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Power Transformer Condition Assessment at Tenayan Raya Power Plant Using Sweep Frequency Response Analysis

Evaluasi Kondisi Transformator Daya PLTU Tenayan Raya Menggunakan Metode *Sweep Frequency Response Analysis*

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Abstrak

Transformator merupakan salah satu peralatan penting dalam sistem tenaga listrik. Kegagalan transformator pada pusat pembangkit dapat mengganggu kontinuitas pasokan listrik. Oleh karena itu, pemantauan kondisi dan deteksi dini kerusakan transformator penting untuk dilakukan agar transformator dapat bekerja dengan baik dan sesuai dengan usia pemakaian maksimumnya. Salah satu jenis kerusakan yang dapat terjadi adalah perubahan struktur mekanis pada komponen internal transformator. Kerusakan ini dapat dideteksi menggunakan metode Sweep Frequency Response Analysis (SFRA) yang merupakan teknik pengujian non-invasif dengan menganalisis perubahan respons frekuensi akibat gangguan mekanis internal. Penelitian ini melakukan analisis SFRA pada transformator daya di PLTU Tenayan raya dengan membandingkan kondisi sebelum dan sesudah perbaikan. Perbandingan dari tiga periode pengujian menunjukkan variasi paling signifikan terjadi antara tahun 2020 dan 2022, terutama pada rentang frekuensi tinggi, yang mengindikasikan potensi deformasi belitan akibat stres operasi. Sebaliknya, perbandingan sebelum dan sesudah pemeliharaan menunjukkan respons yang stabil, sehingga dapat disimpulkan bahwa aktivitas pemeliharaan tidak menimbulkan deformasi belitan yang signifikan.

Keyword: Deformasi Transformator, Diagnostik Transformator, Transformator, SFRA.

Abstract

Transformers are one of the important equipment in electrical power systems. Transformer failure at power plants can interrupt the continuity of electricity supply. Therefore, monitoring the condition and early detection of transformer damage is important to ensure that transformers can work properly until their maximum service life. One type of damage that can occur is a change in the mechanical structure of the transformer's internal components. This damage can be detected using the Sweep Frequency Response Analysis (SFRA) method, which is a non-invasive testing technique that analyzes changes in frequency response due to internal mechanical disturbances. This study conducted an SFRA analysis on power transformers at the Tenayan Raya Power Plant by comparing the conditions before and after repairs. Comparisons across three test periods showed that the most notable variations occurred between 2020 and 2022, mainly at high frequencies, indicating winding deformation due to operational stress. In contrast, the pre- and post-maintenance comparison revealed stable responses, confirming that maintenance activities did not cause significant winding deformation.

Keyword: Transformer, Transformer Deformation, Transformer Diagnostic, SFRA.

1. Introduction

Transformers are one of the important equipment in electrical power systems. In power plants, power transformers are used to increase the output voltage of generators to a level that is suitable to be sent to load centers through transmission lines. Failure of transformers at power plants can disrupt the continuity of electricity supply and lead to economic losses. Therefore, monitoring the condition and early detection of transformer damage is important to ensure that transformers can work properly according to their maximum service life [1]. This issue is particularly relevant for the power transformer at Tenayan Raya Coal-Fired Power Plant because the unit has been in service for a considerable period. As a baseload unit and one of the primary electricity suppliers in Riau, Tenayan Raya Coal-Fired Power Plant frequently operates under high loading conditions. These operating characteristics can cause additional mechanical and thermal stress on the transformer, making regular monitoring of the transformer's condition important to ensure electricity supply continuity in the Riau region.

Various monitoring methods have been developed to assess the condition of transformers, including the transformer health index method, which combines data drom dissolved gas analysis, oil insulation quality, and furan content [2], [3]. In addition, a number of failure diagnosis methods such as Total Dissolved Combustible Gas (TDCG), Roger's Ratio, and Duval's Triangle are widely used to detect early indications of thermal and electrical disturbances in transformer insulation systems [4], [5], [6]. However, these approaches are only effective for assessing insulation system degradation and cannot directly detect structural changes in the internal components of the transformer. One method that can be used to detect changes in the mechanical structure of a transformer is Sweep Frequency Response Analysis (SFRA). SFRA works by mapping the frequency response of the transformer terminals and comparing it with a baseline or reference to identify changes in inductance, capacitance, and inter-winding coupling parameters. Previous studies have demonstrated the ability of the SFRA method to detect internal transformer faults [7], [8], [9].

Gezeğin & Usta [10] conducted SFRA testing on a 62.5 MVA transformer after it experienced a short circuit. The results of routine SFRA testing were compared with the test data after the disturbance. The analysis results showed deviations in all frequency ranges, identifying deformation of the transformer windings due to the short circuit. Habibi et al. [11] applied SFRA to routine inspections of 500 kV transformers in East Java, Indonesia. By comparing SFRA measurement results from two different periods, changes in the mechanical structure of the core and windings can be detected through shifts in the frequency response curve. Measurements taken every six years showed that the transformers were still in good condition with shrinkage of less than 20% of the standard. This study emphasizes the importance of comparing SFRA results with reference data (fingerprints) to monitor changes in the mechanical condition of transformers over time.

Furthermore, Nisworo et al. [12] applied SFRA to Generator Transformer (GT) Unit 20 at the Rembang Coal-Fired Power Plant using the DL/T 911-2004 standard. The results of the study showed that all transformer windings were in Normal Winding and Slight Deformation conditions, with relative factor values in the low frequency range, medium frequency range, and high frequency range still within safe limits.

Previous studies have shown that SFRA is effective in detecting mechanical issues in various types of transformers and locations. However, few studies have observed at how the condition of a transformer changes over time by using SFRA data collected during different periods of use and maintenance. Addressing this gap, this study aims to analyze the mechanical condition, particularly winding deformation, of the power transformer at Tenayan Raya Coal-Fired Power Plant using SFRA through a historical comparison of three measurement periods. Using these data, the research tracks the change of the transformer's mechanical condition due to regular operation and maintenance work. Through these observations, the study provides a clear view of condition changes that can support routine assessment and maintenance planning. These contributions strengthen the practical application of SFRA in Indonesia's power system and demonstrate its value for risk-based maintenance planning.

2. Theoretical Background

2.1. Sweep Frequency Response Analysis (SFRA)

Transformer is an equipment in an electrical power system that is used to convert voltage from one level to another. It mainly has two parts: an iron core and a coil. These two components can be modeled as an electrical circuit consisting of resistance, inductance, and capacitance elements. Changes in the geometry or physical condition of transformer's core and coil can affect the values of these three elements [13].

Based on these characteristics, Dick and Erven first introduced frequency response analysis for checking the condition of transformers. This analysis is performed by injecting sinusoidal waves with varying frequencies (sweep) within a certain frequency range. The voltage at the input terminal is used as a reference and the voltage measured at the output terminal is used as the response signal. The comparison between the two voltages is then analyzed to obtain the frequency response characteristics of the transformer. Sweep Frequency Response Analysis (SFRA) is a reliable, non-destructive, and sensitive method for evaluating the condition of power transformer mechanical structures. This method is increasingly being used because it has advantages such as high sensitivity to damage, faster measurement times, and lower costs compared to traditional methods [10].

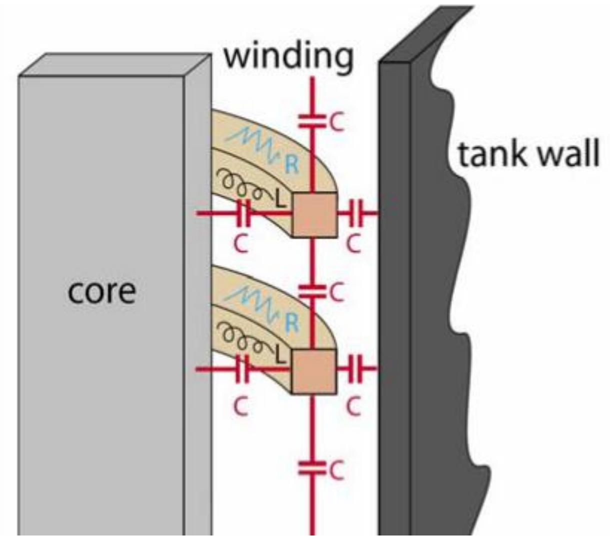


Figure 1. Network behaviour of a transformer's active part (simplified) [14]

2.2. SFRA Test Configurations

SFRA measurements are performed by applying a low-level sinusoidal voltage from the test instrument to the transformer, with the excitation frequency swept from 20 Hz up to 2 MHz. In the Omicron FRAnalyzer, the measurement uses three types of probes: an input probe (signal probe), which delivers the sinusoidal signal to the phase under test, a reference probe, which serves as the reference point for the measurement and is connected to the same bushing as the input probe, and an output probe (measurement probe), which captures the response from the winding being tested [12].

SFRA measurement is carried out using several measurement configurations, which are open-circuit, short-circuit, capacitive inter-winding, and inductive inter-winding tests. In the open-circuit test configuration, a single winding is measured while all other terminals are left floating. The short-circuit test is performed by measuring one winding while the associated winding is intentionally shorted to emphasize winding impedance. Capacitive inter-winding measurements are conducted between two electrically isolated windings with all remaining terminals floating. Inductive inter-winding measurements are performed between two windings with one end of each winding grounded to evaluate their inductive coupling [15]. An example of the probe connection is shown in Figure 1.

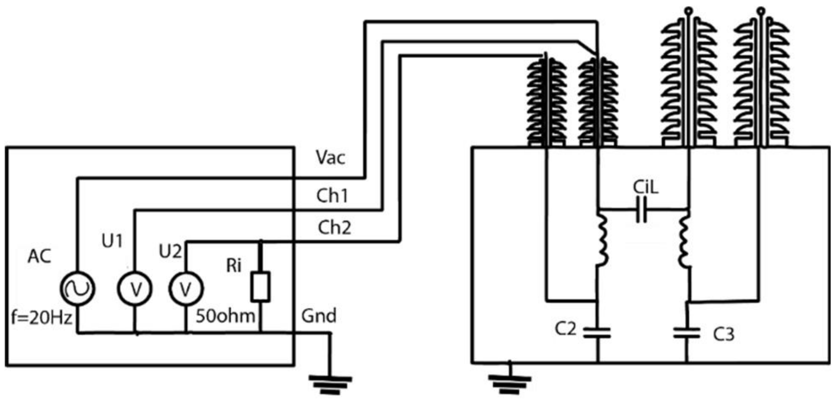


Figure 2. The measurement circuit of frequency response in LV winding [11]

2.3. Type of Recordings

The condition of the transformer is determined by comparing two SFRA measurement results, before and after a certain period of operation. If there is no deviation between the two measurement curves, it can be concluded that the transformer is in good condition. Conversely, a shift in the resonance points or deviation in the SFRA magnitude indicates damage to the transformer. Based on the availability of reference data, SFRA results are interpreted using three main approaches [16]:

3. Analysis with historical reference data

The ideal approach is to compare the latest measurement results with baseline data from the Factory Acceptance Test (FAT) or, if there is no FAT data, to use historical data from previous tests. This data represents the “fingerprint” of the transformer's initial condition.

4. Analysis without historical reference data

In cases where historical reference data is not available, SFRA analysis can still be performed. The analysis is carried out by comparing SFRA measurement results between phases in a single transformer or comparing identical transformers with the same specifications and manufacturer.

3. Method

3.1. Study Object

The object of this study is the three-phase Transformer Unit at the Tenayan Raya Power Plant, with data obtained from field tests using OMICRON SFRA measurement equipment. The analysis was conducted using the trace comparison method, which compares the test results before and after the regasketing and purification processes, to assess changes in the internal condition of the transformer as a result of these repair measures.

3.2. Study Method

Figure 3 shows the flowchart of this study that analyze power transformer conditions at the Tenayan Raya Power Plant using the SFRA method.

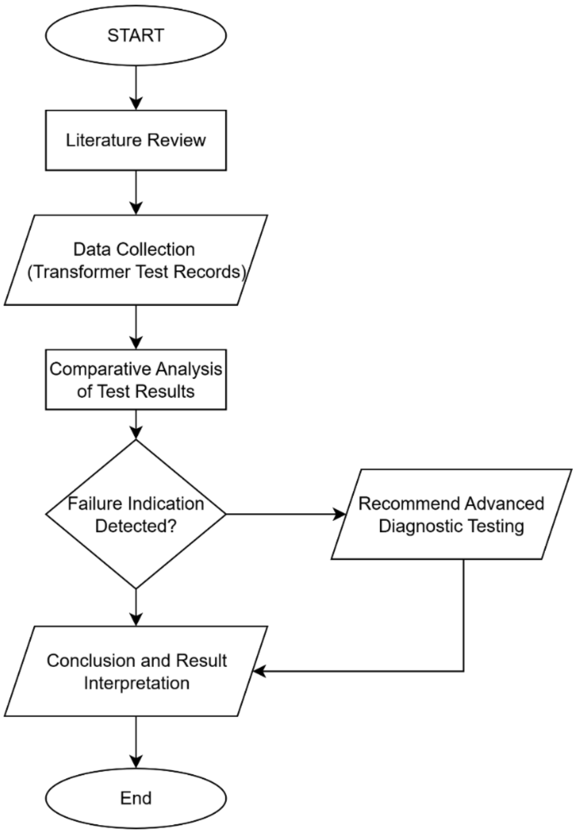


Figure 3. Study Flowchart

The research begins with a Literature Review, which involves collecting and reviewing relevant scientific references related to transformer condition diagnosis methods, particularly those using SFRA analysis. This step aims to understand the basic principles, important parameters, and common damage patterns found in power transformers. Following this, historical data from SFRA tests on the same transformer is collected. The data collected covered three measurement periods (conditions), which are:

- Condition A (February 8, 2020): initial SFRA measurement data,
- Condition B (February 7, 2022): SFRA measurement data before maintenance, and
- Condition C (February 23, 2022): SFRA measurement data after maintenance.

Each test was performed three times, once for each phase, and included five types of measurements:

- High voltage side measurement with low voltage side open (R, S, T)
- Low voltage side measurement with high voltage side open (rs, st, tr)
- High voltage side measurement with low voltage side shorted (R, S, T)
- High voltage side to low voltage side measurement (Rr, Ss, Tt)
- High voltage side to grounded low voltage side measurement (Rr, Ss, Tt)

The next step is to conduct a comparative analysis of the test results. This stage aims to compare the SFRA curves of the two test conditions on the same transformer in order to detect any changes in the internal mechanical characteristics of the transformer refer to IEEE Std C57.149-2012 [15]. The analysis was conducted through two comparisons, which are:

- Operational Comparison (Condition A vs Condition B), this assesses changes in the transformer's internal characteristics that occurred due to service operation between 2020 and 2022.
- Post-Maintenance Comparison (Condition B vs Condition C), this evaluates possible structural deformation or displacement induced by maintenance or regasketing activities.

The results of the analysis, in the form of a comparison of frequency response curves, become the basis for determining whether there are indications of failure.

3.3. Interpreting Winding Deformation Using SFRA

This study identify transformer winding deformation using graphical observation of SFRA test records. Winding deformation affect the transformer's electrical properties and it leads to changes in the frequency response on SFRA test result. Deformation is typically indicated by shifts in resonance frequencies, changes in magnitude, or the appearance or disappearance of peaks when compared with reference traces. Interpretation follows IEEE Std C57.149 guidance [15], which outline radial and axial deformation to specific frequency ranges. Low frequencies are mainly core-dominated and show limited sensitivity to winding deformation, mid-low frequencies provide supporting indications, and mid-high frequencies are the most sensitive and reliable for detecting winding movement. The detail interpretation of SFRA test result for winding deformation based on IEEE Std C57.149 guidance can be seen in Table 1 and 2.

Table 1. Radial winding deformation interpretation [15]

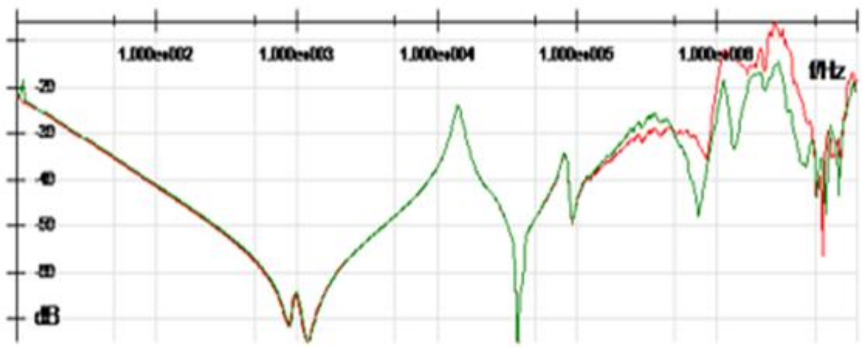
Frequency range	**Radial winding deformation** Assuming, no other failure modes exist:
20 Hz – 10 kHz	**Open Circuit Tests:** This region (core region) is generally unaffected during radial winding deformation. **Short Circuit Tests:** Results in an increase in impedance. The FRA trace for the affected phase generally exhibits slight attenuation within the inductive roll-off portion.
5 kHz – 100 kHz	**Open Circuit and Short Circuit Tests:** The bulk winding range can shift or produce new resonance peaks and valleys depending of the severity of the deformation. However, this change is minimal and difficult to identify. The changes will be greater for the affected winding, but it is still possible to have the effects transferred to the other winding(s). The response in the bulk region should be used as secondary evidence to support the analysis.
50 kHz – 1 MHz	**Open Circuit and Short Circuit Tests:** Radial winding deformation is most obvious in this range. It can shift or produce new resonance peaks and valleys depending on the severity of the deformation. The changes will be greater for the affected winding, but it is still possible to have the effects transferred to the other winding(s).
> 1 MHz	**Open Circuit and Short Circuit Tests:** This range is generally unaffected. However, severe deformation can extend into this range.

Table 2. Axial winding deformation interpretation [15]

Frequency range	**Axial winding deformation** Assuming, no other failure modes exist:
20 Hz – 10 kHz	**Open Circuit Tests:** This region (core region) is generally unaffected during axial winding deformation. **Short Circuit Tests:** Results in a change in impedance. The FRA trace for the affected winding causes a difference between phases or previous results in the inductive roll-off portion.
5 kHz – 100 kHz	**Open Circuit and Short Circuit Tests:** Axial winding deformation is most obvious in this range. The bulk winding range can shift or produce new resonance peaks and valleys depending of the severity of the deformation. The changes will be greater for the affected winding, but it is still possible to have the effects transferred to the other winding(s).
50 kHz – 1 MHz	**Open Circuit and Short Circuit Tests:** Axial winding deformation can shift or produce new resonance peaks and valleys depending of the severity of the deformation. The changes will be greater for the affected winding, but it is still possible to have the effects transferred to the other winding(s).
> 1 MHz	**Open Circuit and Short Circuit Tests:** The response to axial winding deformation is unpredictable.

4. Results and Discussion

The following figure (Figure 4-8) presents several examples of Sweep Frequency Response (SFRA) curve comparisons for the tested transformer. The comparison results show that curve deviations become noticeable in the high-frequency region, with varying degrees of difference across measurement configurations and phases. Higher deviation levels indicate potential winding deformation. The results also show that high-frequency deviations are more prominent in the historical comparison between 2020 and 2022 (pre-maintenance) than in the comparison between 2022 pre- and post-maintenance data. In some cases, differences at low frequencies are also observed, which may be attributed to core defect or residual magnetization effects.



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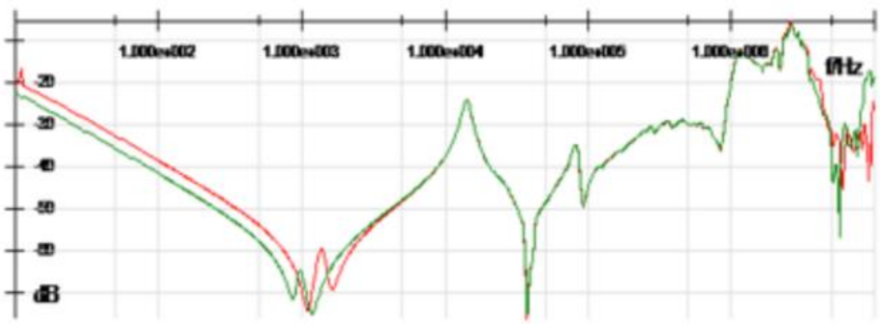
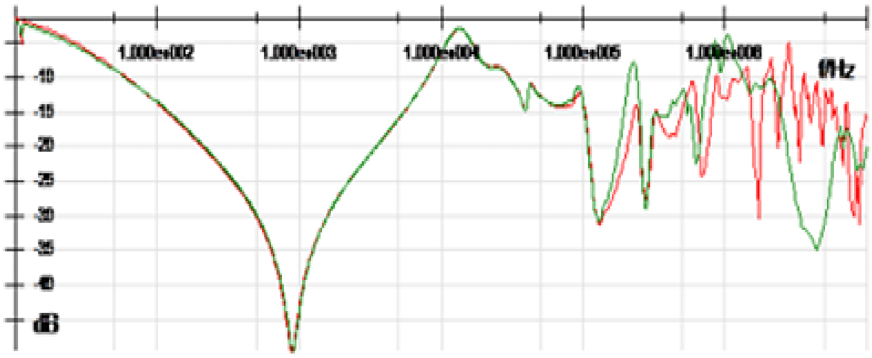


(b)

Figure 4. HV Open Circuit Test (R) (a) Operational Comparison (b) Post-Maintenance Comparison



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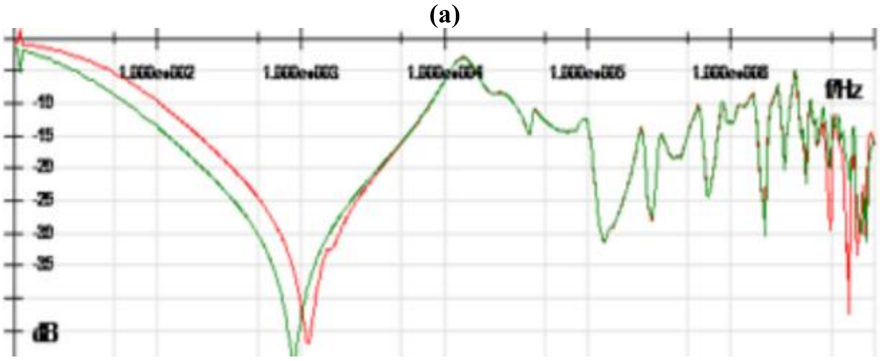
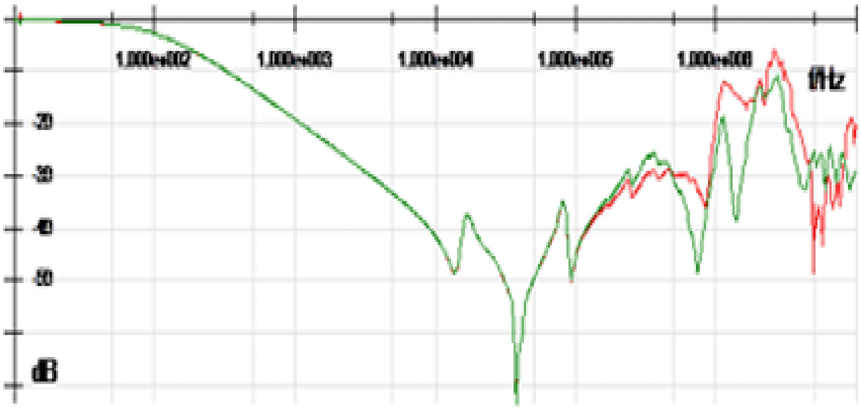


(b)

Figure 5. LV Open Circuit Test (rs) (a) Operational Comparison (b) Post-Maintenance Comparison



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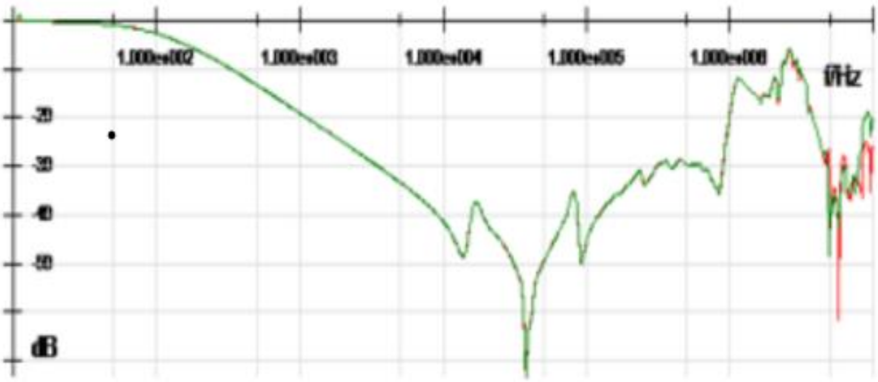
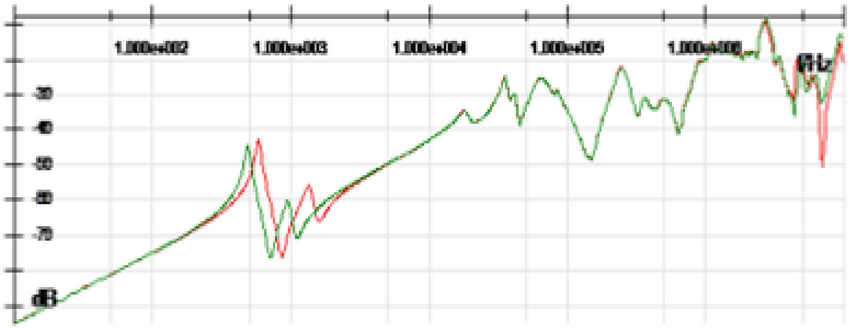


(b)

Figure 6. HV (LV Short) Test (R) (a) Operational Comparison (b) Post-Maintenance Comparison



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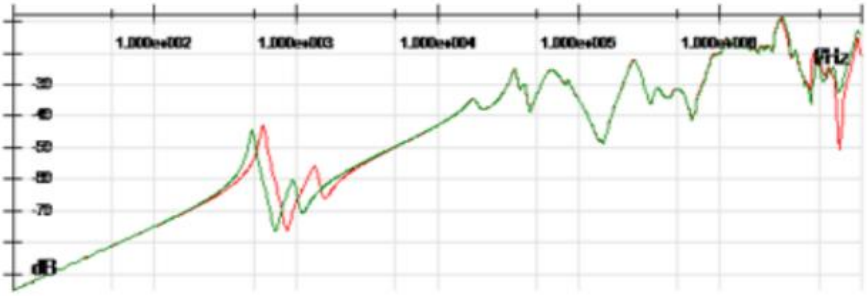
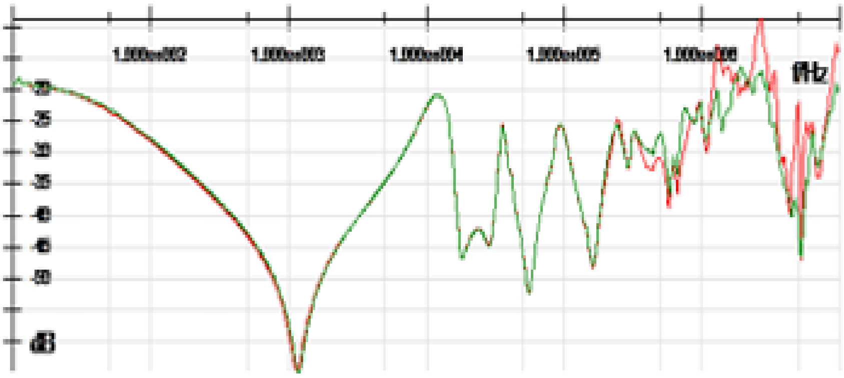
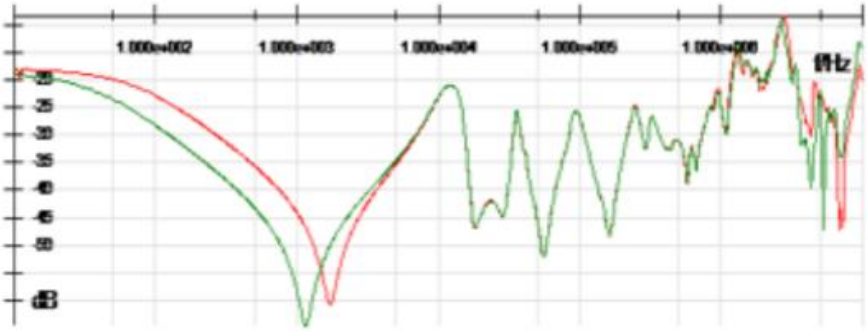


(b)

Figure 7. HV to LV Test (Rr) (a) Operational Comparison (b) Post-Maintenance Comparison



(a)



(b)

Figure 8. HV to LV Grounded (Rr) (a) Operational Comparison (b) Post-Maintenance Comparison

The comparison between the 2020 and 2022 pre-maintenance data (A VS B) reveals several distinct variations within the high-frequency range. These variations indicate changes in the winding system's characteristics, likely caused by positional displacement of winding layers resulting from thermal expansion and vibration during operation. Such phenomena are common in transformers that have been in service for extended periods, where repeated electromagnetic forces and temperature cycles can induce partial mechanical relaxation in the winding structure.

In contrast, the pre- and post-maintenance comparison (Condition B vs C) exhibits relatively stable response patterns, with only minor deviations at high frequencies. This suggests that the maintenance process (regasketing and oil purification) did not cause significant mechanical alterations in the winding configuration. Minor discrepancies observed are more likely attributed to terminal connection variations or slight dielectric property changes after maintenance.

Table 3. Detail Result of SFRA Comparative Assessment

No	Winding Side	Phase	Result	
			Operational Comparison	**Post-Maintenance Comparison**
1	HV Open Circuit	R	Slight Deformation	No Significant Change
		S	Slight Deformation	No Significant Change
		T	Obvious Deformation	No Significant Change
2	LV Open Circuit	rs	Slight Deformation	No Significant Change
		st	Obvious Deformation	Minor Change
		tr	Obvious Deformation	No Significant Change
3	HV (LV Short)	R	Slight Deformation	No Significant Change
		S	Slight Deformation	No Significant Change
		T	Obvious Deformation	No Significant Change
4	HV-LV	Rr	Normal Winding	No Significant Change
		Ss	Normal Winding	No Significant Change
		Tt	Normal Winding	No Significant Change
5	HV-LV (Grounded)	Rr	Normal Winding	Minor Change
		Ss	Normal Winding	No Significant Change
		Tt	Normal Winding	No Significant Change

The comparative summary of 15 SFRA measurements across the three testing periods is presented in Table 3. Comparison between pre- and post-operation conditions indicates signs of winding deformation in several test cases. In contrast, the comparison of pre- and post-maintenance measurements shows that 13 out of 15 tests exhibit "No Significant Change". These results indicate that the mechanical variations occurred during normal operational (comparison of condition A to B), while maintenance activities (comparison of condition B to C) introduced no significant widespread impact on the transformer's mechanical integrity apart from two localized anomaly. Hence, transformer windings can be considered mechanically stable post-maintenance, with no evidence of severe deformation.

5. Conclusion

This study evaluated the mechanical integrity of a power transformer at the Tenayan Raya Power Plant using Sweep Frequency Response Analysis (SFRA). Comparisons across three test periods showed that the most notable variations occurred between 2020 (A) and 2022 (B), mainly at high frequencies, indicating winding deformation due to operational stress. In contrast, the post-maintenance comparison (B-C) revealed stable responses, confirming that maintenance activities did not cause significant winding deformation.

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