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PS2 Beyond the mineral oil-immersed transformers and reactors

Beyond the top oil temperature limit

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SUMMARY

The ability to operate transformers at high temperature bring substantial advantages to power grids with a high share of renewables or that need to handle contingencies. Insulation systems based on ester liquids allow high temperature operation, but so far research and development efforts into thermal limits has been largely focused on the winding insulation. This paper addresses additional aspects of the top liquid temperature limit by considering the related thermal limits for core steel and for transformer accessories. A review is made of standard temperature limits. Experiments on hydrogen gas generation from core steel are performed by placing a core steel bundle in an ageing vessel at a fixed temperature for several days and measuring the dissolved gas for both mineral oil and a natural ester. The results show that the onset of hydrogen gas generation from core steel in ester liquids occur at similar temperature as mineral oil, with the implication that the same core steel temperature limits must be applied. Bushing and tap-changers procured according to existing standards are constrained by the temperature of the immersion media, but through the choice of design solution this can be kept lower than the top liquid.

KEYWORDS

ester-filled transformers, high-temperature transformers, core gassing, bushings, tap-changers

1 BACKGROUND

Power grids with a high share of renewable power generation increases the variability of loading and make it advantageous to design compact transformers that can withstand occasional high temperature spikes. The ability to safely load transformers to elevated temperatures also benefits contingency planning and capacity increase of existing infrastructure. Operating standard transformers continuously or for a prolonged time at overload and increased temperature leads to higher losses and faster degradation of insulation material, so it will mainly be used for short duration contingencies. New designs and applications are being developed and built to fit grid dynamic loading profiles.

The appropriate maximum permissible temperature limits for high temperature operation are the long-term emergency limits from loading guides such as IEC 60076-7 [1], which are set to ensure safe continuous operation for the price of accelerated ageing. With ester liquids the flash point is higher, and permissible temperature can be increased compared to mineral oil.

Research on permissible temperature limits for esters have largely been focused on the cellulose insulation material, considering the winding hotspot temperature as the main limitation. If aramid insulation is used, then the top liquid temperature instead becomes the limiting factor. In this paper, the implications of increased top liquid temperature limit in an ester-immersed power transformer are investigated.

2 CORE

2.1 Standard temperature limits

The transformer core temperature is determined by the thermal balance between heating by magnetic losses and cooling by the surrounding liquid. It is therefore possible to reduce the core temperature by enhancing the cooling, for example by incorporating cooling ducts within the core. It is also possible to modify the core geometry and materials to reduce magnetic losses [2]. However, even at the limit of negligible magnetic losses, the temperature of the surrounding liquid will constrain how low the core temperature can be reduced. The core extends to the top of the transformer tank, so that the upper part of the core under steady state conditions will have at least the same temperature as the top liquid.

The IEC 60076-7 loading guide [1] distinguishes between two different limitations of transformer core temperature based on hotspot on the surface and hotspot in the interior. The limits are presented in Table 1, also including top liquid temperature limit for ester liquids from the IEC 60076-14 standard on high-temperature insulation materials [3].

Table 1: Core temperature limits

	Normal cyclic loading	Long-time emergency loading	Short-time emergency loading
metallic parts in contact with insulation liquid	140 °C	160 °C	180 °C
inner core hotspot temperature	130 °C	140 °C	160 °C
top liquid temperature (mineral oil)	105 °C	115 °C	115 °C
top liquid temperature (ester liquid)	130 °C	140 °C	140 °C

From Table 1 can be made two observations. First, that the standard would allow higher temperatures on the core surface than the core interior. However, the temperature distribution in the core has to be continuous. This means that the tabulated surface temperature limit becomes superfluous, and that the interior hotspot temperature limit must be interpreted as the actual surface temperature limit. Second, the top liquid temperature limit for ester liquids is the same as the limit for the inner core hotspot. For steady state this would only be feasible if the magnetic losses are negligible and do not heat the core beyond the surrounding liquid. A dynamic thermal phenomenon of short duration compared to the time constant of the core could conceivably also allow the liquid temperature to reach its maximum value without exceeding the inner core hotspot temperature for non-negligible magnetic losses. A realistic value for the steady state value of inner core hotspot at 100% rated induction is 15 K above the top liquid temperature [4]. Keeping the same inner core hotspot temperature limit for ester liquids as for mineral oil would then require reducing the top liquid temperature limit by the corresponding value.

The core temperature limit is attributed to the generation of hydrogen and methane from the thin oil film between core laminations. The mechanism was demonstrated in laboratory tests where core bundles consisting of about 200 pieces of individually cut pieces of core steel were placed in an oil-filled stainless-steel vessel and heated to various temperatures in the range of 100-200 °C [5]. No hydrogen generation was detected below 130 °C. Tests were performed with both a gas absorbing oil (Exxon Univolt) and a gas evolving oil (Shell Diala A) without conclusive evidence of any difference in hydrogen generation level. Although hydrogen gas accumulation in itself is not considered to pose any risk, the hydrogen generation from the transformer core could mask other gassing problems such as partial discharges [6]. The 130 °C limit for core hot spot temperature was therefore recommended.

An older study performed at Mitsubishi Electric had not found any marked effect of different type of transformer oil [7]. This study did not include ester liquids. Since one of the advantages of ester liquids is the ability to increase the operating temperature, this has been considered a knowledge gap.

2.2 Gas generation in ester liquids

A lab study has been undertaken to investigate generation of hydrogen from core steel submerged in a stabilized high-oleic natural ester dielectric liquid (BIOTEMP). For comparison, the corresponding gas generation in a mineral oil (Hyvolt II NG) was also investigated.

The tank preparation and procedure were as follows: A core steel bundle of 10×5×5 cm outer dimensions consisting of about 180 core steel laminates was placed inside a sample tank (see Figure 1) which is sealed tight. A second reservoir tank is filled with about 1700 ml of liquid and also sealed tight. The liquid is slowly transferred from the reservoir tank to the sample tank using a vacuum pump (see Figure 2). The flow rate is approximately 10 ml per minute. The remaining volume of the sample tank is filled with nitrogen. The sample tank is then placed in an oven at the appropriate temperature and kept there for the duration of the test period. A 50 ml liquid sample is taken from the tank each day, and dissolved gas analysis (DGA) is performed using gas chromatography according to the ASTM standard [8]. The total gas is estimated as

$$\text{Total gas} = \text{Gas in oil} \times \left(1 + \frac{1}{K_i}\frac{V_g}{V_\ell}\right) \tag{1}$$

where V_g/V_ℓ is the gas space to oil volume ratio and K_i is the Ostwald solubility coefficient. The change in volume due to thermal expansion at each temperature level and due to oil volume reduction after each sampling had to be taken into account.

Control samples without the core steel bundle were also tested, and the net gas generation was obtained by subtracting the hydrogen concentration in the control sample from that of the corresponding sample with core steel. The results are tabulated in Table 2.

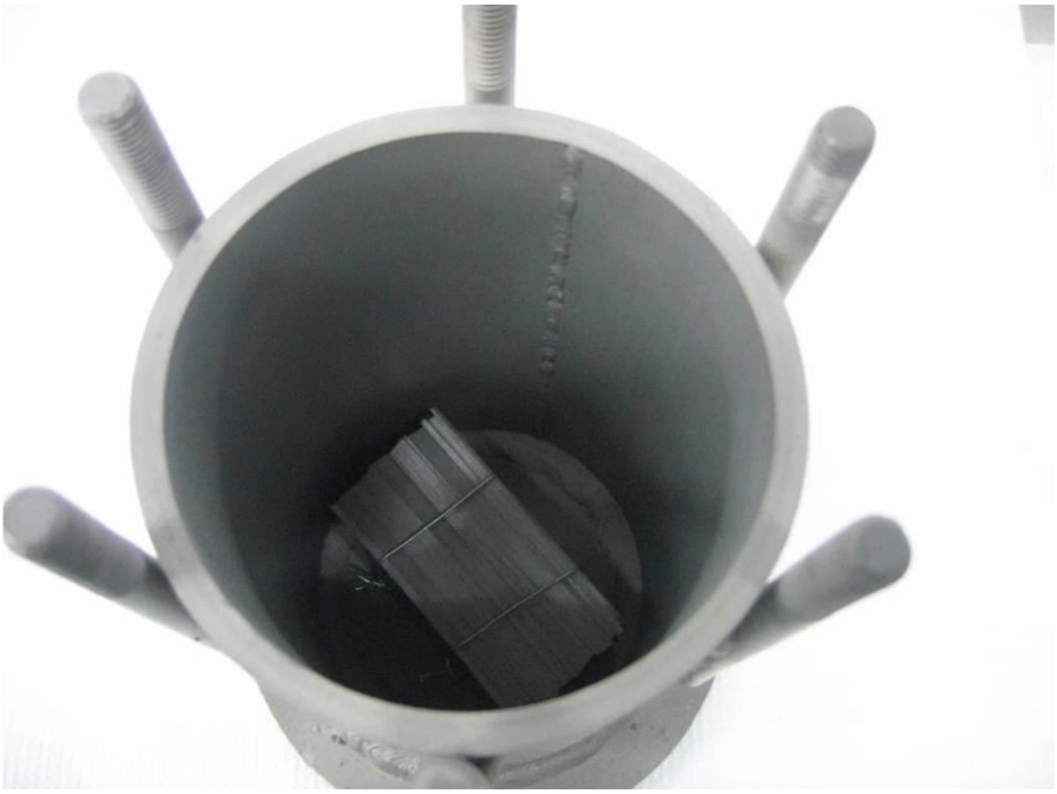

Figure 1 Sample tank with core steel bundle inside.

Figure 2 Liquid filling of the sample tank from a reservoir tank using a vacuum pump.

Table 2 Net hydrogen gas generation (ppm)

	mineral oil			natural ester		
	140 °C	**160 °C**	**180 °C**	**140 °C**	**160 °C**	**180 °C**
Day 1	57	194	460	49	106	93
Day 2	89	194	598	62	101	138
Day 3	110	374	1152	80	292	775
Day 4	142	448	907	98	345	913
Day 5	195	514	693	103	455	921

In the previous lab experiment [5] was noted a levelling off effect of the hydrogen gas level over time. The hypothesised reason for this was that surface activation sites would become engaged as time passed by with loosely attached hydrogen not releasing as hydrogen gas into the oil. The same levelling off effect was seen in the present experiment.

Curves are fitted to the data using a flexible ruler and plotted with hydrogen concentration as a function of time for different temperature levels (see Figure 3) and as a function of temperature for different time periods (see Figure 4). The temperature effect is virtually linear instead of an Arrhenius type exponential rise because of the levelling off effect noted.

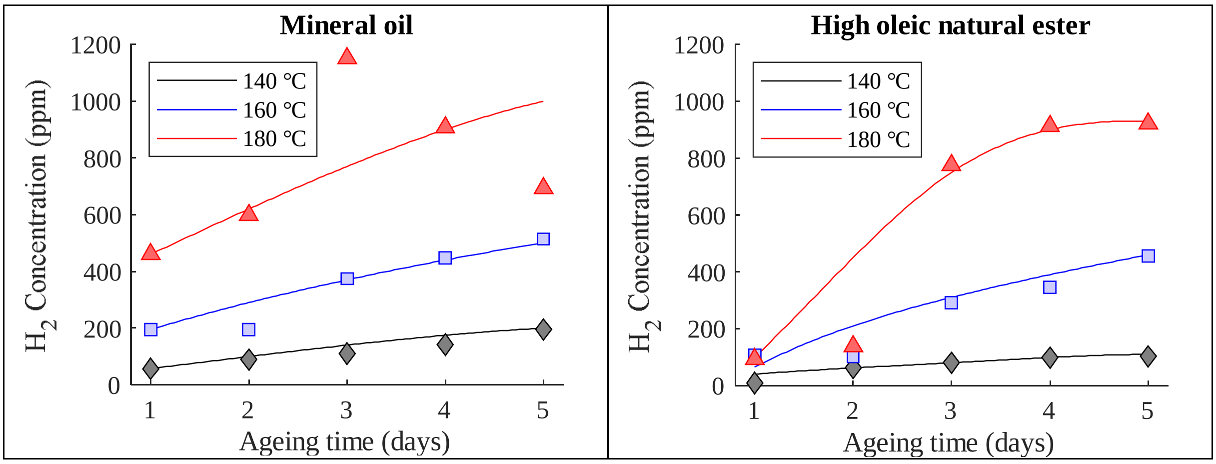

Figure 3 Core gassing as a function of time

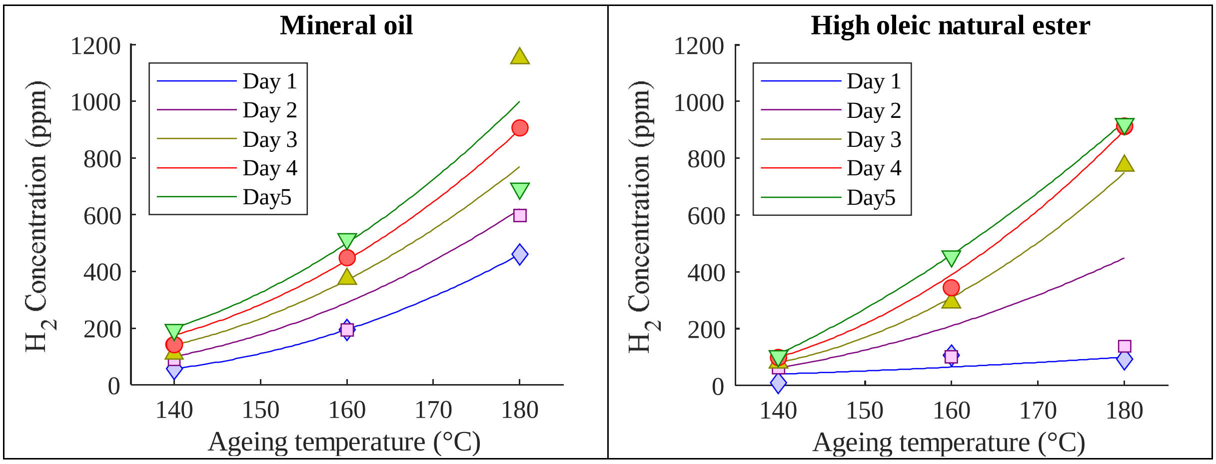

Figure 4 Core gassing as a function of temperature

Although the experiment indicates lower initial hydrogen gas generation from the natural ester compared to the mineral oil, over the longer time period they seem to reach similar values. There is already onset of hydrogen gas generation at 140 °C, indicating that the same top oil temperature limit valid for the core hotspot in mineral oil would also need to be considered for ester liquids.

It may be noted that there is uncertainty to the results of this study; e.g. hydrogen was detected in the mineral oil control samples at fairly high levels day 5 at 160 ^{o}C and at 180 ^{o}C, but none at the lower temperatures and day 1 – 4 at 160 ^{o}C. Also, Ostwald coefficients used for calculation of total gas levels at the studied temperatures were found through extrapolation of curves made from coefficients at lower temperatures and may not be accurate.

3 TRANSFORMER ACCESSORIES

Elevated top liquid temperature will also affect the transformer accessories. The temperature limits for bushings are governed by IEC 60137 [9] and for tap-changers by IEC 60214 [10]. The limits are summarized in Table 3.

Table 3 Temperature limits for transformer accessories and their immersion media

	Bushing (normal loading)	Bushing (overload)	Tap-changer (normal loading)	Tap-changer (overload)
Liquid maximum temperature (daily average)	90 °C	90 °C	n/a	n/a
Liquid maximum temperature (any time)	105 °C	115 °C	105 °C	115 °C
Metal in contact with oil-impregnated paper	105 °C	see text	n/a	n/a
Metal in contact with resin-impregnated paper	120 °C	see text	n/a	n/a

For application of bushings in ester-immersed transformers with increased top-liquid temperature limits, a first condition for the bushings is to be qualified for ester liquids. The application in an alternative insulation liquid can affect both the dielectric-insulation and the thermal performance of the bushing. Thus, the qualification procedure has to include a confirmation of this performance by an appropriate standardized type test for the main styles of bushings to be applied. The second condition is to ensure that the liquid in the vicinity of the bushing installed on the transformer does not exceed the maximum temperature values confirmed for operation by the type test.

The main standard requirements for thermal operation of bushings listed in Table 3 are as defined in bushing standards and there is some discrepancy with respect to the transformer standards. In particular, the bushing standard limits the daily average of the liquid temperature to 90 °C, also in overload condition, while the transformer standard, [1], allows for top liquid at 105 °C in normal cyclic loading, which means that that temperature may persist even for several days. Moreover, the IEC bushing standard advises to rate bushings at only 120% of the rated current of the transformer, which should be enough to withstand all standardized overload situations. The transformer standard [1] defines the maximum long-time emergency loading current at 130%, 150% of the transformer rated current, depending on the transformer size.

Such application has been confirmed in practice for both oil-impregnated-paper (OIP) and dry resin-impregnated-paper (RIP) bushings. For OIP, this is assured by the fact that the maximum temperature of 105°C for OIP material in contact with oil is a limit for long-term application and temperatures above that limit are allowed for short term. Detailed procedures of how to analyse influences of such increased temperatures on paper aging are described in IEEE standards [11]. For the dry bushings, the allowed temporary exceeding of the maximum insulating material limit is mainly related to the glass transition temperature of the material, which is significantly higher than the maximum continuous operation temperature of 120°C, listed in Table 3.

When the top-oil temperature of the transformer exceeds that allowed for the bushing operation, a possible way to ensure the bushing not to face this high temperature is to install it in a chimney separated from the transformer tank. The connection of the chimney to the transformer tank has to be at a lower position, where the oil temperature is sufficiently lower compared to that of the top-oil value. A numerical simulation is needed to confirm that condition. The main routes of heat transfer influencing the temperature in the chimney, which have to be included in the simulation, are shown in Figure 4. An example result of such a simulation applied to a bushing in a cable connection of a synthetic-ester-filled transformer is also shown in Figure 4.

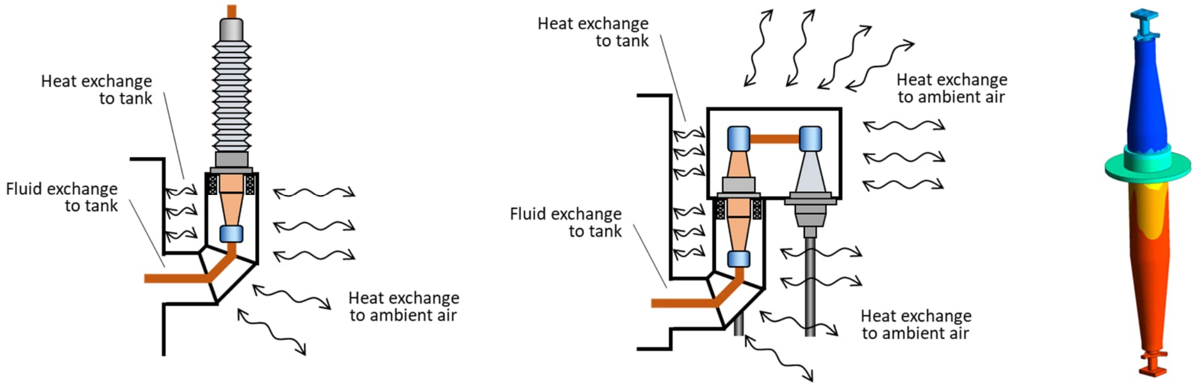

Figure 4 Examples of bushing application for transformer exceeding the standard top-liquid temperature limits. Left and middle: a bushing for an overhead connection and a bushing for a cable connection with a cable box, both with marked main routes of heat exchange defining the oil temperatures in the vicinity of the bushing. Right: example of a result of a numerical simulation to validate application of the bushing.

Similar to the bushing, the tap changer is required to be able to operate in surrounding oil up to 105°C during normal operation and up to 115°C during overload conditions corresponding to the top oil temperature of a mineral oil filled transformer in IEC 60076-7 [1]. These are also the typical limits that one finds in product catalogues from tap changer suppliers. Going beyond 105°C top oil temperature during normal operations requires a tap changer designed especially for this purpose or a tap changer placed in a location where it is not in contact with the top oil.

4 CONCLUSION

The transformer core and the transformer accessories impose thermal limits that are stricter than the top liquid temperature limit allowed by the high-temperature operation for ester-filled transformers. These limitations can be overcome but require changes in the standard. Furthermore, there are contradictions regarding overloading in the standards that need to be addressed. The considerations described in this paper will support the work going forward to define appropriate top liquid temperature limits that can ensure reliable operation of transformers with the new requirements set by the power grids of the future

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