Cold start of a 5.5MVA offshore transformer

Bram Cloet (1); Pieter Jan Jordaens (2); Jama Nuri (1); Raymond Van Schevensteen (1)
(1) CG Power Systems Belgium; (2) OWI-lab (Sirris)
bram.cloet@cgglobal.com, +32 15 283218
pieterjan.jordaens@sirris.be, +32 491 345382

1 Abstract

SLIM® transformers are compact liquid-immersed transformers according to IEC 60076-14, customized for typical applications such as on- and off-shore wind turbines. The state of the art SLIM® wind turbine generator transformers (WTGT) have to operate in wind farms which are often located in remote locations with harsh conditions and sometimes with very low temperatures. After some days of no wind the transformer can be cooled down to -30°C or even -40°C, these conditions need to be tested in advance.

To ensure the reliability of CG Power System Belgium's WTGT's and the possibility to start in cold conditions several tests were conducted in OWI-Lab's large climatic test chamber. OWI-Lab's test facility is the first public test centre in Europe that deals with extreme climatic tests of heavy machinery applications up to 150 ton with a special focus on wind turbine components.

When WTGT's have to operate in cold conditions, CG wants to prove that the internal cooling is still working properly. Due to the higher viscosity at low temperature of the used cooling liquids, the natural convection cooling of the internal windings may be limited. According to the properties of the cooling liquid that is used inside the WTGT it remains 'liquid' above -45°C (pour point), but due to the high viscosity the natural convection may be limited and it may be possible that the initial losses generated inside the transformers' windings cannot be evacuated fast enough. To verify if the natural convection starts, a full load cold start test was conducted at -30°C to prove that the natural cooling of the internal windings starts immediately. During the cold start test the internal pressure and several temperatures where measured such as the top oil. Also a storage test was done at -40ºC to check if the transformer can resist this ambient temperature. This storage test was conducted to prove that no leaks or other visual issues occurred on the tank and gaskets.

2 Introduction

SLIM® transformers are highly reliable, low loss, high-temperature liquid-immersed transformers according to IEC 60076-14, customized for typical applications such as installation in WTG [1] [2]. Their cooling liquid (silicone fluid in SLIM® and synthetic ester in Bio-SLIM®) is fire class K3 as per IEC 61100.

First a storage test was done at -40°C on a synthetic ester filled Bio-SLIM® transformer. Secondly a cold start test was done on this Bio-SLIM® transformer to verify that the transformer is well suited to cope with a full load start after the transformer was cooled down to -30ºC. These tests were conducted at the brand new climate chamber of OWI-lab located in the port of Antwerp [3].

3 Description of test object

The tests are performed on a synthetic ester filled off-shore WTG Bio-SLIM® transformer with the following properties:

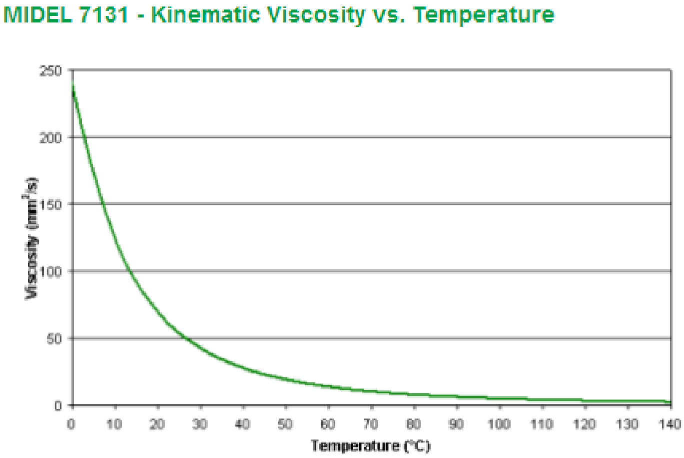
Rated power: 5560kV
High voltage: 33kV
Low voltage: 690V
Short circuit impedance: 12%
Total losses: 50kW
Total mass: Approx. 11ton
Cooling Liquid: Synthetic ester (integrally filled)

4 The need for cold start testing

In this section the following paragraphs describe some reasons why testing of transformer is needed at cold environments.

4.1 Cooling performance at low temperatures

However it is not expected to have cooling problems at very low temperatures there is still a risk for reduced cooling due to the much higher kinematic viscosity of the used cooling liquids at low temperatures. A high kinematic viscosity prevents the cooling liquid from flowing, thus the natural convection is limited and may not evacuate the generated losses fast enough during startup of cold transformer. This may generate local hot spot spots inside the winding. These hot spots may cause local production of dissolved gasses, insulation degradation and eventually in worst case breakdown and failure of the complete transformer. This situation has to be avoided at all times, because the total costs for replacements or repairs of off-shore transformers can be several times the value of the transformer itself, excluding the loss of production. Figure 1 shows the kinematic viscosity in function of the temperature. At -30ºC the kinematic viscosity is 60 times bigger than at +20ºC [4].



Temperature °C	-30	-20	-10	0	10	20	30	40	50
Kinematic Viscosity mm^2/s	4200	1400	430	240	125	70	43	28	19.5

Temperature °C	60	70	80	90	100	110	120	130	140
Kinematic Viscosity mm^2/s	14	10.5	8	6.5	5.25	4.4	3.7	3.2	2.8

Figure 1: Midel 7131 Kinematic Viscosity versus temperature

In almost all cases synthetic ester is used in WTGT’s because of their high fire point and environmentally friendly properties. These advantages have a much higher value than the disadvantages of the higher kinematic viscosity at low temperatures compared to other fluids (see graph below). But the higher viscosity has to be taken into account in the design and practical operation of the WTGT. In order to discover and understand the effects of this higher viscosity at lower temperatures tests at low temperatures have to done.

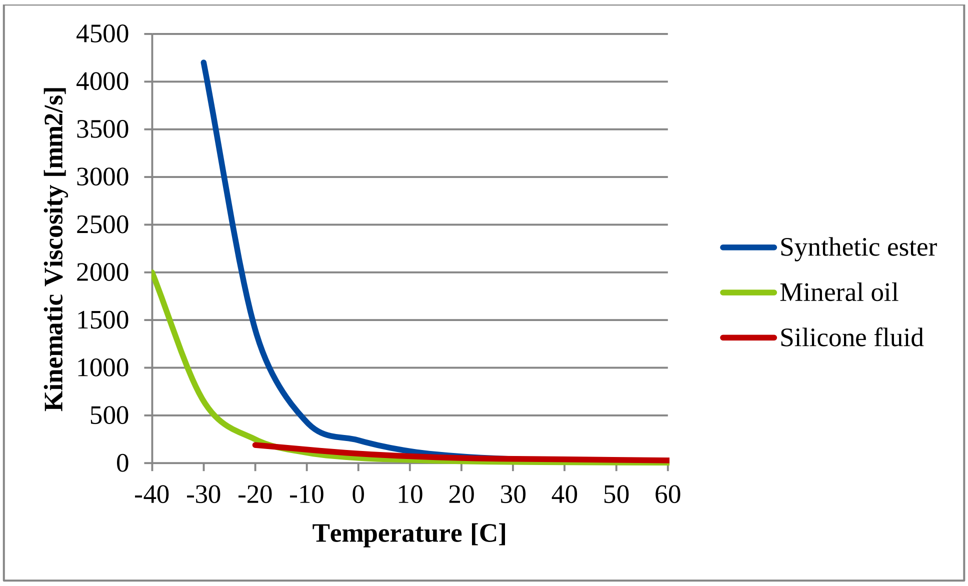


Figure 2: Kinematic Viscosity of different types of cooling liquid.

The graph above shows the higher viscosity of synthetic ester at lower temperatures compared to other types of cooling liquids.

4.2 Lower operating temperatures required by OEMs

More and more OEM's require lower operating temperatures or storage temperatures. As a supplier we need to take this into account to keep delivering high quality products. The table below summarizes some requirements of different OEM's.

OEM	Minimum ambient temperature [ºC]	Application
1	-25 (operating)	WTGT, On-shore
2	-20 (operating), -40 (not operating)	WTGT, Off-shore
3	-10 (operating), -25 (not operating)	WTGT, Off-shore
4	-40 (operating and not operating)	WTGT, On-shore

The cold winter in the US [5] shows that these low temperatures required above are certainly possible.

4.3 Influence on operating pressures

The ambient temperature has also an influence on the internal pressure of the WTGT. After, for example, a few days of cold weather and no wind the WTGT can be cooled down to about the ambient temperature. In this situation the hermetically sealed tank of the WTGT will be in under pressure. At low temperatures this can be as low as -500 to -300mbar depending on the tank design. These large under pressures are rarely seen on normal distribution transformers, which normally are always loaded, especially during cold periods when electricity use increases. When after such a period of no load and low temperatures the wind picks-up, the pressure can increase rapidly to maximum 300mbar. Due to the bigger temperature range, mainly extended to lower temperatures and the more volatile load profiles of a WTGT, more and bigger pressure cycles occur than on a normal distribution transformer. These cycles can cause fatigue problems in the transformer tank which can lead to leaks. OWI-Lab is investigating together with CG the possibilities to perform HALT (highly accelerated lifetime test) tests with pressure cycles in their test facility in Antwerp. This will not be done by only changing the ambient temperature because this would be a too slow process.

5 Overview of the cooling sequences

In this section an overview is given of the different cooling sequences performed on the 5.56MVA off-shore Bio-Slim transformer. In the next sections we will refer back to these paragraphs.

5.1 First cooling sequence to -25°C

The first cooling sequence to only -25°C was to evaluate the pressure inside the transformer tank. We needed to be sure that the negative under pressure wasn't too low for the tank. A too low under pressure could cause permanent deformation of the transformer tank or suck in air into the transformer in case of a leak.

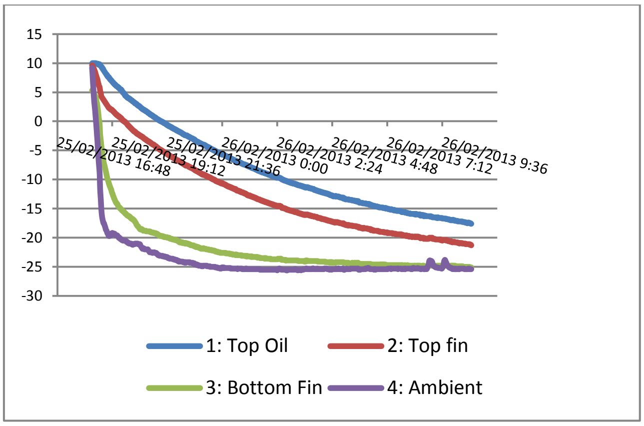


Figure 3: Temperature profile during cooling to -25ºC

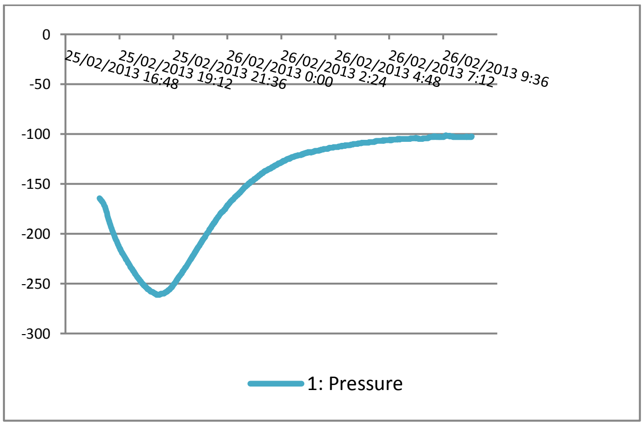


Figure 4: Pressure profile (mBar) during cooling to -25°C

In the pressure profile we see a pressure dip to -260mbar. This is caused by the behaviour of the gas cushion inside the transformer. During the first hours the synthetic ester and the gas cushion are shrinking which causes a bigger under pressure. Only after a few hours gas that is dissolved in the synthetic ester will escape from the synthetic ester due to the under pressure and the low temperature which allows less gasses to be dissolved in liquids. This explains why the pressure starts to rise to about -100mbar.

5.2 Second cooling sequence to -40°C

After the check of the under pressure we could proceed to cool further to -40°C to conduct the storage test. Due to limited time the temperature of the complete transformer was not yet stable at -40°C when we had to start the next sequence.

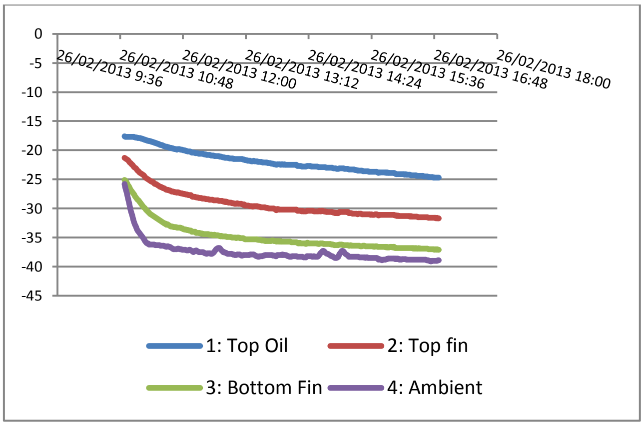


Figure 5: Temperature profile during cooling to -40°C

5.3 *Final cooling sequence at -30°C*

This is the cooling sequence to settle the ambient temperature at -30°C at which the cold start test will be conducted. As you can see in the figure below the complete transformer was cooled below -25°C. This is the minimum ambient temperature according to IEC where the transformer should work normally.

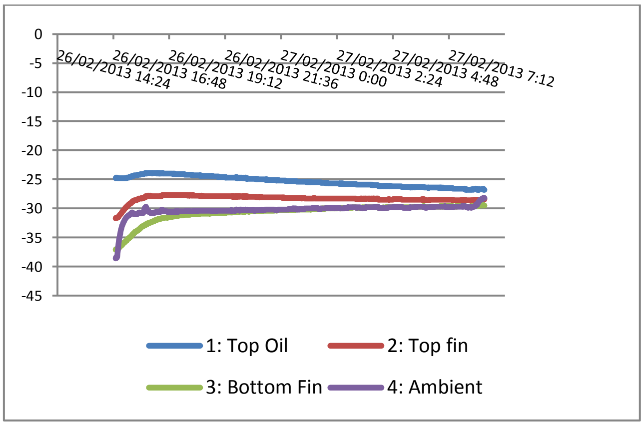


Figure 6: Temperature profile during cooling to -30°C

5.4 Cold start test at -30°C

The figure below shows the temperature profile during the cold start while the ambient temperature was maintained at approx. -30°C to -25°C.

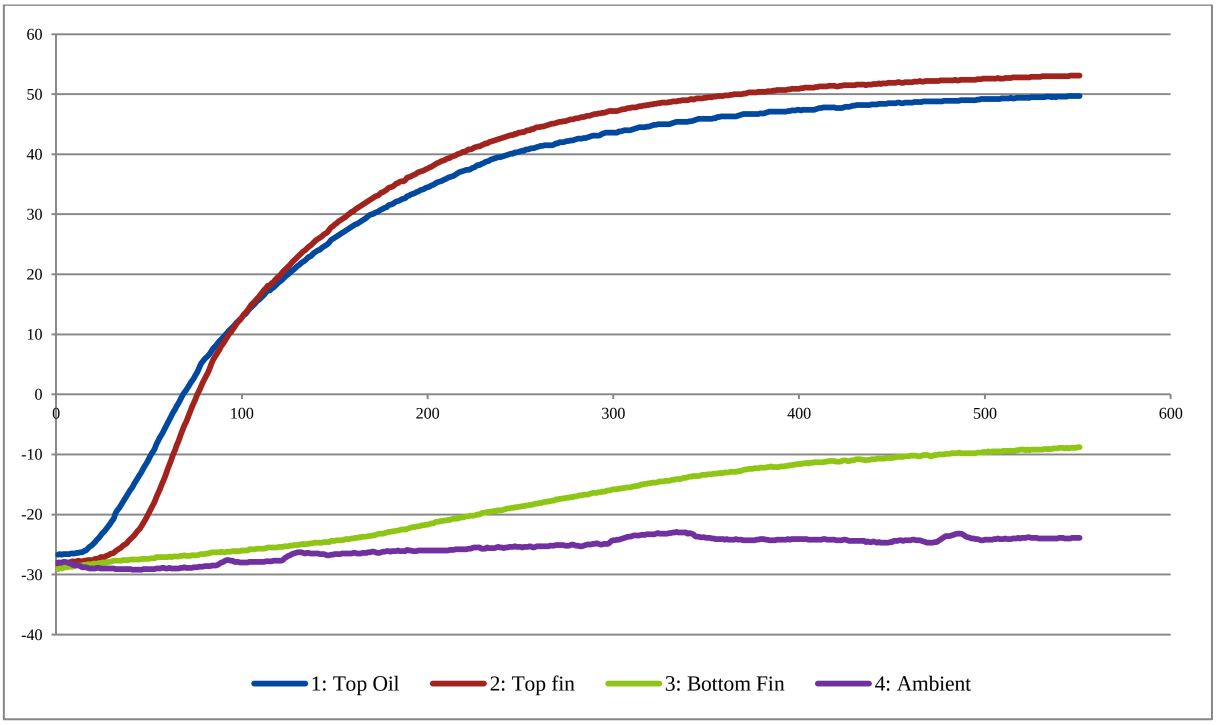


Figure 7: Temperature profile during cold start at -30°C

In the figure above we can see that the top oil starts after about 15 minutes with rising. This indicates that natural convection starts quickly after the cold start with evacuation the losses of the transformers windings. We have also noticed that on top of the cooling fins the temperature starts only with rising after about 25 minutes. This indicates that the synthetic ester in the fins doesn't start flowing immediately at low temperatures.

6 Storage test at -40°C

The goal of the storage test is to check afterwards if there are visual defects or leaks.

The ambient temperature where the 5.56MVA Bio-SLIM transformer of about 11ton was stored was cooled down to -40°C for about 6 hours (See Figure 5). 6 hours was not long enough to stabilize the temperature of the transformer to -40°C. The only reason to not wait for a complete stabilisation was a lack of time. Cooling down the transformer to -40°C took more time than we initial thought. We needed to proceed to the next steps to ensure there was enough time for doing the most important part of the testing: the cold start test at -30°C.

When the ambient temperature was stable at -40°C a quick visual check of the transformer was done to detect possible leaks, cracks or other anomalies. During this check no visual defects where seen.

7 Cold start test at -30°C

7.1 Description of the test

IEC 60076 requires that a transformer operates at a minimum ambient temperature of -25°C. With this cold start test CG wants to test this and even go further. The cold start test was a full load start from 0 to 100% load within a couple of seconds when the Bio-SLIM transformer was completely stabilised at a temperature of -30°C.

When the ambient temperature and the transformer had reached -30°C (See Figure 6) the cold start was started (See Figure 7). The transformer was fed by a mobile generator and an intermediate transformer. The low voltage of the tested transformer was short circuited and the applied voltage to the high voltage was the transformers short circuit voltage. When the generator was switched on, immediately the nominal current was flowing through the Bio-SLIM transformer. This was needed to simulate a sudden cold start up at full load. Due to the internal losses of about 50kW the temperature of the transformer started to rise (See Figure 7).

Figure 8: 5.56 MVA Bio-SLIM transformer inside the climate chamber at -30°C

7.2 Determining time constants

The temperature of the top oil measurement was fitted to Equation 1 to determine the thermal time constant of the transformer during full load.

Equation 1: $T_{oil} = a\left(1 - e^{-\frac{t}{\tau}}\right) + b$

Where:

T_{oil} is the top oil temperature in °C

a and b are the fitted parameters

τ is the fitted time constant in minutes

t is the time variable in minutes

Fitting Equation 1 to the measurement of the top oil results in a time constant τ of 112 minutes. Compared to the time constant of 492 minutes determined during cooling down to -25ºC this is much faster. From this time constant we can estimate how long it would have taken to cool down completely to -40°C during the storage test. If we would repeat the storage test and cooling the transformer down completely to -40°C, we would need about 41 hours or almost 2 days (5 times 492 minutes).

7.3 Analysis of initial temperature rise behaviour

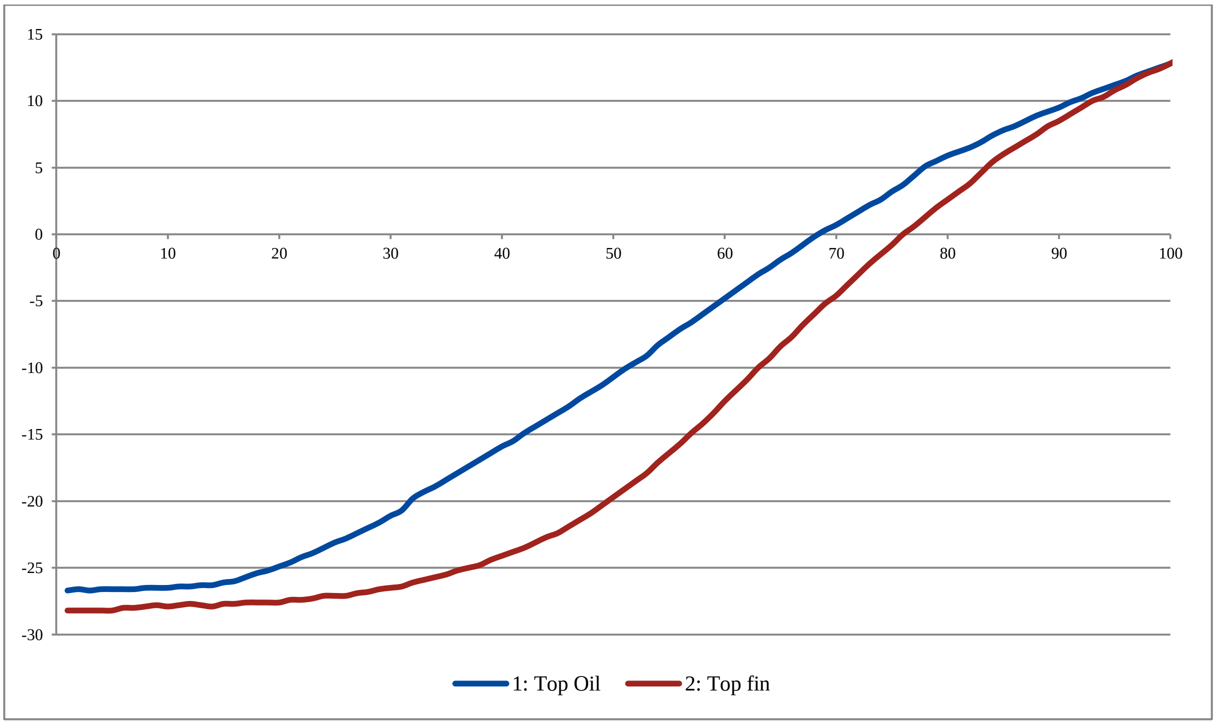


Figure 9: Initial temperature profile during cold start at -30ºC

From experience we know that at normal ambient temperatures of about 20ºC it takes less than 10 minutes for top oil to start rising. In this case it takes about 15 minutes; this indicates that the natural cooling starts slightly slower at low temperatures. The temperature on top of the fins starts to rise later, after about 25 minutes.

In the temperature rise however we do not see strange temperature excursions. In [5] a cold start test at -30 ºC is described on a single phase 167kVA transformer filled with a natural ester. The pour point was above -30ºC for this natural ester. The temperature rises don't exceed the maximum allowable during this test. But a sudden change in temperature rise is seen after about 1-2 hours after the cold start, this is due to the fact that the natural ester was not liquid at start (See Figure 10). This behaviour is not seen in our case which indicates that the synthetic ester in our test was still liquid enough to evacuate the generated losses from the windings.

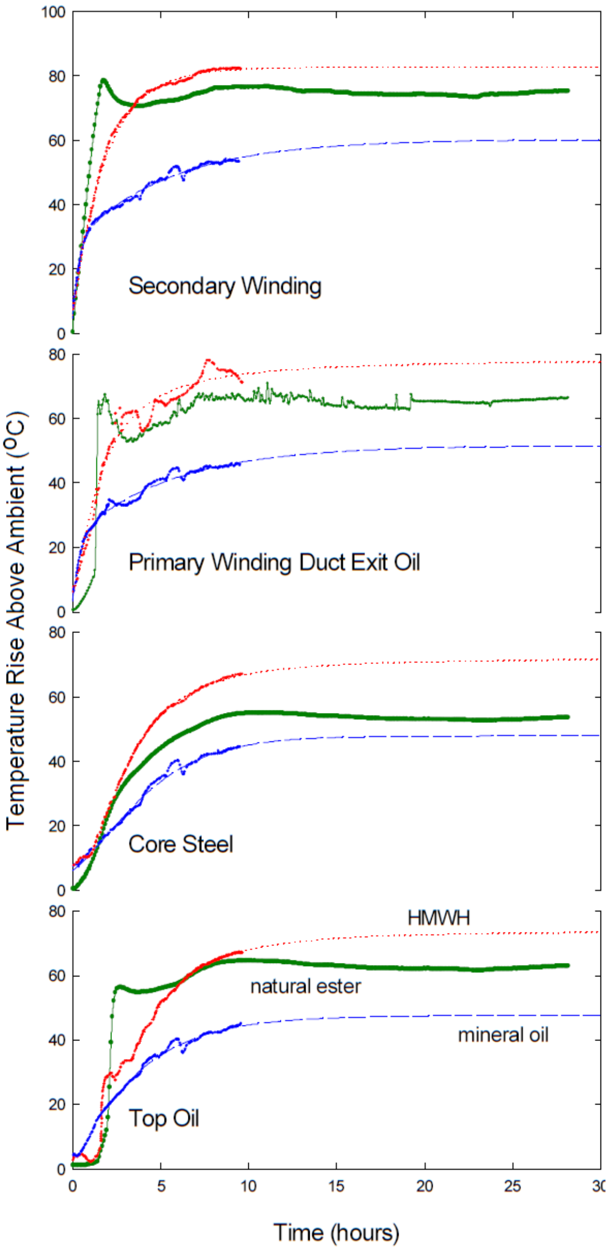


Figure 10: Temperature rise over -30ºC ambient of core steel, secondary winding, top oil, and primary winding cooling duct exit oil. Time starts when transformer is energized at full load. Figure from [5].

8 Possible future tests

This test can be repeated with some other sequences and extra measurements. For example:

- Measurement of the winding temperature with several optical fibers installed inside the windings.
- A voltage withstand test by applying the nominal voltage at a cold ambient temperature. This would need an extra voltage source to feed through the LV of the transformer.
- When doing the cold start test also changing the ambient temperature to the maximum ambient temperature of the transformer, for example +40ºC or even +50ºC to increase the temperature leap

of the transformer. This simulates for example a bad cooling of a small transformer room where temperature rises quickly.
- Doing the cold start test even at lower temperatures e.g. between -40ºC to -60 ºC, be close to the poor point of the synthetic ester to look for the effect on the natural convection.
- Doing similar tests on WTGT's with an external KFAF (K-class liquid forced, air forced) cooling system.
- Conducting HALTs test in the OWI-Lab to simulate mechanical fatigue caused by pressure cycles.

9 Conclusions

From this paper we learned that there is a need for transformer testing at low temperatures. Thanks to OWI-Lab's large climatic test chamber a cold start test has been done on a 5.56MVA off-shore WTGT. This test proved that the synthetic ester filled WTG Bio-SLIM® transformer is able to cope with a sudden full load cold start at an ambient temperature of -30ºC. No abnormal behaviour was detected during this test. Even an ambient temperature of -40ºC, to test the storage conditions, did not bring up any issues.

10 Bibliography

[1] R. Van Schevensteen and J. Declercq, *Performance and fire behaviour of step-up transformers in wind turbines.*

[2] R. Van Schevensteen and J. Declercq, "Transformers for off-shore multi megawatt turbines: discussion on specifications, safety and environment," in *EWEC*, 2005.

[3] OWI lab, "Offshore Wind Infrastructure Application Lab," [Online]. Available: http://www.owi-lab.be/. [Accessed 14 2 2014].

[4] M&I Materials, "MIDEL 7131 - Kinematic Viscosity vs. Temperature," M&I Materials, [Online]. Available: http://www.midel.com/productsmidel/midel-7131/thermal-properties/kinematic-viscosity. [Accessed 14 2 2014].

[5] N. Carey and K. Palmer, "Polar freeze grips United States, disrupting travel, business," Reuters, 06 01 2014. [Online]. Available: http://www.reuters.com/article/2014/01/06/us-usa-weather-idUSBREA000JC20140106. [Accessed 03 03 2014].

[6] K. Rapp, G. Gauger and J. Luksich, "Behavior of Ester Dielectric Fluids Near the Pour Point," in *IEEE Conference on Electrical Insulation and Dielectric Phenomena*, Austin, TX, 1999.