Power Transformer Hysteresis Measurement

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Abstract: The state-of-the-art in power transformer condition assessment includes different electrical measurement to assess the condition of e.g. the windings, bushings or the transformer core. This work proposes a hysteresis measurement to supplement the available diagnostic for transformer cores. When dealing with hysteresis measurements, remanent flux in the transformer needs to be reduced to a minimum in order to reduce e. g. inrush currents or the transformer sound level after energizing. Different laboratory and field measurements of a DC hysteresis showed that the available demagnetization procedures are not sufficient for all the tested transformer cores. As a consequence, two additional demagnetization procedures are proposed. These demagnetization procedures are based on an established demagnetization algorithm implemented in portable transformer test devices. A supplement saturation/hysteresis is proposed to mitigate the inter-phase magnetic coupling of multi-limb multi-winding power transformers. This saturation/hysteresis test can be performed at rated frequency with a sufficient large power source or as DC measurement with a portable transformer test device. In addition to the condition assessment the hysteresis measurement could also be used for power transformer modelling. The DC hysteresis measurement approach was tested with four different transformer types and different rated power from 50 kVA to 300 MVA.

Keywords: Power Transformer, Transformer Hysteresis, Measurement, Asset-Management, Transformer condition assessment

1 Introduction

The heart of power transformers is the magnetic core, which provides the magnetic coupling between two or more windings. Any damages or changes in the transformer core directly affects the electrical and thermal behavior of the transformer. Therefore, the condition assessment of the transformer core can provide additional information of the transformer and can help to identify negative trends in the transformer condition. The condition of the transformer core can be surveyed with a hysteresis measurement. A hysteresis measurement during the factory acceptance test or during the condition monitoring of transformers is currently not established as state-of-the-art. If a hysteresis measurement would be included in the factory acceptance test, an additional ‘fingerprint’ of the transformer could be established. Follow-up measurements could be compared to the initial ‘fingerprint’ in order to identify any changes in the transformer core. Further diagnosis procedures need to be developed for the analysis of the transformer core. In addition to the condition monitoring, the measured hysteresis could be used for electrical transient simulations of power transformers.

2 State-of-the-Art in Demagnetization and Hysteresis Measurement

2.1 Demagnetization of Power Transformer Cores

The remanent flux in a transformer core can be some ten percent of the nominal flux density. Remanent flux in transformer cores can be caused e.g. by faults, energization and de-energization, DC windings resistance measurements or geomagnetically induced currents (GICs). The remanent flux can negatively affect the transformer diagnosis, such as sweep frequency response analysis (SFRA), magnetizing current measurement, magnetic balancing test or transmission ratio measurement. But also re-energizing a transformer with remanent flux can cause increased inrush currents. These high inrush currents itself can cause negative effects such as mechanical damage of the windings, increased transformer audible sound, faulty tripping of protective devices and increased stress on the insulation. Therefore, it is essential to demagnetize the transformer core and thus reduce the remanent flux to a minimum. In order to remove any remanent flux in the transformer core, the magnetic flux density in the transformer core needs to be increased above nominal flux density level to force the transformer on the major hysteresis loop. Lower flux levels will only drive the transformer core on minor hysteresis loop, but will not remove/lower the remanent flux.

Grain oriented steel materials can be demagnetized by three methods:

- (i) increase the material temperature above its Curie temperature
- (ii) strong vibration on the core material
- (iii) applying an opposing magnetic field

The first two methods are not feasible with an assembled and installed transformer. Only the latter method is feasible without damaging the transformer.

The flux in the transformer core is proportional to the voltage and the frequency (Eq. 1).

$$\Psi \propto \frac{U(t)}{f} \qquad \text{(Eq. 1)}$$

The remanent flux in the transformer core can electrically be reduced by using varying $U(t)$ or f. Therefore, three electrical demagnetization options are available [1]:

- (i) variable voltage constant frequency (CVCF)
- (ii) constant voltage variable frequency (CVVF)
- (iii) decreasing amplitude of DC with polarity reversal

whereas (iii) is variation of (ii). The method from (iii) is a modified version of the method suggested in [2]. The CVCF method has two advantages compared with the CVVF method [1]:

(a) easier physical realization as voltage source
(b) requires less time for reduction of remanent flux

In commercially available portable transformer test devices, the method (iii) is implemented. Figure 1 depicts the voltage waveform during a demagnetization with a portable transformer test device.

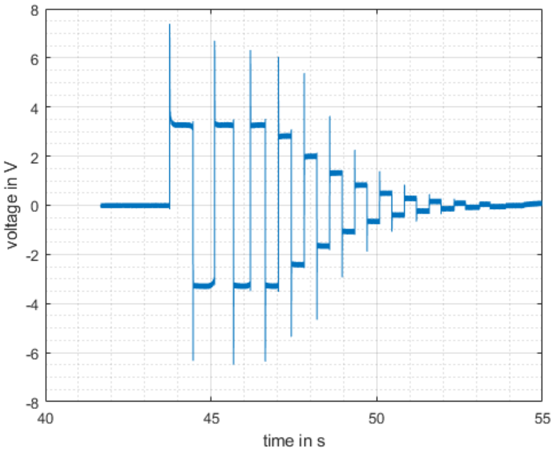

Figure 1: Recorded voltage during demagnetization with a portable transformer test device

The common procedure for the demagnetization of a power transformer core is to apply the predefined sequence between the high-voltage terminal and the high-voltage neutral point.

Depending on the demagnetization sequence of the phases, e. g. U-V-W or V-U-W, and due to the magnetic asymmetry of the magnetic core, a remanent flux can remain on the transformer core. Such a remanent flux shifts the measured hysteresis characteristic, as depicted in Figure 2. For the Ψ-i characteristic, depicted in Figure 2 the transformer phase was demagnetized, but an offset shift is still visible. This indicates that a remanent flux was still present in the core. The same characteristic was also observed with a 50 MVA 3-limb transformer.

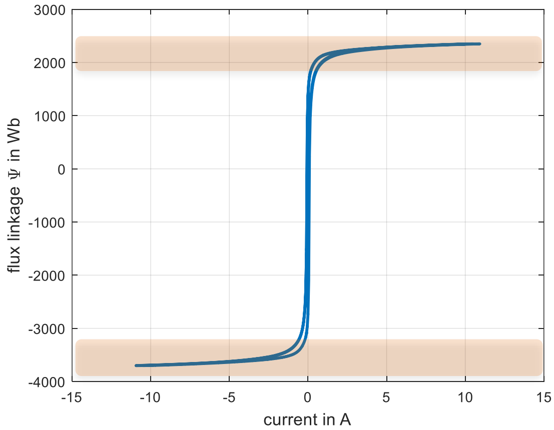

Figure 2: Measured hysteresis characteristic of a 5-limb 300 MVA transformer after demagnetization of each phase

In [3] a demagnetization method with two voltage sources for 3-phase transformers with 3-limb and 5-limb core was tested with topology-corrected models of 3-limb and 5-limb transformer cores.

2.2 Standard Hysteresis Measurements

Hysteresis measurement of already installed or assembled power transformers are currently not defined in any standard. The magnetic properties of the transformer core material are provided by the core material manufacturer to the transformer manufacturer. The magnetic properties are measured according to [4] in an Epstein frame. In an Epstein frame stripe samples of the core material with 280 mm and 320 mm length and 30 mm width are stepped in a rectangular shape, as depicted in Figure 3. Two windings with each 700 turns are distributed equally on the four sides of the probe. The inner winding (next to the core) is the measurement winding and the outer winding is the excitation winding. The excitation voltage is adjusted in a way that the measured voltage is sinusoidal. Thus, the transformer core is not in saturation. The magnetic field strength H and the magnetic flux density B are derived, according to (Eq. 2) and (Eq. 3). Figure 4 depicts a typical result of an Epstein frame measurement.

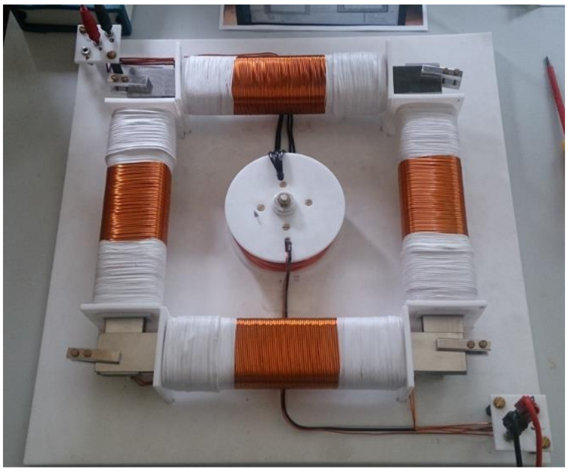

Figure 3: Epstein frame, credit: Institute of Fundamentals and Theory in Electrical Engineering, TU Graz

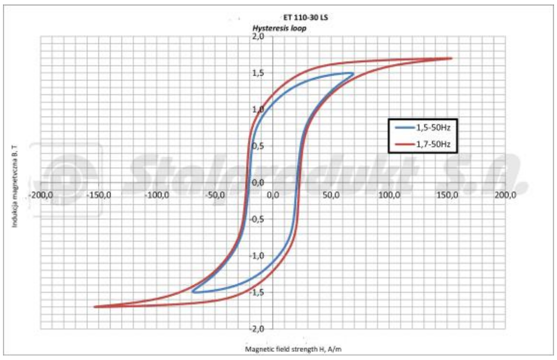

Figure 4: Saturation characteristic from Epstein frame measured from Stahlprodukt S.A

$$H = \frac{N_1 \cdot I}{l} \qquad \text{(Eq. 2)}$$

$$B = \frac{1}{N_2 \cdot A} \cdot \int U(t) \cdot \mathrm{d}t \qquad \text{(Eq. 3)}$$

Where N_1 is the number of turns of the inner winding, l the magnetic path length of 940 mm per definition of the Epstein frame setup, I the measured current, N_2 the number of turns of the outer winding, A the cross-section area of the probe and U the measured voltage.

In an already assembled transformer such homogenous condition as in the Epstein frame are not present. In order to provide conditions closer to the ones given in the Epstein frame, a hysteresis or saturation test on an already assembled transformer should be carried out e. g. via the terminals U-W [5].

3 Hysteresis Measurement on Power Transformers

3.1 Demagnetization of Power Transformers

Before the hysteresis measurement for diagnostic or modelling purpose is conducted, a possible remanent flux in transformer core needs to be reduced to a minimum. The reason for the insufficient demagnetization is the flux distribution in the transformer core. Consider a 3-limb transformer core, which is demagnetized on its middle limb, as depicted in Figure 5 b). Where 1 pu indicates the demagnetization is done via the winding on the middle as depicted in Figure 5 b). The flux in the middle limb can saturate the middle limb and thus can force the middle limb into saturation. After that, the remanent flow can be sequentially reduced to a minimum. Whereas, the flux density in the adjacent yokes and limbs can only reach 50 % of the flux density in the middle limb. This flux density is usually too low to force the adjacent yokes and limbs from a minor loop to the major hysteresis loop and demagnetize these parts of the core.

A new procedure for 3-limb and 5-limb transformer cores is proposed which can be applied with already available portable transformer test devices. All assumptions are neglecting off-core magnetic flux paths. Short circuiting a terminal with the neutral point will cause the flux in the corresponding limb to be vanished. Attention needs to be paid to the induced current in short-circuited windings or in delta connected windings. The induced current should not exceed the rated current to prevent the winding and insulation from damage. If possible, the delta winding should be opened for the measurement.

The procedure #1 is able to cause 1 pu flux density in any limb and yoke. Thus, remanent flux in all parts of the magnetic core can be reduced. During the application of procedure #2 the adjacent yokes to the middle limb will not reach a flux density level of 1 pu, as depicted in Figure 6. Thus, a remanent flux in these yokes can probably not be removed by this approach.

Procedure #1 for 3-limb core (Figure 5):

(1) Demagnetize via terminals U-W
(2) Demagnetize via terminals V-N

Procedure #2 for 5-limb core (Figure 6):

(1) Short circuit terminals U-N and W-N | Demagnetize via terminals V-N
(2) Demagnetize in parallel U-N, V-N, W-N
(3) Short circuit terminals V-N | Demagnetize via terminals U-W

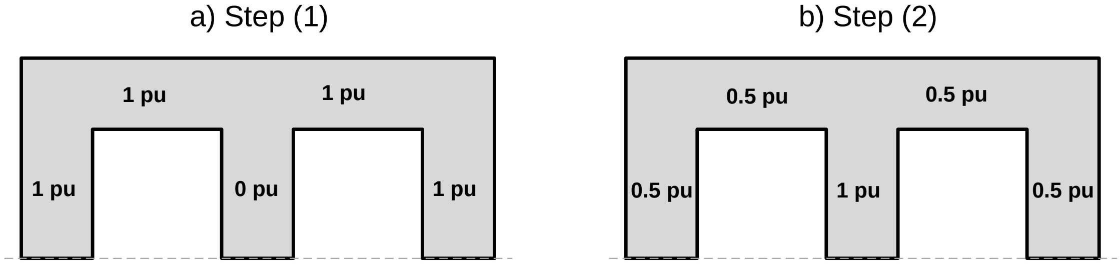

Figure 5: Magnetic flux distribution for procedure #1 in per unit

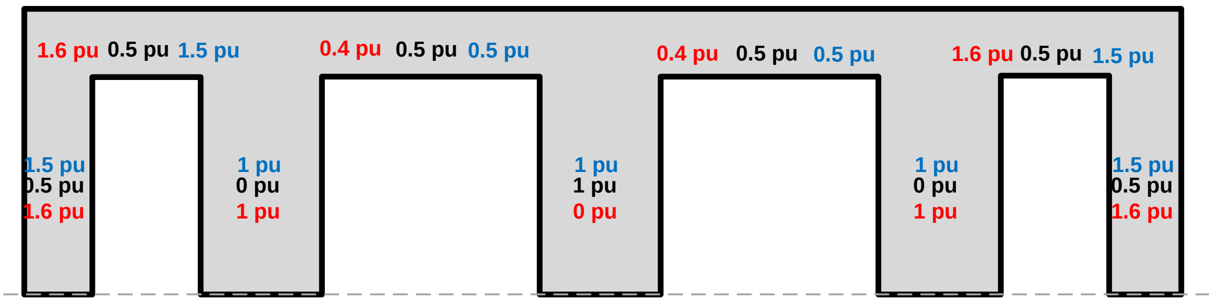

Figure 6: Magnetic flux distribution for procedure #2 for step (1), (2) and (3) in per unit; with yoke cross-section area of 57 % of the limb cross-section area

The laboratory and field test of the aforementioned two approaches is not yet performed at the time of writing. The results will be published in a follow-up report.

3.2 Hysteresis / Saturation Test

The hysteresis measurement of a multi-limb multi-winding transformer from terminal measurements of a transformer can't be used for modelling purposes. The magnetic coupling of the phases gives each phase its individual hysteresis characteristic [6], as depicted in Figure 7.

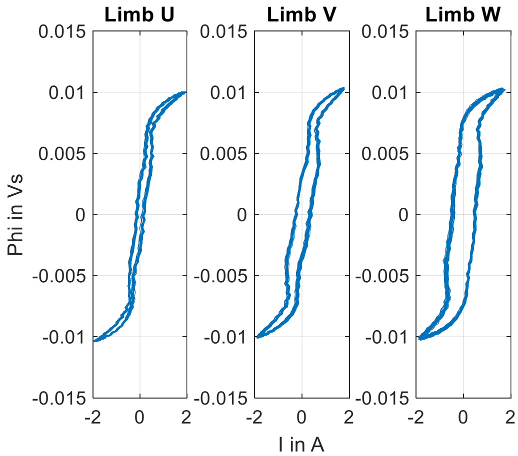

Figure 7: Phi-i characteristic from no-load measurements of a 3-limb 3-phase 50 kVA power transformer

To bridge the gap of a reliable measurement setup to measure the hysteresis characteristic of a power transformer core, a 1-phase measurement setup is proposed.

For the setup a voltage source is connected between the phases of the outer two limbs, as depicted in Figure 8. The flux in the middle limb vanishes, which results in a well-defined magnetic path for the flux, with an equal flux density distribution along the path. This assumption neglects any off-core flux paths and assumes the same cross-section area for the limb and the yoke sections of the core. The equal flux density distribution holds true, as long as the saturation does not increase above 1.95 – 2.0 T. If the flux density is increased further the off-core magnetic flux paths become more dominating. This results in a major deviation of the flux density in the yokes and limbs. To capture the hysteresis characteristic in saturation, the flux density needs to be increased close to 2.0 T. To reach a flux density close 2.0 T, the voltage need to be increase 20 – 30 % above nominal voltage (at rated frequency of 50/60 Hz). This can be achieved by connecting the terminals 1U and 1V between two phases of a stepup transformer or by reducing the test frequency. The pre-defined test current should be selected to satisfy the following equation:

$$U_{\text{meas}} = I \cdot R_{\text{winding}} > 1\,\text{V} \qquad \text{(Eq. 4)}$$

where U_{meas} is the measured voltage, R_{winding} the winding resistance between the measured terminals, and I the test current.

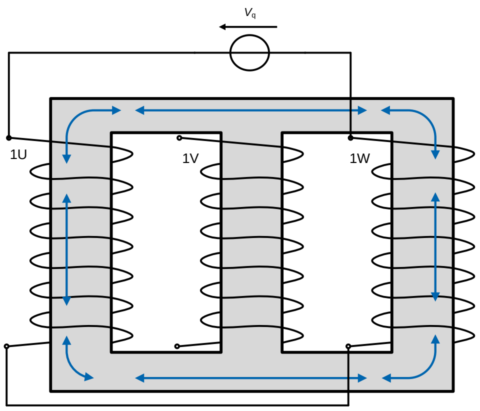

Figure 8: 1-phase hysteresis / saturation setup

In [7] this procedure was used to setup two topology correct transformer models of 3-limb power transformer. The hysteresis/saturation test is used to identify the hysteresis parameters in the transformer model. The transformer model can be used to study the transformer terminal behaviour and its power demand also in saturation with a high accuracy, regarding power power demand and current waveform.

4 Practical Case Studies

4.1 3-limb 50 kVA Distribution Transformer

Figure 9 presents the Ψ-i characteristic of the 3-limb 2-winding distribution power transformer depicted in Figure 10. The transformer from 1974 originally with Yzn5 winding vector group was opened and modified in a way that the low-voltage windings can be reconfigured from outside in zigzag, wye and delta connection. In addition to the low-voltage modification, the high-voltage neutral point was made accessible via a high-voltage bushing. The hysteresis via the U-W terminals has the same maximum flux linkage in both directions. Therefore, no remanent flux was present before the measurement.

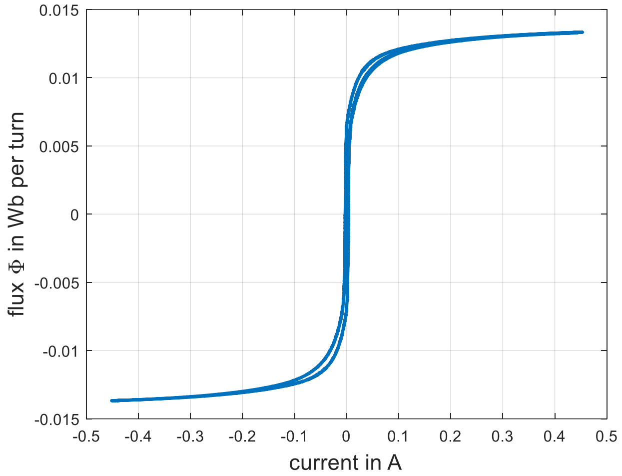

Figure 9: U-W DC hysteresis characteristic of 3-limb 50 kVA power transformer

Figure 10: 50 kVA laboratory power transformer

4.2 2-limb 1-phase 183.3 MVA Transformer

In Figure 11 the comparison of the measured Ψ-i characteristic after a DC winding resistance, after demagnetization and the offset corrected characteristic is depicted. The negative offset after the DC winding resistance is clearly visible. After the demagnetization of phase W, the offset is reduced resulting in a typical characteristic with nearly the same saturation values in both directions. For this case, correct Ψ-i characteristic can also be obtained by subtracting the offset from the measurement with the remanent flux, as indicated with the yellow curve. Figure 12 depicts one of the single phase 183.3 MVA transformers.

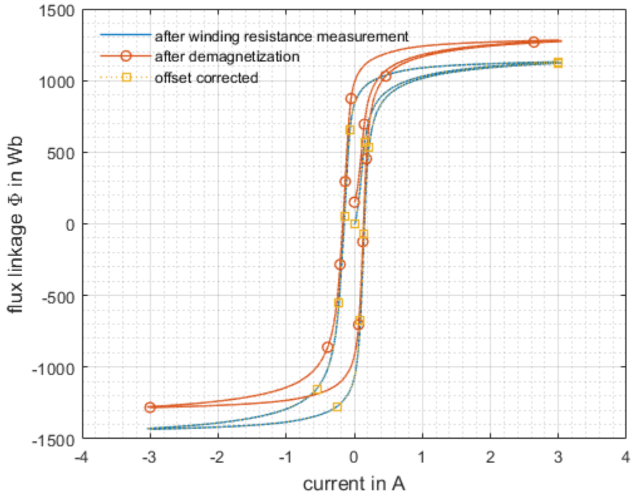

Figure 11: W-N DC hysteresis characteristic of 2-limb 183.3 MVA transformer

Figure 12: 2-limb 1-phase 183.3 MVA transformer

4.3 3-limb 50 MVA Power Transformer

Figure 13 depicts the Ψ-i characteristic from U-W terminal measurement of the transformer visible in Figure 14. Clearly visible is a negative offset, although the transformer limbs were demagnetized before the hysteresis measurement.

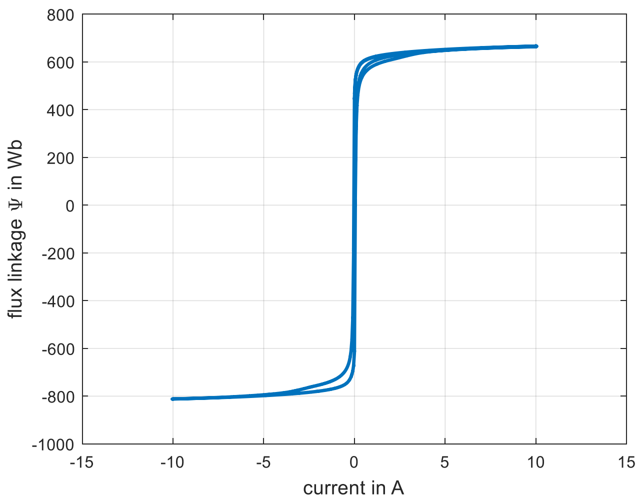

Figure 13: U-W DC hysteresis of 3-limb 50 MVA transformer

Figure 14: 3-limb 50 MVA power transformer during factory acceptance test

4.4 5-limb 300 MVA Power Transformer

In Figure 15 the measured Ψ-i characteristic of the transformer in Figure 16 is presented. The transformer is a spare transformer, currently without connection to the power grid. The Ψ-I characteristic was measured via the U-W terminals with demagnetization of the limbs before the hysteresis measurement. A negative offset indicates that the demagnetization was not sufficient.

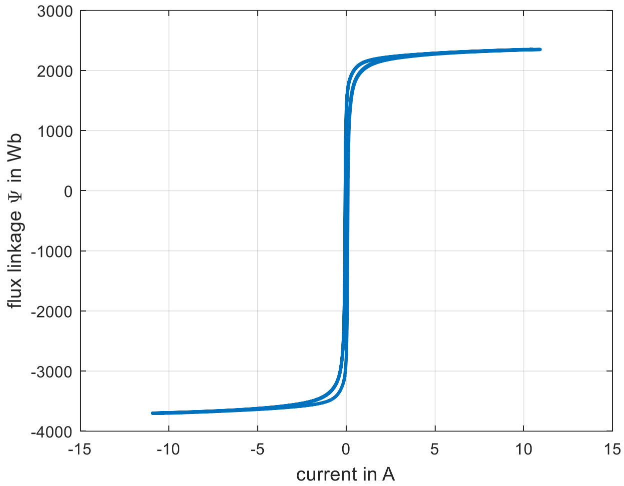

Figure 15: U-W DC hysteresis of 5-limb 300 MVA transformer

Figure 16: 5-limb 300 MVA power transformer

5 Conclusion and Discussion

To conclude, we have proposed two methods for the demagnetization of 3- and 5-limb power transformer cores, as a preparation for hysteresis measurements. Whereas one measurement showed, that a symmetrical Ψ-i characteristic can be obtained from an offsetted measurement. This holds true for the specific case and for the measurements via the U-W terminals. This method needs to be validated for other transformer cores and measurement setups. To prevent the inter-phase magnetic coupling during a hysteresis measurement of a multi-limb multi-phase power transformer, a measurement setup is proposed and tested in the laboratory and in the field. This hysteresis/saturation test at rated frequency of 50 Hz could also be used to setup topology-corrected power transformer models with implemented hysteresis.

Further work will focus on three different fields. The first field will cover the laboratory and field tests of the proposed demagnetization procedures. The second field will focus on the usage of the U-W DC hysteresis measurement for the hysteresis modelling in topology-corrected transformer models. The last field will deal with the usage of the hysteresis measurements for asset management purposes.

During the DC winding resistance measurement and demagnetizing build-in current transducer (CT) cores could get saturated. Therefore, it should be investigated if CTs should also be demagnetize after transformer DC winding resistance measurements.

6 References

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