Comparative Analysis of Dielectric Medium of Transformer Electrical Equipment

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Abstract. The paper presents a scientific comparative analysis of the development of the dielectric medium of transformer electrical equipment, its consistent evolution in the direction of energy efficiency, technical safety and environmental acceptability. Dielectric media in the form of mineral oil, synthetic oil, sulphur hexafluoride and liquid nitrogen are consistently considered on the basis of a historical excursion. Currently, mineral oil occupies a dominant position as a dielectric medium in medium-and high-power power transformers. Its role in transformer electrical equipment is very large, since it is used as insulation due to its high dielectric properties, it provides heat removal from electrical windings. However, the fire and explosion hazard, as well as the environmental impact on the habitat, requires its improvement as a dielectric. In this regard, dielectric media in the form of synthetic MIDDLe oil and sulfur hexafluoride are also presented. It is shown that the dielectric medium in the form of liquid nitrogen has significant advantages, since it allows approximately three times the weight and size parameters of transformer equipment. Along with this, with liquid nitrogen, fire and explosion hazards are excluded and environmental safety requirements are met. At the same time, it is indicated that liquid nitrogen can be obtained in a fairly simple way from the air. This is especially important for autonomous and transport power supply systems.

Keywords: Dielectric medium · Transformer · MIDEL · Liquid nitrogen · Sulphur hexafluoride

1 Introduction

The role of oil in transformer equipment is extremely large. It is used as insulation due to its high dielectric properties, it provides heat removal from the internal parts of the transformer, being a good heat carrier. Currently, mineral oils are widely used in the domestic transformer industry as an insulating and cooling medium, which have low electrical insulation properties and low antioxidant stability. Mineral oils significantly change their properties during the operation of the transformer from the heating of the magnetic circuit, windings. Striving for perfection allows you to improve and stabilize

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the properties of mineral oil, within a wide range, for example, using the speed of heat transfer from the object to the external environment. Another fact is not to go beyond the formation of a high oxidizing ability, to exclude the contact of oil with air.

As a result of long-term operation, the parameters of the transformer oil change, a precipitate accumulates in it, it settles on the transformer elements, which causes their additional heating. In this regard, there is a rapid aging of the electrical insulation of the windings. In addition, oil-filled transformers, due to the fire hazard, cannot be freely installed inside buildings and need a reliable and expensive fire extinguishing system.

Currently, there are a large number of developments in the field of production of electrical equipment with various types of insulation-cooled media, which allow you to level out, and in some cases even get rid of the problems that arise in oil-filled transformers.

2 Materials and Methods

The most common liquid dielectric in the power industry is transformer oil. Transformer oil is an insulating material that is resistant to high temperatures and has excellent electrical insulating properties. It is used as a dielectric medium in oil transformers, some types of high voltage capacitors, fluorescent lamp ballasts, and some types of high voltage and circuit breakers. Its functions are to isolate, suppress corona discharge and arcing when it occurs, and serve as a cooling liquid.

The main functions of transformer oil are insulation of windings, turns and their cooling in the transformer. The oil must have high dielectric strength, thermal conductivity, chemical stability, and maintain these properties at high temperatures for a long period of time. Typical specifications: flash point 140 °C or higher, pour point −30 °C or lower, breakdown voltage 28 kV or more. and above [1]. The average service life of oil-filled transformers is 30 years or more.

Dry-type transformers are air-cooled devices. Requirements for dry transformers minimal maintenance, reliable uninterrupted operation for many years, no moving parts. Under normal operating conditions, as a rule, it provides long and trouble-free operation. Unlike transformers with a liquid dielectric medium, dry-type devices use safe, high-temperature insulation systems.

Dry-type transformers are safe and reliable converters of electrical energy, they do not require fireproof storage facilities, settling tanks or ventilation of toxic gases. These important safety factors allow the installation of dry-type transformers inside buildings near the load, which improves the overall regulation of the system and reduces expensive losses on the secondary line. Dry transformers, suitable for indoor and outdoor applications where safe and reliable power is important, are equipped with cooling channels that allow heat to be removed into the air. For outdoor work, the dry transformer housing usually has blinds for ventilation. One of the disadvantages of dry-type transformers is that in the cooling air environment, the insulation can be affected by aggressive media (moisture, dirt, conductive dust, caustic vapors, etc.).

There are several different methods of construction of dry-type transformers used in production, they are suitable for certain environments and purposes. If you need protection from corona discharge and increased mechanical strength, the best option is a dry-type VPI transformer. Under severe climatic and operational conditions, you can choose a transformer with a cast coil. Another disadvantage of dry-type transformers is the use of more electrical iron in the magnetic circuit in comparison with oil. The service life of dry transformers is less than that of oil transformers. The decommissioned dry transformers, for various reasons, worked from 14 to 35 years; on average, 25 years.

MIDEL is a synthetic dielectric ester liquid designed to provide an alternative to mineral oil, silicone liquid and dry-type transformers. MIDEL, developed in the 1970s and today is a highly reliable liquid for improving safety, used in thousands of new transformers as a dielectric medium. During this time, MIDEL has gained an excellent reputation as a cost-effective transformer fluid for replacing transformer oil.

This dielectric is different: high fire safety, high moisture resistance, harmless to the environment, the liquid has excellent dielectric properties. MIDEL 7131 complies with the IEC 61099 standard and classified as a halogen-free pentaerythrite ether and belongs to the T1 type [2–4].

The MIDEL 7131 liquid is intended for use in various transformers, such as:

- Distribution transformers,
- Power transformers,
- Traction transformers,
- Rectifier Transformers,
- Pole-type transformers,
- On-load tap-changer
- Cooling of thyristors.

One of the key advantages of using high flame point fluids is the ability to run the transformer at a higher temperature. This can have a direct effect on transformer power output, as using a higher oil temperature allows more power to be produced without increasing the size and weight of the unit [5, 6].

In general, the higher operating temperature allowed by the higher thermal power class can result in significant savings in size and weight while maintaining output power and using standard paper insulation.

Since a smaller transformer requires less copper, steel and other materials to produce, this in turn saves on costs and offsets the higher cost of MIDEL compared to mineral oil.

MIDEL 7131 transformer fluid has been proven to be non-toxic and easily biodegradable, making it an environmentally friendly alternative to mineral oil and silicone fluid. MIDEL 7131 is classified by the German Federal Environment Agency as a water-safe liquid essential oil.

The biodegradability of MIDEL 7131 was assessed by an accredited laboratory using a standard test method developed by the Organization for Economic Cooperation and Development (OECD), one of the international standardization organizations. However, MIDEL 7131 is not susceptible to decomposition directly inside the transformer because it is too hot and dry for microorganisms. The average life of a transformer is 40 years, so the fluid used to insulate and cool the system is expected to last just as long, while maintaining its reliability.

Oxygen is known to promote aging of the mineral oil in transformers, which in turn leads to sludge formation and deterioration of the mineral oil properties. In addition, at high temperatures increases even in sealed systems and the oil can age (reducing the rated life). Extensive testing has demonstrated that MIDEL is a stable liquid suitable for both breathing and sealed transformers [7–15].

MIDEL fluid has a very high water resistance. This means that it is capable of absorbing much more water than mineral oil without compromising its dielectric properties. Liquid ether is also able to retain more water, which can slow the aging of cellulose. If mineral oil is used, there is a danger of water being released from it in the form of condensation.

Gas-insulated transformers (GITS) have been used since the 1960s, but use has been limited due to higher costs and other reasons. The gas is used as an insulating and cooling agent in gas-insulating transformers. Sulfur hexafluoride (SF6) is the main gas used in these types of transformers. The main advantage of gas-fired transformers is the possibility of their installation and use in hard-to-reach places of operation.

These gases are not flammable, and fire-fighting equipment is not needed in the transformer room. This type of transformer insulation does not require constant cleaning of the insulation. Gas-insulated transformers can be integrated directly with a gas-insulated switchgear to form a single closed unit. This allows you to save space and integrated control over the gas system [7].

Due to their high safety, gas-fired transformers are installed in environmentally hazardous areas where oil leakage is prohibited. These include hydroelectric power plants and sewage treatment plants. The gas used, whether it is SF6 or its alternative, does not ignite, and the risk of fire is significantly reduced. This means that there is no need for a fire protection system, which leads to significant space savings. GIT can also be installed in underground installations, which is impractical for oil transformers. In case of failures, there is no increase in pressure, which reduces the likelihood of container rupture and damage to the installation. Gas-fired transformers can be connected directly to a gas-insulated switchgear, thereby eliminating the need for separate placement of the transformer. In this way, it is possible to create a completely gas-insulated substation that will serve as one large configuration for internal urban premises and buildings. The height of the transformer room can be reduced, since neither a conservator device nor a pressure relief device is required.

SF6 does not react with materials commonly used in transformers, especially in insulation materials. As the temperature increases, the gas density increases, improving its ability to cool the transformer. Gas has similar cooling methods that have similar properties to oil transformers. SF6 gas has lower cooling characteristics than that of insulating oil. The heat capacity of the same volume is 177 times lower, and the heat transfer coefficient at the same flow rate is 7.3 times lower (SF6 gas with a gas pressure of 0.12 MPa at 20 °C). Gas-insulated transformers are more expensive, but this difference in cost can be compensated for over the life of the transformer, since maintenance is cheaper. The environmental regulations concerning greenhouse gases require that the gas is carefully processed and processed where possible. This may result in additional installation and repair costs, depending on local laws.

Dielectric characteristics of liquid nitrogen. Liquid nitrogen, a gas in the liquid state, has a low temperature of the order of −196 °C with a dielectric permittivity of 1.43. [4].

After the discovery of high-temperature superconductor in 1986, interest in energy applications of superconductivity has increased dramatically. Through a number of successful installations around the world, this technology has shown significant improvements in the compactness, capabilities, and efficiency of power systems.

The development of a superconducting transformer requires thermally stable, mechanically compatible, and electrically efficient dielectrics. In addition, cryogenic dielectric materials must have high tensile strength to withstand operating voltages as well as withstand damage.

Liquefied gas is important to the concept of high-temperature superconductors (HTS) as a coolant and insulator. With a boiling point of 77K and accounting for 78% of the earth's atmosphere, liquid nitrogen (LN2) has become the obvious choice for its use in HTSP transformers.

HTS transformers have technical advantages over classical transformers:

– Limitation of "short-circuit" currents in case of mains failure;
– Low load losses, therefore the efficiency of the transformer is higher;
– Reduced reactance, which allows voltage stabilisation without the need for voltage regulation;

3 Research Methods

Calculations of the main electrical characteristics for transformers with capacities of 10, 16, 25 MVA are carried out according to the following formulas.

1) No-load losses, W:

$$p_{loss} = p_S G_{core} + p_a G, \tag{1}$$

where G_{core} – is the weight of the magnetic core rods; G – is the weight of the upper and lower yoke.

The value of no-load loss must be within the permissible deviation (5%), any other deviation is considered unacceptable and does not fit into the GOST framework.

2) The reactive component of the no-load current:

$$i_{0r} = \frac{q_{core} G_{core} + q_a G + n_{core} q_{load} F_{core}}{10S}, \tag{2}$$

where G_{core} – is the weight of the magnetic core rods; G – is the weight of the upper and lower yoke.

3) Active component of no-load current:

$$i_{0a} = \frac{p_{loss}}{10S}, \tag{3}$$

where p_{loss} – is the no-load loss.

4) No-load current:

$$i_0 = \sqrt{i_{0r}^2 + i_{0a}^2}, \quad (4)$$

where i_{0r} – reactive component of no-load current; i_{0a} – active component of no-load current.

5) Short-circuit losses in the windings:

$$p_{km} = 2.4\Delta^2 G_m, \quad (5)$$

where Gm – total weight of magnetic core.

6) Calculation of losses in bends:

$$p_{bend} = \frac{SI_{f2}}{10^4}, \quad (6)$$

7) Tank wall losses:

$$p_t = 0,0045 \cdot S^{1.5}, \quad (7)$$

8) Short circuit losses:

$$p_{SC} = p_{core} + p_{loss} + p_t, \quad (8)$$

where p_{core} – short-circuit losses in the windings; p_{loss} – losses in bends; p_t – tank wall losses.

9) Calculation of the active component of the short-circuit voltage:

$$u_a = \frac{p_{SC}}{10S}, \quad (9)$$

where p_{SC} – Short circuit losses.

10) Calculation of the reactive component of the short-circuit voltage:

$$\Delta_r = a_{22} + \frac{a_1 + a_2}{3}, \quad (10)$$

$$k_r = 1 - \frac{a_{22} + a_1 + a_2}{\pi 1}, \quad (11)$$

$$D = d + 2a_{01} + 2a_1 + a_{12}, \quad (12)$$

11) The reactive component of the short-circuit voltage as a percentage of the rated voltage is calculated using the following formula:

$$u_r = \frac{0,79 \cdot f_1 \cdot S' \cdot \beta_n \cdot a_r \cdot k_r}{u_t^2}, \quad (13)$$

where ap – refined values of the width of the reduced scattering channel.

12) Calculation of the short-circuit voltage:

$$u_{SC} = \sqrt{u_r^2 + u_a^2}, \tag{14}$$

where u_p – reactive component of short-circuit voltage; u_a^2 – active component of voltage.

13) Calculation of the efficiency curve depending on the load:

$$\eta = (1 - \frac{p_0 + k_.^2 p_{SC}}{k_. S_r cos\varphi_2 + p_0 + k_.^2 p_{SC}} \cdot 100\% \tag{15}$$

The results of calculations of efficiency curves depending on the load factor are given in a summary table, a graph of the efficiency of the calculated transformer is drawn.

4 Results

All the calculations of transformers with different dielectric medium have been summarized and structured in Tables 1, 2 and 3 for convenience and clarity.

Table 1. Summary table of characteristics of calculated 10 MVA transformers

Parameter	Transformer type			Sulfur hexafluoride	HTS
	Oil	Dry	MIDEL		
U_{SC}, %	9.2	10.7	11.2	9.3	3
P_{SC}, kV	22.1	20.7	18.4	20.1	4.2
I_{xx}, %	0.96	0.98	0.92	0.98	0.64
P_{xx}, kV	12.47	14.03	11.6	12.78	6.54
Efficiency, %	98.31	98.42	99.03	98.52	99.85
Mass of magnetic core, kg	10360	10704	9757	10702	5624

After analyzing the results of all the calculations, the superior transformer in terms of electrical parameters was identified. The HTSP transformer outperforms the others by almost two times in all parameters. We have also noticed a tendency that as the power rating of transformers increases, the electrical parameters of HTSP transformers increase much more than those of its competitors. HTSP transformers have potential advantages over conventional transformers in the following areas:

- Reduction of total losses by 60%;
- Reduction of the total transformer weight by 45%;
- Increase in efficiency by more than 1.5%.

Table 2. Summary table of characteristics of calculated 16 MVA transformers

Parameter	Oil	Dry	Transformer type		HTS
			MIDEL	Sulfur hexafluoride	
U_{SC}, %	9.80	11.40	11.93	9.91	3.20
P_{SC}, kV	29.00	27.16	24.14	26.38	5.51
I_{xx}, %	0.75	0.77	0.72	0.77	0.50
P_{xx}, kV	11.50	12.94	10.70	11.79	6.03
Efficiency, %	98.29	98.40	99.31	99.20	99.83
Mass of magnetic core, kg	23330	24105	21972	24100	12665

Table 3. Summary table of characteristics of calculated 25 MVA transformers

Parameter	Transformer type			Sulfur hexafluoride	HTS
	Oil	Dry	MIDEL		
U_{SC}, %	9.80	11.40	11.93	9.91	3,20
P_{SC}, kV	31.30	29.32	26.06	28.47	5.95
I_{xx}, %	0.60	0.61	0.58	0.61	0.40
P_{xx}, kV	19.10	21.49	17.77	19.57	10.02
Efficiency, %	98.31	98.42	99.23	99.29	99.85
Mass of magnetic core, kg	38250	39520	36024	39513	20764

5 Conclusion

The number of distribution and substation transformers filled with mineral oil nearing the end of their normal lifespan is increasing dramatically each year, and supply companies are facing shrinking capital budgets, making it difficult to invest money to buy new transformers.

Electrical engineering companies can now re-equip existing transformers filled with mineral oil, proven dielectrics based on vegetable oil, MIDEL and sulfur hexafluoride, which have a dielectric strength similar to or greater than that of mineral oil. These dielectrics reduce the risk of fire and environmental impact, increasing the service life of the insulation. New dielectrics represent a cost-effective way to help ensure a higher level of overall performance of the energy supply system. And some recent developments in the field of high-temperature superconducting transformers can completely save supplying enterprises from electricity losses.

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