CORE MAGNETIZATION EFFECTS ON THE FREQUENCY RESPONSE ANALYSIS OF TRANSFORMERS

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Abstract: The transformer frequency response analysis test can be influenced in the low frequency range by the presence of core ferromagnetic remaining magnetization, avoiding a further and precise analysis of the measured data. The first stage to avoid this effect is the magnetization identification, what is mainly made comparing different FRA traces at low frequency, where the core effects are visible and then the residual flux must be removed to obtain an adequate measurement, applying DC voltage following an experimental process explained in the article.

1. INTRODUCTION

The Frequency Response Analysis (FRA) is a widespread diagnostic technique that measures the behaviour of the power transformer when a low voltage sinusoidal wave is applied in a wide frequency bandwidth. This measurement can be considered as a fingerprint of the transformer, used to examine the condition of its internal elements without untanking.

Therefore, the SFRA measurement can be done as a predictive method to assess the transformer condition or when an event, that could have been affected the transformer, has occurred and failure can be suspected.

The basis of the method consists on comparing the trace reference (the SFRA measurement usually done in factory, just after the manufacturing process or when a healthy condition in the transformer is supposed) with new measured trace, both traces must be obtained at the same measurements conditions. Any difference between the two curves, e.g. Figure 1, could mean that any element of the transformer has been modified, and therefore, a possible mechanical fault is present.

Consequently, visual comparison is used to know if some elements of the transformer could have changed at first sight and it is a powerful tool to complement other diagnostic techniques.

On the other hand, three main prospects come up when for visual comparing the FRA curves:

- External effects could influence on the measurement so they must be identified, quantified and eliminated if possible.
- It could be difficult to distinguish the exact faulty component and the location of the fault inside the transformer.
- Quantification of the failure and its effect on the lifetime expected for the transformer are complicated to predict.

The first point unfortunately influences on the measurements conditions and they must be taken into account. The most typical causes of variation on the measurement conditions can be summed up, [9]:

- The use of different measurement instrumentation (equipment and wires) and different setup or even different measurement parameters, e.g. applied voltage level, frequency bandwidth, etc.
- A measuring procedure with different configurations of the transformer, e.g. Tap position, type of bushing, quantity of oil, etc.
- The existence of residual magnetization in the transformer core, Figure 3.

In attempting to obtain wider information about the elements of the transformer through the FRA curves, different research based mainly in transformer models, [2], mathematical and statistical techniques and artificial intelligent, [3] have been developed trying to interpret the integral meaning of the FRA curves. However, there is no a complete and well establish diagnostics methodology collected in the FRA guides and standards ([7], [8],[9] ) currently.

Figure 1: Reference and current FRA traces (T phase).

Figure 2: Graphical comparison among four FRA curves of the same 3Ф, 2 MVA YND11 15/0.4 kV transformer measured with different instrumentation and wires.
In the present paper the residual magnetization will be analyzed as an effect that could cause misinterpretation when using the FRA curves to obtain a diagnostic. Then, the causes of this magnetization on the measurement procedure will be enumerated and the visible effects on the FRA waveforms that must be taken into account to distinguish the existence of remaining magnetization. Finally, an experimental procedure to eliminate the magnetization applied during FRA measurements will be expounded.

2. PROBLEM ANALYSIS

The necessity of analyzing the transformer core magnetization will be explained in the following section.

FRA measurements must be done always in the exactly same conditions to assure that the registered changes are only due to variations caused for mechanical failures of the elements inside the transformer.

The FRA technique is usually done as a part of several off line diagnostic measurement, what means that they are carried out during a disconnection period of the transformer and, therefore, in a usually very narrow time window. The visual inspection of the measured FRA curves results suitable enough in this case because it is an easy and fast procedure to discover at a glance.

The residual magnetization changes the energy storage capacity of the magnetic core; it means that the inductance value changes too. The change of the inductance will affect the FRA traces at low frequency range.

The visible FRA curves depiction due to residual magnetization can be mistaken for a mechanical failure, making a false interpretation.

Hence, the remaining magnetization is an event that must be considered, quantified and eliminated if possible, to avoid its effects on the FRA curves.

Firstly, the physical origin of the remaining magnetization is explained.

As it is well known, a flux density \( B \) appears when a magnetic field intensity \( H \) is applied to the magnetic material, as given by (1):

\[
B = \mu H
\]

Where, the permeability \( \mu \) depends on the characteristics of the material. Depicting several values of \( B \) versus \( H \) for a ferromagnetic material, the Hysteresis Curve is drawn, Fig. 4.

The flux density \( B \) is due to the prior orientation of the magnetic material dipoles. The higher the number of dipoles oriented in the same direction is, the higher the value of \( B \). The sinusoidal voltage applied to the power transformer during the working condition presents a positive and a negative semi-cycle what makes that the dipoles continuously changes their orientation between two directions and so, the value of \( B \) is increasing and decreasing. But, if this voltage is suddenly interrupted the dipoles will remain oriented, and density flux \( B \) will remain even when the magnetic induction \( H \) is over \( (B_r \text{ in Figure 2),} [1], [11], [12], [13] \).

The same effect appears if a DC current what generates a magnetic induction \( H \), is applied to the transformer, [11]. This constant induction \( H \) turns the dipoles and hence, a constant flux density \( B \) appears. Even when the DC current is disconnected, the dipoles remain oriented so the value of the flux density \( B \) remains for a period of time as in the previous case.

In the two cases, the dipoles will turn to the minimum energy position at the end, making the residual magnetization disappears, but due to the magnetic viscosity, this process will take a period of time depending on the size and physical characteristics of the magnetic material, [1].

As a result, two main causes can make that a residual flux stands in the ferromagnetic core:

- A sudden disconnection of the applied voltage without a progressive decrease.
- The application of a DC current what generates a constant magnetic intensity, \( H \).
The first event can occur because the voltages applied to the three phase transformer windings, are not necessary equals at the disconnecting instant. As a result, different levels of magnetization could appear depending on the core column.

The second cause is related with other diagnostic techniques carried out during the same maintenance period. Some of these techniques like Winding Resistance or Insulation Resistance require the application of a high DC current to the windings that produce a residual flux in the core. If this point is not considered, the FRA measurement done just after these techniques will be influenced by the remaining flux.

3. IDENTIFICATION AND EFFECTS OF RESIDUAL MAGNETIZATION IN FRA MEASUREMENTS

The first step to eliminate the influence of the magnetization in the transformer core is to identify if it is really recorded and therefore is present on the FRA traces.

On previous sections the remaining magnetization has been categorized as a negative influence in the FRA measurements. Its physical causes have been analyzed and the possible mechanisms during the diagnostic test that can lead to the appearance of residual flux have been enumerated.

Hence, the first issue to take into account is the events executed in the transformer previously to the FRA measurements, highlighting on the following precursor aspects of residual flux:

- Sudden disconnection of the power grid without progressive voltage decrease.
- Asynchronous disconnection among the three phases.
- Previous application of DC current during other diagnostic test.
- Total time since the transformer disconnection. Due to the material magnetic viscosity, after some time the remaining magnetization can decrease, even to zero. In [1], if residual flux is suspected, a 24 hours waiting time is recommended before doing the FRA measurements to avoid the influence. However, the research done by the group has shown cases where even a period of time higher is not enough, (Figure 3). It is believed that giving an exact period of time is not suitable because it will depend on different factors like the size of the transformer or the particular ground connection.

Unfortunately, these effects can be induced by real failures too, like hot spot or short circuit on the laminated magnetic core, so the identification of the residual flux could be wrong. For this reason, additional information, like DGA analysis is needed. The previously mention faults can cause an increase of the produced gases so that the examination of the DGA results could distinguish among these kind of faults of residual flux presence.

Finally, the last step in the identification process is the visual inspection of the FRA waveforms, taking into account the following premises.

The first premise is to analyze the low frequency bandwidth of the FRA curve. On the one hand, the effect of magnetic properties, where residual flux affects, is only visible in the low frequency bandwidth, [1]. On the other hand, the behavior of the windings is only concentrated on the high frequency bandwidth, [5], Figure 4.
Hence, low frequency section must be considered when trying to identify the remaining magnetization.

The second premise is related with the first one. Regarding that the magnetization effects are only visible at the core it is obvious that the measurements were this effect is neglected are not suitable to residual flux identification. When obtaining the frequency response of a phase winding, the effect of the core can be avoided if the other windings (high or low voltage side) are short circuited, [5]. As a conclusion, only end to end open winding measurements (used terminology in [9]) must be taken into account when identifying the residual flux influence.

In Figure 4, the same X1X0 end to end open and short circuit measurement of a 1Φ autotransformer are presented, with and without residual flux. It can be seen that the differences due to the remaining magnetization is only visible in the low frequency bandwidth (as it was explained before) and only in open circuit measurements, where the core influence is present. However, the X1X0 end to end short circuit (in Y1Y2) measurements show the same curves in magnetized or demagnetized condition, because in this kind of measurements the core effect is neglected.

The third premise consists on comparing the end to end open circuit measurement in both HV and LV sides (even tertiary side if it is possible).

Like the residual flux is contained in the ferromagnetic core, the remaining magnetization effect is visible through any winding, therefore, if exists, it can be detected by any open circuit winding measurement and its influence follow the same tendency in all the measurement where the core effect is shown.

In Figure 5 the magnetization effect, what makes that the transformer inductance decrease, is visible only at low frequencies and the same tendency is repeated in the windings of the 3Φ power transformer.

It must be notice that the three previous points can be applied to any kind of transformer (1Φ or 3Φ transformer of any power and independently if it is an autotransformer or not, with shell or wound core tipe).

The fourth considered aspect is only applicable to 3Φ transformers, because it needs the 3 phase’s comparison.

The tree phases reference FRA traces of a 3Φ transformer (healthy condition is supposed), offers the main features due to the shape of the ferromagnetic core, [4], Figure 6.

In Figure 5 the magnetization effect in the 3 voltage sides of the 3Φ transformer.

If residual flux is constrained in the same way all around the core, the previous features will be still in
effect. Therefore, if the reference fingerprint is not available, it would not be possible to detect the residual flux because the responses between the two lateral phases are the same, Figure 7.

Figure 7: Example where, in spite of the magnetization, the lateral phase responses are identical.

However, if the residual flux has an anisotropic distribution inside the material (that is the most common case), the remaining magnetization can be difference depending on the phase of the measured winding, as it is illustrated in Figure 8.

In this case the high frequency bandwidth match in the three phases measurements what means that the three windings are equal, like in the healthy condition. But in the low frequency bandwidth the response differs and the two lateral phases do not match.

Figure 8: Example of asymmetry in the remaining magnetization. The measurements of the two lateral phases H1H0 and H3H0 show different responses at low frequencies. The transformer is the same as shown in Figure 3.

The four previous premises allow identifying the remaining magnetization in the FRA curves even without the reference fingerprint. This demonstrates that the healthy condition response is not indispensable. However, if these curves are available, a fifth premise can be evaluated to recognize the presence of a residual flux influencing the FRA test.

As it is shown in Figure 5, the remaining magnetization decreases the value of the magnetizing inductance comparing the magnetized and demagnetized condition.

4. PROCEDURES TO AVOID THE REMANENT MAGNETIZATION

In section 3, the different steps to clarify if the FRA curve is influenced by the residual flux are enumerated. Therefore, after the effect identification, it is necessary to eliminate it. Three different mechanisms will be discussed to remove the residual flux.

The first procedure consists on waiting enough time to decrease the remaining magnetization. Due to the magnetic viscosity, the residual flux can go to zero if no other source is applied. The needed time calculation depending on the power, size and characteristics of the transformer is proposed for further research.

The second procedure consists on applying an AC voltage source during some periods of the waveform making its amplitude reaches zero. The AC voltage induces an AC current that orients and reorients the magnetic dipoles up to the stable position where the energy and the residual flux are null. But, the required equipment for slow voltage reduction is not always available in the substation where the FRA measurements are performed.

The third procedure consists on Apply a DC voltage source on any winding (HV voltage side is preferable to generate a lower current) during a short period of time. The DC source will induce a current until it stands constant, (Figure ). The rest of the windings must be in open connection. The DC voltage polarity must be changed, applying it during a lower period of time. The procedure is repeated in around 10 stages in, decreasing the application time.

It can be seen that the current is nearly zero during approximately the first minute, then it starts increasing and finally it stabilizes again.

The needed instrumentation shown in Figure 5 is composed by a voltage source (a 12 V battery), the connection wires, a switch and an ammeter.
The procedure was successfully applied to several transformers during FRA Test. The Figure 3 shows an example of the FRA curves with and without residual flux influence.

5. CONCLUSIONS

Residual flux causes a remaining magnetization in the ferromagnetic core that influences the low frequency response of a power transformer, avoiding further and precise analysis in the measured data. Therefore, it is a problem that must be identified and removed.

End to end open circuit FRA measurements are the most adequate to identify a remaining magnetization.

One of the main causes of the residual flux consists on the application of a DC current during other diagnostic test. So, it is highly recommended to perform the FRA measurements at the beginning of the test, during a maintenance period, to avoid undesired effects on the curves.

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7. REFERENCES