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The effect of short circuit fault on one winding to other windings in FRA

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Article Info

ABSTRACT

Monitoring and diagnosis of power transformer in power systems have been examined and debated significantly in last few decades. Recently, more researchers have expressed their interest in these issues as the utilities and network operators operating under a rising cost-effecting pressure. Especially, in studying to monitor winding faults which is found to be the most common fault within transformers. This paper addresses the issue of the effect of inter-windings short circuit fault in a Dyn11 connected transformer. The specific aim is to study the effect of fault at winding of other phases to the response of measured phase. Frequency Response Analysis (FRA) which is discovered to be a powerful and sensitive method to examine and evaluate the condition, including the mechanical reliability of the transformer windings is used.

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1.   INTRODUCTION

Power transformer is one of the most expensive and significant equipment in electric power network [1]. It plays a vital responsibility to maintain a reliable and efficient supply of electricity. However, during operation, transformers are continuously being exposed to thermal, mechanical and electrical stresses. These stresses increase the aging process of the internal part of power transformer thus increasing the risk of failure. Basically, any failure in active part of transformer could consume millions in loss since it will be out of service for a long time, not to mention the cost to repair or replacement [2, 3]. Therefore, it is important to detect any fault that occurs within the transformer at an early stage to avoid any unplanned outage. A survey of faults in transformers is illustrated in Figure 1. It shows that 49.4% of the total faults occur in the windings [4]. Most of the transformer faults mainly occurred on the winding thus has become a major concern for the manufacturers.

Various approaches have been developed by previous researchers with the aim to provide a precise diagnosis method for the transformer. For example, Dissolve Gas Analysis (DGA) [5, 6] and Short Circuit Impedance (SCI) measurement [7, 8]. However, FRA is found to be the most effective and sensitive method for analyzing the winding condition of a transformer. This test is capable of providing the information about the structure reliability of the windings without having to untank the transformer [8]. The frequency response is a function of the RLC network of the windings related to the physical geometry. Geometrical changes within and between the elements of network cause deviations in its frequency response. The mechanical changes within the transformer alter the RLC network and in turn can alter the frequency response [9-11].
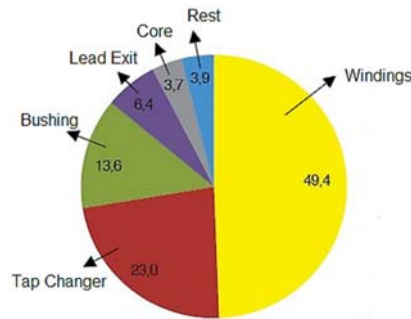
Figure 1. Fault location distribution of transformer failure survey [4]

In this paper, the coupling effect of faulty winding on the non-faulty winding is investigated. FRA measurement is conducted on HV winding of phase A, while 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. It is conducted by measuring and comparing the FRA response before and after the presence of faulty in the winding. For this case, the fault simulated is short circuit (SC) in winding. The focus in this study is to observe the deviations of responses. This is because the short circuit fault affects the magnetic flux, flux path and as a consequence influencing the response at certain frequency region.

2. LITERATURE REVIEW
2.1. Short circuit fault in transformer winding

Aside from aging process, various faults that may occur during its normal operation can impact the transformer's reliability and its life. There are many causes that contribute to transformer faults. However, these are mainly due to aging, operation and transportation [12]. A survey from [13] shows that around 40% of the transformer faults are caused by the huge impact of short circuit annually. During short circuit fault, massive current flows through the windings. The current flow causes an excited of leakage magnetic field and produce a remarkable dynamical electromagnetic force acting on the windings. If the short circuit protection strength of the transformer is not strong enough, insulation performance will decrease due to the damage of the insulation structure. The transformer short circuit faults can be divided into three basic categories. These are, winding-to-ground faults, winding-to-winding faults and turn-to-turn faults on the same winding [14]. Turn to turn or also known as inter-winding short circuit is considered as the most common fault that occurs in the power transformer. Studies in [15] showed that about 80% of the transformer breakdowns is credited to short-circuit between turns. There are many causes to short circuit fault. However, they are commonly generated by different line faults, mechanical damage of insulation, breakdown of electric insulation due to over voltage from wrong operations or due to lightning strike [15]. In worst cases, such fault can contribute to the occasion of explosion of transformer tank, blowout of bushings or even fire.

2.2. Previously FRA measurement method used for short circuit in winding

An internal short circuit through the winding may lead to power supply interruptions, cause power outage, serious damage to winding including winding deformation, interruption or even burst of the transformer due to overheating. Therefore, different techniques have been designed and employed to diagnose transformer winding. Exclusively, to monitor the transformer winding conditions.

Frequency Response Analysis (FRA) test is one of the methods for diagnosing the winding. It is performed by injecting the input signal to one terminal of the winding and then the output voltage is measured at the other end of terminal winding. The comparison of input and output signals generates a unique frequency response which can be compared to a reference data. This test system is an off-line system for identifying winding movements such as due to damage from transportation. Besides this, other causes of winding movement are from the subjection to low impedance through faults, or general looseness of the clamping structures brought on by the normal effects of aging in transformers [12]. The comparison to the earlier FRA fingerprints which is the baseline data is an effective technique to detect the winding damages.

In [16], Ryder has acknowledged many internal faults during his studies by applying frequency response analysis method. He used Cross-Correlation Coefficient Factor (CCF) technique to analyze the response and determine the faulty in transformer. The CCF is a method to measure the level of relationship between two variables. In this case, it is used to establish the relationship between the measured and the

original fingerprint of the transformer's response. The correlation coefficient can be any value between −1.00 and +1.00. The value of −1.00 represents a perfect negative correlation, while no correlation is 0.00 and a perfect positive correlation is at +1.00 [17]. The obtained results presented in [17] were interpreted using three techniques. These are the Chinese standard DL-911/2004 technique, Cross-Correlation Coefficient Factor (CCF) technique and the R^2 relative factor technique. The CCF method shows a better sensitivity in detecting the turn to turn fault compared to Chinese standard DL-911/2004 and R^2 error techniques.

Authors in [18] also have proposed several methods for locating the inter-disc fault within the transformer winding using FRA. At the beginning, CCF is used to calculate the degree of deviation between the normal and responses with faulty winding. Afterward, vector fitting algorithm and Nyquist plot are employed to detect the inter-disc fault location on the windings.

In reference [19], the researchers had improved the diagnosis method for frequency response analysis. They have employed spectral analysis methods in their research. Firstly, the Discrete Fourier Transform (DFT) was applied to estimate the frequency response. However, it was lacking low and medium frequency components. To overpower the problem, Synthetic Spectral Analysis (SSA) method was proposed. The SSA was based on cut-and-concatenation method (CCM) for high quality frequency responses and then utilize the log frequency interpolation for a balanced comparison over the whole frequency range. Thereafter, at which phase the defective winding occurred was determined.

2.3. Theory of magnetic forces affecting transformer winding during short circuit fault

A magnetic circuit can be defined as the closed path traced by the magnetic lines of flux. A simple magnetic circuit for a three-phase core type transformer consists of a cross-sectional area, A with m^2 unit and a mean length of the magnetic path, l which is the flux through in meter. Also consist of a coil of N turns which is wound on each side of the transformer limbs and excited by a supply current, I through the coil. This current carrying coil produces flux, Φ which completes its path through the core as shown in Figure 2. The circuit is analogous to a simple magnetic circuit as shown in Figure 3, where a supply magneto motive force (MMF) drives flux which completes its path through a closed conductor having resistance called as reluctance, R.

Figures below show a core of a three-phase transformer and its equivalent magnetic circuit. End-to-End FRA measurement set up was conducted at phase A which is the right-side limb of the core. Phase B is the center limb while phase C is the left side limb.
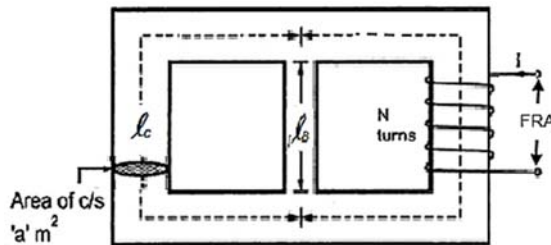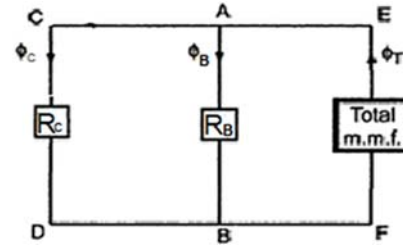

Figure 2. FRA measurement at phase A

Figure 3. Equivalent magnetic circuit of FRA measurement at phase A

where,

R_B = Reluctance of central limb, phase B
R_C = Reluctance of left side limb, phase C
l_B = Length of central limb, phase B
l_C = Length of left side limb, phase C
$\mu = \mu_o \mu_r$ = Magnetic permeability
A = Cross-sectional area refer to the geometry of magnetic core

The expression of flux is very much like the expression for current in an electrical circuit. Meanwhile, electromotive force (EMF) is similar to the MMF and resistance is analogous to the reluctance. If in an electrical circuit, EMF drives current through the circuit, in a magnetic circuit of transformer, MMF drives the flux through the circuit. In theory, the core reluctance is directly proportional to the length of the flux path in the core, and inversely proportional to the cross-sectional area of the core [20]. The relationship is given as (1).

$$R \propto \frac{l}{A} \tag{1}$$

The reluctance parameter is not only influence by the length and cross-sectional area, but also on the permeability, μ of the material. Permeability indicates the ability of easiness of a material in passing the magnetic lines of force and a degree of the simplicity for the core to be magnetized. The permeability is inversely proportional to the reluctance of the core. In which, the greater the value of μ, the more flux lines can easily be created, and more flux will flow in the core. The measured flux, Φ in the core is proportional to the MMF that drive forces in the magnetic circuit, and inversely proportional to the reluctance of the core [21].

$$\Phi \propto \frac{MMF}{R} \tag{2}$$

A magnetic circuit *that* has more than one flux path is known as parallel magnetic circuit. In the case of parallel electric circuit, the current through each resistance is different while the voltage across them is the same. In parallel magnetic circuit, the flux pass through different reluctances with same MMF across them. Meaning the MMF required to pass flux through is the same in each limb. By canceling out the MMF for both sides will give the expression (3) below:

$$\Phi_B = \frac{MMF}{R_B}, \ \Phi_C = \frac{MMF}{R_C}$$
$$\Phi_B R_B = \ \Phi_C R_C \tag{3}$$

The Φ_B and R_B stands for flux and reluctance in phase B. According to Faraday's Law, EMF induced in transformer is proportional to the rate of change of magnetic flux and the N turns of winding [22].

$$EMF = -N\frac{d\Phi}{dt} \tag{4}$$

The minus sign is in accordance with Lenz's Law as the induced EMF would produce a current in such a direction as to oppose any change in the flux Φ through the circuit. After derivation, back EMF develop into the relationship as below [23],

$$back\ emf = 4.44Nf\Phi_{\mathrm{m}} \tag{5}$$

where,
    N = Number of turns in a winding
    Φ_m = Maximum flux in the core in Weber
    f = Frequency of ac input, 50Hz

At normal condition, all back EMF for all windings are fully induced. In other word, the back EMF are 100% induced. Theoretically, the more turns in the coil, the bigger the back EMF and the bigger will be the time delay to reach maximum current [21]. When a short circuit fault occurs at a winding, the number of turns at the winding decreases, thus the produced back EMF also decreases.

3.   RESEARCH METHOD

A three-phase experimental transformer with rating of 360VA, 240/360 V is used in this study. The transformer is measured using a standard test configuration as given in IEEE standard, which is end-to-end open circuit test [24]. It is a per phase open circuit measurement. As the term allude to, the per phase measurement aimed for the particular phase of a winding. It is performed by injecting a sinusoidal excitation voltage with a continuously increasing frequency as an input signal to one terminal of the phase winding and then the output voltage is measured at the other end terminal of the same winding. It is performed using an SFRA test set which is FRANEO 800 from OMICRON. The study is conducted by measuring and comparing the FRA response before and after the presence of short-circuit faults.

In this study, the FRA measurement is conducted at phase A of the HV winding 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. The short causes the winding to lose its number of turns by a third. This is shown in

Figure 4. The experimental three-phase transformer used in this paper is manufactured by KOS. The transformer can be connected to several vector group due to its open terminal characteristic. The transformer details are given in

Table 1.

Table 1. Basic detail of the experimental transformer

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

The study in this paper is discussed in three levels. Initially, the FRA measurement is taken at each winding phase. Thereafter, the presence of the internal short-circuit fault is decided by comparing the FRA responses before and after the fault has occurred. Lastly, the effect of fault occurred at other winding phases on the measured phase is analysed. This is the major contribution in this paper.

The transformer used in this study has two windings (HV and LV) per core limb or per phase. The LV winding itself is constructed of three separate and identical windings. Since these windings are not connected, this allows us to create short circuit fault by shorting the middle section of the LV winding. This is as shown in

Figure 4. In

Figure 4 (a), a short and thin cable was connected at the terminals thus causing 1/3 of the total LV winding to be shorted.

Figure 4 (b) shows the schematic diagram of the short circuit fault in the secondary winding of a Dy11 connected transformer.
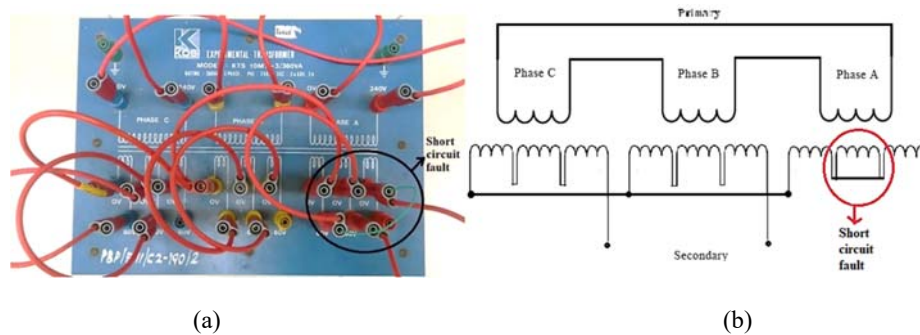
(a)	(b)

Figure 4. (a) Short circuit fault simulated on phase a of LV winding, (b) Schematic diagram of short circuit fault on phase a of LV winding

4. INTERWINDING SC FAULT DIAGNOSIS

The focus in this study is to observe the frequency response at the low frequency region. This is because the short circuit fault affects the magnetic flux, flux path and as a consequence influencing the response at the low frequency region or the first antiresonance [25].

4.1. Measurement on phase A, fault at winding phase A

Initially, the measurement was conducted at the same phase as the location of the SC fault. The measured frequency responses are shown in Figure 5. The results show a very significant change to the response when the winding is faulty. The response at low frequency region extremely shifted to the right. This is mainly due to the amount of flux created in core. Such major change can be explained from the (6) [4],

$$\Phi \propto NI \tag{6}$$

The amount of flux, Φ is directly proportional to the product of the number of turns, N and current flow in the winding, I. Basically, short circuit fault within the winding causes the number of turns to reduce. As the number of turns decreases, the flux produced in the coil also decreases. Therefore, in the response, the amount of shift for the first resonance is significant.
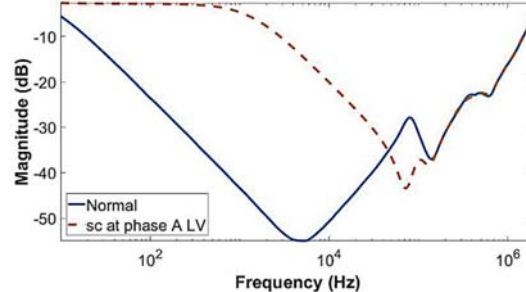

Figure 5. Frequency response of measurement at phase A with SC at phase A (Right-side limb)

During this fault, the magnetizing inductance of the right-side core limb is drastically reduced and therefore the magnitude of transfer function increases in the lower frequency range. This also causes the first antiresonance (valley) to be shifted to the right side or to higher frequency. The large amount of shift is affected by the magnetizing inductance of the limb of the core caused by the short circuit in the secondary winding.

4.2. Measurement on phase A, fault at winding phase B
In the second case, the short circuit fault is applied in the secondary winding of the middle limb or phase B while the FRA measurement was conducted on phase A as before. The measured responses are shown in Figure 6.
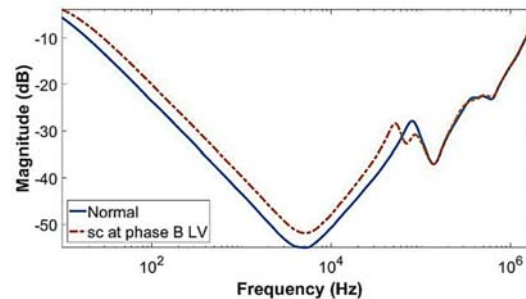

Figure 6. Frequency response of measurement at phase A with SC at phase B (Middle limb)

Figure 6 shows the changes on the response between 10 Hz and 30 kHz. Low frequency region of the response is dominated by the magnetizing inductance. It is shown to be shifted to the right side towards higher frequency. This occurred due to the magnetic forces effect on the transformer winding during short circuit. However, comparing with the previous case where the fault is at phase A, the changes of response in the second case is much less. This is mainly due to the fault is not located at the same phase of the measured response.

4.3. Measurement on phase A, fault at winding phase C
Figure 7 shows the frequency response when fault occurred in the LV winding of the left-side limb of the core which is at phase C. As in the previous case, the measurement is still conducted on HV winding of phase A. While the short circuit fault is applied in the secondary winding of the left-side limb. This is to observe whether fault at winding from other phase could influence the FRA measurement.
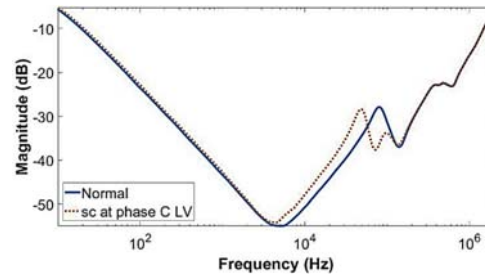
Figure 7. Measured frequency response of measurement at phase A with SC at phase C (Left-side limb)

The response of phase A, winding is seen to be affected by the short circuit fault on the secondary winding of phase C. This is mainly due to the magnetic force effect during short circuit. The initial antiresonance of the response is slightly shifted to the right when compared with the normal response. Nevertheless, the degree of shifting is lesser when compared with the case when the fault is at phase B. This is because the fault occurred at phase C winding is located further away from the measured winding of phase A.
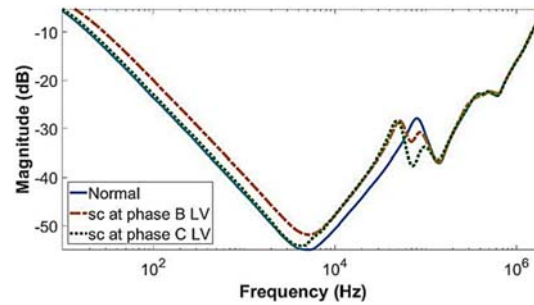

Figure 8. Measured frequency response of phase A (Right side limb)

The comparison between responses when the fault occurs at phase B and phase C while the measurement is taken at phase A is illustrated in Figure 8. The explanation on the reason why fault at phase C created more changes on the response compared to the fault at phase B is as follows:

$$R_B = \frac{l_B}{\mu A} \tag{7}$$

$$R_C = \frac{l_C}{\mu A} \tag{8}$$

To explain this, we will refer to (7), (8) and Figure 3. From Figure 3, when FRA measurement is performed at HV winding of phase A, current flows in the winding, and flux is produced in the core. The flux will flow within 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 path for the l_C, thus the reluctance of the central limb R_B is lower than R_C as evident in s (7) and (8). As the reluctance of the central limb R_B is lower, the flux that pass through in the central Φ_B is higher compared to the flux in left-side limb Φ_C.

Now, it has established that Φ_B is higher than Φ_C, let relate the flux with the back EMF. Technically, the back EMF of phase B is higher compared to back EMF of phase C. This because Φ_B is higher than Φ_C as evident in (5). For this reason, the response of HV winding in phase A when the fault is at phase B is more affected compared to phase C as can be seen in Figure 8.

5.   CONCLUSION

From the FRA measurement study, it was found that short circuit fault which occurred in winding of other phases could actually affect the response of the measured winding phase. This is a significant finding as typically, one will assume that the changes in the response is due to faulty on the measured winding. This finding proved that the response can also be affected by fault from other phases as well. It was also found that the location of the faulty winding determines how severe it is affecting the measured response. From this finding, it can be concluded that one should not simply assume that the changes in the response is due to faulty of the measured winding. It may also be due to fault which is occurred in other winding from other phases.

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