International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 11, No. 1, March 2020, pp. 309~316
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v11.i1.pp309-316 ❒ 309

Interpretation of sweep frequency response analysis traces on inter-turn short circuit fault

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Article Info

Article history:

Received Jun 27, 2019
Revised Nov 12, 2019
Accepted Dec 3, 2019

Keywords:

Frequency response
Short circuit fault
Transformer
Winding

ABSTRACT

Sweep frequency response analysis (SFRA) is a reliable method for detection and diagnosis of faults in the active part of transformers. However, although SFRA is widely employed, the interpretation of SFRA signature is still a challenge and require experts to analyse them. This is due to lack of guideline and standard for SFRA signature interpretation and clarification. This paper presents the interpretation of SFRA signature by classification and quantification on inter-turn short circuit fault on the transformer winding. The short-circuited turns fault on HV winding phase "A" was practically simulated on three different units of three-phase transformers. The results of simulated fault are presented and discussed. A conclusion was drawn which provides the interpretation of the SFRA response due to inter-turn short circuit fault case by using a statistical indicator which is NCEPRI algorithm.

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1. INTRODUCTION

SFRA is a non-intrusive electrical test which avoid opening a transformer tank to assess their electrical and mechanical condition. Opening the tank will cause oil degasification and dehydration, which can minimize the impact on system operation and loss of supply to customers. Therefore, using SFRA can save millions of ringgits in timely maintenance. Besides, it can deliver valuable information regarding the mechanical as well as the electrical conditions of the transformer [1]. SFRA test can be the key in making decision to scrap or reenergize a transformer. To obtain information from SFRA test, it is necessary to make sure the measurements are correct and accurate interpretation is given.

Comprehensive study of previous literature along with experience performing numerous SFRA test can provide an understanding to interpret the SFRA results. Since SFRA interpretation is based on experience, such records of previous measurements are great importance when interpreting SFRA responses. This paper is presenting the frequency response interpretation of faulty transformer winding due to inter-turn short circuit (SC) fault. The measurements in this study were conducted on three units of three-phase transformers at a local research utility company. The end-to-end open circuit test is performed in this study. Three artificial inter-turn SC faults were created by shorting the windings. The findings in this study are then compared with findings from other previous literatures.

2. BIBLIOGRAPHY SURVEY

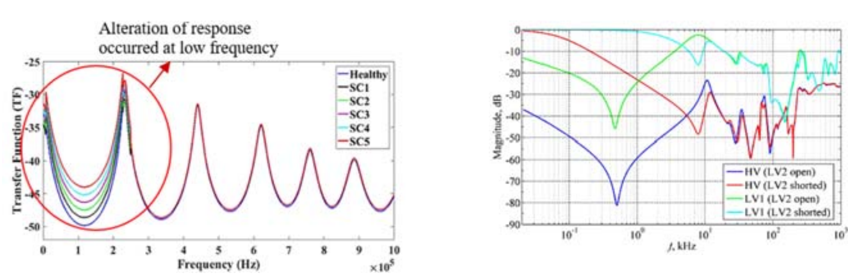
The occurrence of SC fault is quite rare. However, the probability is increased during the transformer lifetime, typically when reaching 50 years [2]. In spite of this, according to [3] about 40% of the transformer faults initiated by huge impact of short circuit annually. Reference [4] also mentioned that fault at winding usually initiated by short circuited. One of the sources which contributes to SC fault is the breakdown of insulation between turns in the winding. Insulation breakdown usually occurs due to high voltage which is above the rated value. The huge current excites an extensive leakage magnetic field and generate a huge dynamical electromagnetic force on the windings. At certain point, the physical strength reaches the point of breaking the winding insulation and unable to tolerate the forces. The breakdown of the insulations could cause flashover and eventually causes the inter-winding short circuit faults. Besides that, according to [5], since the windings are made of copper, thermal losses occur. These thermal losses make hotspots in the winding. This over time reduces the physical strength and eventually initiate the breaking of insulation in the winding. Ultimately this causes short circuit fault on the winding. Another factors to consider which cause this fault are irregular repair, improper or lack of maintenance, deterioration, and manufacturing defect within the transformers. An early detection of low level SC faults is crucial, because if not quickly detected, they usually develop into more serious damage to the transformers. Short circuit is a serious fault which have initiate various transformer breakdowns especially to three-phase transformers [6].

There are three basic categories of SC faults on transformer winding as mentioned in [7]. These are, winding-to-ground, winding-to-winding, and turn-to-turn faults. Turn-to-turn or inter-turn SC fault is found to be mostly occurring. Figure 1 shows the inter-turn SC fault in a transformer winding.

(a) (b)

Figure 1. Inter-turn short circuit fault for (a) Insulation breakdown (b) An actual case [8]

Basically, SC in winding causes the electrical length of the winding to be reduced. Therefore, the winding natural frequencies shall either changed or remain almost unchanged if the SC fault occurs. This is an important property that can be used as the main sign of the winding SC fault. In the case of core-typed three-phase transformers, the internal SC fault will cause an extensive increase of first antiresonance in the low frequency (LF) response [9]. The first antiresonance frequency is typically from hundreds of Hz up to few kHz. However, it may increase significantly depending on the severity of the SC faults as shown in Figure 2(a). Nevertheless, the increase of the frequency is not totally an indication of a SC occurred just in the winding under measurement. This is because the scenario give effect to all first antiresonance responses of windings on the same core [10]. Reference [10] presented by S. Larin shows that short circuiting the LV2 give effect to the measured response of LV1 as illustrated in Figure 2(b). This is due to the mutual coupling between the HV and LV winding when transformer is energized. Table 1 presents the bibliography survey showing the effect of internal SC fault in the frequency response.



(a) (b)

Figure 2. Impact of SC fault on the SFRA signature presented in (a) [9], (b) [10]

Table 1. Dominant frequency range of SFRA due to short circuit fault from bibliography survey

References	Dominant frequency range (Hz)
[11] Devadiga et al. 2018	Low and medium frequency (Significant reduction in impedance and a shift in resonance peaks towards high frequencies)
[12] M.Gutten, Richard Janura, Milan Sebok, Daniel Korenciak, 2016	Low to medium frequencies (up to 100kHz)
[13] Aljohani & Abu-Siada, 2015	High levels of SC have a visible impact along the entire frequency range and influence the resonance frequencies in high frequency range.
[14] Pandya & Parekh, 2014	Low frequency range (1kHz – 10kHz)
[15] Bagheri, Naderi, Blackburn, Phung, & Liu, 2012	Low frequency region (20Hz – 40kHz)
[16] Ilampoornan, Vikash, & Newton, 2012	Low frequency region,
[17] Firoozi, Kharezi, Rahimpour, & Shams, 2011	low frequency range (between 50Hz and 2kHz)
[18] Behjat, Vahedi, Setayeshmehr, Borsi, & Gockenbach, 2011	low-frequency deviation (frequency range below 1 kHz)
[19] Contin, Rabach, Borghetto, & Nigris, 2011	Low frequency range (up to 10kHz)
[20] Bigdeli, Vakilian, & Rahimpour, 2011	low frequency range of (10-100 kHz)
[21] Picher 2008	Low frequency range

Table 1 clearly shows the main effect of internal SC is the shift of frequency response in the low frequency (LF) region. According to [18], the key point to understand the LF deviation caused by shorted turns can be found in the explanation of Faraday's law in shorted turns. The law states that the electromotive force (emf) induced in a turn is equal to the rate of variation of the electromagnetic flux inside it [17].

3. TRANSFORMER USED IN EXPERIMENTAL WORK

Three units of three-phase, core-typed transformers were used in this study. The first experimental transformer is an open terminal transformer that is connected as Dyn11 winding configuration. The second and third experimental transformers are Dyn11, 500kVA and 100kVA distribution transformer. These two tested units are oil-typed transformer which were taken out of service. In this paper, the focus is on the Delta-Wye connection which is most frequently used for distribution transformers. According to [5], winding SC usually occurs to distribution transformers. This is because, the current flow in the primary side winding of the transformer undergoes electromagnetic induction voltage which is stepped down. The current is then stepped up in the secondary winding. Due to this, the windings have to tolerate dielectric, thermal and also mechanical stress. This is one of the factors that contribute winding short circuit fault in the LV winding of the transformer. Table 2, Table 3 and Table 4 show the basic details of the transformers used in this study.

Table 2. Details of 360VA 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 3. Details of 500kVA transformer

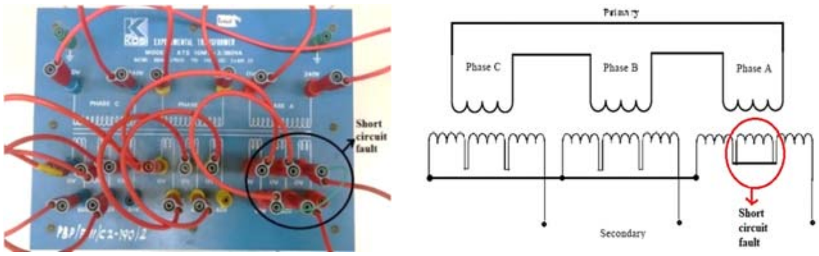
Attributes	Details
Model	ONAN TRANSFORMER DRG. No. MTM 11/3/1-D
Serial No.	T/84/516 8
Manufactured date	21/06/1984
Capacity	Three-phase, 50 Hz, 500 kVA
Total mass	2668 Kg

Table 4. Details of 100kVA transformer

Attributes	Details
Model	MTM TRANSFORMER
Serial No.	1/44/116 0
Manufactured date	05/09/1994
Capacity	Three-phase, 50 Hz, 100 kVA
Total mass	620 Kg

4. TEST METHODOLOGY

Three transformers were used in this study by creating artificial SC fault in the windings. The purpose is to study the variation that might occur in the transformer frequency response due to this fault. In order to diagnose short circuit fault, SFRA measurement is performed before and after the fault has occurred. The comparison of responses before and after fault is then observed and analyzed. This is conducted per phase using end-to-end open circuit configuration. As the term allude to, per phase measurement aimed for a particular phase at one time. In this paper, SFRA measurement is performed on phase A only which is the same phase as the SC fault is applied. Figure 4 shows SC fault which was created on the first transformer.

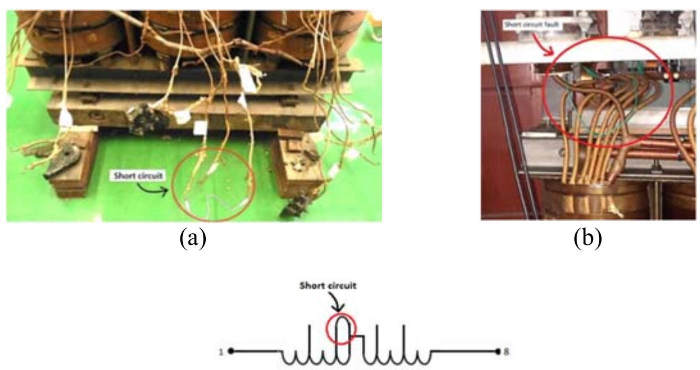


(a) (b)

Figure 3. (a) SC fault simulated on phase A of LV winding, (b) Schematic diagram of SC fault

The open terminal transformer has two windings (HV and LV) per phase. The LV winding itself has three separated and identical windings. Since these windings are not connected, SC fault is created by shorting the middle section of the LV winding. Figure 3(a) shows a short and thin cable connecting the LV windings. This causes 1/3 of the total LV winding to be shorted. Figure 3(b) shows the schematic diagram of the SC fault on phase A of LV winding.

The second short circuit was simulated on the 500kVA distribution transformer as shown in Figure 4(a) and the last short circuit fault is simulated on 100kVA transformer as shown in Figure 4(b).



(a) (b)

(c)

Figure 4. SC fault simulated on transformer tap 3-4 phase A (a) 500kVA transformer, (b) 100kVA transformer, (c) Schematic diagram of the SC fault

As shown in Figure 4(a), the SC fault was created by connecting a wire cable to the exposed transformer tap in the HV winding. The exposed tap is labelled according to their tap references. This causes short fault and the total turns of the HV winding of that phase to reduce. On the other hand, Figure 4(b) shows the SC fault is created by connecting a cable to the transformer taps in the HV winding of 100kVA transformer. Figure 4(c) shows the schematic diagram of winding with short circuit at tap 3-4 for both transformers.

5. SFRA RESPONSE DUE TO SC FAULT

The results of the three artificial SC faults are presented in this section. The SFRA measurements on HV windings of three tested transformers are shown in Figure 5, Figure 6 and Figure 7. Each of the figure shows two traces measured during normal and faulty operating conditions of the transformers. The response is divided into three frequency regions. As referred to [22], the frequency regions are not fix at a certain frequency but should be defined according to the shape of the response. The frequency response will be different depending on the structure, configuration, winding type and power rating of the transformer.

From the measured responses of all three transformers (Figure 5, Figure 6 and Figure 7), the main effect of SC fault is the shift of response at the low frequency (LF) region towards higher frequencies. The shifting is more obvious at LF region and early part of medium frequency (MF) region. Clearly, the faulty traces for the tested transformers show a similar shifting or deviation.

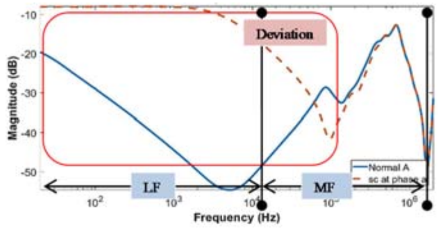


Figure 5. FRA response of normal and short circuit winding of 360VA transformer

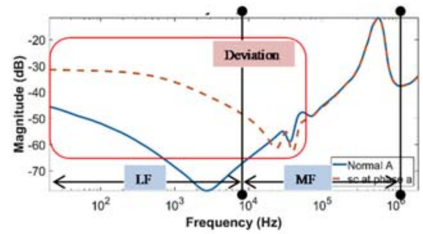


Figure 6. FRA response of normal and short circuit winding of 500kVA transformer

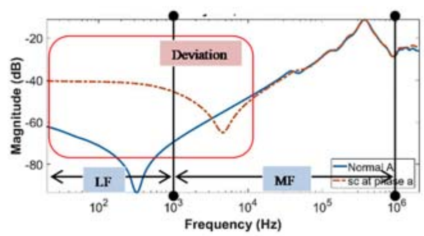


Figure 7. FRA response of normal and short circuit winding of 100kVA transformer

It is clear from the transformers responses, the magnitude (dB) increases and the first resonances at LF region shifted towards higher frequencies. The key point to understand the LF deviations can be found in the explanation of change in the magnetizing characteristics of the transformer initiated by shorted turns. Basically, the impedance of winding is small, meanwhile the impedance of the core is extremely high. This parameter governs the LF region [22]. Therefore, the input signal is dominated by the core. However, as the SC is added, changes in the core are detected. It causes the effect of core saturation to reduce and significantly decreased the magnetizing inductance. Due to this reason, the response of the LF region rises or shifted towards higher frequencies, and it has higher starting dB value than response of healthy winding. This condition can also be explained by using (1).

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

The (1) represents the amount of flux, Φ which is directly proportional to the product of the number of turns, N and the current flow in the winding, I. In general, the internal short circuit leads to a reduction of the electrical length of the winding, meaning reduction in the number of turns [10]. This is an important property that can be used as one of the main signs of the internal short-circuit fault in the winding. As the number of turns reduces, the flux produced in the coil also reduced significantly. Therefore, during this fault, the magnetizing inductance of the right-side limb (Phase A) is drastically reduced and caused the magnitude of the response in LF region to increase. The large amount of shift is affected by the reduction of magnetizing inductance in the core limb. Which is caused by the SC fault in the secondary winding of the same phase as the SFRA measurement conducted.

6. FAILURE INTERPRETATION USING NCEPRI ALGORITHM

In order to analyse and interpret the frequency response, a mathematical indicator is applied. Usually, mathematical or statistical indicator is a method to measure the similarities between two frequency responses. This is performed rather than by visually comparing from the figures only. This method can provide a single value on the extent of the variation between them. To achieve more accuracy in diagnosing the requency response, many statistical and mathematical indices have been proposed in the literature for SFRA application. For example, correlation coefficient (CC), absolute sum of logarithmic error (ASLE), min-max (MM) ratio and root mean square error (RMSE). In this study, an algorithm proposed in [23] which is North China Electric Power Research Institute (NCEPRI) algorithm has been used to analyse the responses. This algorithm is proposed by a group of researcher in [24] as a mathematical indices to analyse the frequency responses.

6.1. NCEPRI algorithm

The NCEPRI algorithm estimates the correspondence of frequency responses by calculating the effective deviation (ED) of two transfer functions using (2).

$$E_{12} = \frac{1}{N}\sum_{i=1}^{N}(TF_{1i} - TF_{2i})^2 \quad (2)$$

Where TF_{1i} and TF_{2i} are the reference and compared transfer functions or frequency responses. N is the number of data. Table 5 shows the interpretation criteria for NCEPRI algorithm. According to NCEPRI standard proposed in [23], the frequency ranges required for the winding assessment factor, E_{12} can be devided into three as shown in Table 6. They are the high-voltage (HV), low-voltage (LV) and tertiary voltage (TV).

Table 5. Failure interpretation criteria of NCEPRI algorithm

Distortion level	Factor (dB)
Normal condition	$E_{12} < 3.5$
Slight distortion	$3.5 > E_{12} \geq 7.0$
Serious distortion	$E_{12} > 7.0$

Table 6. Frequency range defined in [22]

Winding	Frequencies
HV	10kHz - 515kHz
LV	10kHz - 600kHz
TV	10kHz - 700kHz

However, [22] has found that using large frequency ranges for the analysis reduces the sensitivity and makes the failure classification difficult. The frequency regions do not fix at a certain frequency only but should be defined according to the shape of the frequency response. During evaluating the frequency response, user should modify and adjust the frequency region according to the response shape. It can also be generally associated with a much narrower frequency range to achieve higher sensitivity.

6.2. Response analysis using NCEPRI algorithm

Visually comparing all three measurements, Figure 5, Figure 6 and Figure 7 clearly reveal some important features. The inter-turn SC fault cause obvious variations in low and beginning of the medium frequency region. NCEPRI algorithm is applied to measure the similarity between the normal and faulty winding responses. Table 7 shows the frequency ranges defined according to the response features. On the other hand, Table 8 reveals the fault assessment factor of the winding deformation in term of effective deviation between the responses.

Table 7. Three frequency ranges according to size

Transformer	Frequency range		
	LF	MF	HF
360VA	20Hz – 1.5kHz	1.5kHz – 1.6MHz	1.6MHz – 2MHz
500kVA	20Hz – 9kHz	9kHz – 1.5MHz	1.5MHz – 2MHz
100kVA	20 Hz – 1kHz	1kHz – 1MHz	1MHz – 2MHz

Table 8. Fault assessment according to NCEPRI algorithm

Transformer	Fault assessment Factor, E_{12} in dB		
	LF	MF	HF
360VA	33.846	9.942	0.046
500kVA	27.867	5.162	0.135
100kVA	35.598	6.653	1.173

The frequency ranges are different as it is defined according to the response shapes. Obviously, they will be different because the transformer has a different power rating. The frequency ranges can be referred as in Table 7 and illustrated as in Figure 5, 6 and 7 respectively. From Table 8, it can be seen that the fault assessment factor for the low frequency (LF) region is very high. Clearly, all the values are above beyond 7. Therefore, the LF region is considered as serious distorted as referred to Table 5. Meanwhile, E_{12} of MF region for 100kVA and 500kVA is considered as slight distortion. This is differently to 360VA which shows a serious distortion. However, the degree of distortion is not as high as in the LF region. On the other hand, the high frequency (HF) region is considered as in normal condition.

7. CONCLUSION

It was proven that winding short circuit fault gives a significant change on the SFRA response. Findings in this paper conclude that the fault causes serious alteration in the low frequency region and slight alteration in the medium frequency region. The main sign is the significant shift of response in low frequency region towards higher frequencies. The initial magnitude of faulty response is also higher in dB compared to normal response. Besides that, failure interpretation using the NCEPRI algorithm also has proven the finding. It shows that the low frequency region has the highest value of assessment factor, E_{12} and indicate serious distortion. The level of distortion reduces as the frequencies increases. This prove that the inter-turn short circuit fault gives a significant effect to low frequency region. Slightly affect the medium frequency region when it is severe and not effecting in the high frequency region.

ACKNOWLEDGEMENTS

The authors would like to thank the TNB Research, for the provision of test facilities and great support for the experimental tests. This work is supported financially by the Islamic University research grant PRG-IUNAJAF-2019.

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