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Modeling and simulation of 2.5 MVA SF6-gas–insulated transformer

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Abstract: In recent years, environmental awareness has been a great concern, and even governments have sometimes been under pressure to comply with bilateral agreements. Mineral oil/epoxy cast resins are one of the most harmful soil pollutants. Of course, they provide a good insulation material in (distribution/power) transformers, but they present some disadvantages, such as low ignition point, additional insulation costs, requirement for an extinguishing apparatus, long clearance distance, toxicity, costly decontamination, and explosion risk. For this reason, gas-insulated transformers have nowadays been put into specifications. This paper investigates SF6-gas–insulated transformer (GIT) designs for the complex distribution transformer model, i.e. 2.5 MVA open-air type. The model has 34.5/0.4 kV, 50 Hz ratings. SF6 GITs present more reliable working conditions due to the inherited specs of SF6 because it has nonflammable insulation and an explosion-proof design. Therefore, the proposed transformer design is mostly suitable for security risk environments, such as submarines, mines, and nuclear power plants. Apart from these advantages, the new SF6 GIT design is compact in design and lighter than the oil-type or the epoxy cast resin type.

Key words: Distribution transformer, SF6 insulation, epoxy cast resin, transformer oil

1. Introduction

Environmental protection, operational safety, and minimizing maintenance requirements and fire risk are some of the important concepts that must be followed from the design and manufacturing stage to the assembly process of distribution and power transformers. It is especially important for small-size transformers because they are located very near to loads (consumer points) due to economic and technical reasons. In today's conditions, oil-insulated and/or dry-type transformers are mostly operating at their rated powers to meet the increasing power demand, and they are not usually capable of meeting total need. Moreover, the inner temperature of these transformers increases due to their rated and heavy loadings and causes early aging of oil and inner insulating materials. Using them continually at full capacity then brings about high security risks. Therefore, the proposed SF6 gas-insulated transformer considered in this study is deemed a more reliable solution for today's distribution network [1–5]. Electrical power consumption increases every day due to heavy demand, and it requires a great number of substations to deliver electrical power. Nowadays, there are many examples of underground and public substations for economic and environmental reasons in large cities where safety concerns should be highly ensured. For this reason, SF6 gas is investigated in this paper as an insulating material instead of transformer oil.

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This paper proposes an SF6-gas–insulated transformer (GIT) design in complex distribution transformer models and investigates the optimal gas pressure to maximize the insulation level and breakdown voltage limits. The model under analysis is based on an epoxy cast resin type insulated indoor/outdoor distribution transformer (2.5 MVA, 34.5/0.4 kV, 50 Hz). The breakdown voltage characteristics and heat analysis results of the suggested SF6-gas–insulated model are then compared to those of the original model. The proposed model is quite light and environmentally friendly compared to epoxy casting resin types.

In the proposed study, the required know-how of SF6 GIT design will be achieved by expert academics both at home and abroad with the aim of meeting today's energy needs in an economical way. The most important step of this paper is to obtain tank pressure, heat effects, and breakdown curves in homogeneous and inhomogeneous electric fields using complex 3D transformer models.

2. Materials and methods

One of the most important factors in the transmission and distribution of electrical energy is, of course, efficiency. For this reason, high voltage should be used where appropriate. However, as the voltage level increases, insulating problems occur. On the other hand, distribution transformers in particular should be located as near to the loads (the end-users) as possible. In the case of power transformers, there is one at each end of a transmission line and the other is well away from the generators. Supplying electrical power to strategic buildings and large machines through their own distribution transformer is important. Power or distribution transformers are usually manufactured oil or dry types. Dry-type transformers have limited power ratings of 0.03–30 MVA due to inefficient cooling. In contrast, oil-type transformers are manufactured in a wide power range and have a very wide application area [6–8]. For oil-insulated transformers, the health of the oil directly affects the efficiency and working life of the transformer. Therefore, the transformer oil should be tested periodically within the specified maintenance period. As a result of these tests, it is either treated or replaced with fresh oil. Deterioration in the oil may occur over time according to the working conditions and environmental impact of the transformer. The presence of undesirable particles in oil is determined by regular oil analysis and dielectric breakdown tests. If the breakdown voltage is below the specified value during the tests, purification of the oil (treatment process) should be performed. This process helps to remove moisture and particles under vacuum and ensures a desirable breakdown voltage limit. The oil purification process leads to economic loss as well as additional costs in the transformer maintenance process [9,10]. Transformer oil can contain small particles, metal parts, and moisture. In this case, chain theory particles have high dielectric constants that are arranged in the direction of the maximum dielectric field intensity and can lead to partial discharges and breakdowns at low voltage levels. The breakdown strength of transformer oil, compared to gases, is not stable and is affected by the nonuniform electric field intensity distribution. Therefore, the use of gas instead of transformer oil will lead to reductions in clearances between the conductors and insulating materials, as well as the use of a more reliable insulation material rather than unstable oil [11]. The weight of the oil is almost half of the total weight of oil-insulated power transformers, leading to high manufacturing and handling costs. In addition, transformer oil is subject to excise tax; as a result, in recent years, its price has been high.

The Climate Change Kyoto Protocol signed on 11 December 1997 proposes to limit the use of unnatural gases to reduce the greenhouse gas emissions. SF6 gas was not included in the 6 gases (CO2, CH4, N2O, O3, CFC-11:CCl3F, and CFC-12: CCl2F2) at first. However, SF6 is an unnatural gas and has infrared absorption features causing the greenhouse effect. The International Union of Producers and Distributors of Electrical Energy points out that the total production of SF6 gas all over the world is about 6000–8000 tons. According to the report prepared by T&D Europe (previously known as CAPIEL) in January 2000, 3% of total gas production is leakage released to the atmosphere during maintenance work, while 1.5% is loss; that makes a total of 4.5% of the annual production. The total production of SF6 gas in the European Union in 2010 is thought to have been 6200 tons on average. Taking into account the life cycle of a circuit breaker as 30 years, circuit breakers manufactured in the 1980s have been leading to increased emissions since 1980. Measures should be taken to prevent the effects of global warming caused by this natural gas. These measures include limiting the amount of SF6 through the use of appropriate gas mixtures instead of SF6 gas, recycling the SF6 gas remaining in expired high-voltage devices, and so on.

Consequently, the use of SF6 gas as a dielectric insulating material will bring about many advantages, such as optimum design and reduced maintenance costs. It will allow the efficient use of our country's own resources and increase competitiveness. SF6 gas has been used in industry since the 1940s due to properties such as high dielectric strength, chemical stability, nontoxicity, good insulating properties, good heat transmission ability, and arc-extinguishing capability. Particularly, it has been frequently used since the 1980s for circuit breakers and ring main units. In addition to this, SF6 gas is effectively used in 380/154 kV substations, gas-insulated switchgears, current and voltage measurement transformers, high-voltage cables, and gas-insulated power transmission lines today. Some important specifications of SF6, including a comparison with transformer oil, can be found in [12]. Some of these examples cannot yet be seen in our country. SF6 gas is already used successfully in a range of 3–800 kV systems. The aim is to better understand the discharge behavior of other gases and gas mixtures and provide a more economical and optimal electrical insulation properties. In this regard, current research has not fully clarified the breakdown mechanism. This requires more testing and research on this issue [13,14].

Figure 1 shows the 2.5 MVA SF6 gas-insulated distribution transformer under analysis.

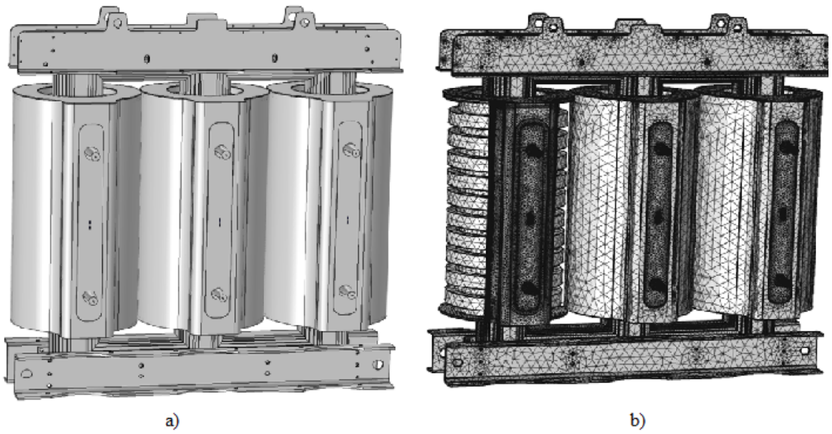


Figure 1. 2.5MVA, 34.5/0.4 kV SF6 gas-insulated distribution transformer, a) general view, b) meshed view.

The original transformer type for Figure 1 is epoxy casting resin. In Figure 1, the overall design is cylindrical to allow high pressure and homogeneous gas distribution inside the tank. HV windings are insulated SF6 gas that both insulates and cools. The design of the tank and the cooling element are similar to the oil-insulated transformer design. The tank is hermetic (airproof) and safe to the touch. High-voltage inputs are the bushing type, while the low-voltage ones are bar-type bushings. For any reason, even if an SF6 gas leak occurs, it is an inert gas and not flammable [15,16].

The cooling of core and windings of the transformer up to a rating of 2.5 MVA can be obtained using natural gas circulation. A driving force can be obtained from temperature differences between hot and cold windings. Natural convection can be enforced by placing the cooling elements in a higher position than that of the windings. Natural convection may not be efficient for the transformers whose ratings are higher than 2.5 MVA. A cooling fan inside the tank is used for accelerating the gas recirculation in higher-power transformers. In the case of using a cooling fan, the location of windings and cooling elements is insignificant, and both can be designed on the same plane.

As the transformer is loaded, positive gas pressure will be increased to a degree as a result of winding temperature. Increased gas pressure will help to increase natural gas circulation and contributes the cooling of the windings, but the increased level of tank gas pressure will be digitally monitored in the proposed transformer. According to simulations, negative gas pressure does not occur even if the transformer is out of service or unloaded. Consequently, the most effective cooling elements and gas pressure in tank will be determined in this work.

Especially in comparison with air, SF6 has a high density (more than 5 times than that of air) and low thermal conductivity. This means an even better heat transfer by natural circulation, and circulation can be further enhanced by increasing ambient pressure and using a fan. The dielectric strength of SF6 is 2–3 times higher than that of air, and it can be compared to transformer oil at 2–3 atm. The decrease in the breakdown strength of SF6 with the increasing temperature should be taken into account, and the most appropriate design will be obtained through computer simulations. Local partial discharges under breakdown voltages may occur where the electric field is not uniform (as in the case of transformers). These discharges can lead to short circuits with increasing voltage. These drawbacks will be minimized using finite element software at the design stage.

Obtaining the breakdown strength of SF6 gas is an important step for this research work. In this way, breakdown voltages between two points for the two transformer models can easily be calculated. Thus, the absence of partial discharges and possible precautions will be determined. Eq. (2) is used to determine the breakdown voltage of the SF6 gas environment [17].

$$V_{SF6} = 1321pd^{0.915}kV \tag{1}$$

In Eq. (2), p is gas pressure in kPa, d is distance between the electrodes in cm, and V_{SF6} is the breakdown voltage in kV. V_{SF6} can be calculated within a margin of error of ±3.5% in a nonuniform electric field (as in a transformer case), with the pd multiplication range of $50 \leq pd \leq 1200\,\text{kPa/cm}$. Therefore, the breakdown voltages of the critical points inside the transformer tank will be calculated using Eq. (2). The larger the pd term, the larger the breakdown voltage.

3. Definition of SF6 GIT model

The SF6 GIT model is a general distribution transformer (2.5 MVA, 34.5/0.4 kV) and all technical drawings belong to a real 3D model in mm. It consists of a core, a yoke, HV and LV windings, HV bushings, SF6 gas, and an inner frame. Unlike the oil-insulated distribution transformers, LV windings are installed outdoors. HV windings are installed around the inner frame inside the tank, which is surrounded by 5 mm-thick plastic to increase the security. The outer part of the tank is grounded and has touch safety. The yoke, tank, core, and LV windings are meshed coarsely, but the HV windings and bushings are meshed more finely to get fast and accurate results (Figure 1).

Figure 2 shows the A-phase winding structure and the selected lines. These lines are simply selected based on their proximity to the nearest HV winding.

Therefore, these lines are selected between the corner of the HV winding and the corner of the cylindrical tank. Figures 3–5 show the electric field calculation at 5 m/s during normal operating conditions.

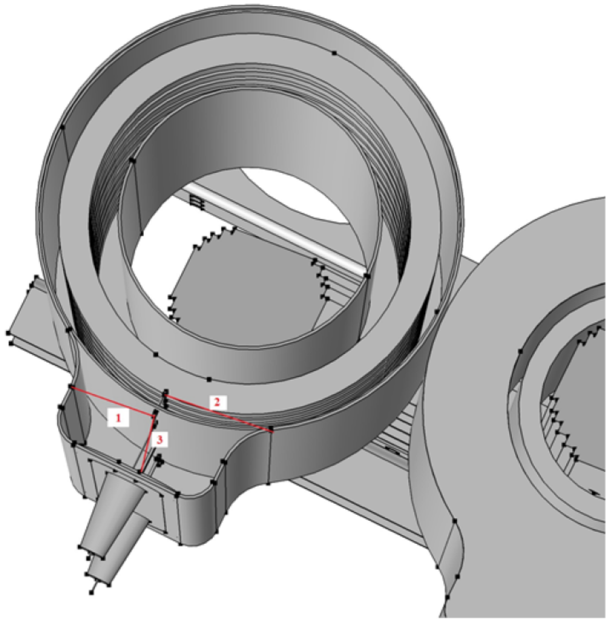


Figure 2. Selected points in Phase A for breakdown studies.

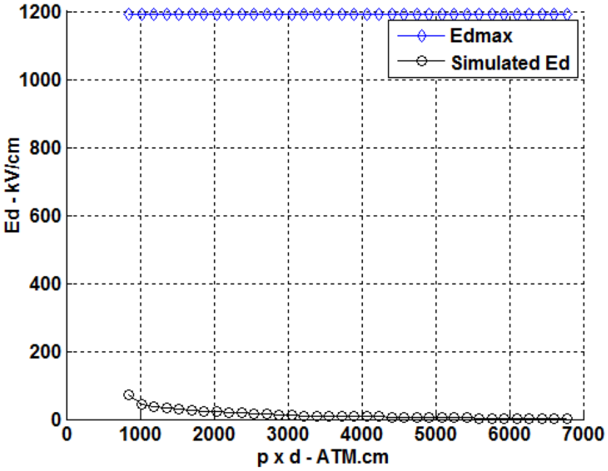


Figure 3. Simulated electric field for line 1 in Phase A.

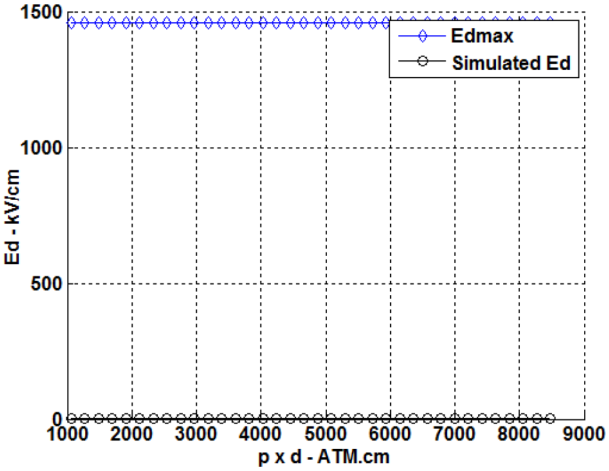


Figure 4. Simulated electric field for line 2 in Phase A.

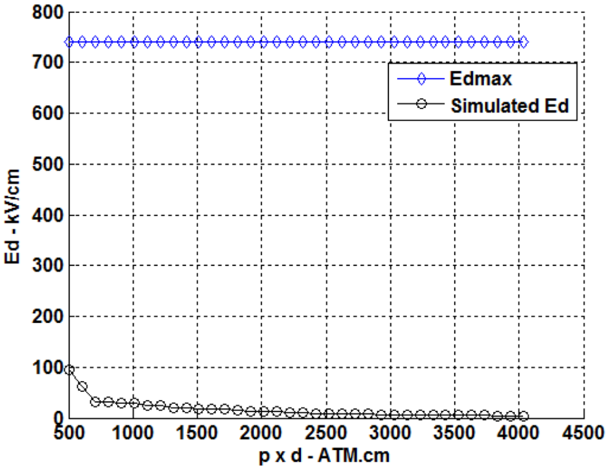


Figure 5. Simulated electric field for line 3 in Phase A.

In Figures 3–5, simulated electric fields under rated operation conditions are very low at low SF6 gas pressures. For normal operation conditions, any SF6 gas pressure of 1 ATM would be desirable. However, it should be tested against lightning over voltages. Figure 6 shows the potential distribution for each line.

3.1. Analysis under lightning impulse voltage

A 1.2–50 μS lightning impulse (according to IEC 60076-3) voltage is applied to Phase B to obtain breakdown curves on the selected lines. Figure 7 shows the potential distribution of Phase B along with contour lines.

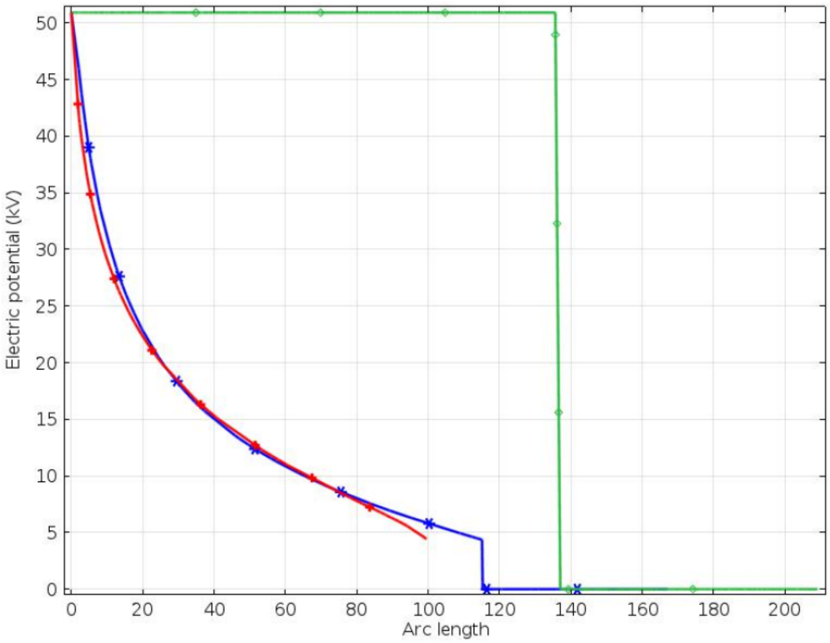


Figure 6. Potential distribution for each selected line in Phase A.

Figures 8–10 show the electric field distribution on the selected lines of Phase B.

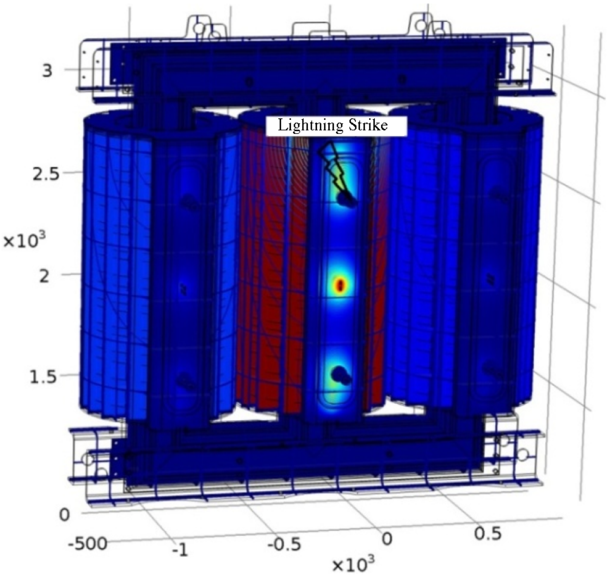


Figure 8. Simulated electric field for line 1 in Phase B.

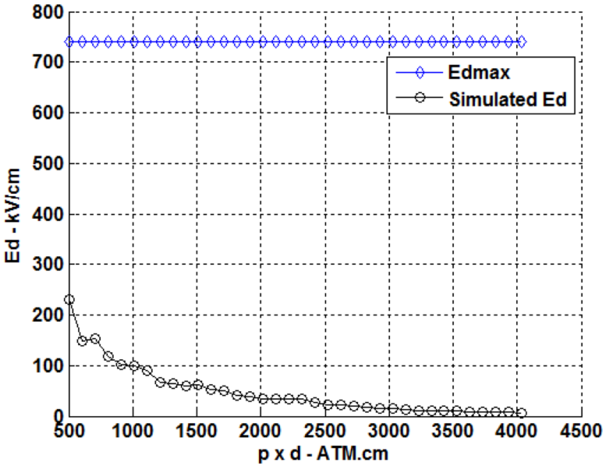


Figure 7. Potential distribution during lightning strike in Phase B.

In Figures 8–10, the critical electric field magnitudes are shown on lines 1 and 3. The proposed model can withstand a lightning strike, since the simulated electric fields are located under maximum electric fields for the selected lines. For this particular example, an SF6 gas pressure of 2 ATM will be desirable to meet the IEC 60076-3 standards (peak level of voltage is 170 kV).

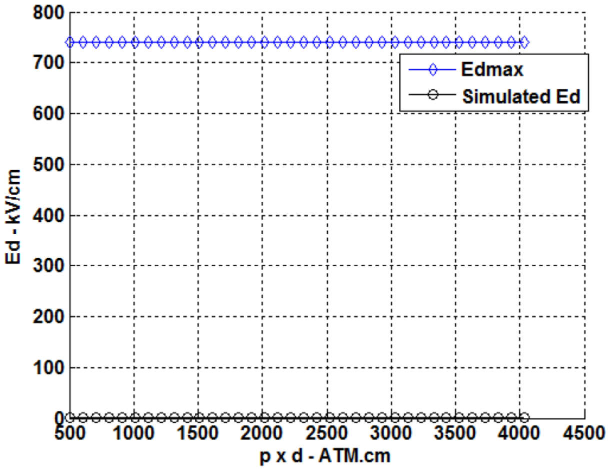


Figure 9. Simulated electric field for line 2 in Phase B.

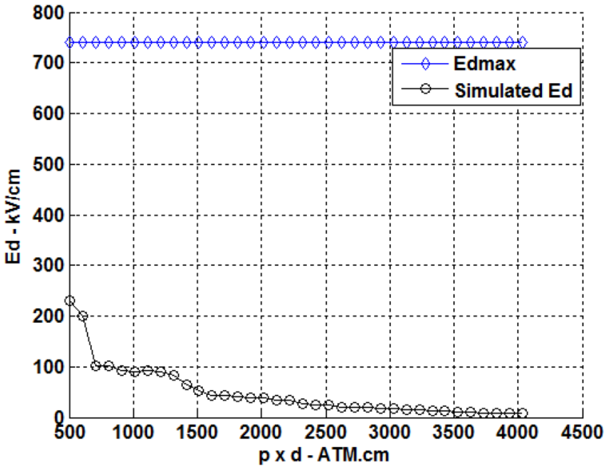
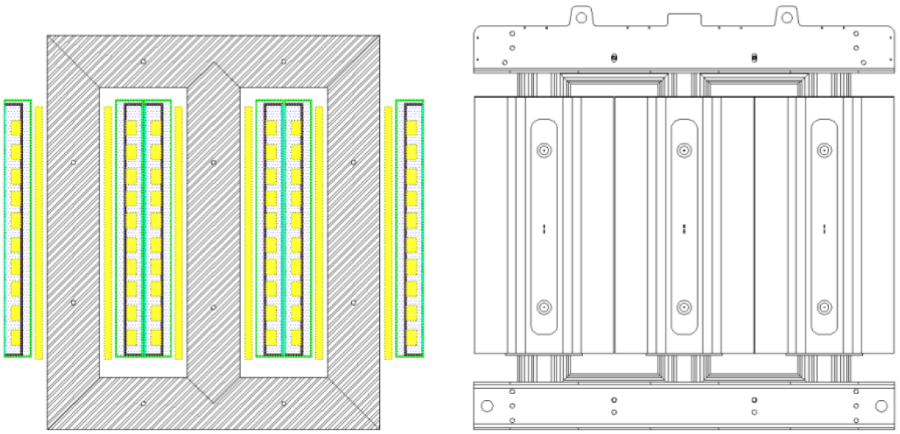


Figure 10. Simulated electric field for line 3 in Phase B.

3.2. Heat analysis

This section investigates hot spot analysis in the proposed SF6 GIT. The winding structure of 2.5 MVA SF6 GIT is used, as it was formerly an epoxy cast resin transformer, and a 2D model is used for heat analysis due to the computational requirements (Figure 11).



a) winding structure b) general view

Figure 11. 2D model of 2.5MVA SF6 GIT for heat analysis.

The LV windings are in the air, but HV windings are inside the tank filled with SF6. Therefore, the 2D model is surrounded with air up to 250 mm from the transformer tank. The temperature-dependent parameters of air are given below [18].

Thermal conductivity, k [W/(cmK[1 / degC])]

$$k = 6.9 \times 10^{-5} T \left[\frac{1}{degC}\right] + 0.0245 \tag{2}$$

Heat capacity at constant pressure, Cp [J/(kgK[1 / degC])]

$$C_p = 0.03711 \times e^{-0.007029T\left[\frac{1}{degC}\right]} + 0.9683 \times e^{0.0002399T\left[\frac{1}{degC}\right]} \tag{3}$$

Density, ρ [g/L]

$$\rho = 0.4562 \times e^{-0.\,007727T\left[\frac{1}{degC}\right]} + 0.8361 \times e^{-0.00127T[1/degC]} \tag{4}$$

Dynamic viscosity, μ [mPa/s]

$$\mu = 4.241 \times 10^{-5} \times e^{0.0002415T\left[\frac{1}{degC}\right]} - 2.502 \times 10^{-5} \times e^{-0.001405T\left[\frac{1}{degC}\right]} \tag{5}$$

The analysis of the 2.5 MVA SF6 GIT is slightly different from that of an oil or epoxy cast resin transformer because it has 2 fluids, i.e. air and SF6. The temperature-dependent parameters of air (Eqs. (2)–(5)) and SF6 (Eqs. (6)–(9)) are solved together. HV windings consist of 10 layers, whereas LV windings have only 1 layer.

SF6 gas is heated and its density, viscosity, and pressure changes inside the tank. The performance curves given in [19] are used to obtain the temperature dependent variables of SF6 gas (Eqs. (6)–(9)).

Thermal conductivity, k [W/cmK]

$$k = -4.1 \times 10^{-6}T^2 + 0.0081T + 1.1 \tag{6}$$

Heat capacity at constant pressure, Cp [J/kgK]

$$C_p = -1.306 \times 10^6 T^{-1.224} + 2956 \tag{7}$$

Density, ρ [g/L]

$$\rho = p0 \times M_{SF6} \,/\, (0.0821T) \tag{8}$$

Dynamic viscosity, μ [mPa/s]

$$\mu = 3.9 \times 10^{-5}T + 0.015 \tag{9}$$

In Eqs. (6)–(9), T is the temperature in K, p is the initial SF6 gas pressure (defined in electrostatic analysis), and M_{SF6} is the molar mass of SF6, or 146.0554192 g/mol.

Eqs. (6)–(9) are simply fitted according to minimum RMS error. The LV winding as a heat source is cylindrical, neglecting any internal effects inside it.

The nonisothermal flow in SF6 is given in Eq. (10).

$$\rho\frac{du}{dt} + \rho\left(u.\nabla u\right) = -\nabla p + \nabla.\mu\left(\nabla u + \left(\nabla u\right)^T\right) - \frac{2\mu}{3}\left(\nabla.u\right)I$$

$$\rho g\frac{d\rho}{dt} + \nabla.\left(\rho u\right) = 0, \tag{10}$$

where ρ is the density, u is the velocity (m/s), μ is the dynamic viscosity, p is the SF6 gas pressure (Pa) and g is the gravity constant (m/s^2).

The conductive and convective heat transfer inside the SF6 is given in Eq. (11).

$$\rho C_p\frac{dT}{dt} + \nabla.\left(-k\nabla T\right) = -\rho C_p u\nabla T + P_{total} \tag{11}$$

where P_{total} is the total rated power of SF6 GIT.

Boundary conditions

At the transformer tank's inner surfaces, radiation is assumed as surface-to-surface radiation, which means that mutual irradiation from the surfaces of the all surroundings can be observed from a specific surface. At the outer surfaces of the tank, radiation is assumed as surface-to-ambient radiation, the pressure is constant, and $x_{velocity}$ is zero, which means that there is no reflected radiation from the surroundings. The ambient temperature is defined as 40 °C maximum, 30 °C daily average, and 20 °C yearly average according to IEEE C.57.12.00TM.

The result of the indicated equations and boundary conditions contributes to the temperature and flow field inside the tank.

Figure 12 shows the radial velocity between the SF6 insulated tank and LV windings. There is a flux of air from the bottom of the transformer to the outer parts.

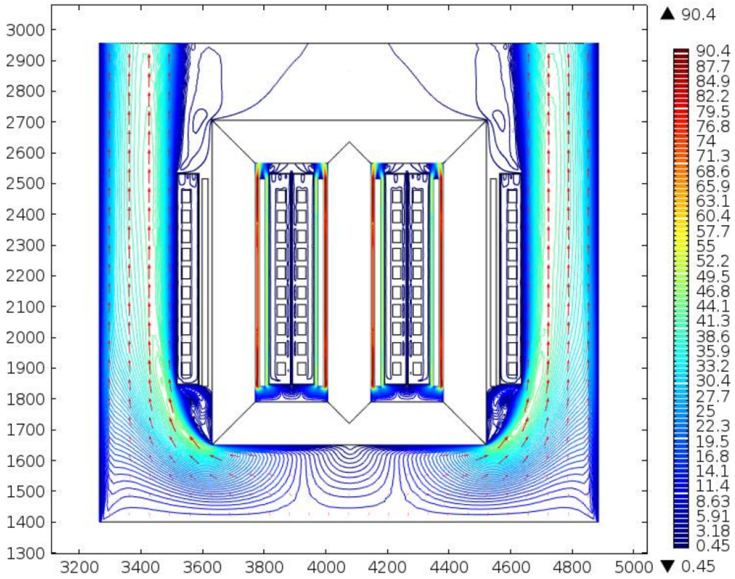


Figure 12. The radial component of the flow field (at 40 °C maximum).

Radial velocity changes inside the analyzed region and, as expected, its values increase in narrow areas. Moreover, the movement of SF6 gas inside the tank can also be seen in Figure 12. One important conclusion drawn from this model is that the variation in viscosity and density improves cooling.

Figure 13 shows the temperature distribution and hot spot point.

In Figure 13, hot spot temperature is 85.17 °C at the maximum ambient temperature of 40 °C, occurring at the top inner windings. For comparison, the hot spot temperature is 103.94 °C occurring at the middle-top inner winding for 2.5 MVA epoxy cast resin transformer (Figure 14).

4. Conclusions

Power and distribution transformers are the key components in power networks, and any failure of them may cause catastrophic results and loss of profit. For a healthy transformer, both electrical and mechanical aspects play an important role in power network operation.

This work addresses the opportunity of gas-insulated distribution transformers in the theoretical study describing the flow behavior of fluids (SF6 and air). SF6 is used for insulating material inside the transformer tank. The proposed model is first tested electrostatically, and then heat analysis is applied to both models (SF6

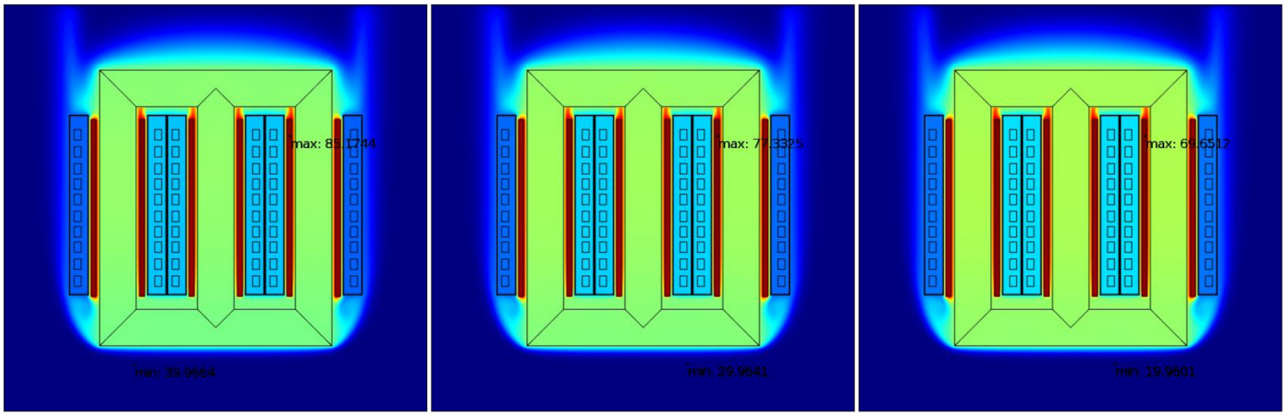


Figure 13. Location of hot spot and the lowest temperatures inside the tank at 40 °C (left), 30 °C (middle), and 20 °C (right) temperatures.

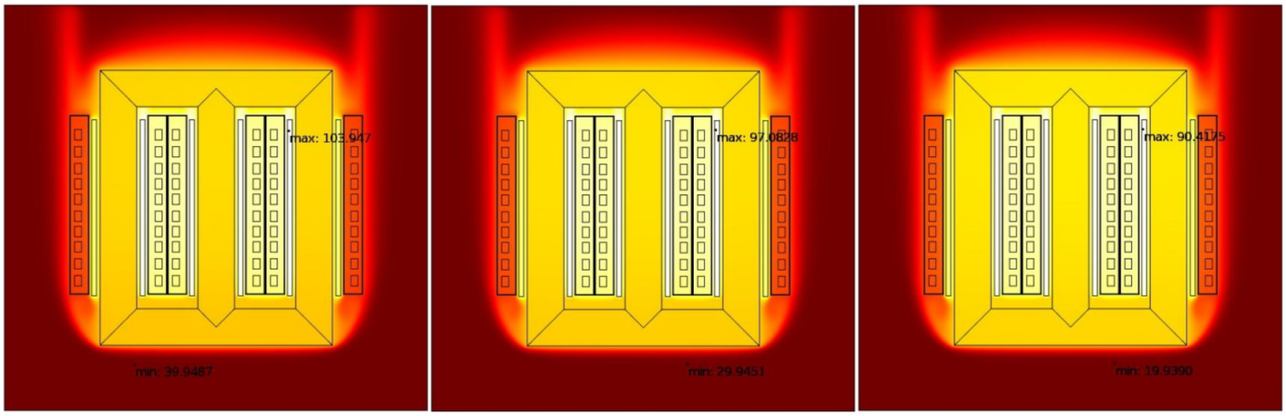


Figure 14. Temperature distribution for the epoxy cast resin transformer cross-section at 40 °C (left), 30 °C (middle), and 20 °C (right) temperatures.

and epoxy cast resin insulated) to analyze temperature hot spots. Electrostatic analysis is performed using 3D models, whereas 2D models are used in heat analysis due to the heavy computational burden. A finite element method with the associated dynamic equations is used for both electrostatic and heat analysis.

The computer simulations presented by the authors are thought to give accurate estimations with a reasonable accuracy and will be pioneers for the real-time implementations to optimize the transformer design with respect to hot spots.

Acknowledgment

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