Pieter Jan Jordaens, Bram Cloet, Jama Nuri, Raymond Van Schevensteen

Cold start of a offshore trans

> As most renewable energy systems are located outdoors, sometimes in harsh conditions ranging from the extreme cold in Inner Mongolia to the scorching desert heat of Australia, a special attention must be paid to the suitability and robustness of the components like transformers

5.5 MVA former

ABSTRACT

SLIM® transformers are compact liquid-immersed transformers according to IEC 60076-14 and customised for typical applications such as on- and off-shore wind turbines. 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 sometime very low temperatures. After a few days of no wind the transformer can be cooled down to -30 °C or even -40 °C so 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 tonnes with a special focus on wind turbine components.

CG wants to prove that when WTGT's have to operate in cold conditions, the internal cooling is still working properly. Due to 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 there is a possibility 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 such as the top oil were measured. Also a storage test was done at -40 °C 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.

KEYWORDS

controlled cold climate testing, Bio-SLIM® transformers, extreme cold start behaviour, live component testing

1. Introduction

SLIM® transformers are highly reliable, low loss, high-temperature liquid-immersed transformers according to IEC 60076-14, customised 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 able to cope with a full load start after the transformer had been cooled down to -30 °C. These tests were conducted at the brand new climate chamber of OWI-lab located in the port of Antwerp [3].

Component suppliers sometimes lack appropriate testing infrastructure to verify all loads that can occur on a wind turbine. This has been the main driver for OWI-Lab to set-up a large climatic test chamber that can support multiple companies when it comes to this challenge

2. 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:	5560 kVA
High voltage:	33 kV
Low voltage:	690 V
Short circuit impedance:	12 %
Total losses:	50 kW
Total mass:	Approx. 11 ton
Cooling Liquid:	Synthetic ester (integrally filled)

3. The need for cold start testing

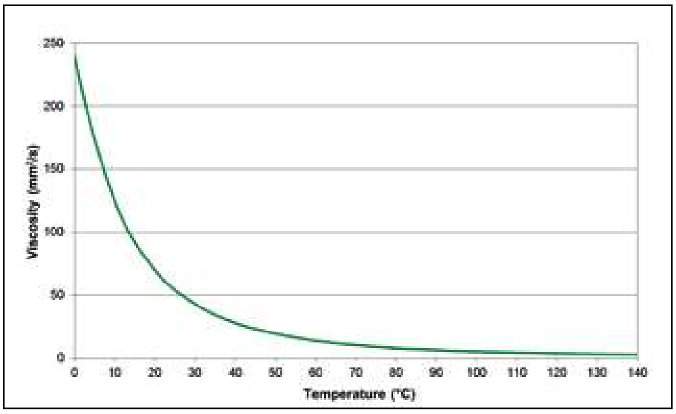
In the following paragraphs the reasons to test transformer at extreme cold environments is explained.

3.1. Cooling performance at low temperatures

Although cooling problems are not expected at very low temperatures, there is still a risk of 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 start-up of a cold transformer. This may generate local hot spots inside the winding. These hot spots may cause local production of dissolved gasses, insulation degradation and eventually, in the worst case scenario, breakdown and failure of the entire transformer. This situation has to be avoided at all times because the total cost of replacements or repairs of the off-shore transformers can be several times the value

Physical cold start-up testing can be a good strategy to increase the resilience and mitigate the risks associated with such extreme events as simulating these effects can be time consuming, complex and costly

of the transformer itself, excluding the loss of production. Figure 1 shows the kinematic viscosity in function of the temperature. At -30 °C the kinematic viscosity is 60 times higher than at +20 °C [4].



Temperature °C Kinematic Viscosity mm²/s	-30 4200	-20 1400	-10 430	0 240	10 125	20 70	30 43	40 28	50 19.5
Temperature °C Kinematic Viscosity mm²/s	60 14	70 10.5	80 8	90 6.5	100 5.25	110 4.4	120 3.7	130 3.2	140 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 the higher viscosity at lower temperatures tests at low temperatures have to be done.
The chart above shows higher viscosity of synthetic ester at lower temperatures compared to other types of cooling liquids.

Transformers can be cooled down to -30 °C or even -40 °C depending on the location of the wind turbine. Due to a higher viscosity of the cooling liquids at such low temperatures, the natural convection cooling of the internal windings may be limited

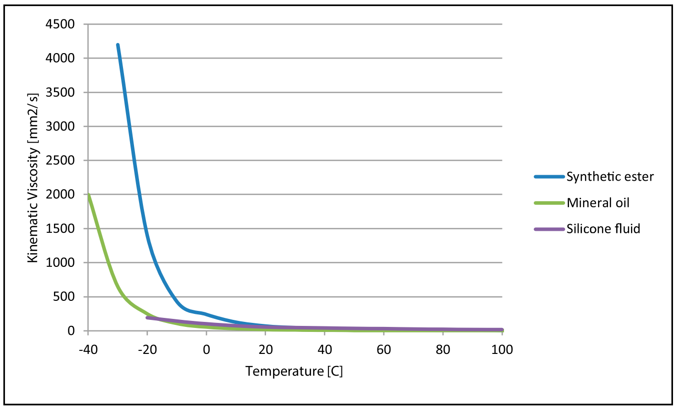


Figure 2: Kinematic viscosity of different types of cooling liquid

Testing the cooling performance of wind turbine transformers during extreme low temperature and high kinematic viscosity is crucial in order to guarantee safe and reliable power solutions for the wind power industry

3.2. Lower operating temperatures required by OEMs

More and more OEMs require lower operating temperatures and storage temperatures. As a supplier, CG Power needs to take this into account to keep delivering high quality products. The table below summarises some requirements of different OEMs.

Table 1: Some requirements of different OEMs

OEMs	Minimum ambient temperature [°C]	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 winters in the US [5] show that the low temperatures required above are certainly possible.

Wind turbine OEMs require transformers that are able to operate at lower temperatures in comparison with their requirements 10 years ago; -30 °C operational limit and -40 °C survival limit is not unusual for many transformers

3.3. Influence on operating pressures

The ambient temperature also has 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 approximate 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 -300 mbar depending on the tank design. These large under pressures are rarely seen on normal distribution transformers which are normally always loaded, especially during cold periods when electricity use increases. When wind picks up after such a period of no load and low temperatures, the pressure can increase rapidly to maximum 300 mbar. Due to the higher temperature range, mainly extended to lower temperatures and the more volatile load profiles of a WTGT, higher pressure cycles occur more often than on a normal distribution transformer. These cycles can cause fatigue problems in the transformer tank which can lead to leaks. OWI-Lab and CG are investigating the possibilities of performing HALT (highly accelerated lifetime test) tests with pressure cycles at their test facility in Antwerp. This will not be done only by changing the ambient temperature because this process would be too slow.

4. Overview of the cooling sequences

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

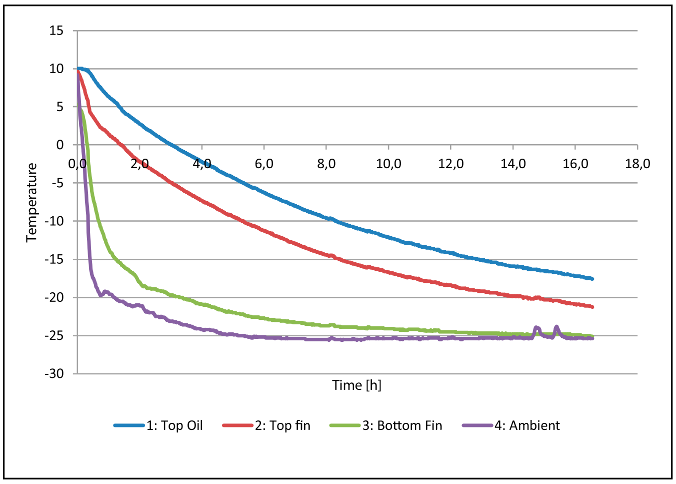


Figure 3: Temperature profile during cooling to -25 °C

4.1. 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 was not too low for the tank. An under pressure which is too low could cause permanent deformation of the transformer tank or suck air into the transformer in case of a leak.

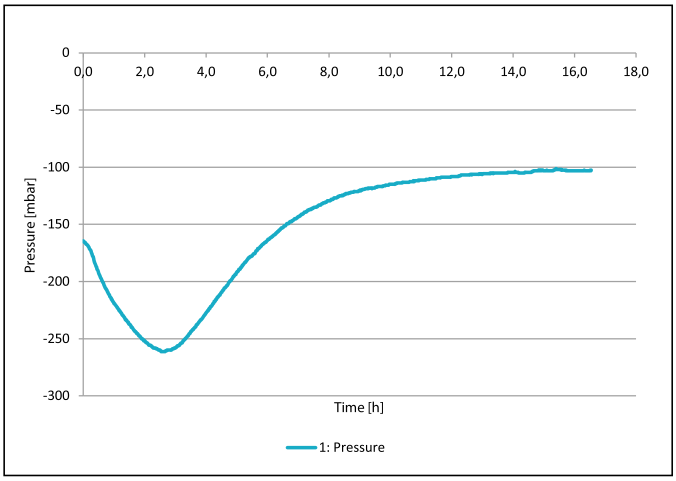


Figure 4: Pressure profile (mbar) during cooling to -25 °C

In the pressure profile we see a pressure dip off -260 mbar. This is caused by behaviour of the gas cushion inside the transformer. During the first hours the synthetic ester and the gas cushion are shrinking, which causes a higher under pressure. After a few hours the gas that is dissolved in the synthetic ester will escape due to the under pressure and the low temperatures, which results in less gases dissolved in the ester. This explains why the pressure starts to rise to about -100 mbar.

4.2. Second cooling sequence to -40 °C

After checking the under pressure, we proceeded to cool down the transformer further to -40 °C to conduct the storage test. Due to limited time, the temperature of the entire transformer was not yet stable at -40 °C when we had to start the next sequence.

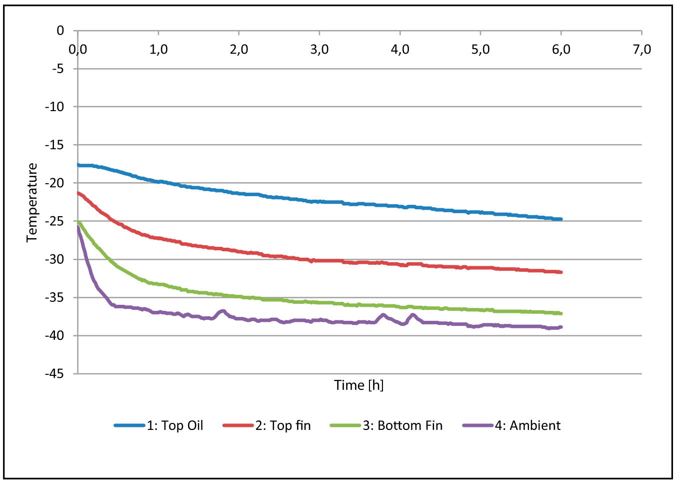


Figure 5: Temperature profile during cooling to -40 °C

4.3. Final cooling sequence at -30 °C

In this cooling sequence the setpoint was at -30 °C ambient. As you can see in the chart below, the entire transformer was cooled below -25 °C. This is the minimum ambient temperature according to IEC at which a transformer should work normally.

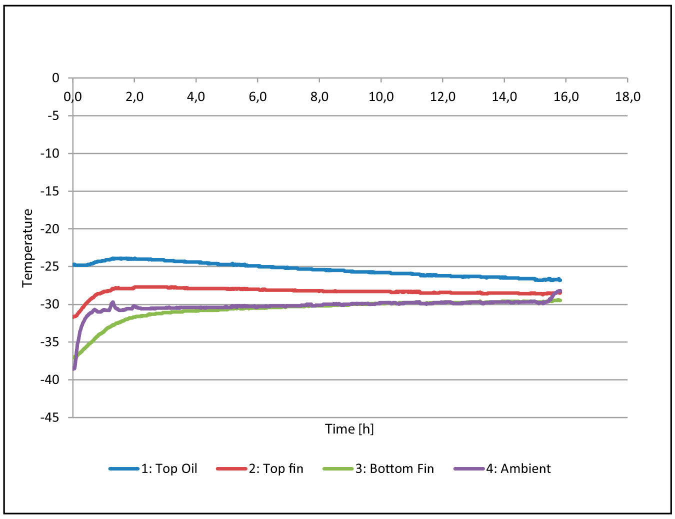


Figure 6: Temperature profile during cooling to -30 °C

4.4. Cold start test at -30°C

The chart below shows temperature profile during the cold start while the ambient temperature inside the chamber was maintained between -30 °C to -25 °C.

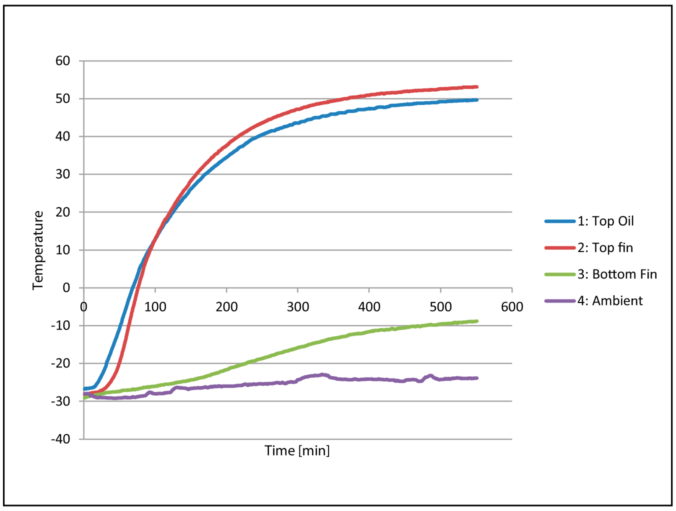


Figure 7: Temperature profile during cold start at -30 °C

In the chart above we can see that the top oil starts to rise after about 15 minutes. This indicates that the natural convection starts soon after the cold start to evacuate the losses of the transformers windings. We have also noticed that on top of the cooling fins, the temperature only starts to rise after about 25 minutes. This indicates that the synthetic ester in the fins does not start to flow immediately at low temperatures.

5. Storage at -40 °C

A storage test at -40 °C was conducted to control the transformer ability to cope with these temperatures without obtaining any defects or leaks. The 5.56 MVA Bio-SLIM transformer weighing about 11 ton was stored at -40 °C for about 6 hours (see Figure 5) but it was not long enough to bring the entire transformer to a steady -40 °C. The only reason we did not wait for a complete stabilisation was the lack of time. Cooling down the transformer to -40 °C took more time than we had initially thought. We needed to proceed with 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 visual check of the transformer was done to detect possible leaks, cracks or other anomalies. During this check no visual defects were noted.

6. Cold start test at -30 °C

6.1. Description of the test

IEC 60076 requires that a transformer fully operates within the designed parameters at a minimum ambient temperature of -25 °C. With this cold start test, CG wanted to ensure good functioning of a transformer and will take one step further and preform the test at -30 °C. When temperature of the transformer was stabilised around -30 °C, full load was applied on the transformer. The transformer was fed by a mobile generator and an intermediate transformer. To simulate full load, low voltage connections were short circuited and the generator was connected to the high voltage side. The generator output voltage was adjusted to have the nominal current in the transformer. Due to the internal losses of about 50 kW, temperature of the transformer started to rise (see Figure 7).

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

The IEC 60076 standard requires that transformers can operate at a minimum ambient temperature of -25 °C. We push this testing limit to -30 °C for operations and -40 °C for storage and survival

6.2. Determining time constants

Temperature of the top oil measurement was used in Equation 1 to determine the thermal time constant of the transformer during full load.

Equation 1:

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

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 of 112 minutes. Compared to the time constant of 492 minutes determined during cooling down to -25 °C, 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 repeated the storage test and cooling the transformer completely down to -40 °C, we would need about 41 hours or almost 2 days (5 times 492 minutes).

6.3. Analysis of initial temperature rise behaviour

From experience we know that at normal ambient temperatures of about 20 °C, it takes less than 10 minutes for top oil to start rising. In this case it takes about 15 minutes and it indicates that the natural convection of the ester lags behind slightly at low temperatures. The temperature on top of the fins starts to rise later, after about 25 minutes. However we do not see strange temperature excursions in the temperature rise. In [5] a cold start test is described at -30 °C on a single phase 167 kVA transformer filled with a natural ester. The pour point of the natural ester is above -30 °C. The temperature rises did not exceed the maximum allowable temperature during this test. But a sudden change in temperature rise is seen after about 1-2 hours after the cold start and this is due to the fact that the natural ester was not liquid at the start (see

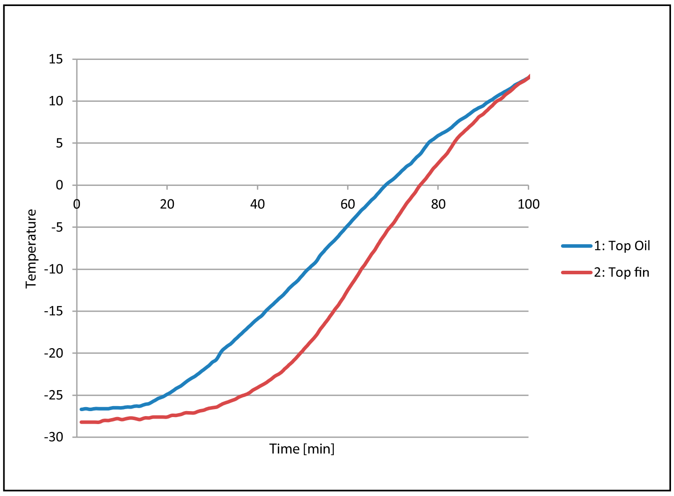


Figure 9: Initial temperature profile during cold start at -30 °C

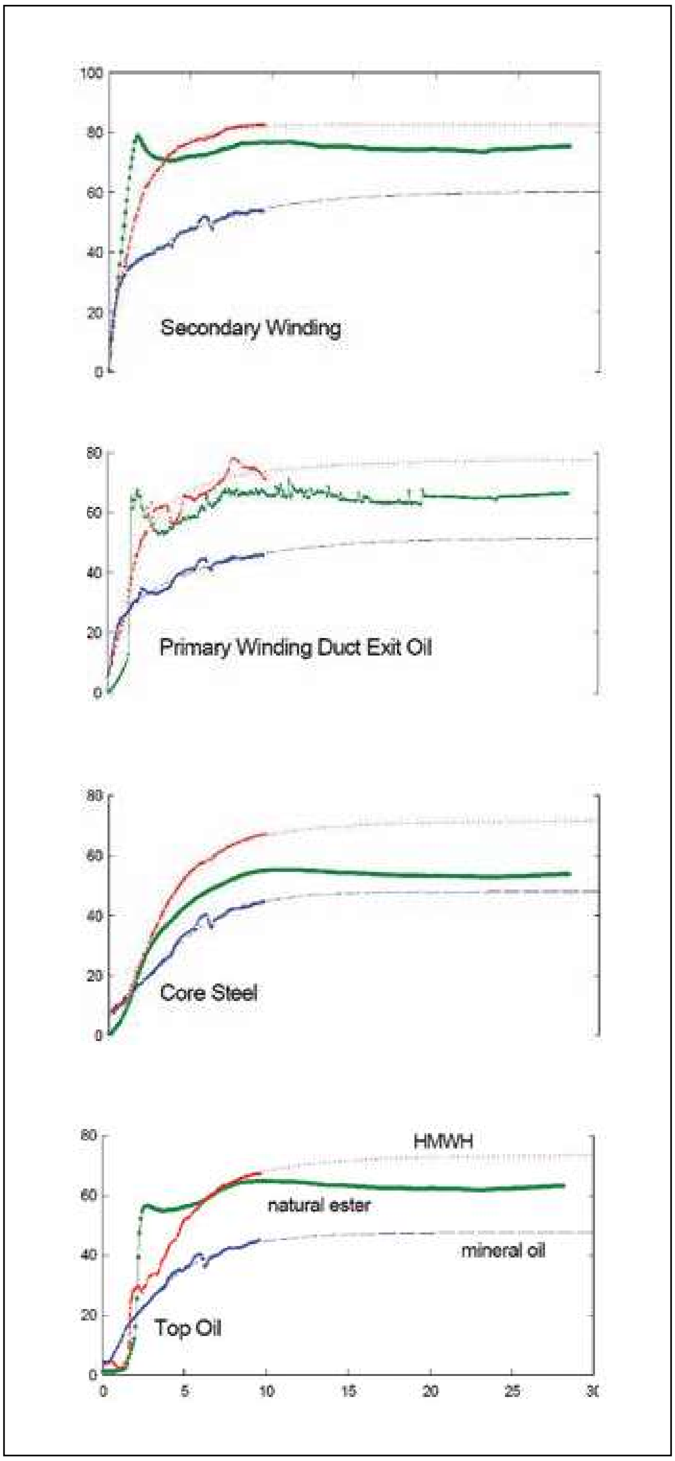


Figure 10: Temperature rise over -30 °C ambient of core steel, secondary winding, top oil, and primary winding cooling duct exit oil. Time starts when transformer is energised at full load [5].

Figure 10). This behaviour is not seen in our case which indicates that the synthetic ester in our test was still liquid enough to start the natural convection and to evacuate the generated losses from the windings.

7. Possible future test

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 low voltage side of the transformer.
- When performing the cold start test, also change the ambient temperature to the maximum ambient temperature of the transformer, for example +40 °C or even +50 °C to increase the temperature leap of the transformer. This, for example, simulates poor cooling of a small transformer room where temperature rises quickly.
- Performing the cold start test even at lower temperatures, e.g. between -40 °C to -60 °C, be close to the poor point of the synthetic ester to look out for the effect on the natural convection.
- Performing 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.

Conclusion

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

References

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

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

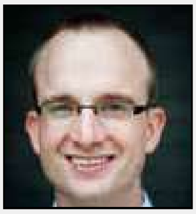
[3] OWI lab, *Offshore Wind Infrastructure Application Lab,* http://www.owi-lab.be/, current 14.02.2014.

[4] M&I Materials, *MIDEL 7131 - Kinematic Viscosity vs. Temperature, M&I Materials,* http://www.midel.com/productsmidel/midel-7131/thermal-properties/kinematic-viscosity, current 14.02.2014.

[5] N. Carey and K. Palmer, *Polar freeze grips United States, disrupting travel, business*, http://www.reuters.com/article/2014/01/06/us-usa-weather-idUSBREA000JC20140106, current 03. 03.2014.

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

Authors



Bram Cloet has been working in the transformer industry since 2007. He obtained his Master's degree in Mechanical Electrical Engineering (option electrical energy) at the KULeuven in Leuven, Belgium. After his studies he started working in Pauwels Trafo Belgium, now CG Power Systems Belgium where he worked mainly on the development and improvement of distribution transformers.He is currently R&D Teamleader at the R&D Centre of Excellence for Distribution Transformers of CG Power Systems.

Pieter Jan Jordaens graduated with an MSc in the field of Electro-mechanical engineering at the KU Leuven - Group T-International University College Leuven. After his studies he joined an International Postgraduate Program in Entrepreneurial Engineering. He joined Sirris - the collective centre of the Belgian technological industry in 2010 initially as a project leader. Since then Pieter Jan has been responsible for setting up the Offshore Wind Infrastructure Application Lab (OWI-Lab). He is currently working at OWI-Lab as a business developer.

Nuri Jama graduated with a Master's degree in Electromechanical Engineering in 2006 at the EHB Brussels, Belgium. He started working at Donaldson and then joined CG Power System Belgium in 2007. He gained his first experiences there as an electrical designer of distribution and small power transformers. He has worked as Project Engineer in R&D Center of Excellence for Distribution Transformers of CG Powers Systems for the past three years.

Raymond Van Schevensteen graduated as an electrical engineer in 1979 in Antwerp, Belgium and started his career at Pauwels Trafo in 1980 as junior designer of Power Transformers. Few years later he transferred to Distribution Transformers to become Assistant Design Manager. In 1990 he joined the Pauwels R&D team and worked on numerous developments, including the SLIM® line. After the acquisition of Pauwels by CG Power Systems, he became R&D Manager for EMEA-DT. Currently he is global Technology Head for Distribution Transformers reporting to the CTO. He is an active member of several IEC and Cenelec committees as well as an IEEE member.