COOLING MODES AND LIFESPAN OF MV DRY-TYPE TRANSFORMERS INSIDE A SHORE CONNECTION SUBSTATION

Thierry CORMENIER
Schneider-Electric – France
thierry.cormenier@schneider-electric.com

Julien MOREAU
Schneider-Electric – France
julien.moreau@schneider-electric.com

Daniel RADU
Schneider-Electric – France
daniel.radu@schneider-electric.com

Pierre LAGACHE
Schneider-Electric – France
pierre.lagache@schneider-electric.com

Bruno LUSSON
Schneider-Electric – France
bruno.lusson@schneider-electric.com

ABSTRACT

This paper describes the impact of cooling modes of dry-type transformers as per standard IEC 60076-11 in a substation designed as per IEC 62271-202. This voltage and frequency transformer substation is designed for on-shore grid connection for ships at berth. For this reason, the service conditions adopted as per standards IEC 60721-3-4 and IEC 60721-2-5 are a key factor in the choice of cooling mode for this prefabricated port installation. The use of numerical simulations is essential for guiding choices towards the most reliable overall solution.

INTRODUCTION

At previous CIRED events [2] [3], we demonstrated the importance of taking thermal performance into account in the design of prefabricated substations housing one or more transformers. Our earlier work focused on standards relating to liquid-immersed transformers. This study is concerned with dry-type transformers, for which there is a growing demand but little operating experience feedback available for prefabricated substations. In addition to the standards mentioned above, test results and simulations were correlated with the loading guide for dry-type transformers (IEC 60076-12).

GENERAL

CFD (Computational Fluid Dynamics) simulation was used to develop the forced-ventilation cooling technique for these transformers, including the use of intake filters to allow for the particular operating conditions of a port environment. As this substation is designed to provide power for ships at berth, frequency conversion is required. The static grid frequency converters (GFC) used for frequency conversion must be cooled in the same way as the transformers. The optimisation work carried out for the frequency converters was also put to use for transformer cooling. Figure 1 is a layout diagram illustrating transformer and GFC cooling requirements.

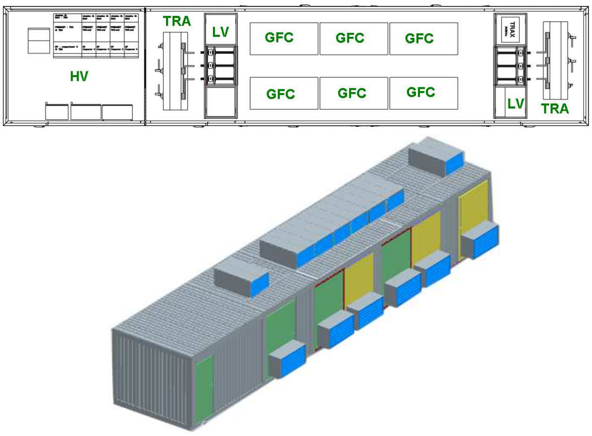


Figure 1: 3MVA shore connection substation

All the thermal interaction between the GFCs and transformers was taken into consideration in the overall thermal analysis. An investigation study was carried out first to check the temperatures reached with different transformer cooling modes and the related ageing rates.

INVESTIGATION TESTS

Equipment

The comparative study used a 3 MVA transformer with a 155°C insulation system and the following rated characteristics:

Type:	Cast-resin transformer
Dielectric:	Trihal
Power:	2000 kVA
Voltage:	20 kV/410V
Coupling:	Dyn11
No-load losses:	4,269 W
Load losses at 120°C:	17,700 W
Short-circuit voltage at 120°C:	6.3%

The substation enclosure is a thermally insulated metal enclosure with an IP24 protection rating. It can be configured for natural or forced air ventilation (AN or AF) as shown in Figure 2. Thermal insulation of the enclosure is essential in the final phase for compartments that do not have a forced ventilation system. Forced ventilation in the transformer room is provided by 1 to 4 axial fans with a unit capacity of 2,880 m3/h. These may be used in conjunction with a radial ventilation system to reach a capacity of 5,600 m3/h.

Figure 2: External enclosure, AN and AF configurations

Simulation

In order to determine the scope of an investigation test, overall thermal performance of the installation was estimated using the same simulation tools as those presented at earlier CIRED events [2], [3]. The losses considered are transformer losses at 1.46 * In, or roughly 42 kW no-load loss. The curves show the estimated air outlet temperature induced by transformer losses, together with the cooling mode according to the use of 3 or 4 extractor fans. This simulation method takes into account climatic impact for the total annual system performance. The cooling mode will be optimised using another tool, as described later in this paper. For forced ventilation, Figure 3 shows a temperature rise of 11 K with 4 fans (Red) and 14 K with 3 fans (Blue) compared with the outside temperature (Green). For natural ventilation, with ventilation grids fitted on 3 sides of the enclosure, the air temperature rise is 18 K for 21 kW as losses.

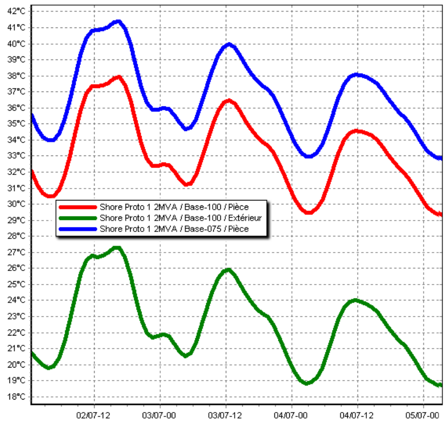


Figure 3: Transformer room air temperatures.
Green: Outside / Red: inside, 4 fans / Blue: inside, 3 fans

Tests

Figure 4 shows various load cycles together with the results obtained:

_1 IP43 enclosure at 1.5 In	AF 11,520 m3/h
_2 IP43 enclosure at In	AF 11,520 m3/h
_3 IP43 enclosure at In	AF 8,640 m3/h
_4 IP43 enclosure at 1.5 In	AF 8,640 m3/h + Radial
_5 IP43 enclosure at In	AN
_6 IP23D enclosure at 1.5 In	AN
_7 IP23D enclosure at 1.3 In	AN
_8 IP23D enclosure at 1.15 In	AN

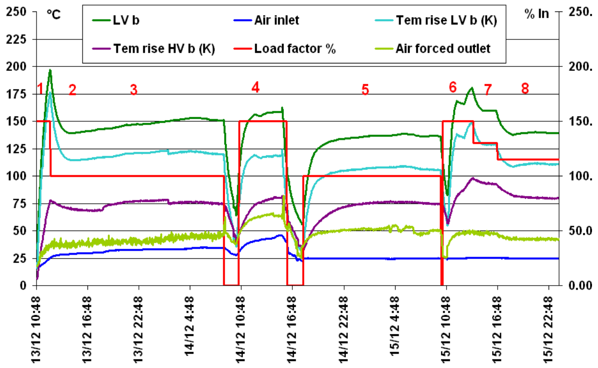


Figure 4: Load and cooling cycles for a 2 MVA transformer with a 155°C insulation system

Based on the results of this test, we can conclude that the q coefficient, which varies from 1.6 to 2 according to the ventilation mode in standard IEC 60076-12, can be much lower if the radial fans shown in Figure 1 are placed under the transformer. Nonetheless, non-optimised forced ventilation remains far less effective than natural ventilation. Figure 5 shows the hot-spot temperature and temperature rise as per standard IEC 60076-12. Where q is the cooling mode constant: q=1.6 for zones 1 to 3, and q=2 for zone 5. However, q=0.06 for zone 4 in order for the standard equations to reflect the winding temperatures given in Figure 4 and observed under test conditions.

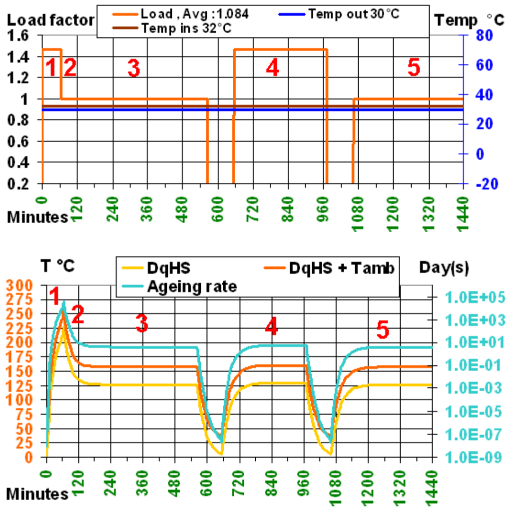
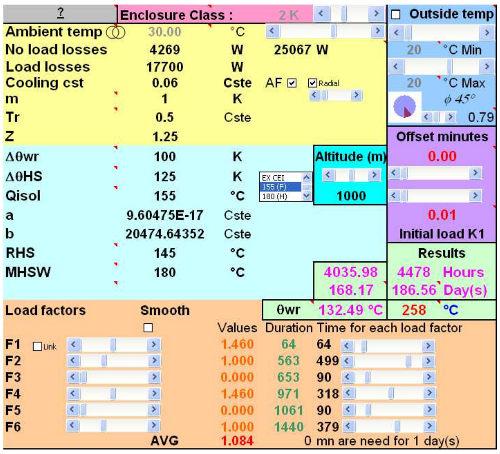


Figure 5: IEC 60076-12 loading guide simulation with test input data

Transformer ageing

Ageing rates are calculated using a tool similar to the one developed as per IEC 60076-7 [1] [2], but adapted to the later standard IEC 60076-12, the interface of which is shown in Figure 6.



? Enclosure Class : 2 K

☐ Outside temp

Ambient temp 30.00 °C

No load losses 4269 W 25067 W

Load losses 17700 W

Cooling cst 0.06 Cste AF ☑ ☑ Radial

m 1 K

Tr 0.5 Cste

Z 1.25

20 °C Min

20 °C Max

ϕ 45° 0.79

Offset minutes 0.00

Δθwr 100 K

ΔθHS 125 K

Qisol 155 °C

EX CEI / 155 (F) / 180 (H)

Altitude (m) 1000

a 9.60475E-17 Cste

b 20474.64352 Cste

0.01 Initial load K1

RHS 145 °C

MHSW 180 °C

Results

4035.98 168.17

4478 Hours 186.56 Day(s)

θwr 132.49 °C 258 °C

Load factors Smooth ☐

	Values	Duration	Time for each load factor
F1 ☐ Link	1.460	64	64
F2	1.000	563	499
F3	0.000	653	90
F4	1.460	971	318
F5	0.000	1061	90
F6	1.000	1440	379
AVG	1.084		0 mn are need for 1 day(s)

Figure 6: Dynamic simulation interfaces as per standard IEC 60076-12.

For a more detailed view of equivalent ageing phenomena in the test, Figure 7 illustrates the impact of temperature variations on ageing, even for an average temperature of 20°C, a load of 1 and in AF cooling mode. Reminder: the ageing rate is doubled or halved every 6 K, depending on whether the temperature change is positive or negative.

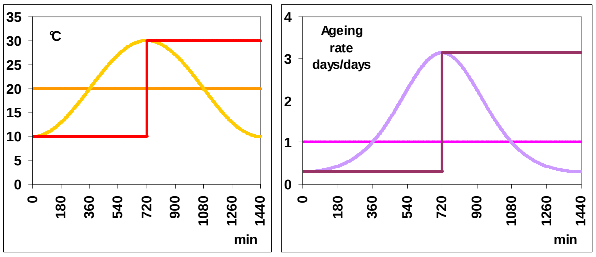


Figure 7: Impact of temperature variation on ageing for a dry-type transformer

Figure 8 is a temperature/load graph under constant ageing conditions for the transformer alone for each insulation system temperature.

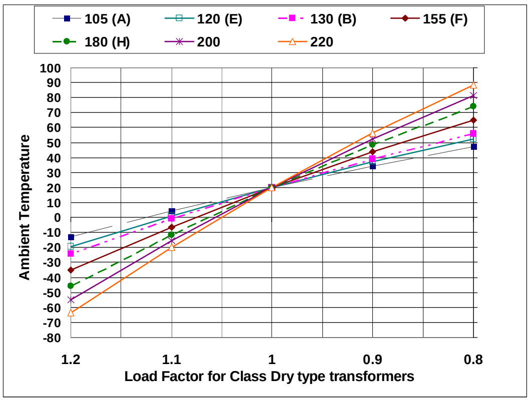


Figure 8: Load factor = f (Amb Temp)

Figure 9 shows the impact of the enclosure and its temperature rise class as per standard IEC 60076-202 in AN ventilation mode, for a transformer with a 155°C insulation system.

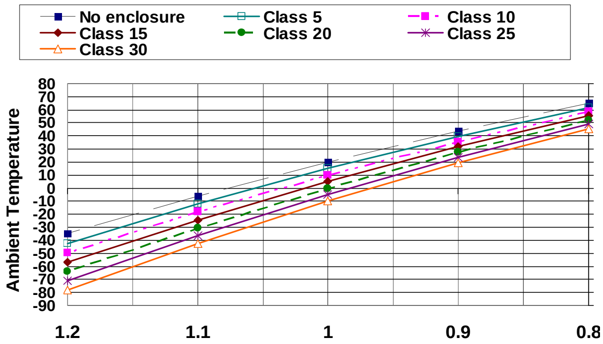


Figure 9: Enclosure classes
Load factor = f (Amb Temp, Enclosure class)

Optimisation of the “Shore Connection” substation by CFD simulation

After the thermal design of each equipment item had been completed, the purpose of 3D thermal simulations was to guide and validate the design of the substation in order to obtain the most effective cooling system under maximum stress conditions. In view of the loss values (48 kW) of each transformer room and the air flow rates required to ensure optimum cooling (7,500 m3/h), a detailed flow study was required. This was done using the ANSYS Icepak CFD code.

This article only addresses the transformer compartment, but the methodology was the same for the entire substation. The study was carried out in three stages:
- Transformer modelling,
- Integration of the transformer into the substation under normal operating conditions,
- Assessment of performance in degraded mode.

Transformer modelling

The first stage of the study involved building a model of the transformer representing its thermal performance in AN ventilation mode at In and in AF mode at 1.5 In. The main difficulties were: characterising the thermo-physical properties of materials like resin; simplifying the geometry; and meshing. Owing to meshing and convergence problems, not all the details of the transformer could be fully represented in thermofluid simulation. For this reason, it was essential to represent the geometry as simply as possible, while maintaining the real air flow characteristics. The model is shown in Figure 10.

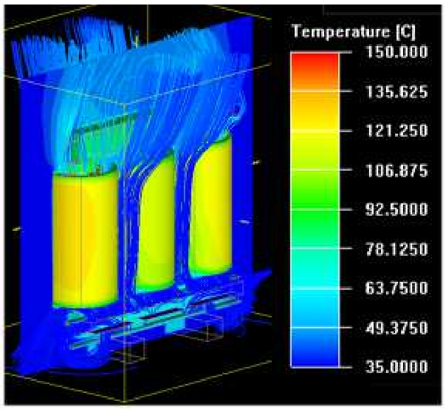


Figure 10: Transformer model

The extreme temperatures observed are close to those revealed in the first part of the paper.

Integration into the substation

The second stage entailed ensuring maximum components cooling, especially for transformers; optimising the position and number of extractor fans; and optimising the position of air inlets and the number and type of filters suited to service conditions, without affecting the protection rating required for the substation enclosure. Several simulations had to be carried out to achieve this.

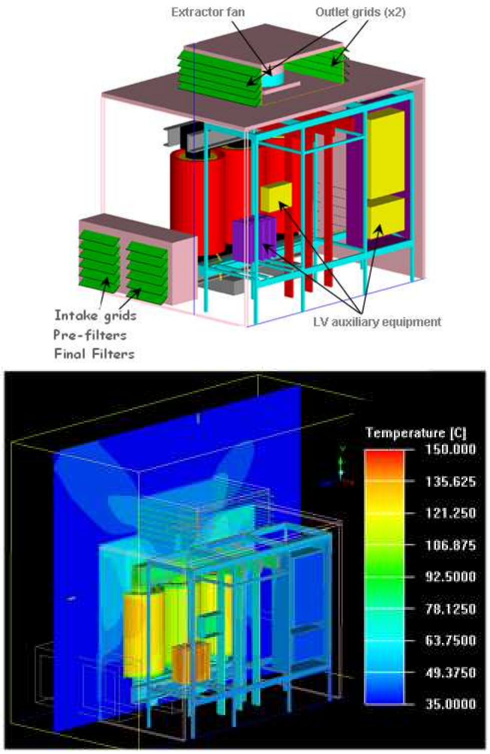


Figure 11: Transformer compartment model

The final design showed that installing the transformer inside the substation led to a temperature rise of 3 to 5 K in the transformer under extreme temperature conditions, with soiled filters and at nominal power. Specifications for equipment located close to the transformer were improved based on temperature results.

Operation in degraded mode

The third stage was aimed at assessing overall performance in the event of failure on a cooling system component. The entire system for the “Shore Connection” application was designed making sure that the power supply remains available throughout the installation’s lifespan. The use of a forced air cooling system, however, can reduce availability compared with a passive natural ventilation system. This aspect was therefore investigated in detail.

The extraction fan, of course, is crucial and not redundant. For this reason, communicating brushless motors were used. These fans have a maximum lifespan and can anticipate any failure.
Our simulation focused on the impact of a failure on a radial fan manifold located under the windings (Figure 1), on transformer temperature rise.

CONCLUSION

The results for this “Shore Connection” application are satisfactory given the stringent requirements and service and integration conditions that the electrical equipment must meet, without degrading the rated characteristics and lifespan of the installation. The results also show that the installation is capable of providing 95% nominal power output under extreme conditions in degraded mode. This mode is reached with soiled filters and maximum temperature and load factor conditions. It entails guaranteeing continuity of service pending maintenance.

As is frequently the case, such results were made possible by combining tests and numerical simulations.

All these data will be vital for any subsequent optimisation required to meet new customer requirements under different service conditions.

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