SWEEP FREQUENCY RESPONSE ANALYSIS TEST AS TOOL FOR DISTRIBUTION TRANSFORMERS MANAGEMENT

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ABSTRACT

Distribution transformers used in secondary substations are strongly affected during faults in low voltage grids. Transformers are expected to survive a number of short circuits without failure but, once any significant winding deformation or core damage is produced, the service life and the likelihood of surviving further short circuits is greatly reduced because of locally increased electromagnetic stresses.

Given the need for diagnosing failures and quickly putting the unit back into service it is evident that a complete set of tests, as done in power transformers' condition assessment, is not an option.

The main objective of this paper is to present Sweep Frequency Response Analysis (SFRA) test as an alternative to assess the mechanical condition of distribution transformers. For this purpose, a special design of a distribution transformer was used to simulate some failure modes and improve interpretation criteria.

INTRODUCTION

Through-fault currents in distribution transformer windings produce severe electromagnetic forces and can result in winding deformations or core damage. These mechanical defects do not cause a condition of immediate failure in the unit, but are capable of generating localized electromagnetic stresses that may, in short or medium term of operation cause unplanned outages.

To avoid this issue, it is important for utilities to have a tool for evaluating the internal condition of transformers and managing the repair and replacement resources.

One of the most developed technique in recent years, mainly for power transformers, is the Sweep Frequency Response Analysis (SFRA), recognized as an advanced electrical test [1] and which allows a comprehensive evaluation of mechanical condition of the unit.

Currently, the biggest challenge with this test is the interpretation of results. There is a working group of CIGRE (WG A2.53: Objective interpretation methodology for the mechanical condition assessment of transformer windings using Frequency Response Analysis) investigating and collecting experiences with the purpose of obtaining objective and systematic interpretation methodologies. This paper presents some experiences on a distribution transformer in order to obtain useful interpretation criteria when evaluating this type of units.

SFRA

To make a SFRA measurement, a sweep frequency voltage is supplied to a transformer terminal with respect to the tank. The voltage measured at the input terminal is used as reference for the SFRA calculation. A second parameter (response signal) is usually a voltage taken across the measurement impedance connected to a second transformer terminal (see *Test types*) with reference to the tank. The SFRA response amplitude is the ratio between the response signal (Ur) and the source voltage (Us) as a function of the frequency (usually presented in dB) [2].

To evaluate SFRA results, actual data are compared with reference data by visual inspection of the curves. There are three approaches [3] for generating reference data:

- previous fingerprint measurements on the same unit;
- measurements on identical (twin) transformers;
- measurements on separately tested limbs or phases.

Test types

The main SFRA test types according to [3] are four. Each one allows to evaluate different elements of the transformer. They are presented below:

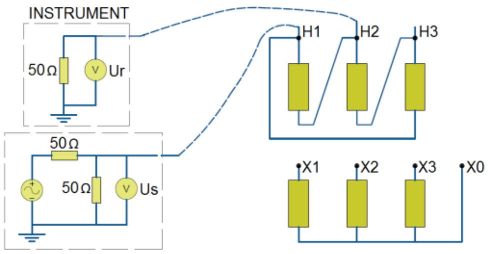

Fig. 1. "End-to-end" test type

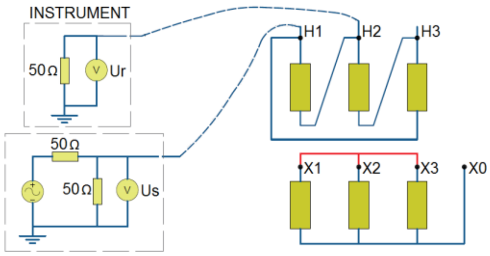

Fig. 2. "End-to-end short-circuit" test type

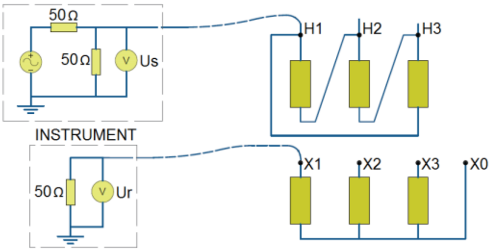

Fig. 3. "Capacitive inter-winding" test type

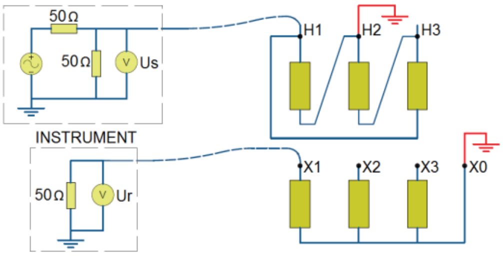

Fig. 4. "Inductive inter-winding" test type

TRANSFORMER UNDER TEST

The transformer used to emulate mechanical defects is a three-phase unit, 13.2/0.4 kV - 160 kVA - Dyn11, paper insulation, similar to those used in South American and European distribution systems, and in this case without tank or oil. It is presented in Fig. 5.

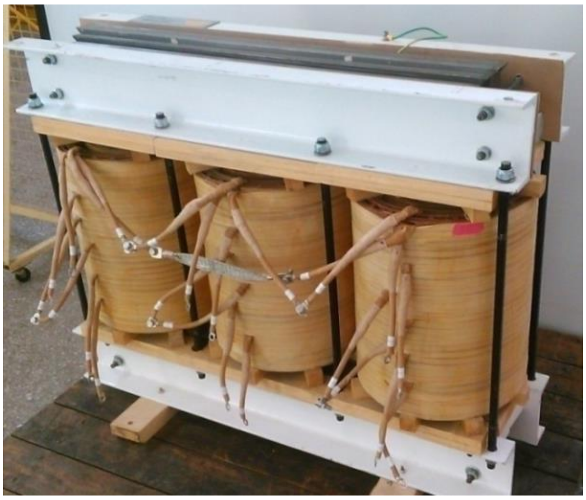

Fig. 5. Transformer used to emulate mechanical defects

The four SFRA test types were made in each phase and for each of the mechanical defects to be emulated. The first test was made in a condition considered as "good condition", which was taken as reference to evaluate the deviations produced in the curves by each mechanical defect.

Failure modes emulated were:

1. Winding turn-to-turn short circuit
2. Open circuited winding
3. Variation in core reluctance
4. Multi grounded core
5. Shifted winding

Winding turn-to-turn short circuit

This is one of the most common faults that occur in distribution transformers. This defect was forced by shorting a single turn in the HV winding of the central column (H3-H2).

Table 1

Defect

Fig. 6. Turn-to-turn short circuit

Test Type	
End-to-end	Great changes in H3-H2. Smaller differences in H1-H3 and H2-H1
End-to-end short-circuit	Without significant deviations
Cap. Inter-winding	Without significant deviations
Ind. Inter-winding	Without significant deviations

SFRA curves

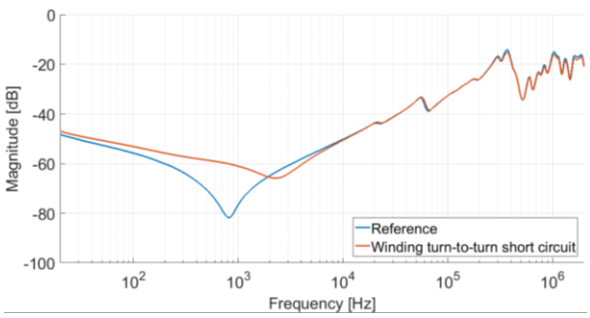

Fig. 7. End-to-end (H3-H2)

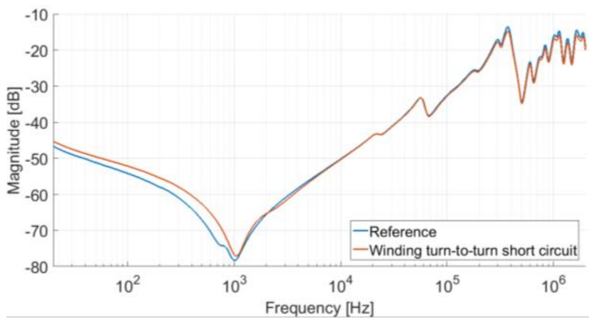

Fig. 8. End-to-end (H2-H1)

Open circuited winding

This defect was emulated by opening two branches of the central winding (H3-H2).

Table 2

Defect

Fig. 9. Open circuited winding

Test Type	
End-to-end	Slight deviations in all windings
End-to-end short-circuit	Great deviations in all windings, mainly in H2-H3
Cap. Inter-winding	Without significant deviations
Ind. Inter-winding	Changes occurred only in the affected winding.

SFRA curves

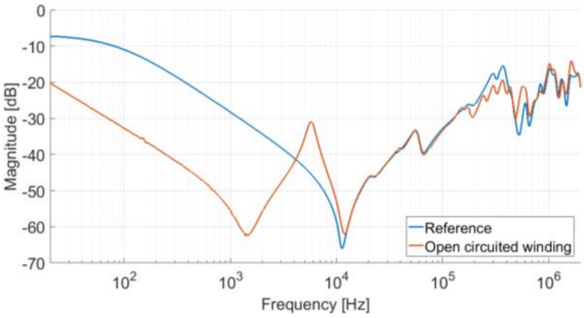

Fig. 10. End-to-end short-circuit (H3-H2). Shorted: X1-X2-X3

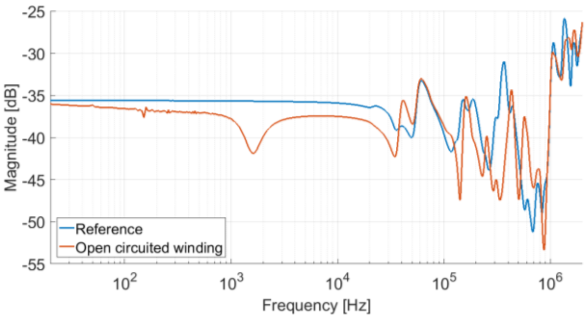

Fig. 11. Inductive inter-winding (H2-X2). Grounded: H3-X0

Variation in core reluctance

This mechanical damage was forced by increasing the core section placing an extra piece of ferromagnetic material on top of the transformer.

Table 3

Defect

Fig. 12. Variation in core reluctance

Test Type	
End-to-end	Slight deviations in all windings
End-to-end short-circuit	Without significant deviations
Cap. Inter-winding	Differences in some resonances
Ind. Inter-winding	Without significant deviations

SFRA curves

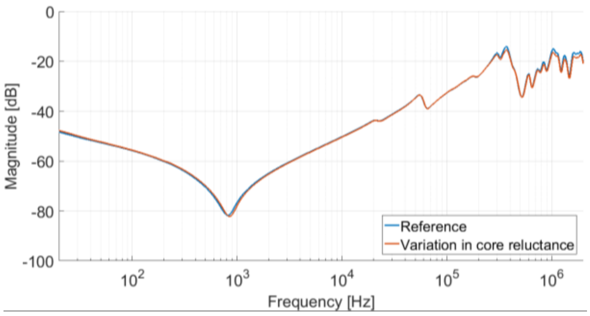

Fig. 13. End-to-end (H3-H2)

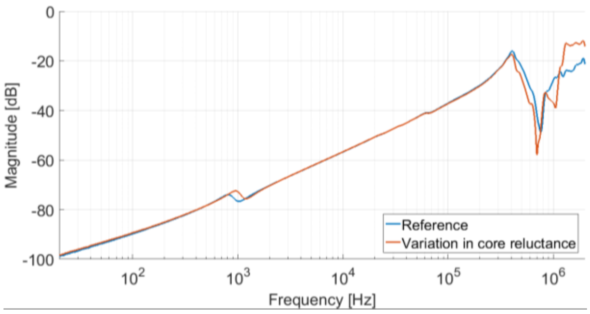

Fig. 14. Capacitive inter-winding (H1-X1).

Multi grounded core

This defect was obtained by placing an additional ground in contact with the laminations of the core.

Table 4

Defect

Fig. 15. Multi grounded core

Test Type	
End-to-end	Small amplitude differences
End-to-end short-circuit	Small amplitude differences
Cap. Inter-winding	Without significant deviations
Ind. Inter-winding	Without significant deviations

SFRA curves

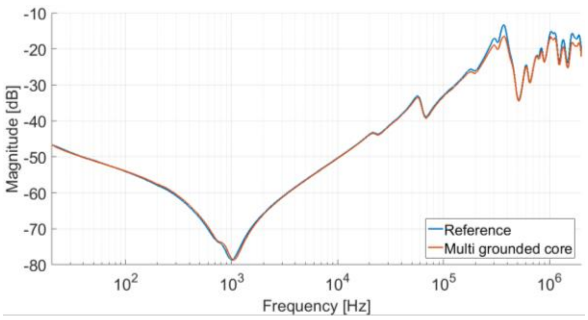

Fig. 16. End-to-end (H1-H3)

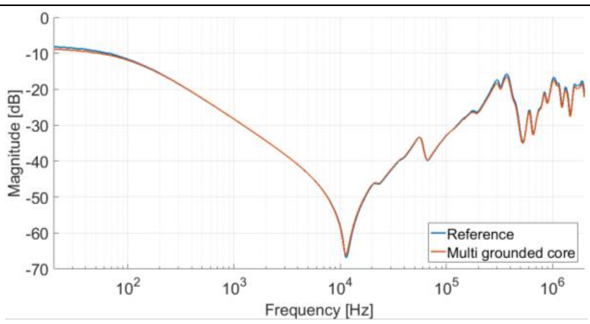

Fig. 17. End-to-end short-circuit (H3-H2). Shorted: X1-X2-X3

Shifted winding

To obtain this mechanical failure the fixing woods were removed and the HV winding of the central column (H3-H2) was moved 3 cm upwards.

Table 5

Defect

Fig. 21. Shifted winding

Test Type	
End-to-end	Resonance shift in H3-H2. Smaller differences in H1-H3 and H2-H1
End-to-end short-circuit	Without significant deviations
Cap. Inter-winding	Without significant deviations
Ind. Inter-winding	Without significant deviations

SFRA curves

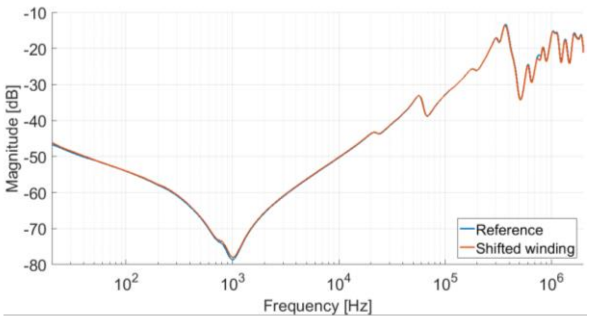

Fig. 22. End-to-end (H1-H3)

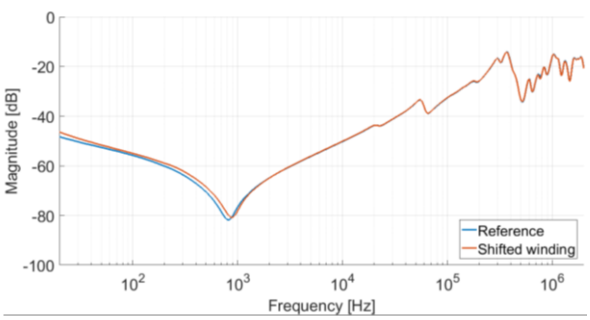

Fig. 23. End-to-end (H3-H2)

ARE SFRA RESPONSES OF DISTRIBUTION TRANSFORMERS DIFFERENT FROM LARGE POWER TRANSFORMERS ?

In order to answer this question, a comparison of IEEE C57.149 [4] with the results measured in the analyzed transformer was made. This guide, in its "failure modes" section, analyzes the effects of transformer deformations on the SFRA curves -only *end-to-end* (EtoE) and *end-to-end short-circuit* (EtoE Sc) type tests- for each frequency range.
For the five failure modes of this paper, Table 6 presents a verification of the diagnosis established in IEEE C57.149. Green color indicates that diagnosis of [4] is verified, and red color means that the diagnosis [4] is not verified.

Table 6

Frequency Range	20 Hz to 10 kHz		5 kHz to 100 kHz		50 kHz to 1 MHz		>1 MHz	
Test Type / Failure	EtoE	EtoE Sc	EtoE	EtoE Sc	EtoE	EtoE Sc	EtoE	EtoE Sc
Winding short circuit	Green	Red	Green	Green	Green	Green	Green	Green
Open circuited winding	Green	Green	Green	Green	Green	Green	Green	Green
Variation in core reluctance	Green	Green	Green	Green	Red	Red	Red	Red
Multi grounded core	Green	Green	Green	Green	Green	Green	Green	Green
Shifted winding	Red	Green	Red	Red	Green	Green	Green	Green

IS SFRA TEST AN ADEQUATE TOOL FOR THIS APPLICATION?

Definitely this test is an adequate tool for the transformer assessment after incidents in medium/low voltage grids. As could be seen, SFRA technique is capable of detecting a wide variety of defects without the need to waste time and resources in performing many tests. With little experience, it is possible to identify the affected component and to take the decision of replacing or re-energizing the unit.
SFRA test has the advantage of being a simple and safe test since voltages involved do not exceed a few volts, important feature when doing tests in passable areas. Also, it is important to consider that the SFRA test is easy to perform in terms of its connections, since stairs, cranes, etc. are not needed due to the size of the distribution transformers.

Additionally, it was demonstrated that SFRA variations have a similar behavior for distribution and power transformers. In power transformers responses have another magnitude considering that capacitance is greater than distribution transformers. That means that the existing interpretation criteria and those that are being developed can be used with some cautions.
Experience has shown that in distribution transformers it is important consider the effect of magnetization on core prior to SFRA tests.
In order to take full advantage of SFRA benefits, it is imperative to train the testing staff and improve interpretation criteria with the own experience.

CONCLUSIONS

The main conclusions are:

a) SFRA test is a useful tool to quickly assess the transformer integrity after failures in low voltage grids because it is capable of detect a wide variety of defects using only one technique.
b) Understanding the typical responses, it is possible to discriminate the type of failure and identify its location.
c) As it was demonstrated, the end-to-end test type is the most sensitive for the majority of mechanical defects so, if there are limitations on the time available, it may be convenient to perform only the end-to-end test on all windings.
d) In distribution systems, where utilities have several transformers of identical specification (twins), the SFRA response can be requested as a type test, and used as a reference for all these units. This represents an important advantage since no reference is needed for each single unit.
e) In grids with high transformer failure rates SFRA test can identify the weak points of the transformer design and implement faster improvements or corrective actions.

Although some interpretation criteria were provided in this work, the adequate training and experience of test operator is essential to obtain reliable results.

REFERENCES

[1] TB CIGRE 445 WG A2.34, *"Guide for Transformer Maintenance"*, February 2011.
[2] TB CIGRE 342 WG A2.26, *"Mechanical-condition assessment of transformer windings using frequency response analysis (FRA)"*, April 2008.
[3] IEC 60076-18-2012: *"Power Transformers - Measurement of Frequency Response"*.
[4] IEEE C57.149-2012: *"IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers"*.