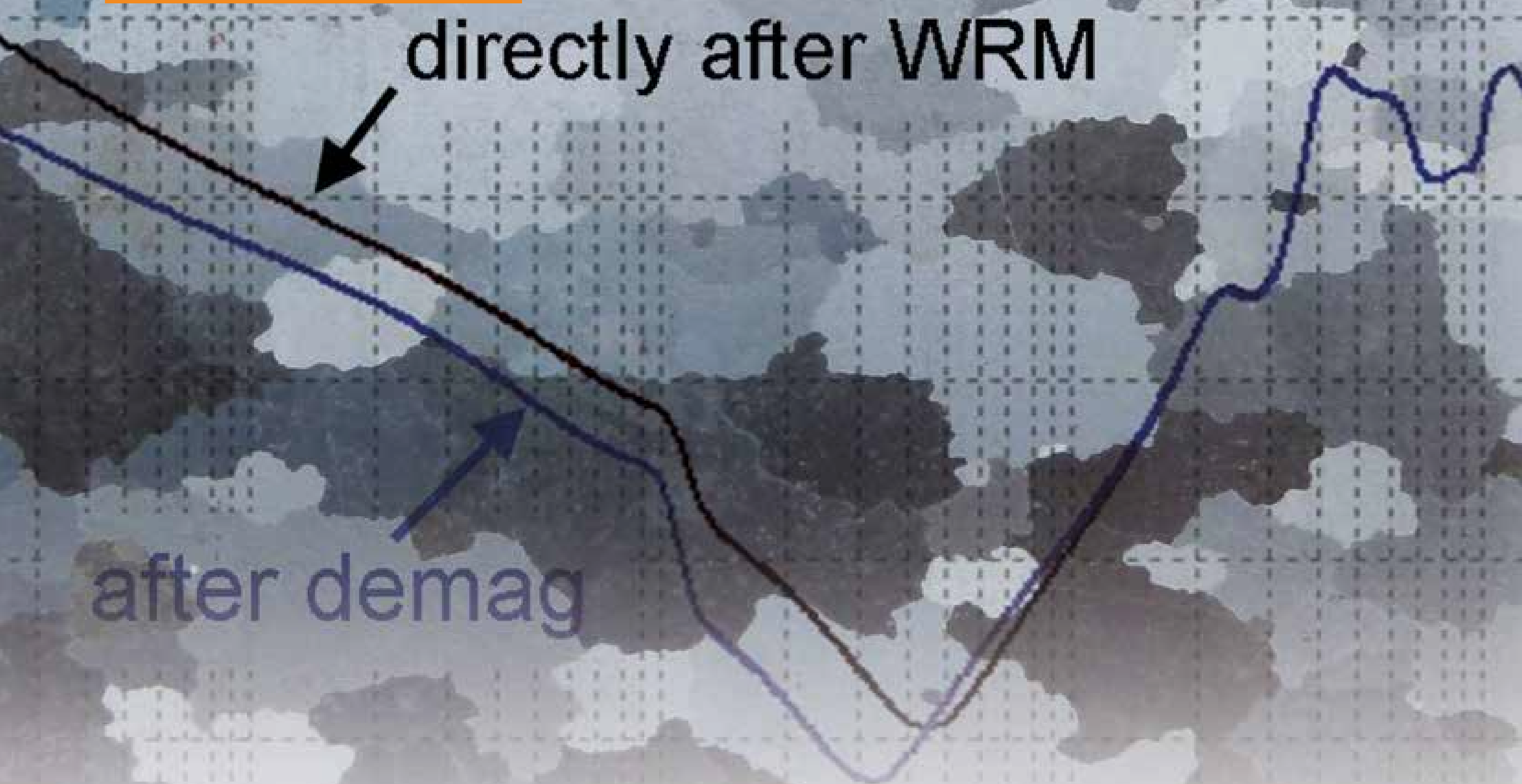

Demagnetisation of grain-oriented electrical steels (GOES)

The process of demagnetisation from the material viewpoint and its implications for transformer testing

ABSTRACT

The magnetisation processes in grain-oriented electrical steels, which are the basic component of transformers cores, are very complex and depend on the amplitude and frequency of excitation. Nevertheless, demagnetisation frequency is of less significance because good quality procedure can result in the same demagnetised state. Demagnetisation is important for transformer testing, especially when using Sweep Frequency Response Analysis, as well as for saturation testing of current transformers.

KEYWORDS

grain-oriented electrical steel, magnetic cores, demagnetisation, transformer testing

Introduction

Magnetic cores of larger transformers operating at mains rated frequency (50 or 60 Hz) are commonly made from grain-oriented electrical steel (GOES). This applies not only to power transformers of any kind (from low voltage to 400 kV and power from single kVA to 1000 MVA), but also to current transformers.

Sometimes it is beneficial or even required that a magnetic core is demagnetised before other test or procedures are carried out. Testing results on a transformer which was not demagnetised can be affected [1] or the transformer can even undergo more severe inrush currents [2].

This paper discusses some underlying processes taking place inside of the GOES material and their importance for the transformer testing.

Internal structure of GOES

There are two main types of electrical steel: grain-oriented (GOES) and non-oriented (NOES). The electrical steels are produced in a special way in order to attain magnetic properties much better than those of common construction steel. This is achieved by a very complex multi-stage process [3] in which sheets of metal with well-controlled chemical composition are produced (typically 96 % iron, 3 % silicon, some additions, but no carbon). The process involves rolling the sheets to specific thickness and multiple annealing to create appropriate crystallographic structure for inducing the best possible magnetic properties.

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The thickness of electrical steel is limited in practice by the effect of additional core losses due to eddy currents, not the process of steel production as such. In practice, for 50 or 60 Hz this means GOES sheets should typically be around 0.3 mm. Thinner sheets would further reduce eddy currents, but they are more expensive to produce. It should be noted that magnetic cores of even biggest transformers in the world are built from thousands of laminations, each around 0.3 mm in thickness (Fig. 1a).

NOES is mostly used for rotating machines and is thus off less concern to the transformer industry.

GOES is a polycrystalline material, whose whole volume is occupied by grains, each of which can be thought of as a monocrystal, which is a single crystal within the whole volume of the single grain. The grains (Fig. 1b) can be very large, up to 30 mm in length [4], and therefore, each grain locally penetrates the whole 0.3 mm thickness. The grains are normally not visible due to a coating applied to GOES for insulation and other purposes. For the benefit of the reader, Fig. 1b shows the grains for uncoated steel.

The spontaneous magnetisation gives rise to magnetic domains, which typically extend through the whole length of the grain, or even beyond a single grain (Fig. 1c). If no excitation or magnetic field strength H is applied and the material is demagnetised, then the domains are arranged in such a way that they all balance each other and there is no net value or induction or flux density B detectable outside of the material. Therefore, if $H = 0$ A/m, then $B = 0$ T, which is the ideal demagnetised state.

During magnetisation or when some H excitation is applied the domain widths change, so that a corresponding net value of B is produced.

Behaviour of magnetic domains and domain walls

However, as depicted in Fig. 1c, the domains can have various widths, even within the same grain. This is dictated by the local crystallographic structure, deviation of the grains from the given direction (rotated horizontally within the plane of the sheet, but also vertically out of the plane), mechanical stresses exerted on the material, etc.

In fact, lower loss and higher permeability GOES can be produced if the width of the domains is reduced to an optimum value. This is achieved by slight scribing of the surface (e.g. with laser [6]) in order to introduce equidistant stress lines perpendicular to the domains, which control the domain behaviour. Such domain-refined high-permeability steel cannot be annealed after slitting or cutting, as this would also remove the beneficial stresses. Such GOES is sometimes referred to as "Hi-B"

Figure 1. Grains in GOES:
a) edge-on view of a core corner submerged in oil of 50 kVA distribution transformer with visible 0.3 mm thick laminations
b) uncoated steel showing grains
c) magnified view – magnetic domains in each grain are aligned with the rolling direction (white lines show grain boundaries) [5]

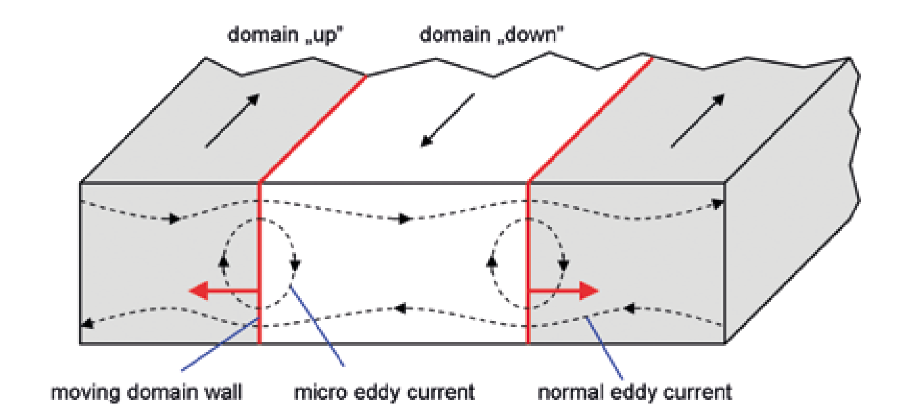

Figure 2. Domains and domain walls penetrate through the whole thickness of GOES [4, 5]

[7] as its lower losses allow designing a transformer to operate at higher *B*, which corresponds to a smaller and lighter core.

All the power lost during magnetisation of magnetic material is represented by the area of a *B*-*H* loop, commonly referred to as magnetic hysteresis loop.

Loss in GOES can be attributed to the movements of the domain walls. These are thin regions separating two neighbouring magnetic domains (Fig. 2). The parallel "bar" domains in Fig. 2 correspond to the parallel bars in Fig. 1c.

Even the eddy currents are related to the domain wall movements because for the eddy currents to arise there first must be a change of *B*, which is always produced by displacement of domain walls. The energy is delivered from the outside, e.g. through the magnetising current in the windings around the magnetic core due to applying voltage to the transformer.

During dynamic magnetisation the domain walls must move (red arrows in Fig. 2), but are impeded by several factors, including the eddy currents. For instance, the internal micro eddy currents (ellipses in Fig. 2) will prevent the wall from moving instantaneously, so that the part of the domain wall at the surface will move quicker than the parts restricted by the micro eddy currents. As a result, severe domain wall bending (usually referred to as "bowing" [8-11]) can take place, as illustrated in Fig. 3.

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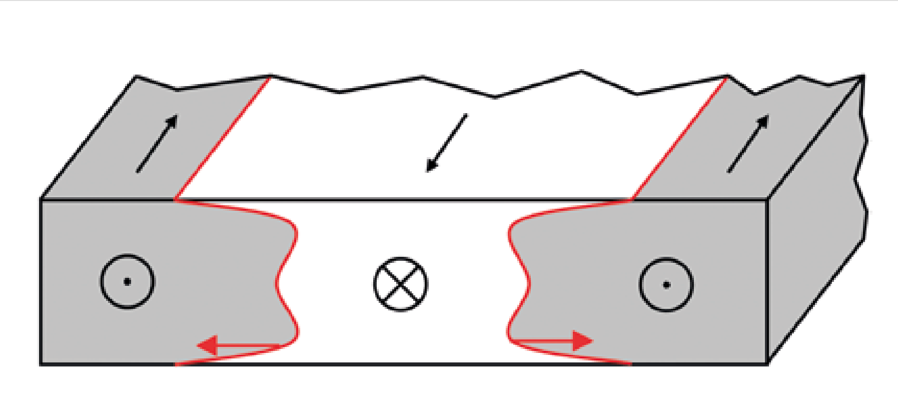

Figure 3. Severe domain wall bowing can occur in GOES under dynamic magnetisation [8, 9]

The domain wall bowing is more severe at higher frequencies, because all the changes are driven at a faster speed. The nature tries to minimise the losses and an interesting phenomenon takes place – new domain walls are created when necessary, depending on the local requirements for minimising the magnetic energy [6]. This is partly visible in Fig. 1c, because some domains are wider and some are narrower. The grain with wider domains has effectively fewer domains per unit width – hence fewer domains locally.

Each wall represents more energy, but if there are more walls, then they can move over shorter distances and at slower speed and still produce the same *B* response. Thus, the energy loss is reduced with the new number of walls per unit of width. The number of walls per unit width can change quite substantially with frequency [10], as illustrated in Fig. 4. The process is fully reversible in the sense that if different frequency is applied, the domain walls are redistributed as necessary. For instance, every saturation (positive or negative) by definition creates one domain and no domain walls. So, the walls are nucleated and annihilated with every magnetisation cycle provided that sufficiently high excitation is applied.

On the other hand, for very small excitation (as described below) the domain movements will be miniscule and new walls will not be created.

During normal operation of the transformer, all these effects are of no concern, as they would be negligibly smaller than any other consequences of significant transients, overvoltages, overloads, etc. Magnetic cores of transformers are renown for their relative resilience to such events, as compared to other components of energy transformation. For instance, very high saturation of the magnetic core will not magnetically damage it. But large overvoltage on insulation might destroy it, and large overcurrent in the windings might distort the position of the conductors. Of course, if the magnetic core is disturbed physically during an overload event this can damage it, but the damage will be caused mechanically, not magnetically.

Studying such phenomena helps in understanding the underlying physics. This in

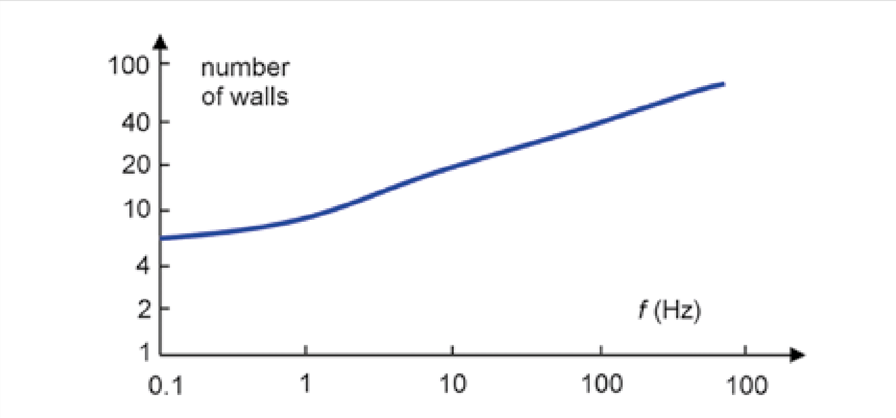

Figure 4. Number of domain walls increases with magnetising frequency in GOES of 0.3 mm in thickness [10]

The ideal demagnetised state is when the net *B*, averaged through the given volume of material, is zero, without any excitation applied to the core

turn allows devising optimum procedures for production of GOES, minimisation of losses, demagnetisation procedures, etc.

Demagnetisation

As mentioned above, the ideal demagnetised state is when the net *B*, averaged through the given volume of material, is zero, without any excitation applied to the core (through current in the windings or external magnetic field). Each domain is still magnetised very locally to saturation, but the contributions of all the domains globally cancel out.

The simplest way of carrying out demagnetisation is to apply an AC sinusoidal excitation with maximum amplitude, which slowly decreases to zero. For "ideal" demagnetisation procedure the initial current in the windings would have to be higher than the highest experienced current in the lifetime of such transformer.

At the nominal frequency this would require voltage higher than the full rating of the transformer, and reactive compensation which fits with the transformer characteristics. Also, the amount of the required power would be beyond what is possible with a portable demagnetiser. Such condition would be equivalent to at least powering up the transformer at the full nominal voltage and supply the full core losses which could be up to 1 % of the rated power [12]. So, even for a small 50 kVA distribution transformer the required power would be up to 500 VA, and it would grow proportionally with the transformer rating. This is just not feasible in practice.

A different technique is therefore used, where a DC excitation is applied to the windings, and the polarity is switched with decreasing amplitudes (switched-DC method). Such approach produces *alternating* current, but of course non sinusoidal, with results similar to sinusoidal AC demagnetisation, but with drastically reduced requirement for the reactive power. Even more importantly – a successful demagnetisation can be produced at a greatly reduced supply voltage, sufficient only to drive the required reversible DC current through the resistance of the windings.

However, the analysis of Fig. 4 gives rise to a question about the *optimum* demagnetising frequency. The definition does not seem to be specified precisely and various magnetic measurement standards give different recommendations. For instance, under very well controlled conditions in laboratories, some measurement standards like ASTM A772 [13] specify that: *"The [demagnetising] frequency used should be the same as the test frequency."* Whereas other international standards like IEC 60404:6 [14] give somewhat more allowance: *„Demagnetization shall be carried out at the same or lower frequency as will be used for the measurements."*

We need to digress here slightly in order to bring up the concept of relative permeability μ_r, which is a measure of the proportionality between the applied excitation *H* and the resultant *B* in the magnetic core, so that $B = \mu_r \cdot \mu_0 \cdot H$ (where: $\mu_0 = 4 \cdot \pi \cdot 10^{-7}$ H/m is the universal magnetic constant). If $\mu_r = 1$, then the behaviour is equal to that of air, which of course would be very "bad" transformer core.

For transformer cores the value of permeability should ideally be as high as possible. Power transformers are usually voltage-driven so for a magnetic core with infinitely high permeability, application of full rated voltage would result with zero current due to the infinite impedance of the windings with such core. This would, roughly speaking, translate into a greatly reduced no-load current. There is also an inverse correlation between permeability and core loss, which is why GOES like Hi-B was invented.

Permeability is not constant, and it changes strongly with the amplitude of excitation. For small amplitudes it has a medium value, then reaches a peak, and towards the saturation it begins to reduce again, so that it will become unity at full saturation. The maximum value for GOES can be at the level of around 30 k [15], and its exact value will depend on the grade of GOES, as well as the operating point of the transformer (1.6-1.8 T).

However, at the very small excitation the permeability reduces significantly, and for a given material it tends to a constant value, which is called *initial permeability* (Fig. 5). Experiments [11] carried out by the author reveal that the demagnetisation frequency does not significantly influence

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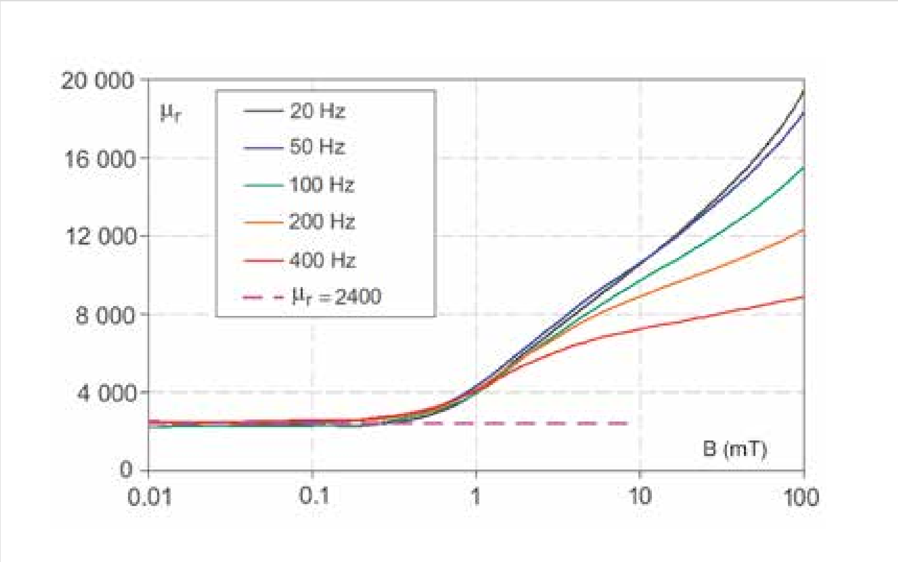

Figure 5. Demagnetisation frequency does not significantly change the initial permeability μ_r = 2400 [7]

The switched-DC demagnetisation can be applied successfully as long as an appropriate control is put in place

the initial permeability of GOES (Fig. 5). The data in Fig. 5 is obtained for reducing the excitation to B = 0.01 mT. However, it can be concluded that the demagnetisation could be stopped as soon as the initial permeability is reached (0.1 mT) or even as soon as all the permeability curves align with each other (1 mT). This is less than 0.6 % of the operating B of the GOES in power transformers, and thus a "good" demagnetisation procedure would have to reduce the residual B to such small values.

However, as seen from Fig. 5, it is not imperative to carry out demagnetisation at the exact frequency of 50 Hz or 60 Hz, but rather that the procedure is carried out correctly, with sufficient amount of steps in which the amplitude is reduced, so that *good* demagnetisation is produced (zero net B). This might not be the case if the current is reversed only a few times, with a very fast decrease of amplitude. But the switched-DC demagnetisation can be applied successfully as long as an appropriate control is put in place [16].

Transformer testing

The initial permeability does not depend on frequency because at very low amplitudes the domain walls are pinned to their locations. Their ends cannot move, for instance because they are held by local precipitations or non-magnetic inclusions. Change of B is then accomplished by slight bowing of the domain walls, and they can return to their original positions when the excitation is removed. As a result, this magnetisation is reversible because there is virtually no hysteresis [11]. Therefore, the permeability becomes independent of the number of domain walls, and for this reason the demagnetisation frequency does not matter.

However, the initial permeability is constant only if the material was demagnetised to very small residual magnetisation, where the "up" and "down" domains (see also Fig. 2) are energetically equalised. If the material is left magnetised at some higher B without demagnetisation, then the energetic conditions are not equalised for the "up" and "down" domains and different behaviour is encountered, with likely higher permeability than the initial value. As a result, a residual magnetism is still present without any voltage nor current source.

This type of material behaviour is significant for such testing like the Sweep-Frequency Response Analysis (SFRA), which is, for instance, implemented in the FRAX analysers [17]. The terminals of a transformer are driven by a small voltage signal, typically 10 V peak-to-peak (safe-to-operate voltage), and the amplitude and the phase response are measured. The input signal is so small that the magnetic core is exposed to very low amplitude magnetising currents (max. 200 mA), over a wide range of frequencies going from a few Hz to few MHz, so that the magnetisation is driven in the region where initial permeability applies (Fig. 5).

It is known that if the core is left magnetised, the SFRA method can give slightly altered readings at lower frequencies because different permeability will alter the impedance (and thus amplitude and phase), as seen from the terminals of the transformer. Such behaviour related to the residual magnetism, which can be seen at lower frequencies of SFRA signatures, does not indicate failure of the transformer [18]. This effect is not very strong, but it is large enough to be detectable (Fig. 6) and the operators should be aware of the implications.

For best and repeatable results, the cores should be demagnetised before any transformer testing. However, this might not always be possible in the field by a built-in function in the instrument or by a dedicated stand-alone demagnetiser.

The problem is important because Winding Resistance Measurement (WRM) is a frequent test performed on transformers. WRM is carried out with DC current so the test is capable of introducing some residual magnetism into the magnetic core (Fig. 6) for all frequencies below 10 kHz. As can be seen, the difference due to non-demagnetised core could exceed 5 dB, or even 10 dB [16].

For such large difference it is difficult to distinguish a real problem with the transformer core from a curve affected by incorrect or lack of demagnetisation. In any case, such difference has no impact on the transformer performance, but in the worst case it might lead to an increase in amplitude of the inrush current as compared to a fully demagnetised state.

Conclusion

The internal structure of grain-oriented electrical steel exhibits very complex behaviour during magnetisation and demagnetisation, depending on the level and

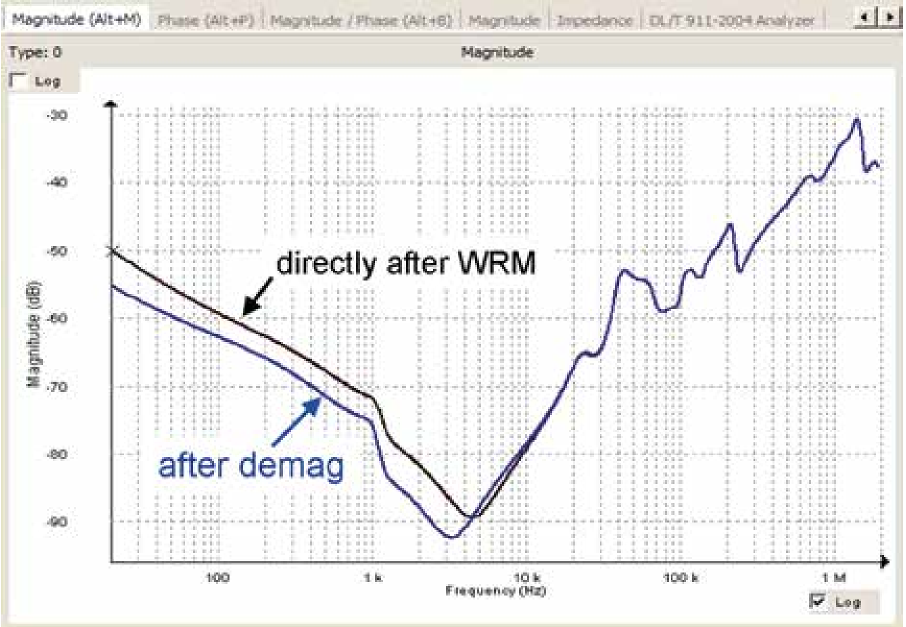

Fig. 6. SFRA (sweep-frequency response analysis) performed after WRM (winding resistance measurement)

> **Good demagnetisation is essential for obtaining high-quality data from such tests like Sweep Frequency Response Analysis**

frequency of excitation. However, if correct demagnetisation is carried out then the demagnetising frequency is of less importance.

Good demagnetisation is essential for obtaining high-quality data from such tests like Sweep Frequency Response Analysis, which is a widely used tool for quick and reliable transformer testing.

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