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SF6 gas-insulated 50-kVA distribution transformer design

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Abstract: There are increasing environmental concerns such that governments are pressured to cooperate with international concurrences. One of the most harmful contaminants is mineral oil when it infiltrates the soil. Although it is a good material in the act of insulating in distribution/power transformers, it presents some environmental hazards and safety disadvantages. For this reason, gas-insulated transformers are considered particularly for hazardous locations. An oil-insulated distribution transformer of 50 kVA, 34.5/0.4 kV, and 50 Hz is investigated and converted to SF6 gas-insulated transformer in this study. The suggested distribution transformer model with SF6 insulated has many benefits, such as being explosion-proof and light, with a compact design. Therefore, the new design provides a safer transformation for security risk environments such as nuclear power plants, mines, and submarines. The prototype is more compact and proposes lighter designs between 25% and 55% as compared to conventional oil-insulated transformers. COMSOL is used for modeling and breakdown optimization studies.

Key words: Distribution transformer, SF6, gas-insulated, electrostatic, heat, COMSOL

1. Introduction

In the design, manufacture, assembly, and installation of transformers some of the important requirements are being explosion- and fire-proof, operational safety, and environmental awareness. There are some limitations of oil-insulated transformers, such as the requirement for a fire-extinguishing appliance, long clearance length, extra insulation costs, low ignition value, and toxic and expensive soil-spill cleanup costs. Explosion is another danger for oil-insulated transformers. Since small-size transformers can be located very close to loads (consumer points), this is of particular importance for them [1–3].

Consumer demand increases with developing technology, forcing distribution transformers (both oil and dry types) into working at rated power. This situation brings about a temperature rise inside the transformer tank as well as aging of the insulation materials in oil. Oil in transformers is used for insulation and cooling. The oil's health acts directly on the working life and efficiency of the transformer. Hence, to maintain reliable insulation, oil is regularly tested and treated to clean (purify) the oil of furanic components (to increase the breakdown level) if needed. The environmental impact of the transformer and terms of working conditions may delay the degeneration of oil [4,5].

The weight of oil in oil-insulated power transformers is almost half of the total weight. In this case, both manufacturing and handling costs lead to serious expense. Also, transformer oil is subjected to excise tax;

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accordingly, in recent years, its price has been high. Therefore, the proposed SF6 gas-insulated transformer presents a more reliable solution for today's power network [6,7].

SF6 gas has been used in industry since the 1950s due to its inherent properties of being nontoxic, having heat exchanging capacity and dielectric stability, and so on [8]. Its first usage in industry was inside circuit breakers, dating back to the 1970s [9]. Subsequently, it has been used in high voltage substations, switchgears, cables-lines, and measurements transformers [10–13]. It is not possible to see some of these examples in Turkey as of today. However, after the oil crisis in 1973, scientists tended to use cheaper solutions, which could be obtained easily for economic reasons by mixing the SF6 with the other gases to obtain an optimal solution [14,15].

2. Definition of the SF6 gas-insulated transformer (GIT) model

The model proposed in this paper is an extended version of that in [1]. In this paper, a new distribution-type transformer model with SF6 gas insulation is proposed. The model has very complex details, including almost every component to examine the electrical field/voltage breakdown levels. A real transformer model of 50 kVA, 34.5/0.4 kV, and delta/star connection is studied in this paper. The breakdown voltage characteristics of the models are then compared to the original model, i.e. the oil-insulated 50-kVA model that is widely used in distribution systems. The proposed transformer model is much lighter than the oil-insulated one and has an explosion-proof design. It can also be designed with a compact structure.

Figure 1a shows the 50-kVA GIT, while Figure 1b shows the meshed structure of the analyzed transformer. The meshing procedure consists of tetrahedral elements for the analyzed models. It is the most general meshing technique using tetrahedral elements and does not pose any limitations on the structure of the geometry. A meshing procedure with small elements has been applied to the regions where electric field concentrates in models. The tank is pressurized with SF6, which is used for both insulation and cooling purposes. Cooling fins are the same as in the oil-insulated transformer in the new type. The high and low voltage connections are also the same as in the oil-insulated transformer. During a gas leak from the transformer tank for any reason the risk is minimum because SF6 is flame-proof and nontoxic [16]. Windings of the transformer and the cooling of the core up to 50-kVA ratings can be acquired using natural air circulation. The cooling process is achieved by natural convection inside the transformer tank. Natural convection is said to enough for cooling the transformer, requiring no additional cooling components for the proposed design. For those transformers whose ratings are higher than 50 kVA, natural convection may not be very effective. Since the transformer is loaded, according to the results of winding temperature, positive gas pressure will be increased to a degree. If further cooling is desired, a simple solution is to increase the gas pressure inside the tank, and its possible effects are studied later. Negative gas pressure studies can also be done according to the loading condition of the transformer (from out of service to full load). However, that is omitted in this study. As stated, SF6 is a nontoxic and inert gas due to its specifications and is well suited for use in transformers. Its density is more than 5 times that of air, and therefore it is suitable for pumping the gas into the lower section of the transformer. The parameters that play important roles in cooling and insulation can be found in the literature [17].

Extensive research has been done to see the SF6 breakdown strength, taking into account temperature rise inside the tank, with a series of computer simulations. It was assumed that there was no partial discharge when obtaining these curves [18].

It is well known that partial discharges occur where electric field distribution is nonuniform and they

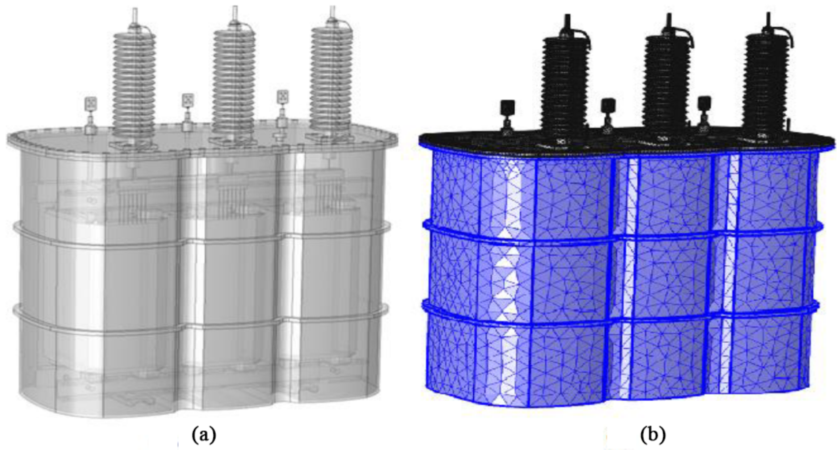

Figure 1. Transformer model under analysis: a) general view, b) meshed view.

will lead to severe short circuit currents if voltage level increases. To avoid unwanted partial discharges in the SF6 environment, gas pressure should be selected as appropriately as possible. In this work, after extensive computer simulations, it is selected as 2–3 atm.

Inside the transformer tank, critical points between the high voltage windings and core materials are defined and the associated electric field and breakdown voltages are calculated by simulation. Analytically, Eq. (1) is then used to obtain the breakdown voltage of SF6 [19].

$$V_{SF6} = 1321pd^{0.915}kV \quad (1)$$

V_{SF6} is calculated analytically using Eq. (1) and the finite element method by computer simulation for the selected critical points. Since the electric field is nonuniform, the multiplication of SF6 pressure and distance between the selected points is calculated within the range of $50 \leq pd \leq 1200$ for the simulations.

Figure 2 shows the breakdown voltages of SF6 gas with respect to the multiplication of pressure and electrode gap in kPa cm [19].

As shown in Figure 2, the larger the product $p.d$ applied to transformer tank, the larger breakdown voltage is obtained.

2.1. Model definition

A 3D model of the SF6 GIT is used for computer simulations and almost all components (core, yoke and its connections, windings, screening elements, supporting materials, and so on) are included in the 3D model.

All the details are included for the model, such as tank, high voltage (HV) and low voltage (LV) bushings, SF6, yokes, core, supporting woods, arc sparking gap, and tap changer on the HV side. Figures 3 shows the details of the proposed model.

In Figure 3, the model includes the tank, SF6 gas, HV winding, dielectric barrier (made of wood), tap changer, core and yokes, HV insulation, sparking gap, LV bushing, winding barriers (made of wood), and LV winding.

2.2. Computer simulations

COMSOL Multiphysics 5.2a is used for computer simulations in this project. Five different materials are used to model the SF6 GIT in the simulation environment. These are wood with ε_r 3, copper, filled epoxy resin with ε_r 3.6, soft iron, and SF6 with ε_r 1.0204.

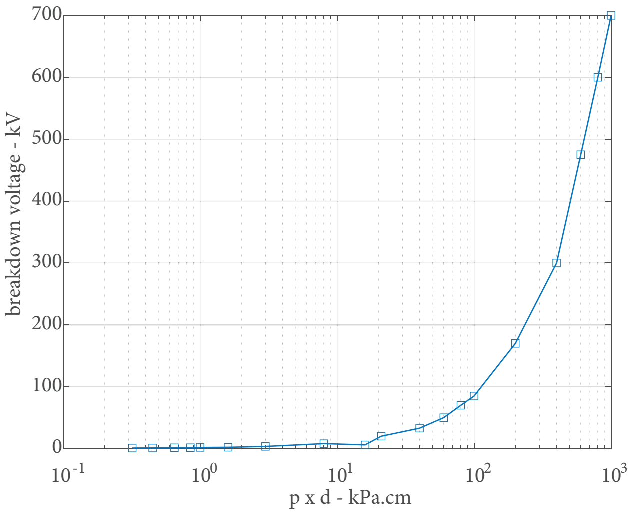

Figure 2. Breakdown voltages of SF6 gas with respect to $p.d$ in kPa cm.

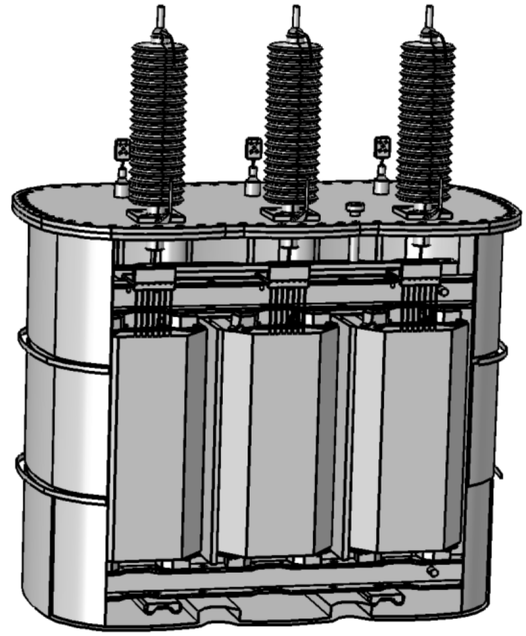

Figure 3. Inner parts of SF6 GIT of 50-kVA model.

Breakdown voltages and electric field strengths are calculated in the electrostatic solutions between the defined lines. Three sample lines are selected according to their importance levels for Phase A winding (Figure 4). For instance, line 1 is between the corner of the HV winding and the nearest corner of the LV winding. Line 2 is between the HV winding and the nearest corner of the dielectric barrier, and, finally, line 3 is between the HV winding and the nearest corner of the yoke.

2.3. Analysis under lightning impulse voltage for 50-kVA SF6 GIT

In this particular example, it is assumed that Phase B is exposed to lightning overvoltages during normal operating conditions. The standard lightning overvoltage of 1.2 – 50 μs in Eq. (2) is applied according to IEC 66076-3 [20].

$$V_L = 175000(e^{-14600t} - e^{-2469135t}) \quad (2)$$

Figures 5–7 show the simulated electric fields on the selected lines for Phase B where lightning overvoltage is applied.

The value of simulated electric fields for Figures 5–7 is below the Ed_{max} curve. For Figure 5, the value of the simulated electric field (125.05 kV/cm) is under the Ed_{max} curve at 231 atm $\times$ cm. At this point, SF6 gas pressure is equal to 1.59 atm inside the tank. Therefore, any SF6 gas pressure inside the tank above the $Ed_{\max}$ curve is desirable. For instance, if SF6 gas pressure is selected at 1.59 atm (231 atm $\times$ cm), the breakdown voltage will be 191.05 kV, which is much more than the peak value of lightning overvoltage (170 kV).

2.4. Heat analysis of 50-kVA distribution transformer

The economic impact on the operation of distribution transformers is of vital importance for power networks. The thermal aspect, among other operational status indicators, plays an important role because it is directly

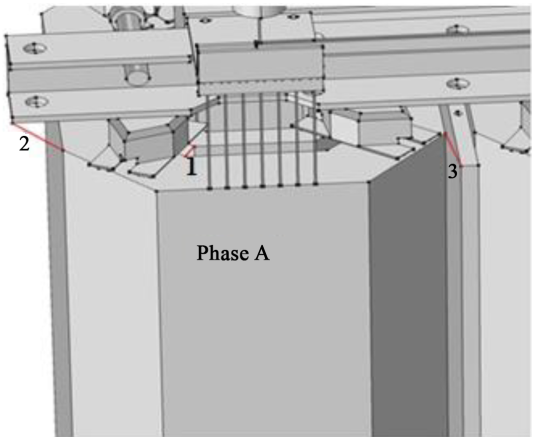

Figure 4. The lines (1, 2, and 3) under electrostatic analysis.

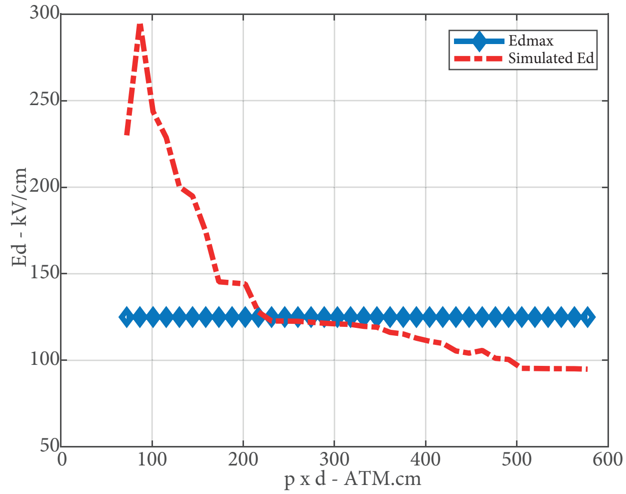

Figure 5. Electric field for selected point 4 for B phase where lightning overvoltage is applied.

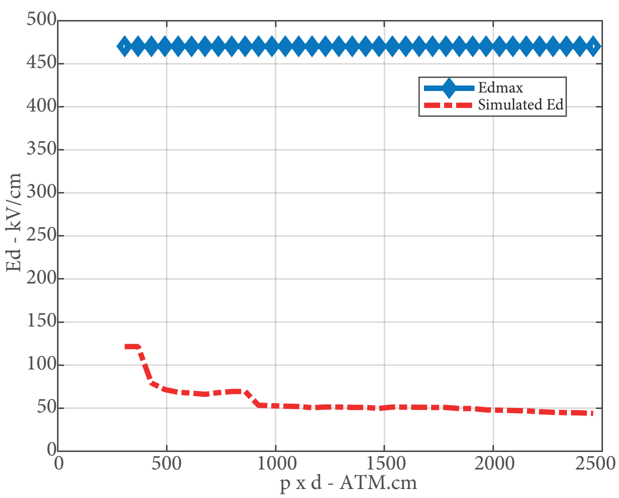

Figure 6. Simulated electric field for point 5 for B phase where lightning overvoltage is applied.

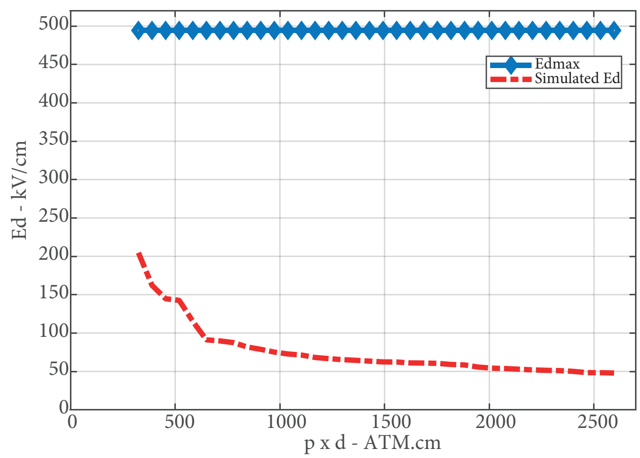

Figure 7. Simulated electric field for point 6 for B phase where lightning overvoltage is applied.

related to the life (aging) of the transformer. An unwanted outage of transformers may cause loss of profits and lead to power quality problems. To avoid overheating and aging, a sufficient cooling system should be designed for transformers. Therefore, thermal analysis for transformers under rated load should be required to define the location of maximum temperature inside the tank.

For this purpose, heat analysis of the proposed SF6 GIT is also performed on the 2D model (Figure 8). 3D modeling is avoided because the solution takes too much time and yields very large files, up to GB levels.

The simulation includes the nonisothermal flow of SF6 gas inside the transformer tank. The aim of the study is to demonstrate the coupling between energy transport through conduction, convection, and radiation (all three forms of heat transfer) induced by density changes in SF6. LV windings are assumed to operate on rated load (50 kVA with 0.9 power factor) and are modeled as heat sources. They transfer heat from the source to the SF6 gas (conduction heat transfer). Then convection heat transfer drives the SF6 gas inside the tank

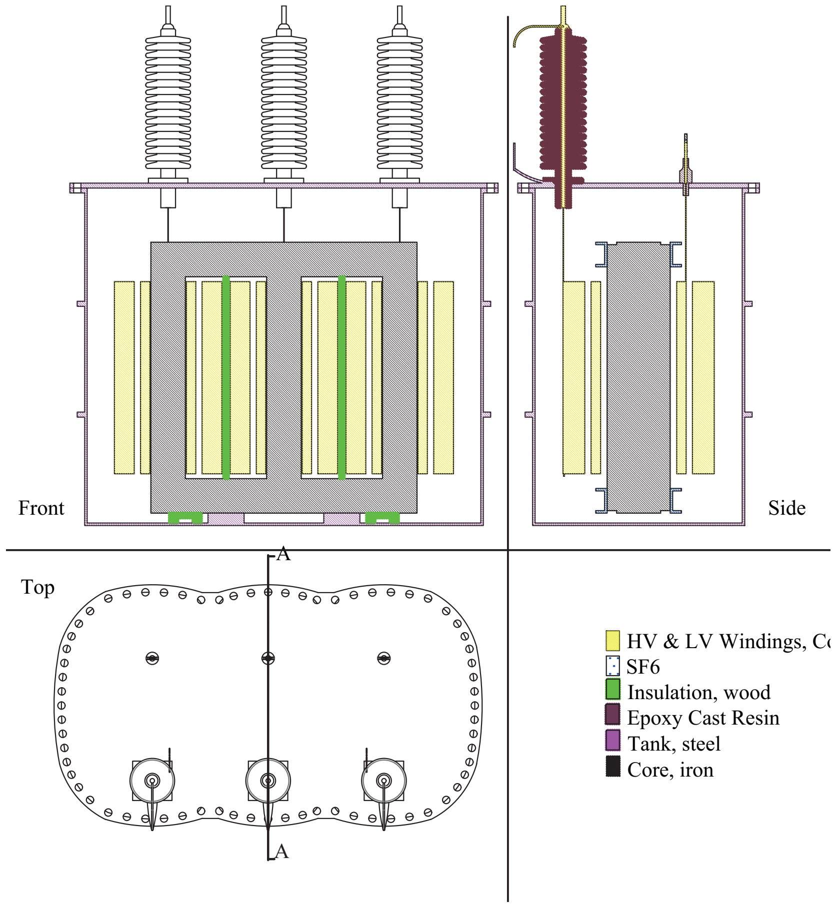

Figure 8. Front, side, and top views of the SF6 GIT.

and transfers the heat to HV windings and core materials. Finally, surface-to-surface and surface-to-ambient radiation is added to simulate the shading and reflections between the radiating surfaces.

As the LV windings are heated with a full load current, the heat generated is transported to the surroundings through conduction, convection, and radiation. During this process, while insulating the medium (SF6 environment), its specific parameters such as pressure and viscosity with respect to temperature are changed. To obtain temperature-dependent equations of pressure and viscosity, curves from the literature are used [21], as defined in Eqs. (3)–(6).

Eq. (3) gives the thermal conductivity, $k[W/(cm.K)]$.

$$k = -4.1 * 10^{-6}T^2 + 0.0081T + 1.1 \tag{3}$$

Eq. (4) gives the heat capacity at constant pressure, $C_p[J/(kg.K)]$.

$$C_p = -1.306 * 10^6 T^{-1.224} + 2956 \tag{4}$$

Eq. (5) gives the density, $\rho[g/L]$, and finally Eq. (6) gives the dynamic viscosity, $\mu[m.Pa.s]$.

$$\rho = p0 * M_{SF6}/(0.0821T) \tag{5}$$

$$\mu = 3.9 * 10^{-5}T + 0.015 \tag{6}$$

In Eqs. (3)–(6), T is temperature in K, $p0$ is the initial pressure, and M_{SF6} is the molar mass, which is 146.055 g/mol.

Eqs. (3)–(6) are fitted with the minimum RMS error. The heat source in the model is the LV winding, which is rectangular in shape.

The nonisothermal flow of SF6 gas, an insulating material, is defined in Eq. (7) [22].

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

$$\rho g\frac{d\rho}{dt} + \nabla.(\rho u) = 0 \tag{7}$$

Here, 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.

Heat transfer in SF6 is defined in Eq. (8) [21].

$$\rho C_p\frac{dT}{dt} + \nabla.(-k\nabla T) = -\rho C_p u.\nabla T + P_{total} \tag{8}$$

Here, P_{total} is the total rated power.

2.5. Boundary conditions

Inside the transformer tank with the use of SF6 surface-to-surface radiation is assumed and it enables radiation from the surfaces of the heat source to all inner surfaces. It is also assumed that the tank surface is surrounded by air and the convection is defined as surface-to-ambient radiation. The ambient temperature is defined according to IEEE C.57.12.00 as 40 °C max., 30 °C daily average, and 20 °C yearly average.

Figure 9 shows the contour graph of the flow field inside the tank at the ambient temperature of 40 °C. The arrows indicate the flow direction.

Similarly, Figure 10 shows the temperature of the hot spot inside the tank at the maximum temperature. As expected, the upper right and left corners of the Phase B winding do not have the highest temperature; rather, it is observed in the slightly upper portion of the middle point of the core.

Hot spot temperature is calculated as 60.08 °C. The results are also compared to the oil-immersed transformer example of the same model. The temperature-dependent parameters of the analyzed oil are given below [22].

$$Density = 875.6 - 0.63T[kg/m^3] \tag{9}$$

$$Dynamic\_vis\cos ity = density * 10^{(-4.726-0.0091T)}[m^2/s] \tag{10}$$

$$Heat\_capacity\_at\_cons\tan t\_pressure = 1960 + 4.005T[J/(kg.K)] \tag{11}$$

Figure 11 shows the hot spot temperatures of both oil- and gas-insulated transformers comparatively. The top figures are for the oil-insulated transformer for the ambient temperature of 40 °C, 30 °C, and 20 °C from left

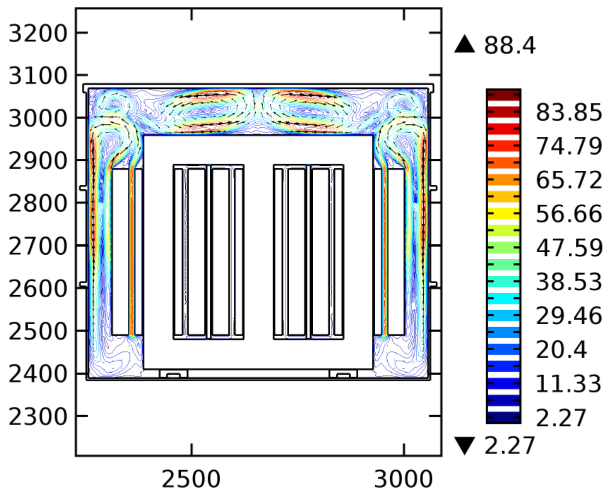

Figure 9. SF6 flow field and direction inside the tank at 40 °C.

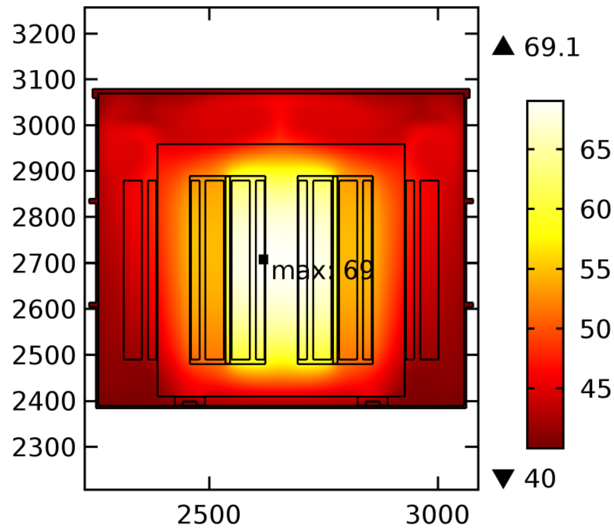

Figure 10. Temperature distribution inside the tank.

to right, respectively. The bottom figures for the gas-insulated transformer are for the ambient temperature of 40 °C, 30 °C, and 20 °C from left to right, respectively.

As is expected, the hot spot point is located at almost the top point of the Phase B winding, whereas the lowest temperature is at the bottom side for an oil-insulated transformer. Surprisingly, the hot spot point is located in the middle point of the phase B winding, whereas the lowest temperature is at the left side for the GIT example.

3. Conclusions

Distribution transformers are the most important elements and any faulty condition may lead to loss of profit and destructive results. In order to have a healthy transformer, there are two aspects that play important roles in power network operation: electrical and mechanical aspects. In this context, this paper investigates SF6 as an alternative insulation material compared to transformer oil and gives useful explanations. The detailed model of a 50-kVA distribution transformer is used for computer simulations. In these simulations both electrostatic and heat analyses are performed. Electrostatic analysis is used for obtaining the maximum breakdown electric field between the critical points in tank. The hot spot point/region is obtained using heat analysis during the rated load condition. Apart from these outcomes this paper simply analyzes the use of SF6 as an insulating material instead of using oil. As seen from computer simulations, the use of SF6 has many advantages over transformer oil in terms of manufacturing processes and hot spot concepts. The computer simulations obtained by finite element technique will help researchers and engineers working in the field of transformer manufacturing.

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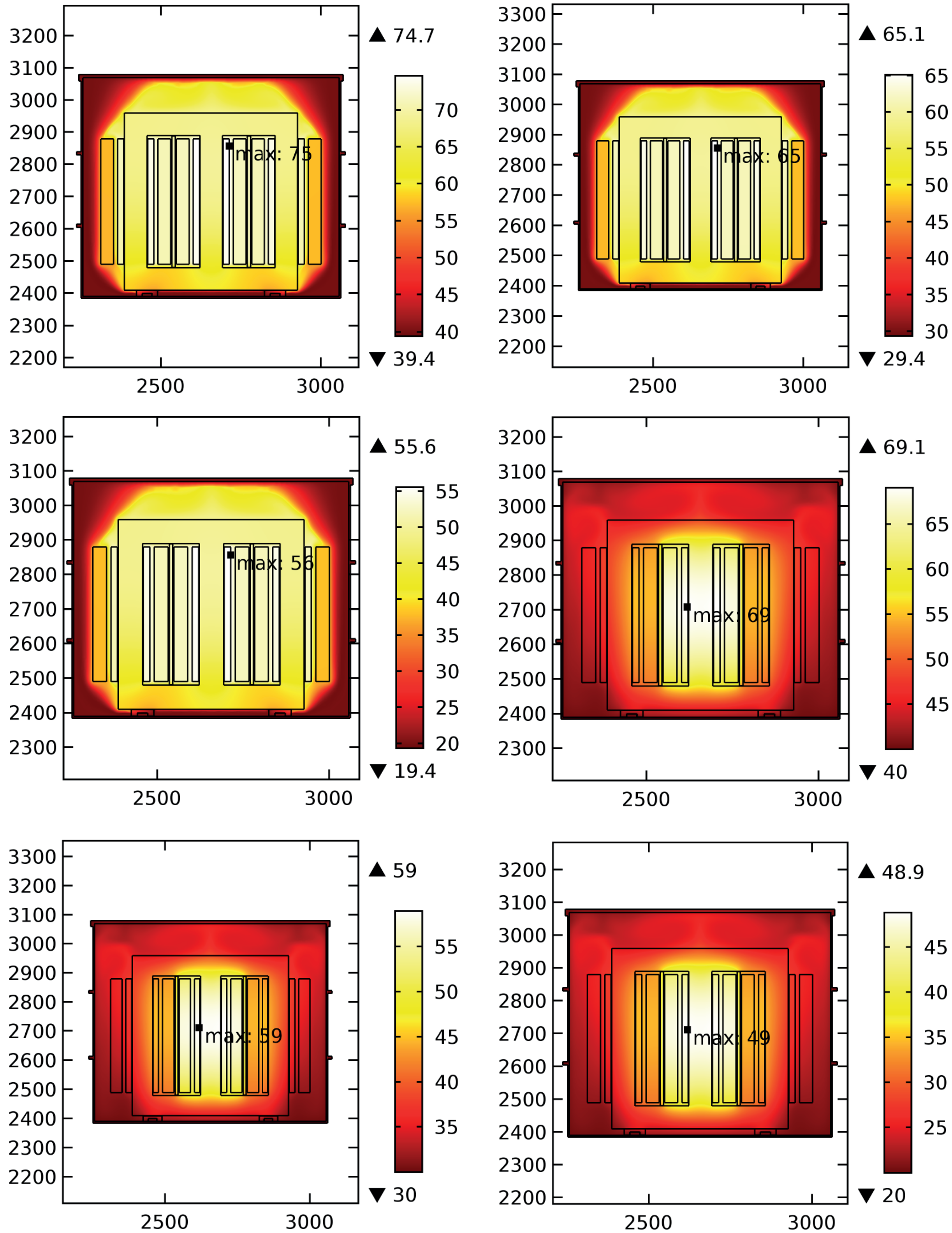

Figure 11. Simulating the hot spot and the lowest temperatures inside the tank for oil and gas insulation according to IEEE C.57.12.00.

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