resistance, sensitivity and performance of the relay will improve due to choosing the minimum slope.

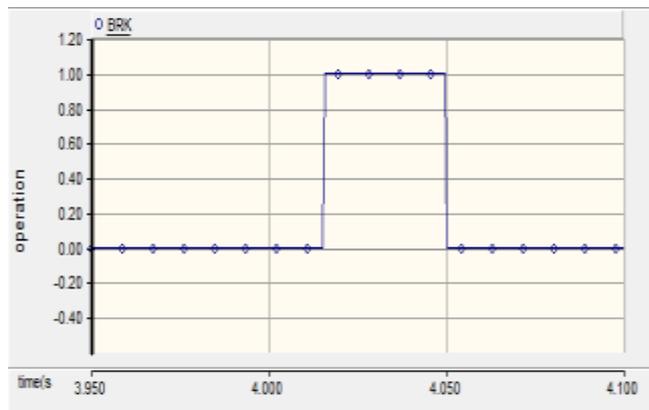


Fig. 17 - Switching with the proposed relay for an internal single-phase fault (A_g)

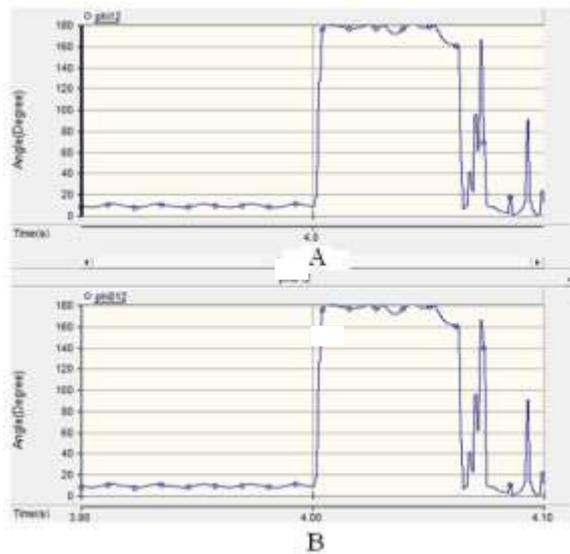


Fig.18 - The calculated phase difference during a single-phase fault (A_g) inside the protected area with resistance, A: ϕ_{12} B: ϕ_{012}

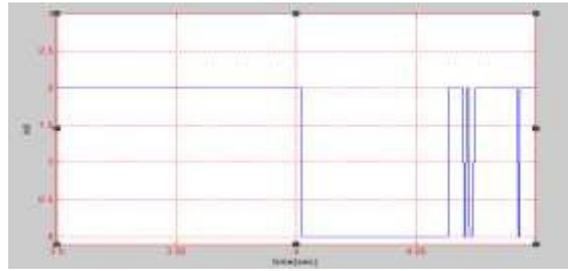


Fig. 19 - The output of the fuzzy block in the case of single-phase fault (A_g) with resistance

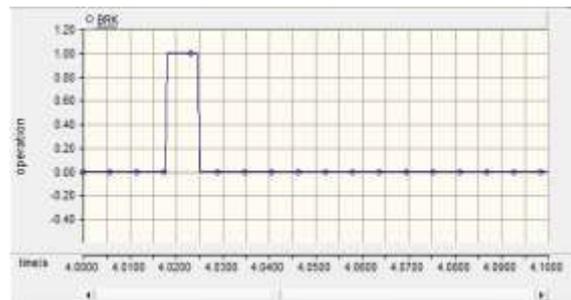


Fig. 20 - Switching with the conventional relay for internal single-phase fault (A_g) with resistance

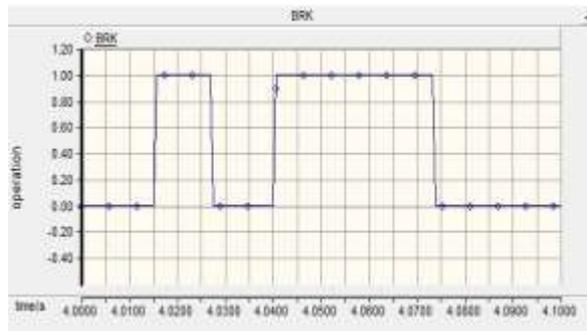


Fig. 21 - Switching with the proposed relay for internal single-phase fault (A_g) with resistance

When single-phase internal fault is tested in the simulation, angles φ_{012} and φ_{12} change from 0° to 180° (Fig. 14) and the fault type is detected based on Fig. 7. The fuzzy rule governing the control system detects the fault as an internal fault (the input of the fuzzy block in Fig. 9 and fuzzy block rules in Fig. 13) and the output of the fuzzy block in Fig. 15 is displayed. Therefore, the trip commands, which is 0 for non-operation and 1 for operation of the breakers, is issued. When the internal resistance is not large in the system, there is no difference between the conventional model and the proposed model in this paper (Figs. 16 and 17). But when a high-resistance fault occurs in the system, the operation of breakers differs (Figs. 20 and 21). Fig. 18 shows angles φ_{012} and φ_{12} during the fault with resistance, which varies from 0° to 180° and, based on the previous explanation, changes the operation of the differential relay.

5. Conclusion

The presented study presented a procedure to help the protection of transmission lines. The proposed method is fit to relays stability characteristics dynamically based on information that has been gathered by fuzzy inference blocks. The proposed method advantageous among others include performance simplicity (fuzzy principles are just consisting of three rules and two membership functions), appropriate performance ability in different power network configuration (single and parallel, short, long transmission lines) without fuzzy inference parameter changing. Furthermore, the proposed algorithm show appropriate fault responses against different faults such as internal and internal with resistance, external and transformer energizing inrush. The performed switching results of this study show that more suitable response are being made for internal faults with resistance than those of the conventional method, while preserving sensitivity against internal faults by the system.

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