KIEE International Transactions on Power Engineering, Vol. 5-A No. 1, pp. 1~8, 2005 **1**

Modified-Current-Differential Relay for Transformer Protection

Yong-Cheol Kang[†] **, En-Shu Jin* and Sung-Ho Won***

Abstract - During magnetic inrush or over-excitation, saturation of the core in a transformer draws a significant exciting current, which can cause malfunction of a current-differential relay. This paper proposes a modified-current-differential relay for transformer protection. The relay calculates the core-loss current from the induced voltage and the core-loss resistance as well as the magnetizing current from the core flux and the magnetization curve. Finally, the relay obtains the modified differential current by subtracting the core-loss and the magnetizing currents from the conventional differential current. A comparative study of the conventional differential relay with harmonic blocking is presented. The proposed relay not only discriminates magnetic inrush and over-excitation from an internal fault, but also improves the relay speed.

Keywords: Core-loss current, Harmonic blocking, Magnetic inrush, Magnetizing current, Over-excitation

1. Introduction

Relays applied to the protection of a transformer must be able to discriminate internal faults from all other operating conditions. Discrimination between internal and external faults is easily achieved using a current differential relay, but problems, that might result in malfunction, can occur during magnetic inrush or over-excitation. To prevent malfunction, restraining or blocking signals derived from the current, voltage or flux are used to stabilize the relay when the exciting current in the transformer is significant[1].

Current derived restraining or blocking methods are based on the harmonic contents in the operating currents [2–5] or wave shape identification[6, 7]. Hayward[2] and Methews[3] used all the harmonics to restrain the differential relay for a transformer. Sharp and Glassburn[4] introduced the idea of harmonic blocking using the second-harmonic. Einvall and Linders[5] introduced a composite restraint function with the second-and fifth-harmonics. The harmonic based restraining or blocking methods ensure relay security for magnetic inrush or over-excitation. However, the methods malfunction for cases with very low harmonic content in the operating current.

Rockefeller[6] proposed a blocking scheme if successive peaks of the differential current fail to occur at about 7.5-10 ms. Another technique[7] was suggested based on the length of the time intervals when the differential current is close to zero. During magnetic inrush, the low current intervals are greater than one-quarter of a cycle and the relay is blocked. For internal faults, the low current intervals are less than one-quarter of a cycle and the relay operates. However, wave shape recognition techniques fail to identify over-excitation.

For the voltage-derived restraint, the so-called “tripping suppressor”[8] used a voltage relay to block the differential relay if the voltages are high. However, this method is slower than harmonic restraint devices.

Phadke and Thorp[9] proposed a flux-restrained current differential relay. This relay calculates the rate of change of flux with respect to the differential current and uses it as a restraint. However, the relay uses the winding current, which is unavailable for a transformer with a delta winding.

Techniques[10-12] have been reported that rely on the electro-magnetic equations of a transformer. Inagaki et al.[10] use nonlinear elements, and Sachdev and Kang et al. [11, 12] utilize linear elements. However, the primary and secondary voltage signals are required as well as the primary and secondary current signals.

When the transformer is energized, the core repeats saturation and non-saturation because the core flux exceeds the knee point in one direction, which is called magnetic inrush. When the over-voltage is applied on the transformer, saturation and non-saturation are repeated in both directions, which is referred to as over-excitation. During magnetic inrush or over-excitation, the differential relay may result in malfunction because of the significant exciting current, which cannot be measured.

The Transactions of the Trans. KIEE, Vol.53A, No.2, pp.80-86, FEB. 2004: A paper recommended and approved by the Editorial Board ofthe KIEE Power Engineering Society for translation for the KIEE International Transaction on Power Engineering.

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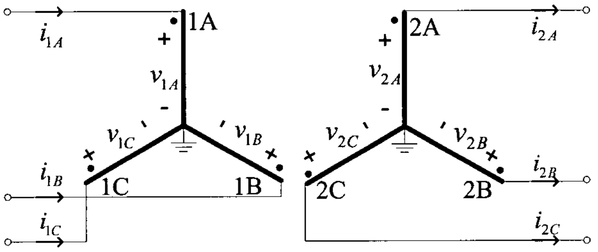
Received June 23, 2003 ; Accepted November 25, 2003

A modified current differential relay suitable for the protection of power transformers is described in this paper. The relay calculates core-loss current from the induced voltage and the core-loss resistance. The relay further calculates the magnetizing current from the core flux and the magnetization curve. Finally, the relay obtains the modified differential current by subtracting the core-loss and the magnetizing current from the conventional differential current. The performance of the relay was investigated and compared with a conventional differential relay with harmonic blocking under various EMTP simulated scenarios including magnetic inrush, internal faults and over-excitation.

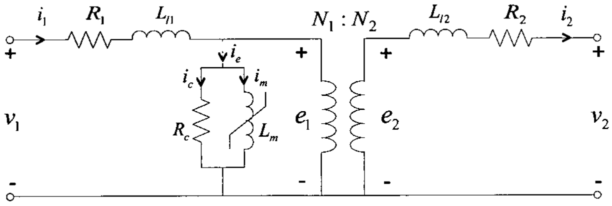
2. A modified current differential relay for transformer protection

Fig. 1 shows a three-phase Y-Y transformer and its per phase equivalent circuit is shown in Fig. 2. The R_c, R_1, L_{l1} in Fig. 2 are assumed to be known in this paper.



v_{1A}, v_{1B}, v_{1C}, v_{2A}, v_{2B}, v_{2C}: Primary and Secondary voltages
i_{1A}, i_{1B}, i_{1C}, i_{2A}, i_{2B}, i_{2C}: Primary and Secondary currents

Fig. 1 Three-phase Y-Y transformer



v_1, v_2: voltages,
e_1, e_2: induced voltages
i_1, i_2: currents,
R_1, R_2: winding resistances
L_{l1}, L_{l2}: leakage inductances
R_c: core-loss resistance,
L_m: magnetizing inductance
N_1, N_2: number of windings,
i_e: exciting current
i_c: core-loss current,
i_m: magnetizing current

Fig. 2 Per phase equivalent circuit

2.1 Harmonic-blocked differential relay

This subsection describes briefly the harmonic-blocked differential relay used for comparison with the proposed relay. A conventional differential relay derives the magnitude of the fundamental component of the operating differential current I_d using

$$I_d = \left|\vec{I}_1 - a\vec{I}_2\right| \tag{1}$$

where, $\vec{I}_1$ and $\vec{I}_2$ are the phasors of the fundamental component of the primary and secondary current, respectively and $a = N_2/N_1$. The magnitude of the fundamental component of the restraining current I_r is obtained by

$$I_r = \frac{\left|\vec{I}_1 + a\vec{I}_2\right|}{2}. \tag{2}$$

The characteristic of the relay is given by

$$I_d \geq I_{offset} + KI_r \tag{3}$$

where, I_{offset} and K is set to 15A and 0.3, respectively, in this paper.

The conditions for blocking the trip signal during magnetic inrush or over-excitation are represented in (4) and (5) and the logic diagram for the conventional current differential relay with harmonic blocking is shown in Fig. 3.

$$I_d < K_2 I_2 \tag{4}$$

$$I_d < K_5 I_5 \tag{5}$$

where, I_2 and I_5 are magnitudes of the second- and fifth-harmonic component of the differential current, respectively and K_2 and K_5 are constants.

2.2 A modified current differential relay

The magnetizing current i_m is significantly increased for magnetic inrush and over-excitation. This paper estimates i_m and the core-loss current i_c and obtains the differential current using (6).

$$i_d = i_1 - ai_2 - i_c - i_m \tag{6}$$

The procedure for estimating i_c and i_m will be shown.

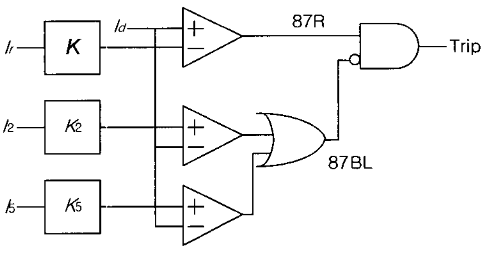


Fig. 3 Differential relay with harmonic blocking

2.2.1 Estimation of i_c

With reference to Fig. 2, i_c is the current flowing on R_c, and as R_c can be obtained experimentally, i_c can be estimated if e_1 is calculated.

If we assume the transformer does not contain an internal fault, v_1 is given by

$$v_1 = R_1 i_1 + L_{l1}\frac{di_1}{dt} + e_1 . \tag{7}$$

Rearranging (7) gives

$$e_1 = v_1 - R_1 i_1 - L_{l1}\frac{di_1}{dt} . \tag{8}$$

As e_1 can be calculated using (8), i_c is estimated using

$$i_c = \frac{e_1}{R_c} . \tag{9}$$

Equation (8) contains a differentiation term, which is approximated numerically using the trapezoidal rule expressed in (10). The use of the trapezoidal rule minimizes approximation errors but can result in numerical oscillations. These are damped using a parallel damping resistance R_p, as indicated in Fig. 4 [13].

$$v_L(t) = \frac{1}{\frac{\Delta t}{2L} + \frac{1}{R_P}}\{i(t) - i(t-\Delta t)\} - \frac{R_P - \frac{2L}{\Delta t}}{R_P + \frac{2L}{\Delta t}} v(t-\Delta t) \tag{10}$$

2.2.2 Estimation of i_m

As e_1 can be calculated using (8), the core flux λ can be obtained by

$$\lambda(t) = \int_{t_0}^{t} e_1(t)dt + \lambda_0 \tag{11}$$

where, λ_0 is set to 0 in this paper.

The magnetization curve relates the core flux to the magnetizing current i_m. Fig. 5 presents the magnetization curve. Therefore, i_m can be estimated by inserting λ into the magnetization curve.

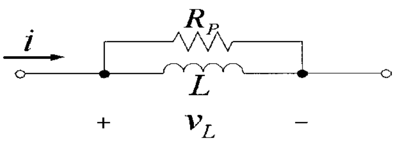


Fig. 4 Inductance model for the parallel damping

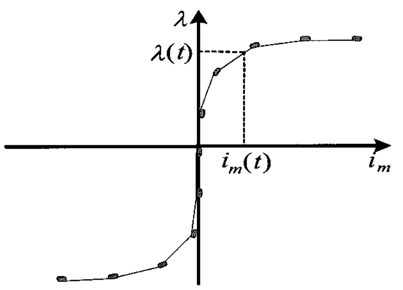


Fig. 5 The magnetization curve

2.2.3 A modified current differential relay

In this paper, the differential current is estimated using (6) and the magnitude of its fundamental component is calculated. In addition, the restraining current is obtained by (2), and the characteristic of the relay is given by (3).

3. Case studies

Fig. 6 illustrates a single line diagram of the simulated system. The two-winding Y-Y transformer (154kV/22kV, 55 MVA), the generator (6 GVA) and the load (55MVA) are modeled using EMTP. The modeling techniques described in [14] are used to represent internal winding faults.

The sampling rate is 64 samples per cycle. Butterworth 2^{nd} order filters with a stop-band cut-off frequency of 1920 Hz (sampling frequency/2) are used as anti-aliasing filters.

The hysteresis characteristics of the core are modeled using a type-96 element and the saturation point of (40A, 334Vs) is selected for use with HYSDAT, a subroutine of EMTP.

The performance of the proposed relay was compared against a harmonic-blocked differential relay operating under various simulated scenarios, including magnetic inrush, internal winding faults and over-excitation. The results for 'A' phase are shown for convenience. K_2 and K_5 in Fig. 3 are set to 10 and 12, respectively.

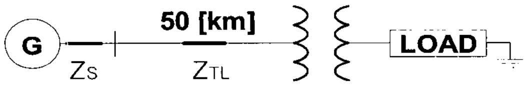


Fig. 6 Model system studied

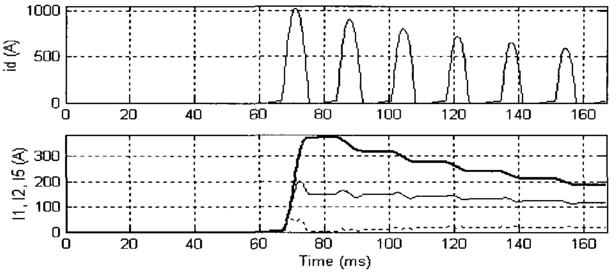
3.1 Magnetic inrush

The magnitude of the inrush current depends on the energization angle, the remanent flux in the core, and the load current. The remanent flux in the core is set to 0%. Two extreme cases are discussed in this section.

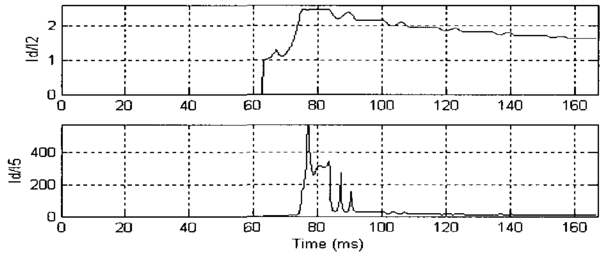
1) Case 1: Energization angle 0 deg, no load

Figs. 7 and 8 depict the results of the conventional and proposed relays for Case 1, respectively. The bold solid line, the fine solid line and the dotted line in Fig. 7a indicate I_d, I_2 and I_5, respectively. The load is disconnected, so the secondary current is zero. The conventional differential current is significant because the primary current becomes the differential current. Therefore, the differential relay (87R) enters the operating zone. However, as I_d/I_2 is less than K_2 = 10 (Fig. 7b), the blocking signal (87BL) is issued at 67.44ms and thus the trip signal is not activated (Fig. 7c). The conventional relay with harmonic blocking signals can prevent malfunction during magnetic inrush, but the operating time of the relay will be delayed during internal faults because of K_2 and K_5. Moreover, the characteristic of the core and the system condition must be considered when setting the values of K_2 and K_5.

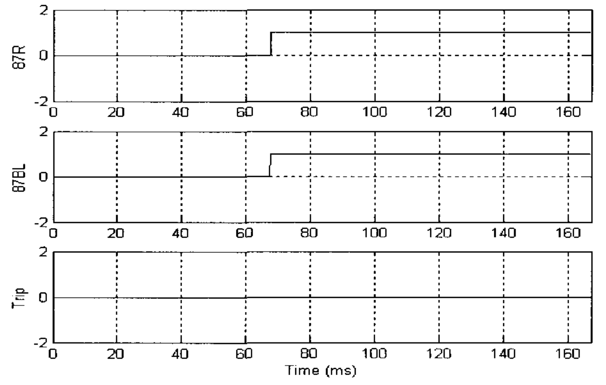
However, the modified differential current of the proposed relay is obtained by subtracting the secondary current, the core-loss current and the magnetizing currents from the primary current. The resulting modified differential current is reduced to a small value (Fig. 8a). Hence, the relay does not enter the operating zone (Fig. 8b).



(a) Instantaneous differential current and its harmonics

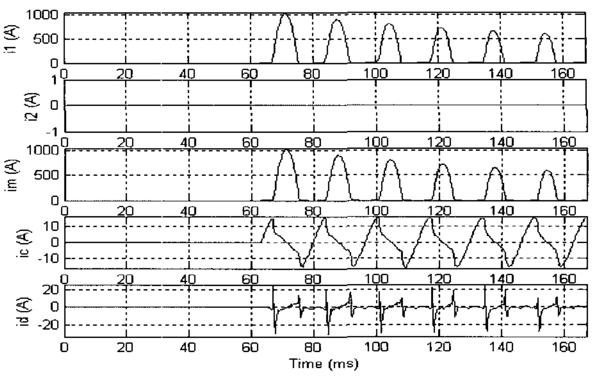


(b) Ratios of the fundamental to the 2nd or 5th harmonic

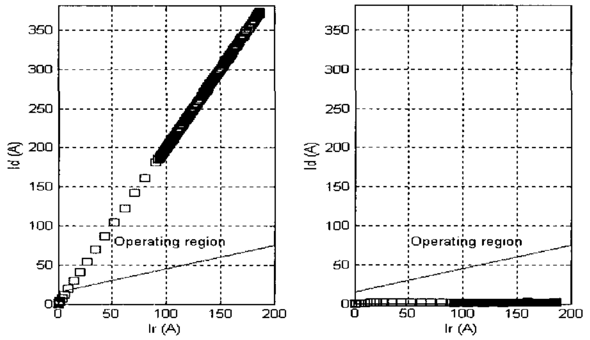


(c) Output of 87R, 87BL and the trip signal

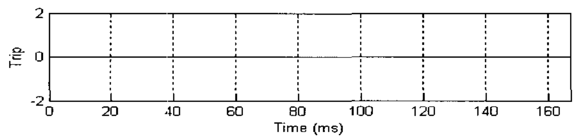
Fig. 7 Results for the conventional relay in Case 1



(a) i_1, i_2, i_m, i_c, and i_d



(b) Conventional (left) and proposed (right) relay

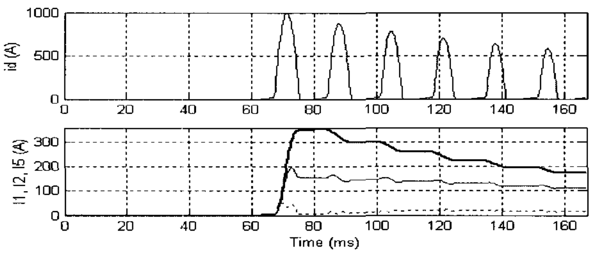


(c) Trip signal

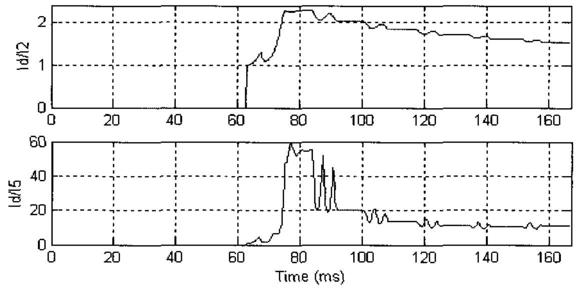
Fig. 8 Results for the proposed relay in Case 1

2) *Case 2: Energization angle 0 deg, full load*

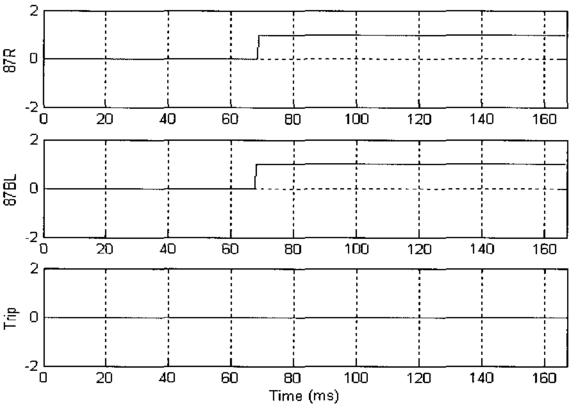
Figs. 9 and 10 show the results of the conventional and the proposed relay for case 2, respectively. The load is connected, so the secondary current exists (Fig. 10a). The conventional differential current in Fig. 9a causes the relay to enter the operating zone (Fig. 10b). Although the differential current is similar to Case 1, the restraining current is dissimilar, so the locus of the relay is singular. However, the blocking signal is issued at 67.96ms and thus the trip signal is not activated (Fig. 9b). The modified differential current remains very small and consequently, the relay does not enter the operating zone and the trip signal stays inactive.



(a) Instantaneous differential current and its harmonics

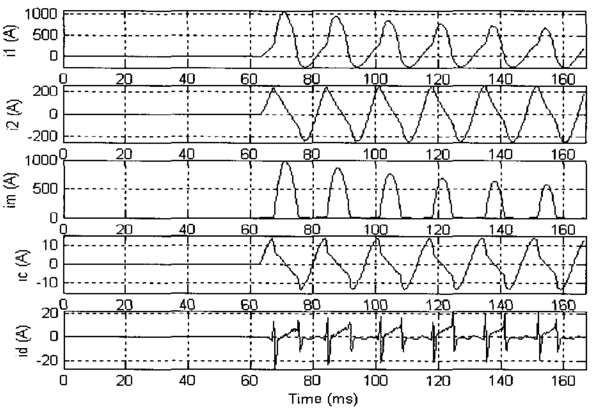


(b) Ratios of the fundamental to the 2nd or 5th harmonic

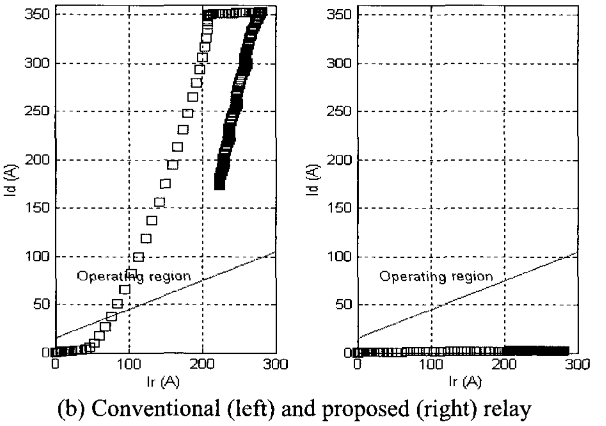


(c) Output of 87R, 87BL and the trip signal

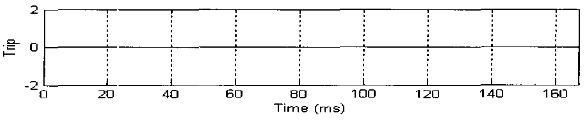
Fig. 9 Results for the conventional relay in Case 2



(a) i_1, i_2, i_m, i_c, and i_d



(b) Conventional (left) and proposed (right) relay



(c) Trip signal

Fig. 10 Results for the proposed relay in Case 2

3.2 Internal winding faults

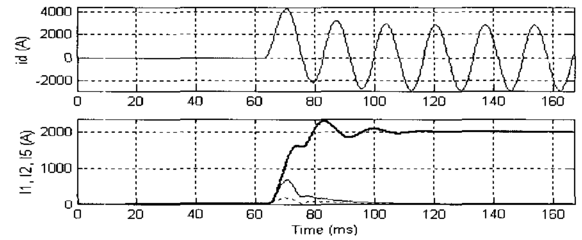
Various types of faults were applied to phase A of the primary winding and two cases are discussed in this section.

1) Case 3: A turn-to-ground fault, located 80% from the neutral end at 0 deg inception angle

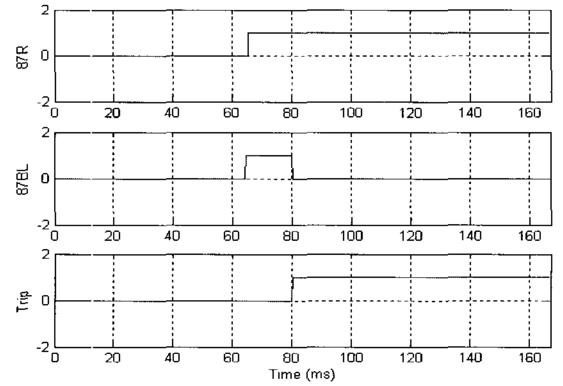
2) Case 4: A turn-to-turn fault, located between 60% and 70% and at 0 deg inception angle

Figs. 11 and 12, and Figs. 13 and 14 indicate the results of the conventional and the proposed relays for Cases 3 and 4, respectively. As shown in Figs. 11a and 13a, the harmonic component is produced during the internal faults, and reduces gradually. The reduction rate depends on the time constant of the system. The operating time of the relay will be delayed when the harmonic exists. In the conventional relay of Case 3, the 87R enters its operating zone 2.9 ms after fault inception, but the blocking signal is issued, which makes the trip signal delayed until 17.7 ms after fault inception. That is, the operating time of the relay is belated by about 15 ms. However, the proposed relay issues a trip signal 2.9 ms subsequent to fault inception.

In Case 4, the conventional and the proposed relays issue trip signals at 17.97 ms and 3.12 ms after fault inception, respectively.

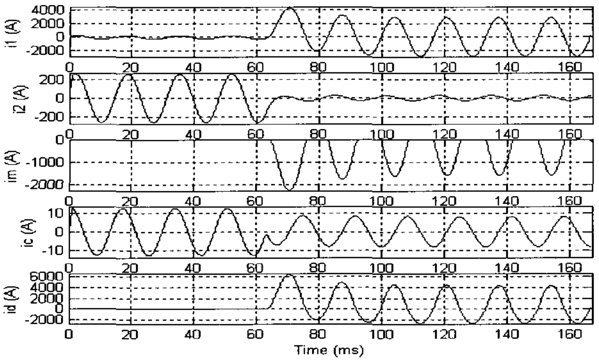


(a) Instantaneous differential current and its harmonics

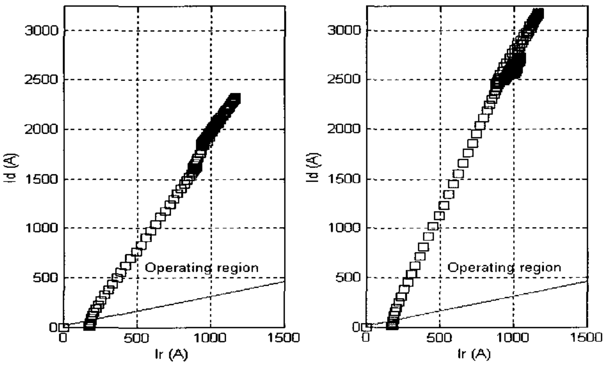


(b) Output of 87R, 87BL and the trip signal

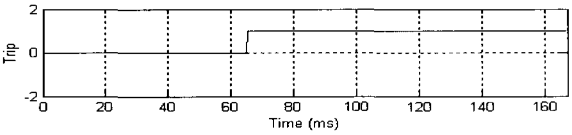
Fig. 11 Results for the conventional relay in Case 3



(a) i_1, i_2, i_m, i_c, and i_d

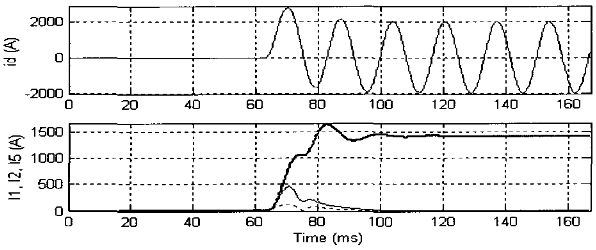


(b) Conventional (left) and proposed (right) relay

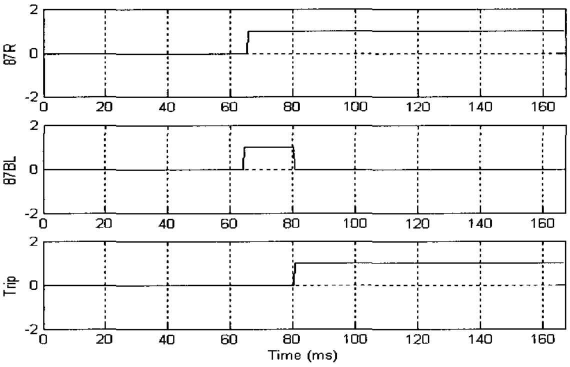


(c) Trip signal

Fig. 12 Results for the proposed relay in Case 3

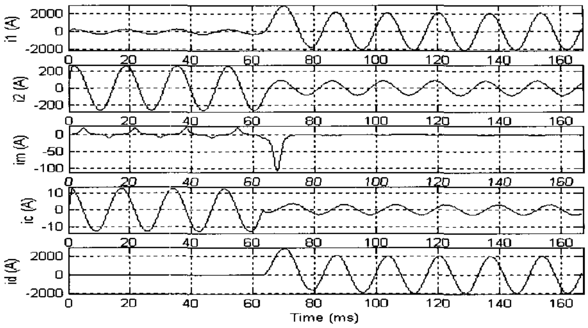


(a) Instantaneous differential current and its harmonics

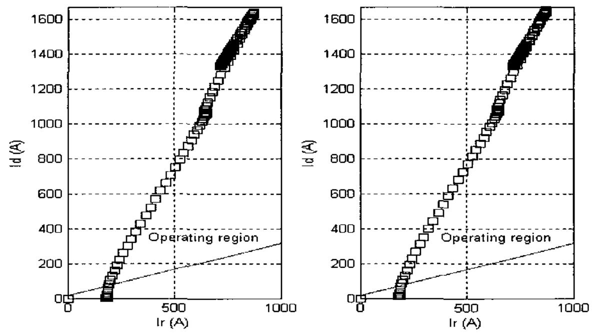


(b) Output of 87R, 87BL and the trip signal

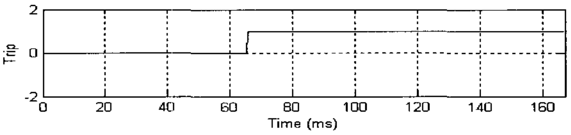
Fig. 13 Results for the conventional relay in Case 4



(a) i_1, i_2, i_m, i_c, and i_d



(b) Conventional (left) and proposed (right) relay



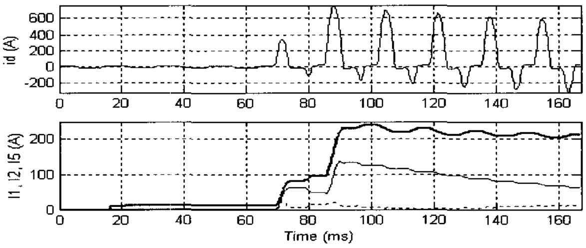
(c) Trip signal

Fig. 14 Results for the proposed relay in Case 4

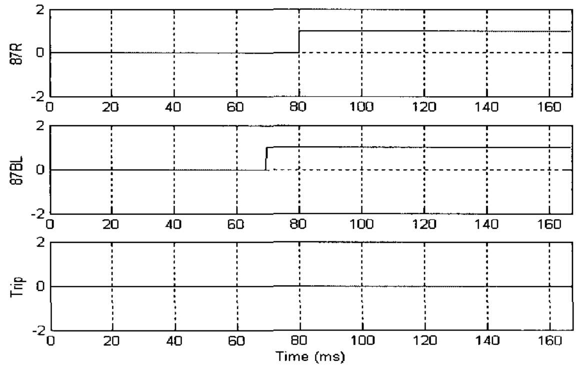
3.3 Over-excitation

1) Case 5: Overvoltage of 150% applied, full load

Figs. 15 and 16 present the results of the conventional and the proposed relays for Case 5, respectively. The conventional differential current increases gradually when the over-voltage is applied at 62.5 ms (Fig. 15a). Thus, after about one cycle, the conventional relay enters its operating zone at 79.94ms (Fig. 16b). However, the blocking signal is issued at 69.27ms and thus the trip signal is not activated (Fig. 15b). In the proposed relay, the differential current is smaller than the threshold. Hence, the relay does not enter the operating zone (Fig. 16b) and the trip signal is not activated (Fig. 16c).

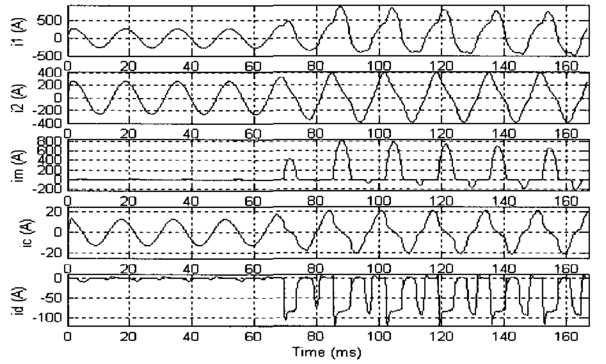


(a) Instantaneous differential current and its harmonics

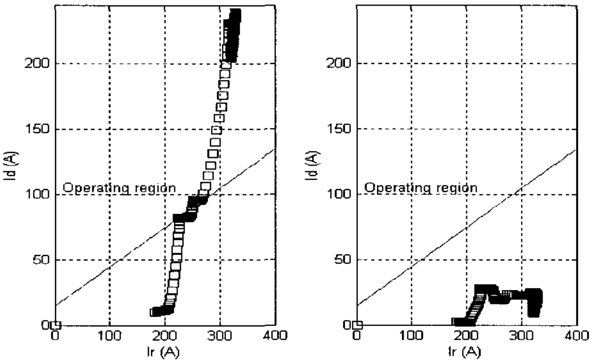


(b) Output of 87R, 87BL and the trip signal

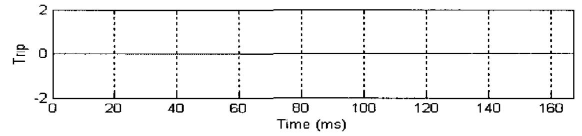
Fig. 15 Results for the conventional relay in Case 5



(a) i_1, i_2, i_m, i_c, and i_d



(b) Conventional (left) and proposed (right) relay



(c) Trip signal

Fig. 16 Results for the proposed relay in Case 5

4. Conclusion

A modified current differential relay suitable for the protection of a power transformer has been described in this paper. The relay calculates the core-loss current from the induced voltage and the core-loss resistance; the relay calculates the magnetizing current from the core flux and the magnetization curve. Finally, the relay obtains the modified differential current by subtracting the core-loss and the magnetizing currents from the conventional differential current.

The results of the comparative study with the conventional differential relay with harmonic blocking are shown. The proposed relay not only discriminates magnetic inrush and over-excitation from an internal fault, but also improves the speed of the conventional relay by approximately 15ms in the case of internal faults.

The proposed relay is irrespective of the harmonic components included in the differential current. Moreover, whilst the conventional relays based on the transformer model necessitate the primary and secondary voltages, the proposed relay needs the primary voltage only.

Acknowledgements

This work was supported by the Post-doctoral Fellowship Program of the Korea Science & Engineering Foundation (KOSEF).

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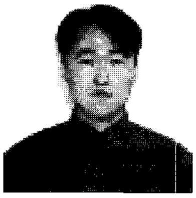

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