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The Effect of short circuit fault in three-phase core-typed transformer

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Article Info	ABSTRACT
	Different techniques for monitoring the transformer condition are continuously discussed. This is due to the fact that transformers are one of the most expensive components in the power system network. Not to mention the cost to fix any failure occurred in the transformer that have becoming more expensive nowadays. Frequency response analysis (FRA) is found to be the best method to monitor the transformer reliability. This paper presents a continuation of study presented in previous paper [1]. The study performed a laboratory test to show that the response of a normal winding phase A can be affected by short circuit fault which occurred at LV winding phase a, b, and c. To further investigate, current paper performed FRA measurement and applied fault on all phases. The same procedure is repeated on a distribution transformer to verify the findings. This is to examine the effect of fault at winding of other phases to the response of measured phase.

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1. INTRODUCTION

Transformers are exposed to various electrical and mechanical failures during their lifespan. Some of these were caused by mishandling during maintenance and transportation, earthquake, and even external faults. Extended outages, costly repairs and potentially serious fault mostly occurred to transformer active parts which are the core and windings. It is found that, core damage is more likely as a result of shocks cause by transportation, while winding damage is caused by short circuit (SC) forces [2,3]. To assess the condition and mechanical reliability of transformers, frequency response analysis (FRA) is proven to be a powerful and effective method [4-8]. It is highly sensitive to electrical or mechanical changes in transformers. For example, [9] has presented the effect of shunt impedance, high voltage bushing and length of measurement lead in the response. In [10], the reference observed the response sensitivity towards the capacitance and mutual inductance between the windings. Reference [11] studied the response sensitivity towards temperature and moisture content of the transformer insulation. It showed there is a considerable change in the response indicating that it is highly sensitive even on non-mechanical factor. Reference [12] had reviewed literature related to the aspect that must be considered when implementing SFRA method, which is connection of non-tested terminals when diagnosing winding failures. Reference [13] has found that the winding response of an autotransformer can be affected by the tertiary winding due to coupling effect between windings. More studies are necessary to further understand this sensitivity of FRA measurement.

This paper is proposing to investigate the effect of fault which occurred in other winding on the response of the measured winding. The measurements in this study were conducted on three-phase transformers at a local research utility company. FRA end-to-end open circuit test is used, and the fault is short circuit turns that was created by shorting the terminals on the tap changers.

2. SHORT CIRCUIT FAULT IN TRANSFORMER WINDING

According to [14], faulty winding usually occurs in distribution transformers. This is because the current flow in the primary winding undergoes electromagnetic induction voltage which is stepped down. The current is then stepped up in the secondary winding. During this process, the secondary windings have to withstand electrical, thermal and mechanical stresses [15]. Several types of faulty windings such as the SC fault commonly occurred due to these stresses. The occurence of SC is quite rare, but the probability is increased during the transformer lifetime which is typically up to 50 years [16]. In spite of this, according to [3], about 40% of the transformer faults are initiated by huge impact of SC every year.

One of the sources contribute to SC fault is insulation breakdown. Insulation breakdown usually occurs due to high current and voltage which is above the rated values. The breakdown of the insulation results in flashover between two turns and causes inter-turn SC fault. Besides that, thermal losses in copper will produce hotspots in the winding. This over time causes tear of the insulation and decrease of the physical strength up to the point of breaking of the winding. Ultimately, causing SC fault in the winding. According to [17], SC faults are divided into three basic categories. These are winding-to-ground fault, winding-to-winding fault, and turn-to-turn fault on the same winding. Turn-to-turn or inter-turn short SC fault is the most commonly to occur. Figure 1 illustrates the occurrence of inter-turn SC fault due to insulation breakdown.

In general, SC in the winding causes reduction of the winding electrical length. In case of winding coupled with magnetic core, the main sign of internal short-circuit fault is a significant increase of first antiresonance in frequency response corresponding to open secondary winding [18]. The frequency range is typically several Hz up to few kHz, which is the low frequency (LF) region. The key point to understand the LF variation affected by shorted turns can be obtained in the description of Faraday's law in the shorted turns. The law states that the "electromagnetic force (emf) induced in a turn is equal to the rate of variation of the electromagnetic flux inside it" [19]. The paper also presents finite-element method (FEM) showing the changes of magnetizing characteristics of core, which causes the LF deviation. This important property can be used as one of the main indications of winding SC fault. However, it must be remembered that the deviation of the LF responses is not a sign the presence of the SC in the winding under measurement only, because the increases occur in the frequency responses of all windings on the same core [20].
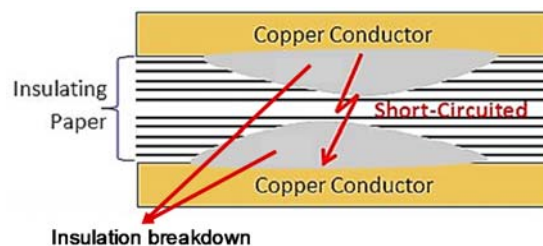

Figure 1. Inter-turn short circuit due to insulation breakdown

3. MEASUREMENT PROCEDURE
3.1. Details of experimental transformer

The basic details of the transformers used in this paper are given in Table 1 and Table 2.

Table 1: Details of 360VA experimental transformer

Attributes	Details
Model	KTS 10MT-3/360 VA
Capacity	Three-phase, experimental transformer of 360VA
High voltage winding	240 V Delta connected
Low voltage winding	3×60 V Star connected
Current	2 A

Table 2: Details of 500kVA distribution transformer

Attributes	Details
Model	ONAN TRANSFORMER DRG. No. MTM 11/3/1-D
Manufactured date	21/06/1984
Capacity	Three-phase, 50 Hz, 500 kVA
Vector group	Dyn11
Oil	672 L – 578 Kg

3.2. FRA measurement connection

FRA configuration used is the end-to-end open circuit test. Measurement is conducted per phase with the secondary winding is left open circuit. The study is conducted by measuring and comparing the FRA response before and after the presence of SC fault in the winding. In this study, the FRA measurement is conducted on the HV winding of phase A, B and C one after another. While the fault is applied at the LV winding of phase a, b and c consecutively. This is to observe whether fault at winding of other phases can actually affect the response of measured phase.

Figure 2(a) shows a short and thin cable was used to connect between two terminals (shown in circle) of a Dyn11, 360VA transformer. This causes 1/3 of the total LV winding to be shorted or removed from the main winding. Figure 2(b) shows the schematic diagram of the short circuit fault. On the other hand, the fault in second transformer is created by connecting a cable to the exposed transformer taps in each phase. This is shown in Figure 3. Figure 3(a) shows the physically simulated short circuit fault on tap 3-4 of phase B and Figure 3(b) shows the schematic diagram of the simulated fault.
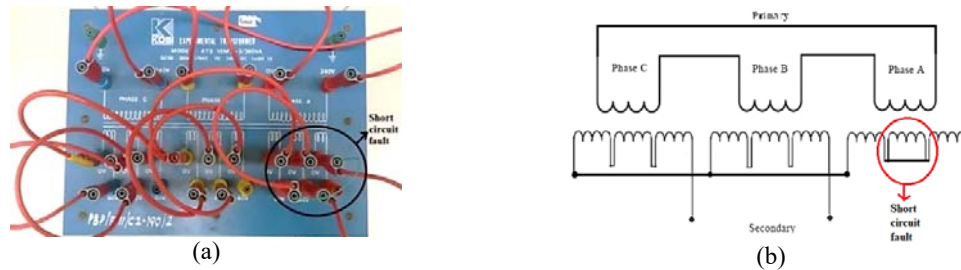

Figure 2. (a) SC fault on LV winding of phase A, (b) Schematic diagram of the winding and fault location.
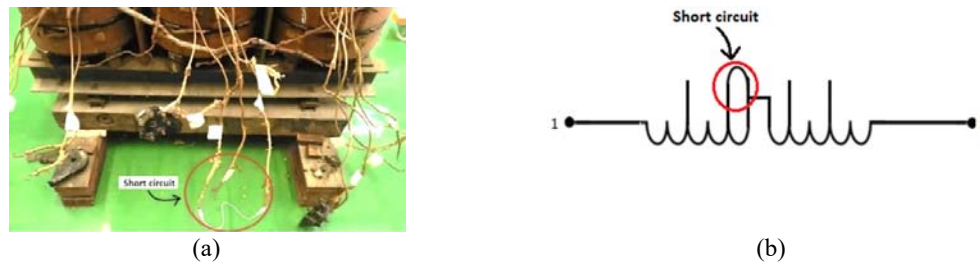

Figure 3. (a) SC fault on tap 3-4 of phase B, (b) Schematic diagram of the winding and fault location

4.   THE ANALYSIS OF SHORT CIRCUIT EFFECT TO OTHER WINDING PHASES

Figure 4 and Figure 5 show the frequency responses of two different transformers before the fault is simulated on the transformer windings.

From Figure 4, the low frequency region of FRA response for phase B, which is middle phase winding shows a slight variation from the other two phases. As discussed in [13], this is due to the magnetic path of middle phase which is slightly different from the side phases (side limbs). Meanwhile, the variation of FRA responses at medium frequency region is affected by the three-phase coupling between the windings.

Figure 5 shows the measured responses of end to end open circuit test on the 500kVA transformer. Clearly it shows there are slight variations between phases A, B and C. Such variation is due to the condition of the transformer which is not new. The transformer itself was manufactured in 1984 and was taken out of service due to a fault near bushing. The windings have several dents, but these were minimal. The turn ratio and winding resistance test for both transformers indicate that the windings are still in good conditions.

4.1. Response phase A

Figure 6 shows the responses where FRA measurement is conducted at phase A of HV winding. The short circuit fault is simulated on phase a, b and c of LV winding consecutively. From Figure 6, response 'Normal A' represents the response before the short circuit fault is applied on the winding. The other responses represent the response after fault have applied on the winding respectively.
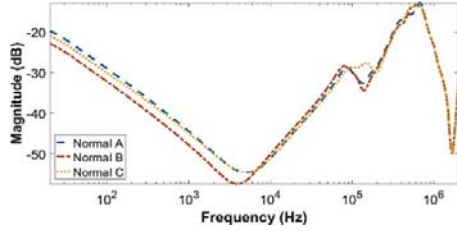
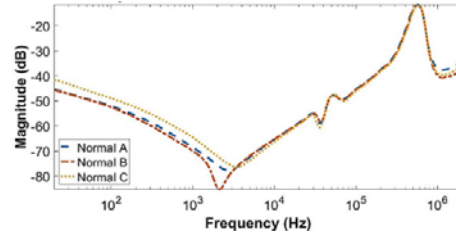Figure 4. FRA response on normal winding condition
of 360VA transformer

Figure 5. FRA response on normal winding
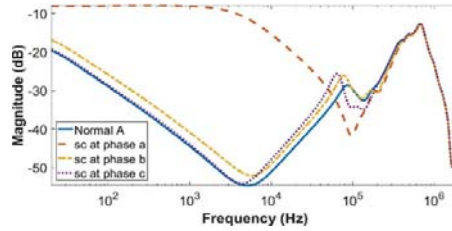condition of 500kVA transformer

Figure 6. Frequency responses of phase A from 360VA transformer

Figure 6 shows the comparison of response normal A and when SC fault has occurred on its LV winding. It is the result of the FRA measurement that was conducted at the same phase as the faulty winding. The response significantly shifted to right, towards higher frequencies. This can be explained using (1),

$$\Phi \propto NI \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (1)$$

Equation (1) shows that the amount of flux, Φ is directly proportional to the product of the number of turns, N and the current flow in the winding, I. In general, the internal SC leads to reduction of the electrical length of the winding, meaning reduction of N [20]. When the number of turns reduces, the flux formed in the coil also reduced. As a result, during SC fault, the magnetizing inductance of the right-side limb is drastically reduced and caused the magnitude in low frequency region to increase. The large amount of shift is affected by the magnetizing inductance in the limb of the core caused by the SC fault in the secondary winding of the same phase. It causes a substantial effect in the response of phase A.

Figure 6 also shows the responses when SC fault is on phase b (LV winding). The response of LF region is seen to be slightly shifted towards higher frequencies. The shifting is much less when compared to the previous case. This is because the faulty is not located at the same phase as the measured winding. Finally, for response when fault occurred in phase c, the initial antiresonance of the response is marginally shifted towards higher-frequencies. The degree of shifting is smaller when compared to the previous cases. This is because the fault occurred at winding phase c that is located furthest away from the measured winding (Phase A). Basically, the response of winding phase A when faulty in phase b shifted more compared to when fault in phase c. This can be explained with the help of Figure 7, (2) and (3).
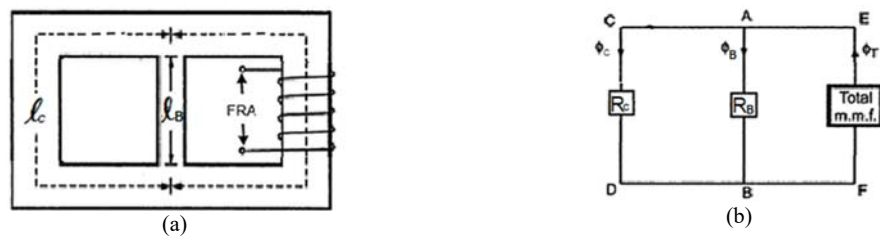

Figure 7. (a) The core of a three-phase transformer with FRA measurement at phase A, (b) Equivalent
magnetic circuit of FRA measurement at phase A

Where R_B is the reluctance of central limb (phase B), R_C represents the reluctance of left-side limb (phase C), l_B is the length of central limb (phase B), l_C is the length of left-side limb (phase C), μ is the magnetic permeability which is the product of $\mu_o \mu_r$ and A is the cross-sectional area refers to geometry of the core.

$$R_X = \frac{l_X}{\mu A} \tag{2}$$

From Figure 7, when FRA measurement is performed at winding of phase A, current flows in the winding and flux is produced in the core. The flux flow in the core and pass through each limb. The length of flux path flowing from phase A (source) and pass through the central limb, l_B (phase B) is measured from point E, A, B to F. Meanwhile, the length of flux path for the left-side limb, l_C (phase C) is measured from point E, A, C, D, B to F. The l_B is shorter compared to the l_C, thus the reluctance of the central limb R_B is lower than R_C as in (2). χ in (2) is either phase A, B or C. As the reluctance of the central limb, R_B is lower, the flux that pass through central limb, Φ_B is higher than the flux in left-side limb, Φ_C.

$$back\ emf = 4.44 N f \Phi m \tag{3}$$

Now that we have established that Φ_B is higher than Φ_C, let relate the flux with the back EMF. Theoretically, the back EMF of phase B is higher compared to back EMF of phase C. This is because Φ_B is higher than Φ_C as referred to (3). As a result, the response when the fault is at phase b is more affected compared to fault at phase c as can be seen in Figure 6.

Figure 8 shows the FRA response for Dyn11, 500kVA transformer where the measurement is conducted at Phase A, while the SC fault is simulated on phase a, b and c winding consecutively. Clearly, when fault is simulated at the same phase, the response significantly shifted towards higher frequency. It is also shown that response due to faulty in phase b shifted more compared to faulty in phase c. This finding is similar to the previous case on the first transformer.

4.2 Response phase B
In this case, the FRA measurement is conducted at winding of the middle limb, phase B, while fault is applied on the LV windings consecutively. The measured responses are given in Figure 9.
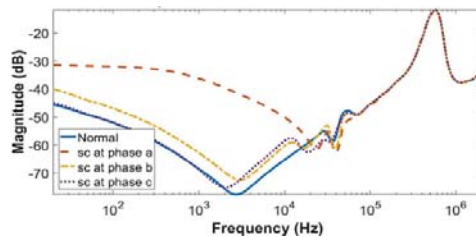

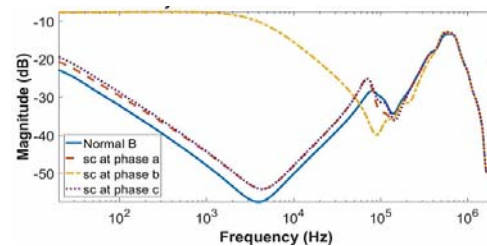Figure 8. Frequency response of phase A from 500 kVA transformer.

Figure 9. Frequency response of phase B for 360VA transformer

From Figure 9, the response shows different pattern of effect when compared to the previous case. In this case, the response when SC fault occurred in the phase a and c affected almost similarly. This is because the fault is on phase a and c that are located adjacent to the measured phase which is phase b. This can be explained by Figure 10 and (2).

From Figure 10, when FRA measurement is performed at HV winding of phase B, current flows in the winding and flux is produced in the core. The length of the flux path flowing from phase B (source) and pass through the right-side limb, l_A (phase A) is considered from point E, C, D to F. Meanwhile, the length of flux path for the left-side limb, l_C (phase C) is measured from point E, A, B to F. The length for both flux path is similar, thus the reluctance for both right and left-side limb, R_A and R_C are also similar. This can be prove using equation (2). As the reluctance of both limbs are similar, the flux that pass through in both right and left side limb are also similar. In addition to that, Φ_A is almost similar to Φ_C. Therefore, the back EMF of phase A is also almost similar to back EMF of phase C as referred to (3). For this reason, the FRA response when short circuit fault occurs in phase a and c, the response is almost similarly affected as can be seen in Figure 9.

On the other hand, when the fault is located at the same phase of the measured winding, the effect of fault on the response is very large. This is similar to the case of FRA measurement on phase A and fault is on phase a.

Again, the procedure is repeated on the second transformer to verify this initial finding. Figure 11 shows the FRA responses for Dyn11, 500kVA transformer when measurement is conducted at phase B.

From figure 11, the FRA response for SC fault at phase a and c shows a slight variation. Here, we are expecting that responses of phase B with fault at phase a and phase c will have similar variations. However, both responses are not exactly similar. This is probably due to the condition of the winding (phase a and c) itself which are not perfectly identical even though the same faults are being applied. As mentioned earlier, this is a transformer that manufactured more than 30 years ago. Therefore, such slight different between fault at phase a and fault at phase c is acceptable.

4.3. Response phase C

The last case presents the FRA measurement conducted at the HV winding of the left-side limb or phase C, while the faulty winding is on the LV winding of phase a, b and c consecutively as previous cases.

Figure 12(a) shows the responses experience the same pattern as in the first case where the measurement is conducted on phase A. Basically if the fault located on the same phase as measured winding, the effect on response is huge. On the other hand, if the fault is located further away from the measured winding, the effect is smaller or reduced. Similar trend can be seen on the second transformer as shown in Figure 12(b). These results verify the initial finding in [1]. Table 3 shows the summary of the results obtained.
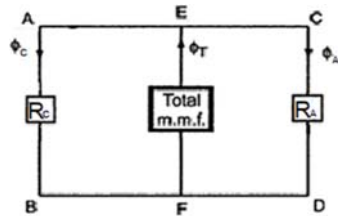

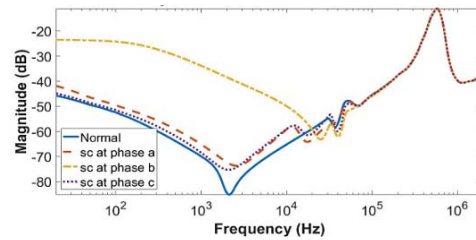Figure 10. Equivalent magnetic circuit of FRA measurement conducted at phase B

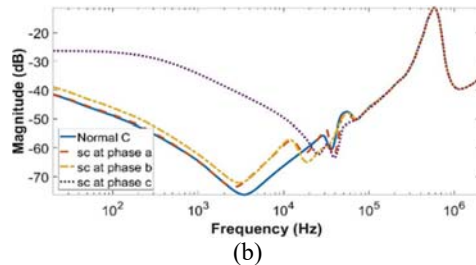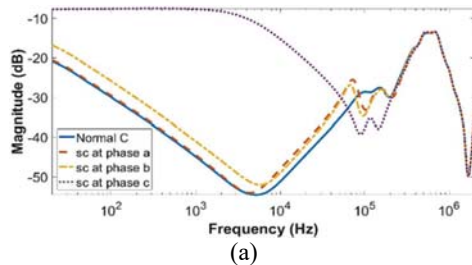Figure 11. Frequency response of phase B for 500kVA transformer

(a)

(b)

Figure 12. Frequency response of phase C for (a) 360VA transformer, (b) 500kVA transformer

Table 3: The effect of fault on one winding to response of other windings

Simulation studies (changes of parameters)		Significant changes in low frequency region		
		Severely affected	Less affected	Least affected
Interaction between windings of similar phase	FRA measurement is at same phase as faulty	√	X	X
Interaction between windings of different phase	FRA measurement is next phase (adjacent) to the faulty	X	√	X
	FRA measurement is at further phase to faulty	X	X	√

5. CONCLUSION

As a conclusion, it was proven that faulty occurred in winding of other phases could actually affect the response of measured phase winding. The location of the faulty winding determines how severe it is

affecting the measured response. From this finding, it can be concluded that when faulty is at the same phase as the measured winding, it will cause major variation on the response. The response will significantly be shifted towards higher frequencies. Meanwhile, when the faulty is near or adjacent to the measured phase winding, the response will moderately be affected. In case of FRA measurement is conducted in the middle limb, responses of both right and left side limbs will be affected almost similarly. Finally, as the faulty winding is located furthest away from the measured phase winding, the response will be slightly shifted towards higher frequencies.

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Mohd Fairouz Mohd Yousof received Dip.Eng, B.Eng. and M.Eng. from Universiti Teknologi Malaysia (UTM) in 2005, 2008 and 2010, respectively. In 2015, he obtained Ph.D. degree from The University of Queensland, Australia. He is with the Department of Electrical Power Engineering at Universiti Tun Hussein Onn Malaysia since 2009. He was a visiting researcher at Tenaga Nasional Berhad Research from 2018 to 2019. His main research is condition based monitoring and assessment of transformer and rotating machine.

Mohd Aizam Talib has over 19 years of experiences in dealing with transformer diagnostic, condition and life assessment and failure analysis of power transformer. After graduated, he has worked with ABB Transmission and Distribution Sdn Bhd as Design Engineer and in 1998; he has joined TNB Research Sdn Bhd as Research Engineer. He is currently holding a position as Technical Expert (Transformer) with TNB Research Sdn Bhd.

Muhammad Saufi bin Kamarudin obtained his B.Eng. and M.Eng. Degrees in Electrical Engineering (Power) from Universiti Teknologi Malaysia (UTM) in 2003 and 2005, respectively, and a Ph.D. in High Voltage Engineering from Cardiff University, UK, in 2014. Currently, he is a senior lecturer in the Faculty of Electrical & Electronic Engineering at Universiti Tun Hussein Onn Malaysia (UTHM). His research interests include gas discharges, high voltage surge arresters, and dielectrics and electrical insulation system.