Study Committee D1

Materials and Emerging Test Techniques

Paper D1-PS3-11111

# Use of Multiphysics Simulation Tools for Making a Digital Twin of Power Transformers

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## 1. INTRODUCTION

- The pairing of the virtual and physical worlds allows analysis of operational data measured by monitoring systems to optimize operation and head off problems before they even occur.
- However, to really benefit from digital opportunities, a digital representation with more capabilities than the physical object is desirable.
- In this contribution, the digital twin of a power transformer is made using three-dimensional Multiphysics simulation models which are validated by experimental setup and onsite measurements.

## 2. THERMAL MODELLING

- A digital twin for a distribution transformer (400 kVA/10 kV, ONAN) is made by CFD thermal modelling. A *heat run test* is performed to measure oil and hotspot temperatures at different locations in the active part. A *CFD model* is created to study the transient thermal behavior of the transformer during the heat run test. Because oil flow is dependent on the temperature and vice versa, dynamic CFD calculation has to be applied.
- Figure 1 shows the development of measured temperatures and the CFD simulation results with a starting temperature of 20 °C for the first 16 hours.
- The CFD simulation shows that the hotspot occurs at the third inner layer of HV-winding in the top stack and has a temperature of 88 °C. Since no sensor can be attached to the inner layers of HV-winding, the sensor at the outer layer of HV winding is used for the validation. Comparison between the measured temperature at the HV-winding and the numerical 3D calculation shows a deviation of 3 K at the end of the heat run test.

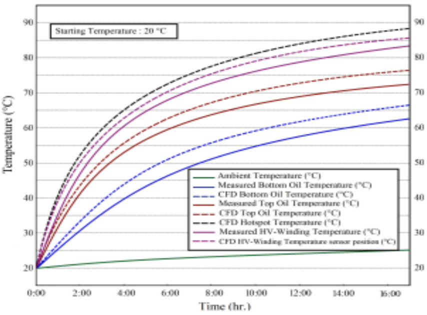


Figure 1. Comparison between the measurement and CFD simulation at starting temperature of 20 °C

## Overload Capability of a Wind Farm Transformer

- To calculate the overload capability, two different thermal models are trained with measurement data of a wind farm transformer during operation with active cooling (ONAF) on high loads.
- After training by minimizing the least square error both models can predict the change of the top-oil temperature depending on the load factor $K$, ambient temperature $\theta_a$, and the fan state. In Figure 3 the validation of both models is displayed by comparison of measured and calculated top oil temperature.

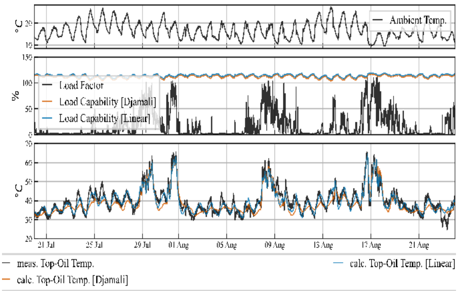


Figure 2. Calculation of top-oil temperature and overload capability during summer

- Hotspot temperature $\theta_h$ is calculated according to

$$\theta_h = \theta_o + H \cdot g_r \cdot K^y$$

with the winding exponent $y$ and the hotspot factor $H$ according to the IEC 60076-7 and the rated winding gradient $g_r$ given by the datasheet of the manufacturer.

- The overload capability can be calculated by considering the maximum hotspot temperature during normal load of 120 °C with an ageing rate > 1

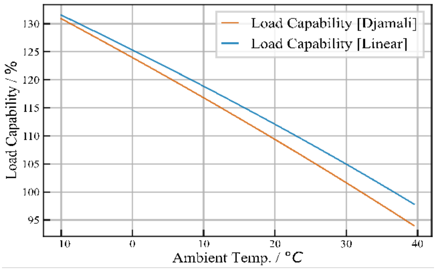


Figure 3. Calculated overload capability dependent on ambient temperature for ONAF cooling

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## 3. TRANSFORMER FREQUENCY RESPONSE MODELLING

- The purpose of using a 3D high-frequency model is to emulate the behaviour of real transformers regarding the interpretation of FRA measurements. CST MW Studio is employed to generate a digital twin based on 3D electromagnetic (EM) simulations using finite integration technique (FIT). A turn-based 3D high-frequency model of a three-limb, three-phase, core type, 3 MVA transformer is simulated.

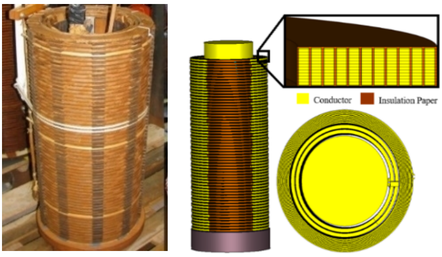
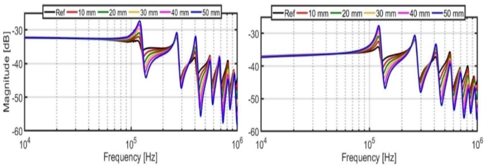



Figure 4. Experimental setup (left) and CST model (right)

- Validation of the model was performed with measurements of both healthy and deformed windings.
- In the deformed case, both the experimental setup and the CST model implement five steps of axial displacement (each step equals 10 mm) in the HV winding. The results indicate good agreement between simulations and measurements, providing evidence of the applicability of the HF model for the interpretation of FRA.
- Difference between simulation and measurement indicates that it is difficult to generate accurate FRA fingerprints of the transformer due to limited accuracy. However, this model can be used to study the effects of different fault types on FRA.




(measurement) (simulation)

Figure 5. FRA (IIW) for different levels of axial displacement

## Application of Digital Twin for Condition Assessment

- Axial Displacement Fault (ADF) is simulated in digital twin, where the HV winding of the B-Phase is displaced downward by Δh = 30 mm (~3.5% of windings height).
- Under ADF, the interaction of the windings and hence the mutual couplings i.e., interwinding capacitance and mutual inductance are changed. Consequently, the effects of ADF are mainly appreciable at medium and high frequency.
- The deviations in the reference and faulted FRA signatures are quantified using the Standard Deviation of Difference (SDD). SDD is a vector-based indicator that plots the difference between a pair of FRA signatures as a function of frequency. The minimum value of SDD (MSDD=-14.1) indicates maximum deviation and it can be used to set a criterion of deformation. It was reported in the author's previous work that MSDD< 5, leads to a deformed winding.
- In this way a digital twin offers new possibilities to investigate objective interpretation methods of FRA and define limits for a ok/fail decision.

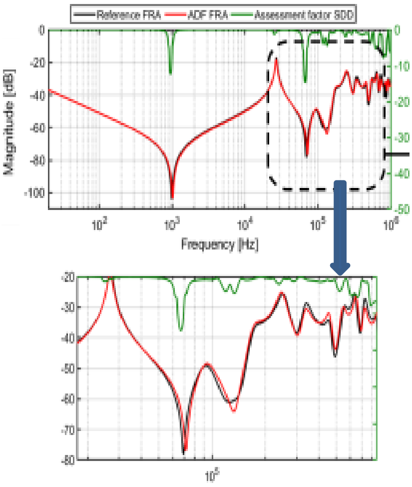



Figure 6. FRA of healthy and axially displaced B-phase winding and SDD assessment factor

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## 4. SIMULATION OF PD ELECTRO-MAGNETIC WAVE PROPAGATION

- Since the propagation paths inside a transformer are complex, localization algorithms, such as time difference of arrival (TDOA), lead to significant errors.
- With a digital twin, PD sources and receivers can be placed in various parts of the transformer and be used to analyse the signal propagation paths.
- A digital twin of a 300 MVA transmission transformer was built in CST Microwave Studio to study the propagation of PD signals and validated based on experimental results which were obtained from onsite measurements on the transformer during scrapping.

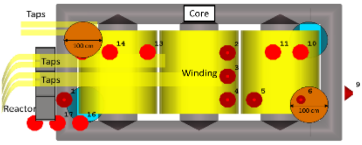


Figure 7. Simulation model of 300 MVA transformer

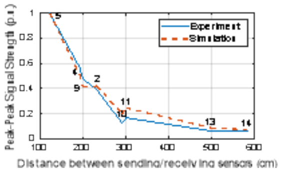


Figure 8. Comparison of experimental and simulated attenuation of signals received from source 6

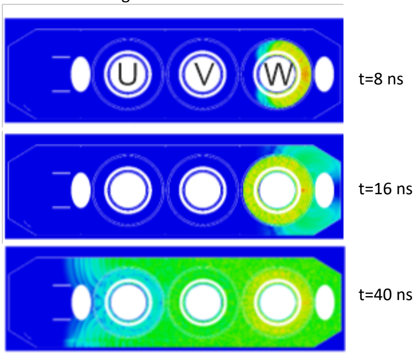


Figure 9. Electromagnetic wave propagation at different time instants when the PD source is inside the winding of phase W

- Based on the validated digital twin, sensor positions can be analysed to determine the optimal locations and numbers of sensors required for sensitive PD source detection and localization.
- Best positions to install sensors on the transformer tank are on the top of the transformer tank and near the outer limbs of the core. These positions experience lower field stress from the 50/60 Hz supply and can detect signals from various sources without the signal becoming noisy.
- It was also determined that only one sensor installed on the tank could not detect signals from all parts of the tank without the signal becoming too noisy. Therefore, at least two sensors are required for PD detection to provide complete coverage of the tank. For PD localization, at least 4 UHF sensors are required.

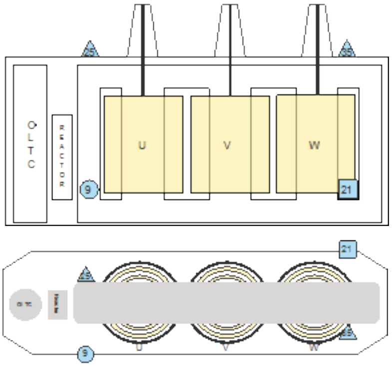


Figure 10. Primary configuration for possible PD localization with two sensors on the top and two sensors on the vertical tank walls while maintaining a separation from high field-stress regions

## 5. CONCLUSION

- Digital twins of power transformers are validated virtual replicas of physical transformers, which can be used to understand the operational behavior better.
- However, a digital twin that reflects the entire technological properties of a transformer is not yet feasible today due to the considerable computing and development efforts.