# A Feasible Solution to Distinguish the Transformer Winding Deformation from Insulation Characteristic Impacts on FRA Spectrum

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***Abstract***

Frequency Response Analysis (FRA) is popular technique which has been used since the last decade as a diagnostic method for transformers. However, accurate interpretation of FRA measurements is still challenging. Recent studies reveal that apart from winding deformation, FRA data can also be influenced by moisture variation in transformer paper insulation. Hence, a specific transformer's model is fabricated for this study and the experiment was concentrated on the paper moisture variation and mechanical deformation influences on FRA spectrum deviation. Different physical changes to the test object are investigated and the results are discussed. At the end, the weakness of FRA evaluation indicators to recognize winding deformation under different circumstances is highlighted and a feasible solution is recommended.

***Keywords*****—**Frequency Response Analysis, FRA Evaluation Methods, Moisture Variation, Transformer, Winding Deformation

## I. Introduction

Frequency Response Analysis (FRA) has been used as a diagnostic method for transformers since the last decade [1]-[2]. FRA was initially developed for winding deformation recognition [3]. However, researchers now recognized that FRA signature is sensitive to any changes in transformer active parts or even insulation system [4]-[8]. Thus, research efforts are now focused on investigating this technique. Transformer temperature variation and moisture migration from the paper insulation and their impacts on the frequency response spectrum are under investigation [9].

In fact, each phenomenon inside the transformer tank has its own influence on the FRA spectrum[10]-[13]. Among all, this study focuses on the effect of moisture variation on transformer paper insulation and winding deformation influences on FRA data. In order to do this, a transformer's model with air-core concentric continuous disc type HV and LV windings was fabricated and used as the test object. To compare the moisture variation in paper insulation and winding deformation influences on FRA spectrum, the HV/LV windings frequency response spectra of the test object for various temperatures are measured, and deviation in resonance frequencies discussed. Afterwards, as a kind of deformation study, mechanical deformation in transformer is emulated through intentional turn-to-turn short circuit in model transformer windings and FRA spectra are recorded. Deviation in FRA data due to the mechanical changes are compared with moisture variation in transformer winding paper insulation. FRA evaluation indicators which are now commonly used in industrial equipment, to assess the transformer FRA spectrum, are calculated. Incorrect assessment by these methods due to the temperature and moisture variation in FRA measurement is highlighted and discussed. This is in fact a significant issue for industry to distinguish the winding deformation from insulation characteristics (specifically moisture variation) influence on FRA spectrum, and even sometimes leads to make incorrect discussion. Hence, as the main contribution of this study a feasible solution to distinguish the impact of these phenomena on FRA spectrum is introduced and examined on a transformer's model. The novel solution is quite useful for making correct decision on transformer condition and ultimately taking appropriate action.

## II. Experimental study

In order to study the impacts of moisture content variation as well as winding deformation on the FRA spectrum, a model for transformer with air-core concentric continuous disc type windings was fabricated and used. The tank was manufactured using plexiglass material. Line and neutral leads of the windings were brought out from the tank through appropriate HV and LV bushings. The HV winding consists of 8 disks with 8 conductor turns per disk. The LV winding has 10 disks with 6 conductor turns per disk. A single cylinder having 2 mm thickness was used between HV and LV windings, and mineral oil was filled into the transformer container to paly liquid insulation system for this study. Also, a drain valve was mounted at the top cover of the transformer's model for oil injection and oil drain. Our prototype is shown in Fig. 1. The FRA setup was then prepared based on test object HV and LV winding terminals as illustrated in Fig. 2 (end-to-end measurement [14]).

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Fig. 1. Manufactured glassy air-core transformer.

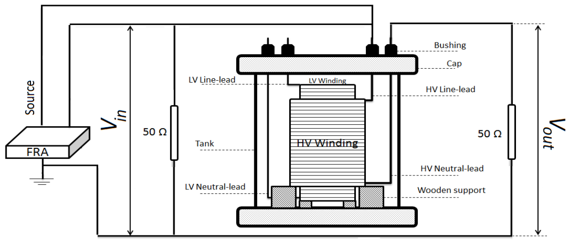


Fig. 2. Implemented FRA measurement setup on glassy model transformer.

### *A. Study on Moisture Variation*

The test object was placed inside the oven and wiring connections for FRA measurement were brought out through a bushing mounted on a small opening on the oven top. The oven was equipped with a sensitive thermostat and a digitally controlled heater to govern the internal temperature. The FRA test setup was then kept unchanged for the entire experiment. FRA measurement was performed on a winding by injecting a swept sinusoidal signal $V_{in}$ of 20 volts (peak-peak) at the line-lead, and detecting the response $V_{out}$ at the neutral-lead. The measurement was conducted for the frequency band 20 Hz- 20 MHz. The reason for choosing such frequency band is the air core of model which generally causes the FRA spectrum oscillations at very high frequencies.

To run the experiment, initially the transformer drain valve was opened and the transformer was deliberately left exposed to the laboratory ambient for two weeks to saturate the paper insulation with moisture. The average readings of ambient temperature and relative humidity were 23 ºC and 26 %, respectively. Hence, the initial moisture content for paper insulations was 4.1 %, calculated according to [15]. Afterwards, the glassy tank was filled with dry transformer oil (< 5ppm, at 70 ºC) then left until the paper is fully impregnated by oil, and eventually both of them reached equilibrium.

The moisture content of the oil was measured using KFT method at 23 ºC and moisture content of the paper insulation was derived through MIT oil-paper equilibrium curves [16], accordingly. These values were 11 ppm and 4 %, respectively. Derived moisture contents of the paper insulation through air relative humidity and KFT methods led to similar results (4.1% and 4 %). Next, the test object was heated up to 30 ºC to be ready for the initial stage of FRA measurement. FRA measurements were performed over the range of 30 to 90 ºC in 10 ºC increments but the spectra were recorded for HV winding at 30, 50, 70 and 90 ºC. The frequency response trace for HV winding was recorded over the range 20 Hz – 20 MHz while its terminals were left open circuit (end-to-end measurement). FRA spectra of HV windings for 30 ºC and 90 ºC (the lowest and highest temperatures) are shown in Fig. 3 over the frequency range of 5 kHz – 20 MHz. The frequency response magnitude over the frequency range 20 Hz – 5 kHz was constant at 0 dB which is not shown in Fig. 3.

According to Fig. 3, when frequency increases and reach to 800 kHz, all of the traces are perfectly matched. Moving from 800 kHz to higher frequencies, the discrepancy between the spectra becomes obvious.

As the test object temperature changed from 30 to 90 ºC, the local resonances in FRA spectra have slightly shifted to lower frequencies. Detailed analysis of Fig. 3 shows that the oscillations trend of the spectra seems to be similar, while the resonance frequencies are shifted toward lower frequencies as the temperature increased and equilibrium was reached. In the meantime, some of the resonant magnitudes are reduced. This deviation comes certainly through windings' inductance, total capacitance, and resistance or insulation conductance changes. The result obtained in this practical study in turn verifies simulation result achieved in [5].

From a mathematical point of view, local resonances and anti-resonances in FRA spectra can be generated due to the interaction between inductive and capacitive reactances [17]. Obviously, each local resonance ($i^{th}$ resonance) can take its own inductance and capacitance values ($L_i$ and $C_i$). Resonance frequencies in FRA spectrum would be changed if the inductance or total capacitance is changed.

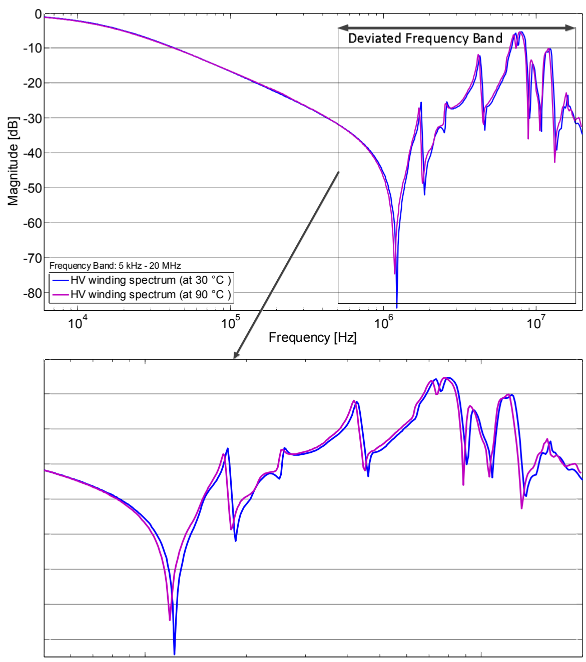


Fig. 3. FRA spectra for HV winding due to moisture migration from paper into the oil insulation at 30°C and 90°C.

Measurement results on inductance and resistance variations for low, mid and high frequencies show that these parameters are not altered significantly due to temperature changes and moisture variation [5]; therefore, deviation of resonant points in FRA spectrum seems to be coming through changes in the total capacitance.

Study on frequency response spectra, when the temperature decreases from 90 to 30 ºC, led to similar results. Although moisture absorption for paper insulation is different with desorption, the equilibria should be the same and hence similar spectra were observed in the reverse procedure.

## B. Study on Winding Deformation

### B1. Influence of internal short-circuit

At first, the frequency response trace of the model transformer is recorded from the HV side while the LV side is left open circuit.

In order to study the internal short circuit, the short circuit on LV terminals is modified on the test object. This alteration can in turn block the flux flow in the transformer air core and model winding internal short-circuit. Fig. 4 shows the frequency response spectra when the LV winding is left open- and short-circuited, respectively.

According to Fig. 4, when the LV winding is short-circuited, changes to the frequency response of the HV winding occurred in the range from 20 Hz to 3 MHz. For frequencies above 3 MHz, there is no significant discrepancy between recorded spectra. The reason lies in the fact that the winding self-inductance

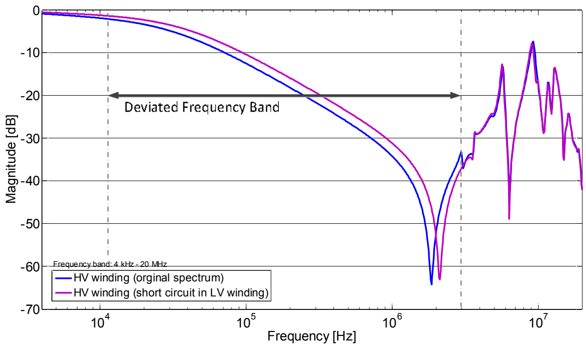


Fig. 4. HV winding frequency response spectrum when LV winding is open-circuited (original spectrum) and short-circuited..

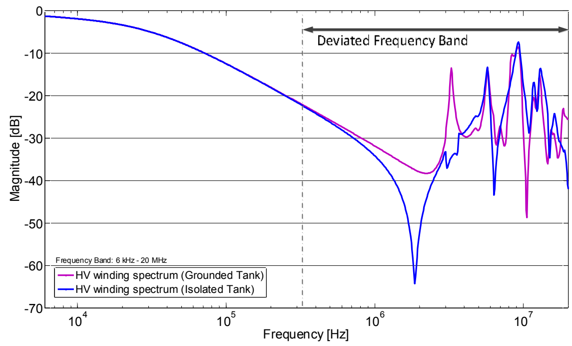


Fig. 5. FRA spectra of HV winding for isolated and grounded tank.

has changed due to the short circuit deliberately created.

In addition, in the case of short-circuit, the low frequency band of FRA spectrum shows different trend to reach to the first anti-resonance as compared to the original spectrum. In fact, its falling curve is slightly moderated. This means that transformer HV winding experiences less inductance when having internal short-circuit than 'normal' state in LV winding.

### B2. Influence of tank grounding

In order to conduct this experiment, the aluminum tank of the test model was grounded through laboratory earth. FRA trace for the HV winding was measured while LV terminals were left open circuit. HV winding FRA spectra for isolated and grounded tank are shown in Fig. 5.

According to Fig. 5, the number of resonance frequencies for grounded tank has increased as compared to the un-grounded case, in particular the mid-frequency band. It can be explained through shunt capacitance increment. In addition, the magnitude of the first anti-resonance in HV trace has varied considerably due to changes in conductance between HV and LV windings with respect to the tank. This can be interpreted by winding loss factor (conductivity).

All in all, either the moisture migration or winding mechanical defects has their own impacts on FRA spectrum; however, FRA was just developed earlier to recognize mechanical defects in the transformer. In addition, FRA assessment methods are also supposed to be influenced just due to winding deformation and no other incidents.

A common method to interpret frequency responses of transformer windings and exploring the winding deformation is statistical indices or indicators (evaluation indicators), which have been introduced by various researchers over the years. In order to exploit FRA test results for extracting more information, a software package was developed to calculate statistical indicators. Using the developed software, evaluation of FRA spectra obtained in this study was examined through conventional statistical measures such as the cross correlation (*CC*) and the standard deviation (*SD*) for Figs. 3, 4 and 5. Table I provides the assessment results and Table II gives the *CC* and *SD* criteria.

According to Table I, this study reveals that statistical indices (*CC* and *SD*) do not have enough accuracy in FRA spectrum interpretation, when FRA traces have been taken under different temperatures and moisture contents. Indeed, they led to incorrect decision and resulted in winding deformation diagnosis for the spectra depicted in Fig. 3. To address this issue, a method to distinguish insulation characteristic influence from winding deformation is recommended in the next Section.

TABLE I
CALCULATED STATISTICAL INDICATORS

| Test Object | Statistical indicators | |
|---|---|---|
| | *CC* | *SD* |
| Moisture migration (Figure 3) | 0.9974 | 1.5258 |
| Turn-to-turn faults (Figure 4) | 0.9186 | 1.3032 |
| Tank Grounding Fault (Figure 5) | 0.7312 | 1.9563 |

TABLE II
CC AND SD CRITERIA [18]

| Statistical indices | Boundary values for winding deformation |
|---|---|
| *CC* | <0.9998 |
| *SD* | >1.0 |

## III. Feasible Solution to Distinguish the Transformer Winding Deformation from Insulation Characteristic Impacts

According to results in the last Section, to obtain the maximum accuracy in transformer frequency response evaluation, the statistical indicators need to be modified and the moisture and temperature variations are brought into consideration. In fact, distinguishing temperature and humidity impacts on the FRA spectrum from the winding deformation is the challenge.

A study by Ryder in [19] did not consider moisture variation and its impact on the FRA spectrum; however, as a caution he advised using inter-phase comparisons for those cases suspected of experiencing relative humidity changes. It means that to recognize the relative humidity changes in transformer FRA signature, the FRA spectra recorded for different phases on HV side can be compared together and their discrepancy is taken as the influence of humidity changes. Similar procedure can be performed for LV side. However, it should be noted that this suggestion is feasible only for three-phase transformers[19].

This paper believes the recommended solution by [19] has fundamental limitations. Even for the lateral windings in a three-phase transformer (phases *A* and *C*), having similar frequency responses is often not practical. There are many cases in which lateral FRA fingerprints are quite dissimilar. Also, the assessment of the middle winding frequency response will remain a challenge. Its spectrum is not comparable to the others.

Ryder's suggestion could be extended into inter-winding instead of inter-phase comparison. Inter-winding comparison can be performed between the HV and LV windings for each and every phase independently. In fact, a differential spectrum ($X_{i(HV)}$-$X_{i(LV)}$) can be calculated using HV and LV winding frequency response spectra and called DFRA. DFRA spectrum which comes through the difference between HV and LV winding spectra should remain unchanged and also not altered due to moisture and temperature changes. Any changes in paper moisture or temperature in HV winding would occur for the LV winding as well. As far as DFRA spectrum is not changed for the transformer entire life, it means that transformer humidity has remained unchanged and the measured FRA spectra can be examined through statistical indicators to explore winding deformation. This approach seems to be more feasible than what has been recommended in[19], but it still has a drawback. The volume of crepe paper insulation for HV and LV conductors as well as paper insulation thickness for each winding might be different. In addition, a transformer might have an enameled winding in LV side and a paper insulated winding in HV side. Thus the water absorbed through the HV and LV windings in a phase would be different and result in an incorrect prognosis. Therefore, this approach also appears to be not quite accurate. Hence, a comprehensive practical solution which provides an independent result for each and every winding would be preferable. This solution is discussed hereinafter.

Indeed before the evaluation of FRA spectra through the statistical indicators, a preliminary calculation should be performed to distinguish insulation characteristic influence from winding deformation. Fig. 6 presents the flowchart of a new technique to address this issue. This procedure distinguishes the insulation impact from the mechanical impact on the frequency response of transformer winding. The reference and measured spectra are numerically processed to determine whether further evaluation by statistical indicators can proceed, or other actions are required (including possible outcome of 'no action').

In the chart provided in Fig. 6, $\bar{\alpha}$ and $\bar{\beta}$ are considered as the lower and upper limits of FRA trace deviation and will be determined only through the FRA signature (reference trace). At first, the moisture content of the paper insulation should be measured during the FRA signature measurement. Next, the measured value for the paper moisture is taken as the reference value ($WCP_{ref}$) in percent for FRA trace signature. Afterwards, deviation in the measured FRA spectrum in Bode diagram due to the moisture migration from paper insulation is calculated (*FSD*), and the moisture diffusion (*WCP change*) is derived. Then, $\bar{\alpha}$ and $\bar{\beta}$ can be determined through (1) and (2) considering 0.5 % ($W_{ll}$) and 4 % ($W_{ul}$) as the lower and upper criteria for moisture content of the transformer paper insulation (different standards or guidelines may recommend different criteria for maximum and minimum moisture content in transformer paper insulation).

Comparing $R_n \triangleq R\{X_i, Y_i\}_n$ in Fig. 6, $\bar{\alpha}$ and $\bar{\beta}$, appropriate decision can then be made. In fact, $R_n$ should remain between $\bar{\alpha}$ and $\bar{\beta}$. Where $\bar{\alpha}$ is the

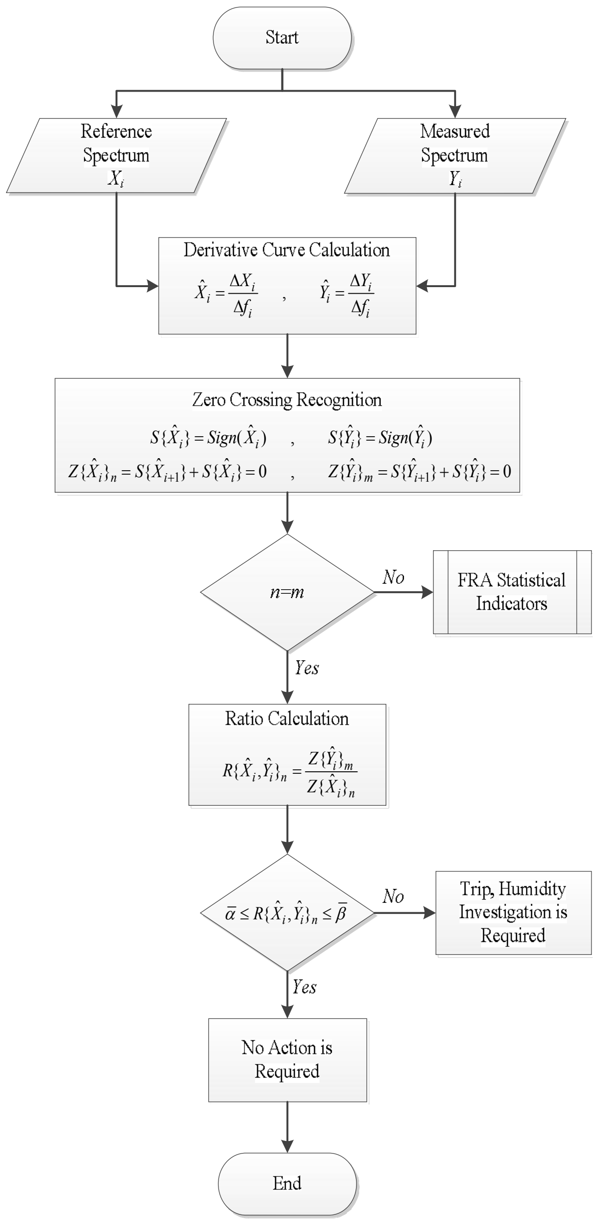


Fig. 6. The chart on preliminary calculation on FRA traces to distinguish insulation deviation from winding deformation; $X_i$ and $Y_i$ are defined i[th] samples in FRA fingerprint and measured traces.

maximum permissible lower limit for FRA trace deviation due to the insulation characteristic changes, and $\bar{\beta}$ is the upper criterion. They both are influenced by $W_{ll}$ and $W_{ul}$ respectively. If $W_{ll}$ and $W_{ul}$ as the lower and upper criteria for moisture content of the transformer paper insulation are changed, then maximum lower and upper limits for trace deviation ($\bar{\alpha}$ and $\bar{\beta}$) would be changed accordingly.

$$\bar{\alpha} = 1 + FSD\frac{\left(W_{ll} - WCP_{ref}\right)}{WCP\quad Change \times 100} \tag{1}$$

$$\bar{\beta} = 1 + FSD\frac{\left(W_{ul} - WCP_{ref}\right)}{WCP\quad Change \times 100} \tag{2}$$

## IV. Case Study on Model Transformer

### *A. Case Study 1, Moisture Assessment via Recommended Solution*

In order to test the recommended method, FRA spectra of HV winding of the glassy model transformer taken at 30 and 90 °C were examined. A program was developed, and according to the procedure presented in Fig. 6, FRA spectra ($X_i$ and $Y_i$) were loaded in the program. Afterwards, $\hat{X}_i$ and $\hat{Y}_i$ were calculated to derive the resonant frequencies. In fact, wherever $\hat{X}_i$ and $\hat{Y}_i$ experience zero value, a resonant peak has happened. Fig. 7 shows the references ($X_i$ and $Y_i$) and derivative spectra ($\hat{X}_i$ and $\hat{Y}_i$) for the HV winding of the test system at 30 and 90°C.

$Z\{\hat{X}_i\}_n$ and $Z\{\hat{Y}_i\}_m$ should then be calculated. This in turn helps to realize number of resonant points and ascertain whether the winding is mechanically deformed. $n{\neq}m$ will require statistical indicators to be utilized as an evaluation method, while $n{=}m$ reveals normal mechanical condition for the winding. Therefore as the next step, $S\{\hat{X}_i\}$ and $S\{\hat{Y}_i\}$ were calculated and $Z\{\hat{X}_i\}_n$ and $Z\{\hat{Y}_i\}_m$ were derived. Table III shows the calculated values for $Z\{\hat{X}_i\}_n$ and $Z\{\hat{Y}_i\}_m$. Based on Fig. 6, similar number of resonant points in FRA spectra ($n{=}m$) indicates that no further action is required for statistical indicators calculation, and deviation in FRA spectrum is probably initiated by moisture influence. In Table III it is obvious that $n{=}m$ and FRA statistical indicators are not required to

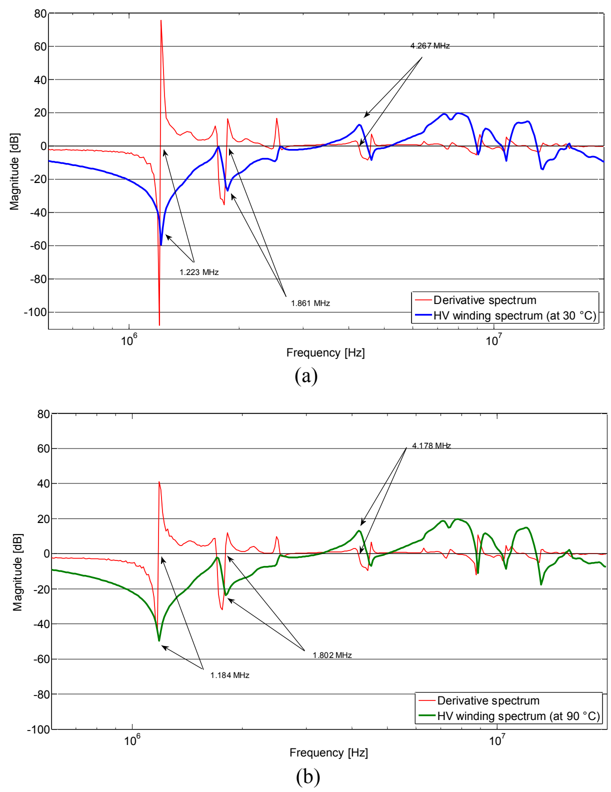


Fig. 7. Reference and derivative spectra for HV winding of glassy model transformer, (a) Spectra at 30°C, (b) Spectra at 90°C.

be considered. Therefore as the next step in the chart; *Rn* should be calculated. Hence, $R_n \triangleq R\{X_i, Y_i\}_n$ were calculated and illustrated in the last column of Table III.

To obtain $\bar{\alpha}$ and $\bar{\beta}$, the moisture content of the reference trace was used, equal to 4 %, as it was measured earlier in Section II. Upper limits ($W_{ul}$) and lower limits ($W_{ll}$) for moisture content were taken as 4 % and 0.5 %, respectively. Also the *WCP change* for this case was taken as 0.5. According to (1) and (2), $\bar{\alpha}$ and $\bar{\beta}$ are obtained as:

$$\bar{\alpha}=1+0.79\frac{(0.5-4)}{0.5\times100}=0.9447 \tag{3}$$

$$\bar{\beta}=1+0.79\frac{(4-4)}{0.5\times100}=1 \tag{4}$$

Considering calculated values for $R_n \triangleq R\{X_i, Y_i\}_n$ in Table III, all values satisfy the criteria in (5). It means that the winding has "Normal" condition and "No Action Required". Based on our knowledge about the test object in Section II, the calculated result in (5) is quite reasonable for this case.

$$0.9447=\bar{\alpha}\le R_n \le\bar{\beta}=1 \tag{5}$$

*B. Case Study 2, Winding Deformation Assessment via Recommended Solution*

In order to study the winding deformation recognition through the recommended solution in Section III, the glassy model test object was again examined.

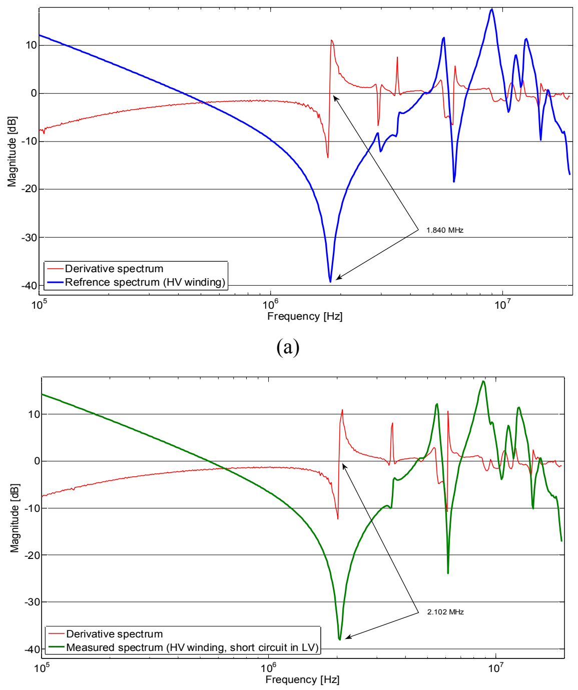


Fig. 8. HV winding spectra (a) Reference spectrum and its derivative (100 kHz – 20 MHz), (b) Measured spectrum and its derivative (100 kHz – 20 MHz).

TABLE III
CALCULATED VALUES FOR $Z\{\hat{X}_i\}_n$ AT (30°C) AND $Z\{\hat{Y}_i\}_m$ AT (90°C)

| $Z\{\hat{X}_i\}_n$ [Hz] | $Z\{\hat{Y}_i\}_m$ [Hz] | $R_n \triangleq R\{X_i, Y_i\}_n$ |
|---|---|---|
| 1223110 | 1184837 | 0.968708456 |
| 1740778 | 1689525 | 0.970557417 |
| 1861823 | 1802298 | 0.968028647 |
| 2347992 | 2277552 | 0.969999898 |
| 2481509 | 2407063 | 0.969999706 |
| 2565236 | 2488279 | 0.970000031 |
| 2771751 | 2688598 | 0.969999830 |
| 4267881 | 4178285 | 0.979006912 |
| 4559604 | 4422816 | 0.970000026 |
| 7253854 | 7038179 | 0.970267530 |
| 7510670 | 7275650 | 0.968708517 |
| 7927191 | 7689375 | 0.969999966 |
| 8952855 | 8684270 | 0.970000073 |
| 9359869 | 9077133 | 0.969792740 |
| 10686194 | 10365608 | 0.969999983 |
| 11546489 | 11200095 | 0.970000058 |
| 11804773 | 11550630 | 0.978471166 |
| 12213072 | 11836980 | 0.969205782 |
| 13480431 | 13176018 | 0.977418155 |
| 15067130 | 14605416 | 0.969356208 |
| 15393943 | 14932125 | 0.970000019 |
| 15913342 | 15535942 | 0.976284051 |
| 18182201 | 17627035 | 0.969466513 |
| 18578695 | 18221334 | 0.980765011 |

TABLEIV
CALCULATED VALUES FOR REFERENCE SPECTRUM $Z\{\hat{X}_i\}_n$, AND MEASURED SPECTRUM $Z\{\hat{Y}_i\}_m$

| $Z\{\hat{X}_i\}_n$ [Hz] | $Z\{\hat{Y}_i\}_m$ [Hz] |
|---|---|
| 1840822.911 | 2102123.015 |
| 2961946.861 | 3382387.641 |
| 3028202.732 | 3496511.071 |
| 3420008.789 | 3654687.782 |
| 3535401.565 | 3777998.756 |
| 3654687.782 | 4765873.542 |
| 3777998.756 | 4872481.525 |
| 4765873.542 | 5626005.61 |
| 4872481.525 | 6284034.927 |
| 5688581.755 | 8952855.389 |
| 6284034.927 | 9673607.699 |
| 9153122.082 | 9781203.931 |
| 10805053.01 | 10805053.01 |
| 11674917.05 | 11546489.36 |
| 12203072.06 | 12203072.06 |
| 12896990.82 | 12896990.82 |
| 14891496.72 | 14891496.72 |
| 15913342.45 | 15913342.45 |
| 18578695.3 | 17972300.97 |
| 18785339.78 | 18172200.75 |
| ---- | 18578695.3 |
| ---- | 18785339.78 |

At first, the frequency response trace of the model transformer was recorded from the HV side while the LV side was left open circuit and test object tank did not have oil. Next, to model a mechanical defect in the test object, the modification involved the short circuit on LV terminals was performed such exactly examined in Section II part B1. This modification can in turn block the flux flow in the transformer air core and model winding internal short-circuit on LV side (see Fig. 4).

To examine the recommended solution S{Xˆi } and S{Yˆi } were calculated and Z{Xˆi }n and Z{Yˆi }m were derived. Table IV shows the calculated values for Z{Xˆi }n and Z{Yˆi }m. From zero crossing recognition in Table IV, it is now obvious that n≠m and the transformer is suspected to have mechanical defect. In addition, the ratio of Z{Xˆi }n and Z{Yˆi }m are not following a linear trend in this Table. Therefore, FRA statistical indicators are required to be taken into consideration. The reference and measured FRA spectra as well as their derivative curves for HV winding are illustrated in Fig. 8.

## V. Conclusion

The study presented in this article explored the moisture migration impacts on the FRA spectrum. Also, mechanical defects was modelled through the internal short-circuit as well as tank grounding, and the frequency band affected by these phenomena was identified. Based on this study, for accurate interpretation of the FRA results through statistical indicators, mechanical deformation of winding should be distinguished from the moisture influence. Indeed, these indicators have to be modified or their criteria must be revised or even a pre-assessment is implemented. To this end, a feasible method to distinguish winding deformation from insulation characteristic impacts of FRA spectrum was recommended as a pre-assessment method. This method seems to be effective to be implemented on spectra before statistical evaluation of FRA traces. The results are then available to be inserted in statistical indicator formulas for final assessment. However, further works as well as more practical studies are necessary to reach a reliable, accurate and sensitive method on this case.

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