Identification of the most sensitive frequency response measurement technique for diagnosis of interturn faults in power transformers

V Behjat\textsuperscript{1}, A Vahedi\textsuperscript{1,3}, A Setayeshmehr\textsuperscript{2}, H Borsi\textsuperscript{2} and E Gockenbach\textsuperscript{2}

\textsuperscript{1} Center of Excellence for Power System Automation and Operation, Iran University of Science & Technology, Narmak 16846, Tehran, Iran
\textsuperscript{2} Institute of Electric Power Systems, High Voltage Engineering Section (Schering-Institute), Leibniz Universität Hannover, Callinstr. 25 A, D-30167 Hanover, Germany

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Abstract

Interturn winding faults are one of the most prevalent and potentially destructive electrical faults in power transformers. This contribution is an initiative to explore the potential of the sweep frequency response analysis (SFRA) method in detecting interturn winding faults and also identifying the most appropriate measurement configuration for making sensitive frequency response measurements. This application enables timely warning of the rising failure and so is of particular importance, as these kinds of defects, if left undetected, can propagate and lead to catastrophic phase–ground or phase–phase faults which can finally cause the breakdown of the whole transformer. In this paper contribution is made to a better understanding of the transformer performance and modification of the transformer winding frequency response in the presence of interturn faults. The paper includes a full description of the details of the SFRA method and measuring procedure, along with principal experiments conducted on a 100 kVA distribution transformer. A large number of measurements with different transfer functions, various terminal configurations and three categories of measurement types was conducted to identify the most appropriate configuration for making SFRA measurements. The experimental results proved that the identified measurement configuration is sensitive to detect unambiguously interturn faults even down to 0.2\% shorted turns along the winding.

Keywords: power transformer, interturn faults, measurement technique, SFRA, fault diagnosis

1. Introduction

Reliable and continued performance of power transformers as the most expensive and strategically important components of any power generation and transmission system is the key to profitable generation and transmission of electric power. Therefore, intensive maintenance of power transformers is the main target for power supply companies, since they must operate in a competitive market. According to the statistics of modern transformer breakdowns over a period of years, undetected interturn short circuit faults are the leading cause of transformer catastrophic failures which result in unplanned power transformer outages and impose substantial costs on operation of the electric power network \cite{1, 2}. Although traditional diagnostic tests such as magnetizing current, turn ratio, leakage reactance and winding resistance measurement are extensively used for detecting winding faults in power transformers, these methods have proven not to be sensitive enough to detect failures of a few shorted turns on a winding.
to investigate the mechanical integrity of the windings [3].

late 1970s, FRA has been widely applied to power transformers to investigate the mechanical integrity of the windings [3]. There are two ways of making FRA measurements: sweep frequency response analysis (SFRA) and low voltage impulse method (LVI). Many early practitioners tried impulse systems and have continued to try them up to the present. Though appealing in terms of speed, the LVI method has never been able to match the range, resolution or repeatability and signal to noise ratio of the sweep method [4]. A detailed evaluation of the relative merits of the two methods can be found in the research works carried out in [3–13]. Given the potentials of sweep frequency analysis, this paper deals with the development of a diagnosis approach based upon sweep frequency analysis, for detecting interturn winding faults.

In recent years, the applicability and sensitivity of the SFRA method in evaluating mechanical integrity of core, windings and clamping structures within power transformers have been extensively tested by means of fault simulations in laboratory and real case studies of transformers on site [3–24]. However, despite its importance, research on interturn fault diagnosis using the SFRA method is rather limited. A literature review indicates that all of the contributions pertinent to the present study have concentrated only on inter-disk type faults and found it enough to show the overall changes of the frequency response of the transformer as a result of fault [25–27]. The modification of the winding frequency response as a result of interturn fault has neither been systematically analyzed nor have reasons for it been ascertained in the existing literature.

Investigating the sensitivity and feasibility of the SFRA method as a diagnostic tool to detect interturn winding faults especially low-level interturn faults in power transformers, identification of the most appropriate test configuration for this application and reliable information about the relationship between the changes of the winding transfer function and interturn faults are the issues that, so far, remain unreported. This research work is aimed at extending the previous studies for sensitive detection of interturn faults utilizing characteristic signatures associated with the interturn faults extracted from the SFRA records through a systematic study. The adopted approach keeps at its disposal a 100 kVA, 33 kV/400 V distribution transformer, on which interturn faults were imposed, and a measurement setup consisting of a network analyzer for measuring the transfer function in the required frequency range.

While the effects of the interturn faults are known to be problematic, the current study was focused upon obtaining a better understanding of the complex physical behavior of the transformer in the presence of interturn faults. In order to see these relationships most clearly, a finite element model of the tested transformer was developed. Obviously, a correct understanding of what governs the modification of the physical behavior of the transformer as a result of interturn faults would assist in justifying the changes of winding frequency response and hence developing a reliable and sensitive fault detection method.

The paper is organized as follows. Section 2 focuses on various basic concepts related to the SFRA method and the methodology used for doing the measurements. Section 3 presents a brief description addressing the electrical characteristics of the tested transformer and illustrates how interturn faults were staged on the windings of the transformer. The most appropriate test configuration for making sensitive SFRA measurements will be identified in section 4. Section 5 describes the results of applying the SFRA method in order to diagnose interturn faults on the windings of the tested transformer. Experimental tests which are presented in this section verify that the identified configuration can be declared as the preferred way of making frequency response measurements on transformers. Finally, conclusions will be presented in the last section.

2. SFRA—basic principles and measurement method

The SFRA method injects sinusoidal low voltage signals of varying frequencies into one side of the winding and measures the output signals as they exit the winding in order to obtain the winding transfer function. Treating a power transformer, undergoing SFRA, as a two-port network, the transfer function of the network is defined as the quotient of the output to input frequency responses when the initial conditions of the network are zero. Figure 1 illustrates a basic SFRA measurement circuit including two-port network model of the transformer. The tested impedance, in this case the impedance of the winding and probably other parallel impedance paths between the input and output bushings, has been represented by $Z_{12}$. However, due to the generally small size of $Z_{12}$ compared to any other paths, it is a close approximation to the winding impedance under most circumstances. In a case where the input and measured signals
are generally referenced to ground, \( Z_{11} \) and \( Z_{22} \) represent the impedance paths to the ground, through the bushing insulation. \( Z_{21} \) represents the impedance between the two reference grounds, which in practice approaches zero because the negative terminals in the above diagram are short circuited through the transformer tank when the transformers are tested. Finally, \( S \) is the source used for generating the input sinusoidal signal and \( Z_0 \) is the impedance of the source. Although any two-port network can be reduced to a combination of four impedance elements, as mentioned above, it is customary to use the equivalent input and output impedance of the network, defined as below, to describe the behavior of the two-port network:

Equivalent input impedance:  \[ Z_i(f) = \frac{V_{in}}{I_{in}}. \]  
Equivalent output impedance:  \[ Z_o(f) = \frac{V_{out}}{I_{out}}. \]

In the circuits composed of ‘\( n \)’ two-port networks, the equivalent output impedance of the ‘(\( n-1 \))th’ network is the equivalent Thevenin impedance of the ‘\( r \)th’ network connecting to the ‘(\( n-1 \))th’ network. Obviously in the considered SFRA measurement circuit in this study, which includes just the two-port network model of the transformer, the output impedance is an open circuit and the output current is zero. The equivalent input impedance of the two-port network model of transformer is one of the most often used transfer functions for SFRA measurements. Conventionally, there exist two types of transfer functions which are normally used in FRA analysis for diagnostic purposes: voltage ratio (\( V_{out}/V_{in} \)) and impedance (\( V_{in}/I_{in} \)) such that

\[
H_1(f) = \frac{V_{out}}{V_{in}} \quad (3)
\]
\[
H_2(f) = \frac{V_{in}}{I_{in}} \quad (4)
\]

It is worth pointing out that when using the input impedance of the two-port network model of transformer as the transfer function for SFRA measurement, just one of the winding ends is connected solidly to the ground and hence the input impedance of the network \( H_2(f) \) realistically represents the impedance of the transformer winding \( (Z_{12}) \). Furthermore, since the voltage ratio measurement is usually made with a 50 \( \Omega \) termination, the 50 \( \Omega \) impedance must be incorporated into the transfer function. Equation (5) shows the relationship of the winding impedance, \( Z_{12} \), to the voltage ratio transfer function:

\[
H(f) = \frac{V_{out}}{V_{in}} = \frac{50}{50 + Z_{12}}. \quad (5)
\]

It should be noted that the sensitivity of each transfer function to defects and changes in the transformer assemblies is very different. Therefore, the user of the method has to find the most sensitive signal for defect detection. The transfer function is conventionally represented in the frequency domain and is denoted by the Fourier variable \( H(j\omega) \), where \( (j\omega) \) denotes the presence of a frequency-dependent function and \( \omega = 2\pi f \). Both magnitude and phase relationships can be extracted from the transfer function. The preferred method for presenting the measurement results in the modulus-argument form is the Bode diagram which plots the magnitude and phase as follows:

\[
A(dB) = 20\log_{10}(H(j\omega)) \quad (6)
\]
\[
A(\theta) = \arctan(H(j\omega)). \quad (7)
\]

It is possible to display the plots in either a linear or logarithmic scaling. The authors prefer the logarithmic scale, which is used throughout this paper.

When considering SFRA measurements in power transformers, winding measurements practically consist of three main categories including HV winding, LV winding and inter-winding measurements. HV winding measurements are performed having each terminal of the HV winding as input and the respective neutral terminal as output, keeping all HV and LV non-tested terminals floating. In a similar manner, LV winding measurements are performed having two ends of the LV winding as the input and output while keeping all the other non-tested terminals floating. Inter-winding measurements are performed having the terminal of each phase of the HV winding as input and the corresponding terminal on the same phase of the LV winding as output, keeping all non-tested terminals (HV and LV) open and neutral terminals grounded. While the HV and LV winding measurements describe the winding impedances, the inter-winding measurement describes the leakage impedances, coupling capacitive, between the low voltage and high voltage windings. Furthermore, the relevant standards specify two alternatives for terminal connections: open circuit and short circuit measurements. Open circuit and short circuit measurements are made on one tested winding, while open and short circuiting non-tested windings, respectively. To identify the most appropriate test configuration for making SFRA measurements, all the above-mentioned categories of measurement types will be made on the test specimen of this study.

The SFRA method is a comparative method which means that an evaluation of the transformer condition is done by comparing an actual set of SFRA results to reference results, i.e. fingerprints. Differences between an SFRA fingerprint and the result of an actual measurement are an indication of mechanical or electrical variations of the internal components of the transformer. This type of comparison which uses previous test results is known as time-based comparison and is the most often used and the most accurate method of comparing SFRA results. If there is no fingerprint measurement available, two further types of comparisons including a comparison using the results of identically constructed transformers usually called sister units (type based) or separately analyzed blocks of windings (construction based) are possible [28].

Determination of the transfer function in the frequency domain was performed with a network analyzer which was used for generating the input sinusoidal signal, and also making the voltage measurements and manipulating the results. The Omicron measuring system (Bode 100) was used in the measurements carried out in this paper. The tracking
generator of the network analyzer produced an alternating voltage of 5 V in amplitude as the reference signal of the measuring system. Two leads carrying input (reference) and output (test) signals were used for the connections between the network analyzer and the bushings at two ends of the test winding. The transformer tank and lead ground shields were connected together to assure that no external impedance is measured and the effect of noise and environmental effects is also reduced. This measurement setup accompanied by the experimental test object which will be introduced in the following section completes the test setup for performing SFRA measurements. In the tests reported in this paper, the measured frequency range is 100 Hz to 1 MHz with 400 frequency points per decade. The use of such a high number of points, which leads to increasing time taken to make each measurement, is justified by the decrease in the probability of missing true resonance points and losing resolution in the approximated transfer function with the collected data points. With the used sweep settings, an SFRA scan could take a few minutes.

3. Experimental setup

SFRA measurements were carried out in a high voltage laboratory on a three-phase, two-winding, 35 kV/400 V, Yzn5, 50 Hz, 100 kVA, oil-immersed, ONAN, core-type distribution transformer. The LV and HV windings of the transformer had layer- and disk-type configurations, respectively. Interturn faults were imposed on the turns of the outermost layer of HV disks, which was the only accessible part of the transformer’s windings. To develop interturn short circuit faults, in steps, the transformer oil was pumped out and the front wall of the transformer tank was removed to expose the windings. After the windings were allowed to dry, two conductors on the farthest layer of one of the HV disks, located at two ends of the layer, were chosen and the insulation over them at a point on each was carefully removed to make tapping points. The next step was extracting leads from the tapping points on the chosen conductors. Low impedance-insulated wires were attached to the conductors by means of specific clamps embracing the conductors at the tapping points. The leads were then brought out of the transformer to allow easy access to the internal turns and also to provide the possibility of externally producing interturn faults. Figures 2 and 3 represent a physical view of the tested transformer and a closer view of the tap positions on HV winding of the transformer after refilling the oil, respectively.

Since it was difficult to quantify exactly the number of turns involved by the fault, so after the connections were completed, the winding was energized by a low voltage power supply and the open circuit voltage between the tap conductors was recorded. This measured voltage between the taps, divided by the line to neutral value of the measured voltage applied to the winding, was an exact measure of the fraction of the winding that was involved. The fault level that could be realized by shunting the tap conductors was equal to 0.2% of the turns on the winding, which involves a very small percentage of the winding. Before reassembling the transformer, an insulation resistance test was performed to verify that the resistance of the tap conductors to ground was greater than 1 MΩ. A glass wall as a replacement for the front wall of the transformer tank was fixed to the tank by screw bolts and then the oil refilled. Thereafter, interturn faults could be staged by connecting two taps to each other through a low impedance knife switch to be able to handle the extremely high circulating fault currents flowing through the shorted turns. To adjust the fault severity in the shorted turns, a variable resistor was used in series with the switch in the conductive path between the terminals of the fault region. Various levels of fault severity could then be attained by changing the value of the fault resistance in this leakage path.

Before conducting the experiments, a full-load test was performed on the transformer with the taps open to verify that the modifications had not changed the transformers’ normal operating characteristics. Once this test was completed,
selected fault scenarios could be staged to make the SFRA measurements.

4. Identification of the best measurement configuration

To identify the most appropriate test configuration for making SFRA measurements, two different transfer functions, various terminal configurations and three categories of measurement types were studied. The sensitivity of the two transfer functions mentioned earlier, i.e. voltage gain and impedance, in detecting interturn faults was investigated by analyzing the frequency responses determined by each of the methods. Once the appropriate transfer function for fault detection was identified, the next step was to determine the most appropriate combination of terminal connection and measurement type for achieving the maximum fault detection ability. Open and short circuit terminal configurations and three categories of winding measurement including high voltage, low voltage and inter-winding measurements were made to identify the most sensitive configuration for detecting interturn winding faults.

4.1. Transfer function

As mentioned earlier, there exist two conventionally used transfer functions in applying the SFRA method: voltage gain and impedance. At the outset, it must be emphasized that the sensitivity of a winding transfer function in detection of physical changes inside the winding depends on the number and the frequency value of resonances points of the transfer function. When a transfer function is reduced to its simplest form, it generates a ratio of two polynomials. The roots of the denominator are referred to as ‘natural frequencies’ or resonances which form the main characteristics of a transfer function. The more resonance points in those frequency ranges showing significant physical changes, the greater the sensitivity of the response in detecting defects [23].

Figures 4 and 5 show the amplitude frequency response corresponding to the impedance and voltage gain transfer functions of three phases of HV winding of the studied
Figure 6. Voltage gain as a measured transfer function of three phases of the HV winding with all LV terminals shorted (logarithmic frequency scale from 100 Hz to 1 MHz).

transformer respectively, when the transformer is without oil. Comparing these two figures, it becomes evident that the voltage gain is superior to the impedance transfer function owing to preparing a larger number of resonance points in the frequency range between 100 Hz and 1 MHz, which causes the voltage gain transfer function to be more sensitive in detecting winding defects.

4.2. Terminal connection

SFRA as an offline and low voltage measurement does not impose precautions on terminal configuration such as those that exist in HV tests that all non-tested windings must be short circuited to prevent their accidental damage due to transferred/induced voltages [29]. Thus, the primary objective in these low voltage tests, in contrast to HV tests, is to achieve the highest possible fault detection ability. The relevant standards specify two alternatives for terminal connections, open circuit and short circuit measurements. An open circuit measurement is made from one end of a winding to another with all other terminals floating. A short circuit measurement is made with the same SFRA test lead connections as an open circuit measurement but with the difference that another non-tested winding is short circuited.

Figure 6 shows SFRA measurements in the form of a trace of response in dB against frequency in kHz made on three phases of HV winding of the transformer without oil while the non-tested LV windings were shorted. Comparison of the given results in figure 6 with figure 5, which illustrate the transfer function of the winding in two states, shorting out and floating the non-tested windings, respectively, indicates that short circuiting the non-tested windings removes the information from the FRA response at lower frequencies below 10 kHz. In analyzing SFRA traces, the low frequency range, which is the inductive region of the SFRA scan in general, tends to relate to the magnetic core. Since the penetration depth of the magnetic field decreases with increasing frequency, the core effects are expected at lower frequencies in the frequency response, while for higher frequencies the core acts effectively as an earthed boundary [30]. In [7] it is stated that the core effects are located in the frequency range below 1 kHz, and for frequencies greater than 1 kHz, the iron core does not play a significant role. In [4] the effect of the core becomes significant for frequencies lower than 2 kHz. Anyhow, there is an agreement between all experts [4, 7, 10, 19, 30–33] that the core effect is identified in the lowest frequency bandwidth of the frequency response.

Shorting out the non-tested windings, constrains the flux in the transformer to follow certain paths around the winding conductors rather than penetrating the iron core which results in removing the core effects and consequently the loss of potentially useful data at lower frequencies. In contrast, in configurations in which the non-tested winding are left floating, the windings on the transformer are tested taking into account the interferences from the core and hence provide further information about the transformer condition.

4.3. Measurement type

Conventionally, as mentioned earlier, winding measurements in SFRA tests consist of three categories including HV winding, LV winding and inter-winding measurements. Figure 5 shows the results of SFRA measurements for each phase of HV winding of the transformer when the transformer is without oil. Comparing traces of the three phase plots, it becomes evident that at medium and high frequencies, the results of the three phases agree quite well, while the center phase exhibits deviation from the two outer phases at lower frequencies. Clearly, the center phase exhibits a single low frequency resonance, while the outer phases show two resonance points. Theses resonance points are caused by interaction of the shunt capacitance of the windings with the magnetizing inductance [10]. The difference between three phase SFRA results in the low frequency range is owing to distinct magnetic flux paths in the core and hence different magnetizing inductance seen by each phase of the transformer. The outer phases see two distinct magnetic paths with different lengths which are reflected in the two resonance points while
the center phase shows two similar paths which results in a single reluctance path and consequently single resonance point.

Figure 7 shows the results of SFRA measurements for each phase of LV winding of the transformer when the transformer is without oil. An inspection of the amplitude response plots for both LV and HV winding measurements, figures 7 and 5, clearly reveals some important differences. Due to the low impedance property of the high current side of the transformer, LV winding measurements have least attenuation as compared to the HV winding. Similar to HV winding, the low frequency response of the LV winding is typically characterized by a decreasing amplitude reaching a minimum in a core resonance at or below 1 kHz; however, in contrast with low frequency behavior of the HV winding, the first peak after the core resonance approaches 0 dB and is concave and smooth. At high frequencies, which are characterized by a more confused group of resonances, corresponding to the interaction of the shunt and series capacitances with air-cored inductances of parts of the windings [10], the LV winding has fewer fluctuations and is flatter. This characteristic is due to the simple construction of the LV winding, which contributes to less complexity in its distributive network and fewer resonance points as compared to the HV winding.

Figure 8 shows the SFRA results taken by inter-winding measurements for each phase of the transformer in normal operating condition which are plotted as dB responses against frequency. As seen in the plots given in figure 8, the traces start with high attenuation, between $-30$ and $-40$ dB. As opposed to HV and LV winding responses, which are characterized by decreasing amplitude in the low frequency range, the inter-winding measurement produces a smoother trace in this range due to domination of the capacitive component of the transfer function determined by inter-winding measurement. Obviously such behavior causes the inter-winding measurements to be made with no reference to the core effects at lower frequencies.

The comparison of transfer functions obtained by three types of measurements, offers greater ability of the HV winding measurements, as compared to the two other categories, to detect winding defects owing to preparing a
larger number of resonance points and also effectively taking into account the core effects at lower frequencies.

5. Diagnosing faults

To consider the sensitivity of the identified configuration for making SFRA measurements, a fault involving 0.2% turns was staged on the phase ‘U’ of the HV winding of the transformer. It should be noted that the imposed fault involves a very small percentage of the winding. The smallest value of the fault resistance was chosen as well to account for a metal-to-metal contact and dispose of an extreme value which helped to evaluate trends. Over the course of the experimental tests, a series of experiments was conducted, in some cases with several trials of each to verify the correctness of the measurement records. Figure 9 gives two traces collected under normal and faulty operating conditions of the transformers when the transformer is filled with oil. It is clear from the results that the faulted response is substantially different from the non-faulted response over the low frequency range below 1 kHz.

The key point to understand the low frequency deviation caused by shorted turns can be found in the explanation of Faraday’s law in the shorted turns. Faraday’s law states that the electromotive force (emf) induced in a turn equals the rate of variation of the electromagnetic flux inside it. A well-known conclusion from this law is that at a fixed frequency, the amount of flux entering the turn is fixed by the emf at its terminals. From this assumption, when a short circuit occurs at a given turn, the voltage is forced to drop in it and consequently circulating current flows in the short-circuited turn, to limit the flux entering the turn. Let us consider an ideal situation where a turn with null resistance is short circuited by a null fault resistance. In this condition, the shorted turn would have a null voltage at its terminals and hence no flux would enter its contour. The larger the fault resistance, the larger is the flux entering the turn. In contrast, as the severity of the short circuit increases, i.e. the turns are short circuited with smaller fault resistance, a larger amount of flux would be surrounding the shorted turns. The flux plot of the transformer generated by the FEM of the studied transformer under normal operating condition and after a short circuit fault arising along one of the transformer HV windings’ disks on phase ‘U’ are given in figures 10(a) and (b) respectively. It can clearly be seen from figure 10, how the distribution of the magnetic flux is fundamentally altered after the fault occurrence on the winding. There is a strong leakage flux that, despite the normal leakage flux, surrounded the damaged turns through air paths and reduced flux lines inside the shorted turns on the core limb due to fault occurrence. Dense flux trajectories outside the faulty region in figure 10(b) correspond to higher levels of flux density, outside the damaged turns, and reduction of it on the transformer core limb. Figure 11 shows a cross-sectional analysis of the flux density at the height of the damaged disk on phase ‘U’, for healthy and damaged transformers at the same time instances respectively. It can readily be seen from the figures that the flux density decreases inside the damaged disk and increases outside the said disk. Both facts agree with the aforementioned explanations. By considering all these observations, one can conclude that the winding short circuit fault changes the magnetizing characteristics of the transformer core which in turn causes the low-frequency deviation of the winding frequency response. As discussed earlier, the core effect is located in the frequency range below 1 kHz, on the winding frequency response when measuring across a winding with other windings floating and not shorted.

Interturn faults, in addition to the changes at lower frequencies of the frequency response, will also give differences at mid-frequencies. In a range of 10 up to 100 kHz, the differences are very significant. As can obviously be seen from the response traces in figure 9, the general effect of the interturn fault is a shift of the transfer function toward higher frequencies. The movement of the resonant frequency pointing

![Figure 9. Transfer function for phase ‘U’ of the HV winding under normal and faulty operating conditions of the transformers (logarithmic frequency scale from 100 Hz to 1 MHz).](image-url)
Figure 10. Flux plot of the transformer under normal and faulty operating conditions generated by the FEM model of transformer: (a) flux plot of the transformer under normal operating condition; (b) flux plot of the transformer after a short circuit fault occurrence along one of the transformer HV windings disks on phase ‘U’.

Figure 11. Magnitude of the electromagnetic flux density at the height of the damaged disk on phase ‘U’ under normal and faulty operating conditions of the transformer.

to the right on the response plot, as a result of interturn fault occurrence, is much more obvious in the frequency range of 10 to 60 kHz. Trends of increasing and decreasing absolute values of the response are also detectable in this frequency range. A closer look at the zoomed transfer function plot in figure 9 indicates that the magnitude of the transfer function changes as much as 6 dB in the pronounced mid-frequency resonance at around 38 kHz from the faulty case where the fault resistance is almost equal to zero to the normal response. This absolute effect is comparable to the uncertainty of the measurement. There is a general agreement between some experts that any difference within about 0.2 dB from one
set of SFRA measurements to the next is usually considered an indication of a physical change inside the transformer [34]. The normal and faulty traces are almost identical at all frequencies above approximately 100 kHz where traces overlay very well in this range.

It should be noted that although the influence of the fault on the faulted phase response is much more obvious, the differences of the two other phases responses as a result of fault occurrence are noticeable too. Figures 12 and 13 present the frequency responses of phases ‘V’ and ‘W’ of the transformer HV winding under both normal and faulty operating conditions, retaining the same fault case considered above. Again behavior similar to the faulted phase response, i.e. movement of the transfer function to higher frequencies and change of the absolute values of the transfer function, is observed for the responses of failure-free phases. Albeit, as compared to faulted phase response in which the effect of the interturn fault reaches into the midrange of the frequency response up to 100 kHz, figure 9, the effect of the fault is negligible above 60 kHz for phase ‘V’ and 25 kHz for phase ‘W’ in their corresponding frequency responses. The effect of the fault on the low frequency range of the responses of non-faulted phases is seriously different. Figures 12 and 13 reveal that, except for removing one of the core resonance points of phase ‘W’, there is no other serious modification in the low frequency responses of the non-faulted phases in spite of the drastic change in the low frequency range of the faulted phase response.

To better prove the characteristic signatures attained for interturn faults inferred based on the inspection of the transfer function of the winding under faulty and normal operating conditions, additional experiments were performed with different degree of fault severity in the shorted turns. Figures 14–16 show the magnitude plot of the transfer functions corresponding to three phases of the transformer HV winding obtained from a frequency sweep analysis as a result of 0.2% winding short circuit but with different fault resistance values to create the desired fault severity level. Considering figures 14–16 proves that the main characteristic features associated with interturn faults extracted from the frequency response measurements, namely displacement of the resonant frequency points to the right and a change in the transfer
function magnitude, are discernible for all the fault severity levels in the mid-frequency range of three phase frequency responses. Furthermore, the change in the low frequency response of the faulted phase is clearly noticeable for all the fault severity levels. Zoomed transfer function plots showing these aspects are illustrated in figures 14–16.

Figure 17 illustrates the frequency response of phase ‘u’ of the transformer LV winding before and after interturn fault occurrence on phase ‘U’ of the HV winding. It can clearly be seen that the most important feature in regard of diagnosis is the deviation of the low frequency response of the transfer function and also creation of one new resonance point around 20 kHz as a result of fault occurrence. The comparison of HV and LV winding measurements, figures 9 and 17, indicates that contrary to HV winding measurements, in which the effects of interturn fault reach into the midrange of the frequency response up to 100 kHz, in LV winding measurements, high frequencies above 40 kHz are not affected by the fault. Obviously, this behavior contributes to less sensitivity of the LV winding measurement in detecting interturn faults as compared to the HV winding.

Figure 18 shows the SFRA results, taken by inter-winding measurements having the terminal of phase ‘U’ of the HV winding as input and the corresponding terminal on the phase ‘u’ of the LV winding as output, prior and after interturn fault occurrence on the phase ‘U’ of the HV winding. While...
reviewing the trace from left to right, a partial difference is seen between normal and faulty responses starting from just above 10 kHz and continuing to around 45 kHz in the form of shifting the resonance points to the right and changing the absolute values of the transfer function. However there is no visible fault indication in the low frequency range of the transfer function, which looks very different to the HV and LV winding measurements described in the previous sections. In fact, such behavior is not surprising, as the low frequency deviation in the winding response as a result of interturn fault is governed by the interaction between core and windings while the inter-winding measurement is made with almost no reference to the core effects at lower frequencies as discussed earlier.

The measurements performed in this section prove the observations made in the previous sections that the voltage gain transfer function when measuring across a HV winding with other windings floating and not shorted is more sensitive to interturn winding faults. It is also proved that the inter-winding measurement is less effective in detecting interturn faults as compared to the two other HV and LV categories. The experiments performed in this study proved that the structure and shape of the transfer function appears to be a function of the type, overall physical size and complexity of the transformer winding. Two types of windings, namely disk and layer type, were investigated in this study. Future work ought to focus on interleaved winding, to extract certain features specific to the transfer function corresponding to this type of winding.
Figure 18. Frequency response of phase ‘U’ of the transformer taken by inter-winding measurements before and after interturn fault occurrence on phase ‘U’ of the HV winding (logarithmic frequency scale from 100 Hz to 1 MHz).

6. Conclusion

Detection of interturn faults on the windings of a real transformer was successfully demonstrated using a sensitive frequency response analysis. Even though sweep frequency response measurement has been increasingly used in recent years to assess the mechanical integrity of transformers, yet this contribution is novel and of practical relevance since detection of interturn winding faults and especially low-level faults on actual windings has not been reported so far. Various basic concepts related to SFRA were presented considering the transformer as a two-port network. Also, a measuring method which assures sufficient reproducibility of the SFRA measurements was explained. The experiments on a distribution transformer for estimating the sensitivity of different transfer functions in detection of interturn faults were the first results. Subsequently, the transformer windings with different types of measurements and terminal configuration were investigated to determine the most suitable set of test configuration which would have the highest possible ability for interturn fault detection. An effort was made to obtain a correct understanding of what governs the modifications of the winding transfer function as a result of fault occurrence by developing a FEM of the tested transformer. Shifting the resonance points to higher frequencies and amplitude differences are general effects of the interturn faults on the winding frequency response. Also, the low frequency measurements proved to be very helpful for accurately monitoring the health condition of the transformer windings. It was found through the experiments that measuring voltage gain across the HV winding of the transformer constitutes the appropriate pair of system function and measurement type, because of preparing the maximum number of natural frequencies and so significantly improving the achievable sensitivity. Inturn faults along the winding will cause significant changes in the magnetic behavior of the transformer and hence give deviation in the low frequency range of the frequency response where it is much affected by the magnetic core. Since by shorting out the non-tested terminals the measurement is made with almost no reference to the magnetic core, it is strongly recommended to use the floating terminal configuration for achieving the highest possible ability for detection of interturn fault. Thus, the voltage gain measurement across the HV winding of the transformer with other windings floating and not shorted is the most appropriate configuration for detecting interturn faults along the windings. It is also proved that the inter-winding measurement is less effective in detecting interturn faults as compared to the two other HV and LV categories. According to the applied tests, the sensitivity of the SFRA method can recognize an interturn fault involving 0.2% of turns on the transformer winding.

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