Power Transformer Demagnetization

Field Application Evaluation

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***Abstract*—Switching operations and direct current applied during routine testing procedures of static winding resistance measurement leave residual magnetization in the core and/or fully saturate the core of the transformer.**

When a magnetized power transformer is energized, it will face extremely high magnetizing currents due to the non-linear phenomenon of core saturation. The high level of inrush currents generated upon energization may affect the internal winding geometry of the transformer and also trip harmonic protection devices in the system.

This paper will discuss the demagnetization of the magnetic core of power and distribution transformers. Different algorithms are applied to a variety of transformer designs and the results are validated with excitation current measurements and Sweep Frequency Response Analysis (SFRA) tests. The knowledge acquired and the best practices suggested for transformer demagnetization are summarized for practical application in the field.

Keywords—magnetization; demagnetization; transformer; core; excitation current; SFRA; winding resistance

I. Introduction

Though not necessarily a failure, the effect of transformer core saturation has been addressed in international standards and major technical references [1] - [6]. A magnetized core may result in potentially damaging in-rush currents and, therefore, demagnetization is recommended before a transformer is energized and before off-line routine and advanced AC testing procedures such as exciting current and SFRA are carried out.

During DC static winding resistance measurements, core saturation is desired because it cancels the inductive effect and allows only the voltage drop through the resistive component of the winding to be measured. The transformer core may otherwise become saturated due to an abrupt change in the voltage applied to it. This may be caused by switching transients, out-of-phase synchronization of a generator, external faults and fault clearance.

In transmission and distribution networks, energization of transformers is a common practice and it is generally performed without any adverse consequences [6]. Nevertheless, switching operations generate currents and voltages that are transient in nature and may create power quality issues during the energization of the transformer.

A way to satisfactorily demagnetize the core of the transformer before energization is needed. Generic algorithms to demagnetize the transformer in the field may work well for one transformer and not that well for other transformer construction. Therefore, the limitations and advantages of different demagnetization algorithms should be described and best practices implemented to assure an efficient process in the field.

II. Core Saturation

A. *Effect on Inrush Current*

Although inrush currents are not generally as damaging as fault currents, the duration of exciting current inrush is in the order of seconds or even minutes. Inrush Current is a form of over-current that occurs during energization of a transformer and is a large transient current which is caused by part cycle saturation of the magnetic core of the transformer [7]. The flux in the core is equal to the integral of the excitation voltage. Assuming the condition of energization when the voltage passes through zero and the flux is zero, the sinusoidal flux will be fully offset from zero. The energization of a transformer normally yields the most severe case of inrush current as the flux in the core can reach a maximum theoretical value of 2 to 3 times the rated peak flux but slowly decreases by the effect of oscillation damping until it finally reaches the normal exciting current value[6][10].

The flux-linkage/current relation is nonlinear and is determined by the saturation curve of the transformer. Therefore, the magnetization current of a transformer contains harmonics. When a transformer is energized, the initial value of the flux may differ from the prospective flux. This causes a DC offset of the flux-linkage and a higher-than-rated peak value. The result is an inrush current that may be several times the value of the nominal current.

For the ideal transformer working under normal operation conditions, the *v-i* curve is depicted in Fig. 1.

Under real conditions, where the transformer core materials experience a flux that periodically changes, the B-H curve depends on the magnitude of the flux density and the periodic frequency.

The main factors affecting the inrush current magnitudes can be divided into: transformer design, initial conditions, and network factors. The effect of inrush current and residual flux is presented in Fig. 2.

The design of a transformer can affect the magnitude of the inrush current as it can shift the steady state operating point on the saturation curve. A transformer with an operation point closer to the knee area of the saturation curve is easily brought into saturation.

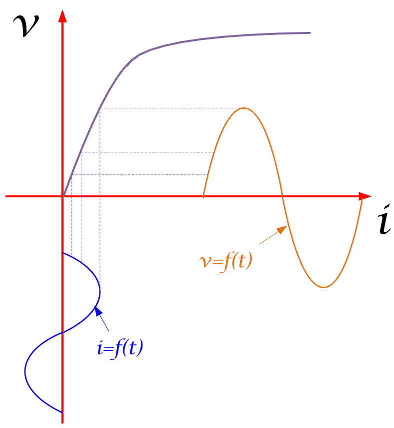

Fig. 1 *v-i* curve of a transformer under normal operation conditions

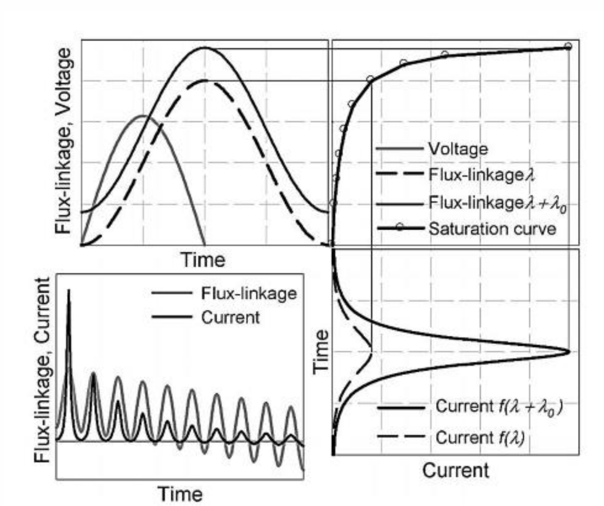

Fig. 2 The inrush current and the effect of residual flux [6]

The generic and simplified equation that has been used in the industry to calculate the peak value of the first cycle of inrush current in Amps is as follows:

$$I_{pk} = \frac{\sqrt{2}\cdot U}{\sqrt{(\omega \cdot L)^2 + R^2}} \cdot \left(\frac{2 \cdot B_N + B_R - B_S}{B_N} \right) \tag{1}$$

Where:

U – Applied voltage [V]

L – air-core inductance of the transformer [Henry]

R – DC resistance of the transformer winding [Ohms]

BR – Remnant flux density of the core [Tesla]

BS – Saturation flux density of the core material [Tesla]

BN – Normal rated flux density of the core [Tesla]

An improved, more rigorous, calculation for inrush current has been developed by ABB in 2007 [7] which takes into consideration additional design parameters of the transformer:

- The magnetizing inductance of the transformer core adjusted for the transient nature of the inrush current phenomenon.
- Impedance and short circuit capacity of the system.
- Core geometry, winding configurations, and winding connections in 3 phase transformers.

As clearly observed, transformer saturation is a highly nonlinear phenomenon and hence the inrush current contains harmonic and DC components besides the fundamental component. The 2nd harmonic is by far the most dominant one.

To minimize and control transformer inrush currents, and prevent undesirable effects on the electric system, the following methods have been proposed:

- Controlling the switching times of the energizing circuit breaker
- Installing pre-insertion resistors in series to the energizing circuit breaker
- Adjusting the load tap changer before energizing the transformer
- Reducing the system voltage before energizing the transformer
- Energizing the transformer using air-break disconnect switches
- De-fluxing / de-magnetizing the transformer core before energization

B. *Effect on off-line Testing Practices*

IEEE C57.152 – 2013 section 7.2.7.4 Demagnetization after winding resistance measurement and section 7.2.11.1.1 Effect of residual magnetism on excitation current measurement, address the effect of core magnetization on off-line testing procedures.

The transformer core may have residual magnetism present as a result of being disconnected from the power line or, as is frequently the case, as a result of dc measurements of winding resistance. The residual magnetism results in the measurement of higher-than-normal excitation current.

IEEE C57.152 – 2013 section 7.2.11.1.2 Methods for demagnetization describes two proposed procedures to demagnetize the core. The first method is to apply a diminishing alternating current to one of the windings. For most transformers, due to the high voltage ratings involved, this method is impractical and involves safety hazards.

A more convenient method is to use direct current. The principle of this method is to neutralize the magnetic alignment of the core iron by applying a direct voltage of alternate polarities to the transformer winding for decreasing intervals. The process is continued until the current level is zero. On three-phase transformers, the usual practice is to perform the procedure on the phase with the highest excitation current reading.

IEEE C57.149 – 2012 and CIGRE 342 address the effect on the Sweep Frequency Response Analysis (SFRA) off-line advanced transformer diagnostic method which is fundamentally a comparative test.

The influence of residual magnetism may have an influence on the trace comparison, as presented in Fig. 3. When a benchmark is created, residual magnetism can cause the lower frequencies (up to about 5 kHz) of the trace to be slightly offset. For SFRA measurements, lower magnetizing inductance due to a magnetized core will result in an increase in the frequency of the first main resonance in the SFRA curves as compared to the demagnetized results [3].

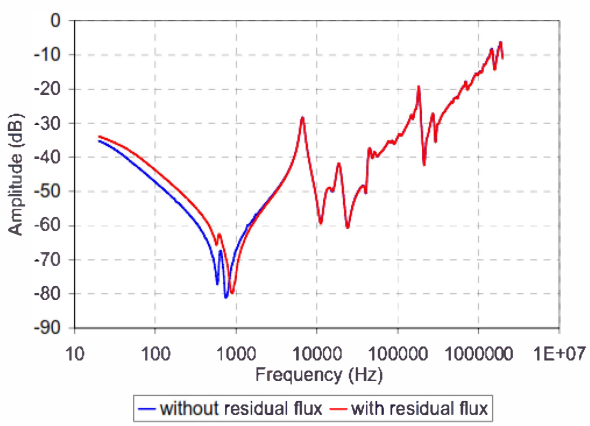

Fig. 3 Effect of magnetized core on FRA results [4]

Therefore, those in charge of analyzing SFRA results understands that residual magnetism in the core of the transformer is not a failure condition, but is an indication of the flux density that remains in the core steel.

III. Experimental Work

The demagnetization of transformer cores can be performed in several ways as discussed in [9]:

- Variable Voltage Constant Frequency (VVCF) source;
- Constant Voltage Variable Frequency (CVVF) source;
- Decreasing the amplitude of an alternating DC current.

In this section a variety of algorithms are tested. Validation of the efficiency of the procedure is measured by the SFRA method and excitation current measurement on the HV side of the transformer.

Saturation of the core is reached by an AC overvoltage signal applied to the secondary winding of the experimental unit and also by DC current injection.

A. DC demagnetization – generic algorithm

The generic algorithm, mainly used in the field, is based on the effect of an alternating direct current applied to the HV winding to neutralize the magnetic alignment of the core iron by applying a direct voltage of alternate polarities to the transformer winding for decreasing intervals.

The alternating DC injection is reduced for each cycle, and the process is continued until the current level is practically zero. On three-phase transformers the usual practice is to perform the procedure on the HV phase associated with the highest exciting current reading. Initial current correspond to the current needed to saturate the core during the DC winding resistance test. As indicated in [1], in most cases, experience has demonstrated that this procedure is sufficient to demagnetize the whole core. Most instruments today apply switched DC current for demagnetization as shown in Fig. 4.

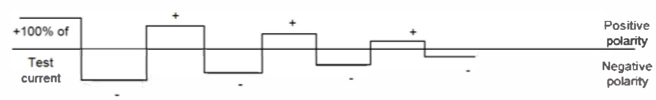

Fig. 4 Demagnetizing sequence of a switched DC source.

Depending upon transformer size and instrumentation capability, performing several demagnetization attempts and/or on different terminal pairs may sometimes improve demagnetization.

B. DC demagnetization – Volt·second approach

In this approach the instrumentation performing demagnetization is capable of determining the saturation of the core on the positive and negative side of the hysteresis. The procedure scales the flux axis and determines accurately the initial magnetization position and the end of the magnetization process very close to zero remnant magnetization.

Depending upon transformer construction and core material, on three-phase transformers the procedure might need to be applied to not only one limb of the core to attain better demagnetization results.

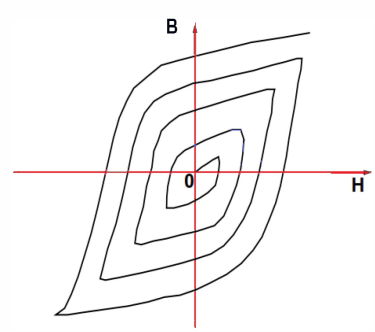

Fig. 5 Visual effect of demagnetization

C. Case study

A 1MVA 3-ph, 13.8/0.48 kV transformer a Dd0 configuration is used. The SFRA response of the HV winding in open circuit mode when the unit is fully demagnetized is presented in Fig. 6 and of the LV winding in open circuit mode in Fig 7.

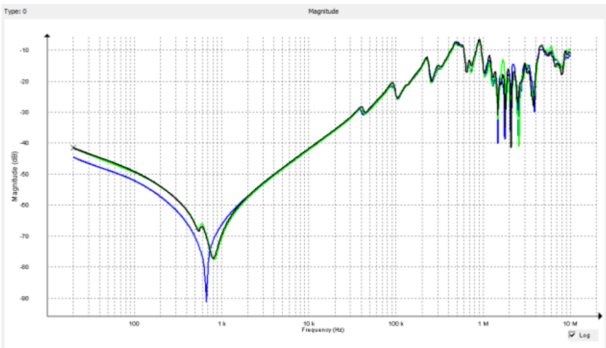

Fig. 6 Open circuit response for fully demagnetized HV windings of Experimental unit

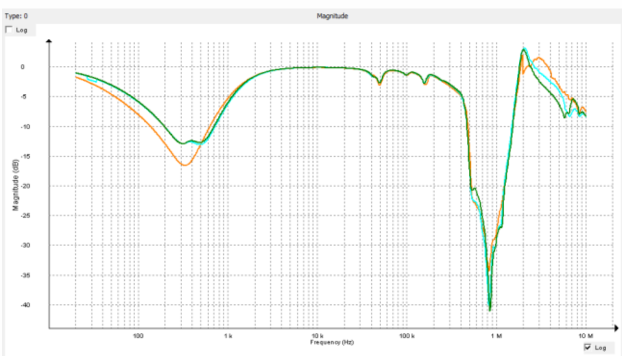

Fig. 7 Open circuit response for fully demagnetized LV windings of Experimental unit

Saturation of the core is obtained by static winding resistance measurement on all three phases. Fig. 8.

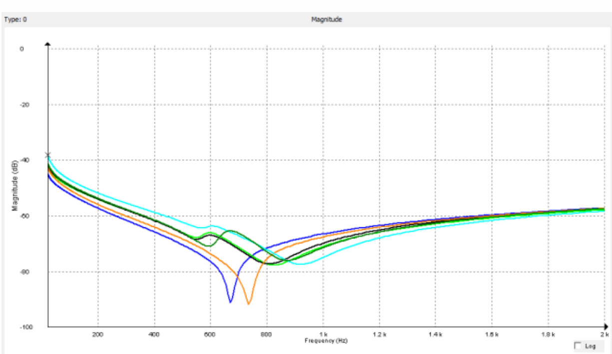

Fig. 8 Open circuit response for magnetized windings of Experimental unit

The effect of saturation is clear and without in-depth analysis we can see that the symmetry of the phases has been altered. It is time now to approach demagnetization using the DC algorithm described above. First the algorithm is applied to only one phase (B) and results are observed in SFRA response Fig. 9.

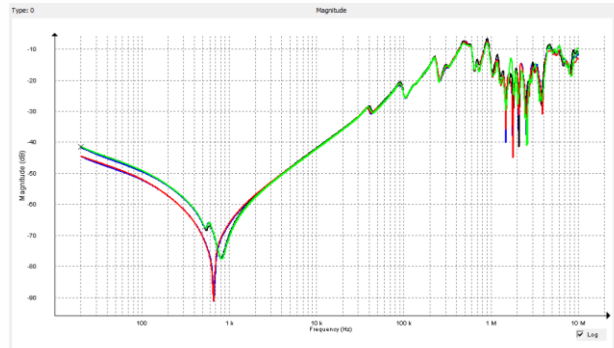

Fig. 9 Original signature of HV windings and after demagnetization of B phase

Looking at the full scale, it is almost impossible to visualize any difference with respect to the benchmark signature. A closer look is needed in the linear scale as presented in Fig. 10.

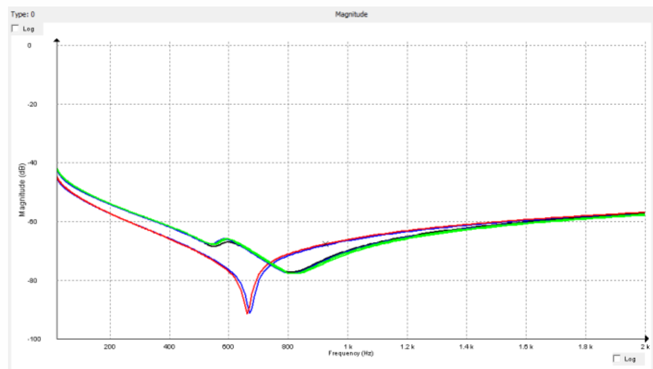

Fig. 10 Frequency band from 20Hz to 2kHz - Original vs. demagnetization on B phase

As observed, the algorithm has effectively responded and is now clear a minor discrepancy visible only in the linear scale for the first point of resonance.

Next, the demagnetization algorithm is applied to each and every phase following the flux sequence.

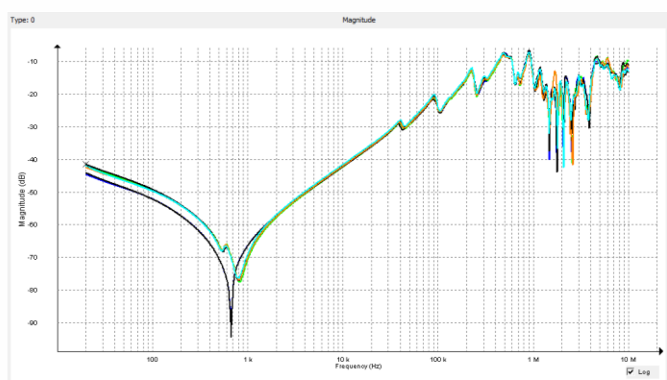

Fig. 11 Original response vs. demagnetization of all 3 phases

Once again, there is a good correlation between the original signature and the after demagnetization signature. The linear scale of the lower frequency band shown in Fig. 12, describes better the effect of this procedure.

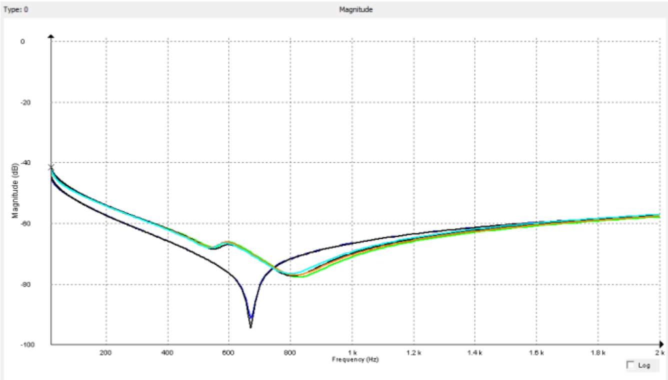

Fig. 12 Frequency band from 20Hz to 2kHz - Original vs. demagnetization on all 3 phases

IV. CONCLUSIONS

Demagnetization of power transformers in the field is practical using the DC method of switching pulses and volt-second. Approaches to demagnetize the transformer might be different, only one phase or all phases.

The effect of each individual approach might be different depending on the type, size and construction of the transformer. Minor discrepancies may be encountered in a more detailed analysis is performed in the linear scale and in the frequency range from 20 Hz up to 2 kHz. The deviations observed must be understood by SFRA users not to confuse with potential problems in the core of the transformer.

The algorithm shall be validated in the field, generic algorithms may work or may direct the flux in a way that saturation of the core remains. A visual volt-second as a function of current hysteresis is ideal to determine demagnetization of the core. Further work is carried out validating algorithms with other methods such as magnetic balance.

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