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Using Sweep Frequency Response Analysis and Dissolved Gas Analysis in Diagnosing of Power Transformer

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Diagnosing of Power Transformer.

ABSTRACT

This article presents two diagnostic techniques for assessing the mechanical and electrical condition of oil-immersed power transformers: sweep frequency response analysis (SFRA) and dissolved gas analysis (DGA). The SFRA method detects potential mechanical faults in transformer windings by applying the correlation coefficient (Rxy). For a 63 MVA, 115/23/11 kV transformer, experimental results show that the winding is considered normal when RLF ≥ 2.0, RMF ≥ 1.0, and RHF ≥ 0.6, whereas RLF < 0.6 indicates severe deformation. In contrast, the DGA method identifies internal faults such as partial discharge, low-energy and high-energy discharges, and thermal faults by analyzing gas concentrations in the insulating oil. For a 20 MVA, 110/22 kV transformer, measured gas concentrations (µl/l, ppm) include H_2 (0.00), CH_4 (40.43), C_2H_6 (18.24), C_2H_4 (20.92), C_2H_2 (0.00), CO_2 (8932.66), and CO (2131.18), corresponding to a "thermal fault below 300°C." Both diagnostic methods are integrated into user-friendly MATLAB-based tools to support testing centers in Vietnam. The combination of SFRA and DGA enhances diagnostic accuracy, enables timely maintenance decisions, and contributes to improving the reliability of power supply systems.

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1. Introduction

In operating and maintaining power transformers (PTs), diagnosing mechanical and electrical faults is essential to prevent failures and power interruptions. Undetected winding deformation or core displacement can cause dielectric or thermal damage, leading to costly repairs or replacement. Therefore, mechanical integrity should be checked after transportation, periodically, and after short circuits. The Sweep Frequency Response Analysis (SFRA) technique is a powerful tool for detecting minor displacements in windings and magnetic circuits, with ongoing research [1]–[10]. In [11], failures were analyzed using Transformer Turns Ratio (TTR) and SFRA, showing a linear correlation and confirming TTR's ability to detect short-circuit faults. However, TTR cannot identify discharge faults or internal damage. In [12], SFRA was used for temporary condition checks by comparing healthy and faulty responses, with discussion on analysis methods and limitations. In [13], transformer parameters were estimated from SFRA data using an RLC model with mutual inductance, achieving good agreement between the simulated and measured responses; however, the approach was limited to single-phase transformers.

In [14], an improved SFRA-based fault localization method applied regression analysis on data from 70 oil-immersed PTs of various designs, capacities, and manufacturers. In [15], climate, oil thermal parameters, and photovoltaic (PV) systems were studied for their effect on thermal performance, focusing on hottest-spot temperature (HST) and top oil temperature (TOT) under ONAN cooling, without addressing ONAF types or mechanical/electrical discharge faults. The work in [16] used SFRA with statistical parameters to detect and locate short-circuit faults, deriving Min–Max (MM) ratios from healthy and faulty measurements, but considered no other fault types. In [17], partial discharge detection was achieved using multi-wall carbon nanotubes (MWNT) for online monitoring, though mechanical and short-circuit detection were not covered.

In [18], SFRA was applied to evaluate insulation degradation by analyzing winding capacitance changes from peak frequency shifts; negative changes indicated deterioration. The authors in [19] diagnosed voltage regulator faults using SFRA with multiple configurations and correlation coefficient (CC) analysis, showing sensitivity to tap changer coking (low-frequency magnitude drop at 20 Hz–2 kHz) and pitting (shift to higher frequencies). During PT operation, oil decomposition under heat and high electromagnetic fields produces gases such as H_2, CH_4, and C_2H_6. Measuring gas content in insulating oil aids early diagnosis. Dissolved Gas Analysis (DGA) with gas generation monitoring detects electrical faults, supporting safe, efficient operation, with ongoing research [20]–[27]. In [28], DGA diagnosed partial discharges, low/high-energy discharges, and low/medium/high thermal faults using dissolved gas concentrations, applying techniques like the new approach, conditional probability, and Duval methods. However, [28] addressed only electrical faults. Since PT faults can be mechanical or electrical, research should address both diagnostics and develop tools to support effective fault identification.

2. Sweep frequency response analysis (SFRA) technique

2.1. Principle of SFRA

The Sweep Frequency Response Analysis (SFRA) technique [7]–[10] measures the transformer's impedance-to-conductance ratio across a wide frequency range. This amplitude, expressed as a transfer function, serves as the PT's "fingerprint," and deviations from the baseline indicate abnormalities in the coil or magnetic circuit. The SFRA wiring diagram and phase frequency response characteristics (amplitude and phase angle) are shown in Figure 1 and Figure 2.

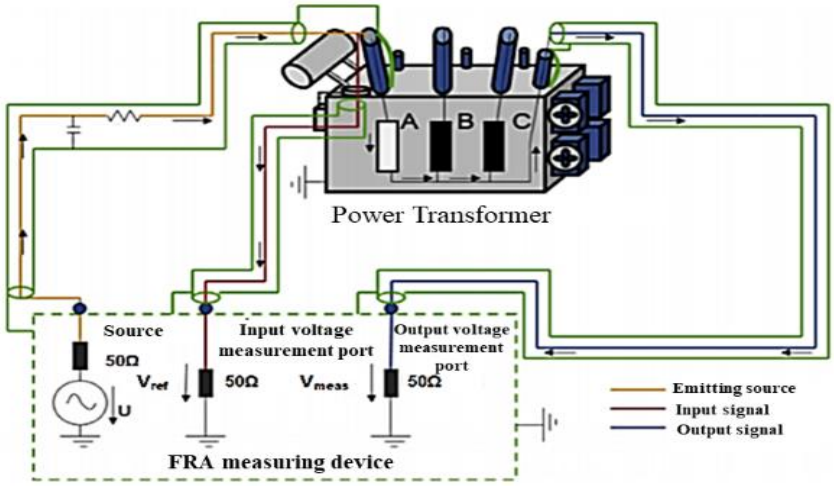


Figure 1. *SFRA measurement wiring diagram.*

For SFRA measurement, a low-voltage sinusoidal signal (1–10 Vrms) with variable frequency (typically 20 Hz–2 MHz, depending on coil structure and measurement system) is applied. The amplitude and phase angle of the frequency response are calculated using equations (1) and (2):

$$\text{Amplitude } (dB): 20\log_{10}(|V_{meas}|/|V_{ref}|) \quad (1)$$

$$\text{Phase angle } (^0): pha\{V_{meas}\} - pha\{V_{ref}\} \quad (2)$$

SFRA is mainly applied to detect mechanical faults, including winding deformation, displacement, and core movement. This makes SFRA particularly suitable for identifying structural problems that affect the mechanical integrity of transformers.

2.2. Scope and conditions of application of SFRA

SFRA is commonly applied to transformers above 6 kV and should be used in the following cases, based on international experience:

These include all new PTs to obtain initial data (the fingerprint), as part of routine electrical tests, and after reinstalling the PT. SFRA is also recommended in cases of long-term short circuits downstream

of the transformer, after repairing the tap changer, and following vacuum treatment, oil filtration, or oil regeneration. Furthermore, the method should be applied after any faults occur in the PT. The application of SFRA measurements for PTs is regulated under the IEC60076-18 standard [29].

2.3. The SFRA's ability to detect faults

SFRA can detect winding deformation, displacement, short and open circuits, loose core components, coil collapse, core grounding damage, and tap changer faults. It can also identify faults at the core joints, localized coil collapse, damage to the core grounding, and movement of the core. Additionally, SFRA is effective in detecting issues related to the connection between the windings and the porcelain input, as well as the on-load tap changer. It is noteworthy that the influence of mechanical deformations on SFRA characteristics may vary depending on the structure and design of the PT.

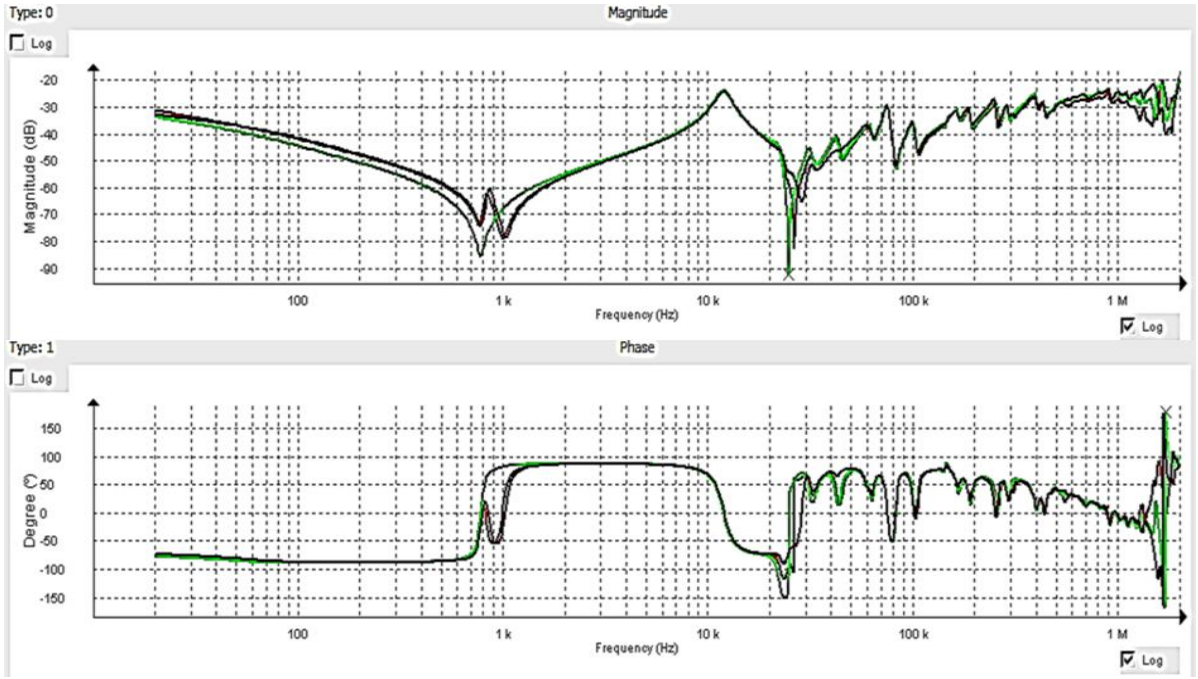
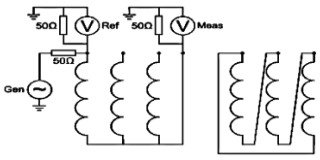


Figure 2. *Phase frequency response characteristic (amplitude, phase angle), 63 MVA, 110/22 kV, YNyn0d11.*

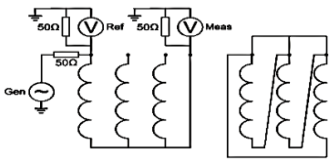
2.4. Diagnosis of PT quality using SFRA

2.4.1. Qualitative analysis method

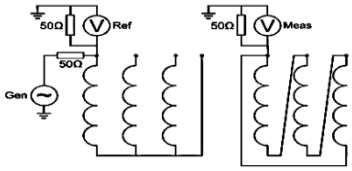
Analyze the differences in the SFRA characteristics [29], [30]. There are 4 basic SFRA measurement schemes presented in Figure 3:



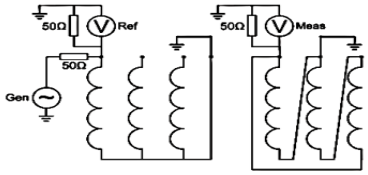
(a) End-to-end open-circuit (EEOC)



(b) End-to-end short-circuit (EESC)



(c) Capacitive inter-winding (CAP)



(d) Inductive inter-winding (IND)

Figure 3. *Four basic SFRA measurement schemes.*

(a) Figure 4 show the LV winding buckling and its frequency response.

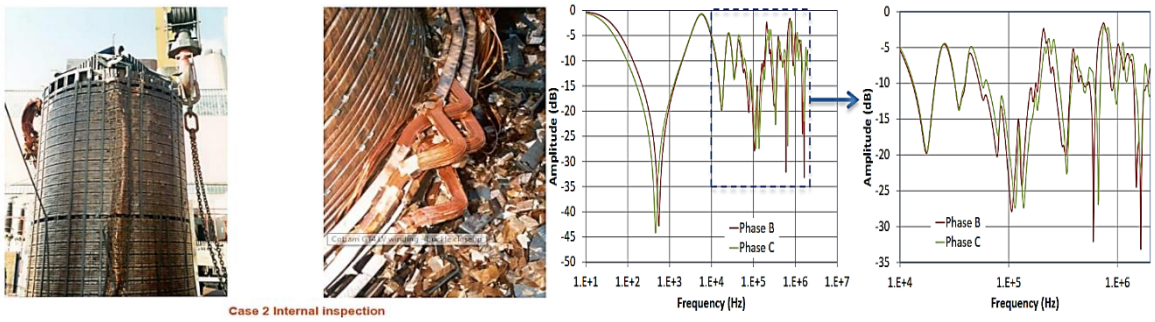


Figure 4. *LV winding Buckling and SFRA frequency characteristics.*

(b) Figure 5 and Figure 6 illustrate twisting and loosening of the clamping fault and its frequency response.

Figure 5. *Twisting and loosening of the clamping fault.*

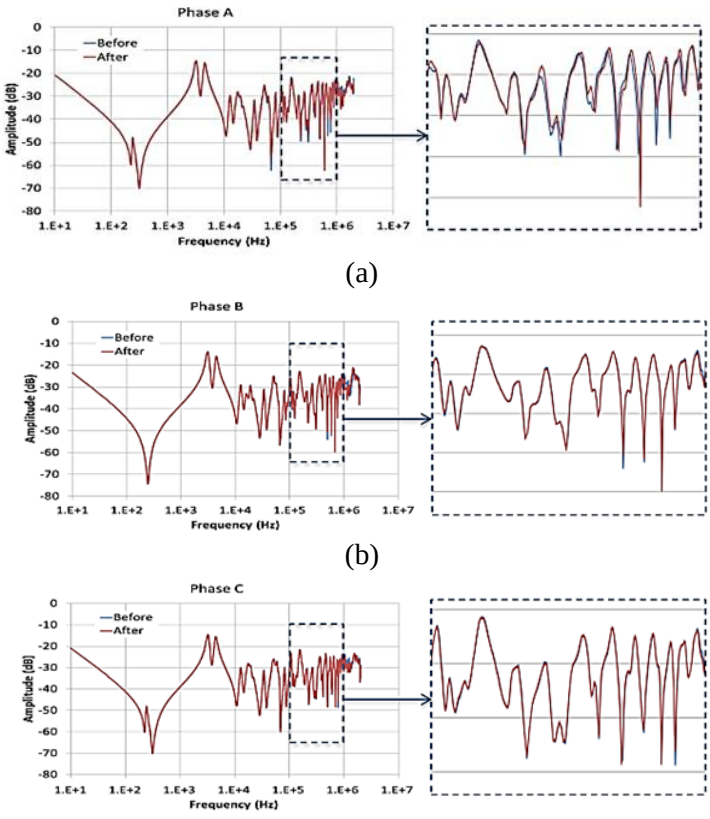


Figure 6. *SFRA frequency characteristics curves in the case of twisted and loose PT winding*.

(c) Figure 7 and Figure 8 present axial deformation of the LV winding and its frequency response.

Figure 7. *Winding axial deformation problem.*

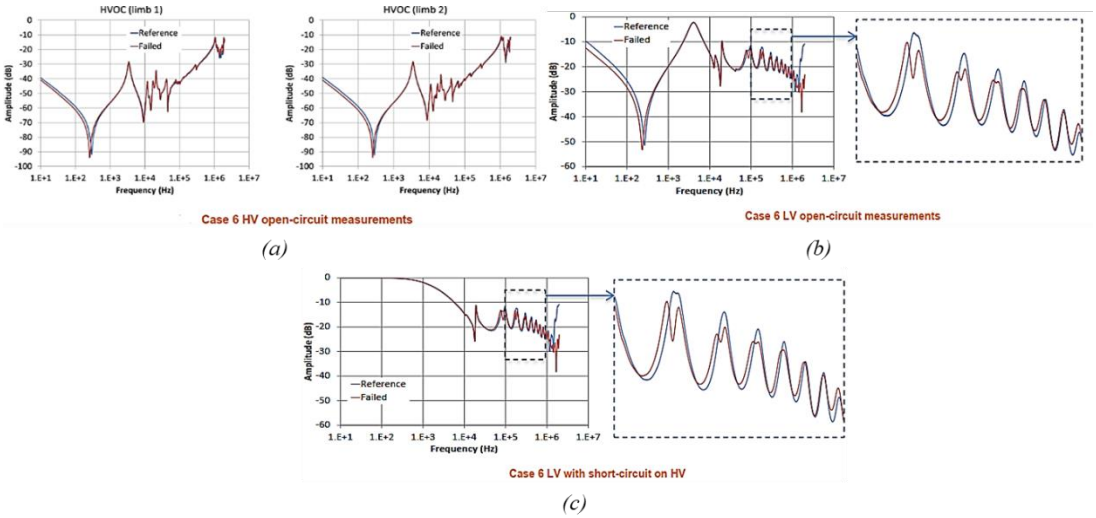


Figure 8. *SFRA frequency characteristics in the case of winding axial deformation.*

(d) Figure 9 and Figure 10 show a short circuit inside the winding and the corresponding frequency response.

Figure 9. *Short circuit inside the winding.*

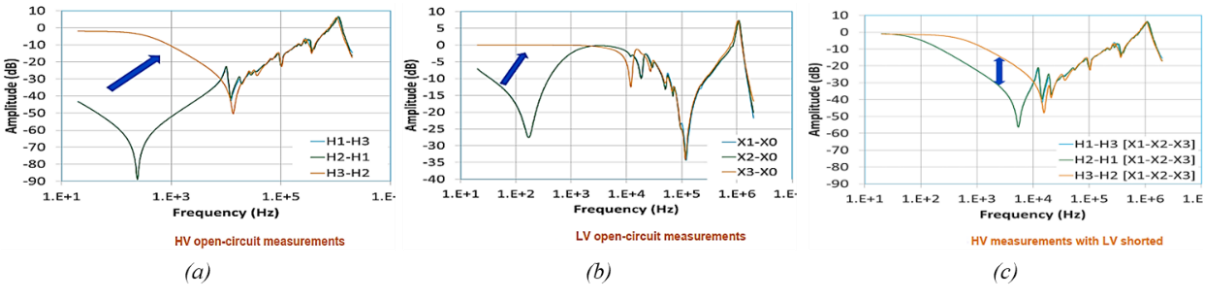


Figure 10. *SFRA frequency characteristics in the case of a short circuit inside the winding [3].*

2.4.2. Quantitative analysis method: using the correlation factor through SFRA measurement

(a) The Chinese standard DL/T 911 – 2004 [31] is the only international standard that addresses how to quantitatively compare two frequency responses by calculating the correlation factor - R between two signals in three frequency ranges: Low frequency: from 1 kHz to 100 kHz, Medium frequency: from 100 kHz to 600 kHz, High frequency: from 600 kHz to 1 MHz.

Suppose that there are two results obtained, with N amplitude values corresponding to *N* frequencies, denoted as *X(k), Y(k)*, where *k= 0, 1... N-1*. The correlation factor *R* can then be calculated through the following equations from (3) to (7):

Calculate the standard variance of these two sequences according to equations (3) and (4):

$$D_x = \frac{1}{N}\sum_{K=0}^{N-1}\left[X(k) - \frac{1}{N}\sum_{K=0}^{N-1}X(k)\right]^2 \quad (3)$$

$$D_y = \frac{1}{N}\sum_{K=0}^{N-1}\left[Y(k) - \frac{1}{N}\sum_{K=0}^{N-1}Y(k)\right]^2 \quad (4)$$

Calculate the covariance of these two sequences according to equation (5):

$$C_{xy} = \frac{1}{N}\sum_{K=0}^{N-1}\left[X(k) - \frac{1}{N}\sum_{K=0}^{N-1}X(k)\right] \times \left[Y(k) - \frac{1}{N}\sum_{K=0}^{N-1}Y(k)\right] \quad (5)$$

Calculate the normalization covariance factor of these two sequences according to equation (6):

$$LR_{xy} = C_{xy}/\sqrt{D_x D_y} \quad (6)$$

Because the LR_{xy} value is always in the range [-1,1] and usually has a very small value, it can be converted to the quantity R_{xy} for easy comparison.

Calculate the correlation factor according to equation (7):

$$R_{xy} = \begin{cases} 10 & 1 - LR_{xy} < 10^{-10} \\ -\lg(1 - LR_{xy}) & others \end{cases} \quad (7)$$

From there, the correlation factor R_{xy} quantifies the difference between two signals. According to the DT/T911–2004 standard, the calculated values are assessed using the criteria in Table 1.

(b) Diagnosis of potential faults according to the SFRA method for a typical PT.

The quantitative diagnosis of potential transformer faults using the SFRA method is presented in Table 1.

Table 1. *Quantitative assessment of transformer winding mechanical fault diagnosis.*

Winding Deformation degree	Winding Deformation degree
Severe Deformation	$R_{LF} < 0.6$
Obvious Deformation	$1.0 > R_{LF} \geq 0.6$ or $R_{MF} < 0.6$
Slight Deformation	$2.0 > R_{LF} \geq 1.0$ or $0.6 \leq R_{MF} < 1.0$
Normal Winding	$R_{LF} \geq 2.0$, $R_{MF} \geq 1.0$ and $R_{HF} \geq 0.6$

Note: R_{LF} represents the correlation factor when the curve is in low frequency band (1 kHz~100 kHz); R_{MF} represents the correlation factor when the curve is in medium frequency band (100 kHz~600 kHz); R_{HF} represents the correlation factor when the curve is in high frequency band (600 kHz~1000 kHz).

Analyzing the SFRA characteristics of the Phan Thiet 63 MVA, 110/22 kV, YNyn0d11 Transformer is shown in Figure 11 and the correlation factors are presented in Table 2.

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Table 2. *Correlation coefficient determined from the SFRA characteristics of the Phan Thiet 63 MVA, 110/22 kV transformer.*

Phase	R_{LF}	R_{MF}	R_{HF}
[A-N (open)]-[B-N (open)]	1.25	1.92	1.09
[B-N (open)]-[C-N (open)]	1.38	1.55	1.08
[C-N (open)]-[A-N (open)]	1.02	1.87	1.36

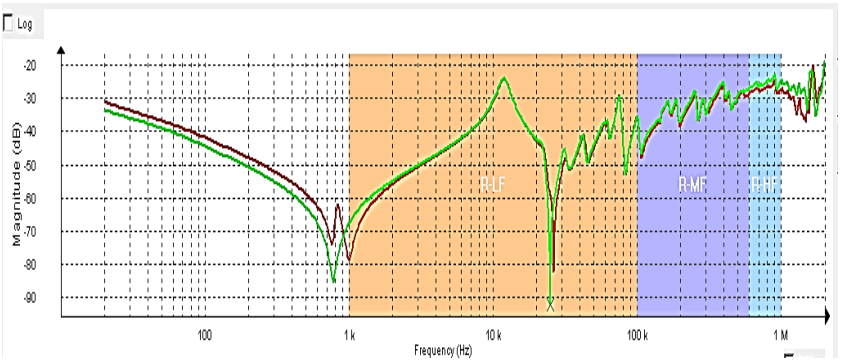
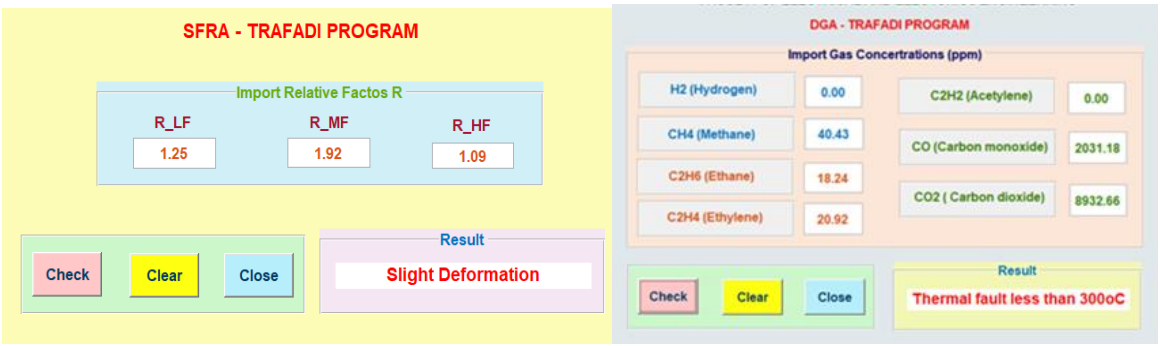


Figure 11. *SFRA frequency characteristics in the case of short circuits inside the winding.*

To support users in making quick decisions regarding the diagnosis of transformer faults, the MATLAB-based SFRA-TRAFADI program was developed using correlation factors RLF, RMF, and RHF. Its interface is shown in Figure 12a.



(a) (b)

Figure 12. *SFRA – TRAFADI and DGA – TRAFADI program interface.*

This interface is not only a guide in Matlab but also demonstrates the practical implementation of the SFRA–TRAFADI program. By providing a user-friendly environment, the tool allows engineers at testing centers to apply SFRA diagnostics directly, supporting quick and accurate decision-making without requiring complex programming knowledge.

The correlation data determined from the SFRA characteristics and the results of diagnosing potential faults of the Phan Thiet 63 MVA, 110/22 kV transformer using the SFRA-TRAFADI software, compared with the diagnostic results from the Southern Vietnam Power Testing Company (EVNSPC), are presented in Table 3 and Table 4, respectively.

Table 3. *Conclusion of Diagnosis of Transformer Phan Thiet 63 MVA, 110/22 kV Condition.*

Phases	Results
[A-N (open)]-[B-N (open)]	Slight deformation
[B-N (open)]-[C-N (open)]	
[C-N (open)]-[A-N (open)]	

Similarly, the correlation coefficients determined from the SFRA characteristics of the Ngai Giao 40 MVA, 110/22 kV transformer and the results of diagnosing potential faults using the SFRA-TRAFADI software, compared with the diagnostic results from the Southern Vietnam Power Testing Company (EVNSPC), are presented in Table 4 and Table 5.

Table 4. *Correlation Coefficients Determined from the SFRA Characteristics of the Ngai Giao 40 MVA*, 110/22 kV Transformer.

Phases	R_{LF}	R_{MF}	R_{HF}
[A-N (open)]-[BN (open)]	2.01	2.58	2.52
[B-N (open)]-[C-N (open)]	2.3	2.25	1.86
[C-N (open)]-[A-N (open)]	2.03	2.6	1.85

Table 5. *Conclusion of Diagnosis of Ngai Giao 40 MVA, 110/22 kV Transformer Condition.*

Phases	SFRA-TRAFADI	EVNSPC
[A-N (open)]-[B-N (open)]	Normal	Normal
[B-N (open)]-[C-N (open)]	-	-
[C-N (open)]-[A-N (open)]	-	-

3. Dissolved gas analysis techniques (DGA) in transformer oil

3.1. Principle of DGA

Dissolved Gas Analysis (DGA) [21], [22], [24], [27] diagnoses thermal and electrical faults in transformers by measuring the concentration of dissolved gases in insulating oil or extracted gas samples. This technique has been standardized according to the international standards IEEE C57.104 [32] and IEC 60599 [33]. In contrast, DGA is primarily used to diagnose electrical and thermal faults, such as partial discharges, low-energy and high-energy discharges, and overheating at different temperature levels. This enables early detection of insulation and thermal degradation inside the transformer.

3.2. DGA assessment methods

- Main gas method: C_2H_4; CO; H_2; C_2H_2.
- Roger ratio method [30], [31] uses the ratios: CH_4/H_2; C_2H_4/C_2H_6 and C_2H_2/C_2H_4.

The gas generation diagram according to PT temperature is presented in Figure 13.

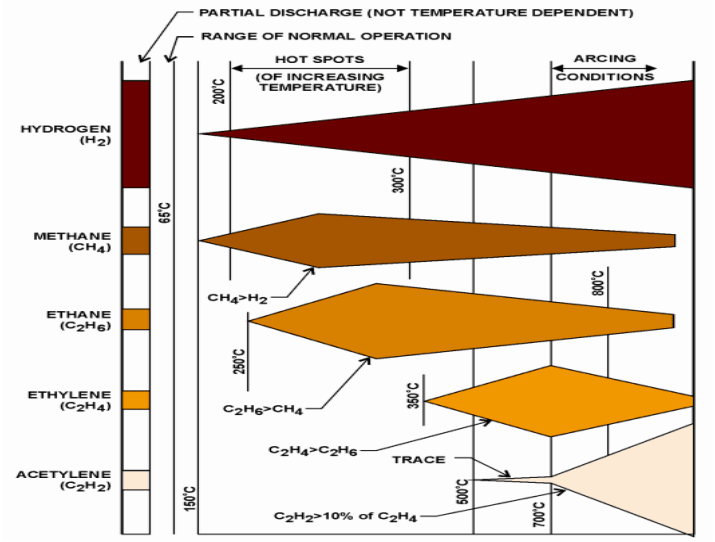


Figure 13. *Diagram of gas generation according to temperature in PT oil.*

3.3. Fault classification

Table 6 presents the fault of classification according to the IEE C57.104 standard [32]. Table 7 provides the fault classification based on temperature in oil of PT in accordance with the IEC 60559 standard.

Table 6. *Fault classification according to temperature in oil of PT according to IEEE C57.104 standard.*

Thermal fault*:* 150°C<t≤500°C	Between 150°C and 500°C, oil decomposition produces mainly hydrogen and methane, with smaller amounts of ethylene and ethane.
Discharges of low energy	Low-energy discharges generate hydrogen, methane, and traces of acetylene.
Discharges of high energy t ≥ 700°C	High-energy discharges (700–1800°C) significantly increase acetylene content.

Table 7. *Fault classification according to temperature in oil of PT according to the IEC 60559 standard.*

Case	Characteristic fault
PD	Partial discharges
D1	Discharges of low energy
D2	Discharges of high energy
T1	Thermal fault, t < 300°C
T2	Thermal fault, 300°C < t < 700°C
T3	Thermal fault, t > 700°C

3.4. The measurement of DGA in insulating oils

Dissolved Gas Analysis (DGA) measurements were performed using an Agilent 7890A Gas Chromatograph (Agilent Technologies) in accordance with the ASTM D3612C standard method, with a detection limit of 1 ppm. The detectable gases included O_2, N_2, H_2, CO, CO_2, CH_4, C_2H_6, C_2H_4, C_2H_2, C_3H_6, and C_4H_8. The Agilent 7890A chromatograph system was employed to quantify the concentration of dissolved gases in transformer oil samples. DGA method is widely used in transformer fault diagnosis.

Table 8 shows the concentrations of individual gases and total dissolved gas.

Table 8. *Single gas concentration in oil (µl/l, ppm), TCG: total combustion gas concentration (ppm) of Transformer T1.*

CO_2	**C_2H_4**	**C_2H_2**	**C_2H_6**	**H_2**
8932.66	20.92	0.00	18.24	0.00
O_2	**N_2**	**CH_4**	**CO**	**TCG**
7805.28	53315.2	40.43	2131.18	2118

- According to the concentration of flammable gas in the oil

Table 9 presents the threshold for flammable gas concentration (single) in oil (µl/l, ppm) according to IEC 60599 [33].

Table 9. *Threshold for flammable gas concentration (single) in oil (µl/l, ppm) according to IEC 60599.*

C_2H_2	**H_2**	**CH_4**
1	100	120
C_2H_6	**CO**	**C_2H_4**
65	350	50

- According to the Roger combustion gas ratio [32], [33], Table 10 presents threshold of flammable gas in oil according to IEEE C57.104.

Table 10. *Threshold of flammable gas in oil according to IEEE C57.104.*

Faults	R1 CH_4/H_2	R2 C_2H_2/C_2H_4	R5 C_2H_4/C_2H_6
No fault	> 0.1 to < 1.0	< 1.0	< 1.0
PD (corona partial discharges)	< 1.0	< 1.0	< 1.0
Arc of high energy	0.1 – 1.0	0.1 – 0.3	> 3.0
Low temperature	> 0.1 to < 1.0	< 1.0	1 - 3
Temperatures below 700°C	> 1.0	< 1.0	1 - 3
Temperatures above 700°C	> 1.0	< 1.0	> 3.0

Table 11 presents threshold of flammable gas in oil according to IEC 60599.

Table 11. *Threshold of flammable gas in oil according to IEC 60599.*

Case	Characteristic fault	C_2H_2/C_2H_4	CH_4/H_2	C_2H_4/C_2H_6
PD	Partial discharges	-	< 0.1	< 0.2
D1	Discharges of low energy	>1	0.1 – 0.5	> 1
D2	Discharges of high energy	0.6 – 2.5	0.1 -1	> 2
T1	Thermal fault t <300°C	-	-	< 1
T2	Thermal fault 300°C < t <700°C	< 0.1	> 1	1 - 4
T3	Thermal fault t >700°C	< 0.2	> 1	> 4

To assist users in diagnosing transformer faults, the MATLAB-based DGA-TRAFADI program was developed using the Rogers ratio method. Its interface is shown in Figure 12b. The input parameters of the DGA - TRAFADI program are the concentrations of the measured gases, including: H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO_2, and CO. The output data are the result of diagnosing potential faults in the PT.

The interface of the DGA–TRAFADI program illustrates its readiness for practical use. It simplifies the diagnostic process for testing engineers, enabling them to apply the DGA method quickly and effectively in real operating conditions. This highlights the applied contribution of the study beyond theoretical analysis. The results of diagnosing potential faults in the T1 20 MVA, 110/22 kV transformer using the DGA-TRAFADI software, compared with the diagnostic results from the Southern Vietnam Power Testing Company (EVNSPC), are presented in Table 12.

Table 12. *Conclusion of Diagnosis of T1 20 MVA, 110/22 kV Transformer Condition Using the DGA Method*.

Gas Concentration	DGA-TRAFADI	EVNSPC
H2: 0.00	Thermal fault below 300°C	Thermal fault below 300°C
CH4: 40.43	-	-
C2H6: 18.24	-	-
C2H4: 20.92	-	-
C2H2: 0.00	-	-
CO: 2031.18	-	-
CO2: 8932.66	-	-

Similarly, the results of determining gas concentrations and diagnosing potential faults in the T2 63 MVA, 220 kV transformer using the DGA-TRAFADI software, compared with the diagnostic results from the Southern Vietnam Power Testing Company (EVNSPC), are presented in Table 13.

Table 13. *Conclusion of Diagnosis of T2 63 MVA, 220 kV Transformer Condition Using the DGA Method.*

Gas Concentration	DGA-TRAFADI	EVNSPC
H_2: 5.124	Slight increase in combustible gases	Slight increase in combustible gases
CH_4: 6.587	-	-
C_2H_6: 0.00	-	-
C_2H_4: 3.041	-	-
C_2H_2: 3.531	-	-
CO: 7.635	-	-
CO_2: 2.286	-	-

After diagnosing transformer faults using SFRA and DGA, any detected issues are repaired according to industry standard 623ĐVN/KTNĐ of the Vietnam Electricity Corporation, followed by re-examination to ensure safe operation. These diagnostic methods have been successfully applied at the Southern Vietnam Power Testing Company (EVNSPC).

This paper presents both methods to propose a comprehensive solution covering all transformer fault types: DGA for thermal and electrical faults through dissolved gas analysis, and SFRA for mechanical faults. Although methodological novelty is limited, the study shows how established diagnostic techniques (R_{xy} for SFRA and Roger ratio for DGA) can be successfully applied in practice, while more advanced approaches have recently been reported in the literature [34], [35].

4. Conclusions

This study demonstrates the combined application of Sweep Frequency Response Analysis (SFRA) and Dissolved Gas Analysis (DGA) for diagnosing power transformer faults. The SFRA–TRAFADI tool effectively identifies mechanical issues in transformer windings, while the DGA–TRAFADI tool diagnoses electrical and thermal faults through gas concentration analysis. Both tools have been implemented and validated with data from the Southern Vietnam Power Testing Company (EVNSPC), thereby demonstrating the practical significance of the research for power utilities in Vietnam.

The main contribution of this work lies in its practical implementation in Vietnam, where reliable transformer operation is critical to power system stability. By integrating these methods into user-friendly MATLAB-based programs, the approach enhances accuracy, supports timely maintenance decisions, and contributes to ensuring a secure and continuous electricity supply.

Future research will explore integrating SFRA and DGA outcomes with advanced approaches such as regression analysis, sliding-window techniques, and AI/ANN-based models to further improve diagnostic reliability and address data limitations.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon request.

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