Digital Relaying Algorithm for Power Transformer Protection using Fuzzy Logic Approach

Chul-Won Park* and Myong-Chul Shin**

Abstract - Power transformer protective relay should block the tripping during magnetizing inrush and rapidly operate the tripping during internal faults. Recently, the frequency environment of power system has been made more complicated and the quantity of 2nd frequency component in inrush state has been decreased because of the improvement of core steel. And then, traditional approaches will likely be maloperate in the case of magnetizing inrush with low second harmonic component and internal faults with high second harmonic component. This paper proposes a new relaying algorithm to enhance the fault detection sensitivities of conventional techniques by using a fuzzy logic approach. The proposed fuzzy based relaying algorithm consists of flux-differential current derivative curve, harmonic restraint, and percentage differential characteristic curve. The proposed relaying was tested with relaying signals obtained from EMTP simulation package and showed a fast and accurate trip operation.

Keywords: digital relaying, power transformer, onternal faults, magnetizing inrush, flux-differential current, fuzzy logic, EMTP

1. Introduction

The function of power system protective relaying is to initiate the prompt removal of abnormal conditions from service of elements of power system. Since the appearance of microprocessor in the mid-seventies, digital protective relaying has attracted much attention [1]. The power transformer is one of the important elements in power system. Electrical protective relaying of power transformer is based on a percentage differential relaying technique in which transient magnetizing inrush and internal fault must be distinguished [2].

Harmonic-restrainted differential relay is based on the fact that the magnetizing inrush current has a large second harmonic component, and nowadays the above technique is widely applied. But this technique must be modified because harmonics occur in a normal state of power system and the quantity of 2nd frequency component in inrush state has been decreased because of the improvement in core steel [1]-[6]. There are cases in which the presence of differential currents cannot make a clear distinction between fault and inrush. New relaying technique with high reliability is required for flexibility in spite of change of condition in power system.

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Recently, to advance the conventional approaches, several new AI(artificial-intelligence) features for protective relaying have been developed [7]-[10]. Luis et al. proposed algorithm based on artificial neural networks [7]. Wisziewski et al. suggested differential protective relay based on fuzzy logic [8]. Wavelet based algorithm is reported [10]. Most of these approaches are liable to maloperate in the case of magnetizing inrush with low second harmonic component and internal faults with high second harmonic component.

This paper describes fuzzy logic based relaying for power transformer protection and includes clear fault discrimination between magnetizing inrush and internal faults. To enhance the fault detection sensitivity of traditional percentage differential current relaying algorithm, fuzzy logic approaches are used. Input variables of the proposed fuzzy based relaying are flux-differential current derivative curve, second harmonic restraint, and percentage differential characteristic curve [11], [12]. To evaluate the performance of the proposed relaying, we used the transformer inrush currents, external fault currents, and internal fault signals, which were sampled with 720Hz per cycle and obtained from EMTP simulation software [13]-[15].

2. Digital Relaying for Power Transformer

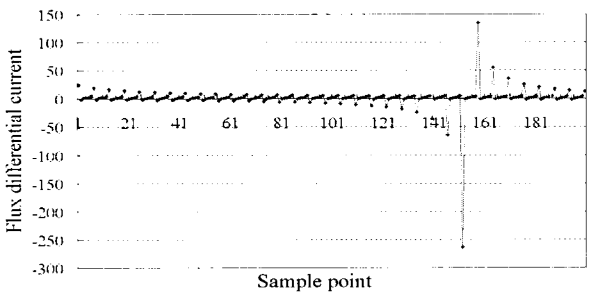
The digital protective relaying scheme based on the harmonic-restrained percentage differential relaying for power transformer is most commonly used [1], [2].

2.1 Flux Differential Current Slope

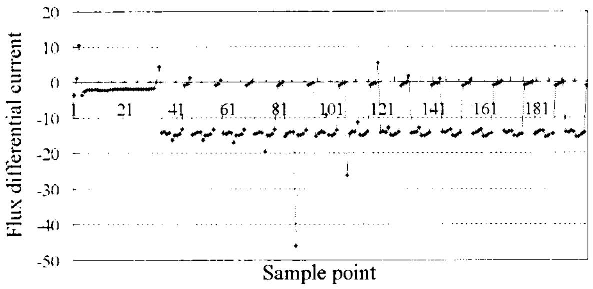
Flux-differential current slope method is not affected by remnant flux because it uses the slope of $\Phi - i_d$ curve, which can solve problems of prior flux-current method [11], [12]. Flux-differential current slope method is calculated by (1).

$$\left(\frac{d\Phi}{di_d}\right)_k \cong \frac{\Phi_k - \Phi_{k-1}}{i_{p.k} - i_{p.k-1}} = \frac{\left\{\frac{\Delta t}{2}(v_{p.k} - v_{p.k-1}) - L_p(i_{p.k} - i_{p.k-1})\right\}}{\{(i_{p.k} - i_{s.k}) - (i_{p.k-1} - i_{s.k-1})\}} \quad (1)$$

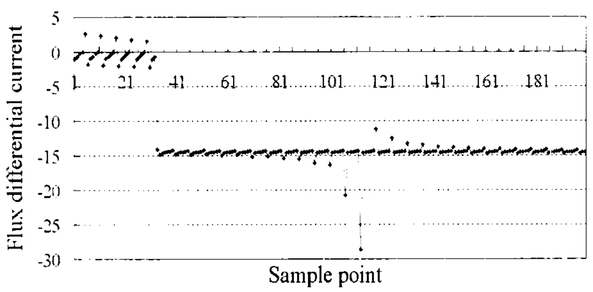
Where subscripts p and s represent primary side and secondary side of power transformer, Δt is sampling interval, i_d is differential current and L_p is the leakage inductance of the primary winding at kth sample.



(a) Under steady state



(b) While energized



(c) Under internal fault

Fig. 1 Transition characteristics of flux differential slope

To discriminate the various phenomena of transformer, Fig. 1 is plotted by characteristics of computed flux differential slope in one phase. X and Y axes indicate sample point and flux differential current value by (1), respectively. We can see that the computed values arrive close to zero in case of steady state, the values fluctuate between around 15 to 0 when energizing the transformer, while the values show around 15 under internal faults.

3. Design of Fuzzy Logic based Relaying

Fuzzy inference is a process that makes a decision in parallel. Because of this property, there is no data loss during the process and so final fault detection will be far more precise than that of conventional relaying techniques.

3.1 Fuzzfication

Fuzzy information approach is used. Fuzzification gives the following results; uncertainty of input relaying signal is quantified and all data contained in input relaying signals are acquired without loss. The rationality of quantified uncertainty and quality of acquired data depends on input and output fuzzy sets. Now, the proposed fuzzy based relaying uses three fuzzy inputs defined by (2)~(4). We obtain (2) through analysis in Fig. 1.

$$FI_1 = \frac{A}{B} \quad (2)$$

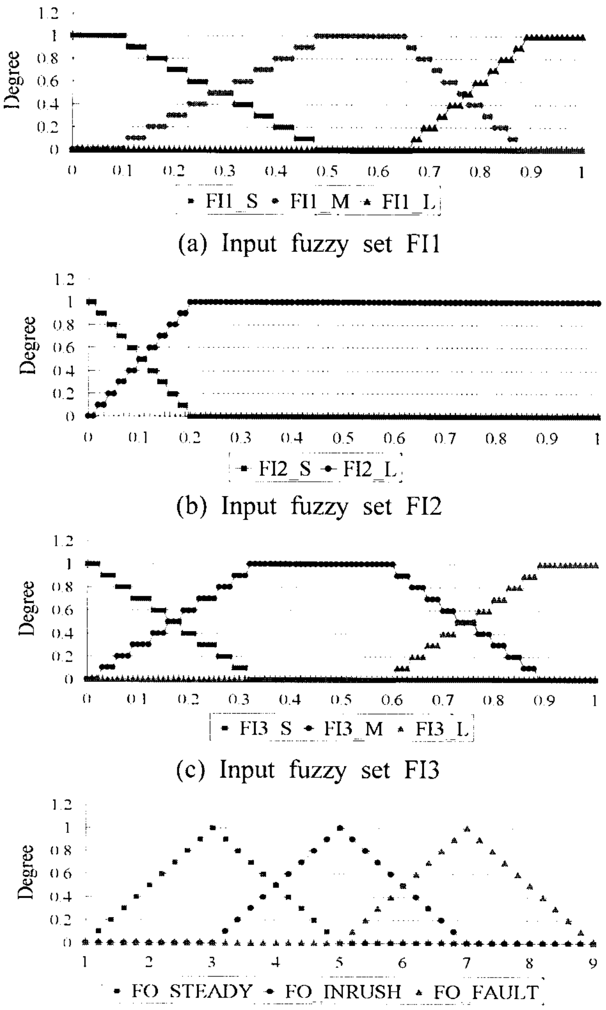
$$FI_2 = \frac{C}{D} \quad (3)$$

$$FI_3 = \frac{E}{B} \quad (4)$$

Where A is number of sample in which $\frac{d\Phi}{di_d}$ value is smaller than $-\frac{L_p}{2}$ within a cycle, B is number of sample within a cycle, C is magnitude of 2nd harmonic within a cycle, D is magnitude of 1st harmonic within a cycle, E is number of sample in which $\frac{i_{d.k}}{i_{r.k}}$ value is larger than 40% within a cycle, and $i_{r.k}$ is kth sample of restraining current.

Membership functions of each input and output fuzzy set are shown in Fig. 2. Membership function of Fig. 2(a) is defined after making analysis made on Fig. 1.

For fuzzification of defined three input variables from (2) to (4), a range is set between 0 to 1; membership values range from 0 to 1 at intervals of 0.01. FI1 is composed of three fuzzy ranges; FI1_S(small), FI1_M



(a) Input fuzzy set FI1

(b) Input fuzzy set FI2

(c) Input fuzzy set FI3

(d) Output fuzzy set FO

Fig. 2 Membership functions

(medium) and FI1_L(large). FI1_S, FI1_M, FI1_Lsupport steady state, energized and internal faults, respectively. FI2 consists of input fuzzy set FI2_S, FI2_L. FI2_S, FI2_L support steady state and internal faults, respectively. FI2 consists of input fuzzy set FI2_S, FI2_L. FI3 consists of input fuzzy set FI3_S, FI3_M, FI3_L. FI3_S, FI3_M, FI3_L support steady state, energized and internal faults, respectively. Fig. 2(d) shows that fuzzy output set is established in range from 1 to 9 at intervals of 0.2. There is just one output fuzzy set for fault trip. Range of output fuzzy set is established the defuzzified value to be around 3 under no faults and the defuzzified value to be around 6 under faults.

3.2 Inference Method

Number of fuzzy inference rules for proposed relaying is 19. All rules consist of two antecedent for input sets and a consequence for output. 19 fuzzy inference rules are classified to three categories depending on the mixture of input variables.

As an example rule in Table 1 :

R_1 : If FI_1 is FI_1S and FI_2 is FI_2S, then FO_FUZZYSET is DEFINITELY FO_STEADY

We used the method of compositional fuzzy inference. Max-Min method is chosen to perform a mathematical operation.

Table 1 A summary table for fuzzy rule

FUZZY RULE BASE

Rule type FI1 FI2

FI2 \ FI1	S	M	L
S	R1 std.	R2 inr.	R3 fau.
L	R4 std.	R5 inr.	R6 fau.

Rule type FI1 FI3

FI3 \ FI1	S	M	L
S	R7 std.	R8 inr.	
M	R9 inr.	R10 inr.	R11 inr.
L		R12 inr.	R13 fau.

Rule type FI2 FI3

FI3 \ FI2	S	L
S	R14 std.	R15 std.
M	R16 inr.	R17 inr.
L	R18 fau.	R19 fau.

std. : steady
inr. : inrush
fau. : fault

Definitly Quite

3.3 Defuzzfication

The output of proposed fuzzy based relaying is the FO_FUZZYSET. For defuzzification, we used center of area method in (5).

$$Defuzzification\ value = \frac{\sum_{i=0}^{n} d_i \mu_F(d_i)}{\sum_{i=0}^{n} \mu_F(d_i)} \quad (5)$$

Where d_i is the value of each point on a domain of final output fuzzy set and $\mu_F(d_i)$ is the membership value at each point. Fig. 3 shows block diagram of proposed relaying technique with fuzzy inference system. The specification of the proposed relaying technique is given in Table 2.

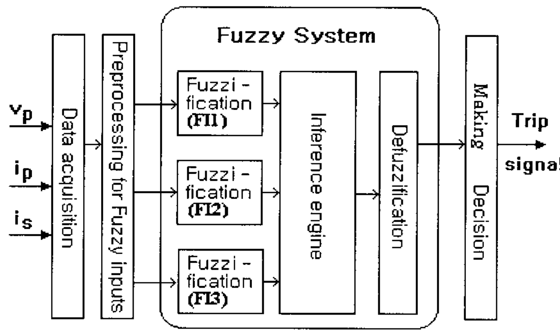


Fig. 3 Block diagram of the proposed relaying

Table 2 Specification of the proposed fuzzy based relaying

Measurements	Transformer primary voltage *vp.k* Transformer primary current *ip.k* Transformer secondary current *is.k*
Relaying output signal	Trip command
Trip operation	Defuzzified output value ≥ 6
Trip decision speed	Within a cycle

4. Testing the Relay

4.1 System Modeling

For an evaluation of the proposed fuzzy logic based relaying, we used the transformer inrush currents, external fault currents, and internal fault signals, which were sampled with 720Hz per cycle obtained from EMTP simulation. The 3Φ, 45/60MVA, 154/23KV transformer is simulated by the saturable transformer model and the BCTRAN routine. Fig. 4 shows the selected power system model in this study [13]-[15].

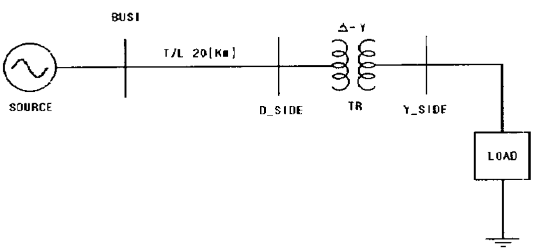


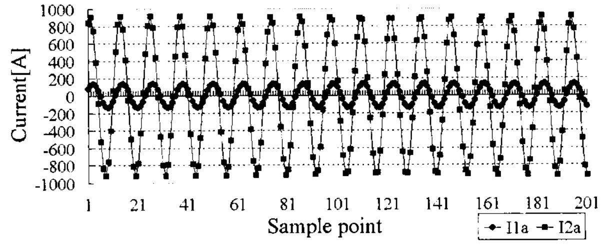
Fig. 4 One line diagram of power system model

4.2 Relay Performance

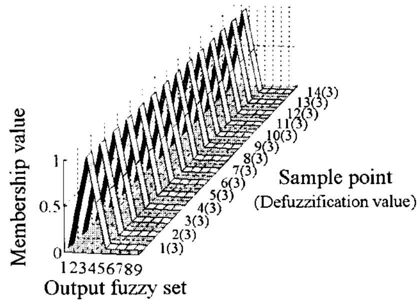
Fig. 5(a) shows the primary and secondary currents during steady state. Fig. 5(b)shows a course in the renewal in computed output fuzzy set. X, Y and Z axes indicate domain of output fuzzy set, sample point(defuzzification value) and degree of output fuzzy set(membership value), respectively. The computed defuzzified values in the paper are used to discriminate internal faults using comparison with predefined threshold value. In this case, we can see that the computed defuzzified value is constant. This satisfies no trip at trip condition.

Fig. 6(a) shows relaying signals when energizing at about 0.0444sec(at the 32th sample). Fig. 6(b) shows computed output fuzzy set by the proposed relaying. Trip command signal not issued because defuzzified values are below threshold value 6.

Fig. 7(a) shows relaying signals in the case of turn-to-turn fault at about 0.0486sec(at the 35th sample). The fault in winding is located within 5:80:15 part on the HV winding of phase B. For convenience, Fig. 7(b) is

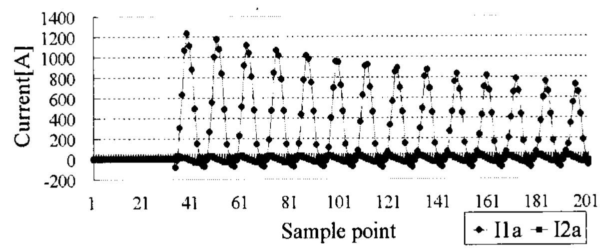


(a) A phase current signal

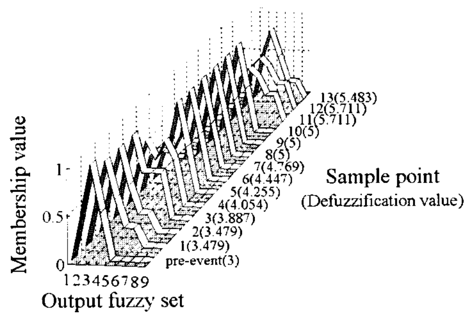


(b) Output fuzzy set

Fig. 5 Under steady state



(a) A phase current signal

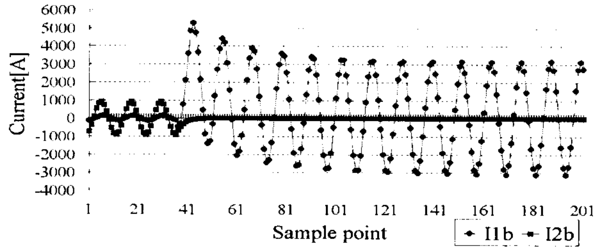


(b) Output fuzzy set

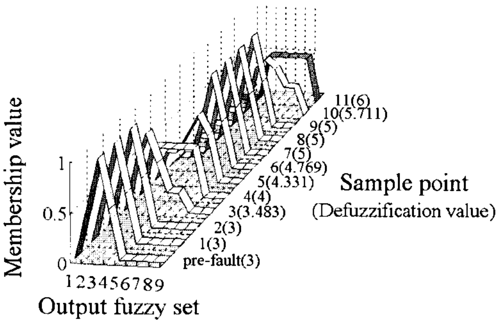
Fig. 6 While energized condition

plotted by computed value of output fuzzy set after fault inception. As shown in Fig. 7(b), the computed value represents steady state at first, the value comes more than 6 at around the 11th sample after fault inception. It means fault detection, and then the relay issues the trip signal.

Fig. 8(a) shows the current signals at turn to earth fault in about 0.05sec(at the 36th sample). The location of the fault is defined between 20% and 80% on the HV winding of phase B. Fig. 8(b) shows computed value of output fuzzy set after fault inception. As seen in Fig. 8(b), defuzzified value shows below 6 at first, and the value will be more than 6 at 10th sample after fault inception. Thus, the relay issues the trip signal.

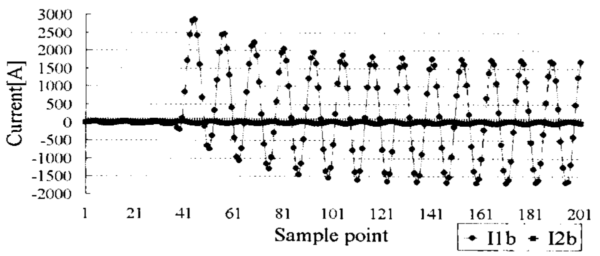


(a) B phase current signal

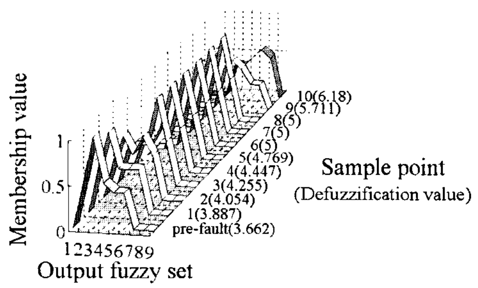


(b) Output fuzzy set

Fig. 7 Under turn-to-turn fault



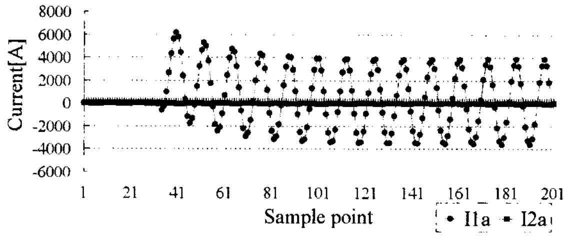
(a) B phase current signal



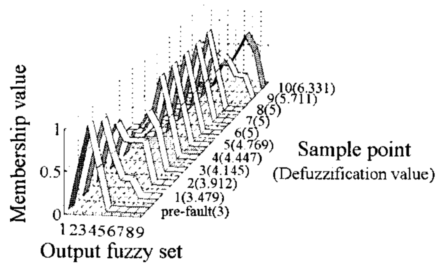
(b)Output fuzzy set

Fig. 8 Under turn to earth fault

Fig. 9(a) shows relaying signals at A phase terminal fault in about 0.0472sec(at the 34th sample). Fig. 9(b) indicates fault detection within the 10th sample because defuzzified value will be more than 6 at 10th sample after fault inception.



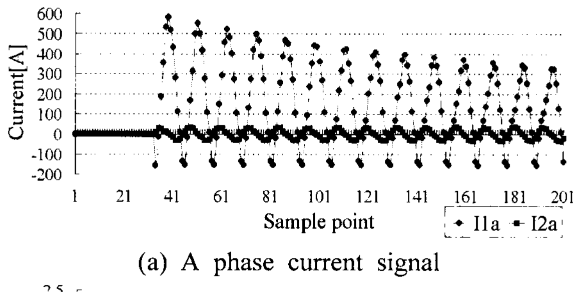
(a) A phase current signal



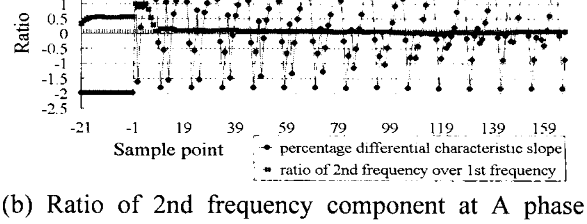
(b)Output fuzzy set

Fig. 9 Under terminal fault

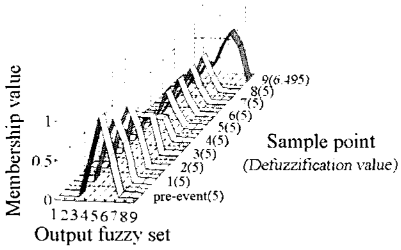
Figs. 10, 11 represent extraordinary points proposed in particular cases. Fig. 10(a) shows relaying signals while energized with low second harmonic component at about 0.0472sec. After magnetizing inrush, the ratio of second frequency component over fundamental frequency component is about 10 %. Fig. 10(b) represents the value of percentage differential characteristic slope $\frac{i_{d,k}}{i_{r,k}}$ and the ratio of second frequency component over fundamental frequency component. Fig. 10(c) illustrates the results of fault discrimination by conventional technique. Fig. 10(d) illustrates the results of fault discrimination by the proposed relaying. In this case, the conventional technique maloperates. As seen in Fig. 10(d), defuzzified values converge below 6. It means blocking the trip signal.



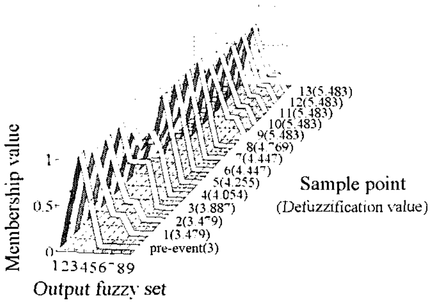
(a) A phase current signal



(b) Ratio of 2nd frequency component at A phase



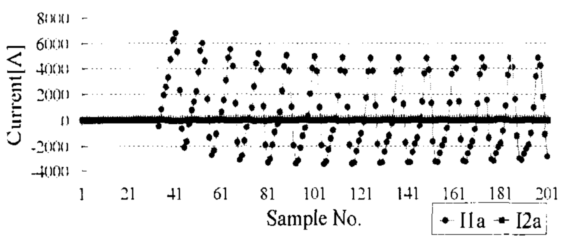
(c) Output fuzzy set by conventional technique



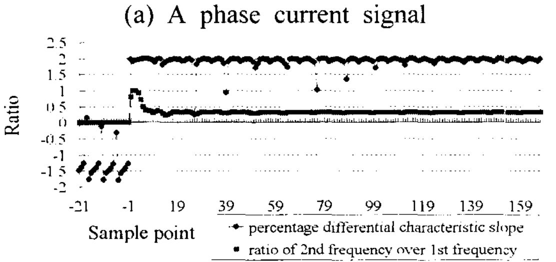
(d) Output fuzzy set by the proposed technique

Fig. 10 While energized condition with low 2nd frequency ratio

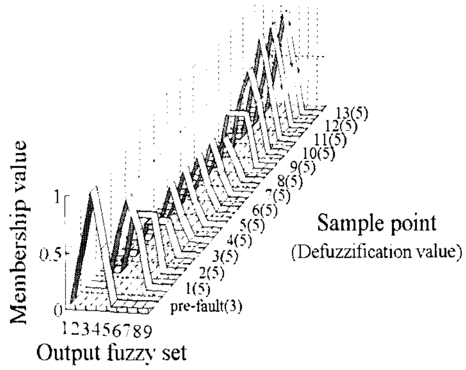
Fig. 11(a) shows relaying signals under A phase terminal fault with high second harmonic component at about 0.0472sec. Fig. 11(b) represents the value of percentage differential characteristic slope and the ratio of second frequency component over fundamental frequency component. Fig. 11(c) illustrates the results of fault discrimination by conventional technique. Fig. 11(d) illustrates the results of fault discrimination by the proposed relaying. As seen in Fig. 11(d), computed value of output fuzzy set indicates fault detection within the 10th sample after fault inception because defuzzified value is more than 6. These results of Figs. 10(c), (d) and 11(c), (d) show the difference between the technique suggested in this paper and the conventional technique.



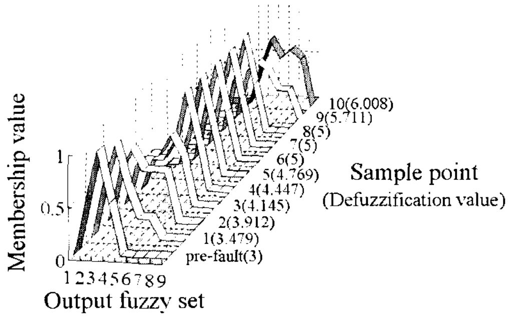
(a) A phase current signal



(b) Ratio of 2nd frequency component at A phase



(c) Output fuzzy set by conventional technique



(d) Output fuzzy set by the proposed technique

Fig. 11 Under terminal fault with high 2nd frequency ratio

5. Conclusions

In this paper, a digital protective relaying algorithm for power transformer using a fuzzy logic was developed. The proposed fuzzy logic based relaying made use of flux-differential current derivative curve, harmonic restraints, and percentage differential characteristic curve for the purpose of overcoming limits of conventional relaying.

For evaluation, we used the relaying signals obtained from EMTP simulation. The test results are given as the following.

The proposed fuzzy based relaying algorithm prevents trip maloperation of relay in the case of magnetizing inrush with low second harmonic component and internal faults with high second harmonic component and then show improved accuracy and robustness against the change in conditions in power system. Simulation results show that the proposed relaying reveals high sensitivity to the fault detection and operates with average tripping time about 3/4 cycle. Therefore test result for fault discrimination is reliable and speedy. Because the change of fuzzy inputs and inference rules is flexible, the proposed relaying can be applied to various transformers and conditions.

A future research would be to develop IED(Intelligent Electronic Device) with the proposed fuzzy algorithm.

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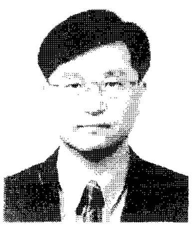

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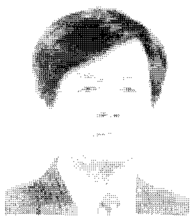

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