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Case study for assessing the integrity of a service-aged transformer repair using Frequency Response Analysis (FRA)

R. S. A. FERREIRA[1], H. SIMARD[2], P. PICHER[3],
V. BEHJAT[1], I. FOFANA[1] and H. EZZAIDI[1]
[1]Research Chair on Aging Power Network Infrastructure (ViAHT),
Université du Québec à Chicoutimi (UQAC)
[2]Énergie Électrique Rio Tinto
[3]Institut de Recherche d'Hydro-Québec (IREQ)
Canada

SUMMARY

In recent decades, there has been a growing interest in power transformer condition assessment. This is mainly attributable to the ever-growing energy demand, combined with the increasingly aging population of transformers in utilities around the world. A large number of operational transformers worldwide are approaching or have passed the end of their theoretical design lives. Rio Tinto, which operates approximately 167 transformers with a total power of more than 2,000 MVA and an average age of over 60 years in the region of Saguenay–Lac-Saint-Jean (QC, Canada), has been dealing with this situation.

In these circumstances, managing the aging population of power transformers has become one of the most critical issues faced by today's managers and engineers responsible for substation transformers. A simple solution would be to replace all aging and risky transformers with new and reliable ones. However, such an approach is not financially realistic. Besides, monitoring results for these transformers show that many, perhaps most, are in good operation condition. Thus, a more realistic solution is the regular assessment of power transformer conditions. Continuous monitoring allows for preventive repair and planned replacements and increases system reliability. Among diverse condition monitoring techniques, Frequency Response Analysis (FRA) stands out as an important method that is increasingly in use by the electric industry for the condition assessment of the active part of transformers.

This paper describes the condition assessment of a 20-MVA power transformer based on frequency response measurements. The transformer under evaluation was removed from service and repaired in Rio Tinto workshop facilities after an internal water cooler leak and a thermal fault were detected. Before and after repair, FRA measurements were conducted to evaluate the integrity of the active part. The main results from these investigations are presented and discussed.

KEYWORDS

Condition monitoring, Frequency Response Analysis, Power transformers

regelii.suassuna-de-andrade-ferreira1@uqac.ca

1. INTRODUCTION

Transformers are expensive and critical equipment in power systems. They play a significant role in electricity transmission and distribution but, even though they are reliable, failures do occur. Over the years, there have been considerable developments in the assessment of transformer condition. Today, the main drivers of advances in transformer condition assessment techniques are the increasing age of the transformers in service and the growing demand for electricity.

To maintain reliable power system operation, it is important that engineers assess the condition of in-service transformers and make decisions on their operation, repair, refurbishment or replacement. The understanding of transformer failure modes is valuable in identifying affected parts and determining the appropriate response.

The main failure modes in power transformers are dielectric, electrical, mechanical, chemical and thermal. According to [1], they are approximately 38% dielectric, 22% mechanical and 18% electrical in origin. Accounting for almost 80% of all transformer failures, dielectric, mechanical and electrical are also the most commonly monitored conditions in transformers. The most frequently-used monitoring and diagnostics methods include: Dissolved Gas Analysis (DGA) [2, 3], Partial Discharge (PD) measurement, winding DC resistance measurement, power factor testing, thermal scans, Dielectric Frequency Response (DFR) [4], and Frequency Response Analysis (FRA) [5-8].

FRA is currently one of the most common techniques used to detect mechanical changes in the active part of transformers. The analysis of frequency response traces makes it possible to determine whether the transformer is intact and can continue its normal operation or presents deviations that could compromise its operation and thus requires repairs before re-energization. FRA compares reference and post-event measurements. Deviations in frequency response traces can indicate electrical or mechanical faults in a transformer's internal structure and point to the need for further analysis by experts.

Using FRA measurements, this paper describes an investigation of active part integrity following the repair of a 161/13.2-kV, 20-MVA transformer. The transformer under analysis is over 60 years of age and was removed from service due to a water leakage problem detected in its internal cooling system. Thermal faults were also identified after DGA tests. The transformer was repaired in the Rio Tinto workshop facilities and, in order to confirm the quality of the active part after the repair task, pre- and post-repair FRA measurements were conducted. The main results for these investigations are further presented and discussed in the following sections.

2. CONDITION ASSESSMENT OF POWER TRANSFORMERS

Monitoring and diagnosing power transformers requires the assessment of different conditions. For the purpose of this discussion, two main monitoring techniques were involved in the investigations conducted. The first, DGA, was used to identify thermal faults inside the transformer and was the determining factor in its removal from operation. The second monitoring technique used was FRA. For this investigation, FRA was used to verify the integrity of the active part after the repair tasks were performed in the transformer.

Dissolved Gas Analysis

DGA is a commonly-used technique for on-line fault diagnosis in oil-filled transformers. The main challenge in using DGA for fault detection is determining the correct correlation between fault and gas generation. Insulation breakdown from electrical, thermal and mechanical stresses releases small quantities of gases and the composition of these gases is related to the fault type.

Gas generation sources include arcing, corona discharge, low energy sparking, and insulation overheating due to severe overloading or cooling system failure. The faults are identified according to the gases generated and the gases that are typical at different temperatures. Gases evaluated during DGA are: hydrogen (H_2), methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), acetylene (C_2H_2), carbon monoxide (CO) and carbon dioxide (CO_2) [2]. Other indices are also verified during DGA testing, such as total combustible gases (TCG).

Frequency Response Analysis

FRA is a powerful tool for detection of mechanical changes in the active part of power transformers. Since a transformer can be considered as a complex network of RLC components (representing the resistances of windings, inductances of coils and capacitance from the insulation layers), a variation in the frequency response may indicate a physical change inside the transformer.

FRA obtains a measurement at each frequency by injecting and measuring a sinusoidal waveform with constant amplitude at the reference point and measuring the amplitude and phase shift at the response point [6, 7]. The most usual measurement type is end-to-end, where the signal is applied to one end of the winding and measured at the other end. Another measurement type is inter-winding, where the signal is applied to one winding and measured at another. For example, the signal is applied to the high voltage winding and measured at the low voltage winding.

To identify the changes inside the transformer, FRA needs to be compared to a healthy response, ideally a response before the defect in the same transformer. However, a previous response may not be available, so a comparison with an identical transformer (sister unit) or even between phases can be an option.

3. CASE STUDY

The transformer under evaluation, shown in Figure 1, is a single-phase unit rated 20 MVA, 161/13.2 kV manufactured by General Electric in 1951. The transformer is also composed of an off-load tap changer and an internal water-cooling system.

(a) (b)

Figure 1: 20-MVA transformer (a) fully assembly and (b) out of the tank for inspection and repair.

During usual routine maintenance, the generation of an abnormal level of dissolved gases was detected. A summary of the DGA report from the last samples before de-energization is shown in Table 1. From the DGA report and based on the comparison with Rio Tinto's transformer population, it was possible to verify an increase of H_2 over the time, as well as abnormal values of C_2H_4 and CO. These abnormalities indicate thermal fault and the need for repair in the next months.

Table 1: Summary of DGA report

Sample date	July 3, 2018	June 13, 2018	May 9, 2018	
Fluid Temperature	50	46	48	℃
Hydrogen (H_2)	73!	68!	47	µL/L
Methane (CH_4)	21	21	21	µL/L
Ethane (C_2H_6)	11	11	11	µL/L
Ethylene (C_2H_4)	229*	230*	226*	µL/L
Acetylene (C_2H_2)	0	0	0	µL/L
Carbon Monoxide (CO)	1205	1175	1167	µL/L
Carbon Dioxide (CO_2)	7977*	8072*	7674*	µL/L
Equivalent TCG	1.473	1.444	1.417	%
Moisture	21	18	18	mg/kg

(!: sharp increase, *: abnormal level)

In addition to the DGA results, a routine inspection of the transformer's water cooling system identified the presence of transformer oil in the cooling water. The leakage of oil to the cooling system indicated the need for immediate intervention in the transformer. The DGA and the presence of oil in the cooling system were the main deciding factors for taking the transformer out of operation.

After de-energization, the transformer was taken to the workshop facility for further inspections. Since it was necessary to dismantle the windings and core to ensure the mechanical integrity of the transformer assembly, FRA tests were conducted before and after winding removal. The tests were conducted according to the IEC recommendations [6].

First, a FRA measurement was performed with the transformer active part out of the tank (Figure 1b). The windings were removed from the core and several insulation failures were identified during the visual inspection. The main failures identified are shown in Figure 2. The failures were then repaired, and the transformer was ready for reassembly. After reassembly, a new FRA measurement was taken to check for changes in the transformer subsequent to the disassembly, repair and reassembly.

Following the last post-repair FRA test, the transformer windings were re-clamped and returned to the tank. The tank was refilled with oil, and the bushings were installed. Before refilling, the oil was treated to remove impurities and moisture.

(a) (b) (c)

Figure 2: Insulation failures (a) top yoke core sheets, (b) core clamp bolts, (c) metallic structure to tank.

To further investigate the mechanical integrity of the transformer, an FRA comparison with a sister unit was also performed. This new comparison was conducted after the transformer was fully reassembled, i.e., active part was inside the tank, the bushings were installed and the tank was filled with oil. Measurements on the fully assembled transformer were necessary in order to compare with the sister unit measurements. It is important to mention that the sister unit was not submitted to the same alterations and repairs as the transformer under evaluation.

4. FRA RESULTS AND DISCUSSIONS

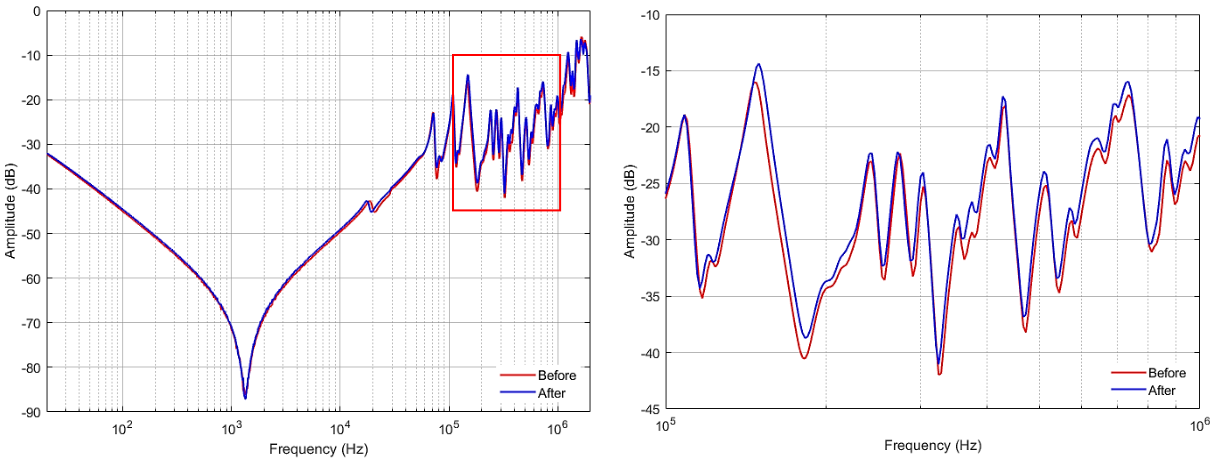
The pre- and post-repair traces for the high voltage and low voltage windings are shown in Figures 3 and 4, respectively.

The zoomed-in 100 kHz to 1 MHz portions of the graphs in Figures 3 and 4 show considerable deviations between traces. Since there was no change in winding resistance or inductance, it can be assumed that the series and/or parallel capacitances changed to justify the deviations.

After investigating the possible changes in the insulation capacitances, the capacitances from winding to ground were identified as the main cause for deviation in the traces. In fact, when the core was repaired, the connections between core and ground were modified (see Figure 5). In the previous connection scheme (Figure 5a), the lower end frame was electrically connected to the core, which was connected to the upper end frame, and then the structure was grounded. After repairs (Figure 5b), the lower and upper end frames were independently connected and then grounded, and the core was grounded separately. Both ground connections were made through a small bushing located in the transformer cover.

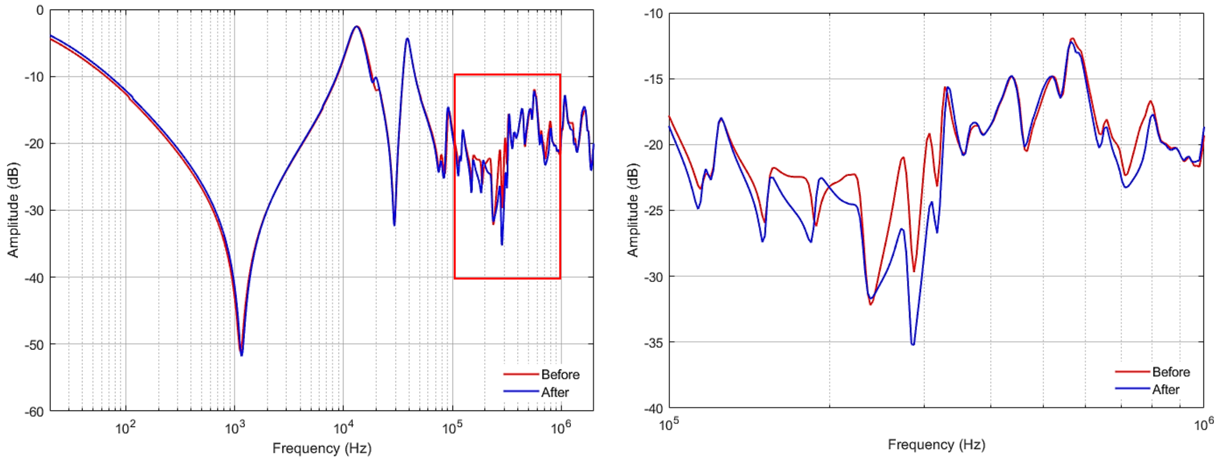
It was also apparent that the clamping pressure was not the same for both measurements. For the first measurement, before disassembly, the winding clamping pressure was the same as in operation. However, for the second measurement, after reassembly, clamping pressure was not applied. As discussed in [9], a change in clamping pressure can influence the magnitude of resonance peaks without changing their frequency, as noted on Figures 3 and 4.

Another change to the transformer structure is shown in Figure 6. The structure connecting the upper end frame to the tank was modified, replacing the previous (Figure 6a) metallic structure with a composite one (Figure 6b).



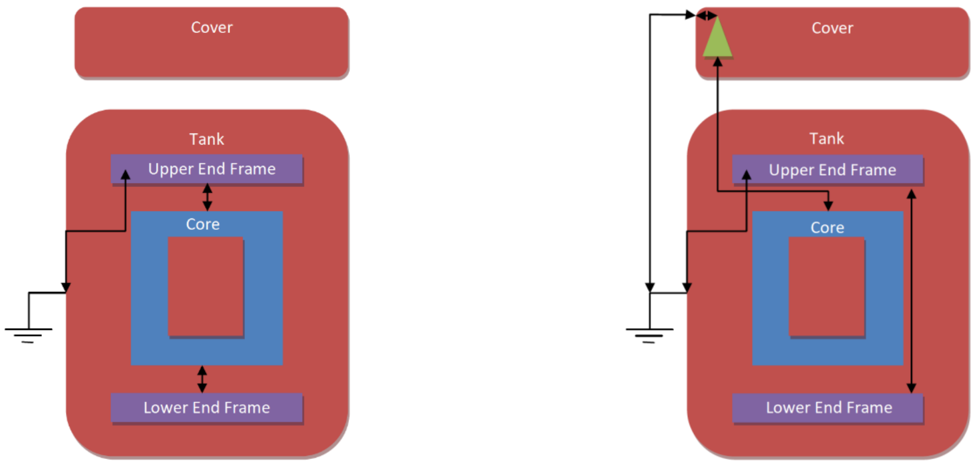
(a) (b)

Figure 3: Frequency response traces for 20 MVA HV end-to-end open circuit measurement (a) complete frequency range and (b) zoomed portion.



(a) (b)

Figure 4: Frequency response traces for 20-MVA LV end-to-end open circuit measurement (a) complete frequency range and (b) zoomed portion.



(a) (b)

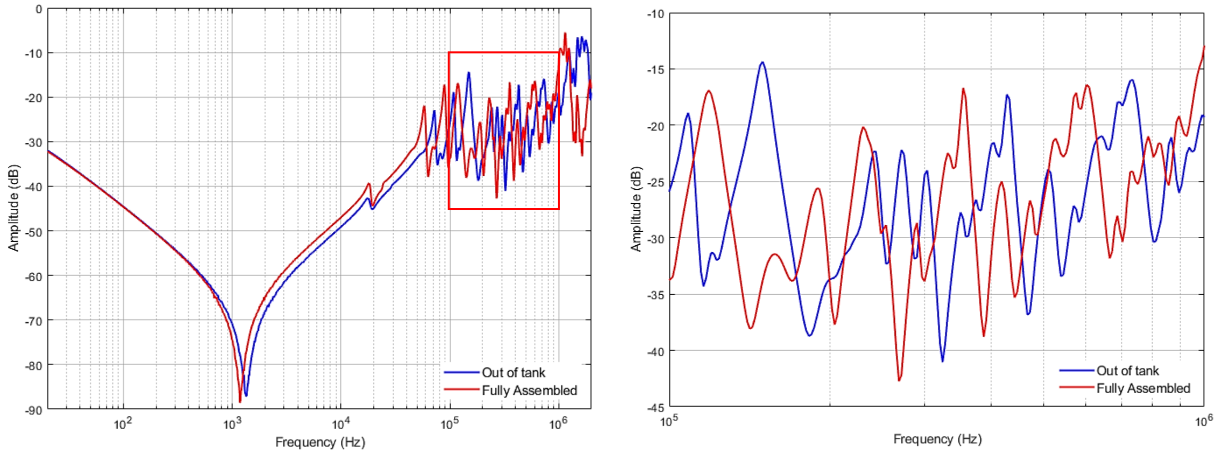
Figure 5: Core to ground connection (a) before repair and (b) after repair.

(a) (b)

Figure 6: Upper end frame structure connection to tank (a) before repair (metallic connection) and (b) after repair (composite connection).

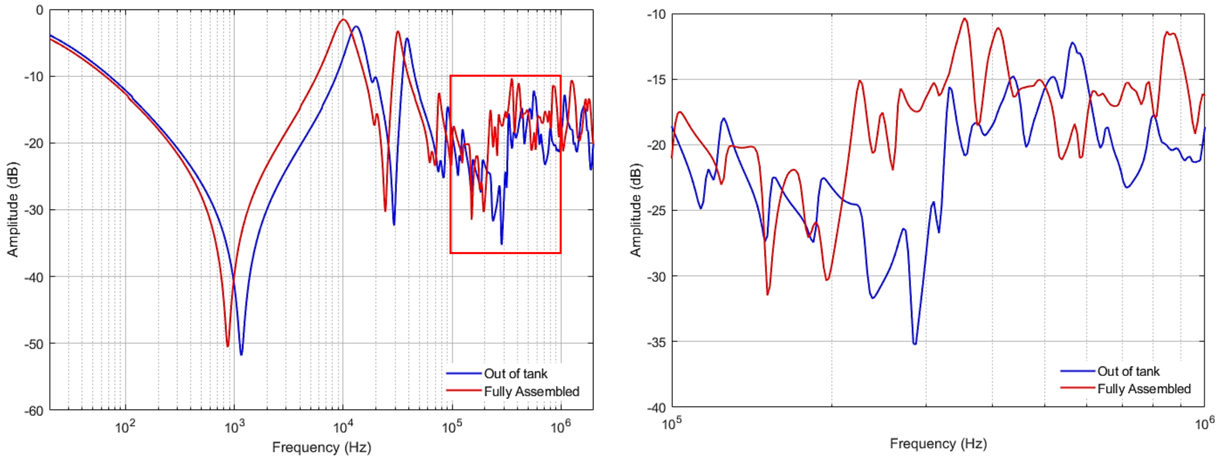
The modifications in the core-to-ground connection, along with the changes in the connecting frame and tank structures, may influence the earth capacitances of the windings. Evidence of these changes were shown in FRA measurements of both the high voltage and low voltage windings.

Furthermore, the transformer was fully assembled and a comparison of post-repair measurements, one with the active part out of the tank and the other with the transformer fully reassembled, is shown in Figures 7 and 8. From this example, it is possible to identify the influences of the insulating oil, tank and bushings in the measurements. The presence of oil has a considerable effect on the permittivity of the medium, reducing the resonance frequencies and shifting the entire curve to the left [5]. In addition, other capacitive effects such as the presence of the tank and bushings may affect the frequency response in different ways. Consequently, other deviations can be found in Figures 7 and 8, such as a reduction in resonance amplitude, new resonances and an absence of resonances.



(a) (b)

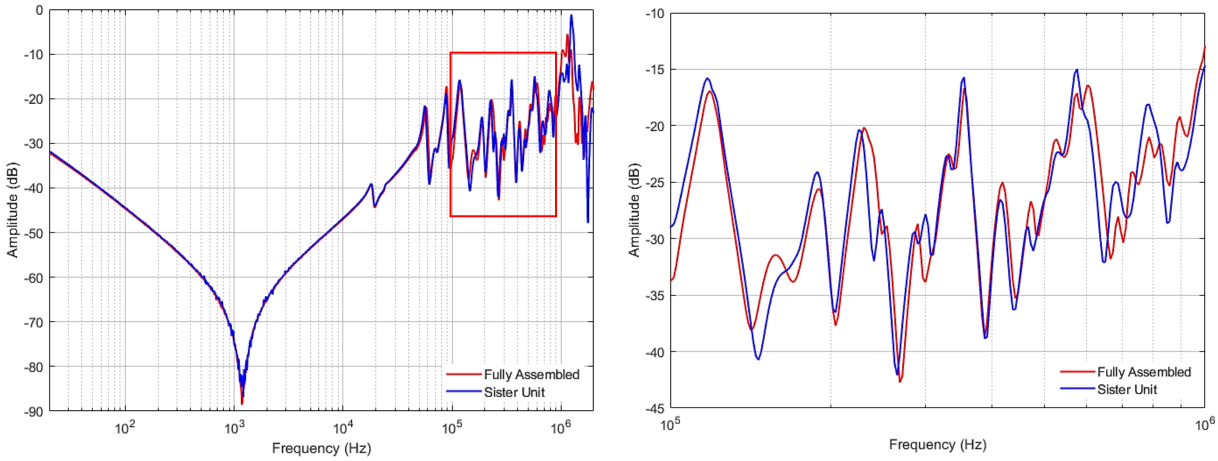
Figure 7: Frequency response traces for 20 MVA HV end-to-end open circuit measurement out of the tank and fully assembled (a) complete frequency range and (b) zoomed portion.



(a) (b)

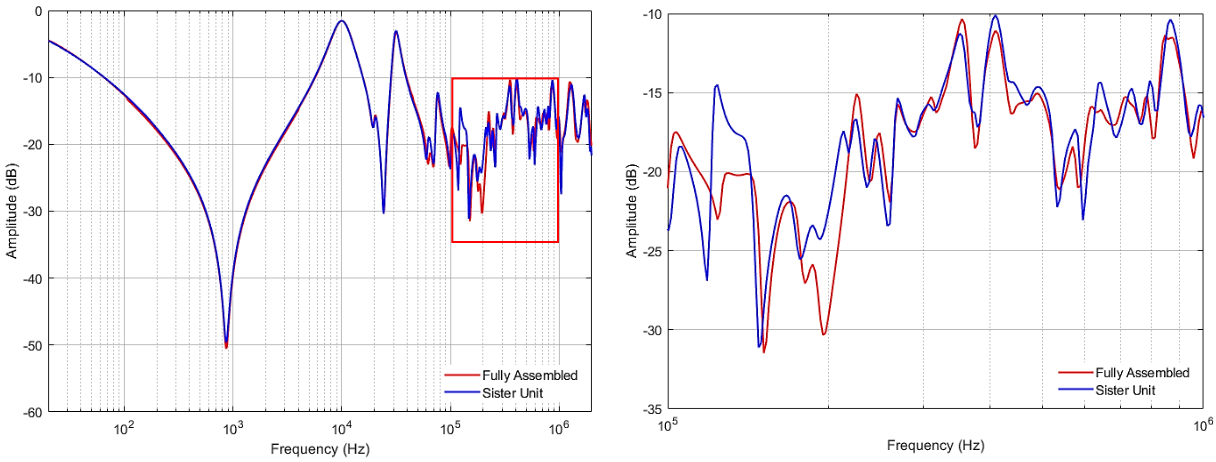
Figure 8: Frequency response traces for 20-MVA LV end-to-end open circuit measurement out of the tank and fully assembled (a) complete frequency range and (b) zoomed portion.

The post-repair traces for the fully assembled transformer were also compared with a sister unit installed in the same substation. Both traces are shown in Figures 9 and 10. For the sister unit comparison, the acceptable deviations are higher. Despite having the same characteristics (e.g. technical specifications, year of manufacture and consecutive serial numbers), manufacturing tolerances result in slight deviations. Therefore, the traces shown in Figures 9 and 10 can be considered a good match. However, it is important to consider that the sister unit has not been submitted to the same repairs and modifications as the transformer under evaluation. This can also explain the deviations beyond the manufacturing tolerances found in the traces.



(a) (b)

Figure 9: Frequency response traces for 20-MVA HV end-to-end open circuit measurement and sister unit (a) complete frequency range and (b) zoomed section.



(a) (b)

Figure 10: Frequency response traces for 20-MVA LV end-to-end open circuit measurement and sister unit (a) complete frequency range and (b) zoomed section.

Finally, it may be assumed that the repair did not have any impact on the integrity of the transformer. Thus, it can be considered ready for re-energization.

5. CONCLUSION

This paper presents the validation of the integrity of the active part of a 20-MVA transformer after a repair of insulation faults in its core. FRA measurements were compared before and after the repair and a sister unit comparison was also performed.

The FRA traces before and after repair showed relevant variation in the traces in the medium frequency range. The variations were caused by the interaction between windings and the winding structures. The deviations were also associated with the core-to-ground connection that was changed during core repair and with a change in winding clamping pressure.

The comparison with the sister unit's FRA results showed a good match between the traces, despite small variations due to normal tolerances and the fact that the sister unit had not undergone repairs or changes comparable to those performed on the transformer under evaluation.

Consequently, it was possible to conclude that the integrity of the active part of the transformer was maintained following the repairs.

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