EXPERIENCE OF THE APPLICATIONS OF FRA METHODOLOGY TO EVALUATE SHORT-CIRCUIT TESTS IN DISTRIBUTION TRANSFORMERS

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ABSTRACT

The normalized terminal short circuit test takes as evaluation approaches, the comparison of the results of the routine tests carried out before and after the applications followed by the visual inspection by means of disassembly of the machine (extracting of the active parts out of the tank). The objective of the present work was to respond to if the evaluation by means of the comparison of the Frequency Response Analysis, (FRA) carried out before and after the short circuit applications, can be such a sensitive tool as the suitable ones in the applicable Standards. More than 120 results from 5 to 1,000kVA distributions transformers tests are presented obtained in standardized tests and the performance of this method is compared with regard to the standard methods of fault detection. It can be concluded that the FRA methodology is a useful tool in the determination of the fault type and localization before the transformer disassembling.

INTRODUCTION

The design and manufacture of transformers should keep in mind the efforts taken place during short-circuits in order to avoid damages that impede its operation after clearing the system fault. Although there are analytic methods to foresee the thermal and mechanical effects due to short-circuits, whenever it is possible experimental tests should be carried out to validate the design. The international standards specify the capacity to withstand short-circuits stresses that should possess the transformers and the necessary tests to verify it [1, 2].

The standardized tests for the verification of the capacity of withstand short-circuits simply consist on a series of applications of short-circuits in transformer terminals during predetermined time durations. One of the most important and difficult aspects to be defined is the criterion that should be used to emit the verdict of the test result, because it should be clearly established if the transformer had withstood the short-circuit stress. The behavior is clear when the machine suffers considerable damage, but it is quite complex to define it when the solicitation produces structural modifications that are not evidenced as a fault, but that they impede its normal operation. Standards in general indicate procedures to help to verify if there was damage during the short-circuits, but there are many cases where it is left in charge of the test responsible to define if these damages imply that the transformer doesn't withstood the test. The most accurate methods to verify damages are that of comparison of the leakage impedance measured before and after the tests, and the visual inspection of the windings after the transformer has been disassembled.

The windings movements and displacements due to electro-dynamical stresses caused by short-circuits, are particular types of fault. These displacements many times are not detected until the insulation is damaged and a fault that prevents that the machine continues operating takes place. Exist several not standardized methods that allow to detect these movements with enough accuracy like the Frequency Response Analysis, (FRA), Low voltage impulse (LVI) and the no-load current measurement [3]. These methods have the particularity that can also be applicable to detect the state of transformers in service being an excellent tool for the predictive maintenance.

In this work the Frequency Response Analysis is used to assess the transformer behaviour by comparing the FRA results before and after the short-circuit applications in order to detecting eventual deformations in the windings that facilitate the emission of the state verdict. In addition, the application of the FRA in these tests configures a good test platform to analyse its effectiveness when predicting damages in transformers.

The technique of frequency response analysis applied to transformers

The frequency response of the windings of a transformer to an injected signal in one of its terminals was considered from many years ago as a diagnosis form of the structural state of the transformer [4]. The form in which the technique is carried out has many alternatives, those that have been evolving in time and are still in continuous development.

The frequency response can be obtained in diverse ways. One of them is the transformer response from a low voltage impulse signal LVI. This response obtained in the time domain can be transformed to the frequency domain by using the Fast Fourier Transform (FFT). In this way the amplitudes of the component frequencies of the applied and transmitted signal can be calculated, which are compared by means of the Frequency Response Analysis (FRA). This frequency response comparison is known as Impulse Frequency Response Analysis (IFRA).

Since the objective of the method is to obtain the frequency response, an alternative is to carry out a sweeping of frequencies directly by means of sinusoidal signals, obtaining individually the response to each frequency. This methodology is denominated SFRA (Sweep Frequency Response Analysis), or simply FRA. The technique consists on the application of a sinusoidal voltage between one the terminals of the transformer under analysis and the transformer tank or chassis, as shown in Figure 1. This voltage is considered as reference signal (Ve) being compared with the response, measured between another of the terminals and the tank (Vs). The frequency response can be obtained in amplitude and angle.
amplitude response is obtained by means of the quotient between the applied and the exit voltages (Ve/Vs), while the phase response is obtained by means of the phase difference among Ve and Vs in degrees [5].

$$R(f) = 20\log_{10} \frac{V_e(f)}{V_s(f)}$$

In this process of application of a sinusoidal signal of dissimilar frequencies (sweeping), the windings behave like an impedance composed by the inductive, capacitive and resistive parts. The capacitive and inductive components change their magnitude and phase angle with the frequency, being more significant the inductive reactance for low frequencies and the capacitive for high frequencies.

The distribution of the components of the characteristic impedance of the winding is very complex, and depends of the geometry of the different elements and of the state and composition of the present insulation. This makes that the response, that is to say the impedance measured at dissimilar frequencies, be the same only if there are not modifications in the structure and composition of the active part of the transformer.

**Methods of obtaining FRA**

The obtaining of the frequency response of each winding can be done by means of diverse forms of signal application and response obtaining. Generally the measurement is carried out individually on each winding, applying the signal in a winding end against earth and measuring the response in the other winding in the same way. This measurement way it is only possible in the windings connected in Y (or zig-zag) since it is possible to apply the signal on each phase insulator and to measure the response in the neutral terminal (or vice versa). But this is not possible in the Delta connection, since the windings of the different phases are connected internally, making more difficult the discrimination of the faulted phases [6].

Since the transformers in study in this work are of distribution type, with Delta-wye connection, two measurement methods were used as shown in Figure 2 [7].

**Method 1 (end-to-end):** the signal is applied on one of the high voltage (HV) terminals and the response is measured in another of the HV terminals. This way the response of only one phase is obtained, but always the measurement is influenced by the effect of the other two windings. With this method, three records are obtained in three-phase transformers, being in general very difficult to discern which is the windings or the windings that can present problems. For single-phase transformers, this method can be only applied in those transformers that operate under line-to-line voltage in the HV side.

**Method 2 (inter-winding):** the sign is applied on one of the HV terminals and the response is measured in the Low Voltage (LV) homologous terminal. In three-phase transformers, this method could give a better indication of the affected LV winding. This method can be applied to single-phase transformers for line-to-ground voltage in the HV side (single insulator type).

**Statistical indicators**

The application of the FRA method for the diagnosis of faults or winding displacement of transformers, requires of a comparison among the obtained response with regard to one of reference. This comparison in general is carried out in graphic form, that is to say superimposing the response graphics and visually detecting the differences. This methodology requires of an expert to obtain information that can be valid. This is usually an obstacle when applying the method in field tests carried out with commercial equipment and for personal not always fully qualified for the diagnosis.

For this reason, during the last years several researchers have been trying to develop methodologies that allow to obtain information that can be evaluated without the need of an expert. One of these methods uses Statistical Indicators to compare the different FRA responses. In the today references, three indicators can stick out as those more used: Correlation Coefficient (CC), Standard Deviation (SD) and the Absolute Sum of the Logarithm.
Errors (ASLE) [8, 9].

a) Correlation Coefficient (CC):
\[ CC_{(x,y)} = \frac{\sum_{i=1}^{n} X_i Y_i}{\sqrt{\sum_{i=1}^{n} X_i^2 \sum_{i=1}^{n} Y_i^2}} \]

b) Standard Deviation (SD):
\[ SD_{(x,y)} = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - X_i)^2}{n}} \]

c) Absolute Sum of the Logarithm Errors (ASLE):
\[ ASLE_{(x,y)} = \frac{\sum_{i=1}^{n} \left| 20 \log_{10} Y_i - 20 \log_{10} X_i \right|}{n} \]

**Dynamic short-circuit test of transformers**

The standardized dynamic short-circuit test of transformers consists simply on a series of applications to the primary winding with a limited duration and with rated voltage, being the secondary winding with their terminals in short-circuit [1, 2]. These applications can be per-phase or in three-phase form, assuring that the three phases will be stressed. In addition, the position of the tap-changer is modified in position among applications, in order to guaranteeing that the stresses take place with the parted windings in all their extreme portions.

This test is carried out in distribution transformers that generally have connection Delta-wye at the Electric Power System Protection Institute (EPSPI or IPSEP in Spanish) for more than thirty 30 years [10]. The scheme more commonly used at the moment consists on the connection of the transformer through the primary winding (HV) with the secondary winding (LV) previously short-circuited in single-phase form.

To verify that the transformer overcomes the test, routine tests are carried out before and after the short-circuit applications. This way the results are compared in order to evidencing damages or movements that represent a potential fault risk. Of all the methodologies for fault detection, the most sensitive one is the comparison of the leakage impedance, particularly their inductive component (Xcc), since small variations of the measured values before and after the short-circuit applications indicate damages that many times are not visually detected. For this parameter, the standards give a maximum difference of 2% for transformers with concentric circular windings and of 7.5% for transformers with concentric rectangular windings.

**EXPERIMENTAL RESULTS**

Once the necessary adjustments to obtain a correct application of the FRA were carried out, this comparison method was applied in systematic form, as a complement in the standardized short-circuit tests that are normally carried out at the IPSEP for protocollization reasons.

From 2011, were carried out a total of 135 tests with this modality. The results of these tests were positives in 99 cases, that is to say the tested transformer withstood successfully the test (PAS), while the 36 remaining tests the transformers did not withstood (overcome) the test (NOP).

The already described methods 1 and 2 were used to apply the FRA methodology [7]. The method 1 was applied in all the cases, while the method 2 began to be applied after the test number 54 (81 cases).

As an example, in Figure 3 FRA response diagrams are presented by using the mentioned methods corresponding to a transformer that did not experience damages in the short-circuit test. In the graphics the comparative results of FRA response are shown, before and after the short-circuit applications. A constant voltage value of 10 V was applied in one of the terminals and the response was measured in the other winding terminal. The frequency sweeping was made between 0.1 kHz and 5 Mhz. Assuming that the variation observed between 0.1 and 2 kHz is due to the difference in the remnant magnetism among the measurements, in the rest of the sweeping there is total agreement. This result coincides with the one obtained by means of the measurement of the leakage reactance (ΔXcc% = 0.28%) indicating that there is no appreciable deformation in the active part of the transformer.

**Application of Numeric Indexes to evaluate the FRA**

With the objective of obtaining an indicator that allows to carry out a more objective diagnosis of the result of the FRA methodology, a study with numeric indicators was carried out.
The analysis of the results obtained with FRA was carried out by means of the application of three statistical indicators, the Correlation Coefficient (CC), the Standard Deviation (SD) and the Absolute Sum of the Logarithm of the Errors (ASLE).

The application of these indicators was done on the response in frequency records of 63 tests of three-phase transformers.

To establish a comparison among the obtained data each indicator was plotted as function of the variation of the leakage reactance ($\Delta X_{cc}$%), registered before and after the short-circuit applications. This way it can be related the level of damage taken place by the short-circuits, reflected by the variation in the leakage impedance, with the value of each numeric index. The calculation of each indicator was carried out in the total range of the sweeping of frequencies and in three areas defined in the following way: 50 Hz to 3 kHz; 3 kHz to 100 kHz and 100 kHz to 5 MHz. This scheme makes more sensitive the detection method for statistical indicators, allowing to define the area that presents differences.

Figure 4 presents the results for the CC indicator. This coefficient have a tendency to 1 when there is exact coincidence among $X$ and $Y$ vectors and tends to zero as there is higher difference among them. The results indicate that with a value of $\Delta X_{cc} > 8 \%$ the index shows values that would indicate windings movement.

The results of the SD are presented in Figure 5. In this case the value tends to zero when there is coincidence among $X$ and $Y$, having a tendency to increase as both vectors differ. The results indicate a growing tendency as $\Delta X_{cc}$% increases.

Figure 6 shows the results of the Index ASLE. This value also tends to zero when the coincidence is absolute, reaching higher values as both responses differ. The results also have a growing tendency as $\Delta X_{cc}$% increases.

In order of obtaining a relationship between the value of the dissimilar indexes and the level of damage of the transformer after the short-circuit test, the value of the three indexes were compared in different frequency zones with the variation of the leakage reactance ($\Delta X_{cc}$%) registered before and after the applications. Were taken out of the analysis the indexes obtained in the zone from 50 Hz to 3 kHz since it was observed that in this area, influenced by the magnetization inductance, frequently there are variations between measurements due to the remnant magnetism (an example is shown in figure 4).

In Tables 1 and 2 the values limits for each index are presented, considering three-phase transformers. For these
These conclusions leave outlined for the future a give complementary information. It is advisable the application of both methods, since both the not involved terminals keep open. It is concluded that Method 2 (inter-winding between HV and LV), both with denominated as Method 1 (end-to-end HV applied) and distribution transformers with connection Dy, to those FRA response, finding as the most efficient for the presence of faults. Should be supported by other evidences to confirm the importance to stress that these indicators are a good tool for being shown the last one as the most efficient. It is windings. The applied indexes were CC, SD and ASLE, shown, with the two used measurement methods.

<table>
<thead>
<tr>
<th>Index</th>
<th>Without fault</th>
<th>Probable fault</th>
<th>Faulted</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>&gt;0.9996</td>
<td>0.9996&lt;CC&gt;0.9900</td>
<td>&lt;0.9900</td>
</tr>
<tr>
<td>SD</td>
<td>&lt;0.01</td>
<td>0.01&lt;SD&lt;0.06</td>
<td>&gt;0.06</td>
</tr>
<tr>
<td>ASLE</td>
<td>&lt;0.30</td>
<td>0.30&lt;ASLE&lt;2.30</td>
<td>&gt;2.30</td>
</tr>
</tbody>
</table>

Table 2

It is also important to verify the efficiency of each index, that is to say, in what percentage of cases the value of each index indicates a definitive result, that is to say “Without fault” or “Faulted”, in agreement with the result of the ΔXcc%. In the Table 3 the results of the three indexes are shown, with the two used measurement methods.

<table>
<thead>
<tr>
<th>Index</th>
<th>Method 1</th>
<th>Method 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC</td>
<td>55.32%</td>
<td>13.04%</td>
</tr>
<tr>
<td>SD</td>
<td>42.55%</td>
<td>39.13%</td>
</tr>
<tr>
<td>ASLE</td>
<td>51.06%</td>
<td>69.57%</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The systematic application of the Frequency Response Analysis in commercial distribution transformers facilitated the study of methodological aspects and of results processing that now are being treated by specialized researchers. Next the more significant conclusions are described:

- The statistical indicators shown with a good certainty the presence of deformations or displacements in the windings. The applied indexes were CC, SD and ASLE, being shown the last one as the most efficient. It is important to stress that these indicators are a good tool for the diagnosis, but not just for itself, it is necessary that should be supported by other evidences to confirm the presence of faults.
- Different measurement methods were used to obtain the FRA response, finding as the most efficient for the distribution transformers with connection Dy, to those denominated as Method 1 (end-to-end HV applied) and Method 2 (inter-winding between HV and LV), both with the not involved terminals keep open. It is concluded that it is advisable the application of both methods, since both give complementary information.

These conclusions leave outlined for the future a continuity of the study in two fundamental aspects:

- To consolidate an effective tool that allows to easily detect (without experts) and without doubts, if there are faults or defects in the active parts of the transformer. In this sense, the numeric indicators are very promissory, for what their systematic application will be continued trying to specify with more definition the evaluation criteria.
- The other aspect is to recognize the way from the response to the FRA taken place by the different fault types that can be presented in the tests. That is to say to relate the response mode with the fault type or present defect. This analysis requires of the study of a higher number of cases that allows to carry out an appropriate characterization of the different responses of the FRA.

REFERENCES