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Fuzzy Logic Based Relaying Using Flux-differential Current Derivative Curve for Power Transformer Protection

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ABSTRACT

Power transformer protective relay should block the tripping during magnetizing inrush and rapidly operate the tripping during internal faults. But traditional approaches maloperate in the case of magnetizing inrush with low second harmonic component and internal faults with high second harmonic component. To enhance the fault detection sensitivities of conventional techniques, flux-differential current derivative curve by fuzzy theory approaches is used. This paper deals with fuzzy logic based protective relaying for power transformer. The proposed fuzzy based relaying algorithm consists of flux-differential current derivative curve, harmonics restraint, and percentage differential characteristic curve. The proposed relaying was tested with relaying signals obtained from Salford EMTP simulation package and showed a fast and accurate trip operation.

1. Introduction

The function of power system protective relaying is to cause the prompt removal of abnomal 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 important elements in power system. Electrical protective relaying of large power transformer is based on a percentage differential relaying technique in which transient magnetizing inrush and internal fault must be distinguished. So, differential relay should not operate false.

From 1980's on, research efforts on digital relaying based on microprocessor have been investigated for the protection of medium and large power transformer [2, 3].

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 [1~6]. But this technique must be modified because harmonics occur in a normal state of power system and 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. 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. Wisziewski *et al.* suggested differential protective relay based on fuzzy logic. But these approaches have a possibility of maloperation 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 a clear fault discrimination between magnetizing inrush and internal faults. To enhance the fault detection sensitivity of traditional percentage differential current relaying algorithm, fuzzy theory approaches are used. Input variables of the proposed fuzzy based relaying are flux-differential current derivative curve [11~13], second harmonic restraint, and percentage differential characteristic curve. To evaluate the performance of the proposed fuzzy logic based relaying, we used the transformer inrush currents, external fault currents, and internal fault signals, which are sampled with 720 Hz per cycle and obtained from EMTP (Electro-magnetic Transient

Program) [14~16] simulation.

2. Digital Differential Protection of Transformers

Generally, differential protection is applied to transformer banks of 10 MVA and above. Conventional power transformer protection uses only current measurements. In applying differential protection, several factors must be considered. Algorithms for digital relay have been presented in reference [3]. The algorithms include finite duration impulse(FIR) filters, least-squares curve fitting, the digital Fourier transform algorithm, and flux-restrained current differential algorithm, etc.

2.1 Biased Differential Relaying Principle

The most commonly encountered transformer protection arrangement is based on the differential current principle. In normal state, differential current is zero. If an internal fault occurs within the transformer, the balance between the primary and secondary current is disturbed and a differential current signal then causes the relay to operate.

If the transformer is equipped with a tap changer, the imbalance between the primary and secondary currents introduced by the variation of the turns ratio can be great enough to cause malfunction under external fault conditions. Imbalance under healthy conditions can also be caused by mismatch between the current transformers or by saturation.

It is therefore important that this situation should be considered in the engineering of transformer differential protection systems. A common way of overcoming such problems is to bias the operation of the relay by deriving a biasing signal equal to the sum of the currents measured on each side of the transformer [2]. This is illustrated in Fig. 1.

2.2 Harmonic-restrained Differential Relay

The differential protective technique described above is generally satisfactory under normal operating conditions, but is prone to operate false during energization of the transformer. Under this condition, an inrush current flows only through one winding, which consequently appears to be an internal fault on the relay. The problem can be overcome by using the fact that inrush current usually contains predominant second harmonics. The digital protective relaying technique based on the 2nd harmonic-restrained percentage differential relaying is employed the most commonly [1, 2].

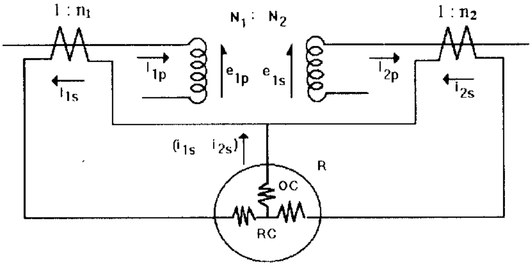


Fig. 1. Basic principle of transformer differential protection.

2.3 Flux-restrained Current Differential Relay

This algorithm basically uses the flux-current relation of the transformer to obtain the restraint function. If the flux could be estimated correctly, it would provide a sound basis for detecting over excitation as well as magnetizing inrush conditions.

Consider a single phase with two-winding transformer such as that shown in Fig. 2 [11, 12].

It will be assumed that winding resistance is negligible. The relation between the primary applied voltage v_p, the primary current i_p, and mutual flux linkages Φ of the transformer is given by

$$L_p \frac{di_p(t)}{dt} + \frac{d\psi(t)}{dt} = v_p(t) \qquad (1)$$

where L_p is the leakage inductance of the primary winding. By rearranging Eq. (1) and integrating from t_1 to t_2, we obtain the flux linkages at these times such that

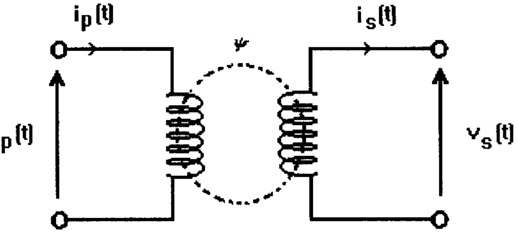


Fig. 2. Two-winding single phase transformer.

$$\psi(t_2) - \psi(t_1) = \int_{t_1}^{t_2} v_p(t)\,dt - L_p[i_p(t_2) - i_p(t_1)] \qquad (2)$$

Applying the trapezoidal rule to the integral part of Eq. (2) results in

$$\psi(t_2) \fallingdotseq \psi(t_1) + \frac{1}{2}(t_2 - t_1) + [v_p(t_2) - v_p(t_1)] - L_p[i_p(t_2) - i_p(t_2)] \qquad (3)$$

If the voltage and current waveforms are sampled at an intervals equal to Δt, then at the kth sample, Eq. (3) can be expressed, using sample notation, as

$$\psi_k = \psi_{k-1} + \frac{\Delta t}{2}(v_{p.k} - v_{p.k-1}) - L_p(i_{p.k} - i_{p.k-1}) \qquad (4)$$

where $v_{p.k}$, $i_{p.k}$ are the kth samples of primary voltage and current. At time t_k, the differential current $i_{d.k}$ is given as

$$i_{d.k} = i_{p.k} - i_{s.k} \qquad (5)$$

Where subscript p and s represent primary side and secondary side of power transformer. From transformer theory, the differential current $i_{d.k}$ is equal to the magnetizing current of the transformer. Thus the samples of the differential current and flux linkage ($i_{d.k}$, ψ_k) are expected to fall on the open-circuit magnetizing curve of the transformer. Fig. 3 shows the magnetizing curve of transformer in this study.

Eq. (5) can be satisfactory when the residual flux in the core of the transformer is close to zero. Practically this is not always the case. To overcome this problem, we use the flux-differential current derivative curve which is not affected by remanent flux because it uses the slope of $\psi - i_d$ curve which can solve problems of the prior flux-current method [11, 12]. Flux-differential current derivative curve is calculated by Eq. (6).

$$\left(\frac{d\psi}{di_0}\right)_k \simeq \frac{\psi_k - \psi_{k-1}}{i_{p.k} - i_{p.k-1}} = \frac{\left\{\frac{\Delta t}{2}(v_{p.k} - v_{p.k-1}) - L_p(i_{p.k} - i_{p.k-1})\right\}}{\{(i_{p.k} - i_{s.k}) - (i_{p.k-1} - i_{s.k-1})\}} \qquad (6)$$

Where Δt is sampling interval, and L_p is the leakage inductance of the primary winding at kth sample. Fig. 4 shows the transition of $d\psi_k/di_{d.k}$ in the various cases of this study.

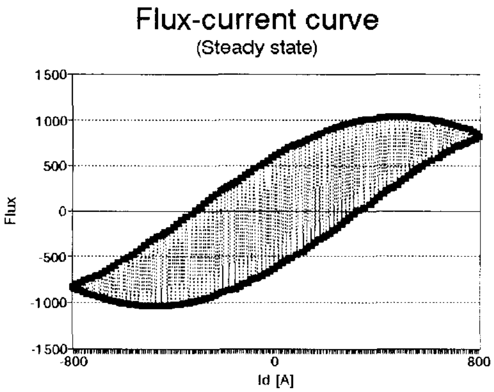


Fig. 3. Transformer magnetizing curve.

3. Design of Fuzzy Logic Based Protective Relay

Fuzzy inference is a process which 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 Fuzzification

Fuzzy information approach is used. Fuzzification gives the following results; uncertainty of input relaying signals is quantified and all data contained in input relaying signals are acquisited without loss. The rationality of quantified uncertainty and quality of acquisited data depends on input and output fuzzy sets. The proposed fuzzy based relaying uses three fuzzy inputs defined by Eq. (7)~(9).

$$I_1 = \frac{\text{No. of sample which } d\psi/di_d \text{ value is smaller than } -L_p/2 \text{ within a cycle}}{\text{No. of sample within a cycle}} \qquad (7)$$

$$I_2 = \frac{\text{Magnitude of 2nd harmonic within a cycle}}{\text{Magnitude of 1st harmonic within a cycle}} \qquad (8)$$

$$I_3 = \frac{\text{No. of sample which } i_{d.k}/i_{r.k} \text{ value is larger than 40\% within a cycle}}{\text{No. of sample within a cycle}} \qquad (9)$$

Where $i_{r.k}$ is kth sample of restraining current. Fig. 5 shows defined membership functions of input and

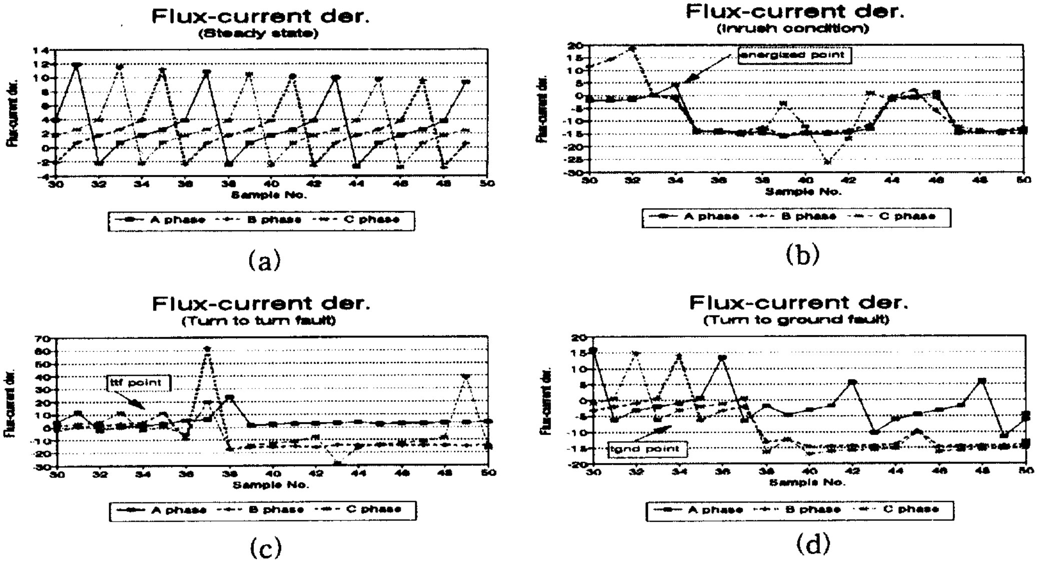


Fig. 4. Transition characteristics of $d\psi_k/di_{dk}$. (a) under steady state, (b) under energized, (c) under turn-to-turn fault, (d) under turn-to-ground fault.

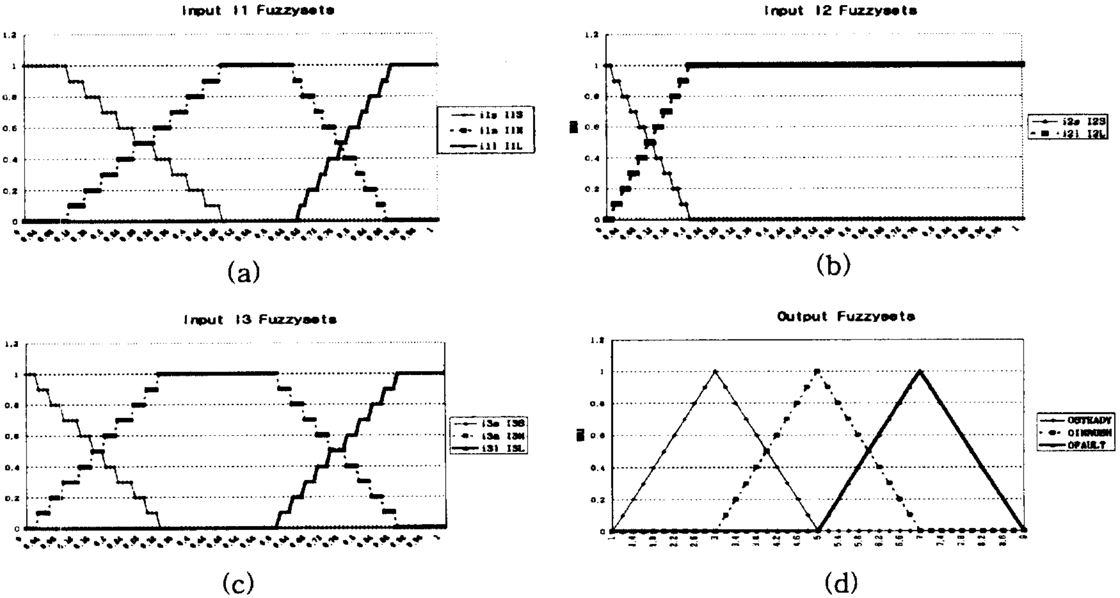


Fig. 5. Membership functions for (a) input I_1, (b) input I_2, (c) input I_3, (d) ouput O.

output fuzzy sets in the proposed fuzzy based relaying.

3.2 Inference Method

Number of fuzzy inference rules for proposed fuzzy based relaying is 19 and all rules consist of two conditional fuzzy propositions for input sets and a conclusional fuzzy proposition for output. 19 fuzzy inference rules which are defined above are classified to three categories depending on the mixture of input variables.

As an example rule in Table 1:

R_1: If I_1 is I_{1S} and I_2 is I_{2S}, then FOUTFZYSET is DEFINITELY OSTEADY

Table 1. A summary table for fuzzy rule

FUZZY RULE BASE

Rule type 12

I2 \ I1	S	M	L
S	▨ R1 std.	R2 inr.	▨ R3 fau.
L	R4 std.	▨ R5 inr.	R6 fau.

Rule type 13

I3 \ I1	S	M	L
S	▨ R7 std.	R8 inr.	
M	R9 inr.	▨ R10 inr.	R11 inr.
L		R12 inr.	▨ R13 fau.

Rule type 23

I3 \ I2	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

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

3.3 Defuzzificaion

The output of proposed fuzzy based relaying is the FOUTFZYSET. For defuzzification, we used center of area method in Eq. (10).

$$\text{Defuzzification value} = \frac{\sum_{i=0}^{n} d_i \mu_F(d_i)}{\sum_{i=0}^{n} \mu_F(d_i)} \qquad (10)$$

Where d_i is the value of each point on a domain of final ouput fuzzy set and $\mu_F(d_i)$ is the membership value at the each point. Fig. 6 shows block diagram of proposed entire relaying technique with fuzzy inference system.

In this paper specification of entire relaying with fuzzy logic is given in Table 2.

4. Testing the Relay

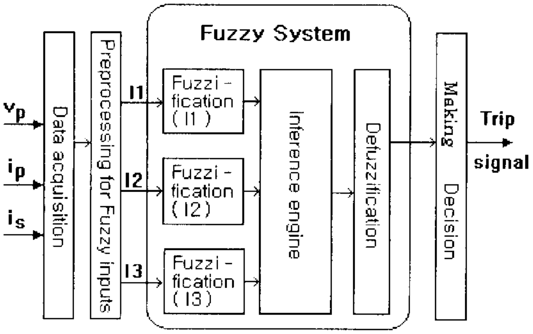


Fig. 6. Block diagram of the proposed fuzzy based relaying.

Table 2. Specification of entire the proposed fuzzy based relaying

Measurements	Transformer primary voltage $v_{p,k}$ Transformer primary current $i_{p,k}$ Transformer secondary current $i_{s,k}$
Relaying output signal	Trip command (relay trip signal)
Trip condition	Defuzzified output value ≥ 6
Trip decision speed	Within a cycle

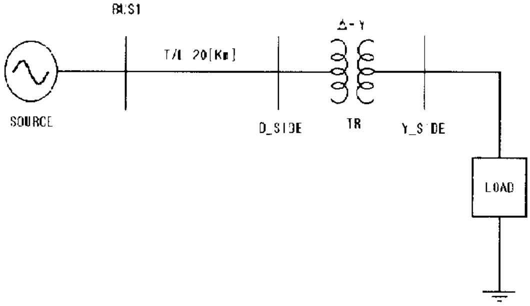


Fig. 7. One line diagram of power system model.

4.1 System Modelling

For an evaluation of the proposed fuzzy logic based relaying, we used the transformer inrush currents, external fault currents, and internal fault signals, which are sampled with 720 Hz per cycle obtained from EMTP simulation. The 3Φ, 45/60 MVA, 154/23 KV transformer is simulated by the saturable transformer model and the bctran routine. Fig. 7 shows the selected power system model in this study [14-16]. Data sheet of transformer is given in Table 3.

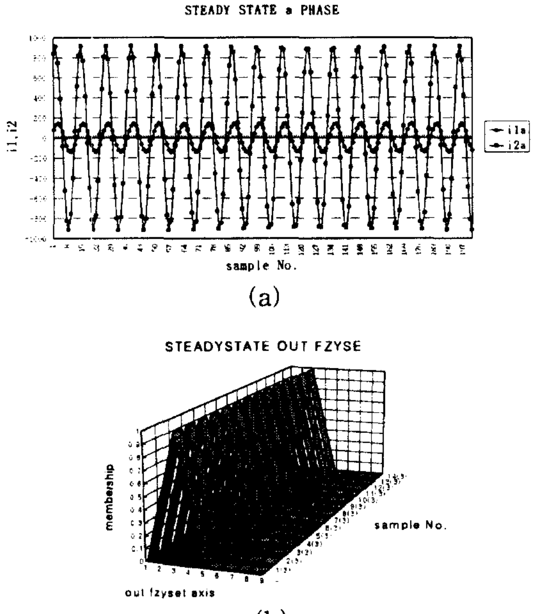
4.2 Overall Relay Performance

Relaying signals are shown in Fig. 8(a). Results of fault discrimination at steady state are shown in Fig. 8(b). Transition of defuzzfied value I_1, I_2, I_3 during steady state is given in Table 4. SN means sample number and DFV means defuzzified value. We can see that the transition of fuzzy output sets is constant. This satisfies no trip at trip condition.

Fig. 9(a) shows relaying signals when energizing at about 0.0442 sec(at the 33th sample). Fig. 9(b) illustrates the results of fault discrimination. Transition of defuzzfied value I_1, I_2, I_3 during inrush state is given in Table 5. We can see that the transition of fuzzy output sets converges for magnetizing inrush support after fluctuations. It

Table 3. Data of power transformer

No load loss [KW]	Load loss [KW]	Efficiency [%]	% Exciting current [%]
44.8	226.8	99.4	0.7
% Z [%]	Winding resistance [Ω]	Leakage inductance of primary side [H]	
15±1.125	2.6/0.0047	14.55	



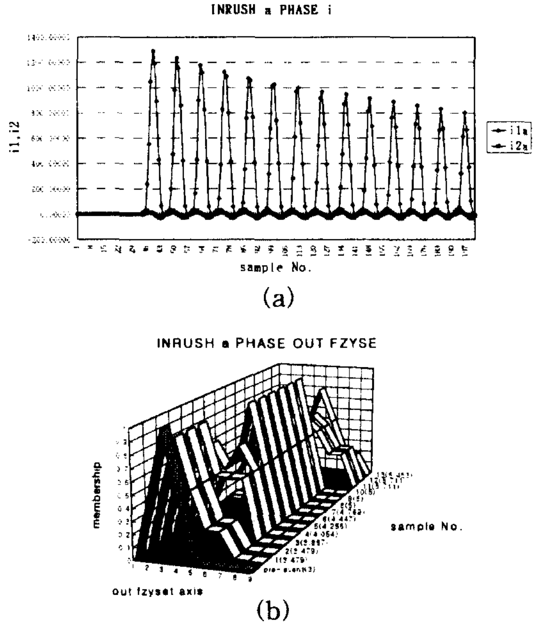
(a)

(b)

Fig. 8. Under steady state. (a) current signal at a phase and (b) transition of final fuzzy output set.

Table 4. Defuzzfied value during steady state

SN	1	2	3	4	5	6	7	8	9	10	11
I_1	0	0	0	0	0	0	0	0	0	0	0
I_2	0	0	0	0	0	0	0	0	0	0	0
I_3	0	0	0	0	0.8	0.8	0.8	0.8	0.8	0.8	0.16
DFV	3	3	3	3	3	3	3	3	3	3	3



(a)

(b)

Fig. 9. Under energized condition. (a) current signal at a phase and (b) transition of final fuzzy output set.

means blocking the trip.

Fig. 10(a) shows relaying signals in the case of turn-to-turn fault at about 0.0484 sec(at the 36th sample). The fault in winding is located in 5 : 80 : 15 part in *a-b* phase. Transition of defuzzfied value during I_1, I_2, I_3 turn-to-turn fault state is given in Table 6. Fig. 10(b) indicates fault detection within the 11th sample after fault inception because of computed threshold over 6.

Fig. 11(a) shows the current signals at turn-to-earth fault in about 0.0497 sec(at the 37th sample). The fault in winding is located in 20 : 80 part in *a-b* phase. Transition of defuzzfied value I_1, I_2, I_3 during turn-to-earth fault state is given in Table 7. Fig. 11(b) indicates fault detection within the 10th sample after fault inception because of computed threshold over 6.

Fig. 12(a) shows relaying signals at a phase terminal fault in about 0.0442 sec(at the 33th sample). Transition of defuzzfied value I_1, I_2, I_3 during terminal fault state is given in Table 8. Fig. 12(b)

Table 5. Defuzzfied value of a phase during inrush

SN	Pre-event	1	2	3	4	5	6	7	8	9	10	11
I_1	0	0	0	0.08	0.16	0.25	0.33	0.41	0.5	0.66	0.75	0.75
I_2	0.56	0.99	0.9	1	0.97	0.83	0.7	0.54	0.38	0.27	0.25	0.25
I_3	0.08	0.16	0.25	0.33	0.41	0.5	0.58	0.66	0.75	0.75	0.75	0.75
DFV	3	3.48	3.48	3.88	4.05	4.25	4.44	4.77	5	5	5	5.71

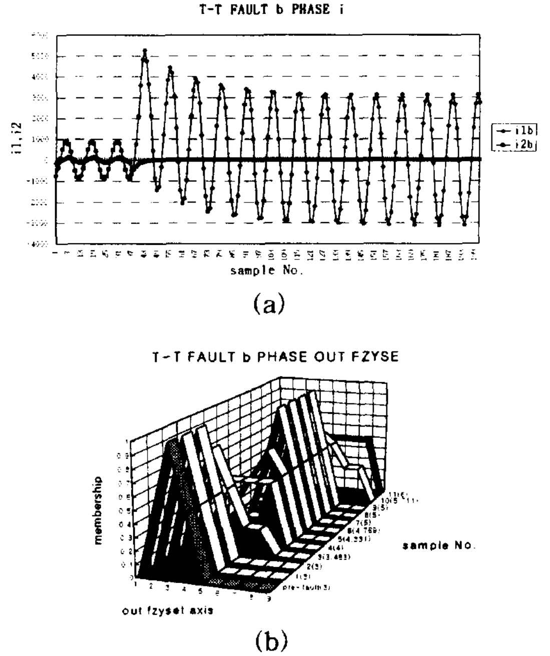


Fig. 10. Under turn-to-turn fault. (a) current signal at a phase and (b) transition of final fuzzy output set.

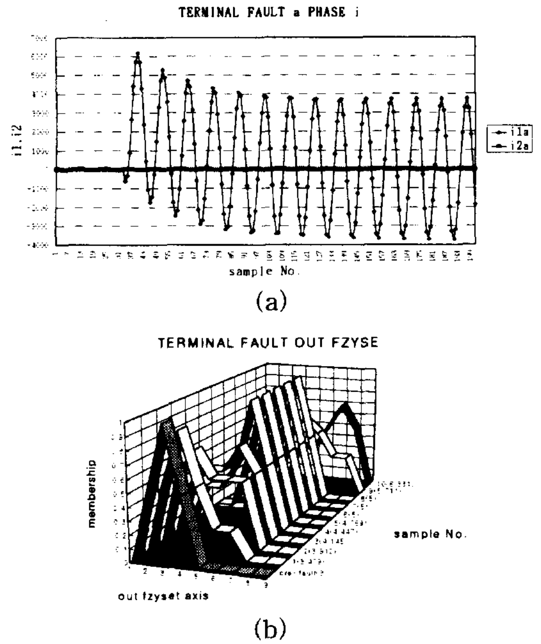


Fig. 11. Under turn-to-earth fault. (a) current signal at b phase and (b) transition of final fuzzy output set.

indicates fault detection within the 10th sample after fault inception because of computed threshold over 6.

Fig. 13(a) shows relaying signals under energized with low second harmonic component in about 0.0442 sec(at the 33th sample). Fig. 13(b) illustrates the transition of $K_k=i_{d,k}/i_{r,k}$ and the ratio of second frequency component over fundamental freqency component under magnetizing inrush. Fig. 13(c) illustrates the results of fault discrimination by conventional technique. Fig. 13(d) illustrates the results of fault discrimination by the proposed technique. Transition of defuzzfied value I_1, I_2, I_3 during inrush state is given in Table 9.

After magnetizing inrush, the ratio of second frequency component over fundamental freqency component is about 10%. In this case, conventional technique maloperates. But from Fig. 13(d), we can see that the transition of fuzzy output sets converges below 6. It means blocking the trip.

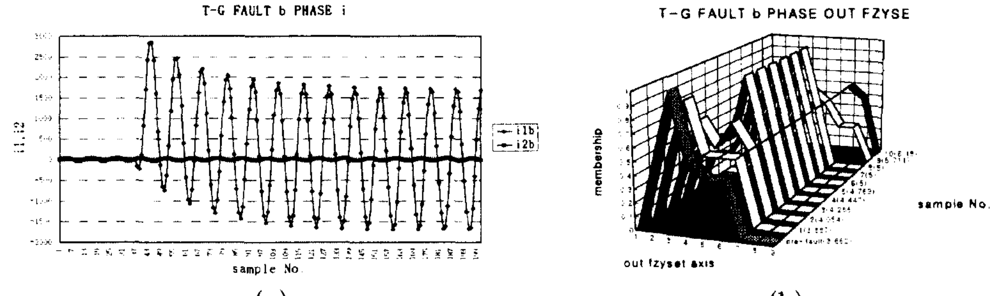
Fig. 14(a) shows relaying signals under a phase terminal fault with high second harmonic component in about 0.0442 sec(at the 33th sample). Fig. 14(b)

Table 6. Defuzzfied value of b phase during turn-to-turn fault

SN	Pre-event	1	2	3	4	5	6	7	8	9	10	11
I_1	0	0.08	0.08	0.16	0.25	0.33	0.41	0.5	0.58	0.66	0.75	0.83
I_2	0	0.09	0.12	0.32	1	1	1	0.69	0.43	0.22	0.11	0.12
I_3	0	0	0	0.08	0.16	0.25	0.33	0.41	0.5	0.58	0.66	0.75
DFV	3	3	3	3.48	4	4.33	4.77	5	5	5	5.7	6

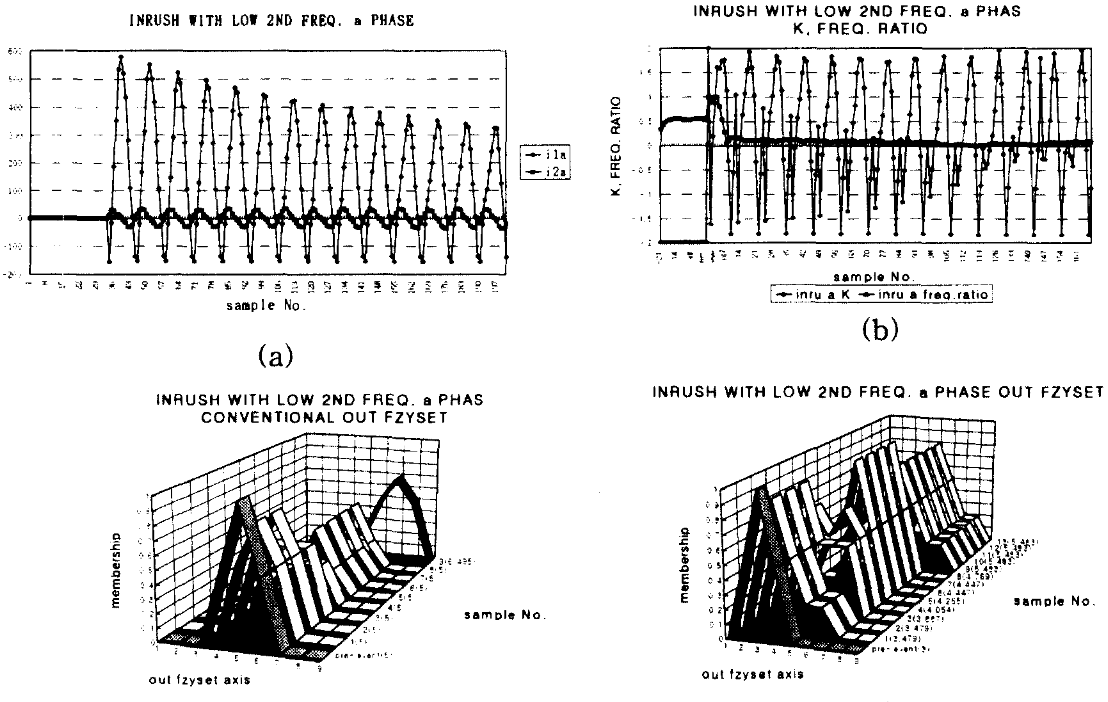
Table 7. Defuzzfied value of b phase during turn-to-earth fault state

SN	Pre-event	1	2	3	4	5	6	7	8	9	10
I_1	0	0.08	0.16	0.25	0.33	0.41	0.5	0.58	0.66	0.75	0.83
I_2	0	0.82	0.78	1	1	0.92	0.71	0.51	0.33	0.17	0.06
I_3	0	0.08	0.16	0.25	0.33	0.41	0.5	0.58	0.66	0.75	0.83
DFV	3	3.48	3.91	4.15	4.45	4.77	5	5	5	5.71	6.33



(a) (b)

Fig. 12. Under terminal fault. (a) current signal at a phase and (b) transition of final fuzzy output set.



(a) (b) (c) (d)

Fig. 13. Under the energized condition with low 2nd frequency ratio. (a) a phase current, (b) transition of frequency ratio, (c) transition of defuzzified value by conventional technique and (d) transition of defuzzified value by the proposed technique.

Table 8. Defuzzfied value of b phase during terminal fault state

SN	Pre-event	1	2	3	4	5	6	7	8	9	10
I_1	0	0.08	0.16	0.25	0.33	0.41	0.5	0.58	0.66	0.75	0.83
I_2	0	0.45	0.57	0.73	1	1	0.78	0.59	0.41	0.24	0.11
I_3	0.16	0.16	0.25	0.33	0.41	0.5	0.58	0.58	0.66	0.75	0.83
DFV	3.66	3.89	4.05	4.26	4.45	4.77	5	5	5	5.71	6.18

illustrates the transition of $K_k = i_{d,k}/i_{r,k}$ and the ratio of second frequency component over fundamental freqency component under a phase terminal fault with high second freqency harmonic component. Fig.

Table 9. Defuzzfied value of b phase during magnetizing inrush with low 2nd frequency ratio

SN	Pre-event	1	2	3	4	5	6	7	8	9	10	11
I_1	0	0.08	0.16	0.25	0.33	0.41	0.5	0.58	0.66	0.75	0.83	0.82
I_2	0	0.79	1	1	0.94	0.72	0.5	0.39	0.38	0.36	0.31	0.33
I_3	0	0.08	0.16	0.25	0.33	0.41	0.5	0.58	0.66	0.75	0.83	0.83
DFV	3	3.48	3.91	4.15	4.45	4.77	5	5	5	5.71	6.01	6.01

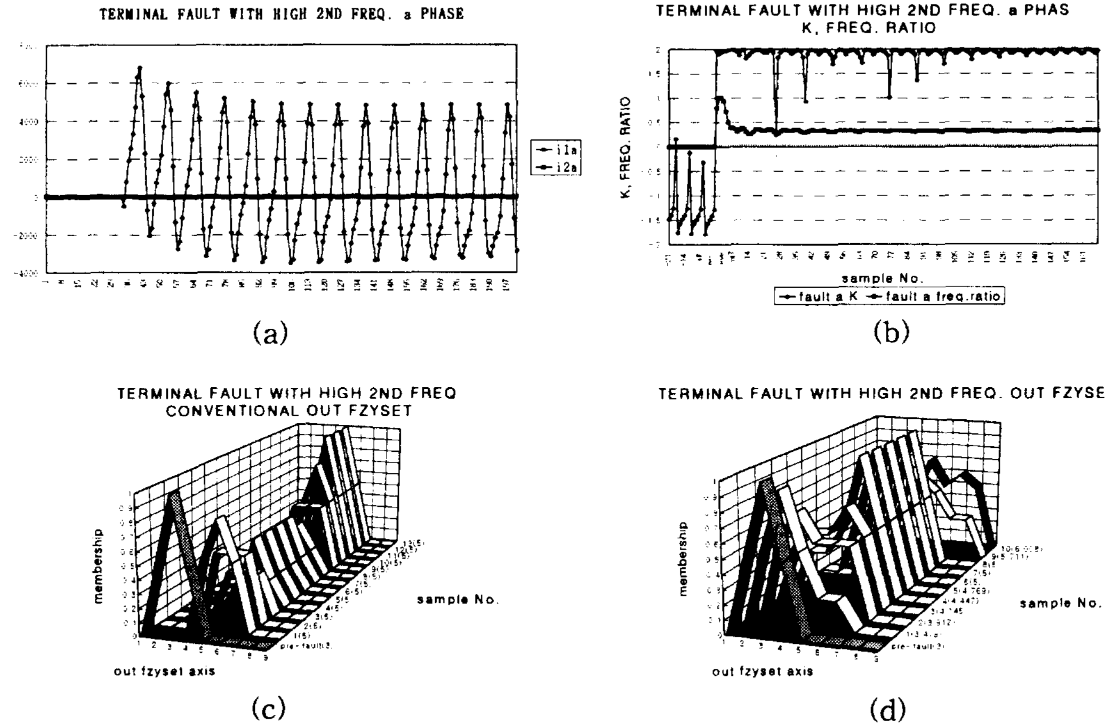


Fig. 14. Under terminal fault with high 2nd frequency ratio. (a) a phase current, (b) transition of frequency ratio, (c) transition of defuzzified value by conventional technique and (d) transition of defuzzified value by the proposed tecnhique.

Table 10. Defuzzfied value of b phase during terminal fault with high 2nd frequency ratio

SN	Pre-event	1	2	3	4	5	6	7	8	9	10	11
I_1	0	0	0	0.08	0.16	0.25	0.33	0.3	0.41	0.5	0.58	0.66
I_2	0.56	0.99	0.89	1	1	1	0.81	0.5	0.29	0.07	0.1	0.17
I_3	0	0.08	0.08	0.16	0.25	0.33	0.41	0.5	0.58	0.66	0.66	0.66
DFV	3	3.48	3.48	3.89	4.05	4.26	4.45	4.45	4.77	5.48	5.48	5.48

14(c) illustrates the results of fault discrimination by conventional technique. Fig. 14(d) illustrates the results of fault discrimination by the proposed technique. Transition of defuzzfied value I_1, I_2, I_3 during inrush state is given in Table 10.

We can see that Fig. 14(d) indicates fault detection within the 10th sample after fault inception because of computed threshold over 6. This results of Fig. 13(c), (d) and Fig. 14(c), (d) show the difference between the technique suggested in this paper and the conventional technique.

5. Conclusions

In this paper, a digital protective relaying algorithm for power transformer using a fuzzy inference 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 overcomming limits of the conventional relaying.

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

(1) The proposed techniques prevent relaying maloperation 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 changed conditions in power system.

(2) Simulaton 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 discriminant is reliable and speedy.

(3) Because the change of fuzzy inputs and inference rules is flexible, the proposed fuzzy based relaying is able to be applied to various transformers and conditons.

Finally, the proposed relaying can be applied to power system protection using an AI technique.

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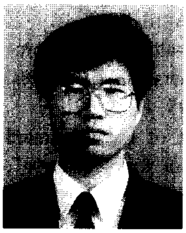

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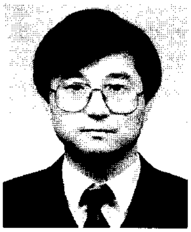

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