

# A NEW APPROACH TO FAST INRUSH CURRENT DISCRIMINATION BASED ON TRANSFORMER MAGNETIZING CHARACTERISTICS

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**Abstract** - This paper investigates the necessity of protection devices that implement fast relaying algorithms for distribution systems to meet the demands for high reliability from the viewpoint of power quality. In designing high speed protection systems, the fast discrimination of magnetizing inrush current is also indispensable to prevent the false tripping of relays. The conventional method of inrush current detection for transformer protection recognizes the ratio of the second harmonic component of the differential current. The authors propose a new approach to detecting the inrush current based on the transformer magnetizing characteristics. An inrush current occurs when the transformer core becomes saturated. The proposed method estimates the transformer core saturation by the linear relation between the differential current and the integral of voltage. Experimental results obtained on a single-phase transformer and a three-phase transformer are presented.

**Keywords** - *distribution system, protective relay, fast fault detection, transformer, inrush current, magnetizing characteristics*

## 1 INTRODUCTION

Recently, more and more large-scale industrial plants and commercial facilities have introduced on-site generators, such as cogeneration systems, to increase electric power reliability. Critical or sensitive customer loads suffer from power quality related problems caused by voltage sags caused by faults on the utility system. The ITIC (Information Technology Industry Council) curve is well-known for power acceptability[1]. To avoid the influence of faults on sensitive loads, the on-site generator is separate from the utility system, and power is supplied to the sensitive loads from the on-site generator, so that continuous operation of sensitive loads is enabled. Also in FRIENDS (Flexible, Reliable and Intelligent Electric eNergy Delivery System), a new concept of distribution system, a fault must be quickly detected and removed the fault, and a high-speed switching system is also being investigated[2].

As stated above, there are demands for the improvement of reliability of power supply of distribution systems from various viewpoints. To decrease the duration of voltage sags when a fault occurs, fast fault detection is necessary. For transformer primary protective relays, to prevent false tripping due to an inrush current, a technique using the content of the second harmonic compo-

nent in the current waveform is commonly used. However, this method requires a longer time to determine the second or higher harmonic components in a transient current waveform, and cannot detect inrush current within the one short cycle. Therefore, the authors examined a discriminating method using the magnetization characteristics of the transformer core to detect an inrush current within one cycle[3].

A considerable number of studies of detecting inrush currents have been made and a method using the equivalent circuit of the transformer[4], a method observing the active power flowing into the transformer[5], a method using artificial neural networks[6], a multi-criteria approach[7], a method using the similarity between the waveforms of current and voltage[8], and a method using wavelet transformation[9] have been proposed. Another method similar to the proposed method of detecting an inrush current based on the magnetization characteristics of the transformer core has been proposed[10]. These methods have been proposed as more reliable methods than the conventional method using the second harmonic component. The authors examined a method aiming principally at fast discrimination because they intend to apply the method to a fast protection system for distribution systems.

## 2 FAST FAULT DETECTION IN DISTRIBUTION SYSTEMS

In Japan, the reliability of power supply is remarkably high because of the large investment in power transmission and distribution equipment as compared to the reliability in foreign countries. However, some users, such as semiconductor manufacturing plants, require considerably high quality of power, and instantaneous voltage sags owing to a fault, such as lightning, in the utility system can result in serious damage in these plants. Figure 1 shows a power supply system with an on-site generator and a high-speed circuit breaker on the plant bus. Sensitive loads are arranged on the on-site generator side of the plant bus separate from the non-sensitive loads. When a fault occurs in the utility system, the fault is detected based on the current and voltage values on the plant bus, and the fast circuit breaker isolates the on-site generator from the utility system to protect the sensitive loads. In some other plants, a fast power switching system (SSTS: Solid-State Transfer Switch) has been used. This system receives power through two sources, and enables the seamless transfer

of energy from a primary source to an alternative source when a fault occurs in the utility system[11].

For another example, since the needs of consumers will vary because of the recent tendency toward electric utility deregulation, a flexible, reliable and intelligent electric energy delivery system (FRIENDS) has been proposed. This system has power quality improvement centers (QCC: Quality Control Center) that implements distributed power sources and power storage equipment between distribution substations and consumers, and uses an information network to realize highly reliable power supply, energy conservation and high-quality customer service. When a fault occurs on such a system, it is necessary to detect the fault in a short time. A system switching method using thyristors has been proposed[2].

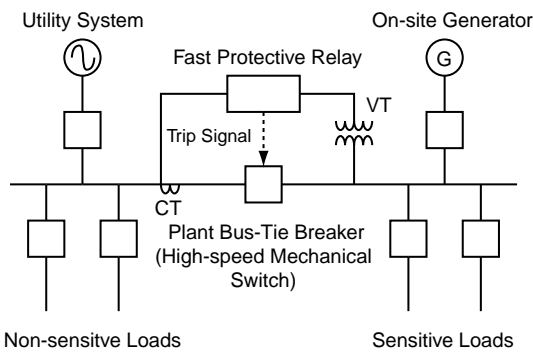


Figure 1: Example of sensitive load protection system.

As stated above, methods of quickly removing faults in the utility systems and avoiding the influence of faults have been examined from various viewpoints for distribution systems to increase the reliability of power supply. Therefore a technique to quickly detect faults is important as a basic technique in these systems. The influence of an instantaneous voltage sag of a half cycle upon load devices is considered to be insignificant with respect to power electronics devices, induction motors and electromagnetic switches. Therefore, to protect these devices from the influence of instantaneous voltage sags, it is necessary to reduce the duration of an instantaneous voltage sag to less than a half cycle and to detect a fault and open the switch in a few milliseconds. As for circuit breakers, a fast mechanical switch by an electromagnetic repulsion method that ensures an opening time of 1 ms or less has been developed[11]. The demands for fast discrimination may be satisfied by fast sampling at, for example, 10 kHz or more, in a fault detecting device using hardware, such as DSP, and the implementation of an algorithm that is quite different from the conventional protective relay algorithm[14].

In power supply systems in customer facilities the protective system composed of overcurrent devices based on time grading coordination is mainly used. The overcurrent device basically detects faults based on only the magnitude of the current, so the implementation of the faster algorithm of the overcurrent detection to digital relays is not considered to be difficult although some consideration must be given to determine the time-current setting of the overcurrent devices. Avoiding fault tripping

of the transformer protection relay due to an inrush current is normally a function specific to the transformer primary protective relay. However, to design a fast protection method for distribution systems, it will be required to implement the inrush detection algorithm to protective relays other than the transformer primary protective relay, such as overcurrent devices.

### 3 BASIC PRINCIPLE AND ALGORITHM

#### 3.1 Theoretical Background

The magnetizing characteristics of a transformer core are indicated by the B-H curve as shown in Figure 2. The magnetic field intensity  $H$  is in proportion to the current value  $i$ , and the change in magnetic flux density  $B$  from residual magnetic flux density  $B_r$  is in proportion to the integral of voltage  $v$ . The B-H curve inherent to each transformer can be divided into two linear segments, one is segment A-D, the condition in which the transformer core is not saturated and the others are segments A-B and C-D, the condition in which the transformer core is saturated because the magnetizing current in the non-saturated condition is negligible small.

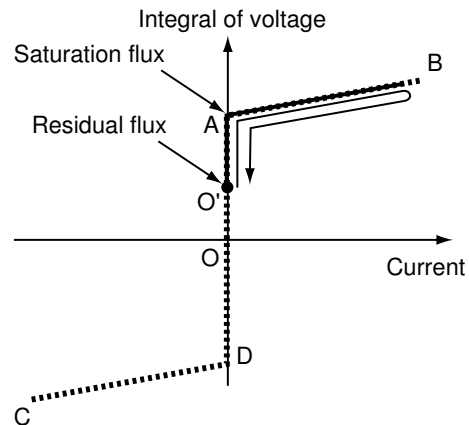
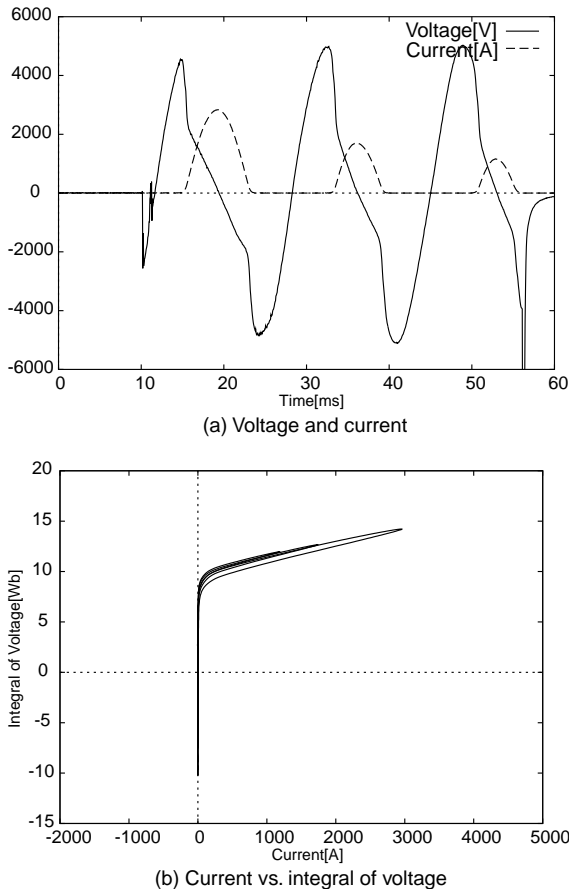


Figure 2: Magnetizing characteristics of transformer core.

Although it is difficult to obtain the initial magnetic flux density during energizing, it exists between A and D because the transformer core is not in a saturated condition. Suppose that the initial magnetic flux density is  $B_r$ . After the transformer energizes, the relationship between the current value  $i$  and the integral of voltage  $v$  changes along the magnetization curve of the core as the arrow shown in the figure. When the magnetic flux density  $B(t)$  reaches the saturated magnetic flux density, point A, an inrush current starts to flow. The value of the integral of the voltage is zero, so the origin of the diagram in this figure can be regarded as point  $O'$  because  $B_r$  is unknown. In other words, when the locus obtained by the measured voltage and current is moved parallel by  $B_r$  in the y-axis direction, the curve will overlap with the original curve shown by the broken line in the figure.

A method has been proposed that detects an inrush current by estimating dynamically the magnetization curve by plotting the integrals of the voltage and the sums

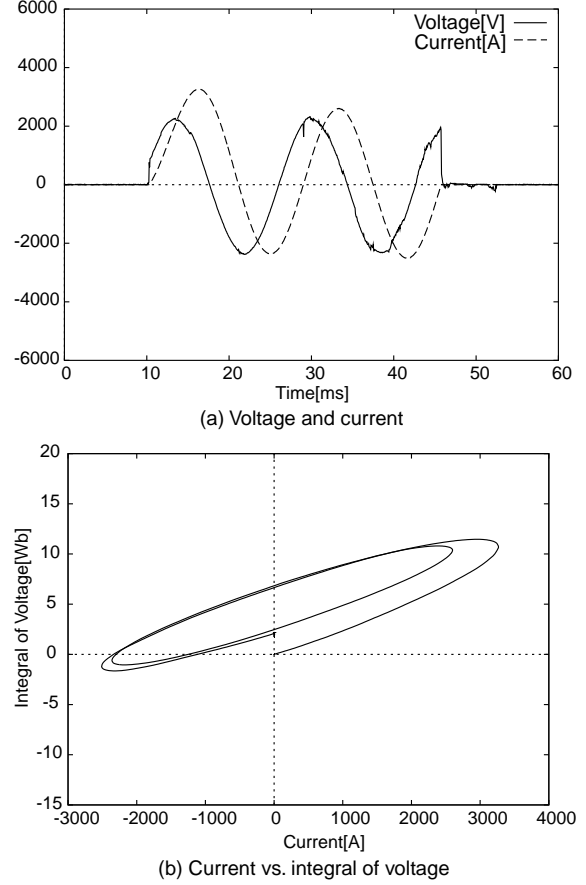
of current of each winding and examining whether the plotted  $(H, B)$  locus crosses the zones according to the predefined zones[10]. The method proposed in this study discriminates an inrush current by predicting the segment of the magnetization curve. Since the transformer becomes equivalent to an air core condition when the magnetic flux density  $B(t)$  exceeds the saturated magnetic flux density, the reactance looks to be apparently almost constant. Therefore, if the ratio of the current value to the voltage integral value becomes almost constant in the predetermined time range of some milliseconds, the transformer core is supposed to be saturated, and the current is considered to be an inrush current. When an internal short-circuit fault occurs, the voltage and current waveforms show sinusoidal waves, and also the voltage integral values show a sinusoidal wave. Therefore, when the relationship between current values and voltage integrals is plotted, the locus shows a curve like a Lissajous figure. The shape of the Lissajous figure depends on the phase difference of the voltage and current determined by the impedance to the fault point and normally has a shape of a gradient ellipse, so the locus is monotone decreasing or increasing.



**Figure 3:** Measured waveform of voltage and inrush current, and the locus by the proposed method.

The proposed method was validated by a simulation using actual measurement data on current and voltage waveforms of a 3300[V]/100[V], 1200[kVA] single-phase transformer. The voltage and current waveforms on the primary side were measured in two cases, one being an

inrush when the secondary side was open and the other a short-circuit fault when the circuit on the secondary side was shorted to simulate an transformer internal fault, and the integral values of the voltage and current values were plotted using these waveform data.



**Figure 4:** Measured waveform of voltage and short-circuit current, and the locus by the proposed method.

Figure 3 shows the waveforms obtained when an inrush occurred, and Figure 4 shows the waveforms obtained when a short-circuit fault occurred. As is evident from these figures, the locus obtained when an inrush occurred is similar to the magnetization curve, while the locus obtained when a short-circuit fault occurred has a shape like a Lissajous figure.

### 3.2 Inrush current discriminating algorithm

Considering that the relationship between the integral value of voltage  $v$  and the current value  $i$  becomes almost linear when an inrush occurs, it is possible to detect an inrush through the following calculation with respect to the integral value of voltage  $v$  and the current value  $i$ .

First, the moving average of  $n_1$  measurements in the past is calculated at the time  $k$  to remove higher harmonic components. The moving average of the current values at each point in time is  $x_k$ , and the moving average of the integral values of the voltage is  $y_k$ . The linear regression line is determined with respect to the sample having a larger window width  $n_2$  than the moving average from the data  $\{(\bar{x}_i, \bar{y}_i) \mid i = k - n_2 + 1, \dots, k\}$ .

$$y = a_k x + b_k \quad (1)$$

The average deviation from this linear regression line is defined as follows.

$$\varepsilon_k = \frac{1}{n_2} \sum_{i=k-n_2+1}^k \{\bar{y}_i - (a_k \bar{x}_i + b_k)\}^2 \quad (2)$$

An inrush is discriminated by verifying whether the following equations are met to determine whether the deviation of the  $n_2$  moving average data in the past with respect to the linear regression line is small and whether the gradient of the linear regression line is close to the air core inductance  $L_{air}$  by (3) and (4), where  $K_1$  and  $K_2$  are pre-defined threshold constants.

$$\varepsilon_k < K_1 \quad (3)$$

$$|a_k - L_{air}| < K_2 \quad (4)$$

The parameters  $n_1$  and  $n_2$  should be chosen according to the sampling frequency and the discrimination time. In our research, the sampling frequency is more than 10KHz, so  $n_1$  and  $n_2$  are set to less than 10 and 20 respectively. In addition, the threshold values of the parameters  $K_1$  and  $K_2$  are determined to 10% of the air-core inductance.

#### 4 APPLICATION TO THREE-PHASE TRANSFORMER

##### 4.1 Consideration of helping effect

The application of the above method to three-phase transformers is shown below. For three-phase transformers, consideration should be given to the winding connection and the neutral point connecting method. The primary distribution system in most industrial plants or commercial facilities is in the range from 3.3kV to 33kV, and insulated neutral point to earth methods are used widely in Japan. In the following investigation, the windings of the three-phase transformer are wye-delta connection, and the neutral point is ungrounded. Almost similar considerations can be made with respect to the delta-wye connection transformer.

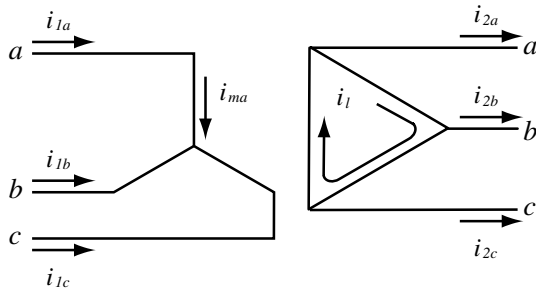


Figure 5: Helping effect in three-phase transformer.

When an inrush occurs in a phase of a three-phase transformer, since the current corresponding to the inrush current flows in the secondary delta winding, the current

flows to the other phases in which an inrush has not occurred in the primary side[12]. Assume that an inrush occurs in phase A while the secondary side is open. Suppose that the primary current values in the phases are  $i_{1a}$ ,  $i_{1b}$  and  $i_{1c}$  and the current flowing the secondary delta winding is  $i_l$ . If the single-phase inrush current in phase A,  $i_{ma}$ , if the helping effect is of no effect, the relation of  $i_{1a}$ ,  $i_{1b}$ ,  $i_{1c}$ ,  $i_{ma}$ ,  $i_l$  are described in (5), (6) and (7) as follows.

$$i_{1a} = i_{ma} - i_l \quad (5)$$

$$i_{1b} = -i_l \quad (6)$$

$$i_{1c} = -i_l \quad (7)$$

Where  $i_{ma}$  and  $i_l$  can be determined by these equations.

$$i_{ma} = \frac{3}{2} i_{1a} \quad (8)$$

$$i_l = \frac{1}{3} i_{ma} = \frac{1}{2} i_{1a} \quad (9)$$

For the proposed method, it is not necessary to use the measured current of each phase itself directly, but the single-phase inrush current  $i_{ma}$  of each phase.

To simplify the calculation in the above examination, it is considered that an inrush occurs only in one phase. However, since the magnetic flux of each phase changes according to the topology of the magnetic circuit depending on the core structure, magnetic saturation may occur not in a only single phase, but in some phases. In the following calculation, the single-phase inrush current values of the phases are  $i_{ma}$ ,  $i_{mb}$  and  $i_{mc}$ . Loads are considered to have been connected on the secondary side, and the secondary current values of the phases are  $i_{2a}$ ,  $i_{2b}$  and  $i_{2c}$ . Of the secondary delta winding current, the part that contributes to the helping effect is  $i_l$ . Thus, the following equations are obtained.

$$i_{1a} = i_{ma} - i_l + \frac{1}{3}(i_{2b} - i_{2a}) \quad (10)$$

$$i_{1b} = i_{mb} - i_l + \frac{1}{3}(i_{2c} - i_{2b}) \quad (11)$$

$$i_{1c} = i_{mc} - i_l + \frac{1}{3}(i_{2a} - i_{2c}) \quad (12)$$

Then,  $i_l$  is eliminated to obtain the following equations.

$$i_{ma} - i_{mb} = i_{1a} - i_{1b} - i_{2b} \quad (13)$$

$$i_{ma} - i_{mc} = i_{1a} - i_{1c} + i_{2a} \quad (14)$$

$$i_{mb} - i_{mc} = i_{1b} - i_{1c} - i_{2c} \quad (15)$$

It is impossible to predict in which phase of phases A, B and C an inrush will occur. However, there is a very small possibility that an inrush will occur in all phases. If inrushes occur in phases A and B,  $i_{mc}$  is regarded as zero, and  $i_{ma}$  and  $i_{mb}$  can be obtained from (14) and (15) by substituting measuring the primary current values and secondary current values on the right side of (14) and (15).

When inrushes occur in phases B and C, and phases A and C they are considered in the same manner. The current values to be used for discrimination  $i_{ma1}$ ,  $i_{ma2}$ ,  $i_{mb1}$ ,  $i_{mb2}$ ,  $i_{mc1}$  and  $i_{mc2}$  are defined as follows.

$$i_{ma1} \equiv i_{1a} - i_{1b} - i_{2b} \quad (16)$$

$$i_{ma2} \equiv i_{1a} - i_{1c} + i_{2a} \quad (17)$$

$$i_{mb1} \equiv i_{1b} - i_{1c} - i_{2c} \quad (18)$$

$$i_{mb2} \equiv -i_{1a} + i_{1b} + i_{2b} (= -i_{ma1}) \quad (19)$$

$$i_{mc1} \equiv -i_{1a} + i_{1c} - i_{2a} (= -i_{ma2}) \quad (20)$$

$$i_{mc2} \equiv -i_{1b} + i_{1c} + i_{2c} (= -i_{mb1}) \quad (21)$$

These defined values can be obtained from the measured current values. The voltage in each phase is as shown below.

$$v_{ma} = v_{1a} - R_{1a}i_{1a} - L_{1a}\frac{di_{1a}}{dt} \quad (22)$$

$$v_{mb} = v_{1b} - R_{1b}i_{1b} - L_{1b}\frac{di_{1b}}{dt} \quad (23)$$

$$v_{mc} = v_{1c} - R_{1c}i_{1c} - L_{1c}\frac{di_{1c}}{dt} \quad (24)$$

The relationship between combination of voltage and defined current values to which this proposed method is applied and the phase in which an inrush is discriminated is shown below: The relationship between combination of voltage and defined current values to which this proposed method is applied and the phase in which an inrush is discriminated is shown below:

$$\begin{aligned} (v_{ma}, i_{ma1}) \text{ or } (v_{ma}, i_{ma2}) &\Rightarrow \text{inrush in phase A} \\ (v_{mb}, i_{mb1}) \text{ or } (v_{mb}, i_{mb2}) &\Rightarrow \text{inrush in phase B} \\ (v_{mc}, i_{mc1}) \text{ or } (v_{mc}, i_{mc2}) &\Rightarrow \text{inrush in phase C} \end{aligned}$$

The proposed method is applied to these six combinations of voltages and currents, and an inrush in each phase can be discriminated.

#### 4.2 Simulation results by experimental data

The proposed method was investigated based on the experimental data obtained by using a 6600[V]/210[V], 300[kVA] wye-delta connected transformer. The primary current, primary voltage and secondary current were measured when the transformer was energized in two cases: when the secondary side of the transformer was open, and when a short-circuit fault was caused to simulate an internal fault.

First, the results in the case of an inrush are described below. Figure 6 shows the primary current obtained when the transformer secondary side was open. The proposed method is applied to the relationship between the current

values determined by the equations from (16) to (21) using the measured current values and the integral values of voltage in each phase. There are six combinations of determined current value and voltage in each phase as shown above. Figure 7 shows only two combinations in which an inrush was discriminated. In this case, inrushes occur in phases A and B. It is possible to observe an inrush on the phase A winding from the relationship between the integral value of  $v_{ma}$  and the current  $i_{ma2}$  and an inrush on the phase B winding from the relationship between the integral value of  $v_{mb}$  and the current  $i_{mb1}$ . With the application of (3), inrushes on the phase A winding and phase B winding were detected at 1.8 ms and 3.8 ms after the current became larger than the given threshold respectively, before the current value reached the peak. This means that the proposed method is effective even for inrushes in two phases.

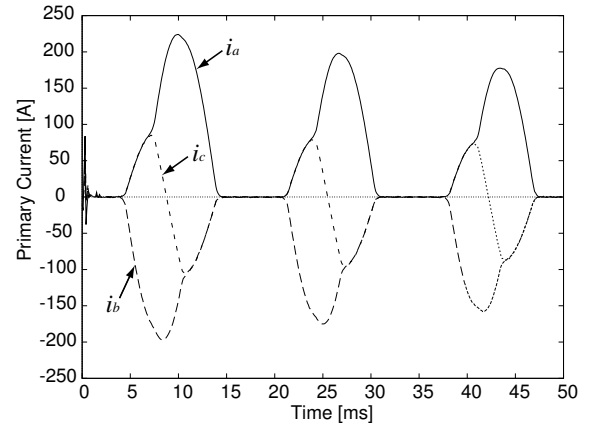


Figure 6: Waveform of current during inrush.

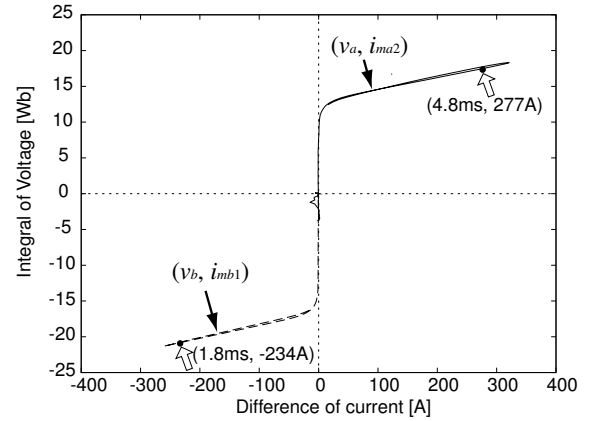


Figure 7: Magnetizing characteristics during inrush.

Next, the results in the case of a fault in the transformer are described. Figure 8 shows the primary current curves obtained when the three phases were short-circuited on the secondary side of the transformer. Figure 9 shows the relationship between the difference of current in each phase and the integral value of the potential of each phase from the neutral point under the same conditions as in Figure 8. One of the six combinations is shown in this figure. As the result of use of (3), an inrush was not observed in all six combinations.

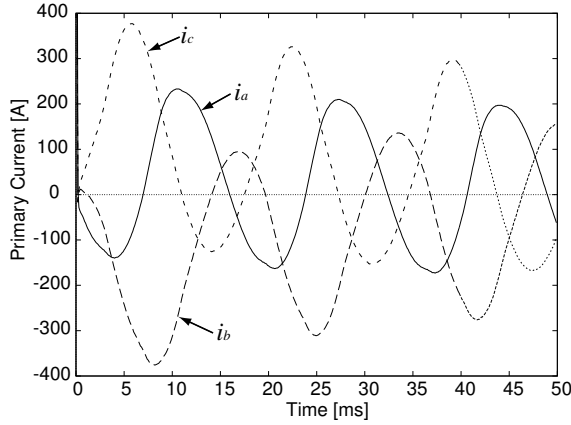


Figure 8: Waveform of current during internal fault.

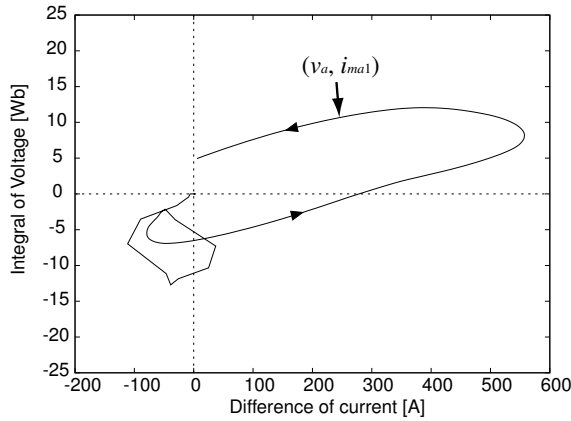


Figure 9: Magnetizing characteristics during internal fault.

#### 4.3 Discrimination of inrush with simultaneous short-circuit fault

When a short-circuit fault between phases occurs, if the voltage sag in the other phases is small, an inrush may occur on the windings of these phases. Figure 10 shows an example of this condition. Then, when the state in which the condition of  $|i_{ma1}(= -i_{mb2})| > i_{min}$  has lasted for a determined time,  $t_{min}$ , if the conditions of  $(v_{ma}, i_{ma1})$  and  $(v_{mb}, i_{mb2})$  are not discriminated the inrush, i.e. there is a strong possibility that an inrush has not occurred in phase A or phase B, and it is considered that a short-circuit fault may have occurred. Also  $i_{mb1}(= -i_{mc2})$  and  $i_{mc1}(= -i_{ma2})$  are evaluated in the same manner, and, when the short-circuit fault is observed in at least two of these three conditions, it is considered that a short-circuit fault has occurred. The condition of detecting a short-circuit fault is as follows:

if at least two of the following three conditions:

if  $\{|i_{ma1}(= -i_{mb2})| > i_{min}\}$  and  $\{(v_{ma}, i_{ma1}) \text{ and } (v_{mb}, i_{mb2}) \text{ not inrush}\}$

if  $\{|i_{mb1}(= -i_{mc2})| > i_{min}\}$  and  $\{(v_{mb}, i_{mb1}) \text{ and } (v_{mc}, i_{mc2}) \text{ not inrush}\}$

if  $\{|i_{mc1}(= -i_{ma2})| > i_{min}\}$  and  $\{(v_{mc}, i_{mc1}) \text{ and } (v_{ma}, i_{ma2}) \text{ not inrush}\}$

then short-circuit fault

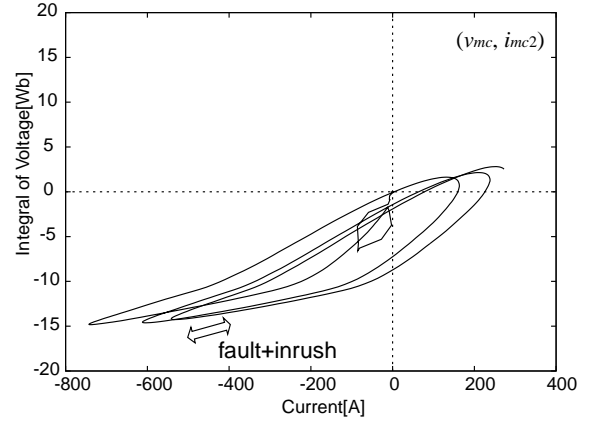


Figure 10: Example of inrush during short-circuit fault.

## 5 DISCUSSION

### 5.1 Relationship between residual magnetic flux density and inrush

The magnitude of an inrush current depends on the residual magnetic flux and the voltage applying phase of each phase. Figure 11 shows an example in which the inrush cannot be detected. The reason for this failure is that the amplitude of the inrush current is too small. In the proposed method, the appropriate threshold of detecting an inrush current has to be determined. It is appropriate to set the threshold to several times as much as the base current.

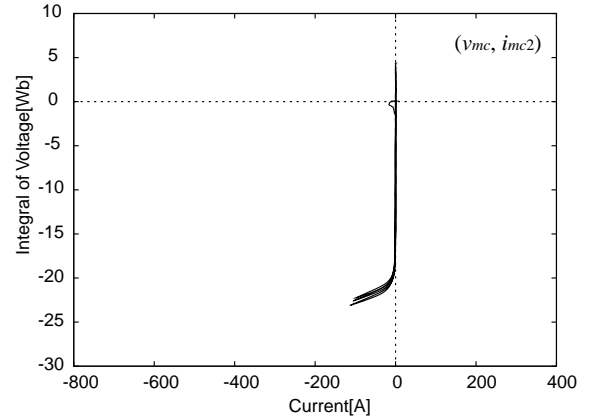


Figure 11: Example of failure to detect an inrush.

If the residual magnetic flux is obtained when a transformer stops, the occurrence of an inrush current can be prevented by synchronous controlled switching suitable for each of three phases. However, in the transformers used on plant facilities of customers, it is generally difficult to obtain the residual magnetic flux before the transformers energize. Therefore, it is considered to be difficult to prevent an inrush by optimal controlled switching in plant facilities of customers.

### 5.2 CT saturation

Since the proposed method is based on the magnetization characteristics of the transformer core, its discriminating performance may degrade when CT is saturated if the voltage sag is small, because the CT saturation affects

the secondary signals and the saturation characteristics of the transformer core cannot be estimated correctly by the distorted signals. However, measuring devices, such as Rogowski coils and optical CTs, will be mainly used in distribution systems. Although Rogowski coils have some problems, such as a problem of noise removal, because of their low sensitivity, recently, those on the practical use level have been developed[13]. Optical CTs are characterized by their compact sensor blocks, ease of ensuring electrical insulation and resistance to external noises because they obtain measurements based on the optical Faraday effect. The use of such CTs without a core will decrease the problems of CT saturation.

## 6 CONCLUSION

This paper proposed a new fast discriminating method of magnetizing inrush in energizing transformers in distribution systems.

Distribution systems require fast fault detection from the viewpoint of power quality. Therefore, discriminating an inrush to meet the demand for increased reliability is also indispensable. Formerly, the function of detecting an inrush was a function specific to the transformer primary protective relay. However, it will be required to provide overcurrent relays with this function on distribution systems.

Therefore, an new method of discriminating inrush current that predicts the magnetization characteristics of the transformer core based on the relationship between integral values of voltage and current values was proposed. To apply this method to a three-phase transformer, it is necessary to use the single-phase inrush current values determined in consideration of the helping effect.

The authors validated the proposed method using test data obtained with the transformer of actual equipment. The proposed method could detect an inrush current within a half cycle, 4 to 5 ms, and proved to be effective.

The authors will examine the discriminating algorithm in more detail based on the results of the experiments, the hardware architecture to which the algorithm will be implemented, and the fast protection system using this method on distribution systems.

IEEE Power Engineering Education Committee, Advancements in Microprocessor Based Protection and Communication, IEEE Tutorial Course, 97TP120-0, 1997

## REFERENCES

[1] G. T. Heydt, R. Ayyanar and R. Thallam, "Power Acceptability", IEEE Power Engineering Review, Vol.21, No.10, pp.12–15, 2001

[2] R. Hara, T. Suzuki, H. Kita, E. Tanaka, J. Hasegawa and I. Iyoda, "The Effects of the Transfer Switching on the Low Voltage Side of Quality Control Center in FRIENDS", Proc. of POWERCON 2000, pp.667–671, 2000

[3] M. Kitayama and M. Nakabayashi, "A Fast Discrimination Method of Inrush Current based on Transformer Magnetizing Characteristics", Trans. on Electrical Engineering in Japan, Vol.121, No.8, pp.982–989, 2001

[4] K. Inagaki, M. Higaki, Y. Matsui, K. Kurita, M. Suzuki, K. Yoshida and T. Maeda, "Digital Protection Method for Power Transformers Based on an Equivalent Circuit Composed of Inverse Inductance", IEEE Trans. on Power Delivery, Vol.3, No.4, pp.1501–1510, 1988

[5] K. Yabe, "Power Differential Method for Discrimination between Fault and Magnetizing Inrush Current in Transformers", IEEE Trans. on Power Delivery, Vol.12, No.3, pp.1109–1118, 1997

[6] B. Grčar, G. Štumberger and J. Pihler, "Transformer Protection based on the New Theoretical Background and with Improved Inrush Recognition", Proc. of 12th PSCC, pp.101–106, 1996

[7] B. Kasztenny, E. Rosolowski, M. M.Saha and B. Hillstrom, "A Comparative Analysis of Protection Principles for Multi-criteria Power Transformer Relaying", Proc. of 12th PSCC, pp.107–113, 1996

[8] S. Guocai and Y. Dachan, "Identifying Internal Faults of Transformers through the Similarity Degree between Voltage and Current", Proc. of IEEE/PES 2000 Winter Meeting, pp.1151–1156, 2000

[9] Moisés Gómez-Morante and Denise W.Nicoletti, "A Wavelet-based Differential Transformer Protection", IEEE Trans. on Power Delivery, Vol.14, No.4, pp.1351–1358, 1999

[10] J. Koda and K. Yabe, "Dynamic Estimation of Magnetizing Curve for Transformer Protection Relay", Proc. of the ICEE, E02, pp.94–97, 1997

[11] M. Takeda, H. Yamamoto, T. Aritsuka, I. Kamiyama and G. F. Reed, "Development of a Novel Switch Device and Application to a Solid-State Transfer Switch", Proc. of IEEE/PES 1999 Winter Meeting, pp.1151–1156, 1999

[12] W. K. Sonnemann, C. L. Wagner and G. D. Rockefeller, "Magnetizing Inrush Phenomena in Transformer Banks", AIEE Transactions, Vol.77, part.III, pp.884–892, Oct.1958

[13] L. Kojovic, "Rogowski Coils Suit Relay Protection and Measurement", IEEE Computer Applications in Power, Vol.10, No.3, pp.47–52, 1997

[14] IEEE Power Engineering Education Committee, Advancements in Microprocessor Based Protection and Communication, IEEE Tutorial Course, 97TP120-0, 1997