What influence does residual magnetism have on the transformer core?

Some transformer site measurements and the inrush current are impacted by a magnetised core. How can this be avoided?

ABSTRACT

Whenever a power or distribution transformer is isolated from the power system, it is very likely that residual magnetism remains in the core. Residual magnetism also occurs when performing winding resistance test which is also a routine test of the transformer manufacturers and onsite test. This paper discusses the influence of residual magnetism on some diagnostic measurement methods and on the inrush current. It also describes how to overcome the difficulties of demagnetisation onsite with a mobile test equipment.

Keywords

transformer, residual magnetism, demagnetisation, FRA, inrush current, exciting current

1. Introduction

Power transformers are key elements in the electrical grid. If a power transformer fails, the financial impact of the outage time is in most cases considerably larger than the damage on the transformer itself. Due to the fact that the transformer fleets are getting older, the condition assessment and the appropriate maintenance strategy of power transformers is getting more and more important. To assess the condition of a transformer, various electrical measurement methods can be used. But a large number of diagnostic measurements are affected by residual magnetism. Therefore, it is difficult to analyse a reliable condition assessment of transformers. Residual magnetism can also have an impact on the inrush current. A too high inrush current can reduce the lifetime of a transformer due to the mechanical forces on the insulating paper. It is therefore recommended to demagnetise the transformer before performing diagnostic measurements and re-energising it.

1.1 Influence of residual magnetism on electrical routine and diagnostic measurements

The residual magnetism can be as high as 90% of the magnetic flux density (B) during operation. In the event of a fault or during routine tests, various electrical diagnostic techniques can be used for analysing the condition of a transformer. Residual magnetism influences certain diagnostic measurements in such a way that a reliable and meaningful analysis becomes difficult.

Particularly, when performing exciting current measurements, the magnetic balance test, or sweep frequency response analysis for localisation of faults in the core, residual magnetism may have such a negative effect that results become unintelligible.

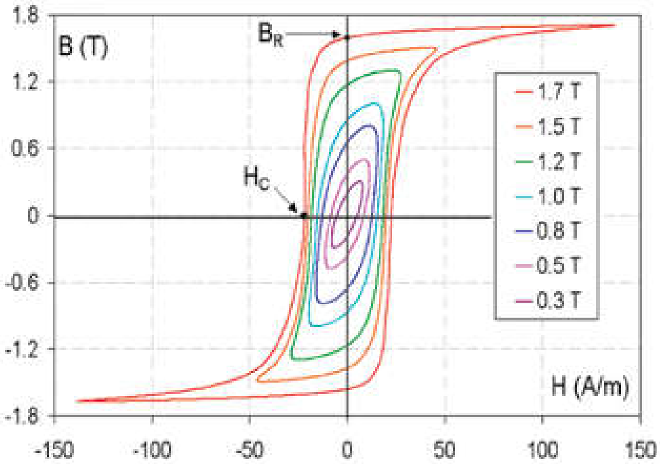

Figure 1: Residual Flux BR and hysteresis loop at different flux densities [1]

1.2 Influence on sweep frequency response analysis measurements (SFRA)

The sweep frequency response analysis (SFRA or FRA) uses frequency response analyses to describe the dynamic characteristics of an oscillating network, which is a transformer in our case, based on its input and output signals. The SFRA measurement method is described in the IEC 60076-18 and IEEE C57.149-2012 and has become increasingly accepted as a diagnostic method.

A transformer reflects an oscillating system consisting of various series and parallel resonances with corresponding inductances (L), capacitances (C) and resistances (R). When one parameter is changed, for example the main inductance due to a core problem or the geometric shift of a winding, one or more characteristic resonance points are also displaced or shifted. Every electrical network has a unique frequency response, its so-called fingerprint. Interpretation of an SFRA measurement is based on a comparison of measurements, for example with the initial fingerprint or with other transformers of the same type. The plot of a fingerprint should not change throughout the entire life cycle of a transformer. All influences which could affect SFRA measurements must therefore be avoided, as they could lead to misinterpretation of the obtained test results.

In a large number of diagnostic measurements, like the sweep frequency response analysis (FRA or SFRA), the exciting current measurement and magnetic balance tests are affected by residual magnetism.

Since residual magnetism influences the frequency response particularly at lower frequencies, where the magnetisation inductance dominates the response, it is vital to ensure that the transformer has been demagnetised before performing the measurement. Meanwhile, because of this pronounced and well understood influence at the lower frequencies, an SFRA measurement is effective in verifying residual magnetism.

The SFRA measurement reflects the main inductance through the first resonance points. Fig. 3 shows those typical resonance points of a three-limb transformer‘s main inductance. Two significant parallel and series resonance points can clearly be seen on the outer windings. This can be described to the two magnetic paths with different lengths. In comparison with this, the winding on the middle limb displays only one characteristic single resonance point.

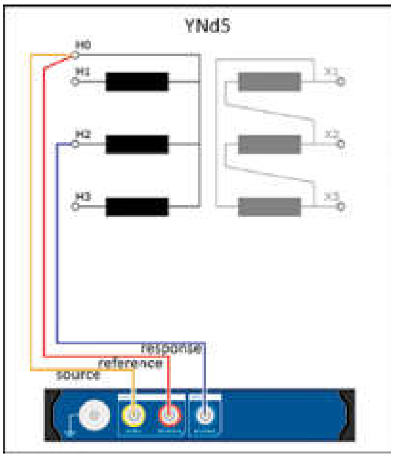

Figure 2: SFRA connection diagram for NV-wiring

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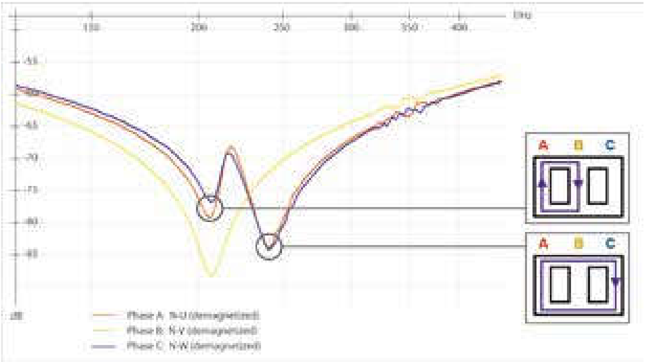

Figure 3: Typical resonance points of a three-limb transformer‘s main inductance

As previously explained for the inrush current, the inductance changes depending on the degree of core magnetisation, whereby $L_{\text{demagnetised}} > L$. A resonance point comprises a network of capacitances and inductances, and can be described using equation (1):

$$f_0 = \frac{1}{2\pi\sqrt{L \times C}} \qquad (1)$$

The lower the inductance becomes, as reflected by a state of higher residual magnetism, the more the resonance points move toward higher frequencies.

1.3 Influence on exciting current measurements

Measuring the exciting current can provide evidence for potential significant faults in the core. Faults in the core lead to increasing exciting current. If reference values for the exciting current are available, these can be used for the assessment. Since exciting currents do not have a linear behaviour to the applied voltage [2], measurements for comparison with the reference values must be performed at the same voltage. The assessment is performed based on a typical pattern of a three-phase transformer or based on reference measurements if they are available. The magnitude of the magnetisation current depends on the length of the magnetised path. This is virtually identical for the windings on the outer limbs (A, C), but lower for the winding on the middle limb (B on Fig. 4. If there is, for example, residual magnetism on the middle limb, this can easily lead to incorrect interpretations and a reliable diagnosis becomes impossible (Fig. 5. The transformer tested was a YNyn0 transformer, 22.5kV/0.4kV, 5.3 MVA)).

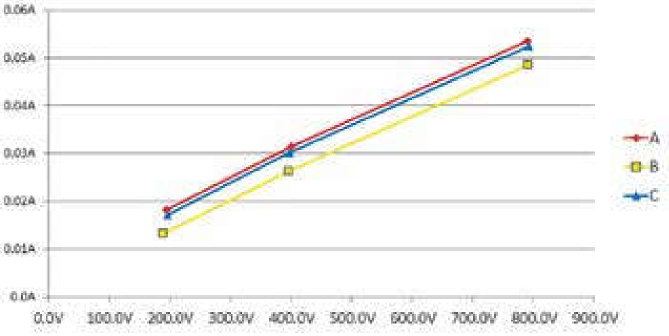

Figure 4: Magnetising current of a demagnetised transformer

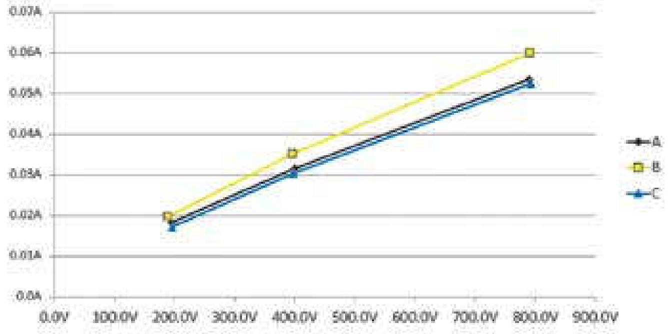

Figure 5: Magnetising current with magnetised middle limb

1.4 Influence on the magnetic balance test

This should result in the following typical pattern: if, for example, a voltage of 100 V is applied to the winding on the middle limb, the measured voltages on the other windings should each display a value of approximately 50 V. This can be explained by the two magnetic paths of the same length. When voltage is applied to one of the windings on the outer limbs, it results in a different pattern as the magnetic paths have different lengths. If the recorded pattern deviates from the anticipated pattern, this can indicate either problems in the core or can be related to undesirable effects of residual magnetism.

Since residual magnetism influences the frequency response particularly at lower frequencies, where the magnetisation inductance dominates the response, it is vital to ensure that the transformer has been demagnetised before performing the measurement.

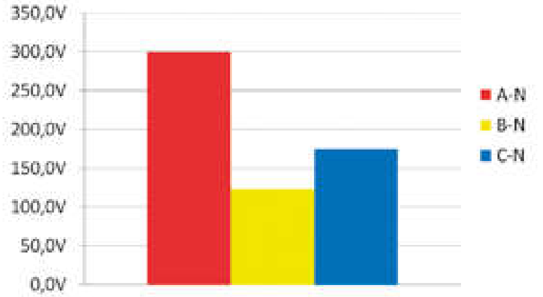

Figure 6: Magnetic balance test with middle limb (B) magnetised, injection on A-N

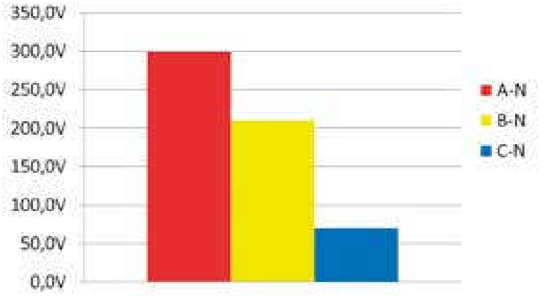

Figure 7: Magnetic balance test pattern with demagnetised core, injection on A-N

1.5 Influence of residual magnetism on inrush current

When a transformer is re-energised directly to its rated voltage, an inrush current occurs that can greatly exceed the nominal current for a few periods. If the transformer core still contains residual magnetism, the first peak current can even reach a level which can be close to the short-circuit current at maximum. These high currents can cause undesirable effects, such as mechanical deformation of the windings and its insulating paper, incorrect triggering of protection equipment, increased stress for the installation and voltage dips in the grid. Only the ohmic components such as the winding resistance are capable of attenuating the high inrush currents to a stable level within just a few cycles (Fig. 8)

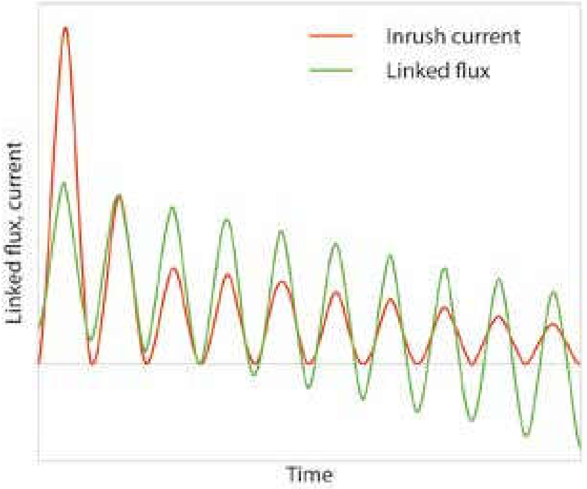

Figure 8: Attenuating the inrush current over time [3]

If there is, for example, residual magnetism on the middle limb, this can easily lead to incorrect interpretations and a reliable diagnosis becomes impossible.

The highest inrush current occurs when the voltage is applied near the zero crossing and the polarity of the voltage is applied in the same direction as the residual magnetism in the core or the corresponding limb (Fig. 9, equations 2-4).

$$u\,(\mathrm{t}) = \hat{\mathrm{u}}\,\sin(\omega t + \alpha)\ where\ \omega = 2 \times \pi \times f \quad [4] \qquad (2)$$

$$\Phi\,(t) = \Phi_{\mathrm{R}} + \int_0^t u\,(t)\,dt \qquad (3)$$

$$= \Phi_{\mathrm{R}} + \frac{\hat{\mathrm{u}}}{\omega}\ (\cos(\alpha) - \cos(\omega t + \alpha))$$

$$\Phi\,(\tfrac{t}{2}) = \Phi_{\mathrm{R}} + 2\,\frac{\hat{\mathrm{u}}}{\omega} = \Phi_{\mathrm{R}} + 2\,\Phi_{\max} \qquad (4)$$

If the core reaches saturation, the transformer‘s inductance is greatly reduced. The current is now only limited by the winding resistance on the high-voltage side and the impedance of the connected transmission line.

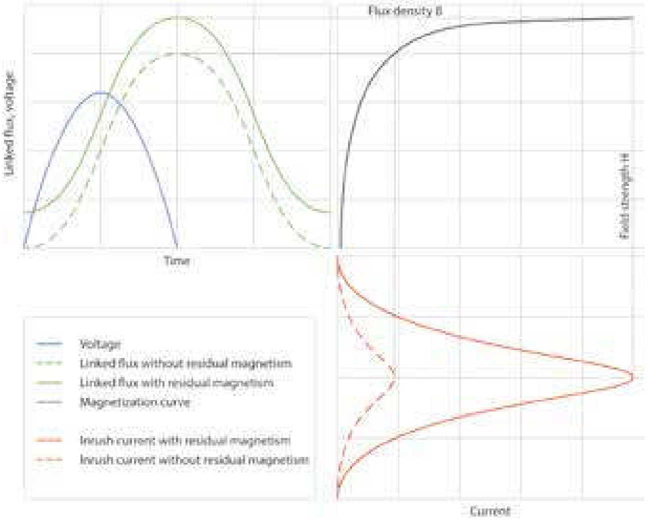

Figure 9: Effects of residual magnetism on inrush current

2. Demagnetisation methods

The following three methods are available for demagnetising magnetic materials:

1. demagnetisation through vibration
2. demagnetisation through heating up to Curie temperature
3. electrical demagnetisation

Since the first two methods cannot be used for a transformer, the electrical method becomes the sole option. Manufacturers can apply nominal voltage at nominal frequency on transformers and instead of shutting down the voltage suddenly, it could gradually reduce the voltage, the core is then progressively demagnetised (Fig. 10). To demagnetise transformer cores on-site, it is often only possible to use reduced voltage and frequency signals. **In many cases, no adjustable high-voltage source, which can provide the nominal voltage of the transformer, can be used to demagnetise transformer cores onsite. Only a single-phase source can be used.**

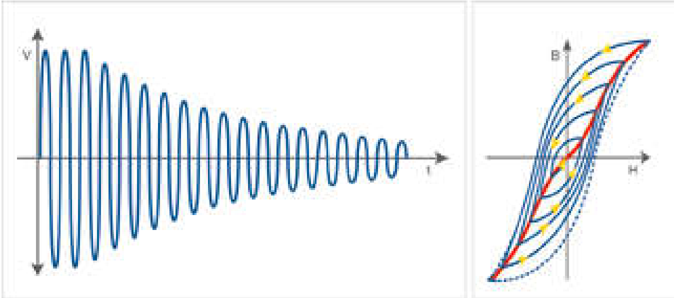

Figure 10: Demagnetisation using a sinusoidal signal [5]

Demagnetisation of single-phase and three-phase transformers can be performed in a similar way. When working on a three-phase transformer, it is important to consider that magnetic coupling takes place between the phases. Therefore, the phase or core limb used during the demagnetisation procedure is extremely important and deliberately chosen with a single phase source. It also makes sense to use the high-voltage side for demagnetisation as there are more turns associated with this winding to generate the magnetic flux. Hence, the total time for demagnetisation can be reduced. Experiments have shown that the middle limb is the most suitable for demagnetisation with a single-phase alternative source. Thereby, the flux is distributed symmetrically over the two outer limbs. To determine which winding is associated with the middle limb in a delta winding, the transformer's vector group is required.

2.1 The art of accurate demagnetisation

There are various approaches for electrical demagnetisation. One of these is to reduce the voltage or the time in predetermined steps. Depending on their type and size, small distribution transformers or large power transformers can have very different core hysteresis parameters. The disadvantage of both approaches is that it takes a long time to ensure that both types of transformers can be reliably demagnetised using the same procedure.

To counteract this problem, you can additionally trigger on a current value while the test is still running to start the next hysteresis cycle. However, since the magnetisation current increases very rapidly when the transformer core reaches saturation, this process is fairly inaccurate. Various experiments have shown that small transformers in particular become re-magnetised by the final cycle, which leads to high inrush currents in return.

To demagnetise transformer cores on-site, it is often only possible to use reduced voltage and frequency signals.

Demagnetisation based on the measurement of the magnetic flux has proven to be the safest and most efficient approach, as it works reliably with both small and large transformers. However, this approach places very strict measuring requirements on the used equipment, as the voltage needs to be continuously measured over time and the integral has to be derived from this, equation (5):

$$\Phi(t) = \int (u(t))dt \tag{5}$$

It is important to avoid any „secondary hysteresis" during demagnetisation. The occurring residual magnetism can lead to an apparent-demagnetisation [6].

2.2 Demagnetisation measurement procedure with current source

Since the voltage, and thereby the magnetic flux of the main winding inductance L_H cannot be measured directly, this voltage needs to be calculated, Fig. 11, equation (6) [7].

$$\Phi_L(t) = \int (u(t) - R \times i(t))dt + \Phi_{R(0)} \tag{6}$$

Therefore, the winding resistance R must be measured first and the voltage drop (Vr) due to the winding resistance then subtracted from the measured voltage (V). Equation (6) shows the calculation of the magnetic flux on the main inductance. Thereby $\Phi_{R(0)}$ represents the initial flux, which corresponds to the residual magnetism.

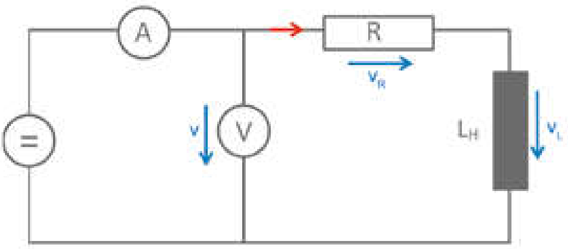

Figure 11: Simplified equivalent electric circuit for the measurement procedure on one winding phase

The test set up for demagnetisation is very simple. It can be done from the high as well as from the low voltage side. However demagnetisation from the high voltage side is faster due to the fact that more windings are available to generate the flux ϕ.

The core must be saturated in both directions. The specific hysteresis parameters, like the maximum flux, per transformer are then determined and the initial flux can be calculated. On the basis of these parameters, an iterative algorithm can then be used to change both the voltage and the frequency. While this is taking place, the devices must constantly measure the flux ϕ in the core. Using multiple iterations, the core can be demagnetised to below a limit of its maximum value. Following the demagnetisation procedure, several magnetic domains revert back to their preferred orientation. This procedure is also referred to as magnetic viscosity. The effect can be determined when performing demagnetisation once again, although it is actually negligible and therefore is not really important in practice.

With this procedure a quick demagnetisation can be done for small distribution transformers as well as large power transformers.

2.3 Example based on a 56 MVA transformer

A 56 MVA-YNd5 power transformer manufactured in 1973 (Elin) and rated 240/10.5 kV was tested.

For verification of state purposes, SFRA measurements were conducted. The transformer's condition was recorded immediately after removing it from service with an initial SFRA measurement. Subsequently, a DC winding resistance measurement was carried out on phase B (which was wound on the middle core limb), and another SFRA measurement was then taken. Lastly, the transformer was demagnetised using previously described method (2.2) and then checked by performing a final SFRA measurement. Furthermore the voltage and current were sampled and the flux calculated according to equation (7). The demagnetisation routine can be seen in Fig. 12 and the flux over the current as hysteresis in Fig. 13.

The results after the demagnetisation procedure are shown below:

Table 1: Results following demagnetisation of the 240 kV transformer

Results	
Current for demagnetisation	7.5 A DC
Maximum flux	+/- 50 Vs
Iterations for demagnetisation	6
Initial remanence	60.3 %
Remanence after demagnetisation	0.7%
Time for demagnetisation	1.5 minutes

Demagnetisation based on the measurement of the magnetic flux has proven to be the safest and most efficient approach, as it works reliably with both small and large transformers.

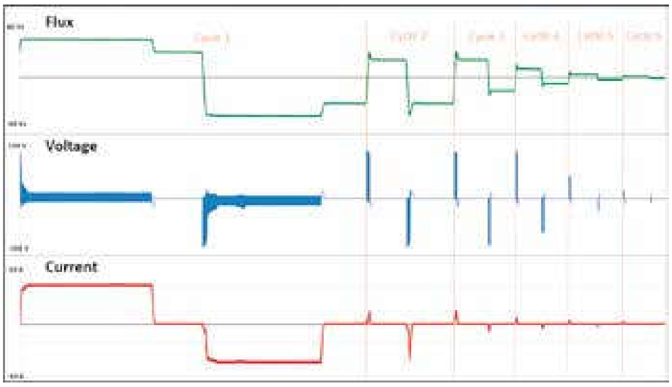

Figure 12: Flux, voltage and current of demagnetisation routine

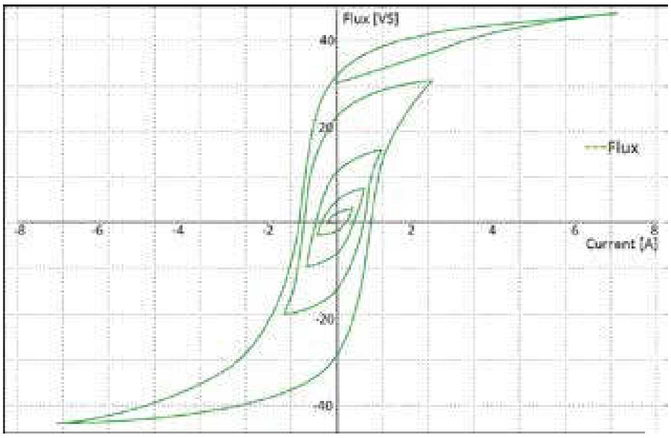

Figure 13: Demagnetisation routine, hysteresis loop (flux over current)

When comparing the SFRA results of the individual phases, it becomes apparent that the transformer displays residual magnetism after being isolated from the power system (Fig. 14). After the demagnetisation procedure, all resonance points moved towards lower frequencies as expected, and the typical SFRA pattern of a three-limb transformer could be seen. The transformer can therefore be considered demagnetised.

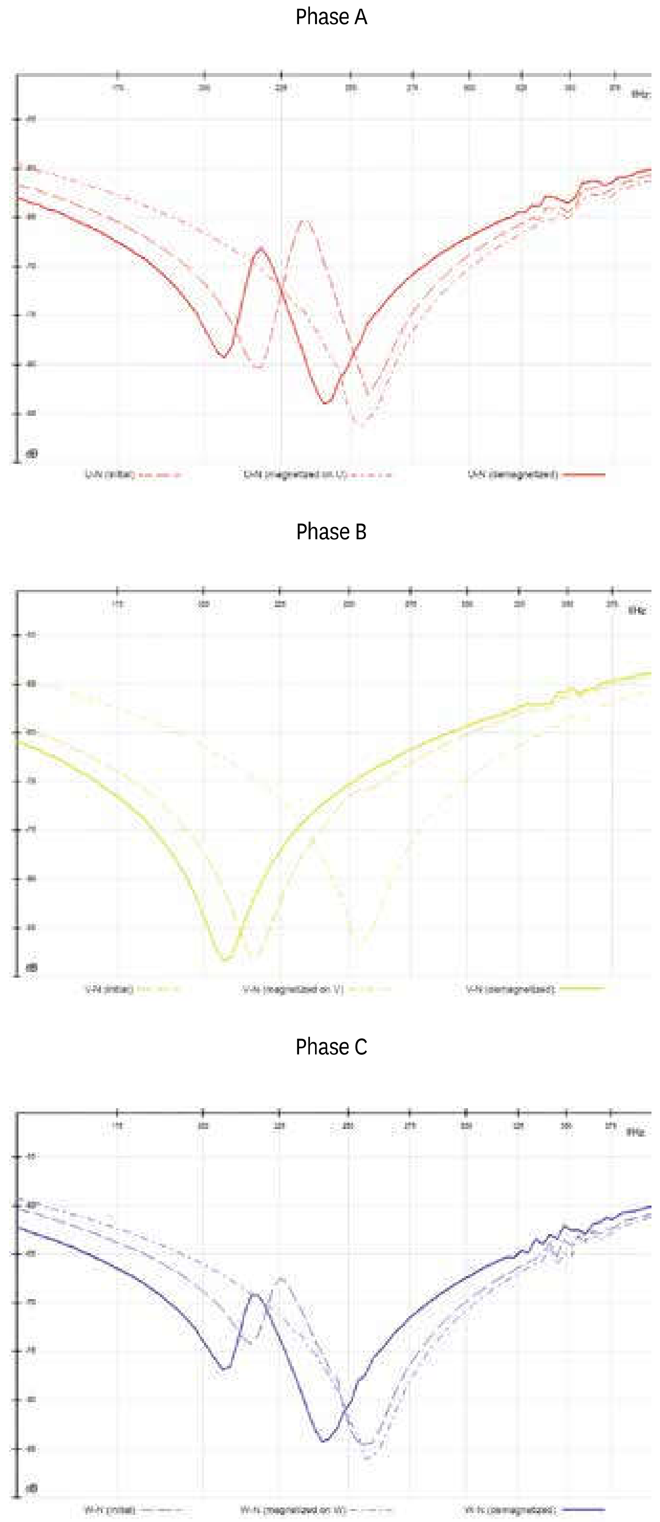

Figure 14: Phase comparison of the SFRA results with different remanence conditions

The specific hysteresis parameters, like the maximum flux, per transformer are then determined and the initial flux can be calculated.

After the demagnetisation procedure, all resonance points moved towards lower frequencies as expected, and the typical SFRA pattern of a three-limb transformer could be seen.

Conclusion

This article highlights the importance and the effects of residual magnetism, on inrush current and some electrical measurements. It should also increase the awareness of the associated risks with re-energising transformers after an outage, especially if the transformer is already presumed to have a bad solid insulation condition.

Within the last few years, the first testing devices (such as OMICRON's CPC 100) have been developed which allow a reliable on-site demagnetisation of transformers without any major additional effort. Demagnetised transformer cores minimise the risk for personnel and equipment during installation. The SFRA measurement method is now described in IEC 60076-18 and IEEE C57.149-2012 and has become increasingly accepted as diagnostic method. To gain reliable and reproducible measurement results, we recommend demagnetising the transformer core before diagnostic measurements such as SFRA measurements.

Equations

Equation 1: $$f_0 = \frac{1}{2\pi\sqrt{L \times C}}$$

Equation 2: $$u(\mathrm{t}) = \hat{u}\sin(\omega t + \alpha)$$

Equation 3: $$\Phi(t) = \Phi_R + \int_0^t u(t)\,dt = \Phi_R + \frac{\hat{u}}{\omega}\left(\cos(\alpha) - \cos(\omega t + \alpha)\right)$$

Equation 4: $$\Phi\left(\tfrac{t}{2}\right) = \Phi_R + 2\,\frac{\hat{u}}{\omega} = \Phi_R + 2\,\Phi_{max}$$

Equation 5: $$\Phi(t) = \int (u(t))dt$$

Equation 6: $$\Phi_L(t) = \int (u(t) - R \times i(t))dt + \Phi_{R(0)}$$

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