Extended Application for the Impulse-Based Frequency Response Analysis: Preliminary Diagnosis of Partial Discharges in Transformer

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ABSTRACT Frequency response analysis (FRA) with low impulse voltage signals (IFRA) is useful in diagnosing faults like the mechanical displacements and inter-turn shorts in transformers. However, they fail to diagnose the presence of any source of partial discharges (PD) across the oil-paper insulation. PD is happening only above its inception voltage level for the applied signal, thereby changing the loading effect of the insulation system and becoming detectable. If FRA tests are extended carefully up to high voltages, they can be even useful for the preliminary diagnosis of the potential sources of PD. Investigations were not carried out so far to get an insight into this aspect. Motivated by this, an investigation was done, first time, on a 315 kVA, 11 kV/433 V transformer. IFRA was carried out carefully at various voltage levels, up to 50% of the Basic impulse insulation level. The IFRA results of the transformer under its healthier condition, under the emulated inter-turn shorts and, the PD sources across the major-insulation were, observed and compared. Low-voltage IFRA is found sufficient, only for diagnosing the inter-turn shorts. When IFRA is extended to moderately high voltage, it is found useful in the preliminary diagnosis of the PD sources.

INDEX TERMS Frequency response analysis, transformer, lightning impulse, transfer function, statistical parameters.

I. INTRODUCTION Condition monitoring of the transformers can be done through several techniques [1]–[3] Frequency response analysis (FRA) approach is one such technique and, is useful in diagnosing the axial and radial displacement of the windings, inter-turn shorts within the windings and, magnetic core issues [4].

FRA uses either a sinusoidal sweep signal (SFRA) or an impulse voltage (IFRA) as the test signal [5]. SFRA uses a sinusoidal sweep signal of constant amplitude ($2V_{\text{peak-peak}}$ to $10V_{\text{peak-peak}}$) with the frequency spanning between 20 Hz to 20 MHz and, different researchers preferred different choices [6], [7]. IFRA uses the impulse signal, which is made up of several sinusoidal signals of different frequencies, as per Fast Fourier Transform (FFT).

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In both SFRA and IFRA, the frequency response offered by the transformer is usually referred to in terms of Transfer Function (TF). The responses can be analyzed in the frequency domain, in various forms such as self-admittance of the winding, self-impedance of the winding, voltage transferred to the other end of the tested winding and, the voltage transferred to the non-tested windings. Accordingly, the transfer functions obtained through these approaches are referred to as Self-Impedance Transfer Function (SI TF), Self-Admittance Transfer Function (SA TF), End-to-End Voltage Transfer Function (EEV TF) and Transfer Voltage Transfer Function (TV TF) respectively. The transformer terminals can also be kept Open, Shorted or grounded and thus, can lead to different test-circuitries [8].

The usefulness of SFRA and low voltage IFRA, in diagnosing transformer windings through different transfer function approaches were, successfully demonstrated by the researchers [9]–[12]. Standards, guidelines and working
group recommendations are now available for conducting the SFRA based mechanical faults diagnosis [13], [14]. The diagnosis of inter-turn shorts with the IFRA was also successfully demonstrated by some researches. Both simulation and experimental works on transformer winding models were reported in the literature [15]–[17]. In the previous article of the authors, the influence of the load on the Impulse Frequency Response Approach based diagnosis of the inter-turn short-circuits in small scale transformers (1 kVA, 240 V/240 V, 1 phase & 5 kVA, 440 V/440 V, 3 phase) were reported [18]. The standardization of procedures for the electrical fault diagnosis is still, underway.

In the pioneering work of Malewski R and Poulin B on the impulse testing of the transformer, the usefulness of IFRA in the diagnosis of the internal faults was demonstrated in an un-tanked transformer disc winding assembly. The fault was artificially created by externally connecting back to back diodes (DIACs) between the winding discs, and the usefulness of "admittance transfer function" in the diagnosis of the internal faults during the Impulse voltage testing was demonstrated [19].

Xuanrui Zhang et al., in his recent work with oscillating impulses, highlighted the prospects of the frequency domain analysis of the test results, in detecting the partial discharges within transformer insulation [20]. Marek Florkowski has recently discussed the effect of impulse voltage parameters such as front time, tail times and peak voltage, on the PD attributes [21]. More experimental works are needed to understand the loading effects of the sources of PDs thoroughly.

Identifying the presence of any the potential sources of Partial discharges within the transformer through the techniques like FRA can be very useful, as it can give an early warning about the conditions of transformers in service.

Simulation works on the PD diagnosis in transformer winding models through the pulse injection technique are, available as literature and, demonstrates the usefulness of the frequency domain correlation techniques [22]. Some non-conventional approaches were also experimented for identifying the type of PD and its location within insulation, through the injection of artificial PD pulses and arbitrary short-duration signals into the insulation. In these works, the signals from a low- voltage pulse generator or PD calibrator were injected at some selected locations in the un-tanked transformer windings and, their responses at the two terminals of the winding were used in identifying the type and location of PD [23]–[26].

In real-time, the Partial discharges are voltage-dependent and, their detection through such non-conventional approaches is complicated. The discharges get initiated only when the voltage across any potential PD Source goes above its PD Inception Voltage (PDIV), thereby changing the loading effect of the insulation system. Though the conventional Low-voltage based SFRA and IFRA are useful in inter-turn short diagnosis, they are found unsuccessful in diagnosing any such potential sources of PD within transformers. Suppose the FRA tests are extended up to some moderately-high voltages sufficient enough to incept a PD, in that case, it may be possible to use them non-destructively, for preliminary diagnosis of any suspected PD sources. Feasibility of such extended application to the IFRA is not thoroughly analyzed so far, on Full-fledged Transformers (with the transformer core, tank, bushings, HV and LV windings and their insulation included effectively in the test). Any research addressing this research gap and providing insight into the preliminary diagnosis of PDs through the FRA approach in real-time is, therefore, becomes significant.

Motivated in these aspects, the authors have carried out experiments on a 315 kVA, three-phase transformer. The transformer has special tappings on one of its high voltage windings (1U-1V), which are accessible through the bushings provided through the sidewall of the tank. Inter-turn shorts and the PDs were artificially created by accessing the winding through these tapping provisions. Figure 1 shows the circuit connections of the transformer with tappings.

The investigations were conducted in two stages. In the first stage, the investigations were carried out with impulses of Low-voltage levels, to demonstrate their usefulness in the diagnosis of the Inter-turn shorts. Subsequently, the shortcomings of these low voltage based FRA approach in identifying the presence of any potential PD sources across the transformer insulation was also demonstrated. In the second stage, the tests were conducted after increasing the voltage to a moderately high level, and the extended usability of IFRA as a preliminary PD diagnostic tool was investigated.

In this second stage, the impulse injection end of the winding and the impulse voltage magnitude were carefully selected based on their minimum required level in incepting the PD at different locations within the winding. The focus was mainly on the feasibility of diagnosing non-destructively, any potential PD source across the transformer insulation, through a moderately - high voltage FRA. Therefore, after several trials, the maximum test voltage level for this Preliminary PD diagnosis was fixed at 37.5 kV. This voltage was at 50% of the Basic Impulse Insulation Level (BIL) of the 11 kV winding, so that, it could incept the PD and, at the same time, did not cause any permanent damage to the transformer. The moderate level of the voltage and the selection of the appropriate terminal of the end of the winding ensure that the approach is non-destructive, but becomes useful, in the preliminary diagnosis of PD. However, this IFRA approach cannot replace the conventional PD tests and, any further confirmation and the assessment of the severity level must be through conventional PD tests.
TABLE 1. Statistical parameters and their typical values.

| S.No | Statistical parameters used | Formula | Typical value expected |
|------|-----------------------------|---------|-----------------------|
| 1    | CSD                         | $CSD_{x,y} = \sqrt{\sum_{i=1}^{N}((x_i - y)^2)}$ | 0 |
| 2    | DABS                        | $DABS_{x,y} = \sum_{i=1}^{N} |y_i - x_i|/N$ | 0 |
| 3    | MM Ratio                    | $MM_{x,y} = \frac{\sum_{i=1}^{N} \min|x_i|}{\sum_{i=1}^{N} \max|x_i|}$ | 1 |

Note: $x_i$ and $y_i$ indicate $i^{th}$ values of the two cases compared. $|x_i|$ and $|y_i|$ indicate their respective absolute values. $\bar{x}$ and $\bar{y}$ indicate their average values. $N$ indicates number of the frequencies covered within a sub-band.

During experimentation, the circuit connections and the procedures suggested in FRA standards and other literature was chosen for getting the FRA results [13], [14], [27]–[32]. The experimental results of IFRA were analyzed with the help of the voltage waveforms, transfer function plots and the statistical features extracted from FRA data. Comparative Standard Deviation (CSD), Absolute average difference (DABS) and Minimum-Maximum Ratio (MM absolute) were the statistical parameters used [29]–[32]. Significant variations of the statistical parameter values from their expected typical values were capitalized to diagnose the fault. Table 1 shows the statistical parameters, Formula used for calculation and their typical values when the two cases compared through the statistical parameter are similar [29].

II. METHODOLOGY

In this section, first, the details of the transformer and the partial discharge (PD) model are explained. Then, the experimental setup, the procedure followed for the experiment and the analysis are presented. Analysis of the results is done using the voltage waveforms, transfer function plots and statistical parameters and, the relevant procedures are explained at the end of the section.

A. DESCRIPTION OF THE TEST SPECIMEN

A 315 kVA, 11kV/433 V, 50 Hz, Dyn 11, ONAN three-phase distribution transformer was used as a test specimen. The delta connected 11 kV side has four artificially created tappings on one of its windings between the (1U) and (1V) terminals (at 87.5%, 62.5%, 37.5% and 12.5% of the winding, referred from the terminal (1U)). These tappings (t2, t3, t4 and t5) were accessible through the low capacitive bushings in the tank. The details were reported in earlier work [33]. The capacitance of the bushings used are, very low (10 pico Coulomb) and hence, they are not affecting the response of the transformer under the test (Impulse) voltage.

During the experimental investigation, these tappings were used for emulating the inter-turn shorts and the partial discharges from the various locations of the winding. Figure 1 shows the circuit connections used for emulating the inter-turn shorts and the PDs. The terminals (1U) and (1V) are also indicated in Figure 1 as (t1) and (t6), respectively.

Inter-turn shorts were emulated by connecting a resistor of 2400 $\Omega$ between the tapping such that, it could allow a circulating current within the shorted portion of the winding well below the current carrying capacity of the winding and represented an inter-turn short at developing stage. For emulating a potential PD Source across the major insulation (between the HV winding and the grounded tank), a transformer oil testing kit, (which was preferred by several researchers for modeling the PD) was connected through the bushing provision, between the winding tapping and the grounded transformer tank. The transparent oil testing kit (with oil surrounding the hemispherical electrode gap of 1 mm) also enabled the visual observation of the PDs in the form of spark between electrodes and, thus, stood as a proof for the occurrence the PD.

For avoiding any permanent damage to the transformer due to the emulated PD during the experimentation, a suitable resistor (43 k$\Omega$, 140 kV, in our case) was purposefully included in series with the PD specimen (transformer oil testing kit). The resistor limited the current within the current carrying capacity of the winding. It can be noted that the resistor damps the impulse, but, is not eliminating any available frequency components [19]. However, it makes the model more realistic by representing a weaker and developing stage PD.

The focus of the present work was, mainly on the PD diagnosing capability of moderately-high impulse voltage. Hence, only the results related to the preliminary diagnosis of PD sources were, presented in detail. The low-impulse voltage-based experiments were done only to demonstrate their usefulness in the inter-turn shorts diagnosis and their shortcomings in diagnosing the presence of any potential PD sources, at such low voltages. As the IFRA based inter-turn short diagnosis is a proven technique, only a brief analysis of the result was included (as sub-section III-A Results and Discussion).

In both the inter-turn short diagnosis and the PD diagnosis, the same procedures were followed for the FRA test and measurements.

B. EXPERIMENTAL SETUP

A Lightning impulse voltage generator (1.2 $\mu$s±30% / 50$\mu$s±20%) was used to apply the impulse voltage at one of the terminals of the Delta winding (1U) [27]. The non-impulsed ends (1V and 1W) of the Delta winding were shorted and grounded through a resistive voltage divider of 245 $\Omega$. The resistive voltage divider was implemented such that voltage received at the other end (1V) of the winding could be scaled down and measured through the Digital storage oscilloscope (DSO). All the terminals of the (Star) side and the tank were, shorted and grounded.

The energy capacity of the impulse voltage generator used was low. Hence, there were loading effects and alterations in the input (impulse voltage wave shape). The impulse shape was acceptable, as, it still had met out the FRA requirements by containing enough high-frequency components.
Different researchers preferred different spectrum of frequencies for their FRA Studies and, mostly concentrated on the frequencies ranging from 100 Hz to 2 MHz [30]–[32]. As the authors experimented on the extended usability of IFRA and were interested in the investigation on the conventional FRA frequency range, a frequency range of 100 Hz to 20 MHz was preferred.

Most of the DSOs do not have sophisticated provisions to carry out FFT or FRA directly, and signal processing methods on the time-domain data to study the frequency information is needed. However, these features are available in some advanced versions of DSOs, which were used previously by researchers for FRA analysis with continuous sinusoidal signals and transient signals (Both SFRA & IFRA) [19]–[24], [26], [34]–[36].

The two Channel, 100 MHz, 2.0 G.sa/sec DSO (Make: Keysight, Model No: DSOX 1102G) with the in-built FRA function was found suitable in investigating the frequency response in the preferred frequency range [34]–[36].

The experiments were carried out in controlled environment so that the effects of noise and other sources of errors are minimal: The experiments were conducted in HV lab with a Double Faraday cage setup which offers adequate shielding up to 50 MHz. Coaxial cables were used for applying the test voltage, measurements of input and response and Data acquisition. Independent Earthing arrangement was used for the test bay.

Figure 1 shows the connections made at the tappings of the transformer winding for the emulation of the Inter-turn shorts & PDs. Figure 2 represents the circuit diagram of the experimental setup. As a representative case, the PD source was shown between the (t2) tapping and the grounded tank (referred hereafter as (PD at t2). Figure 3 shows the photograph of the same. For the investigations of the inter-turn shorts, the same test circuit was used, with the emulated inter-turn shorts substituted in place of the PD model, as shown in Figure 1.b. Table 2 shows the details of IFRA investigations on the ‘Inter-turn short’ diagnosis and their notations.

### C. SELECTION OF IMPULSE INJECTION TERMINALS FOR PD INVESTIGATIONS

The Basic Insulation Level (BIL) level of the 11kV winding for the impulse voltage is 75 kV (peak) [28]. If the impulse injection terminal is appropriately selected, the preliminary diagnosis of PD can be made possible with the impulse voltage at 50% BIL level, i.e., 37.5 kV peak. Thus, any potential damage to the winding during testing can be avoided, and the test becomes non-destructive. Figure 1.a shows the tappings in the (1U-1V) windings.

As shown in Figure 1, the first two tappings (t2 and t3), were available near (1U) terminal. Therefore, even with a moderate magnitude lightning impulse voltage injected at the terminal 1U (50% of the BIL level), a considerable voltage can reach them.

When the PD source is located near the (t4) or (t5) tapping, which is far away from the terminal (1U) but closer to the terminal (1V), their diagnosis using the moderately-high voltage impulse injection at (1U) is difficult. This difficulty is due to the low voltage reaching at these far end tappings, which are insufficient to incept the PD. A higher magnitude

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**Figure 2.** Circuit diagram of the experimental setup.

**Figure 3.** Photograph of the experimental setup.

**Table 2.** Investigations done for the diagnosis of ‘Inter-turn shorts’ and ‘PDs’ and their notations.
impulse voltage is needed to diagnose a PD at this far-end of the winding if the impulse injection is still preferred at (1U).

Diagnosis of PD at the moderate voltage level (50% BIL level) can be still feasible if, the impulse is injected at (1V) terminal of the winding which is closer to these (t4) and (t5) tappings. In such a case, the terminals (1U) and (1W) can be shorted and grounded through the low-ohmic resistor (245 Ω), and the response can be obtained. The impulse injection terminal and the response measurement terminal can thus be interchanged, to diagnose the PD with the same moderately-high impulse voltage.

During the present experimental work, tests were carried out, first, with the impulse injection at the terminal 1U (to diagnose any PD source near (1U)) and then with the impulse injection at the terminal 1V (to diagnose any PD source near (1V)). Table 2 shows the details of the discharge-free cases, and the PD cases investigated and, the notations used to refer to them.

D. EXPERIMENTAL PROCEDURE FOR PD INVESTIGATIONS

The signature patterns of the transformer under discharge-free conditions were developed, after analyzing the loading effect of the modelled PD source (Oil test kit with the 43 kΩ Resistor) under its discharge-free condition.

For this, several preliminary tests were conducted with the impulse voltage injection, first at the (1U) terminal and then, at the (1V) terminal. The PD model was connected between the tappings (t2, t3, t4 and t5) and the grounded tank. With the PD source thus emulated, impulse voltages at 5 kV, 10 kV and 15 kV levels were injected at one end, and their response at the other end of the winding was observed.

No visual discharges were observed across the electrodes of the emulated PD model as the voltage imposed across it was insufficient to incept a PD. Waveforms of the injected impulse, the response and the EEV transfer functions from their FRA data were, observed at these low voltage levels. There were no distortions in the waveforms and, the EEV TF plots were also similar, irrespective of the different locations at which the PD source was connected.

These observations had demonstrated that the loading effect the PD source under Discharge-free condition was negligible and their presence could not be detected at these low voltage levels.

Based on all these observations, it was decided to use the waveforms and the EEV TF plots corresponding to the 10 kV level, as a representative of the discharge-free (i.e. Healthy case where the PD source is present, but, under its discharge-free condition). (DF-1) was thus obtained with the impulse at (1U) and the PD source at (t2). Similarly, (DF-2) was obtained with the impulse at (1V) and the PD source at (t5).

Further investigations at higher impulse voltages revealed that the discharges got initiated across the PD model, for the impulses with the peak voltage above 30 kV. Hence, it was decided to go ahead for the diagnosis of the various PD cases with the impulses of slightly higher magnitudes (37.5 kV peak), so that it was always sufficient to incept the PD. This peak value is only 50% of the BIL level of the 11 kV winding, for the impulse voltage, and thus the methodology implemented was ensured to be non-destructive.

For the PD sources requiring still higher voltages for inception, the diagnosis may not be possible with 37.5 kV level, and the test voltage may need to be increased further, gradually up to the Basic Impulse Insulation Level (BIL). But, It can be emphasised that, even for such PD sources, there will not be any damage to the transformer, as the test voltage is not raised above the BIL level. As the focus of the present work is on the extended application of IFRA, such cases are not modelled and investigated.

For observing the response of the transformer under the cases (PD at t2) and (PD at t3), the impulse was injected at the terminal (1U), and the response was observed at the terminal (1V). (PD at t4) was investigated in two ways: (i) with the impulse at (1U) and (ii) with the impulse at (1V). In a trial test, detection of (PD at t4) with impulse injection at (1U) was found to be possible only with high magnitude of voltage (V1), i.e. 70% of BIL level, which could be more harmful. Hence, the experimentation with this approach was discarded and, further diagnosis of (PD at t4) was made only with the impulse at (1V). For observing the response of the transformer under the cases (PD at t4) and (PD at t5), the impulse was injected at the terminal (1V), and the response was observed at the terminal (1U).

In all the cases, scaled-down versions of the input and response voltages were captured using the DSO. The inbuilt FRA function of the DSO was used to get the FRA data [34]–[36]. For the discharge-free cases and every emulated PD cases at different tappings, the tests were repeated five times. Same experimental connections and procedures were followed throughout the investigation. FRA data was collected every time, through DSO [34]–[36]. The average value of data obtained from the five tests of a particular case was, considered as the representative of that case and, used for analyzing the FRA results.

Based on the insights from the preliminary works, the entire investigation was planned and carried out, so that no harm was caused to the transformer during the IFRA test. Details are summarized below for ready reference:

1. As the influence of inter-turn shorts is detectable at all voltage levels, the test voltage for the diagnosis of inter-turn short was fixed at 5 kV (peak). After carefully removing the modelled inter-turn shorts from the transformer, the extended usability of IFRA was checked.

2. As the presence of the modelled PD source is undetectable up to 10 kV, the frequency response of the transformer at this voltage levels can be directly used for the development of the signature FRA of the transformer in its discharge free condition. Based on the impulse injection end, they are referred as as DF-1 & DF-2

3. When the PD model was emulated at different tappings (Four cases), the inception of discharge was found to occur at different input Impulse voltages (V1). The PD incepts above
30 kV for all the four emulated PD cases. In all the cases, the magnitudes and number of PD pulses were found to increase once the voltage is raised above their corresponding inception voltage range.

As the focus of the work was on the extended applicability of IFRA and not on PD characterisation, a uniform procedure and a standard level of impulse voltage above which the discharge could be ensured in all the four cases was preferred. For assuring discharges in all the four cases and simplifying our investigation process, a test voltage of 37.5 kV was fixed.

E. PROCEDURE IMPLEMENTED FOR DEVELOPING EEV TF PLOTS
As the FRA data for various cases were obtained using the scaled-down version of the input and response signals, suitable correction factors (based on scaling factors of their respective dividers) were incorporated. The actual FRA data at any particular frequency was calculated, as shown in equation (1).

\[
\text{Actual FRA data (dB)} = 20 \log \left( \frac{V_1}{V_2} \right) + 20 \log \left( \frac{400}{41.83} \right) = \text{FRA data from DSO} + 19.61 \quad (1)
\]

This FRA data represents the ratio of the end to end voltage magnitudes across the winding under test and, is referred to as End to End Voltage Transfer Function (EEV TF). The EEV TF magnitude obtained for different frequency components were plotted as graphs by taking magnitude in Y-axis and Frequency in X-axis and, were referred to as EEV TF plots [12], [15], [16].

As per various literature and standards on FRA, any problem in the winding or its insulation can alter the end to end voltage ratio, which is identifiable, at some frequencies [13]–[17]. Such influences, appearing in the form of variations in EEV TF, can be capitalized for diagnosing any suspected PD in the transformer. This aspect forms the basis for the diagnosis of faults in the frequency domain through the transfer function approach.

F. PROCEDURE IMPLEMENTED FOR RESULT ANALYSIS
The results were analyzed by making three types of comparisons: First, comparisons were made between input/output voltage waveforms of various cases, to capitalize any visible variations in the waveforms for the PD diagnosis. Secondly, comparisons were made between EEV TF plots of various cases, to capitalize any noticeable changes in the plots such as variation in magnitude at some frequency/sub-bands and any alterations in the plots in the form of spikes [13]–[17].

However, the variations observed in these two types of comparisons demand expert knowledge for interpretation and conclusions [28]–[33]. Statistical parameters like CSD, DABS and MM ratio can reduce such interpretational difficulties and help in arriving reliable findings [29]–[33]. Hence, the third type of comparison was made between different cases, through these statistical parameters.

III. RESULTS AND DISCUSSIONS
A. INVESTIGATIONS WITH LOW MAGNITUDE IMPULSE VOLTAGES
Experimental works were carried out first, at Low-impulse voltage magnitude of 5 kV to diagnose the emulated inter-turn shorts and the PDs. Table 2 shows the details of the emulated inter-turn shorts and the PDs.

Figure 1 shows the tappings available in the (1U-1V) winding of the transformer. First, the IFRA investigations were carried out in the healthier transformer at 10 kV level and, the signature FRA results were obtained. Then, IFRA investigations were carried out with the two inter-turn shorts, emulated in the transformer winding between (i) (t1) and (t2) tappings and (ii) (t5) and (t6) tappings. Corresponding IFRA results were obtained and compared with the healthier case.

Figure 4 shows the waveforms of the healthy case and the faulty cases (Sh1) and (Sh2). The differences between the cases were not noticeable in the waveforms.

Figure 5 shows the comparison based on their corresponding EEV TF plots, made between the Healthy case and the two inter-turn short cases (Sh1) and (Sh2). There were noticeable differences in the dB magnitude of the plots throughout the frequency range. The spikes and Dips, appearing at different frequencies in Figure 5 demonstrated that the inter-turn shorts (Sh1) and (Sh2) were diagnosable with the low-voltage IFRA.

Table 3 shows the results obtained in terms of the statistical features; CSD and DABS. As highlighted (italics) in the columns (3) & (4), CSD was maximum at the Sub-band (10 MHz-20 MHz), and the DABS was maximum at the
TABLE 3. Statistical comparison between the different cases investigated for inter-turn short diagnosis.

| S.No | Frequency Sub-Band | Healthy case Vs Sh1 | Healthy case Vs Sh2 |
|------|--------------------|---------------------|---------------------|
| 1    | 100 Hz-1 kHz       | 10.64               | 13.84               |
| 2    | 1 kHz-10 kHz       | 8.35                | 8.48                |
| 3    | 10 kHz-100 kHz     | 8.72                | 7.90                |
| 4    | 100 kHz-1 MHz      | 7.64                | 15.12               |
| 5    | 1 MHz-10 MHz       | 14.17               | 10.48               |
| 6    | 10 MHz-20 MHz      | 20.34               | 17.73               |

Sub-band (1 MHz-10 MHz). Both the Inter-turn shorts were, thus, diagnosable through the Low-voltage based IFRA.

With the PD source included at different tappings (t2, t3, t4 and t5) and the injection of impulses of peak magnitude 10 kV at the ends (first, at (1U) and then, at (1V)), IFRA was again conducted and, the results were analyzed. However, the emulated PD cases were found diagnosable at these low voltages. The Voltage waveforms and the EEV TF plots looked similar for the different cases investigated and, the low-voltage IFRA was found unsuccessful in identifying the PDs. After observing the ineffectiveness of low magnitude Impulse based FRA in diagnosing such PDs, further investigations were conducted by preferring moderately high voltages.

**B. INVESTIGATIONS WITH MODERATELY-HIGH IMPULSE VOLTAGES**

PDs were voltage-dependent and got incepted only when the voltage was raised above its inception voltage (PDIV). Moreover, the inception may happen at different voltages, based on the location and severity level of any suspected PD source. Several preliminary tests were done to assess the magnitude of the test voltage required to incept a discharge across the PD model when it was inserted across the major insulation at different locations (between the tappings (t2, t3, t4 and t5) and the grounded tank). These preliminary tests were conducted with the impulse voltage injection, first at the (1U) terminal and then, at the (1V) terminal. For all the PD cases emulated, the tests were conducted by injecting impulse, first, at (1U) and, then, at (1V). Thus, for the PD emulated at different locations, a thorough analysis was carried with both these impulse injection options, to estimate the minimum impulse voltage required for the inception of discharge across the PD model. The discharge inception was found to occur only above 30 kV, after considering both the options of the impulse injection terminal. Hence, for emulating an assured discharge across the PD model during the experiments, the test voltage (impulse voltage) was fixed at 37.5 kV (which is 50% of the basic impulse insulation level and 125% of 30 kV).

Subsequently, further tests for the diagnosis of the emulated PD sources were made as follows: First, with Impulse injection at the (1U) terminal, experiments were conducted to diagnose the presence of any potential PD sources within the top 50% portion of the (1U-1V) winding. Then, with the impulse injection at the (1V) terminal, experiments were conducted to diagnose the presence of any potential PD sources within the bottom 50% of the winding.

Figure 1 shows the winding terminals and tappings. In Table 2, test details are listed. The test connections are explained in sections II-B and II-C.

IFRA results obtained at moderately-high voltages were analyzed with two main objectives. First, to check whether the preliminary diagnosis of PD through the moderately-high voltage based IFRA is possible, and, secondly, to check whether the PDs are locatable.

1) WAVESHAPE BASED COMPARISON

Figure 6 shows the input and response voltage waveforms wherein, Subfigures 6a, 6b represent voltages of the three cases: (i) DF-1, (ii) PD at t2 and (iii) PD at t3, respectively. The Input (V1) and the response (V2) waveforms observed for the (DF-1) was shown in Figure 6a. The waveforms were smooth.

When the cases (PD at t2) and (PD at t3) were experimented (with impulse injection at (1U)), the waveforms were similar, as observed in (PD at t2) & (PD at t3), with the spikes superimposed on the base waveforms of V1 & V2. Therefore, they were not shown here, as separate voltage waveforms. The PDs were physically visible in the form of sparks between the electrodes of the PD.

Thus, from these comparisons made based on waveforms, it was possible to identify the PDs within major insulation of a transformer winding. However, there were difficulties discriminating their location. The results were further analyzed in the frequency domain through the EEV TF approach.
2) EEV TF PLOTS BASED COMPARISON

Three features of the transfer function plots were used for comparison. They are (i) the appearance of any new spikes and disappearance of existing spikes in the plot, (ii) alterations in the dB magnitude in the form of the damping or magnification of spikes and, (iii) shifts in the location of spikes [13], [14].

Figure 7 shows the transfer function plots developed for various cases (DF-1), (PD at t2) and (PD at t3), with the impulse injection at the terminal (1U). For the case (PD at t2), there were several shifts in spikes locations and alterations in the dB magnitudes in the frequency range (1 MHz- 20 MHz). For the case (PD at t3), the deviations were predominant in the frequency ranges (1 kHz- 200 kHz). Thus, (PD at t2) was distinguishable from (PD at t3), as they varied in different ways from the discharge-free case (DF-1).

Figure 8 shows the transfer function plots developed for various cases (DF-2), (PD at t4) and (PD at t5), with the impulse injection at the terminal (1V). Responses of (PD at t4) and (PD at t5) deviated appreciably from (DF-2), in the frequency ranges (10 kHz-200 kHz) and (2 MHz- 20 MHz) respectively. Thus, (PD at t4) was also distinguishable from (PD at t5) There were ups and dips in the plots with considerable variations in dB magnitudes throughout the frequency range covered. Experience and careful interpretation are required to correlate these variations and conclude on the location of the PD. However, they again proved that the PD cases were identifiable and distinguishable in terms of the impulse voltage-based FRA when conducted at moderately high voltages.

Researchers had successfully implemented feature extraction techniques on the statistical parameter basis and minimized the interpretational difficulties of the FRA results [6], [7]. Motivated by this, the third type of comparison was additionally done based on statistical parameters.

3) STATISTICAL PARAMETERS BASED COMPARISON

Table 4 shows the comparison made between the FRA results of different normal and PD cases on the statistical parameter basis. CSD, DABS and MM (absolute) ratio were used for making the comparison. Two cases were compared at a time, on the Sub-band basis [28]–[33].

Statistical parameters were found to offer different sensitivities in exploring the difference between the cases compared. Hence, researchers suggest using more than one statistical parameter to arrive at any conclusion on the condition of the transformer [28]–[33]. The maximum deviation of the calculated statistical parametric values from their ideal values (indicated in Table 1) appearing at some specific Sub-bands was capitalized, to reduce the interpretational difficulty and arrive at a conclusion. They were shown highlighted (Italics) in Table 4.

The total frequency spectrum was carefully split into six sub-bands. This splitting was fine-tuned through several trials such that it could offer maximum sensitivity almost at same Sub-bands. This approach reduced the difficulties in the interpretation, as, an agreement within a group of the
the preliminary diagnosis of the potential PD sources across moderately high voltages was useful, and statistical parameters revealed that the lightning impulse sources across the test specimen, which could be checked waveforms indicated that there could be some potential PD parameters CSD, DABS and MM.

In Table 4, columns (3) and (4) were used to compare (DF-1) with (PD at t2) & (PD at t3), respectively. Thus they represented the investigations for diagnosis of PD near terminal '1U'.

In column(3), the maximum value of CSD & DABS and minimum value of MM ratio appeared at the same Sub-band (10 MHz-20 MHz). Thus, (PD at t2) was easily distinguishable from (DF-1) at this Sub-band. In column(4), the maximum value of CSD & DABS and, the minimum value of MM ratio appeared at the same Sub-band (1 kHz-10 kHz), which were shown in italics. Thus, (PD at t3) was distinguishable from (DF-1) at this Sub-band.

In Table 4, columns (5) and (6) were used to compare (DF-2) with (PD at t4) & (PD at t5), respectively. Thus, they represented the investigations for the diagnosis of PD near the terminal (1V). In column(5), the maximum value of CSD & DABS and minimum value of MM ratio appeared at the same Sub-band (10 kHz-100 kHz). Thus, (PD at t4) was distinguishable from (DF-2) at this Sub-band. In column(6), the maximum value of DABS and minimum value of MM ratio (and second maximum value of CSD) appeared at the same Sub-band (10 MHz-20 MHz). Thus, (PD at t5) was distinguishable from (DF-2) at this Sub-band. All the four comparisons made in Table 4 indicated that the statistical parameter helped in reducing the interpretational difficulties of IFRA results.

In consolidation, the three types of comparisons (waveform based, EEV TF based and statistical parameter based) demonstrates that IFRA at moderately-high voltage with proper impulse injection terminal is useful in the preliminary diagnosis of the presence of PD sources in the major insulation of transformer.

IV. CONCLUSION

Experimental investigations were carried out to check the usefulness of moderately-high impulse voltage-based FRA technique (IFRA) for preliminary diagnosis of any suspected PD source across the major insulation of a transformer winding. For this purpose, some PDs were artificially emulated, between one of the high voltage windings of a 315 kVA, 11 kV, Dyn 11, ONAN distribution transformer and its grounded tank. Experimental results of the transformer under its healthy condition and emulated faulty conditions were compared in three ways: (i) based on their end-end voltage waveforms, (ii) EEV TF plots and, (iii) the statistical parameters CSD, DABS and MM.

The train of spikes, superimposed on base impulse voltage waveforms indicated that there could be some potential PD sources across the test specimen, which could be checked through further investigations. Analysis of EEV TF plots and statistical parameters revealed that the lightning impulse voltage-based FRA at moderately high voltages was useful in the preliminary diagnosis of the potential PD sources across the major insulation of transformer (between the windings and the grounded tank).

Thus, this work demonstrates that IFRA, if extended up to moderately high voltage, with the proper impulse injection end is, useful in the preliminary diagnosis of potential PD sources in major insulation of a full transformer. The magnitude of the test voltage required to diagnose the fault should not be harmful. For avoiding the higher current across of inter-turn shorts, IFRA was restricted to low voltage levels. Only after ensuring the absence of such inter-turn shorts through the Low-voltage based IFRA, the voltage was raised gradually to higher levels, to extend the scope IFRA up to the diagnosis of a potential PD source. The magnitude of the test impulse required could become more when it is far away from the impulse injection end. The investigations on the PD case (PD at t4) with the impulses injected from the different ends of the winding (1U and 1V) indicated that the impulse voltage required for IFRA based diagnosis of PD could be minimised and made less harmful if the impulse injection end is carefully selected. There are noticeable differences among the FRA responses of the Different PD cases and the different Inter-turn shorts.

Moreover, the differences appeared across the different Sub-bands of the investigated frequency spectrum, indicating the further potential of IFRA in fault discrimination and location. More investigations with transformers of different winding type and capacity are required to generalise the approach. The approach is proposed as a preliminary investigation and, the conventional PD tests are required for further assessment of PDs.

The impulse voltage-based FRA approach can further be extended for the PD detection in both the major and minor insulation of larger transformers, with switching impulse voltage as well as steep impulses comprising of higher frequency components. Automation works on PD diagnosis can also be carried out in future, through soft computing techniques. By carefully extracting some similar frequency response features of PD through different techniques, the accuracy of the IFRA approach can also be compared with other diagnostic approaches.

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