COOLING TECHNOLOGY OF SF_6 GAS INSULATED HIGH VOLTAGE POWER TRANSFORMERS

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ABSTRACT

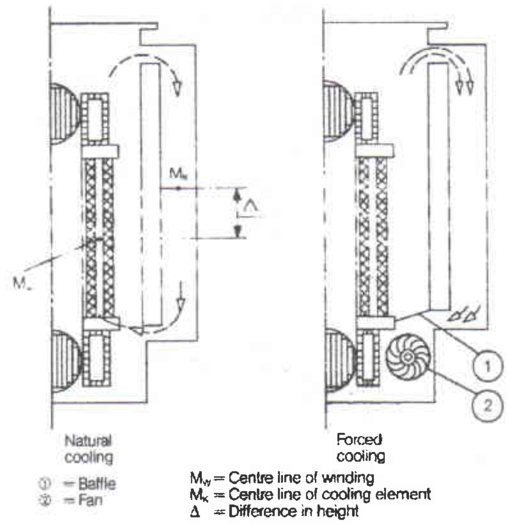
When installing transformers, protection of the environment, operational reliability, maintenance and fire risks are important considerations. This applies in particular to distribution transformers up to 2500 kVA which are often installed close to load centers. Therefore, for such applications the gas insulated power transformers especially come much more to the fore. In this paper, the important cooling principles of gas insulated transformers and their effects on loading capability and winding design are discussed.

1. INTRODUCTION

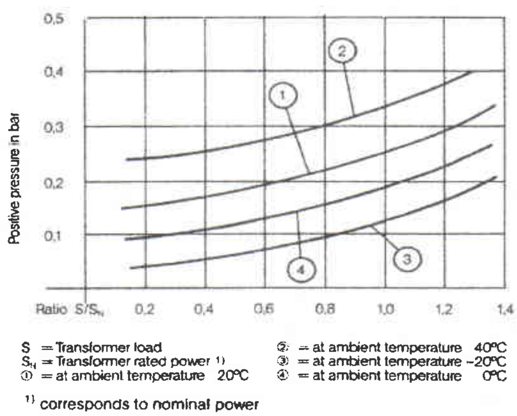
For reasons of economy, transformers, especially in systems with a large number of substantial consumers, are preferably installed as close as possible to the point where the energy is required. This can be in production plants, close to particularly energy intensive machinery, or at strategic points in high-rise blocks of flats or offices. Certain applications require the installation of transformers in hazardous areas, in locations with unusual climatic conditions, or with an increased risk of fire, or in water preservation areas. In such cases, the conventional transformer often proves to be inadequate [1, 2, 3].

2. THE PRINCIPLE OF GAS INSULATED TRANSFORMERS

Up to a rated power of approximately 2500 kVA, the cooling of windings and core is effected by natural gas circulation. The driving force results from the difference in weight between the hot gas column in the cooling ducts of the windings and the cold gas column in the cooling elements (Fig.1). The convection current is intensified by arranging the cooling elements higher than the windings. For technical and economical reasons, fans to boost the internal gas circulation are used only for ratings above 2500 kVA (Fig.1). The difference in height between windings and cooling elements has no effect on this cooling method. In service, gas pressure rises depending on the losses generated, i.e. the temperature rise of the gas. The maximum positive pressure at any permissible operating condition is 0.4 bar. Fig.2 shows internal positive pressure as a function of transformer load at different ambient temperatures.

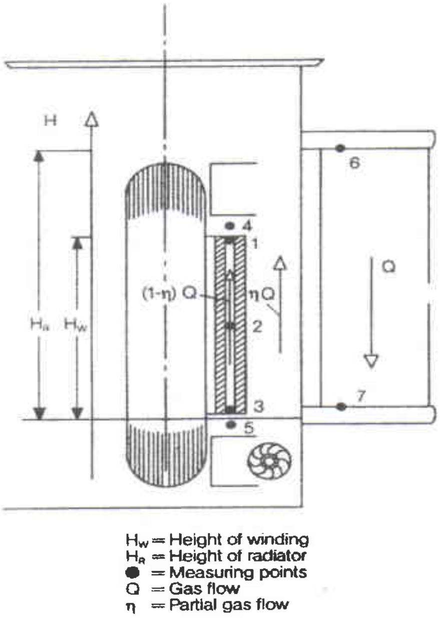


Figur.1: Gas flow in the transformer

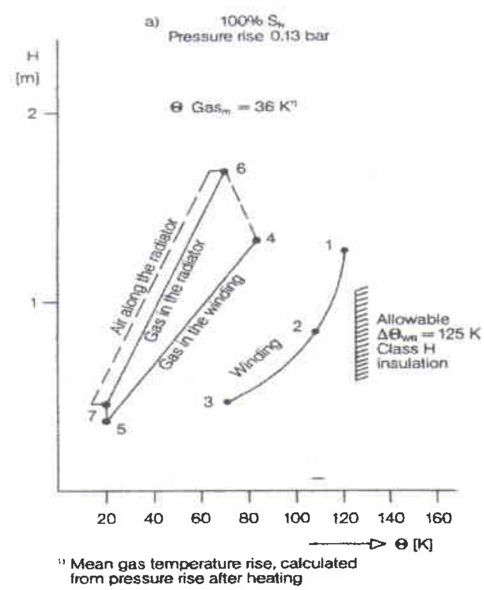


Figur.2: Positive gas pressure in the transformer

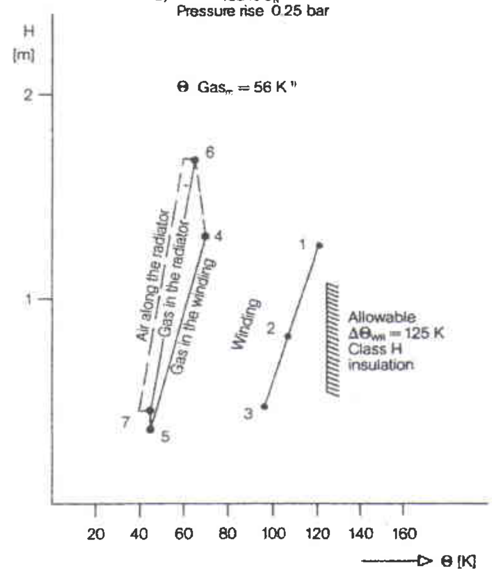
It is pointed out that even at low temperatures and with the transformer switched off, no negative pressure occurs in the transformer. This is important to know for any leakproofness tests. It is interesting to note that raising the gas pressure in such a transformer would lead to improved internal cooling and better insulating properties of the gas. However, this would require a pressure-resistant, i.e. expensive tank, the design and construction of which would have to be in compliance with the regulations for pressure vessels. For the ratings discussed here it is more economical to design the active part and the cooling surfaces large enough to retain the „pressureless" transformer, at least for the time being [3].



Figur.3: Temperature distribution in an SF_6-insulated transformer.



Figur.3a: Natural cooling



Figur.3b: Forced cooling

2.1 The Cooling System of SF6-Insulated Transformers

Fig.3 shows the temperature distribution in an experimental transformer which was operated both with natural (a) and forced (b) cooling.

Temperatures were measured at the following points:

1-2-3 Low voltage (l.v.) winding top (hot spot), middle, bottom

4-5 Gas flow at the upper and lower clamping structure of the windings

6-7 Gas flow into and out of the radiator-like cooling elements.

At points 5 and 7, almost identical temperatures were measured. Since they are also at almost the same height, they were combined into one point for the evaluation. Due to the temperature rise in operation there was also a slight rise in pressure, see Fig.2. This pressure rise is used to calculate the mean gas temperature in the tank. In accordance with the equation, generally applied to gases, p Vol = nRT, the pressure is proportional to the absolute gas temperature, assuming constant tank volume [4].

$$\frac{T_m}{T_{env}} = \frac{273 + \Theta_m + \Theta_{env}}{273 + \Theta_{env}} = \frac{P_{warm}}{P_{fill}} \qquad (4)$$

Θ_m = mean gas temperature rise over Θ_{env} (ambient).
T_m = mean gas temperature [K] .

Conspicuous is the strong slope and the convex shape of the temperature curves in Fig.3a. This is the result of the small convection forces, due to the difference in weight between the hot gas in the windings and the cold gas in the radiator (heat exchanger). The high temperature rise of the winding over the cooling medium is also observed in air-cooled dry-type transformers. The latter have an open cooling system with an unhindered flow of fresh air. The SF6 cooling system is a closed system which makes the description of the gas circulation much easier. The markedly higher winding temperatures, compared with liquid-insulated or cast-resin transformers, are permissible in view of the insulation system chosen and have no adverse effect [5, 6].

3. NATURAL GAS CIRCULATION

For this cooling method, no guide baffles were installed in the experimental transformer. Thus, the gas flow in the transformers is divided into two partial flows: (1- η) Q flows through the cooling ducts of the windings, taking up the largest part of the loss heat; part of ηQ flows past the windings, carrying off the heat radiated by the outer winding surfaces. The two partial flows unite in the top part of the tank, so that at the radiator entry the temperature rise (Θ_6) is lower than at the top of the winding (Θ_4). In the radiator, direction of the gas flow Q is downwards, transferring heat to the external air cooling circuit. The pressure difference needed for circulating the gas is calculated from the mean differences in weight of the gas in the radiator and in the transformer.

$$\Delta p = \{ \frac{\gamma_5+\gamma_6}{2} \} H_R g - \{ \frac{\gamma_5+\gamma_4}{2} H_W + \frac{\gamma_4+\gamma_6}{2} (H_R - H_W)\} g = g \frac{\gamma_5-\gamma_6}{2} - \{ \frac{\gamma_5-\gamma_4}{\gamma_5-\gamma_6} H_R - H_W \} \quad (5)$$

γ = Density [kg/m^3] ; H_R = Height of radiator [m]; H_W = Height of winding [m]; g = Acceleration of gravity [m/s^2].

For a precise determination of the convection forces, the weights of the partial flows should be known. These cannot be measured because the gas flows mix. Equ.5 is thus only an approximation for determining the convection force. Local gas densities $\gamma_{(T1)}$ are calculated from the mean gas density γ_m and the coefficient of expansion $\beta = 1/T_m$ (T_m to Equ.4).

$$\gamma_{(Ti)} = \gamma_m \ . \ (T_m / T_i) \quad (6)$$

$\gamma_m = (293 / T_m) \ . \ 6{,}07$ kg/m^3 ; $T_i = 273 + \Theta_{env} + \Theta_i$

Based on the measured values as per Fig.3a, a pressure difference $\Delta p < 10$ N/m^2 is obtained.

This upward force serves to overcome friction resistance in the cooling ducts:

$$\Delta p = const. Q^{æ} \quad (7)$$

æ = 1 for laminar flow ; æ = 2 for turbulent flow

If heat is introduced into a gas flow, there is a temperature gradient alongside the flow:

$$\Delta\Theta = \frac{P_v}{(\gamma c_p)_o . Q . P} \quad (8)$$

P_v = Loss heat [W]; $(\gamma_{c\,p})_0$ = Heat capacity [kg/ms^2 K]
Q = Gas flow [m^3/s]; P = Gas pressure [bar].

The temperature rise in the gas can be reduced if the pressure is increased. As, however, the quantity of the gas flow is also reduced under higher pressure, the effect of pressure on temperature rise is diminished.

In order to determine the effect of pressure, the convection force to Equ.5 is considered. Basically, only the difference in density $\gamma_5 - \gamma_6$ changes as a function of the gas pressure ($T_5 - T_6 \approx T_m^2$):

$$\Delta p \approx (\gamma_5 - \gamma_6) = \gamma_m T_m (\frac{1}{T_5} - \frac{1}{T_6}) \approx \frac{\gamma_m}{T_m}$$

$$(T_6 - T_5) = \frac{\gamma_m}{T_m} (\Theta_6 - \Theta_5) \sim \frac{1}{Q.P} \quad (9)$$

Using equations (7) and (8), the effect of the gas pressure is:

$$Q \sim P^{\frac{1}{1+ae}} \text{ and } \Delta\Theta \sim P^{-\frac{ae}{1+ae}} \quad (10)$$

In a series of experiments, temperature rise measurements at filling pressures between 1 and 2 bar were carried out in a pressure-resistant transformer tank. The measurements confirmed the relations of Equ.10, assuming laminar flow (æ $= 1 \rightarrow \Theta \sim P^{-0.5}$).

Estimating the flow velocity $v_w = Q/A_w$ in the winding from the temperature difference $\Theta_4 - \Theta_5$ in accordance with Equ.8, results in a velocity $v_w \approx 0.25$ m/s (A = Flow area [m^2]).

Thus, the Reynolds number

$$Re = \frac{v_W . D_H}{v_{SF6}} = 1350 \quad \text{is in the laminar range.}$$

D_H = Hydraulic diameter of duct [m]; w = Winding.

3.1 Winding Temperature Rise With Natural Gas Circulation

The temperature rise in the winding is calculated from the heat flow density and the coefficient of convection

$$\Theta_W = \omega / \alpha \quad \text{where } \alpha = Nu \frac{\lambda}{l} \qquad (11)$$

ω = Heat flow density [W/m^2]; α = Coefficient of convection [W/m^{2}K]; Nu = Nusselt number ; λ = Heat conductivity [W/mK].

l is a length, characteristical for this type of flow. The heat transfer capacity has to be related to a boundary layer temperature of 130^{0}C, since heat transfer occurs mainly in the boundary layers on the winding surface (λ = 0.021 W/mK). There are two partial gas flows around the windings. The external surfaces are cooled by a non-guided gas flow so that the laws of free convection can be applied.

$$Nu = 0,726\,(Gr.Pr.)^{0.25} \;;\; \alpha = 3,1\{\Theta/K\}^{0,25}\{H_W/m\}^{0,25}$$

$$l = H_W \qquad ;\; \Theta_W \sim \{\,\omega\, H_W^{0,25}\,\}^{0,8} \qquad (12)$$

For the experimental transformer to Fig.3a, α is found to be 10 W/m^2 K and $\Theta_w \approx$ 80 K. This is the approximate winding temperature rise over the mean gas temperature. The internal winding surfaces are cooled by a guided flow in the cooling ducts. The theoretical considerations lead to the conclusion that there is an axial temperature gradient along the duct axis, and a radial temperature gradient from the duct axis to the heated duct wall. The axial gradient can be taken to be equal to the gas temperature rise to Equ. 8. The radial temperature gradient is the temperature difference between the temperature of winding and cooling medium, which, in Fig.3a, is approx. 50K. The Siedler &Tate Law,

$$Nu = 1,86\,\{\,Re\ Pr\ \frac{D_H}{H_W}\,\}^{0,33} \qquad (13)$$

Re = Reynolds number ; Pr = Prandtl number
results in considerably higher winding temperature rises, so it cannot be directly applied to the design of gas-insulated transformers.

4. WINDINGS

The design of the windings is determined mainly by the allowable heat flow densities and the required freedom from partial discharges. This results in comparatively long windings with wide cooling ducts. The type of winding depends on the transformer power and the rated design voltage. For medium ratings, low voltage windings are wound from copper sheet with insulating layers of epoxy resin impregnated glass fabric. After curing, the windings form a solid block which has an excellent short-circuit strength. For lower winding currents, layer windings are used. These are wound from copper strip, insulated with high-temperature-resistant synthetic fibers, e.g. Aramid paper. This material has a high dielectric and mechanical strength, suitable for the temperatures permissible for Class H insulation. Even at these comparatively high temperatures, aging is normal; it is accelerated only at temperatures which are well above those occurring in a gas-insulated transformer. For the conductor insulation, consisting of several layers, paper with a high tensile and tearing strength is used, whereas for layer insulation or bandages, a more ductile quality is preferred. For small and medium ratings, wire-wound coil windings are used. The insulation consists of either Aramid paper or impregnated glass silk fabric. Between the coils, specially shaped spacers are used which contribute to the high dielectric strength of the main insulation in SF6. Larger ratings with low rated voltage are designed with strip-wound layer windings, whereas strip-wound double coils, so-called continuous disk coils, are used for transformers with high ratings and high voltages.

5. OPERATIONAL DATA

At rated load, i.e. full load, and max. design ambient temperature of 40^{0}C, the following data are obtained with a representative gas-insulated transformer:

Gas pressure	1.34 bar
Max. gas temp. (in the winding cooling ducts)	125^{0}C
Max. winding temp.	160^{0}C

The gas temperature below the cover and in the cooling elements is approx. 10 to 15^{0}C lower than that in the winding cooling ducts. The lowest gas pressure that can occur, with the transformer deenergized, and at -25^{0}C ambient, is 1.02 bar.

5.1 Loading Capability

In view of standards, e.g. IEC, gas-insulated transformers are treated as dry-type transformers. This is justified since the gas, contrary to liquids, does not impose any additional temperature limit. The relevant loading guide for dry-type transformers states allowable temperature limits for different insulation systems. It is, therefore, the transformer manufacturer's task, to select the insulation materials in accordance with the temperature class. At an ambient temperature of 20^{0}C, the hot-spot temperature can be constantly 175^{0}C without affecting the service life of the transformer, which is expected to be several decades. The table states a max. allowable hot-spot temperature of 220^{0}C for short overload periods. However, although the range between 175 and 220^{0}C is available for load cycles and overload operation, this leads to an accelerated use of life, so that temperatures above 175^{0}C are allowable only for short periods. Since the mean winding temperature, measured by the resistance method, is closely related to the hot-spot temperature (which cannot be measured on a completed transformer), the allowable mean winding temperature rise of 125 K must not be exceeded. Assuming an average annual ambient temperature of 20^{0}C, the annual average winding temperature is 145^{0}C at rated load. The allowable limit values, Table.1, of 175°C for the hotspot (at 20°C ambient), and 125 K for the winding temperature rise are not exceeded, provided they are operated at rated load.

Table:1 Temperature limits for insulation systems in dry-type and gas-insulated transformers.

Insulation system temperature (IEC-726)	Winding hot-spot temperature in °C		Allowable mean winding temperature rise at rated current
	Rated	Max	
°C	Θ_C	Θ_{CC}	$\Delta\ \Theta_{WR}$
105 (A)	95	140	60
120 (E)	110	155	75
130 (B)	120	165	80
155 (F)	145	190	100
180 (H)	175	220	125
220 (C)	210	250	150

It is the user's responsibility to ensure that, under an occasional overload, the allowable hotspot temperature of 220°C is not exceeded. As this cannot be measured, the guideline is that there is no danger for the insulation when, at 20°C ambient, overloading is limited to 1.2 times rated load. Use of life is, however, slightly accelerated under such conditions. Data on emergency operation - which always results in overconsumption of life - are available, on request, although this is unusual and normally not required for the transformer ratings under discussion. Load cycles should preferably be kept below the limit beyond which use of life is accelerated. Permissible periods for load cycles above rated load vary with ambient temperature, preload of the transformer and the intended overload.

6. CONCLUSIONS

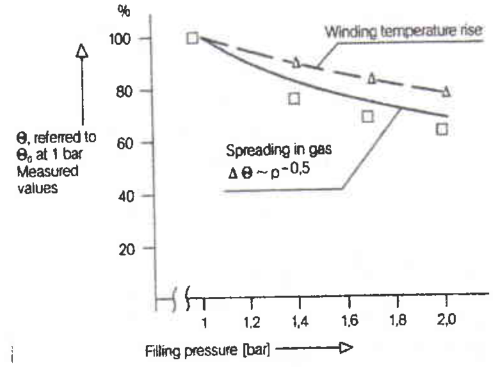
The evaluation of the heat runs revealed that the winding temperature rises considerably over the mean gas temperature. In spite of the higher density of SF6, compared with air, the coefficient of convection is only 1.6 times that of air. The external air circulation follows the internal gas circulation. It follows that the use of natural cooling is subject to two conditions:

a) Preferably, class H insulation materials should be used.
b) Heat radiating tank surfaces must be larger than with an oil insulated transformer.

With transformers above 2500 kVA, condition (b) would lead to uneconomical designs. The following alternatives are available:

1. External fans. This is not very efficient- contrary to the liquid-insulated transformer- since the heating of the tank is only a small part of the overall temperature increase.

2. Higher gas pressure. Raising the pressure to 2 bar, could result in a 20 per cent reduction of the winding temperature. This would require an expensive, pressure-resistant tank (Fig.4).



Figur.4: Reduction of temperature rises when increasing the filling pressure from 1 bar to 2 bar.

3. Forced internal gas circulation. This is the most effective solution, but it is also rather expensive, as it requires special fans and additional guide baffles.

Improvements possible with forced gas circulation can be seen from Fig.3b. The experimental transformer was operated with both natural and forced gas circulation. With the latter, the transformer power was increased to 133%, without raising the limit temperatures. With forced gas circulation, the coefficient of convection is approx. 80% higher than with natural circulation.

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