

Converter Transformer Cold Starts: Specification Nuances and Operational Impacts

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SUMMARY

Canadian utilities often experience weather that tests the lower operating temperature limits for large transformers. This paper compares two case studies of the transformer cooling and cooling control designs that have led to issues energizing large LCC converter transformers, then it compares three other design examples (LCC & VSC) that do not have this issue, and finally it explores some of the solutions that the affected utilities have developed with their manufacturers to mitigate the impact to operations. HVDC converter transformers are among the most massive transformers a utility may own, and as such, are extensively engineered to reduce their mass, and consequently their price. Transformers with oil-directed, air forced cooling (ODAF); or oil forced, air forced cooling (OFAF) typically results in the lowest overall transformer mass at the cost of high complexity in both cooling and HVDC start-up cooling control. An understanding of the nuances of how the converter transformer ODAF/OFAF cooling and cooling control systems interact at low temperatures is critical for optimizing HVDC operations during a Canadian winter.

The primary issue energizing a transformer in cold conditions is that the oil viscosity has increased significantly, so that transformer cooling is far less effective, leading to localized hot spot development. At low enough temperatures, the oil pumps and flow meters do not function properly on cold-start with mineral oil. A secondary issue is that specific designs of the cooling system may nominally operate for cold-starts at slightly warmer temperatures, but the measurement systems and control systems still may not be able to determine that the cooling is functional, thus preventing converter transformer energization. An HVDC owner can mitigate the secondary issues by ensuring that oil flow measurement technology is specified that operates down to the lowest cold-start temperatures. The owner and manufacturer can also write operational procedures that maximize the HVDC link transfer capability in the hours after a cold-start, mitigating the primary issue while safely avoiding hotspot development. These procedures may require slight modifications to the HVDC control and protection interface for the converter transformer.

KEYWORDS

HVDC, Converter Transformer, Cold Start, Specification, Design, Cooling, Low Temperature, Energization, Operations

1. INTRODUCTION

Canadian utilities often experience weather that tests the lower operating temperature limits for large transformers. Multiple Canadian utilities have encountered issues energizing their HVDC converter transformer in low temperatures, while other Canadian utilities in similar climates have had only minor issues or no issues at all. This paper introduces the cooling theory and then compares the transformer cooling and cooling control designs for the converter transformers for five utilities, of which two of those utilities have experienced issues energizing their transformers. This paper then explores the solutions that the affected utilities have developed with their manufacturers to mitigate the impact on operations. The cooling designs of converter transformers that have not had the same issues energizing large converter transformers are contrasted with the problematic designs, and recommendations are developed to allow an HVDC asset owner to specify transformer designs that do not suffer from issues energizing during cold weather conditions.

2. BACKGROUND THEORY

Understanding the components of a cooling system on a converter transformer is essential to understanding how to specify it. This section outlines power transformer cooling class terminology, what cooling systems industry prefers for converter transformers, the physical effects from energizing a transformer in very cold conditions, and the additional considerations for on-load tap changers.

2.1 POWER TRANSFORMER COOLING CLASSES

Methods of cooling for liquid immersed transformers are arranged into cooling classes identified by a four-letter designation as follows:

Medium	Mechanism	Medium	Mechanism
Internal		External	

The internal medium is identified by the first letter and may be designated by one of the following code letters:

- O – Liquid with a flash point less than or equal to 300°C
- K – Liquid with a flash point higher than 300°C
- L – Liquid with no measurable flashpoint

The internal mechanism is identified by the second letter and may be designated by one of the following code letters:

- N – Natural convection through cooling equipment and windings
- F – Forced circulation through cooling equipment, natural convection in windings
- D – Forced circulation through cooling equipment, directed flow in windings

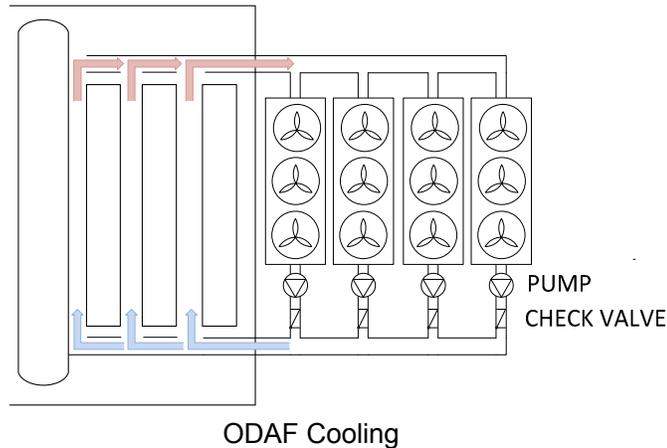
The external medium is identified by the third letter and may be designated by one of the following code letters:

- A – Air
- W – Water

The external mechanism is identified by the fourth letter and may be designated by one of the following code letters:

- N – Natural convection
- F – Forced circulation

In the above cooling types, progressively higher loading capacities above the transformer's base rating may be achieved by employing fans and pumps. For example, the OFAF system increases the rate of heat exchange from the transformer by forcing oil to flow freely inside the tank with pumps. Heat dissipation is then further improved by creating an ODAF system, connecting individually-controlled radiators with an upper and/or lower header to the windings, forcing oil through pre-determined channels in the windings. As the oil circulates through the radiators, the continuously operating fans transfer heat from the fluid to the outside atmosphere.



2.2 AVOIDING HOT SPOT ISSUES WITH CONVERTER TRANSFORMERS

In general, HVDC converter transformers are subject to more severe electrical stresses than conventional high MVA power transformers. In addition to the very high MVA rating requirements that are typical of LCC converters, the possible severe and rapid load swings, and the concern of DC and AC current harmonics all significantly contribute to the potential formation of localized hot spot temperature rises. Hot spots lead to accelerated degradation of the oil impregnated cellulose winding insulation, which reduces its dielectric strength, and creation of dissolved gases in the surrounding oil. Further oil contamination results from the release of furan derivatives from the decomposition of the insulation. The compound effect of all these occurrences is loss of transformer life.

The primary cause of elevated hot spot temperatures is reduced cooling due to insufficient oil flow within certain areas of the transformer tank. The directed oil flow for an ODAF system results in uniform heat transfer in all areas inside the tank, resulting in lower design values of hot spot temperature rise than are achievable through other types of cooling systems. Converter transformers will thus typically be ODAF unless the hot spot heat model is generous enough to allow an OFAF design.

2.3 ENERGIZING A TRANSFORMER IN COLD CONDITIONS

The most critical aspect to consider when cold starting a transformer is its overall dielectric capacity. At the most extreme cold temperatures, mineral oil may theoretically shrink, condense out water and create voids if it cools beyond its pour point (-60°C to -40°C), all of which is a prelude to dielectric failure. Practically, if de-energized for extended periods at ambient temperatures below -25°C , high oil viscosity impedes normal flow and cooling. This creates conditions for localized hot spots to develop if the transformer is immediately subjected to loading. Manufacturers' transformer maintenance manuals may have recommended procedures for the cold starting of transformers. Procedures designed according to IEEE [2] suggestions require the transformer to be energized with the converter blocked for a designated period, and then slowly increasing the power order in designated

increments, with a time delay between each increment. In the case of converter transformers, this procedure is tailored to the specific cooling type that is employed together with the converter start-up sequences in place.

In the sections that follow, real accounts of problems encountered by utilities with HVDC links are presented along with implemented solutions to overcome the issues.

2.4 ON-LOAD TAP CHANGER CONSIDERATIONS

The On Load Tap Changer (OLTC) units within converter transformers account for temperature as the current carrying components and insulation is exposed to the same stresses as the windings within the main tank. Colder temperatures will impose extra forces on the mechanical parts.

Depending on the type of OLTC that is utilized in the converter transformer, different considerations must be made. Current converter transformer OLTCs are placed in a segregated compartment within the main tank, and have their switches and/or contacts directly submerged in oil or installed in vacuum bottles (which themselves may be submerged in oil). When the OLTC is insulated in a vacuum, low-temperature considerations are limited to the remaining oil-submerged contacts and the motor mechanism. When the OLTC is also insulated with oil, the expected arcing occurring from changing taps creates contamination within the OLTC tank. It is critical to ensure that the OLTC tank's oil, diverter contacts, and current carrying components are not exposed to additional moisture or hot spots, as the contamination (carbon, etc.) leads to more severe arcing, which leads to exponentially increasing volumes of contaminants.

OLTC tanks do not incorporate directed oil and/or forced air cooling because they do not create heat. However, they should still have their temperature monitored to ensure the safe operation of the device as colder temperatures can impose extra forces on the moving parts and increase the risk of water condensing out of the oil. In most cases, the manufacturer will provide the OLTC with temperature monitoring for both the oil and OLTC control cubicle to inhibit OLTC operation during severe cold.

When the converter transformer oil begins to reach lower temperatures, the viscosity is increased, and additional mechanical stresses are imposed on the moving components within the OLTC. If the oil becomes too thick and the OLTC is routinely operated in these conditions (OLTC operation is routine in LCC converter transformers as it is used by the alpha and gamma angle controls), it will lead to a decreased lifetime of the OLTC components. Over time, if the OLTC is operating excessively at lower temperatures with thicker oil, warping and disfiguration of the moving and stationary parts can be observed as the oils resist the moving components. Slight warping such as this can cause an OLTC to inadvertently miss the "make before break" transition or fail to rotate wholly and appropriately. OLTCs equipped with vacuum bottles avoid these issues as oil is used between the OLTC itself and main tank to insulate current carrying transformer winding connections.

The OLTC's external mechanical components are equally as important to monitor. If frost accumulates within the housing of the motor and the motor is operated (even under normal conditions), as the motor heats the frost will sublime and introduce moisture to the motor windings. This can cause significant shorting and possible equipment failure. Additionally, for oil type, as oil becomes viscous in colder temperatures, it begins to impede rather than aid in the smooth transition of the OLTCs operation. This places additional stress on the motor, causing the tap gear to work harder to achieve the same result.

OLTCs operated in cold climates should have oil and cabinet temperatures incorporated into the OLTC control blocking logic to prevent unnecessary damage. In the following sections, temperature based OLTC controls are discussed as found within industry designs.

3. ENCOUNTERED PROBLEMS

Utility A and Utility B

Utility A and Utility B each have an in-service HVDC link with single phase converter transformers, ODAF cooling. In the start-up sequence, the DC controls turn on the transformer cooling before transformer energization to reach the “Blocked” state of the converter. The transformer units have five cooling groups, each consisting of one pump and three radiator fans, two of which groups are turned on in preparation for transformer energization in the initial design of the cooling logic. Subsequent cooling groups would come on depending on measured winding temperature. Oil flow indicators are installed in the piping between the radiators of each cooling group and the headers in the main tank. As oil flows from the tank to the radiator, it deflects a metal flap. If no flow is present, a “pump off” indication is shown. If the proper oil flow is experienced through the indicator a “pump on” signal is received, and the corresponding status is communicated back to the HVDC control system. Shut down, with the tripping of converter transformers, is initiated upon either loss of flow or pump failure in all running cooling groups.

The root cause of the issue that Utility A and B found during cold weather energization of their converter transformers was the high viscosity of transformer oil at those low temperatures resulting in low oil flow. For oil forced (OF) and oil-directed units (OD), the oil flow is monitored to confirm that the minimum number of pumps and hence oil flow is achieved to ensure windings and winding hotspots are sufficiently cooled. In some instances, the high viscosity of the oil results in a low flow which is insufficient to activate the oil flow sensors indicating flow and the transformer trips off due to “loss of oil flow.”

Utility A

On-line dynamic performance testing on Utility A’s link was completed in mid-December of the year, which was then followed by the trial operation period. Near the end of the month, during the first real cold snap of the year, one phase transformer experienced “all pumps off or no oil flow” resulting in a shutdown event. Following several hours of investigation and confirmation that the transformer was fit for re-energization, a restart attempt was successful. The cold snap persisted, and several days later, there was more loss of flow alarms associated with at least one cooling group, resulting in the turn-on of all. Due to low DC dispatch levels and temperatures below -20°C, the internal winding and oil temperatures were observed to be dropping significantly with all cooling groups in operation. The cooling system was, in effect, so efficient that the oil viscosity increased to the point where oil flow was not able to be measured. This point occurred when oil temperature had dropped to only 0°C.

Utility B

Similar to Utility A, Utility B encountered issues with the oil flow sensors detecting oil flow during field commissioning in the winter with low ambient temperatures. Ambient temperatures were below -30°C during the commissioning period and the oil flow sensors indicated no oil flow. The commissioning team confirmed that all pumpers were running; however, the oil flow gauges were not sufficiently engaged to pick up oil flow indication. The manufacturer did not allow energization of the units in this condition as the oil flow protection would have to be bypassed to allow energization and could mask a real oil flow issue on the ODAF units. The manufacturers engineering team was consulted for solutions as the transformer energizations were required to progress the overall project critical path schedule.

It was also observed at a site that the problem persisted in ambient temperature conditions at a temperature just below 0°C.

4. SOLUTIONS TO PROBLEM

Utility A

To remedy the problem of low oil flow, one or more cooling groups were switched to manual control and turned off. It was also observed now that all pumps were working, but the flow meters were not registering the flow. This led to an investigation into the suitability of the meters and a request by the utility that they are replaced. The vendor, however, advised that to install an alternate meter would require a complete replacement of all the piping as well, which was not feasible. Instead, the vendor submitted revised cooling group logic to maintain more stability in the oil temperature in cold and low load conditions. In the start-up sequence, only the pumps of two cooling groups were now to be turned on initially, with the fans of these groups coming on upon winding or oil temperature reaching a pre-determined "Stage 1" level.

Then, in February of the following year, after a planned outage of ten days' duration that coincided with another cold snap, the start-up sequence was blocked again due to loss of cooling. External kerosene heaters were set in place around the transformer, and eventually, the oil temperature was raised to a point where the flow was detected upon start-up. Now, a more detailed investigation ensued by the vendor, and the inability of the installed flow meters to register laminar oil flow, such as the case when the oil has increased viscosity, was confirmed. The vendor proposed an overall change in the start-up procedure in the case where the transformers have been de-energized for several days in cold weather and the oil temperature has cooled down to well below 0°C. This included pre-energization of the transformer at no load, further changes to pump and fan turn on sequences and stepwise increase in loading.

Utility B

In contrast to Utility A, Utility B required full link capacity to be available immediately following energization. In this case, the vendor developed a solution employing the winding hot spot direct temperature measurements. The hot spot measurements were present via fibre optic temperature sensors and already being brought into the Electronic Temperature Monitor (ETM) pump/fan controller for monitoring only purposes. The transformer manufacturer modelled oil flow during low temperature/high viscosity conditions to determine the minimum flow and maximum duration without flow that the winding hot spot could handle under immediate high loading conditions. Since the transformer was oil-directed, the flow rate was more of a concern as natural thermal convection of the oil would not cool the hot spot sufficiently.

With modelling analysis and real-world feedback from the fibre optic temperature measurement, the manufacturer was able to develop and implement logic in the ETM to calculate if minimum oil flow has been achieved based on the oil cooler inlet/outlet temperature differential. This logic was used for oil loss protection until the top oil temperature and viscosity were enough to enable the traditional flow switch oil flow confirmation protection. With this, the oil-directed unit did not have to bypass the oil flow logic during cold weather energization. It should be noted that changing the flow switches after the design phase would have involved oil cooler piping changes, oil processing, outage time and impacted the project schedule significantly.

5. ALTERNATIVE DESIGNS IN INDUSTRY

Utility C

Utility C has a similar ODAF cooling control system design as Utilities A and B, but larger pumps and piping with more significant cross-sectional diameter were installed on Utility C's transformers. Also, electronic thermodynamic oil flow indicators were used. The electronic oil flow indicator determines flow by heating a sensor slightly warmer than the oil. As oil flows, it reduces the temperature of the sensor. The temperature differential between the sensor and the oil is used to calculate the flow. Electronic flow indicators have the ability for higher sensitivity in contrast to the mechanical version installed for Utility A and B. Therefore, during cold start scenarios the electronic oil flow indicators can accurately determine oil flow, and to date, no issues have been encountered.

Utility D

Utility D uses an ODAF cooling design, with 4 cooling banks that engage based on increasing winding temperature. In the control scheme, the cooling system (both fans and oil circulation pumps) is inhibited when the oil temperature is below -15°C. Additionally, there is a small passive radiator that is installed on the transformer which allows for energization without any cooling available (unlike the cooling designs for Utilities A, B, & C). Similar to the cooling designs for Utilities A and B, however, this transformer also employs mechanical oil flow measurement sensors.

The only interlocking Utility D has with the HVDC control system that is related to low temperatures is regarding the OLTC. The OLTC controls incorporate a temperature probe in the diverter oil such that when it is below -35°C operations are inhibited. Note that the OLTC operation is also inhibited for Utilities A & C, but at -40°C. In contrast, Utility B required the OLTC to be available for operation at -50°C. In a cold start scenario, energization is permitted while the OLTC is unavailable, however, deblocking is not possible until the oil temperature has increased above -35°C and the transformer can tap to the appropriate level.

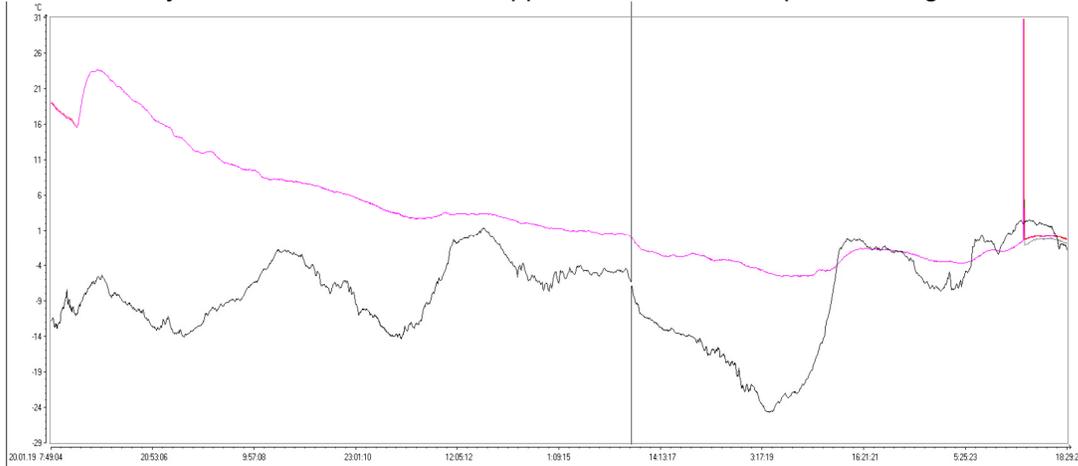
While there is no specific requirement for oil flow to be present (unlike the cooling designs of for Utilities A, B, and C), the operating strategy for this transformer is to plan for additional time between energization and the ramping up of load (similar to Utility A). This allows the oil temperature to rise above certain thresholds before continuing with heavy loading that could form winding hotspots while the viscous oil is not circulating effectively.

Utility E

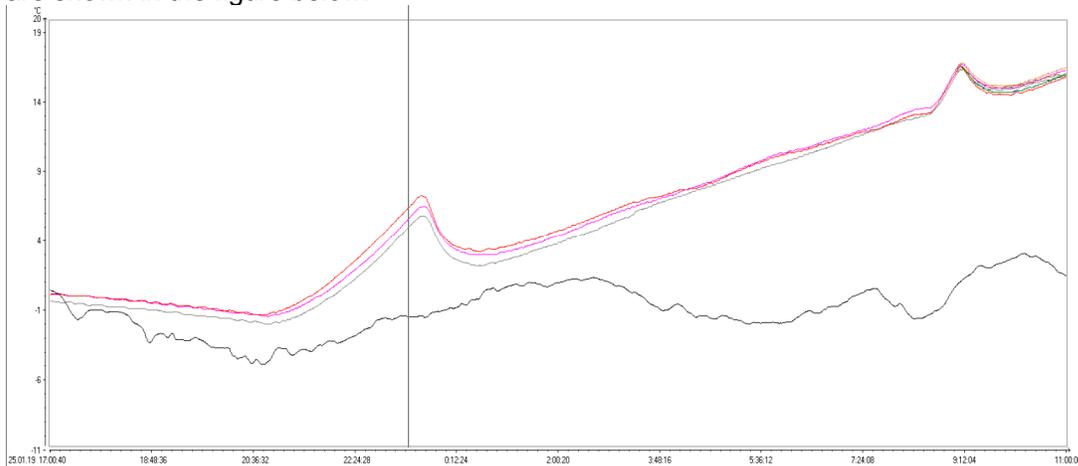
Utility E has a design for an operating environment of -35°C to 40°C and utilizes 9 cooling banks which are enabled based on 2 stages of winding and oil temperature. This particular transformer is filled an insulating mineral oil which has a very low viscosity and still has regular flow at the transformer design limit of -35°C. This transformer has no interlocking on a temperature basis with the HVDC control system. The transformer can be energized in any temperature and if below the design of -35°C, should not be loaded until the transformer temperature increases above the minimum operating temperature. Given the location of this transformer, the ambient rating of -35°C exceeds recorded temperatures for the past 40 years. It is unlikely in its operating lifetime that this transformer will experience a very low-temperature cold start scenario, unlike the transformers for Utilities A, B, C, and D, which all have experienced temperatures around -40°C or colder.

6. CONSIDERATIONS FOR OPERATIONS

It should not be underestimated how crucial proper design consideration is for converter transformers in low-temperature climates. It takes a long time for large volumes of oil such as are present in converter transformers to change temperature. For example, shown in the figure below is a transformer oil temperature (pink line) vs. ambient temperature (black line) trend starting from the approximate time when Utility A's link is tripped off. In this case, it took three days from when the link was tripped off for the oil temperature to get below 0°C.



If the load cannot be transferred until oil temperatures are above 0°C (as was discovered in Utility A's case), operations must consider the time required for the oil temperature to increase to acceptable levels after a transformer is energized and before the link is deblocked. In the above example, energization occurred with the transformers' oil temperatures at -1°C or -2°C and it took approximately 2.5 hours for all three phases' oil temperature to get above 0°C. Note also that it took a further approximate 1.3 hours for all three phases' oil temperatures to get above 5°C at which point the oil pumps started automatically causing an initial cooling of the oil before continued warming. Trends for this are shown in the figure below.



When energizing a transformer in cold conditions (below -20°C), the following best practice can be followed in order to ensure no equipment damage. The transformer should be energized with HVDC controls blocked for 2 hours to increase the oil temperature and then to deblock and load in increments of approximately 25% rated capacity for 30 minutes at each interval, as per IEEE C57.93, Section 4.4.4 recommendations [2]. However, this guideline

can be avoided based on the converter transformer design and recommendations from the manufacturer. This allows for more prompt energization and delivery of full transformer capacity. As an example, as described above, Utility B can energize and immediately load the transformer based on the manufacturer's analysis, relying on the real-time hot-spot sensor feedback implemented in the control system.

7. CONCLUSION

The table below summarizes the operating experience and control system criteria for each of the utilities discussed in this report after any issues with cold start were rectified.

Condition	Utility				
	A	B	C	D	E
Experienced Cold Start (-20°C)	x	x	x	x	
Issues discovered during commissioning	x	x			
Mechanical oil flow indication	x	x		x	x
Oil flow indication required for energization			x		
Oil flow indication required for loading	x		x		
Minimum oil / ambient temperature for energization (°C)	-50	-50	-50	-50	-35
Minimum oil temperature for loading (°C)	0 ¹	-50	-30	-35	-35

1. The oil flow indicators begin to indicate flow at approximately 0°C, which allows for the loading of the transformer.

Looking forward, special attention should be focussed during design review on the proposed cooling systems for the transformer. If oil flow is a cooling control requirement for energization, low-temperature oil flow verification sensors or methodology should be demonstrated with previous project references and be shown in the transformer thermal models. Regardless of the cooling control scheme, it is imperative that owners specify that the manufacturer model and demonstrate full load winding hot spot temperatures during low oil temperature and high viscosity conditions.

8. BIBLIOGRAPHY

- [1] S.D. Myers, J.J Kelly and R.H. Parrish. "A Guide to Transformer Maintenance" (Transformer Maintenance Institute, Division S, S.D. Myers, Inc. Akron, Ohio, 1981).
- [2] IEEE Guide for Installation and Maintenance of Liquid-Immersed Power Transformers, IEEE Std. C57.93, 2019.