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Frequency Response Analysis: An Overview of the Measurement Process and Interpretation of Results for Fault Diagnosis and Location in Power Transformers

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ABSTRACT

One of the main components of a power transformer is the transformer insulation system, namely, transformer insulation oil and transformer insulation paper. Any failure can cause the transformer to fail temporarily or permanently. As a result, regular and non-destructive monitoring of transformers is of particular importance for early detection and prediction of any faults. Frequency response analysis (FRA) is known as a high-accuracy, fast, economical, and non-destructive method for diagnosing the condition of a transformer, which can be used independently or as a complementary method to ensure the results of other diagnostic tests and based on the operational conditions of the transformer, it can be implemented in two methods, online and offline. This paper provides an in-depth discussion of measuring and interpreting FRA results and the ability of this method to detect and locate power transformer faults, especially insulation faults, which have been given less attention in the past .The information confirmed in this survey is expected to provide an important roadmap for future research in monitoring the condition of transformer insulation systems.

I. Introduction

A. Research Motivation

The transformer is a vital and key equipment in the power grid. Its proper operation affects the safe operation of the whole electrical network. This equipment is often exposed to different weather conditions, as well as different electrical and mechanical conditions, and it faces different electrical, electromagnetic, dielectric, mechanical, thermal, or chemical stresses during operation [1-3]. The most common failures that happen to transformers are as short circuits (SC), Axial displacement (AD), radial deformation (RD), coil displacement, disc-space variation (DSV), open circuit (OC), core defect, lightning, etc. Regular and non-destructive monitoring of transformers to detect any changes or faults in the early stages is particularly important for detecting such failures [4-10]. For this purpose, various modern and practical methods including partial discharge (PD), polarization index (PI), polarization and depolarization current (PDC), dissolved gas analysis (DGA), insulation resistance (IR), recovery voltage measurement (RVM), leakage reactance, along with FRA for evaluating the condition of transformers have been presented [11-12]. In the FRA, the amplitude of the applied signal is small. This method is suitable for detecting or locating mechanical faults such as displacement or deformation of windings. On the other hand, it is not able to detect insulation faults between discs or oil and paper faults. Usually, along with this test, other analysis methods such as partial discharge and switching are used. These tests as a supplement to FRA can complete the evaluation results

B. Literature Review

A transfer function (TF) is a tool to explain the behavior of a system. This method is widely used to identify the mechanical integrity of transformers [13-16]. The TF method can be used in the time domain (TD) or the frequency domain (FD). In the FD, it is called FRA. The FRA was first introduced by Dick and Erven in 1978 [17]. All over the world, among other diagnostic methods, FRA is known as a high-precision, fast, economical, and non-destructive method in transformer condition detection [18-28]. FRA can be used as an independent method or as a complementary method to ensure the results of other diagnostic tests [29-33]. The FRA is based on measuring the frequency response (FR) of the transformer in exchange for a wide frequency bandwidth [29]. Because of the winding resistance (R), the inductance of the winding coils (L), and the capacitance (C) of the insulation layers between the coils, windings, winding and core, core and tank, tank and winding, etc., a transformer is modeled a complex network of RLC components. Any change in the condition of the transformer will cause a change in the parameters of this RLC network. The failures, such as SC or OC in the winding, affect the resistance and inductance. AD and RD,

lead to changes in the capacitance or inductance of the RLC network. Therefore, comparing the actual FR with the reference FR when the transformer has no problem can show the changes in the characteristics of transformers and lead to fault diagnosis. The reference FR is called the "signature" or "fingerprint". Therefore, the FRA method is used to identify these small changes in the parameters of the RLC network by examining the FR of the transformer. Based on the operating conditions of the transformer, FRA can be divided into two methods: 1. Offline FRA 2. Online FRA [34-36].

In a steady state, transformers are modeled with a simple model of primary, secondary, and magnetization impedances. But in a transient state, we need a model that provides an accurate response in different conditions. Among the different methods of transformer modeling, the black box model (BBM), a physical model including a multiphase transmission line, detailed and hybrid have been more attention of researchers. The BBM is obtained using the measured results at the transformer terminals. For such modeling, the zero and pole dependence of the system and the structure of the transformer must be known. Physical models are obtained based on the structure and size of the transformer, The physical model is already constrained and valid for a certain frequency range. To increase their frequency range, the details of the model should be increased [28]. Since the frequency analysis method is based on changes in the physical structure and insulation of the transformer, the detailed model is the most suitable model for FRA. In the detailed model, an RLC circuit model is considered for each section of the transformer, so that all the physical and electrical characteristics of that section are included in the model [37-38]. It should be noted that each section can include a turn or a disc of windings. Fig.1 shows the physical structure of the transformer disc winding and how to model each section. As shown in Fig. 1, R and L are respectively the resistance and inductance of each section of the winding, and Rs and Cs model the insulation effect of each section, where Rs is a large value. Rg and Cg are the insulation resistance of each section to ground and the stray capacitance between each section to ground, respectively [39]. In addition, the transformer bushing is modeled using the model shown in Fig. 2.

The equivalent circuit shown in Fig. 3 can be used to model the high-frequency transformer. The elements shown in the equivalent circuit are as follows:

L: inductance of each winding section
M_{ik}: mutual inductance between two windings i and k
RS: ohmic resistance of each winding section
RP: insulation resistance of each section to ground or adjacent windings
Ce: Capacitance of each section to ground (core or tank)
Ki: Equivalent capacitance of each section
CW: Capacitance between two windings

C. Necessity of the research and Novelty

This paper is an in-depth discussion of measuring and interpreting FRA results and the ability of this method to detect and locate power transformer faults, especially insulation faults, which have been given less attention in the past. The information confirmed in this survey is expected to provide an important roadmap for future research in monitoring the condition of transformer insulation systems

D. organization of the paper

This paper aims to peruse the FRA method as an accurate and complementary method for diagnosing and locating transformer insulation faults. For this purpose, the rest of the paper is as follows: Section 2 introduces offline FRA, section 3, the types of FRA configuration, and Section 4, deals with the evaluation of FRA results. Also, in section 5, the FRA frequency range, in section 6, the online FRA, and section 7 deals with FRA results interpretation methods, section 8 deals with fault location based on FRA and finally, in section 9, the conclusions are drawn.

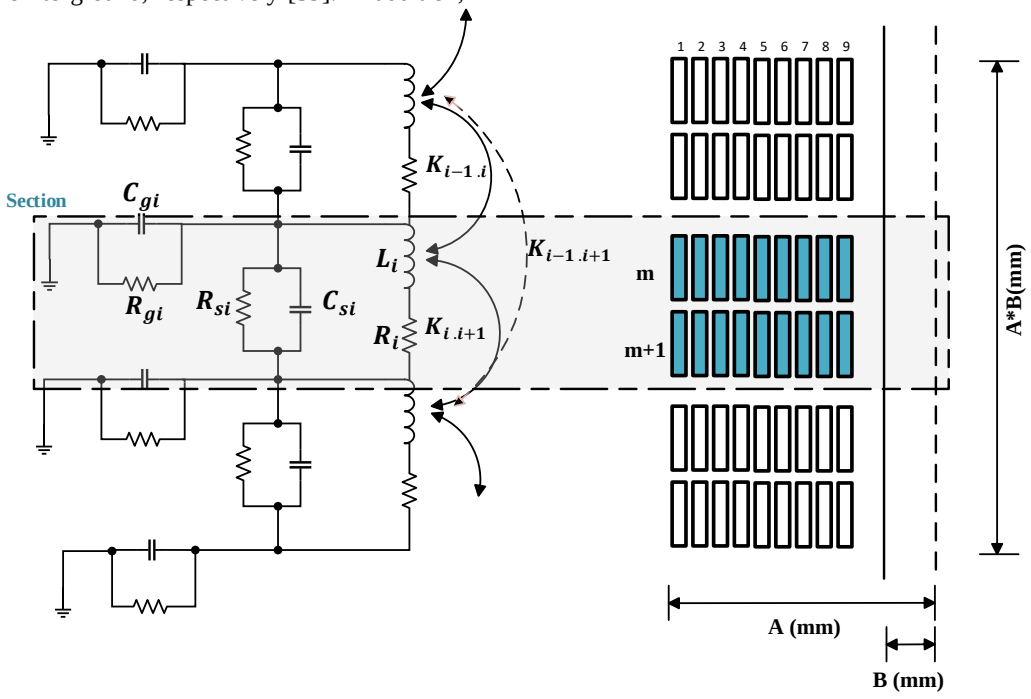


Fig. 1. Detailed model of transformer disc winding [37]

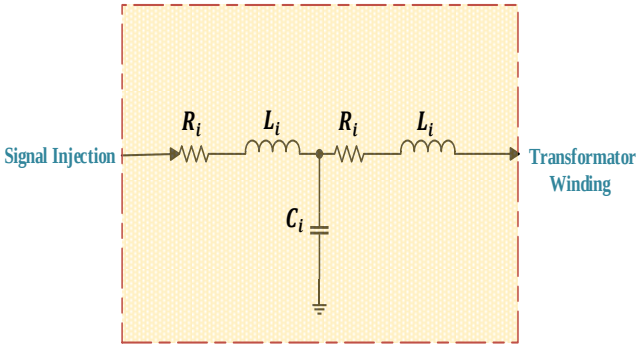


Fig. 2. Bushing model [38]

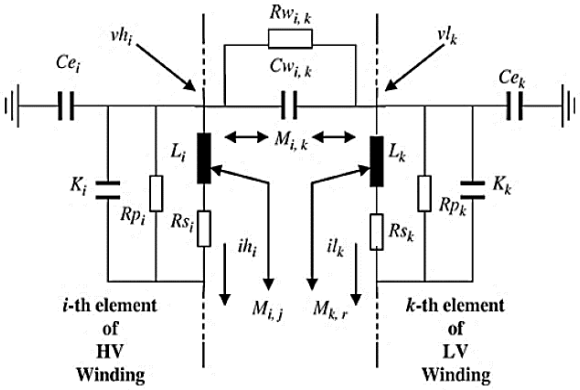


Fig. 3. Detailed equivalent circuit of a winding layer and the connection between them [39]

I. Offline FRA

In the offline FRA method, the transformer must be isolated from the power system source and the tank must be grounded. In this method, an input signal is injected into one of the transformer terminals. It can be sweep frequency, impulse, or step voltage signals to ground. The reference signal is measured through the reference impedance (R_{ref}). According to the type of measurement, the response signal is received through the measurement impedance (R_{me}) which is connected to another terminal. This signal is usually a voltage signal, but can also be a current signal, measured at the output terminal or any other grounded terminal. Fig. 4 shows the schematic of connections in an offline FRA. Two available methods to obtain offline FRA data are frequency domain (FD) and time domain (TD) measurements [36].

A. Measurement in the FD

Measurement in the FD is obtained by applying a sinusoidal voltage signal to the winding. The frequency of this signal varies from Hz to MHz. The response signal is measured and the ratio between the injected signal and the response signal is calculated and displayed. The equipment required to perform offline FRA measurement is shown in Fig. 5. The transformer should be directly connected to the impedance analyzer by some meters of wire [40-43].

B. Measurement in the TD

This method consists of injecting a voltage signal in a short time on the winding structure. The response signal is recorded by digital oscilloscopes or transient recorders. The fast Fourier transform (FFT) analysis is applied to the recorded data. The FFT of signals is divided by the FFT of voltage to obtain the FRA plot [43].

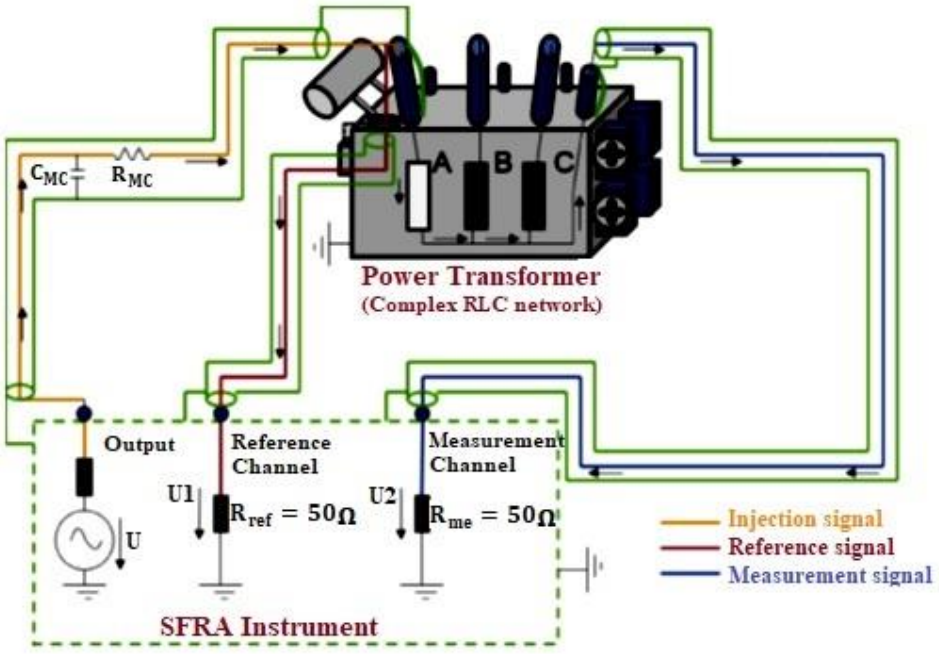


Fig. 4. Connections of offline FRA [36]



Fig. 5. Measuring equipment in the FD [40]

The injection voltage signal can be as follows:

- Impulse voltages: This mode includes low voltage impulse waveforms in microsecond duration.
- Switching overvoltage: these waveforms are similar to the voltages that are produced when the line is turned on or off.
- Lightning overvoltage: these waveforms are similar to those that occur during lightning.
- Wide Bandwidth Noise Signal: the signal frequency does not change and before applying the FFT, the FRA is performed. For this reason, the frequency content of the input signal must be wide enough.

The measurement system in the TD should consist of a signal generator to produce the desired injection signal and recording equipment to record data [43].

C. input signal

There are two methods for injecting the wide range of frequencies required. Based on the injected or reference signal, the FRA can be divided into two groups:

- Sweep Frequency Response Analysis (SFRA)
- Impulse Frequency Response Analysis (IFRA)

SFRA advantages:

- The signal-to-noise ratio is high. Network analysts typically use a narrowband filter to remove noise.
- Given that input and output waveforms are available for a wide frequency range, amplitude and phase angle curves are extracted without any additional conversion.
- The number of desired frequency points can control image resolution. If more precise resolution is required, the range can be divided into multiple frequency bands and then measured. The distribution of points can usually be linear or logarithmic [36].
  - the detection of mechanical faults since these faults cause the high-frequency equivalent circuit parameters to change which, could be detected easily using this test [44].

SFRA disadvantages:

- Using the standard network analyser, it is not possible to determine several TFs at the same time.
- The measurement process takes a long time: depending on the number of points and the amount of filtering, it may take several minutes.
- The signal amplitude is low.
- Averaging techniques are very time-consuming.

IFRA advantages:

- several TFs can be measured simultaneously, reducing outages during revision.
- It is very fast compared to SFRA. The measurement process is usually done in one minute (several impulse signals are applied to create an average time series) [44-45].

IFRA disadvantages:

- Frequency resolution is constant. This leads to poor resolution at low frequencies. This may make it difficult to diagnose electrical faults. In addition, the signals are usually filtered with high-pass filters to reduce the problems associated with the FFT function.
- Noise cannot be filtered.
- The power spectrum of the injected signal is frequency-dependent.
- Signals that are slowly damped are not recorded.
- Noise and faults related to digitizers.
- The reference and response signals are converted to the FD using FFT. Therefore, to some extent, accuracy depends on mathematical calculations [45-46].

SFRA and IFRA should have similar results under the same conditions. Recent research shows these methods can also be used in online FRA [47-48].

II. Types of FRA configuration

The FR can be determined as a voltage ratio (VR) between two terminals of a phase or as the input impedance or admittance of a winding. In practice, using the VR is the most common. Of course, some studies have used input impedance or admittance for FRA and the results show that these TFs can detect faults. As shown in Fig. 6, common circuit connections are [36]:

- open-circuit (OC) connection
- short-circuit (SC) connection
- capacitive inter-winding connection
- inductive inter-winding connection

In Fig. 6, V_r is the reference voltage and V_m is the response voltage [36].

A. Open-circuit

In this connection, the reference signal is injected into one of the winding terminals while all the other terminals are OC, the FR is measured at the other winding terminal (Fig.6(a)). This method is used for windings with Y and D connections as well as for single-phase units. It can be used to evaluate the core [36].

B. Short-circuit

The SC connection is also done in a similar as the OC connection, but on the secondary side, the winding in the identical phase is SC (Fig. 6(b)). Short circuit connection is only suitable for evaluating windings [36].

C. Capacitive inter-winding

In this connection, the reference signal is injected into one of the winding terminals and the response signal is obtained from the same phase winding on the secondary side, while the other terminals are OC (Fig. 6(c)).

D. Inductive inter-winding

This connection is done in the same as the capacitive inter-winding, except that the second terminals of the windings under test are grounded (Fig. 6(d)). The response signal in the low and medium frequency range practically represents the transformer ratio and at higher frequencies does not have beneficial data [35, 42, 45].

According to what has been said, the accuracy of FRA depends on the type of configuration and its components. Some studies have investigated the accuracy and ability to detect FRA in different connections and termination resistors [49-55]. The results show that in many cases, the TFs based on the VR have the highest accuracy and the input admittance has the lowest accuracy in FRA measurement [51]. Also, in the diagnosis of mechanical defects, the capacitive inter-winding connection is

the most precise among the four connections mentioned. Furthermore, adjusting the measuring impedance and terminating resistors significantly reduces the noise in the FRA results [52].

III. Evaluation of FRA results

Response data can be evaluated with reference data, directly (visual inspection) or indirectly (after data processing) [39]. As shown in Fig. 7, three common methods for obtaining reference data are as follows:

A. Time-based

In this method, the fingerprint data is obtained from previous FRA test results on a healthy transformer. This data is obtained when we make sure that the transformer does not have any defects or problems (for example, right after the installation of the transformer) [36].

B. Type-based

Another method to collect reference data is to use the FRA test results of similar transformers. These transformers are named twins or sisters and they mainly include distribution transformers [36].

C. Construction-based

Another recommended alternative method is to use the results of the other phases of the power transformers, due to the symmetry in the construction. This method is mainly used for transformers at the transmission level. [35-36, 42, 57].

IV. Frequency range

The FRA response can be classified into three ranges: low frequency, medium frequency and high frequency. The FRA frequency range should be chosen according to the expected fault. It should be noted that for this purpose, factors such as measuring equipment, noise, natural frequencies of the winding, core magnetization, etc., which can affect the test results, must be taken into account [58-60]. The frequency range is divided into bands which are shown in Table 1. In Table 2, the parameters of the transformer model and the mechanical faults affecting them are given. The effects of ±10% changes in various electrical parameters on the amplitude and resonance frequency of the FRA (compared to the FRA signature) are summarized in Table 3. In Table 4, the effect of changing different parameters of the transformer model on FRA is shown [34].

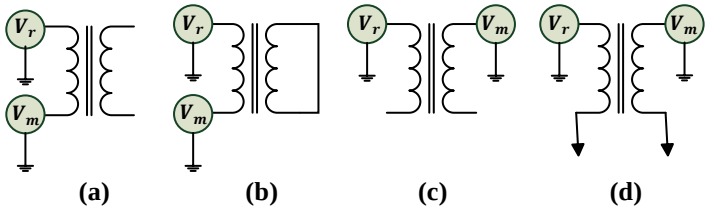


Fig. 6. FRA circuit configurations: a) open-circuit, b) short-circuit, c) capacitive inter-winding, d) inductive inter-winding [36].

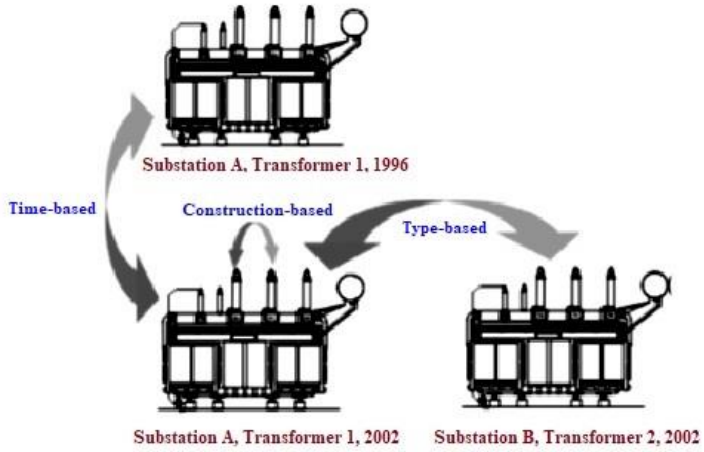


Fig. 7. Types of evaluation in the FRA test

TABLE 1 FREQUENCY BANDS AND THEIR SENSIVITY TO DIFFERENT FAULTS [34]

Fault Sensitivity	**Frequency Band**		
	<20 kHz	20-400 kHz	**>400kHz**
Core deformation, Open circuits, Short turns residual magnetism	Yes	No	**No**
Bulk winding movement, Clamping structure loosing	Yes	No	**No**
Deformation within the main or tap winding	No	Yes	**Yes**
Ground impedance variations	No	No	**Yes**

TABLE 2 CORRELATION BETWEEN MECHANICAL FAULTS AND TRANSFORMER MODEL PARAMETERS [34]

Model Parameter	**Type of Fault**	**Symbol**
Inductance	Disc deformation, Local breakdown, Core deformation and winding short circuit	**L_s**
Shunt capacitance	Disc movement, Buckling due to large mechanical forces, Moisture ingress and loss of clamping pressure	**C_{sh}**
Resistance	Shorted or broken disc, Failure of caulking contacts and tap changer contact wear	**R_s**
Series capacitance	Aging of insulation, Moisture ingress and disc movement	**C_{HL}**

TABLE 3 EFFECT OF CHANGING ELECTRICAL PARAMETERS ON AMPLITUDE AND RESONANCE FREQUENCY [34]

Parameters Variations		**Frequency Range**		
		<20 kHz	20-400 kHz	**>400kHz**
L_s	10% increase	Magnitude and resonance frequencies decreased	Magnitude and resonance frequencies decreased	**Magnitude and resonance frequencies decreased**
	10% decrease	Magnitude and resonance frequencies increased	Magnitude and resonance frequencies increased	**Magnitude and resonance frequencies increased**
C_{sh}	10% increase	No Impact	No Impact	**Magnitude and resonance frequencies decreased**
	10% decrease	No Impact	No Impact	**Magnitude and resonance frequencies increased**
C_g	10% increase	No Impact	No Impact	**Magnitude and resonance frequencies decreased**
	10% decrease	No Impact	No Impact	**Magnitude and resonance frequencies increased**
M_g	10% increase	Resonance frequencies increased	Resonance frequencies increased	**Resonance frequencies increased**
	10% decrease	Resonance frequencies decreased	Resonance frequencies decreased	**Resonance frequencies decreased**
G	10% increase	No Impact	No Impact	**Magnitude decreased**

TABLE 4 EFFECT OF DIFFERENT PARAMETERS ON FRA SIGNATURE [34]

Parameters Variations		**Frequency Range**		
		Low	**Medium**	**High**
L_s	10% decrease	Amplitude change	Resonance peaks shift right amplitude change	**Amplitude change**
	10% increase	Amplitude change	Resonance peaks shift right amplitude change	**Amplitude change**
C_{sh}	10% decrease	No Impact	No Impact	**Resonance peaks shift right amplitude change**
	10% increase	No Impact	No Impact	**Resonance peaks shift right amplitude change**
C_g	10% decrease	Amplitude change	Resonance peaks shift right amplitude change	**Resonance peaks shift right amplitude change**
	10% increase	Amplitude change	Resonance peaks shift left amplitude change	**Resonance peaks shift left amplitude change**
R_s	10% decrease	No Impact	No Impact	**Amplitude change**
	10% increase	No Impact	Amplitude change	**Resonance peaks shift right amplitude change**
G	10% decrease	No Impact	No Impact	**No Impact**
	10% increase	Amplitude change	Amplitude change	**Resonance peaks shift right amplitude change**

V. Online FRA

As mentioned, offline FRA has many advantages compared to other methods of assessing the condition of the transformer, but for this, it is necessary to take the transformer out of service. Due to its high importance in the power system, out of service of the transformer imposes a high cost on the network and will reduce the reliability of the grid. For this reason, research is being developed to conduct the online FRA [36].

The problem arises when the transformer is energized during the measurement process. In this condition, high voltage is available and also oil is circulating inside the transformer tank. Among the major problems in measuring online TF, the following can be mentioned [25]:

- Lack of proper signal for injection.
- Isolating the response of the transformer from the external system.
- Problems related to natural variations within the transformer, such as winding temperature and steady-state magnetization.
- transformer state caused by loading conditions;
- Instrumentation system protection against power signal.
- Effect of LV load on the TF results.
- Oil circulation inside the transformer tank.
- Oil bushing on the LV side of the transformer because it does not have a test tap.

Regarding signal injection, it is important to note that making a direct connection to the high-voltage bus or overhead line between the transformer and the surge arrester is complicated and expensive due to the need for insulation. Therefore, the best way is to use the tap bushing of the transformer as an input/output for testing the transformer. It is also suitable for injecting a low-voltage signal as an input when measuring the online TF. The impulse or sweep frequency can be applied through a coaxial cable or optical fiber through an external connection circuit and create a low voltage on the test tap as a reference signal. Then, on the other side of the winding under test that has passed through the neutral bushing, the response signal can be measured. Accordingly, the neutral test tap will be the output probe. If the neutral bushing is connected to the ground, the protective circuit for the neutral bushing is not necessary. In the case of three-phase transformers, if the connection is delta, a protective circuit is required for the input as well as the output test taps. In addition, the measurement can be done between two phases, in this case, the validity of the measured signal is debatable [25, 60-61].

If the signal is controlled, both SFRA and IFRA tests can be performed, but if the signal is uncontrolled, only the IFRA test is applicable. Due to the connection of the transformer to the network and the mentioned limitations, the response signal needs

filtering and a series of mathematical processes. This process is shown in Fig. 8. It should be noted that due to the connection of the transformer to the network, the FR in the online FRA test is affected by the conditions of the network and the transformer in service, and this problem makes the measurement conditions more complicated. [36, 62].

To detect the deformation of transformer windings, the online methods used are the vibration method [63-65], the communication method [66-68], the current deformation coefficient method [69], the ultrasonic method [70], short-circuit impedance and winding stray reactance method [71] and TF method [72-73]. Fig. 9 provides an overview of the development of the online FRA method based on the type of excitation signal [74-80].

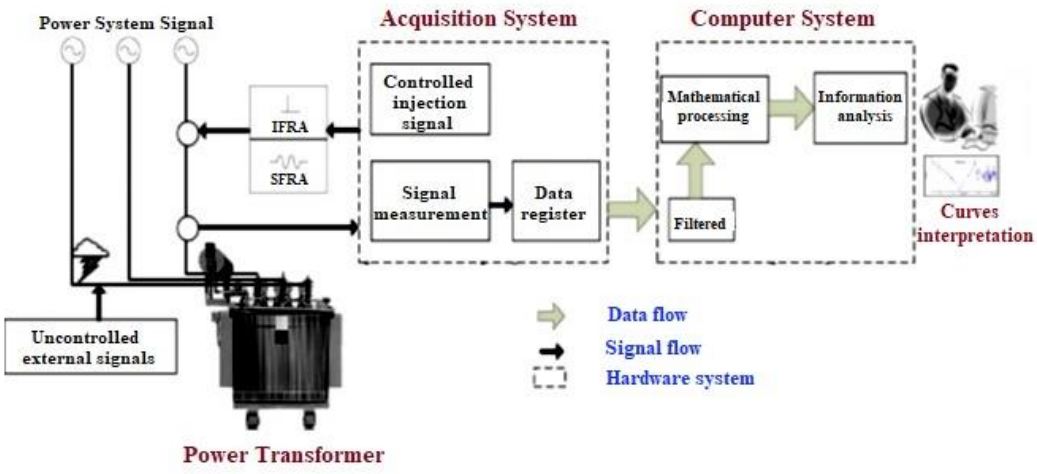


Fig. 8. Online FRA schematic [62]

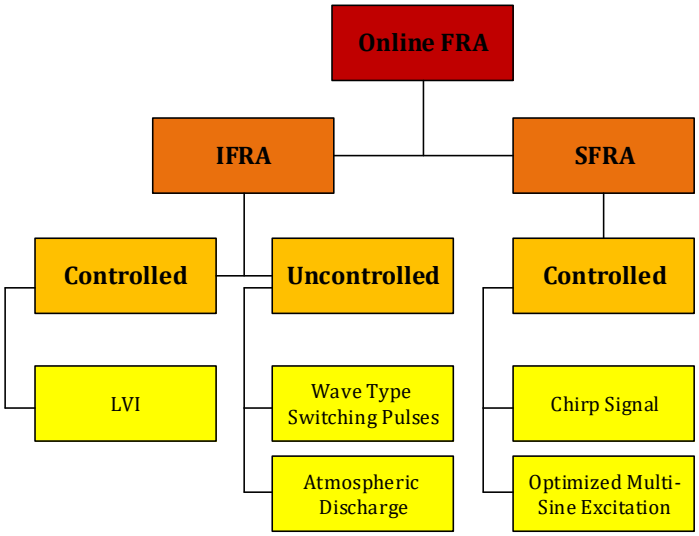


Fig. 9. Online FRA based on the type of stimulation signal

VI. FRA results in interpretation methods

A. Interpretation of FRA results based on numerical indicators

Numerical indices are the most common and intuitive methods to evaluate the amount of change between two FR measurements. Statistical indicators operate based on the degree of compatibility or lack of compatibility between two sets of measurements related to the fault and normal conditions of the transformer [34]. It is easier to use statistical measures and there is no need to calculate the parameters of the models which leads to faults and problems. These indices convert the difference between traces into a unique value that can be easily evaluated [81-88]. The measured indicators can be classified into two main groups:

- Indicators derived directly from FR measurement data (amplitude and phase vectors).
- Indicators based on resonance points (amplitude and frequency)

All indices shown in Table 5, except complex distance (CD) index, are calculated based on amplitude vector. In the CD index, amplitude and phase responses are used to calculate the index. Indicators show different sensitivity to amplitude and FR changes, for example, correlation coefficient (CC) index is not affected by constant amplitude deviation between two traces, so

researchers have developed approaches that combine several indicators [89].

TABLE 5 NUMERICAL INDICES BASED ON FRA VECTORS

Abbreviation	Definition	Equation	References
ASLE	Absolute Sum of Logarithmic Error	$ASLE = \frac{\sum_{i=1}^{N}\lvert 20\log_{10} Y_{1i} - 20\log_{10} Y_{0i}\rvert}{N}$	**[98,119]**
MSE	Mean Square Error	$MSE = \frac{\sum_{i=1}^{N}(Y_{0i} - Y_{1i})^2}{N}$	**[102,108]**
CSD	Comparative Standard Deviation	$CSD = \sqrt{\frac{\sum_{i=1}^{N}[(Y_{0i} - \overline{Y_0}) - (Y_{1i} - \overline{Y_1})]^2}{N-1}}$	**[103]**
ED	Euclidean Distance	$ED = \sqrt{\sum_{i=1}^{N}(Y_{0i} - Y_{1i})^2}$	**[96]**
SD	Standard Deviation	$SD = \sqrt{\frac{\sum_{i=1}^{N}(Y_{0i} - Y_{1i})^2}{N}}$	**[130]**
RMSE	Root Mean Square Error	$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[\frac{\lvert Y_{0i}\rvert - \lvert Y_{1i}\rvert}{\frac{1}{N}\sum_{i=1}^{N}\lvert Y_{1i}\rvert}]^2}$	**[92]**
σ	Spectrum Deviation	$\sigma = \frac{1}{N}\sum_{i=1}^{N}\sqrt{[\frac{Y_{0i} - (\frac{Y_{0i}+Y_{1i}}{2})}{\frac{Y_{0i}+Y_{1i}}{2}}]^2 + [\frac{Y_{1i} - (\frac{Y_{1i}+Y_{0i}}{2})}{\frac{Y_{1i}+Y_{0i}}{2}}]^2}$	**[107,109]**
σ_s	Stochastic Spectrum Deviation	$\sigma_s = \frac{100}{N}\sum_{i=1}^{N}\left\lvert\frac{Y_{0i} + Y_{1i}}{Y_{1i}}\right\rvert$	**[121]**
SSRE	Sum Squared Ratio Error	$SSRE = \frac{\sum_{i=1}^{N}(\frac{Y_{1i}}{Y_{0i}} - 1)^2}{N}$	**[31]**
SSMMRE	Sum Squared Max-Min Ratio Error	$SSMMRE = \frac{\sum_{i=1}^{N}(\frac{\max(Y_{0i}, Y_{1i})}{\min(Y_{0i}, Y_{1i})} - 1)^2}{N}$	**[119]**
MM	Max-Min Ratio	$MM = \frac{\sum_{i=1}^{N}\min(Y_{0i}, Y_{1i})}{\sum_{i=1}^{N}\max(Y_{0i}, Y_{1i})}$	**[105,106]**
CCF	Cross Correlation Factor	$CCF = \frac{\sum_{i=1}^{N}(Y_{1i} - \overline{Y_1}) - (Y_{0i} - \overline{Y_0})}{\sqrt{\sum_{i=1}^{N}(Y_{1i} - \overline{Y_1})^2} \cdot \sqrt{\sum_{i=1}^{N}(Y_{0i} - \overline{Y_0})^2}}$	
ρ	Normalized Correlation Coefficient	$\rho = \frac{\sum_{i=1}^{N}\left[\lvert Y_{1i}\rvert - \frac{1}{N}\sum_{i=1}^{N} Y_{1i}\right]\left[\lvert Y_{0i}\rvert - \frac{1}{N}\sum_{i=1}^{N} Y_{oi}\right]}{\sqrt{\sum_{i=1}^{N}\left[\lvert Y_{1i}\rvert - \frac{1}{N}\sum_{i=1}^{N} Y_{1i}\right]^2 \sum_{i=1}^{N}\left[\lvert Y_{0i}\rvert - \frac{1}{N}\sum_{i=1}^{N} Y_{0i}\right]^2}}$	**[95]**
CC	Correlation Coefficient	$\mathrm{CC} = \frac{\sum_{i=1}^{N} Y_{0i} Y_{1i}}{\sqrt{\sum_{i=1}^{N}[Y_{0i}]^2 \sum_{i=1}^{N}[Y_{1i}]^2}}$	**[97]**
CD	Complex Distance	$CD = \sqrt{\sum_{i=1}^{N}\left(\begin{matrix}\lvert Y_{1i}cos\varphi_{Y_{1i}} - Y_{0i}cos\varphi_{Y_{0i}}\rvert^2 \\ +\lvert Y_{1i}sin\varphi_{Y_{1i}} - Y_{0i}sin\varphi_{Y_{0i}}\rvert^2\end{matrix}\right)}$	**[104]**
DABS	Absolute Difference	$\mathrm{DABS} = \frac{\sum_{i=1}^{N}\lvert Y_{0i} - Y_{1i}\rvert}{N}$	**[103]**

The development of indices based on resonance points involves an additional challenge regarding the position of the resonance points (maximum and minimum), which may seem simple, but especially in the case of noise or small resonances, the detection of the actual resonance frequency is very sensitive and may create faults in these indicators [90]. The vector fitting approach can be used to fit a rational function to the measured FR and thus estimate the maximum and minimum (pole and zero) [91]. The accuracy of the fitting result should be within the reproducible range of the measurement, i.e., the main resonances should be recorded with a frequency deviation less than the recorded frequency resolution [92]. [93] uses the derivative of TF equations by processing FRA data to evaluate the condition of transformer windings. These functions are used for the mathematical description of FRA curves, and by observing the FRA curves produced by these functions, they can check the transformer winding condition.

In Table 5, the most common numerical indices extracted from FRA vectors and also in Table 6, numerical indices extracted from resonance frequency points are presented. In Table 5, Y0 is the reference set of data, Y1 is a set of compared data, $\overline{Y0}$ and $\overline{Y1}$ are the arithmetic mean values of all the accumulated values of a data set and N is the total number of points. In Table 6, the subscripts X and Y refer to new traces and FRA fingerprints, respectively. A(i) and f(i) refer to the amplitude and frequency of the i-th resonance or anti-resonance point, respectively, and AF represents the level below the FRA trace between two anti-resonance points. Pi represents the i-th pole of the rational function, a and b are the numerator and denominator coefficients of the rational function, and m and n are the order of estimation of the numerator and denominator polynomials, respectively. W_{ai} and W_{fi} are the weighting factors of the i-th resonance point.

[94] proposes a transformer winding fault detection method based on the polar plot. The excitation-response ratio is provided

to calculate the relative coefficient for partial fault detection. The fault states are detected by the polar plot distribution, which combines the amplitude-frequency and phase-frequency characteristics.

TABLE 6 NUMERICAL INDICES BASED ON RESONANCE AND ANTI-RESONANCE POINTS

Abbreviation	Definition	Equation	References
MDA	Mean Deviation of Areas	$\mathrm{MDA} = \frac{1}{K}\sum_{i=1}^{K}\lvert AF_Y(i) - AF_X(i)\rvert$	**[90]**
MAD	Mean Amplitude Deviation	$\mathrm{MAD} = \frac{1}{K}\sum_{i=1}^{K}\lvert A_Y(i) - A_X(i)\rvert$	**[90]**
MFD	Mean Frequency Deviation	$\mathrm{MAD} = \frac{1}{K}\sum_{i=1}^{K}\lvert f_Y(i) - f_X(i)\rvert$	**[90]**
IAD	Index of Amplitude Deviation	$\mathrm{IAD} = \sum_{i=1}^{K}\left\lvert\frac{A_Y(i) - A_X(i)}{A_X(i)}\right\rvert$	**[99]**
IFD	Index of Frequency Deviation	$\mathrm{IFD} = \sum_{i=1}^{K}\left\lvert\frac{f_Y(i) - f_X(i)}{f_X(i)}\right\rvert$	**[130]**
F_a	Amplitude Function	$F_a = \sum_{i=1}^{K}\frac{A_Y(i)}{A_X(i)}$	**[132]**
F_f	Frequency Function	$F_f = \sum_{i=1}^{K}\frac{f_Y(i)}{f_X(i)}$	**[132]**
W_a	Weighted Amplitude function	$W_a = \sum_{i=1}^{K}\frac{A_Y(i)}{A_X(i)} \times W_{ai}$	**[103]**
W_f	Weighted Frequency function	$W_f = \sum_{i=1}^{K}\frac{f_Y(i)}{f_X(i)} \times W_{fi}$	**[99]**
FI	Faulted-Intact relation	$\mathrm{FI} = \left(\frac{\sum_{i=1}^{m}\lvert a_Y(i)\rvert}{\sum_{i=1}^{m}\lvert a_x(i)\rvert}\right)\left(\frac{\sum_{i=1}^{n}\lvert b_Y(i)\rvert}{\sum_{i=1}^{n}\lvert b_x(i)\rvert}\right)$	**[100]**
SDP	Sum of absolute Displacement of Poles	$\mathrm{SDP} = \sum_{i=1}^{K}\left\lvert\frac{P_Y(i) - P_X(i)}{P_X(i)}\right\rvert$	**[101]**

B. Interpretation of FRA results based on machine learning

Machine learning and artificial neural networks (ANN) are intelligent algorithms often used for pattern classification by learning from examples. In unsupervised learning, monitoring the network and providing target outputs to match the inputs is unnecessary. In supervised learning, a target output is provided for each input vector injected into the network. Based on the calculated output fault (the difference between the target output and the estimated output), the network adjusts its synaptic weight using heuristic algorithms in each iteration [111-112]. [113] presents a new approach using a multi-layered perceptron model for modeling and direct analysis of FRA data, simulating types and degrees of the transformer winding faults. [114] compares several well-known and widely used classifications of machine learning, including radial basis function (RBF), support vector machine (SVM), and statistical k-nearest neighbour (k-NN). In recent years, due to the ability of these models to solve classification problems, regression, and other applications, they have become very popular in various fields. RBF, SVM, and k-NN networks performed well classification of faults using the CSD index and desired frequency ranges as input.

[115-118] estimates the parameters of a three-phase low-frequency model of the transformer by using the data obtained from the FR. [119-120] estimates the FRA data by a rational function consisting of two polynomials describing the zeros and poles of the transformer model. ANN and fuzzy logic have also been used to compare and interpret the results of the TF of transformers [121-124].

[125] presents an algorithm for interpreting FRA results based on numerical indicators and a supervised machine-learning technique. For this purpose, random forest (RF) classifiers were developed for the first time to identify the

condition of transformer windings and classify various faults in transformer windings. The results show that the

much human intervention. [126] by presenting the enhanced vector fitting algorithm, tries to create an algorithm with appropriate accuracy for the automatic interpretation of the results measured by FRA. However, to detect any spectral deviation as detection of any mechanical damage inside the transformer, the impedance measurement must be free from other influences such as the change in the state of the insulating materials (paper, pressboard and oil) that may cause spectral deviations in the FR of the winding impedance [127].

Furthermore, the laminated steel core can only support magnetic flux up to about 100 kHz. Therefore, any change in a material property (permeability) or clamping structure can

lead to deviation in the FRA spectrum in this frequency range [128]. [129] uses ensemble machine learning techniques to detect and diagnose transformer mechanical faults based on the extraction of winding frequency responses using outlier detection and ensemble algorithms, which together form an efficient hybrid method.

VII. Fault location based on FRA

In many studies, various methods have been presented to detect the type, location, and extent of faults in power transformers. [130] Classification of the type, location and intensity of different faults is done using a support vector machine with cubic polynomial kernel. The accuracy of different indices and amplitude, phase, real and imaginary components of TF have been checked. [131-132] presented a new calculation method of TF comparison indices called windowed calculated index (W-index). The ability and accuracy of the proposed W-index were studied and Fisher discriminant analysis was used to classify the fault as well as to determine the location and intensity of the fault. [133] proposed an algorithm to determine the location and amount of winding buckling. The fault location is determined by comparing the direction of change of the measured and simulated results at resonant frequencies, and the SD index is proposed to determine the amount of deformation of the winding. [134] investigated the mechanical faults of DSV, RD, and AD on three different test samples of similar size using their TF.

To determine the type of fault using the CC index in different frequency ranges, a certain coefficient (α) has been used so that the weight functions of amplitude and frequency can specify the location along with the amount of fault. The disc-disc, RD, and AD faults in the winding are modeled based on the detailed model presented in [135]. Some correlation-based features and other mathematical models of TF measurement were used to train the ANN classifier. The results show an overall accuracy of 98.8% for detecting the type of fault and 95.4% for detecting the location of the fault, and there is no discussion about the amount of fault. [136] proposes a new location method for transformer failure. This method is based on a combination of FRA and evidential reasoning (ER) process.

The wavelet transform (WT) has proven to be very efficient for the study of transient signals, as it can analyze and change the resolution of signals in both the TD and FD. This change occurs because the WT allows good resolution for the analysis of both slowly varying (60 Hz) and rapidly varying components typically associated with high-frequency events [137]. The rationale behind decomposing FRA responses using WT is to create smooth TF versions with different levels of information to improve the signal difference detection process for different frequency regions. This method adds more robustness to the FRA and reduces the possible impact of disturbances during the measurement on the detection result [138]. Also [139] a method based on wavelet transform is proposed as a powerful technique to analyze even slight changes in transformer FR characteristics for fault detection. [140] introduces a new theoretical method to obtain the FR curve with the transformer in service (online) from the transient signals analysis by applying the continuous WT. [141] presents a new method for fault detection and location in power transformers. In this method, the neutral current, whose change is very minor in the event of a minor fault, is analyzed using the WT, and its performance is investigated by considering a fault in different locations. The WT benefits from the TF in three aspects:

1. The neutral current that changes when the fault occurs is seen as a non-constant signal and used directly in the analysis, without any reference to the voltage, as in the TF.
2. The time of fault occurrence can be recognized. This time provides a means to accurately detect the location of the fault in a particular transformer winding, based on the wave propagation speed.
3. It is possible to find very minor faults while it is not possible with TF.

In Table 7, some papers are categorized according to the type of fault identified, and the method of identification and index used.

[142-143] presents a new method for detecting and locating turn-turn faults in power transformers using both the TF method and the ANN technique. Some faults in turn in the winding have been simulated and the corresponding TF has been measured. Then, using ANN and a back-propagation learning algorithm, a method to identify the fault location is presented. The results show that if the ANN network is trained using the provided patterns, it can well detect the location of the fault.

TABLE 7 CLASSIFYING SOME REFERENCES FOR FAULT LOCATION METHOD

Type of Fault	Proposed Method	Ref.
winding fault (SC, OC)	ANN technique	[134],[141], [142]
	Wavelet Transform	[136-140]
	Polar Plot	[92]
Winding deformation (AD, RD, DSV)	Support Vector Machine	[114],[118]
mechanical displacements (AD, RD)	Vector Fitting	[101],[116]

VIII. Conclusion

The power transformer insulation system is one of the vital parts of the power transformer. Thus, the quality of the insulation system must be constantly monitored. One of the most powerful and accurate tools for diagnosing and locating various faults in power transformers is FRA. But interpreting FRA curves still requires a higher level of expertise to identify and quantify faults. Because the FRA interpretive code is not yet widely accepted. Most of the conducted studies have dealt with the detection and location of faults related to the winding. This paper, after an in-depth study of the application of FRA as a fault detection method in transformers, examines the ability of this method to detect and locate insulation faults in transformers. Studies show that based on the detailed model of the transformer, any change in the insulation condition leads to a change in the parameters of this model, and it is possible to detect and locate these types of faults by FRA.

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