Understanding power transformer core magnetism and reducing inrush currents

Authors:

Rowan Sinton[1], Wade Enright[2]

[1] Pringle Beleski and Associates (PBA)

[2] Viva Engineers

Presenter:

Rowan Sinton

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Power transformers are susceptible to drawing an inrush current upon livening that can cause significant grid disturbances. Very large transformers, which are becoming commonplace in New Zealand, can cause proportionally greater disturbances. The inrush currents are a direct result of core saturation, which is usually triggered by residual magnetic flux in the transformer's core. Furthermore, new low-loss core steels experience deeper saturation (and hence larger inrush) once over-fluxed.

Residual magnetic flux can remain in a transformer after de-energising by opening the circuit breaker under loaded, unloaded or fault conditions, or following d.c. winding resistance tests, which are part of standard pre-commissioning or routine test procedures. Fortunately, it is quick and simple to demagnetise a transformer's core using a d.c. winding resistance test-set. A robust methodology is described and results from its successful application are presented, including sweep frequency response analyses (SFRA) that demonstrate the effected changes in core magnetism.

1. Introduction

Power transformer inrush currents are causing growing concern in the generation, transmission and distribution sectors in New Zealand and globally. Although inrush is not a new phenomenon, there are several reasons that it is presently attracting extra attention. New transformer installations are tending to get bigger as the network capacity grows. Individual units are proportionally larger still, as the economics steers us towards operating fewer, larger transformers.

Furthermore, modern transformer designs use increasingly low-loss core steels. Such designs can achieve very low magnetising currents – often less than 0.05% of rated current. However, a disadvantage is that the low-loss steel has a much sharper transition into saturation at the steel's knee-point, and when it is saturated, the transformer draws a larger inrush current. This means that new transformers are susceptible to much larger inrush currents than older transformers.

Larger inrush currents present an increased risk to the network, both in causing undesirable voltage excursions and potentially tripping nearby circuits. Inrush currents can also cause "sympathetic inrush" in nearby transformers, which experience their own concurrent inrush currents [1]. This is common when back-livening large generator step-up (GSU) transformers from the grid. Many new power stations have local service transformers on the l.v. side of large GSU transformers, necessitating back-livening of the GSU transformer before restarting the unit.

Some major asset owners in New Zealand have identified these risks and now require demagnetisation of transformers before they are returned to service. The procedure to demagnetise a transformer simple and quick, but it is not well understood. This paper attempts to explain the mechanisms of transformer magnetism and to offer a description of a reliable demagnetisation technique.

2. Theory

2.1. Electromagnetism in transformers

The flow of electric current creates a magnetic field around the current-carrying conductor. The strength of this magnetic field (H) is directly proportional to the magnitude of the current. In a transformer winding, the current in each turn contributes to the total magnetic field – 10 A through one turn produces the same field as 1 A through ten turns. We will only consider the excitation current – a transformer on load will have equal and opposite load currents in each winding, cancelling out any field produced from them.

When a magnetic field is applied to a material, such as air or steel, it produces magnetic flux. The density of the flux (B) is proportional to the applied magnetic field, but it can also be augmented by the material it is passing through.

2.2. Flux in transformer core steel

In a ferrous material, such as transformer core steel, the atoms each produce their own permanent magnetic flux. These create magnetic domains, which can be thought of as microscopic bar magnets within the material. The domains can become aligned to an externally applied flux and then contribute to the total flux in the core. This means that for a given current and magnetic field strength, more flux flows and consequently voltage can be produced – clearly advantageous for a power transformer. Around 10,000 times more flux is created in the steel core than the surrounding air (or oil), so for this discussion we can neglect the leakage flux, which does not go through the core (Figure 1).

This relationship between magnetic field and magnetic flux in a steel core, due to the magnetic domain alignment, is non-linear (Figure 2). With a low field strength, little extra flux is created because there is insufficient force to align the domains. Then there is a region of relative linearity where the additional flux causes domains to become increasingly aligned. Finally, all the domains have become aligned, no further flux is contributed from the domains, and the material is said to be saturated. At this point, the flux in the steel can still increase with more field, but only as much as it would in air.

Further to the non-linearity, core steel also exhibits hysteresis (dashed lines on Figure 2). This is because the domains tend to remain in their previous orientation, and will require extra magnetic field to re-align them. If the transformer is suddenly de-energised, the hysteresis will cause a residual magnetic flux to remain. If the core steel has been pushed well into saturation, the residual flux will be considerably larger.

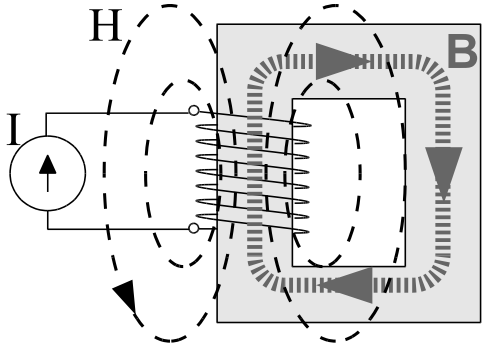

Figure 1: Current in the winding produces magnetic field (H), causing magnetic flux (B) to flow through the core.

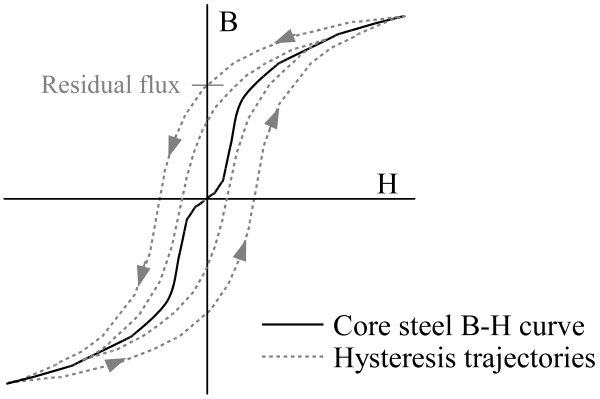

Figure 2: A typical B-H curve for core steel and a possible trajectories due to hysteresis.

2.3. Electrical response to transformer magnetism

The voltage produced in a winding is proportional to the rate of change of magnetic flux (commonly known as Faraday's Law). To see the effect of core steel's non-linearity and hysteresis, simply examine the slope of the lines of the steel's B-H curve (Figure 2). Where the slope is steep, such as at lower values of H, B changes faster and therefore voltage will be induced – this is the region where the transformer is designed to normally operate. At higher values of H (above the knee-point), the slope is much shallower and so B will change slowly, resulting in a lower induced voltage – this region is avoided in normal operation.

If a transformer is suddenly de-energised, the transformer will be left with a residual flux (marked on Figure 2). Note that H is zero because the current in the winding is zero, and there will be no voltage induced because B is not changing (although it is non-zero). In the worst case re-livening, at a voltage zero-crossing with the same polarity as it was de-energised, the flux will increase from the "residual flux" point and the core will quickly saturate. Then, with less voltage induced, the current increases drastically – this is known as an inrush current.

Inrush currents can be many times greater than the rated current of the transformer. Such currents were seen during the livening of Transpower's Pole 3 converter transformer (Figure 3). Although the transformer circuit breaker was fitted with point-on-wave switching and pre-insertion resistors (both of which are methods to reduce inrush peaks and dampen them quickly), the inrush reached a peak of 6 kA and the event lasted for several seconds. Upon

closing the circuit breaker, the point-on-wave relay had assumed that the transformer begun in a zero-flux state (since it also usually controls the opening operation), but it was suspected that the transformers had residual flux as a result of the pre-commissioning d.c. winding resistance testing.

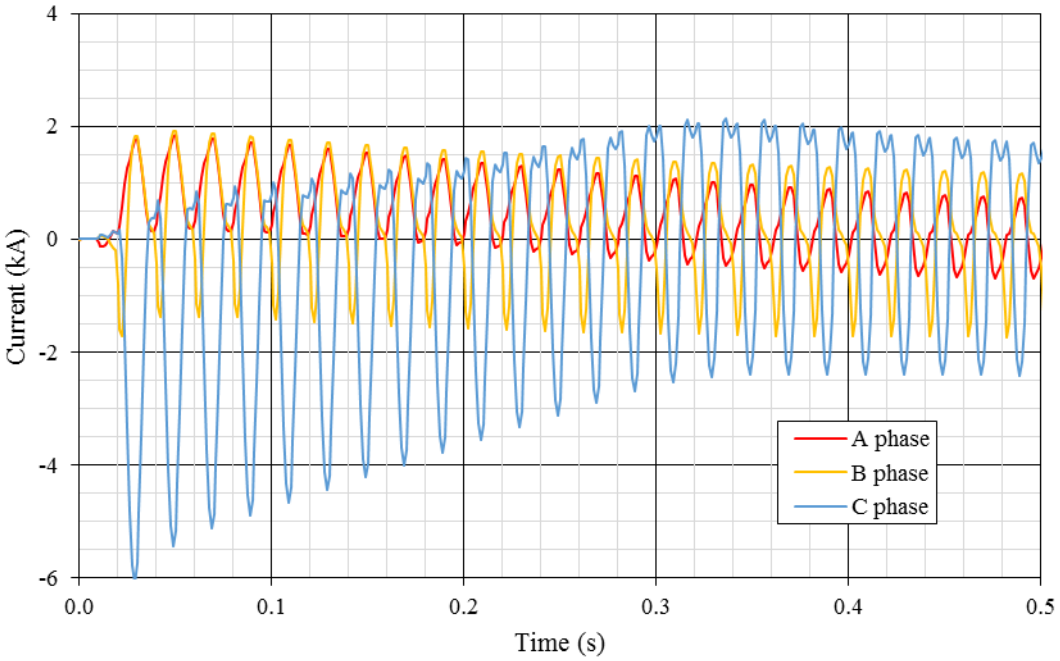

Figure 3: Inrush currents during the first livening of an 813 MVA bank of three single-phase converter transformers.

3. Application

3.1. Magnetisation

There are several reasons that a transformer may be left magnetised. A transformer will always be left with residual flux after its circuit breaker trips, even if a point-on-wave relay is used. The polarity and magnitude of residual flux is difficult to predict; circuit breaker poles do not break line currents at the same time, and on both five- and three-limb core transformers, all three phases are magnetically coupled. Consequently, fault conditions can drive non-faulted phases into deep saturation.

Another common cause of residual flux is from d.c. winding resistance tests. These tests are carried out prior to commissioning of new transformers, or as a routine maintenance check. A d.c. test-set can easily drive a transformer core into saturation – in fact, in order to properly perform a d.c. winding resistance test, the core *must* be driven into saturation. It is therefore likely that the transformer will have very severe residual flux after a d.c. winding resistance test (this is also the reason that d.c. winding resistance tests should always be done after magnetising current and SFRA tests).

3.2. Demagnetisation

The residual flux in a transformer can be nearly eliminated by the careful application of current into the windings. Ideally, an a.c. supply would be used to achieve this. By starting at rated voltage and slowly decreasing the magnitude, the flux may be gradually reduced in the core. Generator step-up transformers without l.v. circuit breakers naturally undergo this

process when the excitation is ramped down prior to unit shutdown. This can also be done in a factory testing environment, where a powerful variable supply is available via a motor-generator set.

Unfortunately, in the field, the required rating of the a.c. supply makes this method impractical. Instead, a series of d.c. currents of decreasing magnitude and reversing polarity can be used. This method effectively replicates an extremely low frequency a.c. supply. Any d.c. winding resistance test-set that is capable of testing a transformer will also be suitable demagnetising the transformer.

The d.c. test-set could theoretically be connected to any winding. Generally, the highest voltage winding will produce a better result, as it has more turns and so will produce flux in the core more easily. However, it is more important to select a star-connected winding – delta-connected windings are problematic because they have two series-connected phases in parallel with the phase under test.

The procedure must also be carried out in such a way that all core limbs and parts of the yoke are demagnetised. It is important to connect the test set phase-to-phase so that full flux is driven through two limbs. If just one phase is energised, the flux will return unevenly through the other two limbs, and could leave residual flux in one limb (Figure 4).

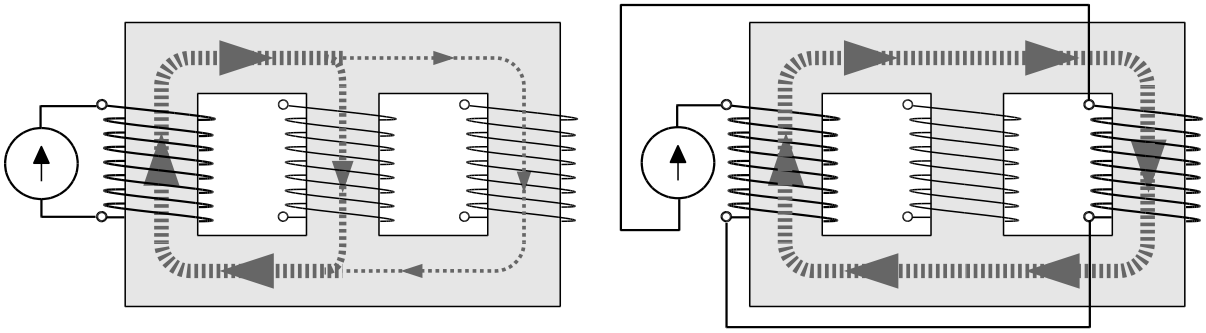

Figure 4: Connecting the test-set across one phase only (left) may result in unpredictable flux in the other two phases. Instead, connect phase-to-phase (right) to ensure full flux is driven through two limbs.

The procedure must then be performed on at least two phase-to-phase pairs so that all three limbs are affected. It is safest to do all three phase-to-phase pairs because otherwise uneven flux distribution within the core may leave residual flux behind.

The current magnitude must be carefully selected to achieve an effective result. The initial current must drive the core into saturation – use the same current that would be suitable for the d.c. winding resistance test. A 220 kV winding will usually begin to saturate around 300 – 500 mA, so 10 A is easily sufficient. Each subsequent current step should be at most quarter of the previous magnitude. The final current injection should be around 10 mA. There should be 6 to 8 current steps in total.

3.3. Verification with sweep frequency response analysis

A change in residual flux can be seen using a sweep frequency response analysis (SFRA) [2] [3]. In an open-circuit SFRA measurement, first resonant point usually falls between 100 and 1000 Hz and is dominated by the main winding inductance. The winding inductance itself is dependent on the reluctance of the core (simply the slope of the B-H curve). The net effect is that if there is residual flux, the first resonant point will tend to move to a high frequency (Figure 5).

Ideally, if there is an SFRA result available from when the core was known to be demagnetised (e.g. after a generator step-up transformer has been de-energised), then the

SFRA after the demagnetisation procedure can be compared – they should match closely. If the demagnetised SFRA data is not available, successful demagnetisation is generally indicated by a shift to the left of the first resonant point when compared to the magnetised SFRA data. Compare all three phases of the open-circuit response on the star-connected winding.

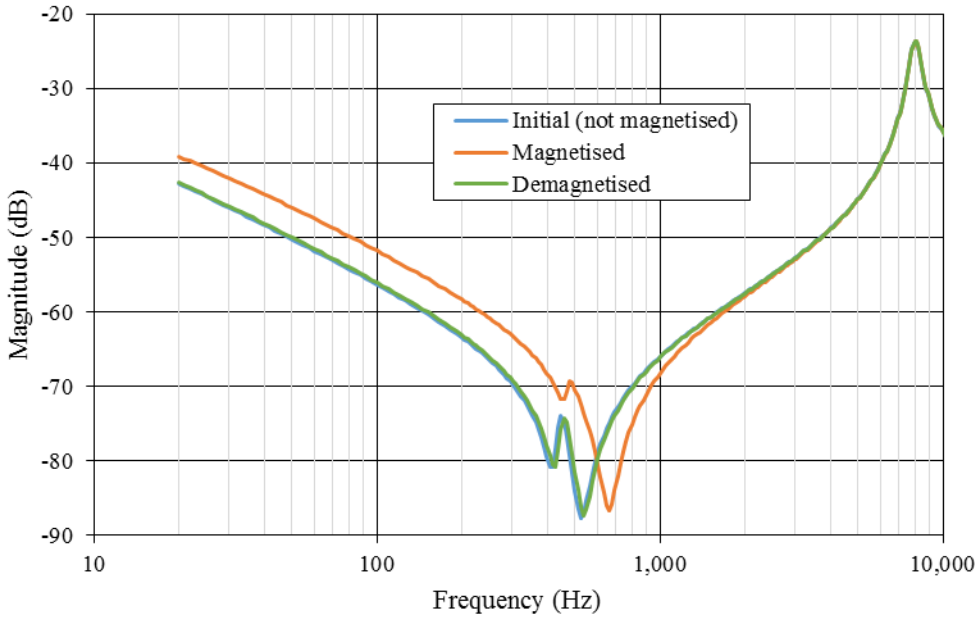

Figure 5: SFRA on A-N of a 220/11 kV, 67 MVA GSU transformer. Measurements were taken following the generating unit being taken out of service (initial), after a winding resistance measurement (magnetised), and following the demagnetisation procedure (demagnetised).

If the SFRA results are not indicating a successful demagnetisation, the procedure can be repeated. Review the choice of winding to be injected, reduce the current magnitude step size, start at a higher current and finish at a lower current. Also consider the possibility that the comparison SFRA data may be misleading, e.g. an assumption that the core was originally demagnetised may be incorrect.

3.4. Time dependency of residual flux

Residual flux does tend to naturally decay over time [4]. The changes can occur within a few hours and days, but significant residual flux may last months or even years. There is currently no published method of calculation for determining how quickly it will decay and to what level.

An example set of SFRA results showing the changes in residual flux over time is presented in Figure 6. An initial SFRA on a generator step-up transformer after it was demagnetised by ramping down the generator's excitation. Another SFRA was performed shortly after a d.c. winding resistance test, showing the fully magnetised state. Four months later, another SFRA shows that the core has naturally tended to lose its residual flux, and finally a demagnetisation procedure brings the core back to near the original demagnetised state.

In the four month period between SFRA results, the transformer was dried in an oven, and the increased temperature is likely to have significantly accelerated the decay in residual flux (the natural decay is thermally related). Without the elevated temperatures, the residual flux may have decreased much less.

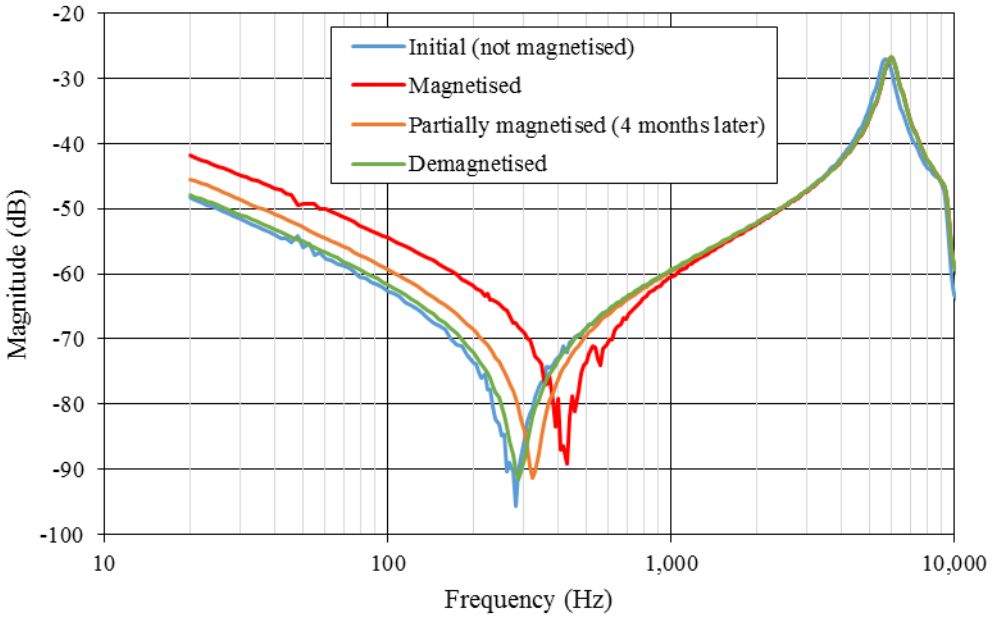

Figure 6: SFRA on B-N of a 220/11 kV, 59 MVA GSU transformer. Measurements were taken following the generating unit being taken out of service (initial), 3 days after a winding resistance test (magnetised), 4 months later (partially magnetised), and following the demagnetisation procedure (demagnetised).

4. Procedure Summary

The following is a summarised description of the demagnetisation procedure.

1. Perform an SFRA on the star-connected winding, with the other winding(s) open-circuit, on all three phases (e.g. A-N, B-N, C-N).
2. Choose the appropriate winding to inject d.c. into – preferably a star-connected winding, or the higher voltage if both are star-connected. The tap position is not important.
3. Connect the test-set voltage and current leads phase-to-phase (e.g. A to B) on the chosen winding, as for a winding resistance measurement setup.
4. Determine an appropriate starting current – this will usually be the same as the appropriate d.c. winding resistance test current. For a 220 kV winding, 10 A is usually sufficient.
5. Inject the starting current. Wait only until the current magnitude is roughly achieved; there is no need for the resistance measurement reading to stabilise.
6. Stop the measurement, reverse the polarity of the leads. Decrease the current magnitude to at least quarter of the previous value and inject again.
7. Repeat step 6 until the current has been decreased to at most 10 mA, or preferably the minimum current that the test-set will allow. There should have been 6 to 8 current steps.
8. Repeat steps 5 to 7 for the remaining phase pairs (e.g. A to C and B to C).
9. Perform an SFRA as for step 1 and compare results.

An important safety note is to ensure that the current has reduced to zero before disconnecting leads, otherwise a large inductive voltage will be produced that can be lethal or damage the winding. This is also true for d.c. winding resistance tests, but is especially pertinent with all of the polarity changes required during this test.

The procedure should take approximately two hours (including SFRA), assuming that the transformer is already set up for electrical testing, i.e. droppers are off, working at heights equipment is in place, test permit issued, etc.

5. Conclusions

Transformer cores can be left with significant residual magnetic flux after loaded or unloaded circuit breaker opening, tripping during a fault or following a d.c. winding resistance test. Re-livening the transformer in this state may result in a large inrush current, which could cause a significant network disturbance.

To mitigate the risk of inrush, the core can be demagnetised through a simple procedure using a d.c. winding resistance test-set. The effect of the procedure can be analysed using SFRA measurements taken before and after, or even better, a comparison with data from a state known to be demagnetised.

6. References

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