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Experimental Study of Clamping Pressure during Step Loading of Power Transformer with and without Prior Energisation

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Abstract: The electrification of society, increasing renewable energy sources and mobility charging lead to new loading patterns for power transformers. Dynamic load conditions induce enhanced mechanical stress on the transformers' windings, potentially causing degradation of the solid insulation over time and compromising the transformer's short-circuit withstand capability. Thermal expansion of the windings, caused by losses in the copper conductors, occurring as the transformer is loaded, increases the stress. Conversely, magnetic losses in the core and tie plate expansion contribute to a reduction in stress. This paper presents the effect of step changes in core losses and copper losses by on-line measurements of the clamping pressure, to better understand the mechanical stresses acting upon the solid insulation cellulose materials. Energisation is found to decrease the clamping pressure following warming up of the transformer, and loading the transformer increased the pressure as the windings increased in temperature. The converse effect was found when unloading and de-energising. The on-line monitoring system provides a new and important step towards ensuring the short-circuit performance of power transformers.

Keywords: power transformer; clamping pressure; transformer energisation; transformer loading; short-circuit performance; on-line measurements

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1. Introduction

Transformers are cornerstones of the electric production and distribution system, enabling the transmission of electric power while minimising losses, by shifting the voltage levels. Electric power typically passes through four to five transformers on the route from producer to consumer. Sufficient winding clamping pressure is required for the transformer to resist the strong forces arising from through-current faults, and is therefore essential for the short-circuit performance of a power transformer [1–3]. Transformer failure is a rare event, but it has been reported that more than one in four failures were due to short-circuit events [4]. Transformers shall be designed to withstand such events [5].

The main function of a power transformer is achieved by having conductors, coiled in windings, wound around a magnetic core. The conductors in the windings are electrically insulated, typically by resin and insulating paper. In operation, core and conductor losses heat up the transformer. An electrically insulating liquid is used to continuously cool the apparatus by transporting heat, and this heat is removed by a heat exchange, typically radiators, on the outside of the transformer tank. The liquid insulation also has an impregnation function on the solid insulation, protecting it and slowing degradation processes. To allow for liquid flow within the windings, pressboard spacers are used to create ducts for liquid flow. The windings are clamped together, compressing the conductors and the solid insulation (cellulose) to the design-required clamping pressure. This ensures the mechanical integrity of the system, which shall resist electromagnetic forces acting upon the windings [5]. In the case of short-circuit events in the grid, the forces from through-currents can be significant and, if windings are not tightly clamped, shifting of conductors can occur, sometimes with catastrophic failure [6].

In operation, the winding clamping pressure will vary due to thermal expansion and contraction of the windings and the clamping system. The clamping pressure is also subject to unintentional variation, due to mainly three effects. First, the strong sensitivity of pressboard and paper thickness on moisture: even a slight increase in moisture inevitably causes swelling and moisture decrease shrinkage of the solid insulation, which has direct impact on the clamping pressure [7]. Second, the thermal effect, which was investigated and reported for the first time in 1999 [8,9]: the clamping pressure fluctuates significantly in the case of temperature transients due to strongly differing temperature expansion coefficients among the involved materials (mainly steel, copper, cellulose insulation). Third, cellulosic insulation undergoes aging, affecting its stiffness and elasticity [10,11] over decades. New transformer loading patterns, caused by the integration of renewable energy production and mobility charging, subject the insulation materials to more rapidly fluctuating thermal and mechanical stresses. The effect this may have on the long-term clamping pressure is not well understood. The present paper focuses on demonstrating transient thermal effects, which can occur within minutes to hours.

Traditionally, transformers can be equipped with sensors to monitor the loading, ambient temperature and top oil temperature. Monitoring of the winding hot spot temperature is often included, as this is the critical temperature for aging of the paper in the windings [12]. Such sensors are commonly fibre optic types, since high electric and magnetic fields in the windings exclude many types of sensors. The integrity of the windings and of the clamping structure can be assessed indirectly through electrical (frequency response analysis) [13] or mechanical (vibrational analysis) measurements. However, novel sensors also allow for quantitative measurements, directly on the clamping system [14]. The interpretation of these on-line measurements can be used for condition-based maintenance. Many of the parameters and effects that can impact a transformers' winding stability are not discussed in this article, as for example the sizing (pre-drying of coils under pressure in the factory), the clamping construction and pressure of the windings per se, moisture increase in operation and related insulation swelling, moisture migration between solid and liquid insulation and decomposition of cellulosic insulation due to aging. When a transformer leaves the factory, the clamping forces are carefully controlled and set to levels that, with appropriate margins, prevent winding movement during anticipated short-circuit stresses. However, there is currently no information on how the clamping pressure will vary due to load changes and aging.

This paper presents winding clamping pressure and temperature variations on-line measurements over more than 10 days from a recently commissioned new 40 MVA power transformer. Particularly, step changes of loading with and without prior energisation were performed and the results are reported.

2. Materials and Methods

A 40 MVA substation transformer (T3) placed in the south-eastern part of Norway was used for this study, as seen in Figure 1. The cooling system of T3 is of ONAN type, i.e., heat exchange between the oil and the windings through natural convection, and heat exchange between the oil and the ambient air (radiators), also through natural convection. The transformer T3 is equipped with sensors for measuring the clamping pressure on-line (fibre Bragg grating), as well as with several temperature sensors (fibre GaAs type) in the windings, as seen in Figure 2. There are fibre-optic temperature sensors for the hot spot and in the middle of both the helix LV- and disc-type HV-windings, as well as for oil temperature into and out of the windings. The oil temperatures at outlet to, and inlet from, one radiator are also measured. Additionally, there is a resistive temperature sensor (Pt100) for top oil temperature and the ambient temperature in the transformer cell is measured some distance below the radiators.

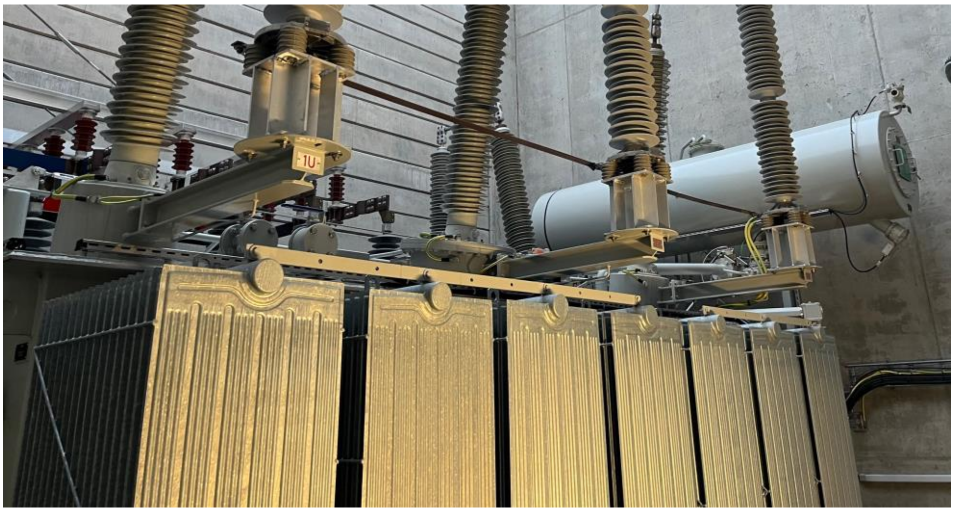

Figure 1. The three-phase 40 MVA power transformer in operation in the substation. The photo focuses on the auxiliary equipment: the radiators in the front, the HV-bushings and the surge arresters on the top and the oil expansion tank in the back.

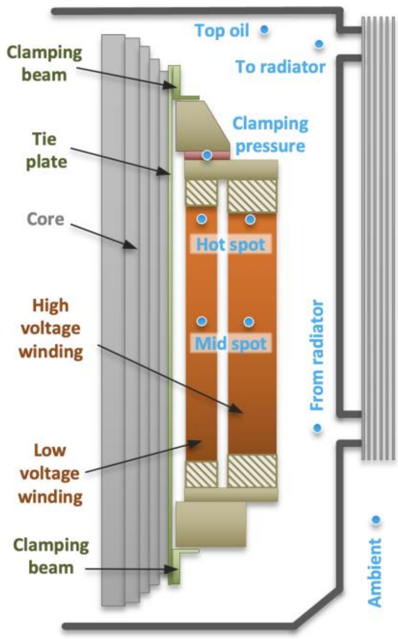

Figure 2. Principal sketch of clamping system, windings and sensor layout (blue circles). The active part of the transformer: the core, the clamping system and the windings, including the solid insulation system, are submerged in an electrically insulating liquid within a sealed tank. The liquid flow cools the active part.

The transformer clamping system consists of top and bottom clamping beams, connected by tie plates mounted along the core legs, as seen in Figure 2. The windings, the laminated wooden blocks and plates and the insulation materials are compressed between these beams. The purpose of the clamping system is to maintain sufficient pressure on the windings to keep the turns/discs/conductors in place. Typical design pressures are of 5 MPa on the radial spacers for disc windings and 2 MPa for layer/helix windings. This pressure is calculated by taking the copper area of the conductors projected onto the spacers (neglecting any corner radius on the conductor strands) [5]. The designed clamping pressure is set during the final stages of fabrication. This is typically achieved by jacking up the winding stack to a high pressure and adjusting the height of the top blocks to fit, such that the designed pressure remains after removing the jacks. The initial overpressure needed to obtain correct pressure is often based on experience or internal procedures.

There are eight clamping pressure sensors installed on the leg of the central phase. These are located on top of the upper winding plate, and underneath the wooden insulation blocks positioned below the steel clamping beams, as seen in Figure 2. Clamping forces compress the sensor unit which leads to strain that can be measured, as seen in Figure 3. The pressure measurements presented in this paper are the numerical average of the sensors. Each clamping pressure sensor unit consists of a temperature sensor and a strain sensor, both on the same fibre. The operating principle of fibre Bragg grating sensors is that the grating acts as a dielectric mirror, for a frequency given by the grating distance. As such, the grating distance can be measured by sending a wide frequency wave package into the fibre, and then measuring the peak frequency of the reflected wave. Mechanical strain and thermal expansion change the grating distance, and thus the reflected frequency. The sensors are calibrated by fitting a third-order polynomial for both the temperature and the mechanical strain sensor. Importantly, the temperature measurement is used to compensate for temperature expansion of the strain sensor when calculating the pressure. The operational details of the sensors and measurements from the transformer heat run test were presented earlier [14].

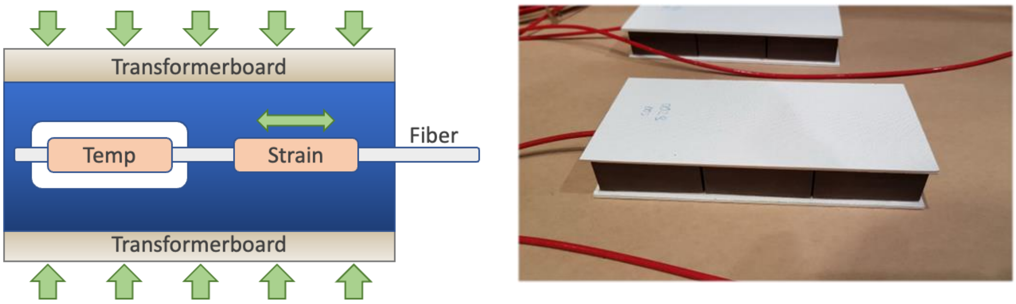

Figure 3. Principal sketch (**left**) and picture (**right**) of clamping pressure sensor. Clamping forces compress the sensor, resulting in mechanical strain in the fibre. The temperature sensor is unaffected by mechanical strain and is used to compensate for thermal expansion strain in the pressure (strain) sensor. The sketch is from [14], reprinted with permission.

Steel (the tie plates), copper (the windings) and insulation materials (wood, paper and pressboard) have different mechanical and thermal properties. Thermal expansion coefficients are typically 12×10^{-6}/K, 17×10^{-6}/K, 70×10^{-6}/K, for steel, copper and pressboard (out of plane), respectively. The insulation materials are much softer and have a higher thermal expansion coefficient than the metals. Increasing the temperature will cause expansion of all the parts, but less for the steel tie plates than the windings, increasing the tensile stress in the tie plates and the compressive stress in the windings. The higher thermal expansion of copper compared to steel adds to this, but the major effect is the difference between the pressboard and the steel. Conversely, cooling the entire system will reduce the pressure in the clamping system. Consider as an example, a clamping system where the steel tie plates are 2 m long, while the total heights of copper and cellulose materials in the winding are of 1.3 m and 0.7 m, respectively. For a change in temperature of 10 K, the tie plates expand by 240 µm, whereas the copper and cellulose materials expand by 221 µm and 490 µm, for a total of 711 µm, in theory. However, the winding cannot expand freely since it is clamped. The result is an increase in clamping pressure. The magnitude of the change in pressure depends on the stiffness (elastic properties) of the clamping system and the windings. Practically, the system is not in thermal equilibrium, neither during normal operation, nor following step changes. The varying temperatures throughout the system will influence thermal expansion of the windings and of the clamping structure, which in turn affects the clamping pressure.

Power transformers have a high efficiency [15]. The losses are low and can be divided into "no-load" losses and "load losses" [16]. Energising the transformer is performed by connecting the HV windings, which magnetises the core. Magnetic losses, also called "no-load losses", are independent of loading. The magnitude of the no-load losses is given by the transformer's design and energisation voltage level, and can be approximated by, e.g., the Steinmetz model [17]. These losses cause core heating, and also affect the tie plates placed along the core legs. The subsequent thermal expansion of the tie plates will reduce the clamping pressure. Core heating affects the temperature of the transformer as a whole, but the tie plates more directly than the windings. The magnetisation of the core does not cause any significant losses in the windings. On the other hand, there are the "load losses", where a major part are the copper losses, occurring in the conductors when the transformer is loaded, and these losses are proportional to the square of the loading magnitude. The conductors are heated by the copper losses, which in turn heat the paper, pressboard and surrounding insulation liquid. This affects the windings more directly than the tie plates and will increase the clamping pressure.

The losses for the transformer in this study are of 16 kW for the core (no-load losses) and 120 kW (load losses) for the windings, at rated power. For a loading of 15 MVA (37.5% of rated power), the core and copper losses will be comparable, while at 20 MVA (50% of rated power) the copper losses will be the double of the core losses. As such, at low loads, the core losses significantly contribute to the total produced heat, and thus to the temperature rise of the transformer.

The transformer (T3) is placed in the grid, as one of two (T1 and T3) in a newly constructed substation. This is a typical configuration, following the "N-1" requirement to be able to supply power in case one transformer should fail. This configuration also enables shifting of the load between the two transformers, as seen in Figure 4. Loading and unloading of T3 is achieved by operating the low voltage circuit breaker (CB-18T3), while the transformer is energised, i.e., the high voltage circuit breaker (CB-132T3) is closed. Energising and de-energising of T3 is achieved by operating the high voltage circuit breaker (CB-132T3), while the transformer is unloaded, i.e., the low voltage circuit breaker (CB-18T3) is open.

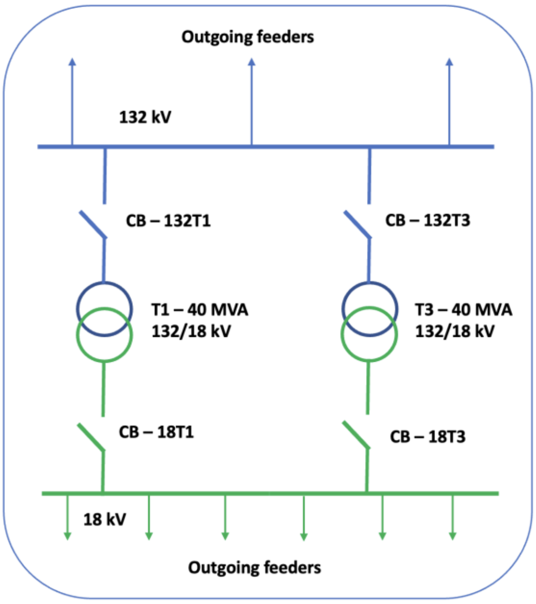

Figure 4. Simplified single line diagram for 132/18 kV substation. The circuit breakers (CB) are operated to energise and load the transformers T1 and T3 individually.

A step loading programme of the transformer T3 can be performed as follows:

1. Resting time. Keep T3 de-energised and unloaded while T1 takes all the load of the substation.
2. Energise T3 by connecting the high voltage side (CB-132T3).
3. Share load between T1 and T3 by connecting the low voltage side (CB-18T3).
4. Disconnect the low voltage side of T1 (CB-18T1) such that T3 takes all the load.
5. Stabilisation time. Keep the transformer energised and loaded.

The operations 2–4, or the reverse, can be performed within one minute. The result is a step increase in load for T3, from a resting (de-energised, unloaded) condition, to taking all the load of the substation. A series of such operations was performed in February 2023, as seen in Figure 5.

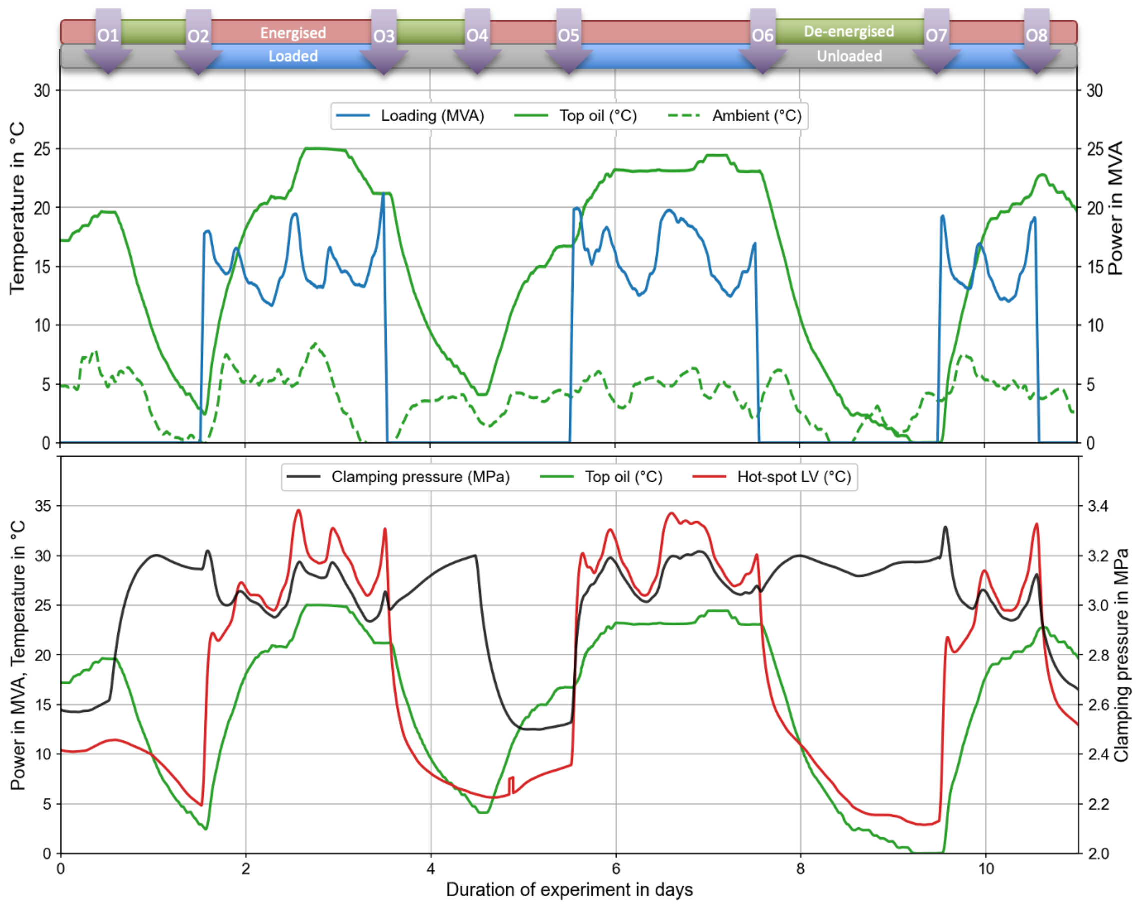

Figure 5. Scheme of operations during the experiment. The arrows on the top indicate the following operations: O1—de-energise; O2—energise and load; O3—remove load and de-energise; O4—energise; O5—load; O6—remove load and de-energise; O7—energise and load; and O8—remove load. The state between operations is indicated by the colours between the arrows. The upper plot focuses on the change in top oil temperature while the bottom plot focuses on the change in clamping pressure.

The scheme of operations for T3 was as follows:

- Initial state: Energised and unloaded (no-load losses).
- O1: De-energise after resting without load for one day (zero losses).
- O2: Energise and load, one day after O1 (no-load losses and load losses).
- O3: Unload and de-energise, two days after O2 (zero losses).
- O4: Energise, one day after O3 (no-load losses).
- O5: Load, one day after O4 (no-load losses and load losses).
- O6: Unload and de-energise, two days after O5 (zero losses).

- O7: Energise and load, two days after O6 (no-load losses and load losses).
- O8: Unload and de-energise, one day after O7 (zero losses).

The main goal of the experiment was to investigate the clamping pressure dynamics while loading and unloading the transformer. The scheme was designed such that the influence of energisation (no-load core losses) can be separated from loading (load losses). The different operations were performed at intervals of one to two days, to allow the system some time to equilibrate between the operations and follow the slower daily load variations. The substation is constructed for the future, having a low loading for now, reaching about 60% of nominal loads during the heavy loading in winter times. The maximum load obtained for T3 during the experimental period presented in this this paper was about 50% of rated power.

3. Results

A series of operations was performed in February 2023, a selection (O1 through O8) of which is shown in Figure 5. The operations consisted in loading/unloading and energising/de-energising the transformer. The figure shows how energisation (no-load losses) and loading (load losses) influenced the LV hot spot temperature, the top oil temperature and the clamping pressure. The top plot in Figure 5 shows that energising (O2, O4, O7) was followed by increasing top oil temperature, and conversely for de-energising (O1, O3, O6) where the temperature decreased following the operation. Loading the transformer also increased the top oil temperature (O5); however, the effect was lower than for energising alone (O4). The ambient temperature was rather low but stable, within the range from -2 °C to 8 °C, throughout the period of 11 days.

The impact on the clamping pressure is shown in the bottom plot of Figure 5. Energisation (O4) and de-energisation (O1) without load (no-load losses) had a significant influence on the clamping pressure, yielding about a 20% change. This change was associated to a change in top oil temperature, indicating a change in core temperature and tie plate thermal expansion. During normal operation (energised and loaded), e.g., the days following O2 or O5, the clamping pressure largely followed the temperature of the winding, which is in turn followed the loading curve, as seen in Figure 5. This is due to load losses and the associated winding temperature variation, causing thermal expansion and contraction effects on the clamped windings. The top oil temperature did not change much during normal operation, and as such, the tie plates temperature remained stable, thus keeping the clamping pressure practically constant.

Figure 6 shows the operations O5 and O7, applying a step load from zero to about half of the rated power, from an energised and a de-energised state, respectively. In both cases, the hot spot temperature increased almost linearly in the beginning, before approaching an exponential behaviour, and then stabilising. One may argue on whether the response is linear for the first part, or whether this is just the beginning of an exponential curve. However, for the first part of the graphs, the temperature out to the radiator does not change, implying that the oil temperature from the radiator, the bottom oil, and the oil into the windings does not change either. The thermal siphon, driven by buoyancy from the reduced density of heated oil flowing through the windings, is not yet fully active. As long as this remains the case, heating continues to be nearly linear. The response was somewhat flatter for O5 than for O7, but with prior energisation (O5), the oil started at a higher temperature and the hot spot temperature rise was also somewhat higher. In both cases, there was a delay before the temperature of the oil into the radiator increased. The initial level for the radiator temperature was much higher for O5, while the delayed increase was more prominent for O7. Oil flow in the windings was not developed during the unloaded state and took some time to develop once the load was applied. The temperature of the hot spot was expected to increase linearly until the flow was developed, and thereafter exponentially when the thermal siphon was activated, cooling the windings. There will be a further delay for the hot oil to reach the radiators, which also depends on whether the flow in the radiators was already developed (previous energisation) or not (from de-energised).

The time to develop the flow is expected to depend on the load and the losses. The initial linear rise was indeed seen to be steeper and shorter during the heat run test performed at the factory acceptance testing [14].

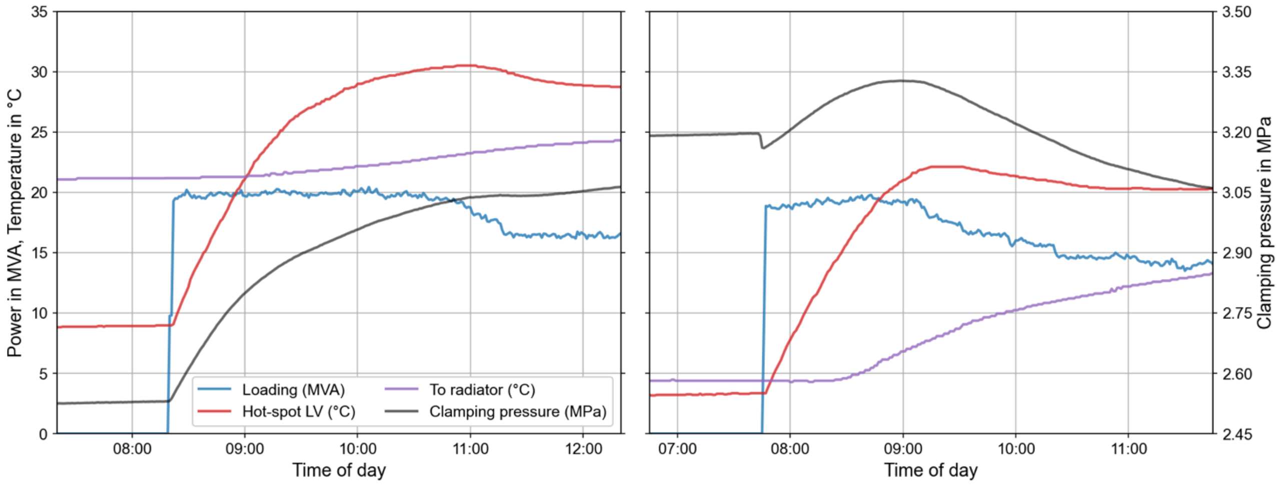

Figure 6. Applying step load to the transformer, with (**left**, O5) and without (**right**, O7) prior energisation.

The difference in clamping pressure between loading from energised (O5) and de-energised (O7), respectively, was profound, as seen in Figure 6. For O5, the pressure increased with the increasing winding temperature, as expected. However, for O7 the initial clamping pressure was higher, then it briefly dropped as the transformer was energised, thereafter increased for some time while the windings warmed, but thereafter reduced in value. The reduction apparently corresponded to the temperature rise in the oil, as made evident by the temperature of the oil flowing into the radiator. The initial pressure drop at O7 was an instantaneous reduction of about 0.03 MPa. Instantaneous, that is, from one second to the next, as the sensor readings were recorded once per second. A similar effect had been observed for the heat run test [14]. This reduction was likely caused by electro-magnetic forces compressing the windings, causing a reduction in pressure in the clamping system. The magnitude of the reduction is somewhat distorted in Figure 6, since the data presented there are averaged minute for minute.

Energisation and de-energisation caused the clamping pressure to change over the course of several hours, presumably following heating and cooling, respectively, of the tie plates and the core. The brief, instantaneous reduction in pressure when energising and loading was rapidly dwarfed by the increase in pressure following the heating of the windings, as seen in Figure 6. However, over the course of some hours, the pressure was again reduced as the transformer and clamping structure warmed up. Removing the load had a similar, but inverse effect, where the cooling of the windings initially reduced the pressure, but the cooling of the tie plates rapidly counteracted this, when the transformer was disconnected and de-energised.

The effect of no-load losses (core heating) on the clamping structure can be separated from load losses, heating the windings by energising and de-energising the transformer under no-load conditions, as seen for O1 and O4 shown in Figure 7. The latter energisation in O4 showed an immediate drop in pressure, followed by a continued reduction. The response when simultaneously energising and loading (O7) can be explained by superimposing energising (O4) and loading with prior energisation (O5). Interestingly, there was no sudden pressure change when de-energising (O1), just a continuous increase. In both cases, the oil temperature into the radiator changed, yet with significant delay in the case of energisation O4, as seen in Figure 7. The change in the core temperature, and specifically to the tie plates, would be the main contributor to these pressure changes. Alas, these components were not fitted with temperature sensors.

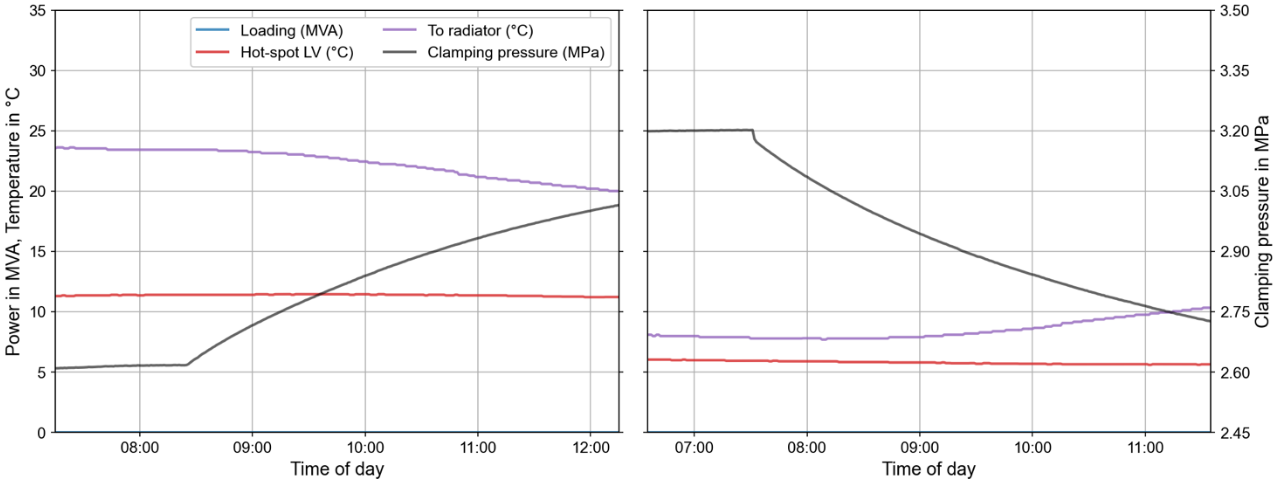

Figure 7. De-energising (**left**, O1) and energising (**right**, O4) the transformer under no load. Note that the loading here is zero and hardly visible on the zero line of the figures, but it is kept in the legend to be consistent with the other similar figures.

Removing load from the transformer is associated with cooling of the windings and the oil, as shown in Figure 8. Corresponding to Figure 6, the clamping pressure followed the hot spot temperature, when the energisation was maintained, as seen for O5 and O8. However, when taking off both the load and energisation (O6), the trend of the clamping pressure reflected a superposition of de-energising (O1) and removing the load (O8).

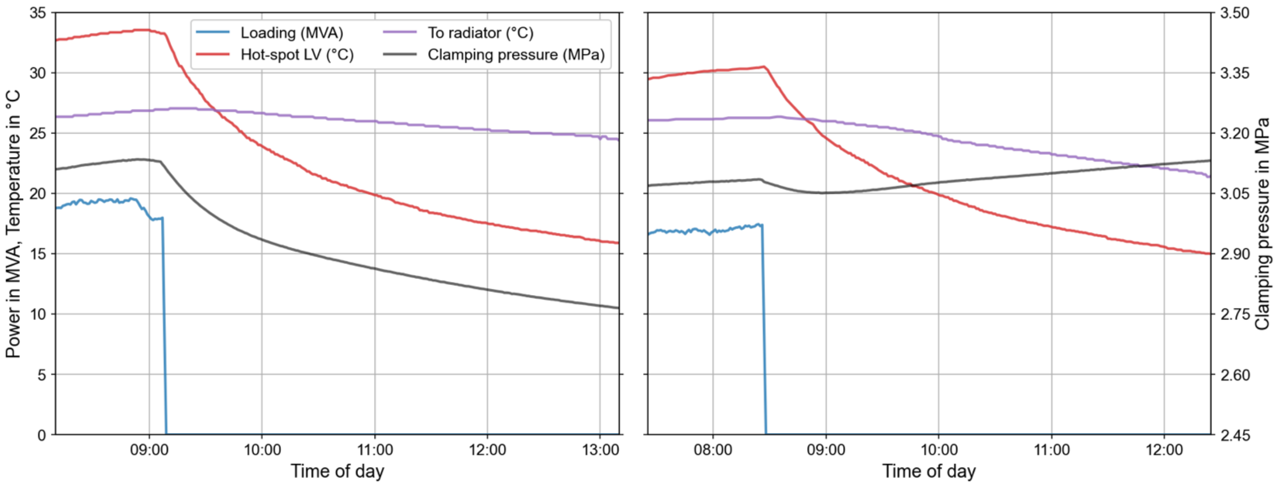

Figure 8. Removing the load of the transformer, then keeping energisation (**left**, O8) and removing energisation (**right**, O6).

Figure 6 details the effect on the clamping pressure when loading with (O5) and without (O7) prior energisation, while Figure 9 details the temperatures in the different parts of the transformer. For O7, all temperatures were between 0 °C and 5 °C. For O5, most temperatures were about 5 °C higher, except the oil into the radiator, which differed significantly, exceeding 20 °C. In both cases, the windings warmed linearly initially, and there was a delay of about half an hour before the oil temperature into the radiator began to increase, with a change more prominent for the second case (O7). The mid-spot sensors stabilised faster and at a lower temperature than the hot spot sensors, while the temperature rise was much steeper and stabilised faster for the LV winding than for the HV winding. The difference between the mid-spot and the hot-spot sensors in the winding is an indication of the time constant of the thermal siphon to develop and the delay before fresh oil from the bottom of the tank arrives to cool the windings. These findings are in line with expectations from the heat run test [14]. However, the heat run test was performed by the short circuit method, i.e., with very low core losses and copper losses exceeding nominal load losses to compensate for the absence of no-load losses. As such, there was a steeper temperature rise and a much higher increase in clamping pressure compared to what was seen in this study.

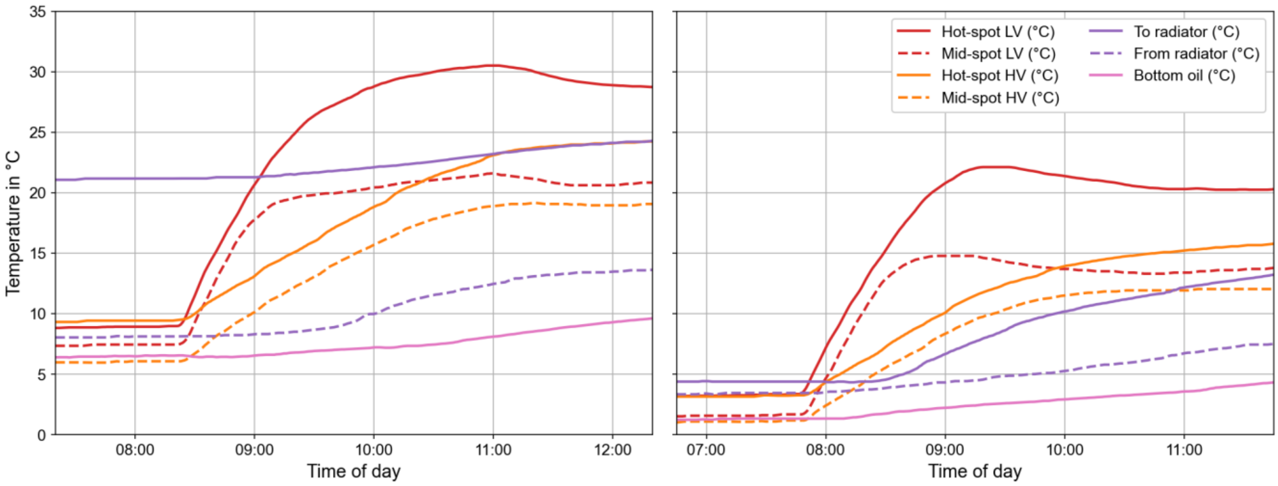

Figure 9. Thermal response of the transformer when applying step load to about 20 MVA, with (**left**, O5) and without (**right**, O7) energisation.

4. Conclusions

For the first time, variations in clamping pressure for a transformer in service were measured during daily load variations and applied load steps, revealing the effects of load and no-load losses on heating and the thermal expansion of both the clamping system and windings. In this study, thermal effects and interactions within the windings and clamping system of a 40 MVA transformer are discussed, interpreting on-line pressure measurements during and after the step-events of energisation, loading, unloading and de-energisation. The substation is newly constructed with a long-term prospective of future loads, its utilisation is currently about 50%, considering the N-1 requirement. At present, about 50% of rated load is about the highest attainable value for the transformer, but this is expected to increase in the future. A step load from zero to rated power is expected to have a much steeper temperature increase in the windings, as the copper losses in this situation are four times larger than for the 50% case. The impact on the clamping pressure is expected to be significant, and larger load changes are as such of further interest but were presently not possible.

The pressure in the clamping system varied with the thermal expansion of the windings and the tie plates. Under normal operation, the pressure varied mainly with the temperature of the windings. However, core energisation and subsequent heating and thermal expansion of the tie plates also had a distinct impact by decreasing the clamping pressure. This was best demonstrated when the transformer was energised but not loaded. The effect of stopping or maintaining energisation (no-load losses) was also visible when loading and unloading the transformer. Energising and loading, or unloading and de-energising, at the same time, reduced the fluctuations in the clamping pressure, contrary to loading and de-loading while keeping the transformer energised. How multiple pressure changes over time affect the solid insulation of a transformer is unknown at this stage. It is desirable to investigate the effects of step loading to higher loads, closer to nominal, if possible, in the future.

On-line monitoring of the clamping pressure can form the basis for future condition-based maintenance. It holds promise for improving the security of energy supply by measuring a key indicator of the transformer's short-circuit performance. Simulation models for the clamping pressure, based on transformer design data and operational data, can also enhance the safety of units not fitted with sensors. The development of such models will be facilitated by measuring the clamping pressure over long timespans and for multiple transformers. Analysing different transformer designs and patterns of operation can provide valuable insights for modelling. Moreover, comparing simulation model results with actual measurements can offer insights into material properties.

The integration of more renewable power sources and mobility charging in the future will increase transformer loading changes. Monitoring can be of particular interest in applications wherein transformers are subjected to heavy and fluctuating loading. Better understanding the mechanical stress experienced by the cellulose materials during such conditions can support estimations of the remaining winding clamping force, indicating the remaining robustness against short-circuit stresses, and thus improve the operational safety.

Supplementary Materials: This work presents transformer data from a 10-day period. The data with minute resolution can be downloaded at: https://www.mdpi.com/article/10.3390/en17122898/s1.

Author Contributions: I.M. performed the investigation, data curation, visualisation and wrote the original draft. A.M. contributed with the resources. All authors contributed to conceptualisation, review and editing of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data are available in the Supplementary Materials.

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Conflicts of Interest: Weidmann invented, designed and manufactured the clamping sensors. Kolektor Etra manufactured the transformer. Elvia is the owner of the transformer. SINTEF performs the Dynaload project. Author affiliations are declared on the front page.

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