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Influence of the Load on the Impulse Frequency Response Approach Based Diagnosis of Transformer's Inter-Turn Short-Circuit

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ABSTRACT Frequency Response Analysis (FRA) is an Off-line condition monitoring technique for the transformers and is successful, in diagnosing mechanical faults and inter-turn short-circuits. Only limited literature is available for On-line FRA works, and the effect of the transformer's load on the fault diagnosing capability of FRA has not yet been analysed. Motivated by this research gap, an experimental investigation was done to analyze the effect of load on IFRA based inter-turn short-circuit diagnosis. A single-phase 1 kVA, 240V/240 V transformer supplying R and R-L loads and a three-phase 5 kVA, 440 V/440 V transformer supplying an induction motor at various load levels were tested. Inter-turn short-circuits were emulated in their windings and, the effectiveness of IFRA in diagnosing the same was investigated. Comparisons were made between the frequency response of the loaded transformers in their healthier conditions and emulated fault conditions, based on the transfer function plots and the statistical parameters. Investigations reveal that the loads alter the useful spectrum of IFRA. The frequency response of the healthier transformer itself varies based on the transformer's load and necessitates a careful focus on the sensitive frequency spectra for effective inter-turn short-circuit diagnosis in loaded transformers.

INDEX TERMS Condition monitoring, frequency response, insulation, statistical tools, transfer function, transformer.

I. INTRODUCTION

Condition monitoring of transformer and fault diagnosis at earlier stages will reduce downtime and maintenance expenditure, thereby ensuring the reliability of the power system. Testing techniques like FRA, DGA, PDC have gained importance and focus and has been an area of attraction among researchers globally [1], [2]. Techniques like DGA and PDC focus on the dielectric behaviour whereas, FRA addresses issues like winding deformation, displacement; both axial and radial [3]. Researchers have identified that the radial deformation of winding, axial winding elongation, overall-bulk and localised movements and short-circuits are the frequent faults of the transformer windings. Winding deformations can also occur due to sudden surges in electrical loading pattern which, if unnoticed, will result in severe damages. Researches in the past have proved that the above issues may be addressed by FRA approach by measuring the electrical transfer functions of transformers, over a wide frequency range [3], [4].

FRA can be done through two techniques: Sweep Frequency Response Analysis (SFRA) and Impulse Frequency Response Analysis (IFRA). SFRA is done by applying a low voltage sinusoidal signal of variable frequency sweeping over a wide range of pre-defined frequency spectrum and, measuring the response as a transfer function, over different bands of frequencies. IFRA plot is obtained from the responses for the various frequency components present in a single impulse signal [5].

Several factors like the winding connections and terminations, grounding, condition of the core, clamping pressure can influence FRA and are discussed in the literature [6]–[10]. Ryder elaborated the effect of winding connection methods, the effect of loosening turns, Hoop buckling and axial

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winding collapse and correlation coefficient based statistical analysis of FRA results on sub-Band basis [11].

Current status and future trends of FRA were also investigated and available as literature, which is motivating further researches [12]. Cigre Working Group recommendations, IEEE and IEC standards are now available as standard references for implementing SFRA as an Off-line diagnostic technique of mechanical faults and explain the general procedures for conducting FRA test through different transfer function approach, measurement and analysis [13]–[15]. Off-line FRA based diagnosis of Inter-turn short circuits within transformer windings through different transfer function approaches were reported in recent literature [16]–[18].

Though FRA approaches for electrical and mechanical fault diagnosis were demonstrated successfully in literature, interpretation of FRA results were found to be complicated, inviting expert service to avoid misinterpretations and to reach subjective conclusions. Such challenges were addressed and, the usefulness of feature extractions from FRA results in the form of statistical tools was successfully demonstrated in recent researches [19]–[21]. Jiangnan Liu et al. combined the Support Vector Machine with FRA to diagnose the transformer faults and, discussed the usefulness of the parameter optimisation algorithms [22].

In 'Off-line' FRA approaches, the transformers will be disconnected from the remaining part of the electrical network. If FRA is implemented as an 'On-line' diagnostic technique, the transformers need not be disconnected from service. This is advantageous, as any power flow through the transformer to the remaining part of a power system network is becoming uninterrupted.

On-line FRA approaches, recently experimented through the capacitive and inductive coupling of test signals into transformer winding, bushing tapping injection approaches, their advantages and difficulties were elaborated in recent literature [23]–[26]. Hardware setup for test signal injection into transformer bushing tapping and the diagnosis of shorted-turns was demonstrated by researchers [25]. Gomez Luna et al. discussed the application of Wavelet transform in FRA [27]. On-Line On-load IFRA approach based inter-turn short diagnosis was demonstrated on a laboratory transformer in earlier work at SASTRA [28]. Mechanical fault diagnosis in the transformer winding through On-line FRA with support vector machine was also available as literature [29]. Zhongyong Zhao et al. demonstrated the usefulness of the multi-scale Complex Continuous Wavelet Transform in getting On-line IFRA signatures [30]. Smart techniques for interpretation of the FRA data during the inter-disc fault diagnosis and its extendability to the On-line FRA approach were demonstrated in recent researches [31].

Literature available for On-line FRA works is limited [23]–[31]. The effect of the 'load connected to the transformer' on the fault diagnosing capability of FRA has not yet been analysed and is still a research gap to address.

Motivated by this, an experimental investigation was carried out at HV lab of SASTRA, on the transformers, with a purpose of getting more insights on the implementation of On-Line IFRA in transformers and the influence of the 'load connected to the transformer' during 'IFRA based inter-turn short diagnosis'. First, a single-phase, 1 kVA, 240 V/240 V transformer supplying power to resistive and inductive loads was investigated. Further, to check the 'influence of load connected to the 3Φ transformers', a 3 phase, 5 kVA, Dyn 11, 440 V/440 V transformer, supplying power to a slip ring induction motor was investigated.

On-Line On-Load FRA (OLOL FRA) approach was found to be complicated when compared to the Off-Line FRA approach, in several aspects. Several issues exist as research gaps in OLOL IFRA like, 'Isolation requirements' between the 'a.c. Source' and the 'Test signal Source', 'Equivalent impedance effect of the Loaded transformer' on the FRA Test setup, 'Possible alterations in spectral sensitivity' of the IFRA, 'Difficulties in comparing the transfer function plots of the loaded transformer (Healthier case versus Faulty case)'. The present work offers more insight into the above issues and investigates experimentally, the 'influence of load' on 'IFRA based Inter-turn short diagnosis' of transformers.

'Load connected to the transformer' alters the impedance offered to some of the frequency components of the impulse voltage. Even under the healthier conditions (referred hereafter as 'Normal or No-Fault' case), the transfer function plots of the transformer at different loads was, found to be distinct (different, for different loads). There are changes in resonant frequencies and some alterations in the magnitudes of the End-to-End Voltage Transfer function. As a result, the effective frequency spectra of the impulse, which can be capitalized to diagnose the fault, get reduced. These above issues were taken care in the present work by giving more attention to the 'Sensitive Sub–band spectral regions' of the total FRA spectrum, where, the changes the transfer function plots were noticeable

The focus was given mainly to get an insight on the 'effect of transformer's load on the IFRA sensitivity' during the Inter-turn short-circuit diagnosis.

The details of the experimental arrangements and test procedures were explained in the Methodology section. The IFRA results were presented and analyzed in the 'Results and Discussions' section.

II. THEORY OF FRA BASED FAULT DIAGNOSIS

FRA is based on the 'Response 'of the transformer to various frequencies of an 'Input' test signal [3], [4]. The ratio of the input test signal to the response or vice versa in the frequency domain is usually referred to as the 'Transfer Function(TF)'.The Transfer Function can be in the form of the (1) Impedance or Admittance offered by a transformer winding at various frequencies of the test signal, (2)Voltage transferred from one end of the winding to the other end of the winding at various frequencies or (3) Voltage transferred from one winding to the other winding at various frequencies. Accordingly, these approaches are referred to as (1) Impedance/Admittance Transfer Function, (2) End to End Voltage Transfer Function (EEV TF) and (3) Transfer voltage Transfer Function (TV TF). When these magnitudes/ phase difference at different frequencies are plotted against their corresponding frequencies, they are referred to as 'TF (magnitude/ phase) plots'.

All these FRA approaches, the frequency response of the transformer can be observed by using the test signal either in the form of an impulse Voltage (comprising several frequency components within it, as per Fourier transform concepts) or, in the form of a sinusoidal sweep of low voltage spanning from few Hertz to few mega Hertz [5]. The Transfer Function magnitude and phase at different frequencies will get altered when any fault develops within the transformer (like 'axial/Radial Displacement within the windings, inter-turn short-circuits, core magnetisation problems). The Transfer function under the 'Healthy condition of the transformer' is viewed as 'Healthy case Transfer Function or Signature Transfer Function'. Similarly, the Transfer function under any suspected faulty condition of the transformer will be viewed as 'Faculty case Transfer function'. The difference between the 'Healthy Case' and the' Faulty Case' Transfer Function magnitudes in the TF plots can be in the form of the (1) appearance/ disappearance any Spikes/Dips, (2) changes in the magnitudes of any Spikes/Dips. In principle, these differences appearing in the TF plots of the transformer under diagnosis with reference to its Healthier case/ Signature TF plot will be analysed and capitalised to diagnose any probable fault within the transformer [11], [13]–[15].

III. METHODOLOGY

A. DETAILS OF THE TRANSFORMERS TESTED

Investigations were carried out on a 1Φ, 1kVA, 240V/240V and a 3Φ, 5 kVA,440 V/440 V, Dyn 11 transformer.

The 1 kVA transformer has tappings on one of its windings at 0V, 30V, 60V, 120V, 200V and 240V levels. Similarly, the 5 kVA transformer has tappings at 0V, 30V, 115V, 230V and 440V levels on all the three phases of the star connected side.

Inter-turn short-circuits, were emulated during experimentation between the tappings within one of the windings, through a 500 Ω, 25 W resistor. The resistor value was selected such that it could represent a short at a developing stage (low level) and the current circulating within the shorted portion of the winding could not exceed the rated current level of the winding. Thus, any possible permanent damage to the transformers during the investigations was, avoided.

B. EXPERIMENTAL SETUP

In principle, FRA is based on the responses to the various frequency components of the injected impulse voltage into the winding. Thus, the test requires only the impulse of moderate magnitude (much below the Basic Impulse Insulation Level (BIL) of the transformer tested) with sufficient frequency components spanning from few Hz to few MHz). Hence, the magnitude and the waveshape of the impulse were not given much importance, as the loading effects of the transformer under loaded condition could anyhow alter the shape of the impulse.

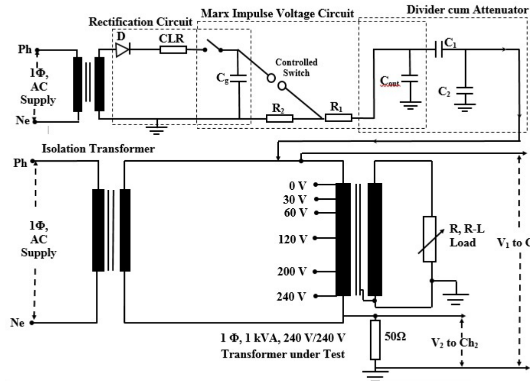

FIGURE 1. Experimental setup for OLOL IFRA on the 1 kVA transformer.

First, the a.c supply was rectified into D.C supply and then fed to the locally assembled multi-stage Marx Impulse voltage generator with adjustable wave-shaping components.

The input a.c voltage was adjusted suitably to develop the impulse with a peak magnitude of 400 voltage.

Isolation/attenuation requirements' between the a.c supply side and the impulse source side is a challenge in OLOL IFRA implementation: the impulse voltage should not damage the a.c. supply system and, the a.c. supply to the transformer should not affect the impulse generator. An attenuator comprising capacitors was included in the test circuit, to tackle the above issue. The impulse was injected into the transformer at the terminal of the primary, through the attenuator cum capacitive voltage divider circuit. The capacitances of the attenuator circuit were selected such that an impulse of appreciable magnitude could enter into the winding, with respect to the ground and, the a.c supply available at the transformer winding could drop almost entirely across the series capacitor 'C1' of the attenuator, thereby minimizing the effect of a.c supply on the impulse generator.

Figure 1 shows the circuit connections of OLOL IFRA on the 1Φ, 1 kVA transformer. In the primary side, the tapping at 0V was connected to the Phase terminal, and the 240 V tapping was connected to the Neutral terminal of the a.c supply. The load was connected across the secondary winding. The impulse was applied at '0 V' tapping of the primary, with respect to the ground. A 50 Ω resistor was connected between the '240 V' tapping of the primary and the ground, which had ensured that the resistor had got included only in the impulse path.

Figure 2 Shows the circuit connection of OLOL IFRA on the 3Φ, 5 kVA transformer and Figure 3 shows its photograph. In the star side, 440 V tappings of the R, Y and B phases were connected to the R, Y and B side of the 3Φ a.c balanced supply. In the delta side, a three-phase induction motor with

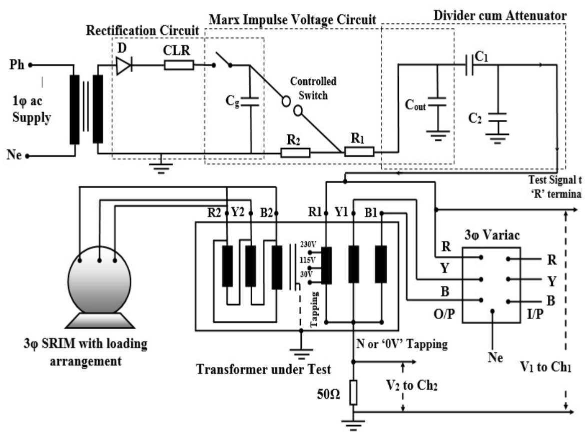

FIGURE 2. Experimental setup for OLOL IFRA on the 5 kVA transformer.

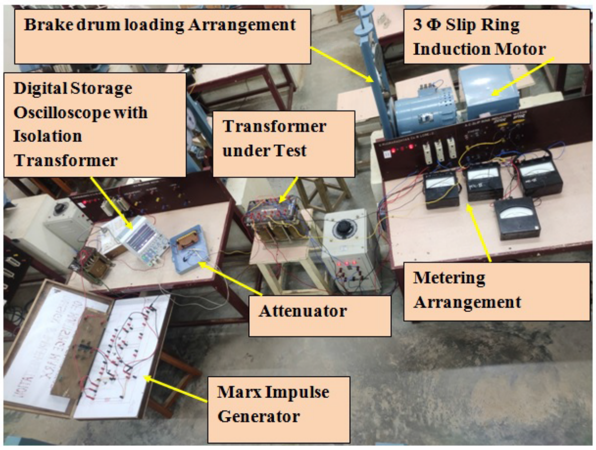

FIGURE 3. Photography of OLOL IFRA setup on the 5 kVA Transformer.

a brake drum loading arrangement was connected as the load. The impulse was applied to the 440 V terminal of the R-Phase of the star side, with respect to the ground. The neutral tapping of the star side was grounded through a 50 Ω resistor which had ensured that the resistor had got included only in the impulse path.

C. PROCEDURE

1) EXPERIMENTATION ON THE 1Φ TRANSFORMER

For the 1 kVA, 0-30-60-120-240V/240V, single-phase dry resin type transformer, the rated 1Φ, 50 Hz a.c supply was given to the primary winding of the transformer. The test signal (Impulse) was injected into the '0 V' tapping of the primary, with respect to the ground and the '240 V' tapping of the primary was grounded through the 50 Ω resistor. The core of the transformer was grounded.

To investigate the effect of load on the IFRA approach, two different loads were considered across the secondary winding: (1) with 'Resistive load' rated 80W, 230V, (referred hereafter as 'NC-R load') and (2) with 'R-L load' comprising the above lamp load in parallel with an inductor rated 200 mH, 2.5 A (referred hereafter as 'NC-RL load').

IFRA investigations were done in the transformer with these two load conditions: Response to the impulse was observed first, under the healthier conditions of the transformer and secondly, under an emulated 'inter-turn short-circuit' between the '0V' and '30V' tappings, near the impulsed end of the winding (referred hereafter as 'Sh1').

The Channels 1 and 2 of a 200 MHz,2.5 GHz, Yokogawa make Digital storage Oscilloscope (DSO) were used for observing the voltages 'V1' and 'V2' respectively. The Inbuilt 'FFT' function of the DSO was used to get the magnitudes (dB) of the frequency components of 'V1' and 'V2'.From these dB magnitudes of the frequency components, the 'End to End Voltage Transfer Function (EEVTF)' which represent how the various frequency components of the impulse voltage get transferred from one end to the other end of the winding, was calculated.

The same procedure was followed for all the cases ('Healthier case with resistive load, the Healthier case with RL load and the inter-turn short-circuit 'Sh1' at both the load levels) and, the respective EEV TF values were obtained. For ensuring the reliability of the results, the experiments were repeated ten times with the same experimental setup, for all these healthier and emulated faulty cases. Subsequently, for each of the healthier and the faulty cases, the average dB values for each frequency components of both the 'V1' and 'V2' were calculated and, used as the 'representative of the case' during further investigations. The corresponding TF plots were developed by taking 'Frequency 'in X-axis and the 'EEV TF magnitudes' in Y-axis.

The objective of this work was to analyze the effectiveness of IFRA in diagnosing the 'inter-turn short-circuits' in loaded transformers. Hence, the focus was mainly on the response of the transformer to the frequency components of the test signal (Impulse). However, it was ensured that the frequency components spanned over a good bandwidth, which was sufficient enough to distinguish the transformer under the healthier condition from the transformer under the fault condition. To avoid any permanent damage during the test, only a mild, developing stage short was emulated, by shorting the tappings through a 500Ω, 25 W resistor.

2) EXPERIMENTATION ON THE 3Φ TRANSFORMER

In the star side, 440 V tappings of the R, Y and B phases were given the rated 3Φ,50Hz a.c balanced supply. In the delta side, a three-phase induction motor was connected as the load. Through the attenuator, the test signal (Impulse) was applied to the 440 V terminal of the R-Phase of the star side, with respect to the ground. The neutral tapping of the star side was grounded through a 50 Ω resistor (which got included only in the impulse path). The core was grounded.

First, the transformer under healthier condition (normal case, without fault) was loaded to four different load current levels (2A, 3A, 4A and 4.8A) and, the effect of the load on the frequency response of the transformer under its healthier condition was investigated (referred hereafter as 'NC-2A', 'NC-3A', 'NC-4A' and 'NC-4.8 A'). Secondly, to analyze the

TABLE 1. Description of the various cases investigated and their notations.

Transformer tested	Description of the case investigated	Notation
1 kVA,	Healthier / Normal Case-with R load	NC-R load
1ϕ, 240V/240V	Healthier / Normal Case- with RL load	NC-RL load
	Inter-turn short circuit between the '0V' tapping and the '30V' tapping – with R Load	Sh-1-R load
	Inter-turn short circuit between the '0V' tapping and the '30V' tapping – with RL load	Sh-1-RL load
5 kVA,	'Healthier / Normal Case' with motor load at 2 A	NC-2A
3ϕ, 440V/440V, Dyn11	'Healthier / Normal Case' with motor load at 3 A	NC-3A
	'Healthier / Normal Case' with motor load at 4 A	NC-4A
	'Healthier / Normal Case' with motor load at 4.8 A	NC-4.8A
	Inter-turn short circuit between the '0V' tapping and the '30V' tapping – with 2A load	Sh-2-2A
	Inter-turn short circuit between the '0V' tapping and the '30V' tapping – with 4.8A load	Sh-2-4.8A
	Inter-turn short circuit between the '0V' tapping and the '115V' tapping – with 2A load	Sh-3-2A
	Inter-turn short circuit between the '0V' tapping and the '115V' tapping – with 4.8A load	Sh-3-4.8A

effect of the loads on the 'IFRA based inter-turn short-circuit diagnosis', the transformer was further tested at 2 A and 4.8 A load levels with some emulated inter-turn short-circuits. For this purpose, two inter-turn short-circuits were emulated in the R–phase of the Star winding: (1) Short between the '0V' tapping and '30 V' tapping (referred hereafter as 'Sh2', and (2) Short between the '0V' tapping and '115 V' tapping (referred hereafter as 'Sh3'). IFRA was carried out with these emulated faults in both load conditions (2A and 4.8A). Thus Four faulty cases were emulated during the investigation: (1) Short between the '0V' tapping and '30 V' tapping - at '2A'load (2) Short between the '0V' tapping and '115 V' tapping - at '2A' load (3) Short between the '0V' tapping and '30 V' tapping - at '4.8 A' load and (4) Short between the '0V' tapping and '115 V' tapping - at '4.8 A' load.

Measurement of the test signal and its response were carried out for the transformer, both under the healthier conditions and under the emulated faulty conditions. The voltage at the '0 V' tapping with respect to the ground was considered as 'V1' and, the voltage at the '440 V' tapping with respect to the ground was considered as 'V2'. Transfer function magnitudes were calculated, and plots were developed for all the healthier and the emulated faulty cases, by following the same procedures explained for the 1Φ transformer.

Table 1 consolidates the various cases investigated and their notations for easy reference.

D. PROCEDURE FOLLOWED FOR THE ANALYSIS

For all the cases investigated in the 1Φ and 3Φ transformers, the End to End Voltage Transfer Function (EEVTF) magnitudes in dB were calculated at different frequencies as

$$EEV\ TF\ magnitude\ in\ dB = \left[20\log_{10}\left({}^{V_1}\!/_{V_2}\right)\right] \quad (1)$$

where 'V_1' is the input impulse signal in volts and 'V_2' is the response signal at the other end of the winding in volts [17], [28]. EEV TF plots for all the cases were developed by plotting the 'EEV TF magnitudes' in Y-axis against the 'Frequency 'in X-axis.

For both the transformers, first, these transfer function plots comparisons were used to make comparison (1) within the healthier cases at different loads (normal cases), (2) between a healthier case (normal case at a particular load) and a faulty case (inter-turn short-circuit) and (3) within the faulty cases.

Difficulties in the comparison of FRA results of two cases were found to get reduced when statistical parameters were employed for extracting the features from the FRA magnitudes on the sub-band basis [19]–[21], [28]. Hence, the comparison was further carried out using three statistical parameters: Absolute Difference (DABS), Min-Max ratio (MM) and Comparative Standard Deviation (CSD).

DABS gives the overall absolute difference between two sets of data compared and a result of '0' suggests no difference and the numerical value shows the severity of deviation [19]–[21]

$$DABS = \frac{\left(\sum_{i=1}^{n}(x_i - y_i)\right)}{n} \quad (2)$$

where n is the number of data samples, x_i and y_i are the EEV TF magnitudes in dB, for two cases under comparison.

Min Max Ratio gives the ratio of minimum value to the maximum value of the two data sets under comparison. A value of '0' or closer to 0 indicates maximum deviation and value of '1' or closer to 1 indicates the closeness of the values [19]–[21]

$$MM = \frac{\sum_{i=1}^{n}|\min(x_i, y_i)|}{\sum_{i=1}^{n}|\max(x_i, y_i)|} \quad (3)$$

where x_i and y_i are the EEV TF magnitudes in dB, for two cases under comparison.

Comparative Standard Deviation (CSD) value needs to be 0 for a complete match between the two data sets compared. Initially, the variation of each data point with respect to its mean is calculated, which is further used to compute the Comparative Standard Deviation [19]–[21]

$$CSD = \sqrt{\frac{\sum_{i=1}^{n}[[x_i - \bar{x}] - [y_i - \bar{y}]]^2}{n-1}} \quad (4)$$

where n is the number of data samples, x_i and y_i are the EEVTF magnitudes in dB, for two cases under comparison.

IV. RESULTS AND DISCUSSIONS

The IFRA results of the two transformers were processed to develop the transfer function plots and extract statistical indices from the transfer function magnitudes at different frequencies [13]–[15]. Subsequently, two types of comparisons were made to analyse the influence of the transformer's load on its frequency response: (1) Comparisons in terms of the EEV-TF plots of different cases and (2) Comparisons in terms of statistical parameters extracted from the EEV TF magnitudes, on sub-band basis [19]–[21].

Comparison of EEV TF plots can reveal the difference between the various cases through the (1) transfer function magnitude at some frequencies, (2) appearance/ disappearance of peaks /dips at some frequencies and (3) horizontal shifting of such peaks/dips in the transfer function plots [13]–[15]. Interpreting such differences between the cases and getting conclusions about the faults or condition of the transformer requires experience/ expert service.

Comparison in terms of the statistical parameters can reduce such interpretational difficulties and, give further insight into the effects of transformer's load on the frequency responses [19]–[21]. Two cases were compared at a time and, from their transfer function magnitudes, the statistical parameters were estimated. To identify the highly sensitive frequency ranges which could be capitalised for the fault diagnosis purpose, the comparisons were made by splitting the total frequency spectrum covered, into three sub-bands: 2 kHz-30 kHz, 30 kHz-300 kHz and 300 kHz -1MHz.

A. RESULTS AND DISCUSSIONS ON 1Φ, I KVA TRANSFORMER

1) EEV-TF PLOTS OF DIFFERENT CASES

Figure 4.a shows the EEV-TF plots of the two healthier 1Φ, 1 kVA transformer with the two loads 'NC-R load' versus 'NC- RL load'. Figure 4. b compares the TF plots developed for the transformer with R-load; 'NC-R load' versus 'Sh-1-R load'. Figure 4.c compares the TF plots developed for the transformer with RL-load; 'NC-RL load' versus 'Sh-1-Rl load.'

Thus, Figure 4.a compares the frequency response of the healthier transformer under two different load conditions. The transfer function plots under the two different loads are not overlapping, and there are noticeable differences in dB magnitudes, throughout the frequency spectrum [13]–[15]. The variations demonstrate that the load connected to the transformer influences its frequency response. Therefore, the healthier case transfer function plot of the transformer at a particular load level cannot be used as the 'Generalized Signature Pattern' of the transformer, for all the load levels. For analyzing the specific influence of transformer's load during an 'inter-turn short-circuit' diagnosis, further comparisons were made by keeping the fault as fixed (short between

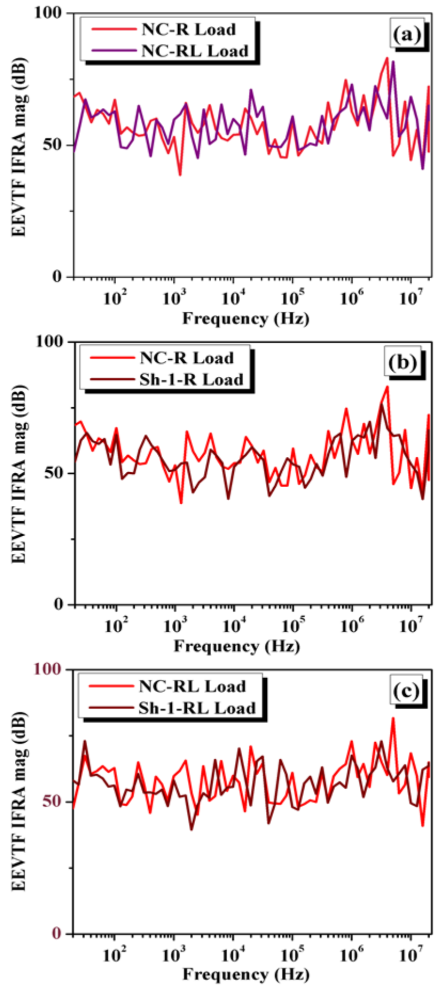

FIGURE 4. EEV-TF plots of 1Φ, 1 kVA transformer: (a) healthier cases at different loads (b) healthier & faulty cases with R load (c) healthier & faulty cases with R-L load of OLOL IFRA setup on the 5 kVA Transformer.

the '0V' tapping and '30 V' tapping) and, changing the transformer's load alone. The Sub-Figures 4.b and 4.c show the transfer function plots of the transformer, with 'R load' and 'RL load' respectively. The comparison was between healthier case responses and faulty case responses.

Two important observations were made from the Sub-Figures 4 (b) and 4 (c):

(1) Though the fault was kept as fixed, the frequency responses (transfer function magnitudes) of the transformer to this fault was, found to be 'load-dependent'. Thus, the frequency responses for the same fault was 'different' for different loads.

(2) The deviation level of the dB magnitudes of the faulty case from the healthier case plots was 'different' for the two load levels. The difference was because of the 'combined effect of transformer's load and the inter-turn short-circuit' on, the response of the transformer to the different frequency components. With the change in the load, the dB magnitudes of the faulty case remained unaltered at some frequencies, increased at some frequencies and, decreased at some other frequencies, similar to Off-Line FRA results [13]–[15].

TABLE 2. Comparison between the various cases of 1 KVA transformer.

Sub-band Frequency	NC R vs NC R-L	NC R vs Sh-1-R	NC RL vs Sh-1-RL
DABS			
2 kHz- 30 kHz	7.99	5.33	8.97
30 kHz-300kHz	4.16	5.53	6.50
300kHz -1MHz	**8.54**	**7.72**	**4.38**
MM(Absolute)			
2 kHz- 30 kHz	0.87	0.91	0.85
30 kHz-300kHz	0.92	0.90	0.89
300kHz -1MHz	**0.87**	**0.88**	**0.93**
CSD			
2 kHz- 30 kHz	9.16	7.16	**10.91**
30 kHz-300kHz	4.64	6.84	7.82
300kHz -1MHz	**9.85**	**11.60**	**3.46**

The frequency response analysis became complicated due to the transformer's loads and increased the difficulties in interpreting the results. Difficulties in the interpretation of FRA results minimizes if features are extracted from the transfer function magnitudes in the form of statistical tools [19]–[21], [28]. With this motive, further analysis of the frequency response results was carried out using the statistical tools.

2) COMPARISONS IN TERMS OF STATISTICAL PARAMETERS

Table 2 shows the comparison made between transfer function magnitudes of the different cases of 1Φ, 1 kVA transformer, through the statistical parameters (DABS, MM ratio and CSD) on 'Sub-band' basis [19]. When the difference between the two cases compared is more, DABS and CSD values will be more and, deviate from '0'. MM (absolute) will differ much from the numerical value '1' if the difference between the two cases compared are more.

'Column-2' in Table 2 indicates the statistical parametric values estimated by comparing between the healthier performances of the transformer under two different loads; 'the frequency response of the healthier transformer with R load (NC-R load)' versus 'the frequency response of the healthier transformer with RL load (NC-RL load)'. In all the three Sub-bands considered, all the three statistical parameters show deviation from their typical values expected under 'No-difference condition'. Thus, they demonstrate once again that the frequency responses of the heathier cases at the two different loads are different.

'DABS' and 'CSD' values are highest, and the 'MM ratio' is lowest at the Sub-band '300 kHz -1MHz'. This agreement among the three statistical tools at the same Sub-band (in the form of maximum deviation from their respective typical values of the 'No-difference condition'), indicates that the effect of load variation on the frequency response is more at this Sub-band. Careful analysis is required at this Sub-band frequency during the On-load FRA investigation, to distinguish the effect of a fault from the effect of load.

'Column-3' in Table 2 compares the response of the healthier case (NC-R) with the response at an inter-turn short-circuit (Sh1), under resistive load (80W). 'DABS' and 'CSD' values are again highest, and the 'MM ratio' is again lowest at the Sub-band '300 kHz -1MHz'. Thus, 'Sh-1-R' causes noticeable variation and, is readily detectable in the Sub-band '300 kHz-1MHz' of the frequency response of the transformer on the 'R-load'.

'Column-4' of Table 2 compares the response of the healthier case (NC-RL) with the response at an inter-turn short-circuit (Sh1), under RL load (80W lamp load in parallel with 250 mH inductor). For the same fault considered, the deviation of 'DABS, CSD and MM ratio' values are moderate only at the Sub-band '300 kHz -1MHz'. The changes in the statistical values indicate the difference between the influence of the 'R-load' and the 'RL-load'.

However, 'DABS' and 'CSD' values are again highest, and the 'MM ratio' is again lowest at a different Sub-band '2 kHz- 30 kHz'. Thus, 'Sh-1-RL' now causes noticeable variation and, is readily detectable in the Sub-band '2 kHz-30 kHz' of the frequency response of the transformer on the 'RL-load'. The changes in statistical values at different Sub-bands demonstrates that IFRA's sensitivity in 'inter-turn short-circuits detection' is influenced by the transformer's load.

B. RESULTS AND DISCUSSIONS ON 3Φ, 5 KVA TRANSFORMER

1) EEV-TF PLOTS OF DIFFERENT CASES

Figure 5 shows the comparisons made between various cases in a 3Φ, 5 kVA transformer. Figure 5.a compares the frequency response of the healthier transformer under four different load conditions, whereas Figures 5.b and 5.c compare the healthier cases with two faulty cases (inter-turn short-circuits Sh2 and Sh3), at a particular load.

Figure 5.a shows the EEV TF plots of the four healthier cases of the 3Φ, 5 kVA transformer; 'NC-2A', 'NC-3A', 'NC-4A' and 'NC-4.8A'. There are differences within the dB magnitudes of the four 'healthy cases'. These differences again demonstrate the effect of the transformer's load on the frequency response.

Figure 5.b compares the TF plots developed for the transformer with 2A load; 'NC-2A', 'Sh-2-2A' and 'Sh-3-2A'.The differences in the transfer function magnitudes indicate that the two faults are identifiable and one faulty case is distinguishable from the other faulty case.

Figure 5.c compares the TF plots at the 4.8 A load level (responses of the transformer under the healthy condition 'NC-4.8 A' and the same faulty conditions, but, at a different load levels 'Sh-2-4.8A' and 'Sh-3-4.8A'. Again, the differences in the transfer function magnitudes indicate that the faults are identifiable and, one faulty case is distinguishable from the other faulty case [7], [11], [17]. The difference in the dB magnitudes at the two different load levels is due to 'combined loading-effect' of the 'inter-turn short-circuit and the transformer's load' and, demonstrates that the sensitivity of IFRA in inter-turn short-circuit diagnosis is 'load-dependent'.

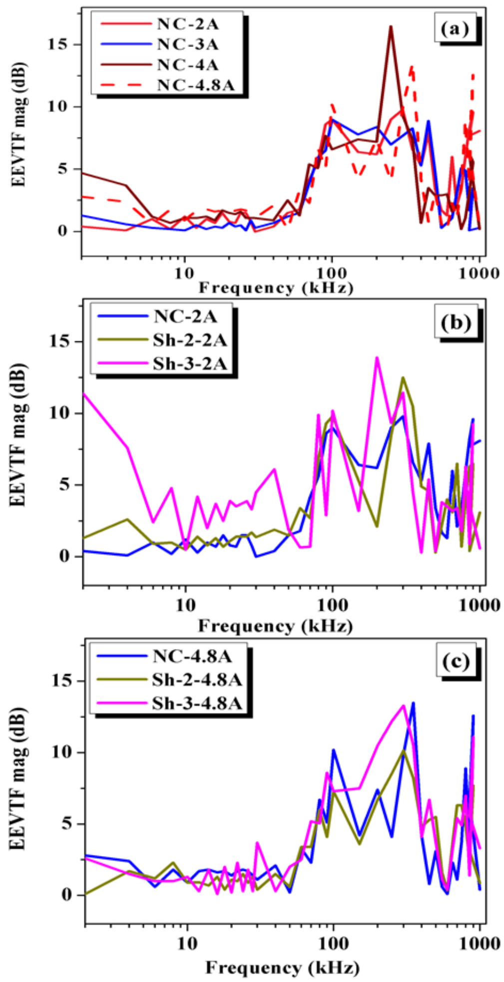

FIGURE 5. EEV-TF plots of 3Φ, 5 kVA transformer: (a) healthier cases at different loads (b) healthier& faulty cases at 2A load (c) healthier & faulty cases at 4.8 A load.

2) COMPARISONS IN TERMS OF STATISTICAL PARAMETERS

Table 3, 4 and 5 show the comparison between the different cases of 3Φ, 5 kVA transformer, through the statistical parameters on 'Sub-band' basis [19]–[21], [28].

In Table 3, 'Columns-2, 3 and 4' show the comparisons made between frequency responses the healthier transformer at different load levels; 'NC-2A versus NC-3A', 'NC-2A versus NC-4A'and 'NC-2A versus NC-4.8A'. The effect of the load on the frequency response is noticeable in the Sub-band '300 kHz-1 MHz'. 'DABS' and 'CSD' values are highest and, 'MM ratio' value is moderate (second high), at this Sub-band.

Table 4 shows the comparisons made between frequency responses of the transformer at 2A load level. 'Columns-2 and 3' compare the healthier case with two different faulty cases (with 'Sh2' and 'Sh3', respectively).

In Table 4, Column-2, 'DABS' and 'CSD' values are highest at the Sub-band '300 kHz-1 MHz'. Hence, in terms of 'DABS' and 'CSD', the inter-turn short-circuit 'Sh2' is detectable at this Sub-band. In 'Column-3', the 'DABS' and 'CSD' values decreases and, are not the highest at this

TABLE 3. Comparison between the normal cases of 5 KVA transformer at different loads.

Sub-band Frequency	NC-2A vs NC-3A	NC-2A vs NC-4A	NC-2A vs NC-4.8A
DABS			
2 kHz- 30 kHz	0.59	0.89	0.93
30 kHz-300 kHz	0.96	1.50	1.80
300 kHz-1MHz	**2.99**	**2.97**	**2.79**
MM(Absolute)			
2 kHz-30 kHz	**0.36**	**0.46**	**0.44**
30 kHz-300 kHz	0.83	0.76	0.69
300 kHz-1MHz	**0.52**	**0.51**	**0.58**
CSD			
2 kHz- 30 kHz	1.51	1.27	0.81
30 kHz-300 kHz	1.35	2.35	2.23
300 kHz-1MHz	**3.53**	**3.06**	**3.64**

TABLE 4. Comparison between the different cases of 5 KVA transformer at 2A load.

Sub-band Frequency	NC-2A vs Sh-2-2A	NC -2A vs Sh-3-2A
DABS		
2 kHz-30 kHz	0.74	**3.43**
30 kHz-300 kHz	1.42	3.27
300 kHz-1MHz	**3.05**	2.91
MM(Absolute)		
2 kHz-30 kHz	**0.47**	**0.18**
30 kHz-300 kHz	0.77	0.56
300 kHz-1MHz	0.55	0.54
CSD		
2 kHz-30 kHz	0.99	3.44
30 kHz-300 kHz	1.74	**3.93**
300 kHz-1MHz	**3.27**	3.15

TABLE 5. Comparison between the different cases of 5 KVA transformer at 4.8A load.

Sub-band Frequency	NC-4.8A vs Sh-2-4.8A	NC- 4.8A vs Sh-3-4.8A
DABS		
2 kHz-30 kHz	0.73	0.87
30 kHz-300kHz	1.12	**2.99**
300 kHz-1MHz	**2.51**	2.00
MM(Abs)		
2 kHz-30 kHz	**0.57**	**0.55**
30 kHz-300 kHz	0.79	0.58
300 kHz-1MHz	0.58	0.67
CSD		
2 kHz-30 kHz	1.77	1.68
30 kHz-300 kHz	1.67	**3.34**
300 kHz-1MHz	**3.31**	3.07

same Sub-band '300 kHz-1 MHz'. However, 'DABS' value increases and is becoming the highest at the Sub-band '2 kHz-30 kHz' and similarly, 'CSD' value increases and is becoming the highest at a different Sub-band '30 kHz-300kHz'.

In terms of 'MM ratio', both the faults 'Sh-2-2A' and 'Sh-3-2A' are, detectable at the same Sub-band '2 kHz-30 kHz'. However, the 'MM ratio' is different in 'Column-2' and 'Column-3', indicating that the two faults 'Sh-2-2A 'and 'Sh-3-2A' are still, distinguishable at this Sub-band '2 kHz-30 kHz'.

For getting further insight into the effect of the load on the fault diagnosis, similar comparisons were made between the frequency responses of the transformer at the '4.8 A load' level. In Table 5, the 'Columns-2 and 3' show the comparison between the healthier case and the same faulty cases (with 'Sh-2-4.8A' and 'Sh-3-4.8A', respectively), but at the new load level (4.8 A).

In Table 5, as shown in 'Column-2', 'DABS' and 'CSD' values are highest at the Sub-band '300 kHz-1 MHz'. Hence, in terms of 'DABS' and 'CSD', 'Sh-2-4.8A' is readily detectable at this Sub-band. In 'Column-3', the 'DABS' and 'CSD' values decreases and, are not the highest at this Sub-band '300 kHz-1 MHz'. However, both the 'DABS' and 'CSD' values increase and are becoming the highest at a different Sub-band '30 kHz-300 kHz'.

In terms of 'MM ratio' value, both the faults 'Sh-2-4.8A' and 'Sh-3-4.8A' are, still, detectable at the same Sub-band '2 kHz-30 kHz'. However, the difference between the 'MM ratio' values in the 'Column-2' and 'Column-3' is, only marginal.

A cross-comparison was also made between the statistical values of Table 4 and Table 5. In Table 4, the differences between the statistical values in 'Columns-2 and 3' are more when the transformer's load is low (at the 2A level). Hence the discrimination between the faulty cases'Sh-2-2A' and 'Sh-3-2A' is easy. However, when the transformer's load is made higher (4.8 A), as indicated in Table 5, the difference between the statistical values in 'Columns-2 and 3' are becoming minimal (only small). These changes demonstrate that the 'cumulative effect of transformer's load and the inter-turn short circuit' can alter the fault diagnosing sensitivity of the IFRA approach.

V. CONCLUSION

An experimental investigation was carried out to analyze the effectiveness of IFRA in diagnosing inter-turn short-circuits within transformers under different load conditions. Some 'inter-turn short-circuits' were emulated purposefully in the windings of a single-phase 1 kVA, 240V/ 240 V transformer and a three-phase 5 kVA, 440V/440 V transformer under different load conditions and, the effectiveness of IFRA in diagnosing the same was analysed.

Investigations on the two transformer specimens confirmed that the inter-turn short-circuit diagnosis in 'loaded transformers' is possible with the On-Line IFRA approach. However, the changes in the transformer's load alter the effectiveness of 'On-line IFRA', by reducing the useful spectrum of the Impulse Response. Statistical analysis of IFRA results was found useful in such cases, by reducing the interpretational difficulties and, helping in reaching out a subjective conclusion regarding the condition of the transformer.

Analysis of the results has led to the following significant insights into the IFRA based inter-turn short -circuit diagnosis of transformers On-load:

The loads connected to the transformer, influence the effective impedance offered to the various frequency components of the impulse.

Based on the transformer's load, the baseline transfer function plot (referred as 'Normal case' plots in the Figures 4.a and 5.a) itself was found to change which showed clearly that, the healthier case plots of the transformer at a particular load level could not be used as a typical/generalised healthier case plot of the 'transformer at all load levels'.

Based on the transformer load, the changes in the frequency response due to the fault (inter-turn short-circuit) are minimal at some sub-bands and maximal at some other/different sub-bands. Thus, ultimately, the type and the magnitude of the load was found to alter the useful spectrum of IFRA (which could be capitalised for fault diagnosis purpose). A careful focus on the sensitive sub-band frequency spectra is therefore needed to capitalise on the fault diagnosing capability of IFRA.

The research can be extended in future for On-line On-load diagnosis of other types of faults and, to get insight into the effect of the power factor of the loads on FRA based fault diagnosis.

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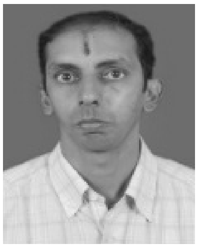

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