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Improved Method for Winding Deformation Detection Sensitivity in Transformer

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ABSTRACT : *Power transformers are one of the most vital as well as expensive equipment in an electric power system. Transformers may be subjected to various types of faults. Of these, the structural fault namely the winding deformation due to either dynamic effect of short circuit current or vibration during transportation or due to short circuit in nearby equipments is severe and needs attentive condition monitoring. The fault may cause a change in the physical condition of transformer which would reflect as variation in the electrical parameters- resistance, inductance and capacitance of the winding. Detection of winding deformation is possible by observing the variation in characteristic resonant frequency of winding due to change in electrical parameters as a result of winding deformation. This paper aims at detection of winding deformation with improvement in detection sensitivity by the use of different test input signal. The proposed method is validated through simulation using lumped parameter model of a transformer winding.*

KEYWORDS : *Transformer, winding deformation, Lightning impulse, detection sensitivity*

I. INTRODUCTION

Transformers are a critical and expensive component of the power system. Failure of a transformer may be potentially severe and may affect safety of personnel and the environment. Due to the long time for repair and replacement of transformers, a major goal of transformer protection is limiting the damage of a transformer that has experienced a fault condition. This necessitates that monitoring and diagnostic methods be developed at various stages starting from design, testing, commissioning and during operation. As windings are the heart of the transformer, assessing the integrity of the winding becomes an essential task. The structural integrity of the winding is sought to be ensured by short circuit tests. The winding deformation in transformers may occur either when the transformer is subjected to short circuit test or during transportation or due to ageing [1].The objective of the short circuit test is to assess the capability of winding to withstand thermal and dynamic effects caused by the short circuit current, which can be many times full load current [2]. From manufacturing view point the test is important part in continually improving design [3]. Details regarding the test current magnitude, the frequency of the test supply, the number of tests to be conducted, the test procedure and the detection of faults and evaluation of test results are documented in standards such as IEC 60076 Part V, 2000 [4]. The ability to withstand the dynamic effects of short circuit shall be demonstrated if required by the consumer, either by tests or by calculation and design consideration. Conventionally reactance measurement was utilized as a diagnostic tool to indicate whether the transformer has passed the test. A method based on cycle to cycle impedance measurement has also been proposed [5]. Determination of transfer function for winding deformation detection using low voltage impulse (LVI) method was proposed in [6],[7] and use of LVI for detection of impulse faults have been proposed in [8],[9]. In this paper a method of winding deformation detection that employs a different test input for improving the detection sensitivity is proposed and validated.

II. CAUSES OF WINDING DEFORMATION IN TRANSFORMER

Most of the failures are caused by transformer winding faults and the faults are generated by lightning and switching surges. As a transformer experiences a fault, it may suffer mechanical shock that gradually displaces and distorts the windings [10]. In the process of winding movement the insulation between the turns can be abraded causing a short circuit and damage to the windings. Mechanical vibration initiated by short circuit forces causes loosening of clamping pressure and collapse winding. The other causes of winding movement may be extensive vibration during transformer transportation. As the winding experiences vibrations it may slacken and subsequently becomes unable to withstand mechanical forces exerted during faults. Ageing also contributes to winding looseness.

In addition harmonics generated under normal operating conditions may cause winding and core vibration. Short circuit forces are potentially very destructive because if the clamping pressure is not capable of restraining the forces involved, substantial permanent winding deformation or collapse can occur almost instantaneously often accompanied by shorted turns. During short circuit condition the axial and radial fluxes in the air gap interact with the short circuit current and produce the short circuit forces that tend to deform the winding. Since windings are characterized by their resonant frequencies, the deformation in windings can be detected by observing changes in resonant frequency as a result of change in electrical parameter.

III. PROBLEM FORMULATION

In general large power transformers are validated for their short circuit withstand capability through short circuit test. As mentioned in the procedure, the short circuit test is performed by short circuiting the low voltage winding and exciting the high voltage winding. In the existing low voltage impulse (LVI) method of winding deformation detection, low voltage impulse is applied to the HV winding and the winding current through it is observed. The winding deformation that may occur due to high short circuit current results in shift in natural resonant frequencies of the winding.Since low voltage impulse signal in frequency domain indicates that the amplitude decreases monotonically with increase in frequency, the winding deformation detection may not be possible with good sensitivity if the resonant frequency lies in the high frequency region. Hence a different test input is required for winding deformation detection for improvement in detection sensitivity. This paper emerged to seek for a solution to this problem.

IV. TEST SIGNAL FOR IMPROVEMENT IN DETECTION SENSITIVITY

The low voltage impulse excitation that is similar to standard lightning impulse (LI) of 1V, 1.2/50µs front time and fall time respectively is initially defined as the test signal to simulate the lumped parameter model of a transformer winding. Fig.1 shows the lightning impulse excitation (LI) in time domain defined in the circuit simulation package.

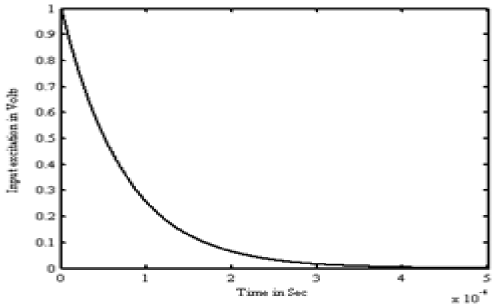

Fig.1 LI excitation in time domain

The LI excitation signal is exported to Matlab package to determine its characteristics in frequency domain and the same is shown in Fig.2. It is observed from Fig.2 that the magnitude of LI excitation decreases monotonically as the frequency is increased. Based on the frequency response measurement concept the input signal magnitude is to be kept constant and as the input signal's frequency is increased, the response of DUT is to be observed to study the frequency domain characteristics. Application of LI to determine the frequency response may not provide the necessary constant input excitation at all frequencies of measurement.

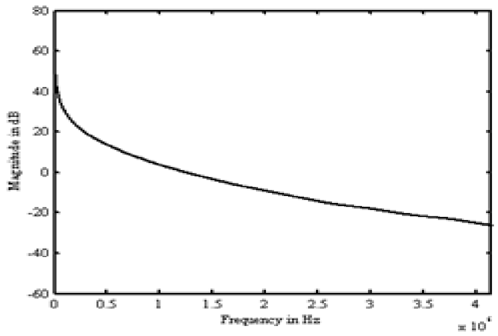

Fig. 2 LI excitation in frequency domain

In order to overcome this problem, a different excitation namely oscillating impulse (OLI) has been proposed as described below. The OLI is generated by super imposing with a standard LI, a sinusoidal signal with frequency equal to the resonant frequency of the winding. The resonant frequencies of the winding exhibits shift in frequency domain as a result of winding deformation. In case if the resonant frequency happens to be in the order of hundreds of KHz, the LI excitation may not indicate the same with good sensitivity. Where as if OLI in which the sinusoidal frequency is defined to be the resonant frequency of interest then that frequency component can be observed with better sensitivity. Fig.3 shows the OLI excitation in which sinusoidal signal of 27 KHz is super imposed with LI. Fig.4 shows the OLI excitation in frequency domain indicating dominantly 27 KHz frequency component.

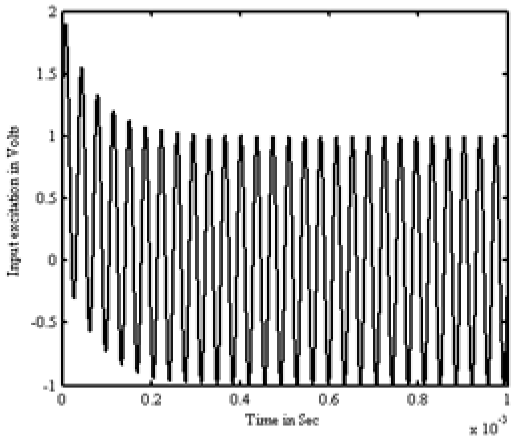

Fig.3 OLI excitation in time domain

From Fig.4, it is observed that the resonant frequency of interest could be studied with input having magnitude not in the noise region and there by improvement in detection sensitivity.

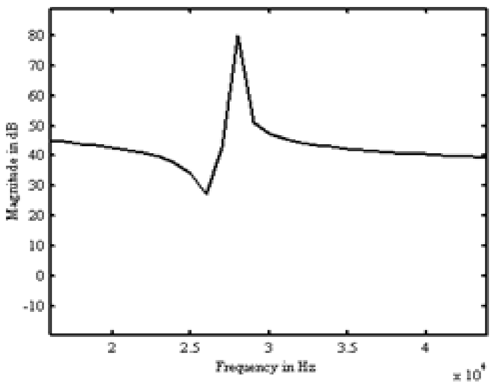

Fig.4 OLI excitation in frequency domain

V. DEVICE UNDER TEST (DUT)

In order to demonstrate the method that improves detection sensitivity, a transformer winding model is essential, to carry out the simulation. The simulation work requires a lumped parameter model of the transformer winding that needs to be considered as the device under test. The model parameters of layer winding and interleaved winding as mentioned in [11] have been used to carry out the simulation.

The parameters of the interleaved winding (DUT 1) are as given below

Inductance of each section =0.5mH
Ground capacitance of each section =0.4nF
Series capacitance of each section =12.8nF

The parameters of the layer winding (DUT 2) are as given below
Inductance of each section =0.5mH
Ground capacitance of each section =0.4nF
Series capacitance of each section =0.1nF

The mutual inductances for both interleaved and layer windings are M_{1-2}=0.25mH, M_{1-3}=0.167mH, M_{1-4}=0.125mH, M_{1-5}=0.10mH, M_{1-6}=0.0833mH, M_{1-7}=0.071mH, M_{1-8}=0.0625mH, M_{1-9}=0.0556mH, M_{1-10}=0.050mH and M_{1-2}= M_{2-3}= M_{3-4}………= M_{9-10}, M_{1-3}= M_{2-4}= M_{3-5}……= M8-10. M_{1-4}= M_{2-5}= M_{1-2}= M_{3-6}……..= M7-10 and so on. Figure 5 shows the ten section lumped parameter model of a transformer winding in general.

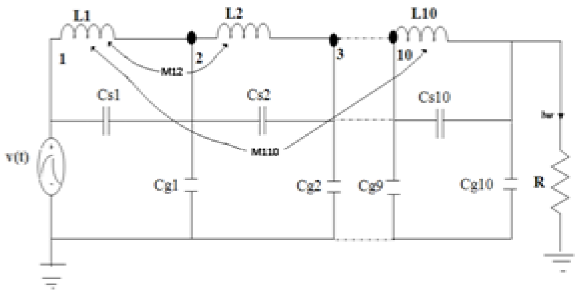

Fig. 5 Ten section lumped parameter model

VI. RESULTS AND DISCUSSION

The validation of proposed method is achieved through simulation of lumped parameter model of winding using LI and OLI excitations. In this regard, the lumped parameter model of interleaved winding (DUT1) is simulated to record the winding current using LI excitation. The winding current I_w through a current viewing resistor R as shown in Fig.5 is analyzed in frequency domain using MATLAB software. The winding current of DUT1 when LI excitation applied is shown in Fig.6 and the corresponding frequency domain response is shown in Fig.7.

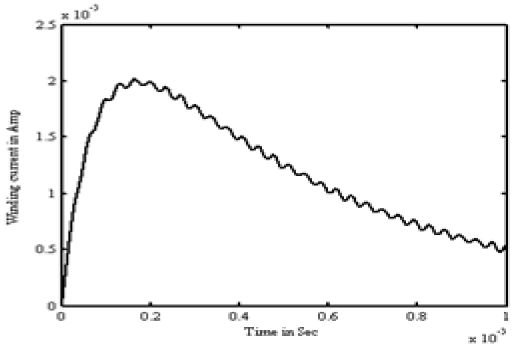

Fig.6 Response of DUT 1 with LI excitation

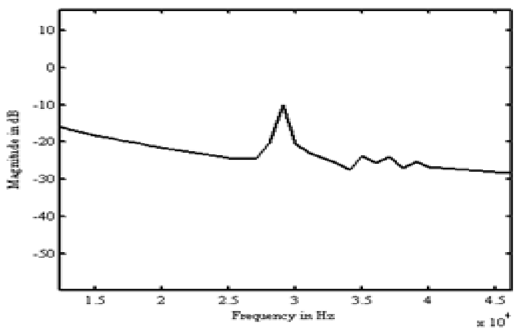

Fig.7 Winding current of DUT 1 in frequency domain with LI excitation

The resonant frequencies of DUT 1 with LI excitation are tabulated in Table 1. Next the winding current of DUT 1 with OLI excitation (LI super imposed with sinusoidal signal frequency of 37 KHz) applied is recorded and its frequency domain response is shown in Fig.8. Table 1 indicates resonant frequencies of DUT 1 with OLI excitation.

Table. 1 Resonant frequencies of DUT 1 with LI and OLI excitation

Excitation	Resonant frequency in KHz	Magnitude in dB
LI	29	-10.19
	35	-23.70
	37	-23.97
	39	-25.29
OLI	29	-3.986
	35	-7.389
	37	2.815
	39	-16.05

It is observed from Table I that the resonant frequency of interest (37 KHz) could be observed with higher magnitude (2.815 dB) than its corresponding value (-23.97 dB) with LI excitation.

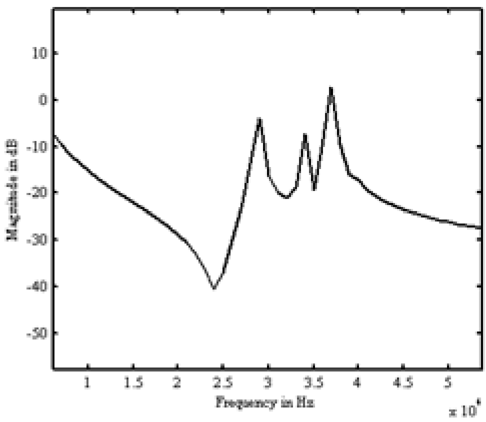

Fig.8 Response of DUT 1 with OLI excitation

The frequency response of interleaved winding model shows only four resonant frequencies in the order of tens of KHz. It would be better if the method is demonstrated for a model that has resonant frequencies occurring in high frequency region which is more prone to noise.

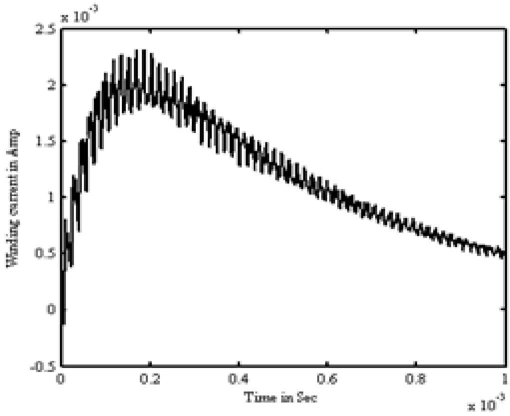

Fig.9 Winding current of DUT 2 in time domain with LI excitation

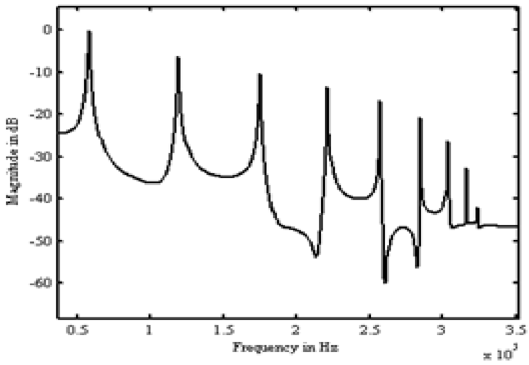

Fig.10 Winding current of DUT 2 in frequency domain with LI excitation

The simulation of lumped parameter model with LI and OLI excitation is repeated for the case of DUT 2.Winding current of DUT 2 when LI excitation applied is shown in Fig.9 and the same in frequency domain is shown in Fig.10. The resonant frequencies of DUT 2 are tabulated in Table 2. Consider the resonant frequency 284 KHz with magnitude -20.87 dB. To observe the effectiveness of OLI excitation to this resonant frequency the winding current of DUT 2 with OLI excitation (LI super imposed with sinusoidal signal frequency of 284 KHz) applied is recorded and its response in frequency domain is shown in Fig.11. Table 2 indicates resonant frequencies of DUT 2 with OLI excitation.

Table. 2 Resonant frequencies of DUT 2 with LI and OLI excitation

Excitation	Resonant frequency in KHz	Magnitude in dB
LI	58	-0.1392
	119	-6.345
	175	-10.33
	221	-13.57
	257	-16.75
	284	-20.87
	303	-26.36
	316	-32.85
	323	-41.99
OLI	58	-0.0497
	119	-5.829
	175	-8.931
	221	-6.773
	257	-4.521
	284	26.86
	303	-9.576
	316	-12.12
	323	-20.25

It is observed from Table 2 that the resonant frequency of interest (284 KHz) could be observed with higher magnitude (26.86 dB) than its corresponding value (-20.87 dB) with LI excitation.

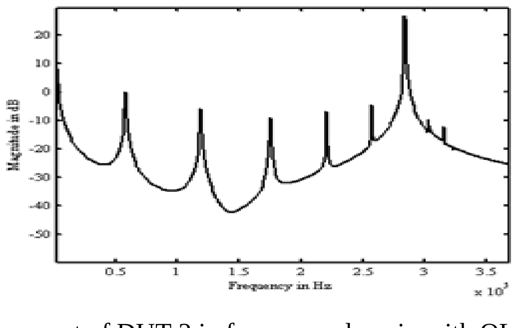

Fig.11 Winding current of DUT 2 in frequency domain with OLI excitation

In order to validate the proposed excitation for improving the detection sensitivity, winding deformation has to be simulated in the lumped parameter model. By introducing change in the model parameters the winding deformation can be simulated. In order to simulate radial deformation, shunt capacitance (Cg) in fifth section (middle of winding in a ten section lumped parameter model) is changed from 0.4nF to 0.5nF. The response of DUT 2 with LI and OLI excitation under no fault and fault introduced conditions are recorded and transformed to frequency domain as shown in Fig.12.

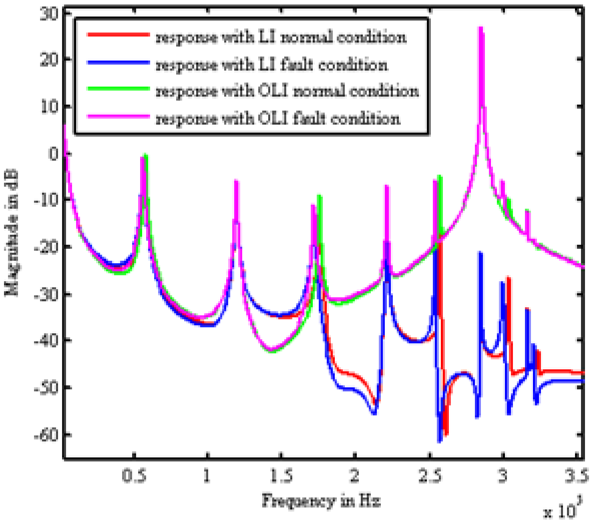

Fig.12 Response of DUT 2 for LI and OLI excitation under no fault and fault condition

Table. 3 Resonant frequencies of DUT 2 with LI and OLI excitation under no fault and fault condition

Excitation	With no fault		With fault	
	Resonant frequency in KHz	Magnitude in dB	Resonant frequency in KHz	Magnitude in dB
LI	58	-0.1392	56	-0.8999
	119	-6.345	119	-6.334
	175	-10.33	171	-11.64
	221	-13.57	221	-13.54
	257	-16.75	253	-16.47
	284	**-20.87**	**284**	**-20.88**
	303	-26.36	299	-27.35
	316	-32.85	316	-33.07
	323	-41.99	320	-40.45
OLI	58	-0.0497	56	-0.8948
	119	-5.829	119	-5.813
	175	-8.931	171	-10.77
	221	-6.773	221	-6.735
	257	-4.521	253	-5.548
	284	**26.86**	**284**	**26.90**
	303	-9.576	299	-5.855
	316	-12.12	316	-12.16
	323	-20.25	320	-18.25

Table 3 shows the variation in resonant frequencies with LI and OLI excitation under no fault and fault introduced conditions. The shift in resonant frequencies and their corresponding magnitude change under no fault and fault introduced condition are indicated. Consider the resonant frequency 284 KHz that has a magnitude of -20.87 dB under no fault and -20.88 dB with fault introduced condition. The magnitude level of this resonant frequency of interest is increased from -20.88 dB to 26.86 dB under no fault and from -20.88 dB to 26.90 dB under fault introduced condition. This proves the effectiveness of OLI excitation for winding deformation detection. Hence it can be appreciated from Table 3 that the proposed excitation improves the winding deformation detection sensitivity.

VII. CONCLUSION

This paper dealt with comparison of the winding deformation detection sensitivities of transformer windings for different test inputs through a simulation study. The winding deformation is simulated by introducing changes in the model parameter (shunt capacitance value in section 5) of the lumped parameter model to simulate radial deformation. The fault detection sensitivities of the winding model with low voltage impulse signal and oscillatory low voltage impulse signal are compared. It is observed that the OLI is more sensitive than LI test signal for the detection of winding deformation.

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