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What it takes to design, manufacture and operate power transformers under arctic temperature conditions

Thomas Schneider | Jinesh Malde

Siemens Energy | M&I Materials Inc.

SUMMARY

Power transformers play a key role within electrical power transmission and distribution grids. Even though their primary purpose is of a conventional nature, they are not necessarily conventional products. Also, power transformer designs need to be adapted to new trends such as decentralization of generation, digitalization or decarbonization and how we care about our environment. These aspects will become increasingly important in the future and drive the further development of design aspects of power transformers. Materials also play an important role in this context. Besides the circumstance that materials substantially drive the overall cost of power transformers, new materials can also be enablers for more innovative features of power transformers or allow different applications that were not available or permissible in the past. Besides silicon steel, copper and cellulose insulation, another key material in power transformers is the liquid insulation. For decades mineral oil was the only liquid insulation material used in power transformers. In the early years of this millennium, alternative ester liquid insulation was introduced. Most early references were on distribution transformer level with small MVA ratings and medium voltage levels. Now almost any power transformer can be designed and manufactured as an ester filled transformer. The major advantages offered by an ester liquid are its high fire safety factor, its biodegradable characteristic, extra safety margin against tank rupture in case of an internal arc and its positive impact on ageing of cellulose insulation.

However, where there are advantages there are also challenges to be addressed for the transformer OEM and operator. One of them is the higher pour point of natural ester liquid compared to mineral oil and similar pour point of synthetic ester but higher viscosity to mineral oil. This means that the viscosities of the ester liquids increase at extreme low temperatures which can lead to malfunctions and failures in case the power transformer is not designed appropriately. Although most references have been in locations around the globe where there are moderate to warm ambient temperatures, Siemens Energy has successfully designed and manufactured power transformers with MIDEL for extreme low temperature conditions.

In this paper M&I Materials (MIDEL) and Siemens Energy describe the major considerations and requirements to design and operate ester filled power transformers for extreme low arctic temperature applications of e.g. down to -50 °C. On one hand the reader will get better understanding of theoretical aspects which include material characteristics and its benefits and challenges. On the other hand, this

Confidential schneidertsthomas@siemens.com

paper also describes results of experimental tests done in controlled laboratory environment, in which transformer operational aspects were tested under extreme low temperatures. Besides the findings from the theoretical phase and the laboratory experiment, this paper will also describe how these requirements were successfully managed on real transformers that are in service in cold regions.

This paper should help engineering, operation, maintenance, asset managers and project planners to understand the benefits and master the challenges of ester liquids at extreme low ambient temperatures. Also, it should help utilities, municipalities, industries and other transformer operators to take advantage of the benefits of ester liquids in power transformers aiming for more environment friendly applications and to reduce the carbon footprint.

KEYWORDS

Synthetic ester, natural ester, cold temperature, Siemens Energy, MIDEL, Cold start, arctic conditions, power transformer

INTRODUCTION

The use of ester liquids has come a long way from when synthetic ester was first introduced in 1970s to retrofill transformers filled with PCBs to the largest transformers currently built rated at 433kV and 420kV from synthetic and natural esters respectively. As the use of ester liquids has increased so has the need to understand the properties and characteristics of the liquids in transformers. One of those key parameters is the pour point of the liquids. Pour point as defined by ASTM D2864 [1] is the lowest temperature at which a liquid can be observed to flow under specified conditions. Pour point of a dielectric liquid plays an important role in the operation of a transformer [2] in cold temperatures because not only does it affect the thermal design of a transformer but it also affects tap changers as well as other auxiliary equipment such as pumps. Understanding the flow characteristics of the ester liquids at cold temperatures allows the design engineers to make adjustments to address the dielectric and cooling mechanism of the transformer.

ESTER LIQUID INSULATION

Ester liquids are used in transformers because they are fire safe as they are considered "less flammable" (fire point ≥300°C); they are environmentally friendly because they are "readily biodegradable"; and because they can improve the life of the insulation system as they have a higher moisture saturation limit than mineral oil (hence holding more water, a key component in the ageing of cellulose insulation). Natural ester liquids are made from vegetable oils. The most commonly used natural esters are made from soybean and canola. Most of the properties of soybean and canola natural esters are similar. However, canola natural ester has a better pour point (-31°C) in comparison to soybean natural ester (-18°C) and it has better oxidation stability because it contains less of the more oxidation-prone fatty acids [2]. Synthetic esters are made from polyol alcohol and carboxylic acid chemicals through esterification process. MIDEL 7131 synthetic ester has a pour point of -56°C hence the capability to perform in extreme cold climates. Synthetic esters are used in sealed and breathing transformers because they have excellent oxidation stability. Natural esters are only recommended for use in sealed transformers.

Ester liquids have different dielectric and thermal properties in comparison to mineral oil that affects its performance in cold temperature.

Dielectric Properties

Moisture plays an important role in the dielectric breakdown strength of an insulating liquid. Since ester liquids are hygroscopic, they hold more moisture than mineral oil does and maintain the dielectric breakdown strength at the higher moisture content. Figure 1 below shows the moisture saturation limit of ester liquids in comparison to mineral oil:

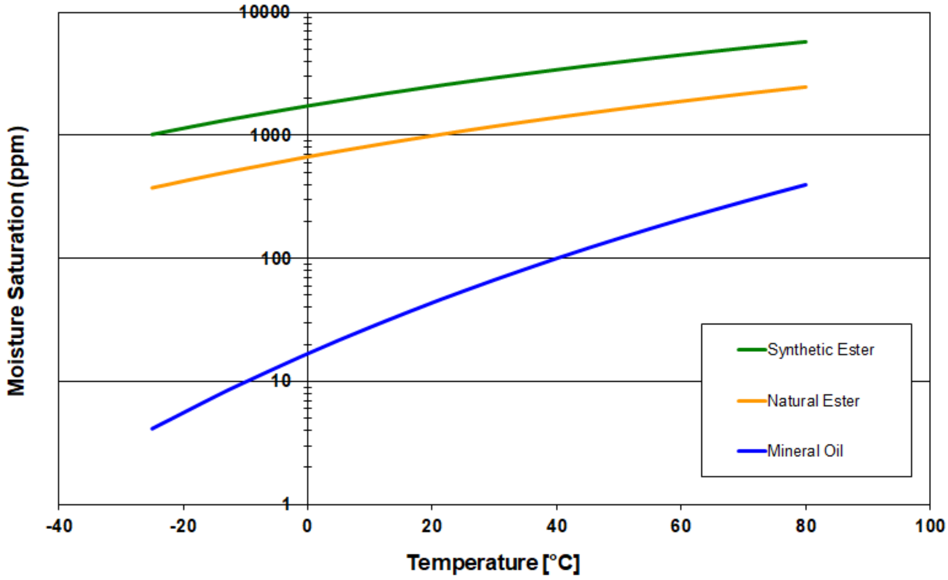


Figure 1: Moisture saturation limit comparison of ester liquids to mineral oil

In cold conditions, esters reduce the risk of dielectric failures because the higher moisture saturation limits of esters lower chances of ice formation. Ice can cause discharge activities due to bubble formation in the solid insulation [3] and conversion to water droplets becomes hazardous during energization of the transformer.

Thermal Properties

The dominant factor that affects the cooling capability of a dielectric liquid is kinematic viscosity. In cold temperatures, the viscosity of the liquids continues increasing to the point that solid deposits start forming within the liquid as shown in Figure 2 below [4]. When the temperature of the entire volume of the liquid gets to the pour point, it completely solidifies.

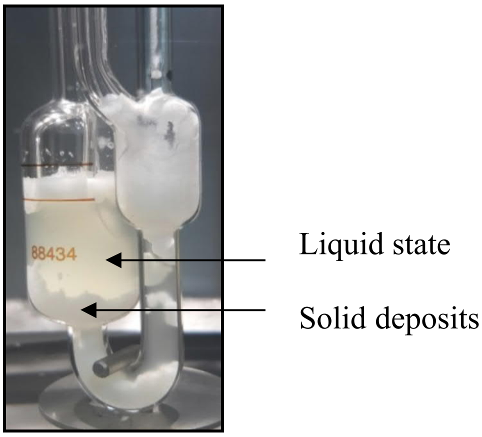


Figure 2: Viscosity change in ester liquid

As the viscosity of the liquid increases, it starts affecting the cooling characteristics of the transformer. When an unenergized transformer is located in colder temperatures, the physical state of the liquid may change depending on the ambient temperature. Table 1 below shows the physical state of the liquid at various temperatures:

Temperature	Liquids		
	Soybean natural ester	Canola natural ester	Synthetic ester
0°C	Liquid	Liquid	Liquid
-5°C	Liquid	Liquid	Liquid
-10°C	Solid deposits	Liquid	Liquid
-18°C	Solid	Liquid	Liquid
-25°C	Solid	Solid deposits	Liquid
-31°C	Solid	Solid	Liquid
-40°C	Solid	Solid	Liquid
-56°C	Solid	Solid	Solid

Table 1: Physical state of ester liquids in cold temperatures

As temperatures get close to the pour point of the liquid, it will begin to crystalize and form solid deposits, however the process is slow. The rate of crystallization is dependent on the volume of the liquid, ambient temperature and the number of days the ambient temperature remains low. In a transformer application, it may take several days at ambient temperature below the pour point for the insulating liquid to completely solidify in the tank [5].

TRANSFORMER DESIGN ASPECTS

There are some major differences between traditional mineral oil based liquid and ester liquids that affect the design of power transformers. Especially the physical properties of the liquids, such as the kinematic viscosity, thermal conductivity, specific heat capacity, flash point and fire point can be

mentioned. The variance between the liquids means that they are not able to be used within a single common design. Other factors to be considered when using an ester as an insulation liquid within a power transformer are the liquid's heat transfer characteristics. The hydraulic resistance of a transformer's cooling system is proportional to the kinematic viscosity. As described above, in comparison with mineral oils, esters have higher viscosity. The complete thermal design of power transformers need to be adjusted in a way that this aspect leads to a safe and reliable product. Viscosity plays a critical role when designing the inner cooling circuits. Higher kinematic viscosity does not necessarily mean that the cooling performance of esters is a disadvantage because the thermal aging of cellulose insulation in esters is significantly better than mineral oil. Compared to mineral oil, an ester liquid's electrical withstand properties have some disadvantage, e.g. in the event of fast transient impulse stresses, esters tend to show a lower withstand capability. Also the tendency of electrical discharges is higher for esters, especially in the case of large inhomogeneous components. This can lead to a significant impact to the insulation design. As a consequence the insulation arrangement for power transformers filled with esters can become larger compared to those filled with mineral oil. In order to achieve an accurate insulation design it is very important to consider exact design requirements. This enables the transformer to withstand the dielectric stresses during testing and operation. [6]
In terms of transformer design it is also important to specify relevant transformer protection and control devices, type of gaskets, tap changer etc. Any such sub-components of transformers need to comply with the characteristics of the chosen ester liquid.

The physical state as shown in Table 1 would be important during the cold start procedure as it would provide indication on the temperatures at which the transformer would be safe to load. The viscosity of the liquid in cold temperatures has to be carefully taken into consideration especially in the rating of auxiliary equipment that controls the flow of the liquid. During the design review, it would be recommended for the end user to provide detailed information with regards to the ambient temperature where the transformer will be located, the operating conditions of the transformers including the load profile during the coldest operating temperatures as well as the maintenance requirement. This will enable the design engineers to specify the right equipment for cold-start of the transformer as well as ensure that the temperature limits of the winding and the liquid are maintained under the extreme conditions. As part of the factory acceptance test, the end user should request the report on the test of the transformer at low temperatures and high viscosity conditions [7].

COLD START OF POWER TRANSFORMERS

As mentioned above, at very low temperatures, transformer cooling liquids become highly viscous. Just to compare some numbers, at -30°C, the kinematic viscosity of mineral oils is typically about a factor of 100 larger than at 40°C (e.g. Exxon Mobile NapOil2 996 mm²/s at -30°C and 9.4mm²/s at 40°C). That ratio is even larger for synthetic ester liquids. For Midel 7131, the viscosity at -30°C is approximately 150 times the value at 40°C (4362 mm²/s at -30°C and 30 mm²/s at 40°C [8]). The viscosity of MIDEL 7131 at -50°C is approximately 25 times more than mineral oil at -50°C. This drastic difference in viscosity leads to a completely different flow of the ester liquids at low or extreme low temperatures. In case of power transformers that have a cooling system designed for natural flow where flow is only driven by thermosiphon effect, this issue is of critical importance. These forces are very small, and a change of hydraulic resistance by a factor of 10 times clearly has a large effect on flow distribution.
An additional point of interest is the energizing of a power transformer with extremely low liquid temperatures at extremely low ambient temperatures. During such a cold start it can take a long time for the liquid to flow through the cooling equipment. Temperatures in the active part can reach undesired levels while the ester flowing through the external radiators may be insufficiently small.[9]
In 2016 Siemens performed a lab test to investigate the performance of a power transformer in an extreme low temperature environment using synthetic ester liquid. The test was performed in a climate chamber and was carried out on a single-phase auto transformer as shown in Table 2. In order to eliminate any no load losses in the core during testing, only short circuit heat run tests had been performed.

The transformer had been equipped with 85 temperature sensors (including fiber-optic sensors inside the windings) and 3 moisture sensors. The sensors were positioned such that temperatures at bottom and top of the windings, winding hot spot as well as tank and radiators could be measured.
The test transformer was equipped with 3 radiators which were mounted on the low voltage side of the tank. With means of extension pipes the radiators were placed further away from the transformer tank. The distance between the tank wall and first radiator panel was 745mm which was more than usual but not as representative as cooling with separate radiator banks. One of the main points of interest of the lab test was the cooling performance of external radiators and therefore one half of the wall and cover had been insulated as shown in Picture 1. Measured heat transfer from the tank surface was reduced and the relative contribution of the radiators was increased in order to represent characteristics of larger transformers.

Rated power	15 MVA (KNAN) / 20 MVA (KNAF)
Rated voltage	55 kV
Short circuit impedance	1.79%
No-load losses	5.9 kW
Load losses (at100% = 15 MVA, 75°C winding temperature)	29.0 kW
Cooling surfaces	3 radiators (106 m²), tank (7 m²)
Fans	3 fans (horizontal flow, ~ 2.5 m³/s total)
Cooling liquid for test performed	Synthetic ester Midel® 7131

Table 2: Properties of the transformer

Picture 1: Test object inside test chamber with walls partially insulated

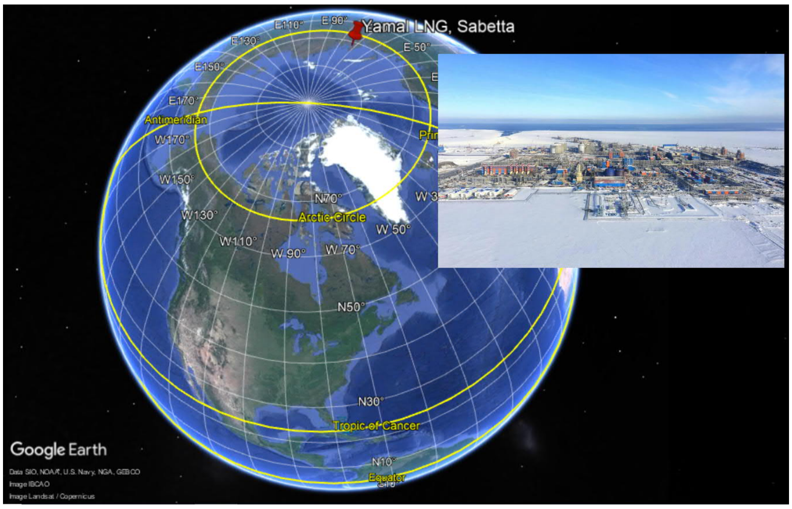
Typically, when a transformer is energized in cold temperatures, the winding temperatures start to rise quickly. Even though the liquid has high viscosity, it will start to flow inside windings and tank. This circulation inside the tank will lead to a slower increase of temperatures because of the larger mass that is involved. As the transformer warms up, temperatures may reach high levels because the liquid

is cooled only by the tank and cover surfaces. External radiators are initially inactive, and it takes a long time to get them active. During that time, temperatures may continue to increase and may overshoot the rated temperature.
For the test transformer in Figure 3, the measured cold start at -40°C with full load did not lead to critical temperatures. At -50°C, the transformer was started at low load without any problem, but was not tested at full load.
One of the most important questions in case of a cold start is the required time to activate radiators. For the test transformer, it took approximately 14 h to turn on the radiators in the cold start at -40°C. The duration would have been longer in case of lower ambient temperature. It would also take very long time in case of separate radiator banks as the long pipes would need longer time to warm up, however this was not tested.
An additional issue remained also in steady state operation at very low ambient temperatures: not all radiator panels were active [9]. For this reason, steady state operation might lead to high temperatures in some cases. With smart control on the radiator valves this issue can be minimized.

CASE STUDY

Russian Project Yamal

Yamal LNG was a joint venture based around a liquefied natural gas plant located in Sabetta at the north-east of the Yamal Peninsula, Russia. That location is within the Arctic Circle in a region where there is permafrost and temperatures can be -50°C or lower. Many challenges had to be mastered in order to accomplish such a project in such extreme arctic conditions. Those challenges affected engineering of 26 power transformers required to keeping the project running in Yamal.
In the case of Yamal LNG, MIDEL 7131, a synthetic ester liquid as described earlier in this paper was used. The selection of that liquid was primarily in order to mitigate freezing and fire risks at that site. Due to the higher flash and fire point of the liquid, an external fault would be far less likely to lead to a failure or fire. This is especially important in a plant where liquefaction of natural gas is performed and consequences of fire could be severe. Picture 2 shows the location of Yamal.



Picture 2: Sabetta, Yamal LNG
Photo credit to Google Earth and https://www.alten.com/yamal-lng-project-gas-arctic-anotech-energy/

In Table 3 there is an overview of transformers located at Yamal LNG plant. All transformers were manufactured by Siemens at its Russian transformer factory. The relevant tests performed in laboratory environment as outlined earlier provided relevant basic knowledge in order to optimize the design of those transformers for operation in the harsh environment.

Number of transformers:	2	6	2	6	4	2	2	2
MVA rating:	125	85	63	40	31,5	20	50	16
Voltage:	110kV/ 36,6kV	110kV/ 36,6 kV	35kV/ 10,5kV	35kV/ 10,5kV	35kV/ 10,5kV	35kV/ 10,5kV	35kV/ 10,5kV	35kV 10,5kV
Number phases:	3PH	3PH	3PH	3PH	3PH	3PH	3PH	3PH
Cooling type:	KNAN/KNAF	KNAF/KNAN	KNAN	KNAN	KNAN	KNAN	KNAN	KNAN
Voltage regulation	OLTC	OLTC	DETC	DETC	DETC	DETC	OLTC	DETC

Table 3: Yamal power transformer data

As can be seen in Table 3, the transformer sizes ranged from 16MVA, 35kV distribution size transformers to 125MVA,110kV power transformers. All transformers were network type transformers and provided power supply to the LNG plant. All transformers were manufactured according IEC and Russian GOST standards. They were energized in 2017 and fulfilled the specified requirements.

German Project TransnetBW

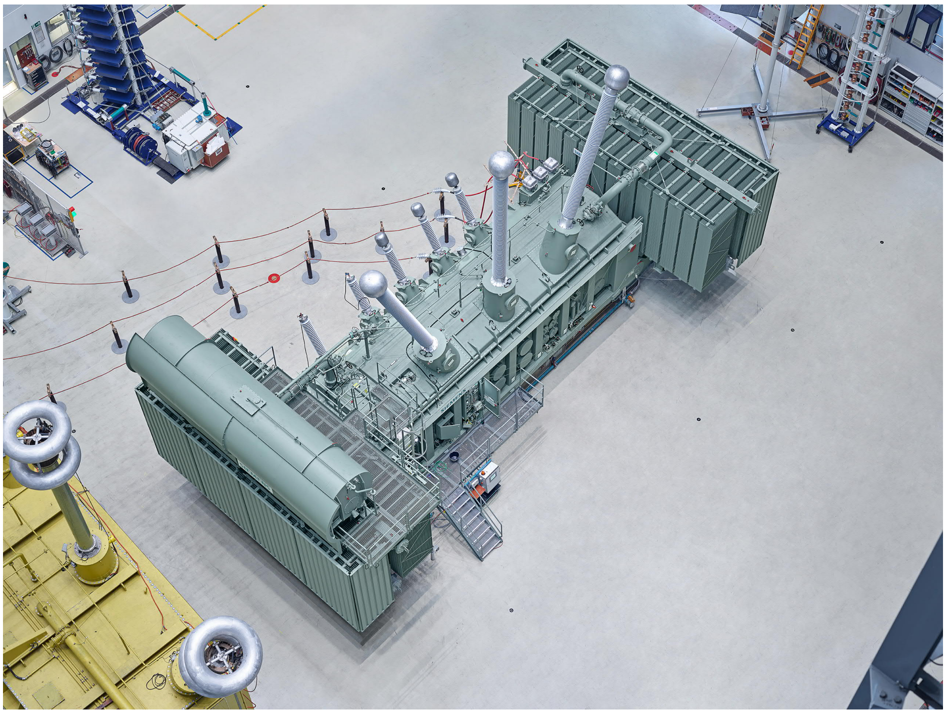
In 2019 Siemens designed, manufactured and tested a 400MVA, 420kV MIDEL eN1204 canola natural ester filled power transformer for German utility TransnetBW. Some years past, Siemens has successfully designed, manufactured, tested and delivered a very similar transformer to same customer, however that transformer was filled with a different natural ester liquid and some operational limitations in low temperature weather conditions had to be considered.

Operational experience of the first 420 kV transformer had been analyzed to upgrade and to optimize the design of the second transformer. Specifically certain mechanical design modifications had been introduced such as different arrangement of pumps for KD mode, adjustment of Buchholz relay, etc. The transformer was designed to operate at conditions with low ambient temperature of -25°C according to the transformer specification and IEC 60076-1 [10]. At no load condition the transformer was designed for the liquid temperature to not drop below -10°C even though ambient temperature may drop to -25 °C. Another benefit was that the transformer was capable of operating at -25 °C even if the transformer was switched off beforehand and the liquid temperature dropped down to -25 °C or even lower. Energizing the transformer at -25 °C was for emergency conditions only. Compared to the ester liquid used in previous transformer, there was an additional margin of low temperature energization of the canola natural ester liquid, because the pour point of the liquid was -31°C. The only operating limitation at cold start was the onload tap changer which was prohibited to be operated at temperatures below -12°C. The limitation was related to mechanical requirements as a consequence of the high liquid viscosity.[11]

Table 4 below shows the main technical data of the transformer and Picture 3 below shows the transformer fully installed at Siemens Nuremberg factory for factory acceptance testing (FAT).

MVA rating:	400 / 400 /75 MVA
Operating Voltage:	405 ± 16% / 115 / 22 kV
Number phases:	3PH
Cooling type:	KNAN/KDAN
Voltage regulation	OLTC

Table 4: TransnetBW power transformer data



Picture 3: Transformer fully installed at factory during FAT

CONCLUSIONS

Ester liquids provide an excellent opportunity for the end user to specify an innovative solution for their transformers as they can get a fire safe, environmentally safe, high performance transformer that can work in extreme low and high ambient conditions. In extreme cold climate it is vital for the end user to make the critical decisions on the type of liquid to use in the transformer as well as the operating conditions. Canola natural ester provides a solution for colder temperature application that in the past was not available for natural ester filled transformers. Synthetic ester liquid provides the ultimate performance for transformers located in any weather conditions, with its proven track record of working in extreme climate conditions.

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