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Protective Relaying Algorithm for 3-Phase Power Transformer Protection based on Fuzzy Decision Making

Sang-Tae Kim, Seung-Jae Lee, Sang-Hee Kang, Myeon-Song Choi, Sang-Hyun Yoon and Tae-Sung Lee

Abstract - The four fuzzy criteria to distinguish the internal fault from the inrush for the power transformer protection have been identified. They are based on the wave shape, terminal voltage, fundamental and second harmonic component of differential current. A systematic way to determine the associated fuzzy membership function is also proposed.

Keywords - protective relay, power transformer protection, differential relay, fuzzy technique

1. Introduction

Large power transformers belong to a class of very expensive and vital components of electric power systems. If a power transformer experiences a fault, it is necessary to isolate the transformer as soon as possible so that the damage is minimized. The differential protection has been used widely for the transformer protection. However, the algorithm has a limitation in making a distinction between an internal fault and other transient phenomena such as inrush, over-excitation. Conventional approach to cope with it is to adopt the percentage differential characteristics combined with the 2nd and 5th harmonic restraints. However introduction of new core material and new design has changed transient phenomena like smaller 2nd harmonic component in the differential current during energization. Further, as the system voltage becomes higher and more underground cables are used, larger 2nd harmonic component in the differential current is observed in case of the fault. The conventional approach seems now to be losing its reliability for the modern transformers, motivating a new approach utilizing fuzzy-logic, neural network [1,2].

This paper presents fuzzy rules for distinguishing an internal fault from an inrush and its associated fuzzy membership function. The systematic method to determine the membership degree is also proposed.

2. Transient Simulation of Transformer

Fig. 1 shows the test system where 154/22.9 kV Y-Y 3-phase transformer supplies a load through a line. About 400 test cases have been simulated for the model varying the saturation characteristic of the transformer and line capacitance [3,4].

Through simulation, rms values of primary terminal voltage, primary and secondary currents and harmonic components of differential current have been obtained. A sampling rate of 16 samples per cycle is used.

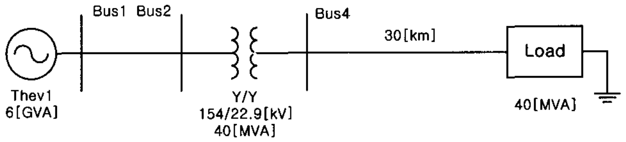

Fig. 1 Simulation Model

3. Fuzzy Rulebase

Generally in distinguishing the internal fault and inrush from the decision signal such as the differential current, there exist a fuzzy region in which no clear distinction can be made. Fuzzy decision rules to handle the signal in this fuzzy region have been derived. Derived rules are based on analysis of one cycle disturbance signal since after one cycle, the second harmonic component of the differential current provides a clear distinction .

3.1 Slope change of primary voltage

When the transformer is in the normal state, the voltage will maintain the constant value, while switching on the transformer, that causes the inrush, will introduce the voltage jump. When the internal fault occurs, the voltage of the faulted phase would decrease. Therefore, the slope change of the voltage could identify the type of the disturbance. Fig. 2 shows the voltage slope for various faults and inrush cases and Fig. 3 depicts the boundaries specified by the minimum slope of the faults and maximum slope of the inrush cases. As expected, it can be seen that the internal fault has a negative slope and the inrush has a positive slope. With the slope represented by Eq.(1), the fuzzy rules can be made as follows:

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$$F_1 = \frac{v[n]-v[n-1]}{\Delta T} \tag{1}$$

Rule1) $F_1 > i_m[n] \rightarrow$ {1/Inrush}

Rule2) $F_1 < f_M[n] \rightarrow$ {1/Internal fault}

Rule3) $f_M[n] < F_1 < i_m[n] \rightarrow$
{x/Inrush}, {1-x/Internal fault}

where,
v[n] : n-th voltage sample
ΔT : sampling interval
$i_m[n]$: minimum boundary function for inrush
$f_M[n]$: maximum boundary function for internal fault

Note that basic probability assignment (bpa) that represents the supporting degree [8] and its associated hypothesis are shown in parenthesis following the arrow, separated by a slash. So Rule 1 says if the voltage slope is bigger than the minimum slope of the inrush case, then it supports the inrush with a degree of 1. How to determine bpa x is described later.

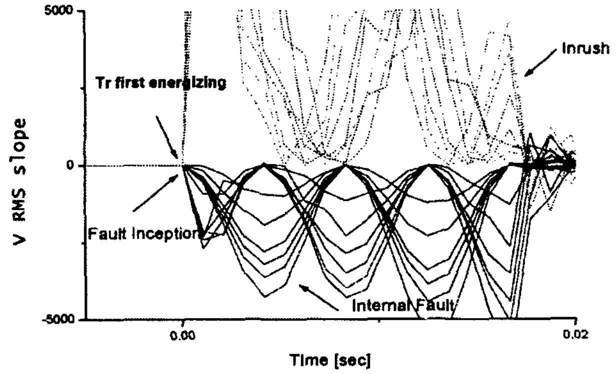

Fig. 2 Voltage slope for various faults and inrush

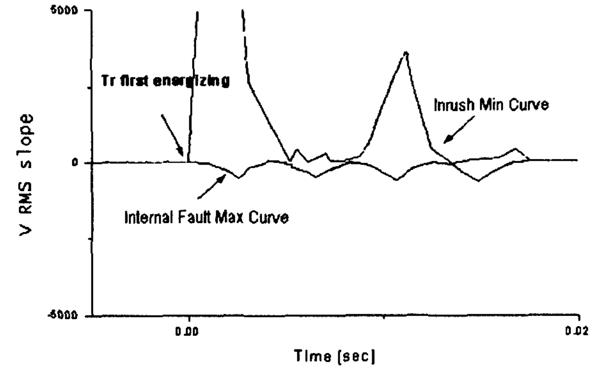

Fig. 3 Voltage slope boundary

3.2 Second Harmonic Ratio

The ratio of the second harmonic component (SHR) over the fundamental component of the differential current has been the major criterion for inrush detection and has been used as the restraint element in the conventional differential relay. Fig. 4 shows the second harmonic ratio for the various internal fault and inrush cases, and their boundaries are depicted in Fig. 5. In the initial stage of the disturbance, the second harmonic ratios for both cases are relatively high but separated by some distance. Note that after one cycle, SHRs for each case remain constant, providing the clear distinction between two. From this observation, the following fuzzy rule for the initial one cycle can be derived. The ratio is defined as Eq.(2),

$$F_2(n) = \frac{i_{d2}[n]}{i_{d1}[n]} \cdot 100 \tag{2}$$

Rule1) $F_2 > i_m[n] \rightarrow$ {1/Inrush}

Rule2) $F_2 < f_M[n] \rightarrow$ {1/Internal fault}

Rule3) $f_M[n] < F_2 < i_m[n] \rightarrow$
{y/Inrush}, {1-y/Internal fault}

where,
i_{d1} : fundamental component of differential current
i_{d2} : second harmonic component of differential current
$i_m[n]$, $f_M[n]$: same as before

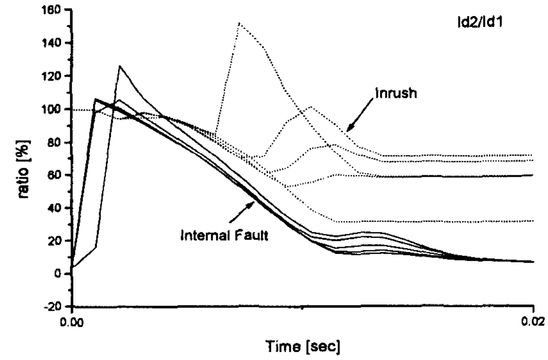

Fig. 4 Ratio of 2^{nd} harmonic component

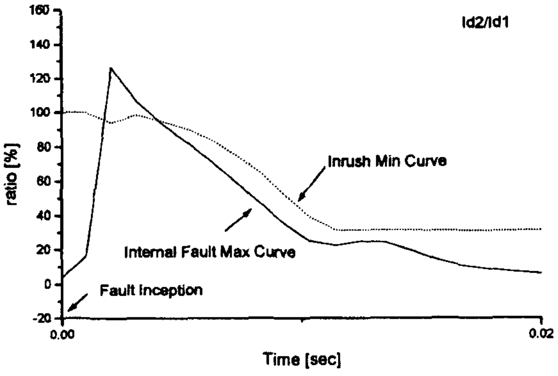

Fig. 5 2^{nd} harmonic boundary

3.3 Waveform of differential current

Analyzing the differential current of the inrush, there is a certain interval (about 1/3 cycle) that shows zero value for all three phases as seen in Fig 7. This phenomena can not observed in the fault case. Therefore this could be a criterion to distinguish the inrush from the fault and the corresponding rule can be expressed as follows with the zero value interval defined by Eq.(3).

$$F_3(n) = \underset{k=0..N-1}{Min}\{\underset{m=0..[N/6],ph=A,B,C}{Max}\left|i_{d.ph(n-k-m)}\right|\} \tag{3}$$

Rule1) $F_3 \le 1 \rightarrow$ {1/Internal Fault}

Rule2) $F_3 \ge 4 \rightarrow$ {1/Inrush}

Rule3) $2 \le F_3 \le 3 \rightarrow$ {z/Inrush}, {1-z/Internal fault}

where,

$i_{d.ph}$: differential current for phase ph

N : sampling rate (=16)

Bpa z in Rule 3 is determined from the B-type membership function to be described later.

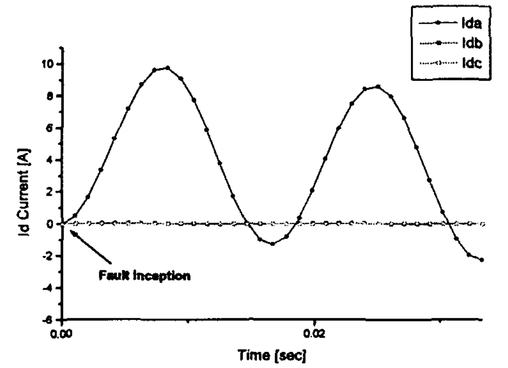

Fig. 6 Differential currents on turn-to-turn fault

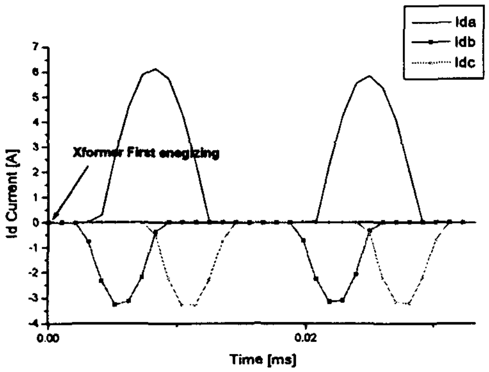

Fig. 7 Differential current on inrush

3.4 Differential Current Change of Three Phases

In case of the fault other than three phase fault, the differential current can be detected from only the faulted phase while in case of the inrush, differential current is observed from all three phases. Based on this observation, it can be said that if differential current is detected in one or two phases only, then it is a fault. When all three phases show a differential current, it is either a three phase fault or an inrush.

Although both cases show differential current, since the three phase fault has a very high value compared to the inrush, it can be distinguished from the inrush easily. With the decision variable defined as Eq.(4), the rule can be expressed as follows;

$$F_4(n) = N(\left|i_{d1.ph}(n)\right| > H_{thd})$$

Rule1) $F_4 = 1$ or 2 $\rightarrow$ {1/Internal Fault}

Rule2) $F_4 = 3$ $\rightarrow$ {1/Inrush,Internal Fault}

where,

N(C) : number of phases that satisfies a condition C

H_{thd} : setting value for differential current change (0.4)

4. Fuzzy Membership Function

Fuzzy rules developed so far have a bpa that represents the certainty or confirmation level of the hypothesis in the rule. A bpa is determined for each sampling time based on the boundary functions of each decision criterion as described below.

Categorizing the pattern of boundary functions into type A and B, two different ways are adopted to determine bpa. Note that Type A is the one that has a certain distant between two boundaries as seen in Fig.8, while Type B is the one that has a discrete number as a boundary. Voltage slope and SHR boundary functions belong to Type A, while differential current phase rule falls in Type B.

4.1 Type A Fuzzy Membership Function

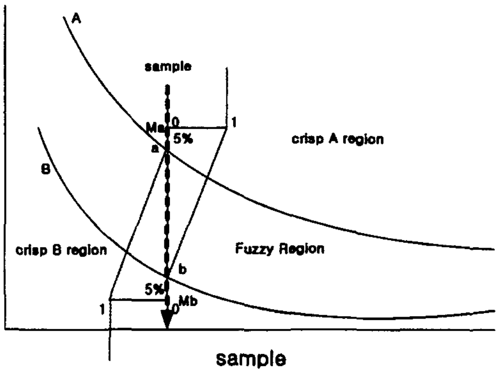

Fig. 8 example of fuzzy membership function

The voltage rule and SHR rule distinguish a fault and inrush based on the signal pattern of Fig.8. If a signal is below or beyond the boundary, then clear decision can be made. However, if a signal falls between two boundaries, then as the signal is closer to any boundary, it can be said that the possibility of being a disturbance that specifies that boundary increases. From this, bpa can be determined by Eq.(5) which has been derived from the basic membership function of Fig.9,where a and b represent boundary values on each boundary as seen in Fig.8.

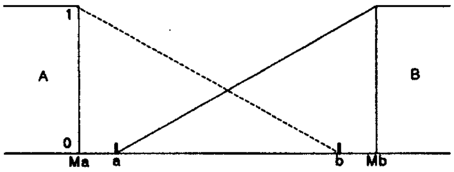

Fig. 9 Type A fuzzy membership function

$$bpa_A = \frac{1}{(M_a - b)}(x-b),\quad bpa_B = \frac{1}{(M_b - a)}(x-a) \qquad (5)$$

where,

$\text{margin} = (a-b)\cdot 0.05$

$M_a = a + \text{margin},\ M_b = b + \text{margin}$

x: sample value of F_1 or F_2

4.2 Type B Fuzzy Membership Function

This is the case of the differential current wave shape. There is a certain interval (about 1/3 cycle or 5 samples in 16 sampling rate) that shows zero value for all three phases as seen in Fig. 7. Corresponding fuzzy membership function expressed in Eq. 6 is depicted in Fig. 10. Note that if the value maintains less than or equal to 1, then the state is considered an internal fault, and if bigger than or equal to 4, this state is considered to be an inrush.

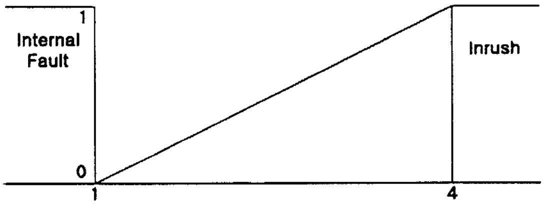

Fig. 10 B-type fuzzy membership function

bpa = (x-1)/3 (6)

6. Conclusion

This paper proposes the four fuzzy rules for identifying the disturbance type of the power transformer. Also the systematic method to determine bpa from the simulation data curves is proposed. Using these rules, a more accurate distinction of the fault can be achieved.

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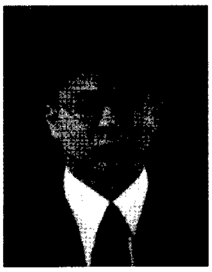

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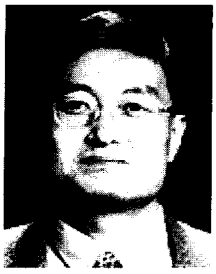

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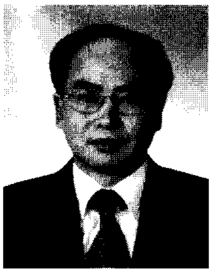

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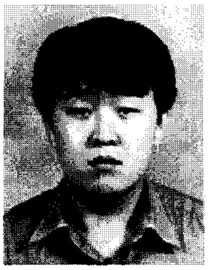

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