FLUIDS

On the energizing of a natural ester-filled transformer

Cold start for offshore application

Ahmed Gamil

ABSTRACT

In cold climates offshore applications, using natural ester liquids reveals challenges due to their higher pour points compared to mineral oil. Laboratory experiments have shown that the critical concern for transformers in cold climates applications is the temperature at which solidification begins, which is higher than the pour point. This study tested a natural rapeseed-based ester liquid for energizing at subzero ambient temperatures. A case study involved exposing a natural ester-filled transformer to -15°C for approximately 400 hours, followed by energization. Liquid samples were taken before and after energization to observe changes in properties under these conditions.

KEYWORDS:

power transformer, cold climate, natural ester, partial discharge, thermal time constant

The solidification of insulation liquids is influenced by both temperature and cooling duration, emphasizing the need for careful consideration in cold climate applications

1. Introduction

Investigation of the insulating liquids performance at subzero temperatures requires investigation of transformers in three stages: storage, energizing, and loading. The solidification of insulation liquids is influenced by both temperature and cooling duration. Laboratory experiments highlight this relationship, emphasizing the need for careful consideration in cold climate applications. In real-scale transformers, additional factors such as the volume and surface area exposed to the ambient play a significant role in the performance of insulating liquids. This necessitates investigations that account for these real-scale conditions.

The most critical moment for energizing a transformer is during the liquid transition phase. During this phase, bubbles released from the liquid can cause failures, making it essential to understand and manage this transition carefully. These bubbles are built by the water content evaporated during liquid defrosting instead of being dissolved in the insulation liquid, as it is still solidified. The typical pour point for natural esters is about -20°C, which presents an additional challenge to avoid liquid solidification or at least a partially crystallized state in such a climate [1, 2]. According to standards, the minimum temperature for energizing a transformer is -20°C [3]. High partial discharge (PD) values, which may be observed during induced voltage tests, can be mitigated by placing the transformer under vacuum for approximately 60 hours. This treatment helps eliminate bubbles and ensures safer energizing [4].

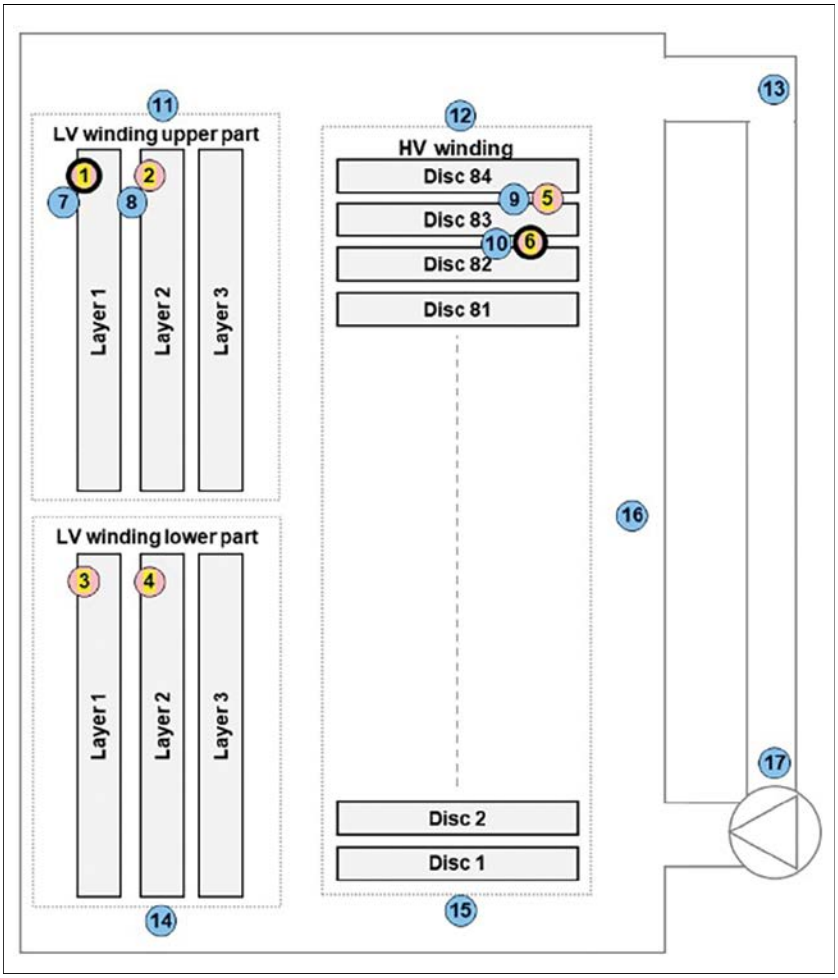

Figure 1. Locations of FOS in the active part

Previous studies suggest using Computational Fluid Dynamics (CFD) simulations for understanding transformers during cold start [5, 6].

The current study investigates the crystallization time of natural ester in a three-phase 16.7 MVA/66 kV KFWF cooled transformer designed for offshore applications. The test involved cooling and energizing the transformer at -15°C despite the liquid's pour point being -33°C. Liquid samples were taken before and after energization to check properties and perform Dissolved Gas Analysis (DGA) for Partial Discharge (PD) detection. DGA can detect PD by analyzing the types and quantities of gases dissolved in transformer oil, which are byproducts of PD events. The presence and ratios of gases like hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H4), and acetylene (C_2H_2) can indicate the presence and severity of PD. Thermal time constants were analyzed to understand the liquid's thermal behavior and the time available for freezing to begin. The transformer was equipped with fiber optic sensors (FOS) in the winding and liquid, along with additional temperature pockets and pressure sensors in the tank and cooler. Temperature measurements during storage and energization phases, along with their locations, explained changes in viscosity and moisture saturation over time. The thermal time constant analysis provided a detailed picture of the liquid's cooling rate at each location. By

Fiber optic sensors were strategically installed at various locations in the active part of the transformer based on calculations of hotspot locations in the high voltage and low voltage windings

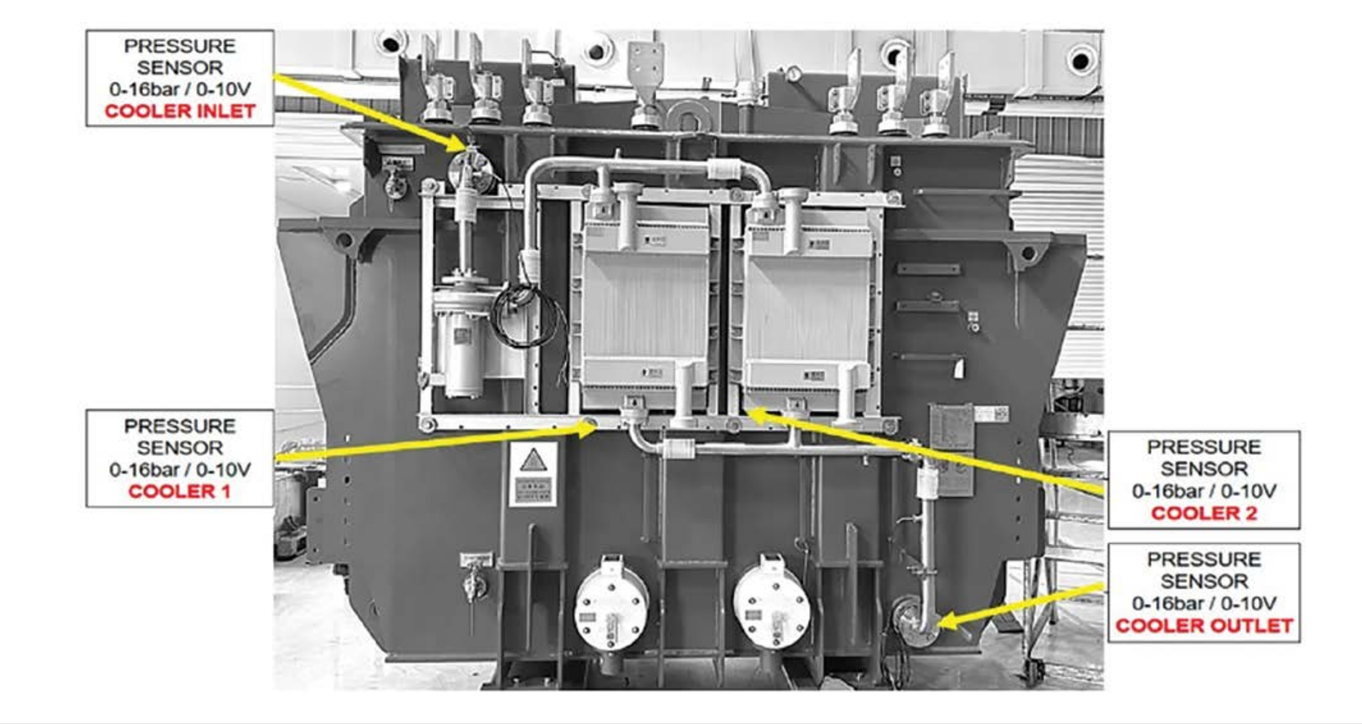

Figure 2. Pressure sensors' locations

correlating these measurements with the upper liquid temperature profile, the study estimated the temperature distribution in the liquid at low temperatures.

2. Measurements

Fiber optic sensors (FOS) were strategically installed at various locations in the active part of the transformer based on calculations of hotspot locations in the high voltage (HV) and low voltage (LV) windings using a thermal model. These sensors measured the winding liquid temperature, aiding in the calculation of winding gradients for different liquid locations within the active part. FOS 1 and 2 measure the LV winding hotspot, while FOS 5 and 6 measure the HV winding hotspot. The temperature differences between FOS 12 and 15, as well as FOS 11 and 14, represent the axial gradient for HV and LV windings, respectively. FOS 7 measures the liquid temperature at the top of the core. These temperature readings can be converted to liquid viscosity and moisture saturation during the storage and energization phases.

In addition to the standard top and bottom liquid temperature pockets, temperature pockets were installed at various locations in the tank and cooler. This setup provided a comprehensive view of the temperature distribution inside the tank and support in liquid condition

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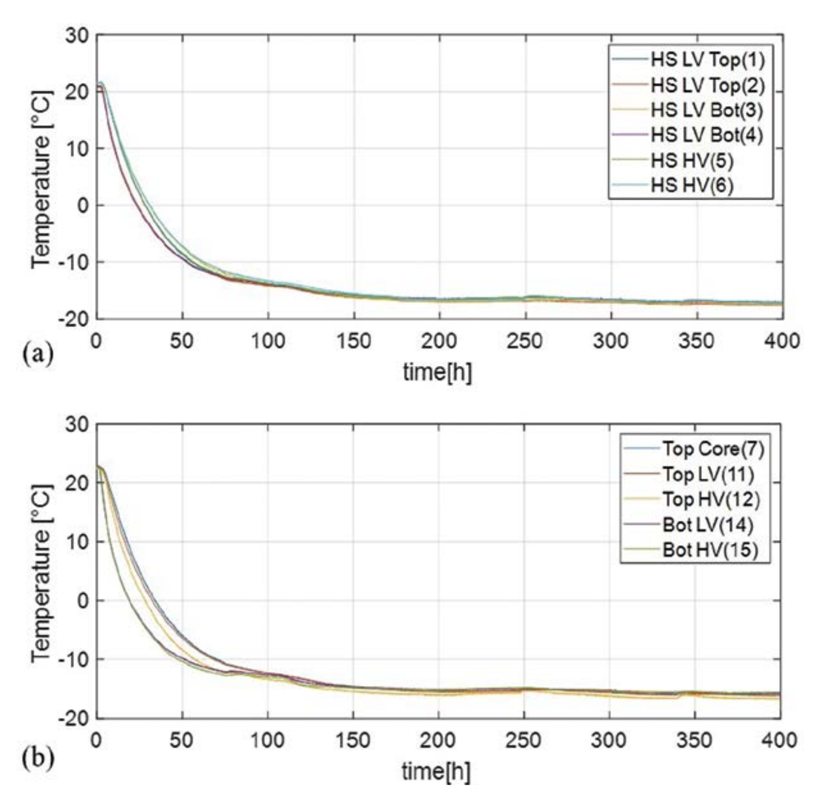

Figure 3. FOS signals during cooling at -15°C: (a) winding hotspot locations, (b) active part liquid

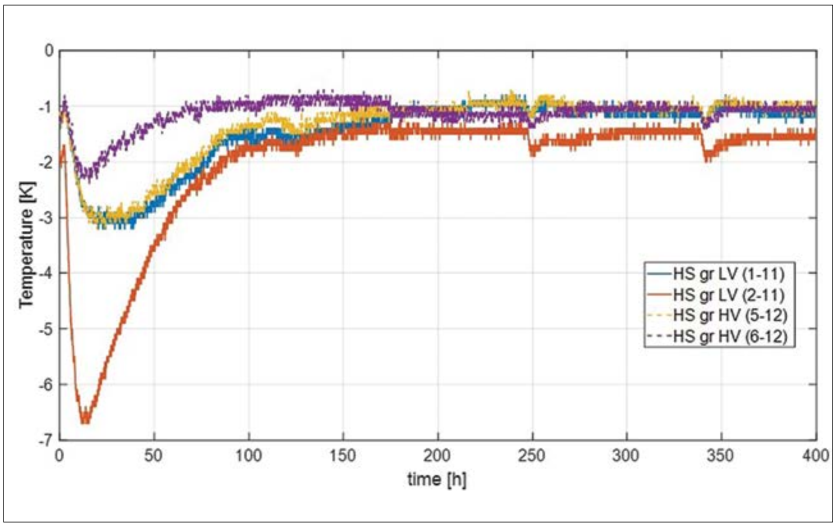

Figure 4. Winding hotspot gradients during cooling at -15°C.

> **The cooling time constants for active part liquid FOS are more varied, ranging from 20 to 35 hours, and exhibit an inverse correlation with FOS temperatures based on their top-to-bottom locations**

monitoring during storage and energization stages.

Pressure sensors were also placed at critical locations in the cooling pipes and tank connection, where liquid solidification would likely begin, as shown in Fig. 2. This pressure monitoring is important for observing the liquid expansion or solidification during heating up or cooling down, respectively. In this case, it is possible to make a decision in time to shut the test down in case the released pressure exceeds the limits of the cooling system or if it is expected to have a leak somewhere in the transformer tank.

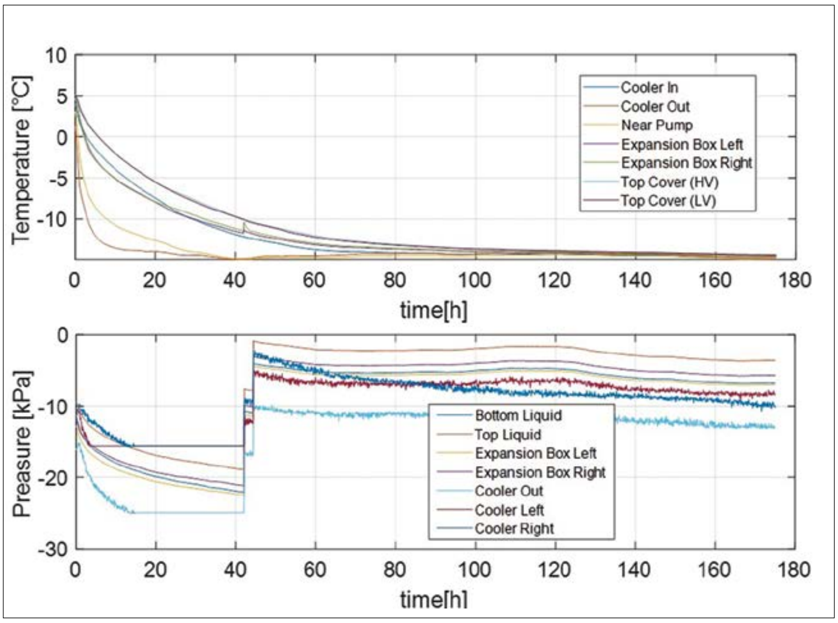

Figure 5. Temperature pockets and pressure sensors signals with the corresponding temperature time constants.

3. Results and discussion

3.1 Cooling in a cold chamber to subzero temperature (Storage Phase)

After connecting the FOS and temperature pockets to the measurement terminal, the cooling chamber was set to -15°C, and recordings from the FOS, temperature pockets, and pressure sensors began. Fig. 3 illustrates the FOS signals attached to the windings (a) and the liquid at various locations in the active part (b).

The analysis of winding cooling time constants for hotspot FOS shows a range of 30 to 35 hours. In contrast, the cooling time constants for active part liquid FOS are more varied, ranging from 20 to 35 hours, and exhibit an inverse correlation with FOS temperatures based on their top-to-bottom locations. These findings align with previous studies [7] on above-zero climates, indicating that liquid time constants are location-dependent.

The core top liquid (FOS 7, Fig. 1) was used as a reference to calculate hotspot gradients, as its thermal time constant is in the same range as the winding hotspots of 35 hours.

The curves in Fig. 4 illustrate how cooling affects the winding liquid at the hotspot location, taking approximately 100 hours for the gradients to stabilize. The maximum absolute value of 6.7 K at FOS 2 has a time constant of about 9 hours, which then decays with a time constant of around 27 hours to reach a stabilized hotspot gradient of 1.5 K. It is evident that the hotspot gradients at FOS 1 and 5 remained at -3 K for about 20 hours, indicating a similar cooling rate during this period before the gradients began to stabilize.

Inside the tank, as shown in Fig. 5, the liquid behavior is different from that of the active part. Even within the transformer cooling system, there is a difference in time constant between the cooler inlet of about 20 hours compared to the cooler outlet with a value of only 3 hours. On the other hand, the liquid in the tank cover has a time constant of about 30 hours.

This difference in time constants, when the temperature signals are converted to viscosity and moisture saturation, it is evident that it takes between 180 and 210 hours for the entire transformer liquid to reach -15°C.

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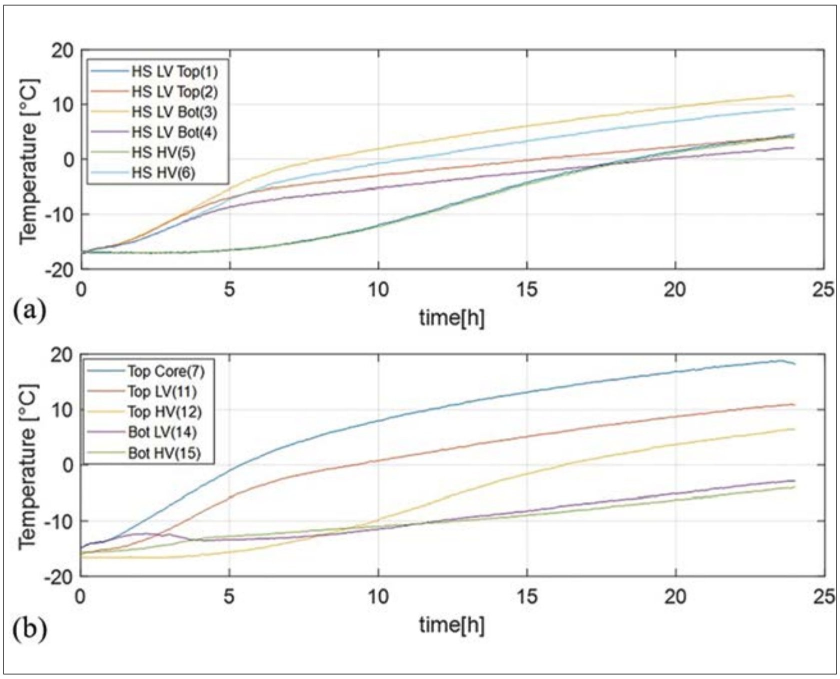

Figure 6. FOS signals during energizing at -15°C: (a) winding hotspot locations, (b) active part liquid.

> **After 400 hours of cooling, some flakes were observed in the liquid samples, indicating a possible start of liquid solidification**

3.2 Energizing in the cold chamber at subzero temperature

After 400 hours of cooling, some flakes were observed in the liquid samples, indicating a possible start of liquid solidification. It was decided to start energization with 110% excitation for 24 hours. It is observed that at two locations of winding hotspots and at the HV winding top, liquid took about 4 hours for the sensor signals to respond to the core heat generated by core losses, as shown in Fig. 6. This behavior indicates solidification at these locations, causing this delay in response to the heat. In addition, the HV winding is a disc type with zigzag cooling layout that requires a longer time to respond to tank liquid temperature change compared to LV layer winding with axial cooling ducts. From the valid calculation of the time constants and by using the extrapolation of the FOS curves, the core top liquid reaches stability at 22°C within 60 hours, while the HV hotspot reaches stability at 13°C within 80 hours.

While energizing, windings act as heat sinks against the core. Therefore, hotspot gradients result in negative values. The locations of FOS 2 (LV Hotspot) and FOS 6 (HV Hotspot) react simultaneously with a time constant of ca. 10 and 5 hours, respectively, as shown in Fig. 7. The extrapolation of the curves of FOS 2 and 6 shows a stabilized gradient of -16.5 and -10.2 K respectively. At FOS 1 and 5, a transient gradient of -20 K took place within the first 10h of energizing, which indicates a sort of phase change causing a 10h delay for the liquid to start circulating.

Temperature pockets on the tank walls show different reactions to energizing depending on their location. In Fig. 8, one can see that the temperature at the cooler outlet and near the pump is close to being unchanged over the whole time of energizing.

The top liquid temperature stabilizes at

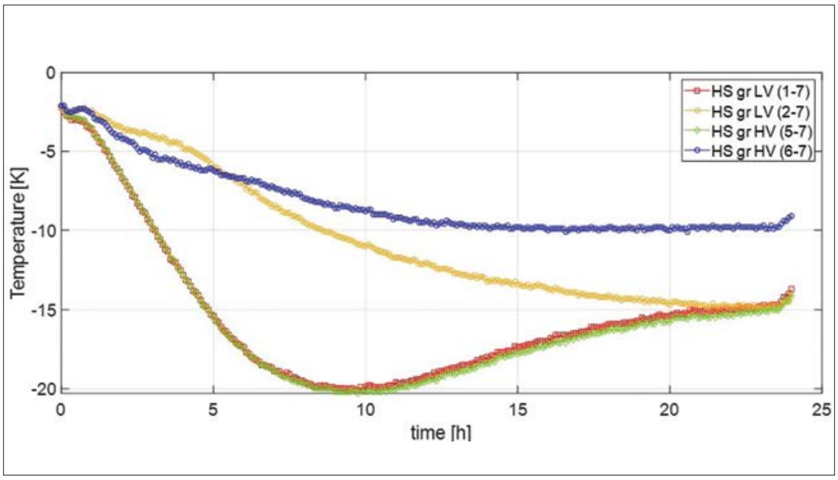

Figure 7. Windings hotspot gradient during energizing for 24h.

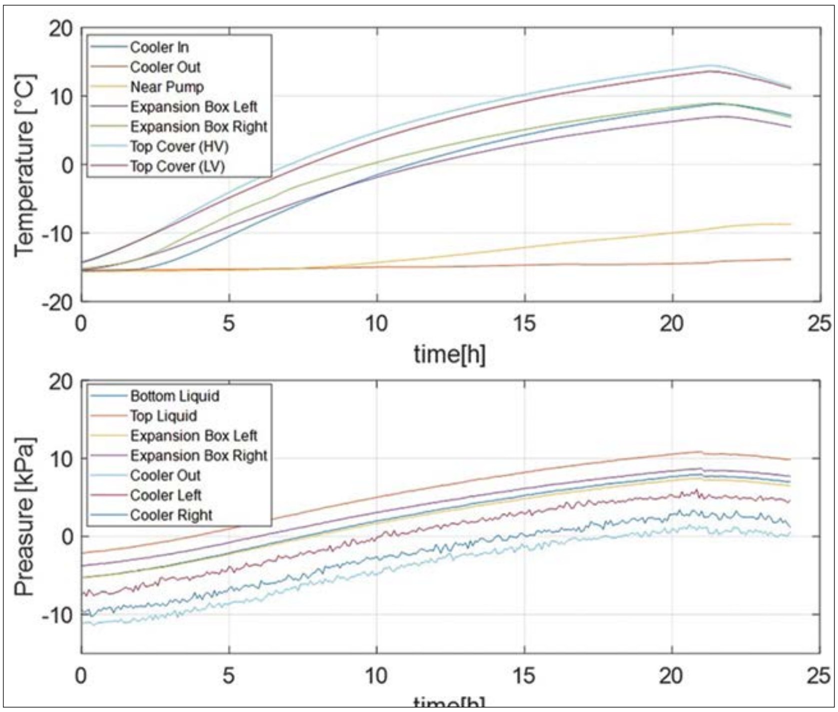

Figure 8. Temperature pockets and pressure sensor signals during energizing at -15°C for 24h

> **Liquid samples were taken from the transformer during cooling to observe how liquid quality changes under these cold conditions**

the tank cover and reaches 19°C with a time constant of 10-12 hours, while the cooler inlet location stabilizes at the same temperature but with a higher time constant of 15 hours. The temperature difference at stabilization between the core top liquid and the tank cover top liquid is minimal, and their time constants are similar. However, the cooler inlet shows a difference with a time constant of 5 hours, indicating that the liquid is more homogeneous in the axial direction than in the radial direction during energization. The lower part of the tank requires more time to react to excitation, and its time constant remains unknown.

A previous study showed that liquid thermal expansion and pressure release caused mechanical damage and leakage in the tank, necessitating the installation of pressure sensors throughout the tank and cooling system [4]. Fig. 8 shows that liquid pressure increased almost 100% during energization, changing from negative to positive. With a maximum pressure of 0.1 bar, there is sufficient safety margin to the design limits. If energization continues for a longer period, the pressure curve of the upper liquid is expected to stabilize at 0.15 bar with a time constant of 12 hours.

3.3 Liquid properties

Liquid samples were taken from the transformer during cooling to observe how liquid quality changes under these cold conditions. The liquid samples were analyzed to measure their dielectric properties and to conduct DGA for checking stray gases. The results shown in Tables I and II are for the reference sample taken at room temperature before the start of the test (Ref.), the sample taken shortly before the start of energization (pre-Engz), and the sample taken after the shutdown of energization at the final liquid temperature of the test (post-Engz).

The water content in the liquid was reduced by 77% during the storage phase at cold temperatures, likely due to moisture migration to the solid insulation. The heat from 24 hours of energization was insufficient to release this water back into the liquid, but longer energization times are expected to increase the water content. The dielectric dissipation factor (DDF) increased by 35% at the end of storage but returned to its original value after 24 hours of energi-

Table 1. Dielectric properties of the liquid samples

Dielectric properties	Ref.	pre-Engz	post-Engz
BDV [kV]	77	77	77
WC [mg/kg]	13	10	10
Acidity [mg KOH/g]	0.01	0.01	0.01
DDF (90°C) [%0]	10	13.5	10.5

zation. If storage at -15°C reaches 400 hours, an increase in DDF is expected but still within IEC limits, and 24 hours of energization can reset the DDF. DGA showed ethane content as the only relevant variation, indicating stray gases. The rapeseed-based liquid used has a higher tendency for stray gases, acceptable up to 525 µl/l. The final ethane value was below this limit but indicated that the storage phase was close to the solidification limit, which should not be exceeded to ensure safe energization and avoid PD.

Using natural ester instead of mineral oil is challenging because the freezing process occurs at a higher temperature than the pour point

Conclusion

Operating transformers in cold climates is critical when ambient temperatures approach the liquid's pour point. Using natural ester instead of mineral oil is challenging because the freezing process occurs at a higher temperature than the pour point. Previous studies have shown that during the solid-liquid transition, natural ester can cause dielectric and mechanical issues, leading to transformer failure. Safe operation in cold environments requires preventing liquid solidification. This study reveals that natural ester, like other esters, will freeze at subzero temperatures, with the time available for freezing being the key difference. Analyzing the liquid time constant helps estimate the time needed for the liquid to reach certain temperatures, determining the onset of freezing. Key factors affecting liquid performance in cold conditions include:

- Volume relative to surface area exposed to the cold environment.
- Transient phase during energization and stabilization time.
- Moisture migration between liquid regions and varying viscosities.
- Maximum storage time before energization.
- Differences in liquid time constants between the tank and active part and the resulting temperature distribution.

The study concludes that natural ester can be approved for energizing in a specific transformer design at -15°C. This is essential for offshore wind turbine applications, as transformer loading would take place after 24 hours of energizing. If the temperature of the liquid in the pump of an OF-cooled transformer is not above -5°C, the energizing phase should be extended, or the loading should take place as ON cooling until the temperature of the pump liquid exceeds -5°C.

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Table 2. DGA analysis of the liquid samples

Gas [µl /l]	Ref.	pre-Engz	post-Engz
Hydrogen (H_2)	11	9	10
Oxygen (O_2)	811	1430	1890
Nitrogen (N_2)	33600	36000	35900
Methane (CH_4)	3	1	1
Carbon Monoxide (CO)	46	48	50
Carbon Dioxide (CO_2)	421	442	430
Ethylene (C_2H_4)	5	5	5
Ethane (C_2H_6)	395	407	412
Acetylene (C_2H_2)	0	0	0
Total Combustible Gas (TCG)	460	470	479

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Ahmed Gamil received his M.Sc. degree from RWTH Aachen, Germany, in 2004 (High Voltage Technology). Ahmed previously worked at the University of Erlangen (FAU, EES) as a scientific research assistant for the development of differential protection systems before joining the SGB-SMIT Group. In 2010, he joined SGB in Regensburg with the aim of building the R&D Department from a technology and management point of view. In his last years as head of R&D, he contributed by different publications to transformer design optimization and technology innovation. His journey at SGB ended in October 2022 to start a new one at Hitachi Energy as a "Business R&D Expert Professional" from November 2022. His focus is to improve testing procedures of insulation liquids for aging and compatibility and to introduce an application guideline for power transformers under environmental stresses. He is an active member of IEC and CIGRE working groups and contributed as an author in the new CIGRE Green Book, "Transformer and Reactor Life Management."