

On-site GIC Withstands Largest Experiment with Statnett on a 1,000 MVA Autotransformer and a 300 MVA 5-limb Transformer

#Disaster Prevention and Resilience #Energy

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Highlight

Geomagnetically induced currents (GIC) flow on the earth's surface because of changes in the geomagnetic field that accompany solar events. In power transformers designed to work at 50 or 60 Hz these currents may cause part-cycle saturation in the transformers' cores. Saturation will draw high excitation currents, rich in harmonics from the network. These effects cannot be experimentally quantified in a test room due to the limited power of typical test room generators. Few on-site tests in stiff networks have been performed in the past few decades, and they have often suffered from lack or failure of sensors in the most interesting locations of the transformers' structures.

In a joint project, Hitachi Energy in Sweden and Germany, and Statnett in Norway, equipped a 300 MVA, 5-limb transformer and a 1000 MVA, 3-limb autotransformer with numerous sensors for an on-site test, connected to the 400-kV network.

Circuit models of the transformers resolving the magnetic paths in the core limbs and yokes, in the tie plates next to the core limbs, between the windings, and between the active part and tank, were used to plan the experiment and to establish a safe procedure for conducting the experiment.

The measured current and magnetic flux waveshapes were in good agreement with the predictions. The measured temperature rises remained within safe limits, even after hours of application of high DC currents.

The measurements confirmed that the effects of GIC can be predicted with good confidence in the circuit simulation models. Furthermore, this validation and knowledge will help to prevent future issues in the electric system such as blackouts.

1. Introduction

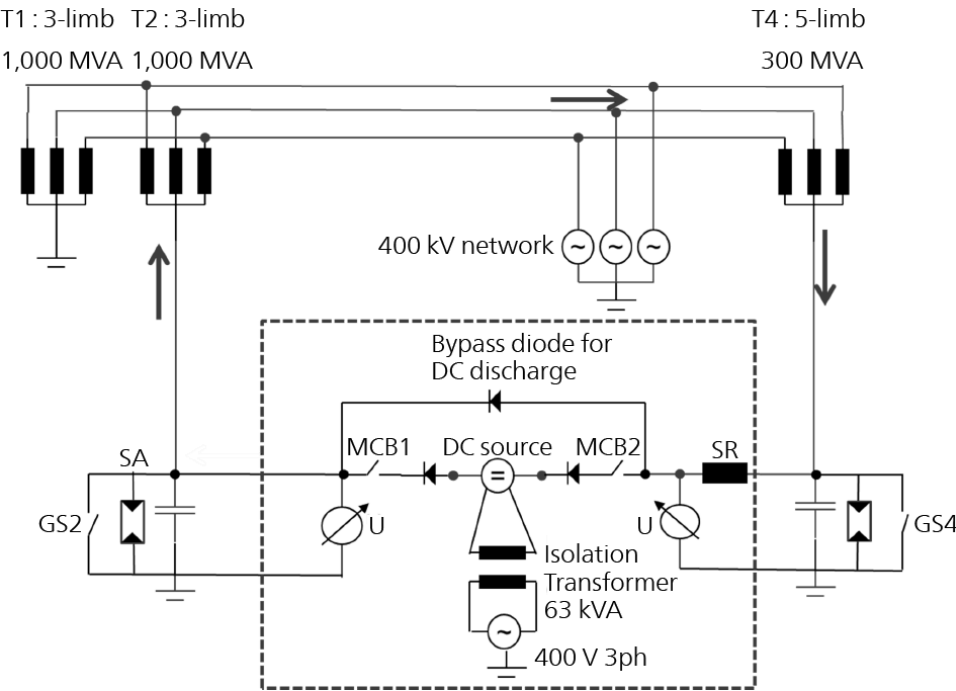
Geomagnetically induced currents (GIC) of 10s and up to 100 A quasi-DC occur frequently on the higher and lower latitudes of the earth, but on rare occasions, every 100 or 500 years, a few 100 A DC may be reached. Such currents passing through the neutrals of power transformers cause severe part cycle saturation of the core, inrush-like, high amplitude spikes in the excitation current and consequently a high reactive power consumption. This may give rise to system instabilities. In addition, excess magnetic flux will excite magnetic structural material in the transformer core and tank, potentially causing hot spots.

The limits of GIC that power transformers can take without damage have been under discussion for a few decades, with scarce detailed experimental evidence under controlled conditions3), 4), 5). Due to the high reactive power demand from a saturating transformer, such measurements cannot be performed in a test room with limited generator power. Very few measurements have been performed on-site in a strong network and up to DC values of a few 100 A since the 1990s. Measurements suffered from sensors not being installed in the most critical locations or failing. To assess the impact of GIC on power transformers and to verify simulation models a joint research project was established by Statnett and Hitachi Energy1), 2). In the project two 420 kV power transformers were designed, manufactured, comprehensively instrumented, factory tested, and finally subjected to up to 220 A DC on-site to study the geomagnetic current effect.

2. Test Set-up

A 1000/1000/100 MVA, 420/300/24 kV auto-transformer and a 300/300/100MVA, 420/138/22 kV transformer were connected to the 400 kV busbar in one of Statnett's substations, providing a very stable voltage, see Figure 1. The normally solidly grounded neutrals of these transformers could be galvanically separated from the substation ground by manual grounding switches (GS1 and GS2) to ensure that the DC injected between the neutrals would flow exclusively through just these transformers and taking all the safety precautions needed. AC currents from the neutrals e.g., due to harmonics, or transients from the busbar, could pass via 50-mF capacitor banks connected between neutral and substation ground in both transformer bays. The voltage to ground at the neutrals - and thus at the DC source and the operator - was limited by surge arresters. AC ripple through the DC source was limited by a smoothing reactor (SR). A 300 V, 225 A, 18 kW power electronic DC source was selected. A free-wheeling diode was connected in parallel with the DC source to prevent high voltages in case of a failure of the DC source.

Figure 1—Test Set-up with Transformers T2 and T4 Connected to the 400 kV Busbar, DC Source, and Modified Grounding



GS: grounding switches, MCB: miniature circuit breakers, SR: smoothing reactor, SA: surge arresters, U: voltmeters

Connections for feeding DC on site. Components inside the dashed box, except for the smoothing reactor (SR), were located inside the substation building, accessible to personnel. The other components were located next to the transformer bays. Transformers are illustrated only with corresponding HV windings.

The transformers were each equipped with data acquisition systems incorporating >30 thermocouple sensors measuring temperatures in and around the cores and structural parts, > 30 fiberoptic sensors measuring temperatures in the windings, six search coils measuring the magnetic fluxes in the tie plates next to the core limbs; and two Hall-effect current transformers.

Phase currents and voltages during the tests were measured using the station current and voltage transformers.

Transient recordings with sampling rates of at least 10 kHz were made of the voltage signals from the flux coils and of the Hall sensor outputs with AC and DC components. Such recordings were triggered manually and synchronized with forced fault recordings in the existing protection system.

3. Simulations

Circuit simulations^{6), 7)} were conducted to assess the anticipated reactive power consumption and potential harmonic distortion in the 420-kV system to secure approval from the network operator for the test. Furthermore, calculations were performed to determine the range for induced voltages in the flux search coils and to specify the parameters for the Hall sensor current transformers. Circuit simulations were performed first for the individual transformers at no-load, with DC circulation between the neutrals of the HV windings and the phase voltage sources.

Reactive power as product of the fundamentals of voltage and magnetizing current was calculated to 20 MVar for the 3-limb transformer and 49 MVar for the 5-limb transformer at 200 A DC through the neutrals.

Further circuit simulations with both transformers connected as in the test plus an additional transformer connected to the 400-kV busbar were performed to identify risks, to dimension the components for the test set-up, and to establish a safe test procedure.

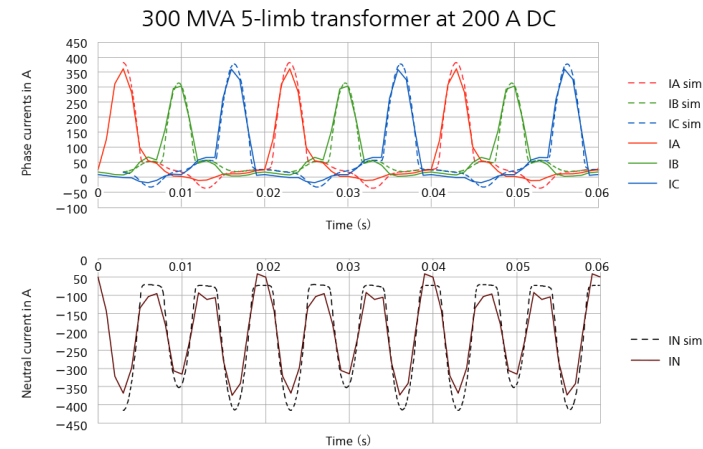
4. Results

4.1 Reactive power and current waveshapes

For the network operator, knowledge of the consumption of reactive power and the current harmonics is important to control the system voltage and to select the proper settings for the protection system. Measured and simulated reactive powers matched quite well.

For the 5-limb core, measured waveshapes (solid) match the circuit model simulations (dashed) quite well, as shown in Figure 2. Phase current transformers (CTs) do not capture DC. For the 3-limb, 3-phase core, the off-core flux paths in the circuit model needed to be enhanced for a good match with measurements, both for the current amplitudes and for their onset with DC. The measurements confirmed that 3-limb core designs are less sensitive to GIC up to a certain threshold DC passing through their neutral. Once this threshold is exceeded, the current amplitudes reach the same order of magnitude as for 5-limb cores, see Figure 3.

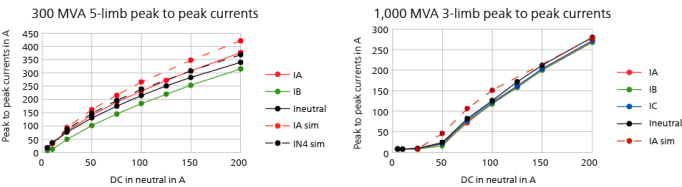
Figure 2—Measured and Simulated Current Waveshapes for the 5-limb Core at 200 A DC



*Red: current phase A , Green: current phase B, Blue: current phase C, Black: neutral current

For the 5-limb core, measured waveshapes (solid) match the circuit model simulations (dashed) quite well. Phase current transformers (CTs) do not capture DC.

Figure 3—Peak-to-peak Currents in Phases A and B, and in the Neutrals, for Both Transformers as a Function of DC through their Neutrals



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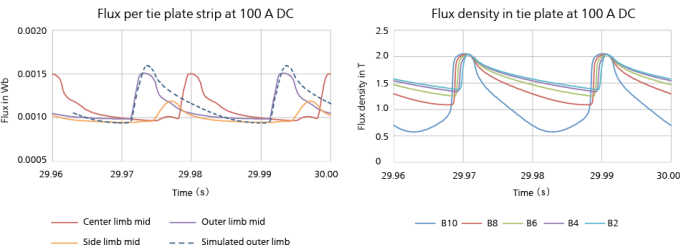
4.2 Magnetic flux in tie plates

The tie plates next to the core limbs are made of high-strength, magnetic steel. The core with its highly permeable steel saturates first. Once it saturates, the less permeable tie plates pick up flux. The tie plates are not laminated from thin sheets but are solid steel bars. Flux parallel to the axis of the tie bars will produce eddy currents flowing around the circumference of the tie plates counter-acting the field penetration, producing losses. When saturation of the entire cross-section is reached the local rate of change of the magnetic field - and thus instantaneous eddy losses - become very low. After penetration, the B-field is temporarily “locked” in the tie plate, until the external field reverses polarity, which forces flux out of the tie plate, producing another peak in the instantaneous losses. The time-averaged eddy losses in the tie plates may reach several kW, resulting in a hot region with a thermal time constant of just a few minutes. The flux variation in the tie plates was measured by search coils wound around them. This phenomenon could be simulated with good quantitative agreement, using so-called ladder circuits^{8), 9)}. In Figure 4, on the right side, one can see that the flux in the layers next to the surface reaches saturation quickly, one layer after the other, and then tends to be locked in by eddy currents, especially for the innermost layers.

4.3 Temperature rises in tie plates

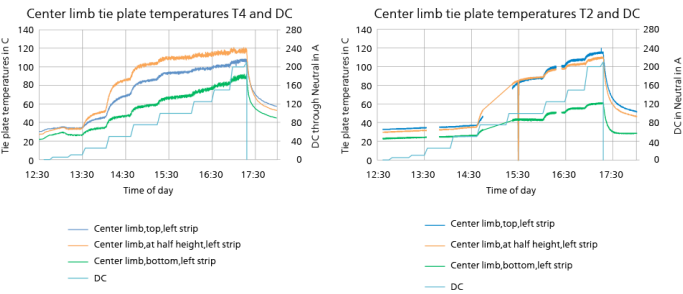
The tie plates next to the core limbs are the most critical components. In the 5-limb transformer up to 130 °C was reached at the tie plate hot spot for 200 A DC, see Figure 5. The time constant was of the order of 5 minutes. In the 3-limb transformer the maximum tie plate temperature reached 115°C. Magnetic saturation and an enhanced heat transfer with high surface loss densities “limit” the temperature rises.

Figure 4—Waveshapes of Magnetic Flux as Measured in Tie Plate Strips of Different Limbs and at Different Depths



Left: Measured magnetic flux per tie plate strip at 3 locations and simulated flux. The DC offset of measured curves depends on the instant of start of integration of the voltages induced in the flux coils. Right: Variation of flux density inside the tie plate; B10 next to surface, B8 - B2 progressing into the bulk of the tie plate.

Figure 5—Tie Plate Temperatures and DC versus Time for Two Transformers



This diagram shows that in the 5-limb transformer (T4) up to 130°C was reached at the tie plate hot spot for 200 A DC. In the 3-limb transformer (T2), the maximum tie plate temperature reached 115°C.

5. Conclusions

The temperatures of the tie plates next to the core for 200 A DC in the neutral for 20 minutes remained below 130°C, with clear indications that both saturation of the tie plates as well as the increase of the heat transfer limit further increase.

The ladder circuit model yields a fair agreement for the flux amplitudes in the tie plates, and the simulated tie plate losses follow the measured ones with a constant factor.

The measurements allow adjusting the off-core flux path in the circuit model representing the tank, resulting in a significant improvement of the simulation of the 3-limb core.

Large power transformers of the designs presented - without special provisions for exposure to high DC currents - can be exposed to DC currents of 200 A through the neutral for several tens of minutes without suffering damage. For designs with different concepts for the cooling of the critical components, or for even higher DC currents, the critical hot spots need to be verified by simulations. The work performed allows improving the simulation models and confidence in the results.

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