Objective Interpretation of Frequency Response Analysis of Power Transformers

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Tag der mündlichen Prüfung: 25.11.2024

Today the world is changing, and the power grid continues to increase in complexity by integrating intermittent renewables, distributed energy resources, etc. All these factors result in more dynamic loading of the transformer which increases the likelihood of failures. The majority of in-service transformers were installed during the period of rapid economic expansion during the 1980s. Irrespective of the changing generation and demand trends, transformers are expected to last for 30 – 40 years, thus, many transformers are well beyond their intended life. This situation has motivated utilities to implement more efficient maintenance and life expansion strategies in the life cycle of power transformers. These strategies demand proper asset management along with the development of advanced and comprehensive diagnostic methods for transformers.

Among advanced methods, Frequency Response Analysis (FRA) has gained popularity as a sensitive diagnostic test to assess the mechanical integrity of the active part of the transformer. In the last decade, many research efforts have been carried which led to the standardization of FRA measurement procedures. However, the interpretation of FRA results is still backed by the analysis of skillful personnel due to the lack of a standard criteria. Consequently, many international working bodies, i.e., CIGRE, IEEE, and IEC are working in parallel to develop a standard for the condition assessment of the transformer based on FRA results. In contribution to this necessity, this research has proposed some novel methodologies for the objective interpretation of FRA results.

A failure mode analysis is conducted to identify the type of failures in the active part of the transformers. As a consequence, a categorized list of failure modes was compiled. Subsequently, a study on the characterization of the effects of failure modes on FRA was carried out. For this purpose, real case studies are presented, and the effects of different failure modes are discussed objectively. Afterward, deviation patterns are generated that summarize the characteristic impact of individual faults on FRA results. Investigation result shows that it is possible to classify different faults based on their deviation patterns in various frequency sub-bands. The failure mode deviation patterns are the basis for the objective interpretation of FRA results. Based on these characterizations, non-expert users can also gain a better understanding of the difference between two FRA results.

Focusing on the current challenge of developing an effective assessment tool, this study provides a detailed analysis of statistical methods to interpret frequency response measurements. In this research, five criteria for an appropriate numerical index are defined. All indices are evaluated with selected case studies and indices which qualify all criteria are selected as appropriate indices. However, it is not possible to set thresholds for the selected indices as they rely on fixed frequency ranges that can lead to erroneous conclusions. To mitigate these limitations, a vector-based numerical method is defined. Subsequently, a winding assessment factor is introduced, and a criterion of abnormality is pro-posed as an indication of the deformed transformer winding.

This thesis also presents an optimized method to obtain a turn-based 3D high-frequency model of a transformer using the finite integration technique. The novelty of this model is that FRA traces are directly obtained from the 3D model of windings without estimating and solving lumped parameter circuit models. In this model, precise and accurate fault simulations are possible. The model is validated with measurements for the healthy and deformed state of the windings. Good principle agreement of simulation results with the measurements proves the applicability of the model for FRA interpretation studies. The model can be used to generate a large database for different types of winding faults, as it is possible to import a CAD file of the transformer into the software and directly calculate their frequency response without intermediate calculation steps.

In the framework of this research, a simple approach is introduced to estimate the main parameters of the equivalent circuit of a power transformer from different types of FRA measurements. For this purpose, a high-frequency model of a three-phase, three-limb core-type transformer is employed. The effect of trans-former equivalent circuit parameters on FRA signature is analysed through sensitivity studies. To overcome the drawbacks of the conventional indicators, these extracted parameters are then used as identifiers to diagnose fault quantitatively. The performance of the proposed method is analysed with different case studies.

It is foreseen that the application of intelligent systems will continue to grow in the future and both manufacturers and utilities will start to implement the intelligent systems into their diagnostic instruments. Accordingly, in this doctoral thesis, an expert system for automatic interpretation of FRA has also been developed. In expert system, the numerical indices and machine learning techniques are combined to establish a method for automatic interpretation of FRA. Five machine learning algorithms are studied, and real case studies are considered to verify the performance of the expert system. The results suggest that the expert system can reliably identify the six common states of the transformer with good accuracy, and without much human intervention.

In conclusion, the proposed methodologies give insight into the transformer frequency response measurements and ease the objective interpretation of FRA results. Thus, this research provides a way forward towards the establishment of the standard algorithm for a reliable and automatic assessment of trans-former FRA results.