Fault Diagnosis of Transformer focusing on Circulating Current

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Keywords: Transformer, Circulating current, Frequency response analysis

Abstract

Transformers may fail due to damage during transportation, deterioration over time, overvoltage and so on. The frequency response analysis (FRA) is attracting attention as a method of electrically diagnosing the transformer. However, the FRA has the disadvantage that somebody must go to the sub-station site for FRA testing and the timing of applying the measurement is not certain. We are investigating the sensing method for the condition of the transformer by using a circulating current flowing in a delta winding. In general, the circulating current has high frequency components like third order, fifth order and so on. When the transformer has faults like a winding short circuited, the magnitude of the high frequency component of the circulating current will change. In case the circulating current in a delta winding is monitored, we will have the signal whether the transformer has faults or not. In this paper, a self-made three-phase tripod transformer was used to measure the circulating current at windings short circuited. To measure the circulating current of the delta winding, it was able to detect even the one turn winding short circuited.

1. Introduction.

Transformers connected to the power grid may fail due to damage during transportation, deterioration over time, stress due to overvoltage and so on. For large capacity transformers, windings and core are installed in a tank, it is difficult to detect a fault by visual or mechanical diagnosis. Therefore, frequency response analysis (FRA) has attracted attention as a method for electrically diagnosing transformers condition and various studies have been conducted [1]-[5]. When impedance of the transformer is measured by the FRA, it is necessary to measure voltage and current. Since a transformer generally has large stray capacitances, there is an apparent difference in impedance depending on the part where the current is measured. Therefore, we stated that the currents of stray capacitances should also be measured accurately [6].

To measure the FRA, we should go to the sub-station and the timing of applying the FRA measurement is uncertain. In recent years, online monitoring methods have also been studied [7]-[9]. Although methods using wavelet transforms have been studied [10], FRA seems to be effective as a diagnostic method but not yet practical for users.

The three phase transformers installed in the power grid have a delta winding to circulate harmonic currents such as the third harmonic caused by the magnetizing characteristics of the iron core. We are studying a transformer fault diagnosis method focusing on this circulating current in a delta winding. When a fault such as a short circuited in the winding of a transformer occurs, the circulating current will change. To monitor the circulating current flowing in the delta winding, it will be able to detect the fault occurrence of the transformer.

In this paper, the change of circulating current in case of short circuited faults in the windings of a self-made three legs transformer is investigated under no load and on load conditions. As a result, even one turn short circuited in the winding caused a difference in the circulating current. It was shown that the occurrence of the fault for the transformer can be detected to monitor the circulating current flowing in a delta winding.

2. Principle of diagnosis by Δ winding circulating current

It is known that the magnetizing current of a transformer contains the some harmonic components such as third and fifth order in addition to the fundamental component of the commercial frequency. Figure 1 shows the three phase magnetizing currents. Common third harmonic current with an amplitude 0.3 p.u. is pulsed to the three phase fundamental currents with an amplitude 1 p.u., while the fifth and subsequent harmonic current components are small and ignored. This figure shows that the third harmonic current is a zero-sequence current.

Figure 2 shows the zero-sequence circuit of a Y-Δ three-phase transformer. Since the zero-sequence circuit is connected between Y winding and Δ winding, the third harmonic current included in the magnetizing current flows in the Δ winding. The fundamental current component is the positive sequence current and of course it flows in the delta winding. However, the fundamental component does not usually appear in the circulating current flowing in delta winding. Because sum of the fundamental currents for three phases is zero.

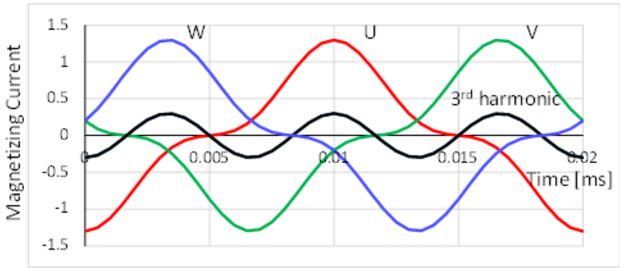

Fig 1. Magnetizing currents and third harmonic current

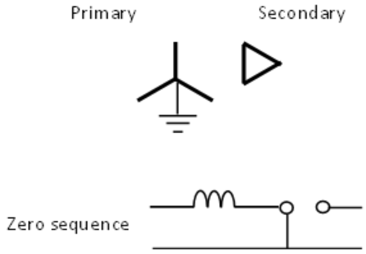

Fig 2. Zero-sequence circuit for Y-Δ transformer

Here, it is assumed that a single-phase transformer has the cross-sectional area S of the transformer iron core, the average magnetic path length l, the number of turns of the primary winding n_1 and the magnetizing current I_0. The voltage V_1 at the primary winding induced by the magnetizing current I_0 is given by the equation (1).

$$V_1 = \frac{-n_1^2 \mu_s \mu_0 S}{l} \frac{dI_0}{dt} \qquad (1)$$

Assuming that the leakage inductance of the transformer can be neglected, the induced voltage V_1 of the primary winding is the same as the supply voltage. When a winding short circuited occurs, n_1 becomes small and the magnetizing current I_0 will be large. Figure 3 shows the current waveform when the fundamental component of U phase current is made larger than the other phases with an amplitude 1.2 p.u. It can be seen that the circulating current in the Δ winding has a fundamental component superimposed on the third harmonic. This fundamental component is corresponding to the U phase current increased by the winding short circuit. Therefore, when the circulating current of the delta winding is measured, the presence of transformer faults such as winding shorts can be detected.

3. Measurement of delta winding circulating current

3.1 Three single-phase transformers

In recent years, three-legged iron core transformers have been used for medium and low voltage transformers. In a three-legged core, the magnetizing characteristics of the middle phase are different from those of the end phase due to the difference in magnetic path length [11]. Since the difference in magnetizing characteristics is expected to affect

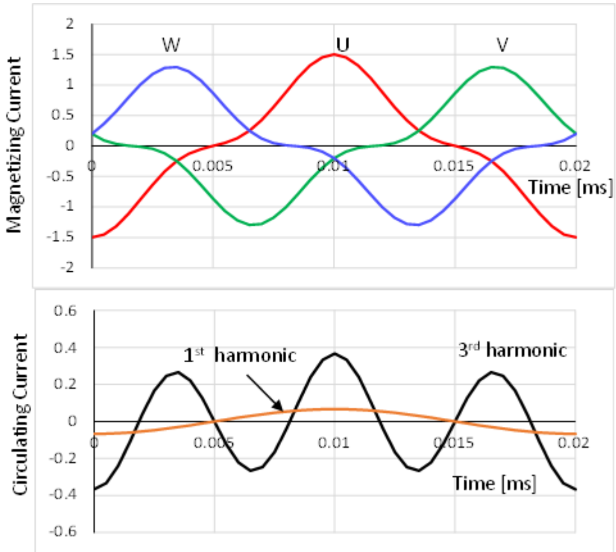

Fig 3. Change of the magnetizing and circulating currents at fault condition

the circulating current of the Δ winding, a three-phase transformer is constructed using three single-phase two-winding transformers with the same characteristics and the circulating current of the Δ winding is investigated by calculations at first. The transformer used has a capacity of 1kVA and a rated voltage of 100V for the primary and 100V for the secondary. The transformers connected Y-Δ windings.

Figure 4 shows the calculated primary line current waveforms and the secondary circulating current waveform. Since all three single-phase transformers are identical, the primary line current waveforms almost equal. The third harmonic component only appears in the circulating current.

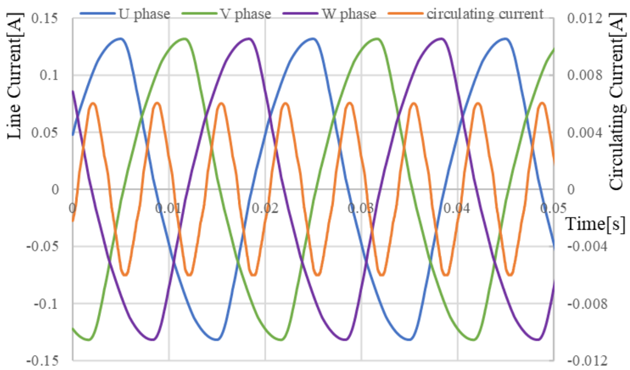

Fig 4. Calculated magnetizing currents and circulating current at three phase 1kVA transformers with healthy condition

To simulate a winding short circuited fault, the primary voltage at W phase was changed from 100V to 90V. Figure 5 shows the calculated current waveforms. The line current at W phase is slightly small. And the circulating current has a fundamental component with the third order component.

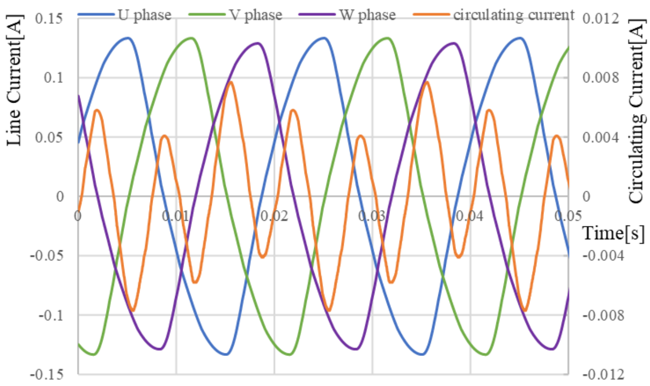

Fig 5. Calculated magnetizing currents and circulating current at three phase transformers with fault condition

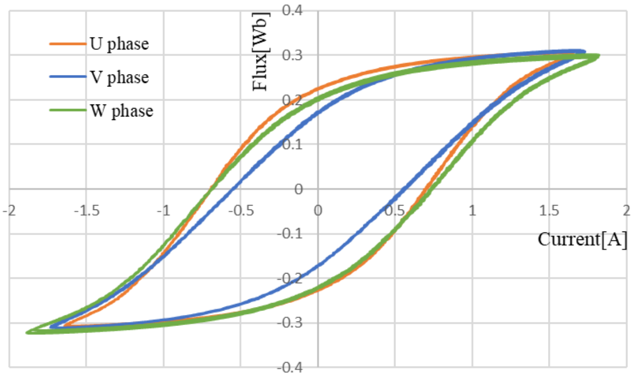

Fig 7. Magnetizing characteristics of each phase of self-made transformer.

3.2 Three-legs core transformer

To investigate the relationship between the degree of winding short circuited and circulating current in detail, a three-legs transformer shown in figure 6 was built by ourself. The transformer had a capacity of 1500 VA and the number of windings was 68 turns for the inner winding (hereafter referred to as 68t) and 141t for the outer winding.

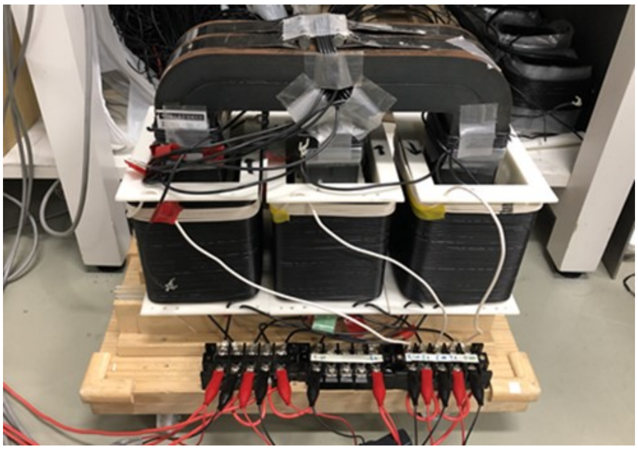

Fig 6. Appearance of self-made transformer.

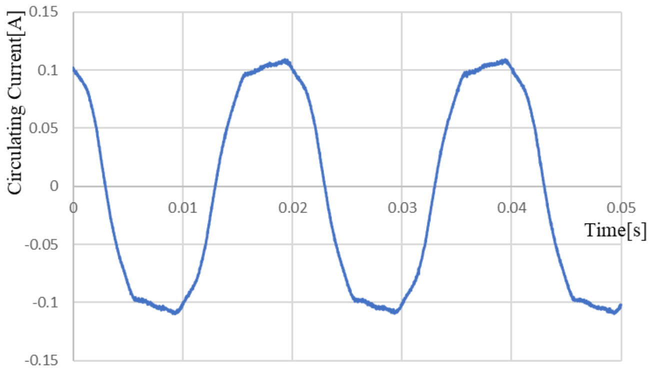

Fig 8. Circulating current waveform.

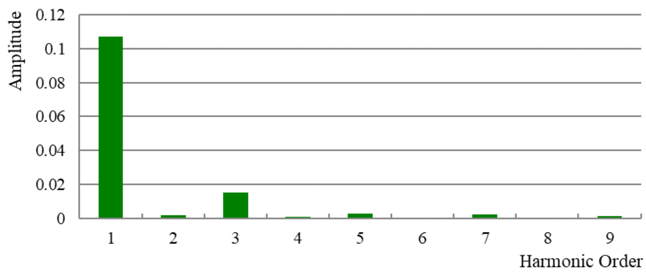

Fig 9. Frequency component of circulating current.

Figure 7 shows the current-flux (I-Φ) characteristics of each phases. Voltages with 200 [V] were applied between the phases of 141t windings and measured for each phases individually. U and W are the edge phases, and V is the middle phase. The magnetizing characteristic of the V phase of the middle phase is narrower than those of the other phases because the magnetic flux path length differs between the middle and outer phases.

Figure 8 shows the circulating current measurement waveform. The primary side (141t) is connected to a Y connection and the secondary side (68t) as a Δ connection. Figure 9 shows the results of the frequency analysis. Due to the differences in the magnetizing characteristics of each phase shown in Figure 7, the circulating current has mainly fundamental wave components, but it can be seen that third harmonic component is also included.

Next, the circulating current was measured under windings short circuited condition. Figure 10 shows the circulating current measurement waveforms when the W phase winding of the primary Y side is one turn short circuited. The waveform in the healthy state is the same as in figure 8. In figure 10, the circulating current at one turn short circuited is larger than the healthy one. In general, it is difficult to detect fault with a one turn short circuited but the circulating current in the delta winding shows changes in amplitude.

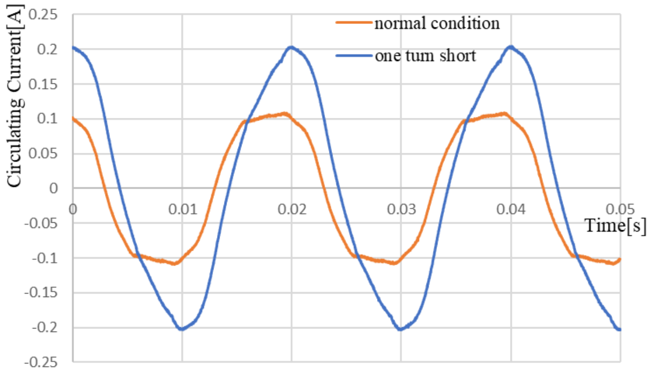

Fig 10. Circulating current comparison between normal condition and one turn short circuited

4. Circulating current under load

4.1 Reproduction of circulating current

We have discussed the circulating current of the delta winding under no-load conditions. When the transformer is in operation, the load current will flow in a delta winding. In a high voltage three phase transformer, the delta winding is unlikely to take the load. But in a Y-Δ connected transformer, the effect of the load current is expected to appear in the delta winding as well. It is difficult to conduct experiments with a load in the university laboratory, the three-legged iron core transformer is modeled and discussed in the following calculations. The measured values of winding resistance and leakage inductance for each phase of the three-legged iron core transformer are shown in Table 1. The current-flux characteristics of the iron core are shown in figure 7.

Table 1 Winding resistance and leakage inductance of the three -legs transformer

	Winding resistance [Ω]		Leakage inductance [mH]	
	Primary	Secondary	Primary	Secondary
Phase U	1.551	0.6704	1.267	0.6333
Phase V	1.529	0.6783	1.372	0.6867
Phase W	1.531	0.6791	1.422	0.7113

Figure 11 shows the comparison between measured and calculated waveforms of the circulating current at healthy condition. The calculated circulating current was good agreed with the measured result. In a winding fault, the number of turns will be reduced because the winding is short-circuited, and the magnetizing characteristics of the iron core will also change as a result.

Figure 12 shows the measured and calculated current waveforms at one-turn short circuit. Aspects of the circulating current at the time of faults can be reproduced by calculation.

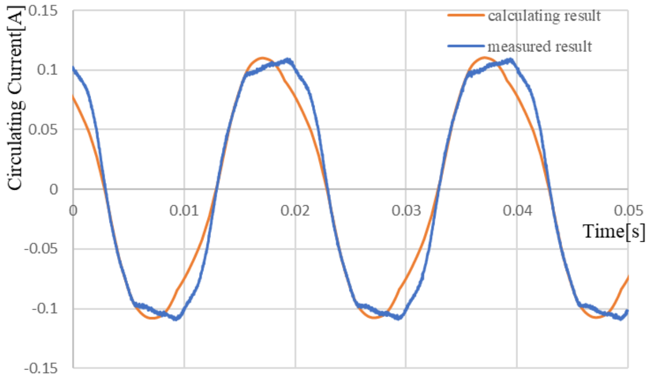

Fig 11. Calculated and measured circulating current at healthy condition.

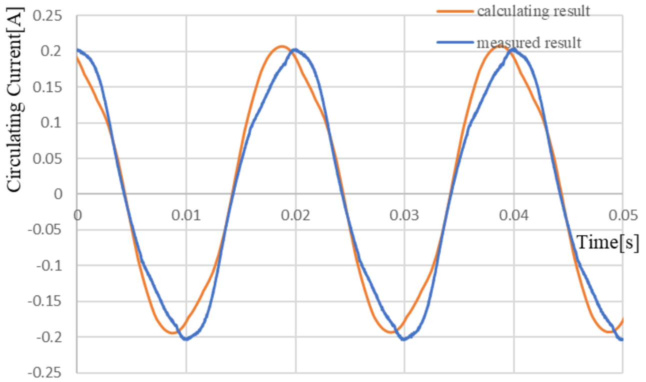

Fig 12. Calculated and measured circulating current at one turn short-circuited

4.2 Circulating current under on load conditions

It is assumed the load is Y-connected and the power factor is 1 and 0. 100Ω resistors are connected to the transformer Δ winding terminals at a power factor of 1, and 100mH inductances are connected at a power factor of 0. The winding short circuited was set to one turn in the W phase of the primary Y winding.

Figure 13 shows the calculated result waveforms at the load of 100Ω resistors. Figure 14 shows the calculated result waveforms at the load 100mH inductances. In both cases, the currents at short circuited are larger than the healthy state.

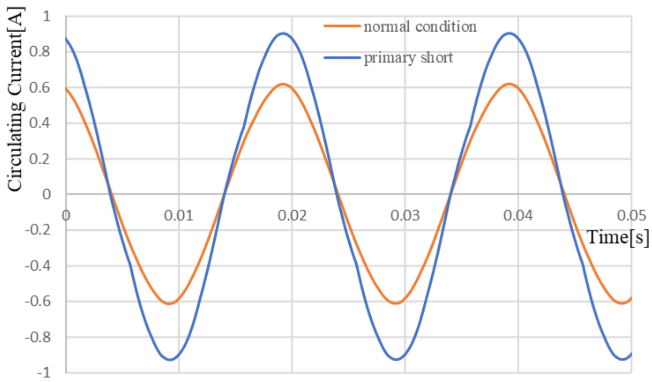

Fig 13. Circulating current under on load condition when R = 100 [Ω]

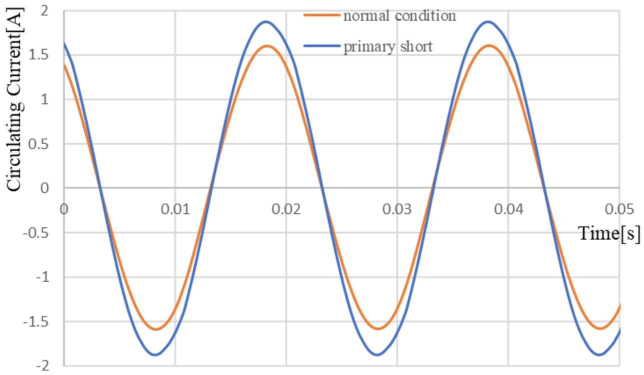

Fig 14. Circulating current under on load condition when L = 100 [mH]

There was no change in the load currents magnitudes at figure 13 and 14. According to another calculations, a difference of about 0.1 A appears in the load current when 30 turns are short circuited. It is not expected to detect the difference about 0.1A by using the CTs installed in the actual power grids. However, since a difference appears in the circulating current, it is thought that a short circuit fault can be detected by monitoring the circulation current even under loaded conditions.

5. Conclusion

In this paper, we proposed a method to detect the occurrence of transformer faults by monitoring the circulating current in delta winding. The effect of winding faults on the circulating current was investigated.

(a) Circulating currents were measured in a three-phase Y-Δ transformer under winding fault condition with no-load. The shape and magnitude of the circulating current changed even with a one-turn winding short circuited.

(b) The circulating current was calculated under the condition that load current was flowing. It was found that the circulating current changes when a one-turn winding short circuited occurs even under on-load condition.

(c) Faults such as one-turn short circuited will be difficult to detect from the monitoring load current and or power system voltages. However, to monitor the circulating current flowing in delta winding, it is possible to detect the occurrence of faults in transformer.

(d) When the change in circulating current is measured, the user will do the FRA measurements. This seems to be a great advantage for transformer users, as inspections can be done without wasting time.

6. References

[1] E. P. Dick, C. C. Erven “Transformer Diagnostic Testing by Frequency Response Analysis” IEEE Trans. on Power Apparatus and Systems, Vol. PAS-97, No.6, pp.2144-2153, 1978

[2] T. Leibfried, K. Feser, “Monitoring of Power Transformers using the Transfer Function Method” IEEE Trans. on Power Delivery, Vol.4, No.4 pp.1333-1341, 1999

[3] CIGRE Working Group A2.26 report “Mechanical-condition assessment of Transformer windings using Frequency Response Analysis (FRA)” 2008

[4] IEEE Std C57.149 “IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers” 2012

[5] Eduardo Gomez-Luna, Guillermo Aponte Mayor, Carlos Gonzalez-Garcia, Jorge Pleite Guerra, “Current Status and Future Trands in Frequency-Response Analysis With a Transformer in Service” IEEE Trans. on Power Delivery, Vol.28, No.2, pp.1024-1031, 2013

[6] Kohei Ishizaka, Tadashi Koshizuka, Hisatoshi Ikeda, Yasuhiko Taniguchi, Eiichi Haginomori, “Investigation on Frequency Response Analysis Measurement Method for Power Transformer Impedance”, IEEE T&D Conference, 2016

[7] M. A. Hejazi, G. B. Gharehpetian, G. Moradi, H. A. Alehosseini, M. Mohammadi “Online monitoring of transformer winding axial displacement and its extent using scattering parameters and k-nearest neighbor method”, IET Gener. Transm. Distrib., 2011, Vol.5, Iss.8, pp.824-832

[8] Ali S. Masoum, Naser Hashemnia, A. Abu-Siada, Mohammad A. S. Masoum, Syed M. Islam “Online Transformer Internal Fault Detection Based on Instantaneous Voltage and Current Measurements Considering Impact of Harmonics” IEEE Trans. on Power Delivery. Vol.32, No.2, pp.587-598, 2017

[9] Vahid Behjat, Abolfazl Vahedi, Alireza Setayeshmehr, Hossein Borsi, and Ernst Gockenbach “Diagnosing Shorted Turns on the Windings of Power Transformers Based Upon Online FRA Using Capacitive and Inductive Couplings” IEEE Trans. on Power Delivery, Vol.26, No.4, pp.2123-2133, 2011

[10] Eduardo Gómez-Luna, Guillermo Aponte Mayor, Jorge Pleite Guerra, Diego Fernando Silva Salcedo, Doris Hinestroza Gutiérrez, “Application of Wavelet Transform to Obtain the Frequency Response of a Transformer From Transient Signals—Part 1: Theoretical Analysis” IEEE Trans. on Power Delivery, Vol.28, No.3, pp.1709-1714, 2013

[11] Yukihiko Himata, Masaya Hiraide, Ryoichi Tanaka, Takashi Nakajima, Tadashi Koshizuka, “Residual Magnetic Flux of Three-Phase Three-Leg Transformer for Controlled Switching,” IEEE T&D Conference, 2018.