R410A Gas Insulated 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 in filtrates the oil. 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 (GITs) are considered particularly for hazardous locations. An gas insulated distribution transformer of 50 kVA, 34.5/0.4 kV is designed and investigated on Comsol Multiphysics environmental in this study. The suggested distribution transformer model with R410A 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 GITs are 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.

Keywords: Distribution transformer, R410A, gas-insulated, electrostatic, heat, COMSOL

Introduction

In the design, manufacture, assembly and installation of transformers some of the important requirements are; protection of the environment, operational safety, minimizing maintenance requirements and the risk of fire. Oil insulated transformers have some limitations such as; low ignition value, additional insulation costs, requirement for an extinguishing apparatus, long clearance distance, toxic and expensive soil spill cleanup costs. Explosion is another danger for oil-insulated transformers. This is especially important for small-size transformers because they can be located very near to loads. There are many examples of underground and public substations for economic and environmental reasons in large cities where safety is of high concern. One of the most important factors in the transmission and distribution of electrical energy is, of course, cost. High voltage should be used where appropriate to minimize losses. However, as the voltage level increases, insulating problems occur. Distribution transformers are located near to the end-users to the greatest extent possible. Supplying electrical power to strategic buildings and large machines power or distribution transformers are usually manufactured oil or dry types. Dry type transformers have limited power ratings of 10 kVA–50 MVA due to inefficient cooling. In contrast, oil-type transformers are manufactured in a wide power range and have a very wide application area [1-4].

Therefore, the proposed R410A gas-insulated transformer project is deemed to be a more reliable solution for today's distribution network [5-8]. For this reason, R410A gas is investigated as an insulating material instead of transformer oil in this paper.

This paper proposes an R410A gas-insulated transformer (GIT) design on complex distribution transformer models and investigates the optimal gas pressure to maximize the insulation level and breakdown voltage limits for a given distribution transformer model. A 50kVA indoor/outdoor distribution transformer is investigated. The breakdown voltage characteristics of the models are then compared to original models, i.e., oil-insulated 50kVA, which are widely used in distribution systems. The proposed transformers are quite light and environmentally friendly compared to oil and epoxy casting resin types. Consequently, the use of R410A gas as a dielectric insulating material will bring about many advantages, such as optimum design and reduction of maintenance costs. Thus, it will allow the efficient use of our country's own resources and increase competitiveness.

Theory

In recent years, the gas insulating principle has been used in high-voltage equipment in terms of reliability, breakdown strength and working life. The expected features from gas used in high-voltage devices can be listed as follows:

- High electrical breakdown strength
- Liquids temperature as low as possible to allow high pressures at different operating temperatures
- The specific heat of the gas
- Thermal conductivity coefficient
- The cooling and arc-extinguishing capabilities of the gas linked to viscosity coefficient
- Maintaining its specific properties during electrical discharges
- Not entering into chemical reactions with other gases
- No inflammation
- Non-toxic

In the proposed study, the required design criteria of R410A gas insulated transformers will be achieved with the aim of meeting today's energy needs in an economical way. The most important step of this project is to obtain tank pressure, heat effects and breakdown curves at homogeneous and inhomogeneous electric fields on complex 3-D transformer models.

The following figures show the R410A gas-insulated distribution transformer examples of 50kVA and 2500kVA.

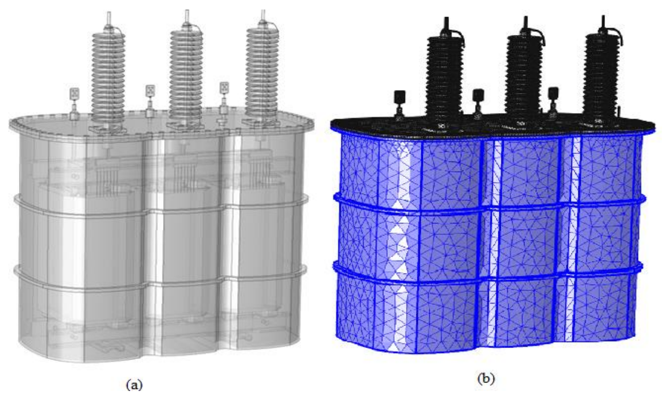

Figure 1. 50 kVA, 34.5/0.4 kV R410A gas-insulated distribution transformer, a) general view, b) meshed view

Figure 1a shows the 50kVA GIT, while Figure 1b shows the meshed structure of the analyzed transformer. The original transformer type for Figure 1 is oil insulated. As seen in the figure, the overall design will be cylindrical shape to allow high pressure and homogeneous gas distribution inside the tank. Core and windings are insulated R410A gas that serves both insulation and cooling. The design of the tank and the cooling element are similar to oil-insulated transformer design. The tank is hermetic and safe to the touch. High-voltage inputs are the bushing type, while the low-voltage ones are bar-type bushings. If for any reason an R410A gas leak occurs, the hazard is minimized as it is an inert gas and not flammable [9].

As the transformer is loaded, positive gas pressure will be increased to a degree by the result of winding temperature. An increased gas pressure will help to increase natural gas circulation and contributes the cooling of the windings, and its effects will be analyzed in the proposed transformer. Besides, negative gas pressure studies can also be done according to the loading condition of the transformer. However, it is omitted in this study. Consequently, the most effective cooling elements and gas pressure in the tank will be determined as a result of this research paper.

R410A GIT model is a general distribution transformer that has 50kVA, 34.5/0.4kV ratings, and all technical drawings belong to a real 3-D model in mm. All the details are included inside the model such as tank, high-voltage (HV) and low-voltage (LV) bushings, R410A, yokes, core, supporting woods, arc sparking gap and tap changer in HV side. Figure 2 shows the details of the proposed model.

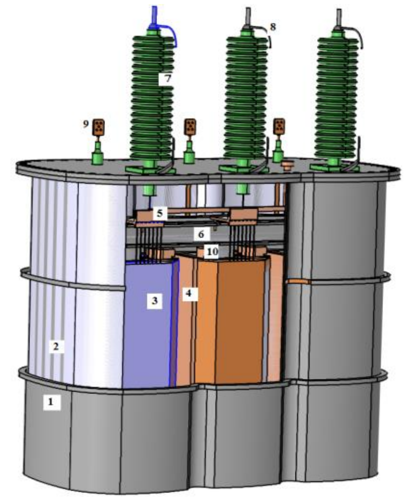

Figure 2. R410A GIT of 50kVA for major details

Stationary and time-dependent solutions are performed for each transformer model. For the stationary solution, breakdown voltages are obtained at the time of 5 msec of peak input voltages, i.e., Phase A voltage is 50192 V and 565 V, and Phase B and Phase C voltages are -25456 V and -282 V for HV and LV windings, respectively.

Simulation

The Comsol Multiphysics 5.2a is used for computer simulations. Five different materials are used to model R410A GIT in simulation environment. These are wood with εr 3, copper, filled epoxy resin with εr 3.6, soft iron and R410A with εr 2.0. In electric field calculations, the norm of the electric fields Ed_x, Ed_y, Ed_z is used in (1).

$$Norm(E) = \sqrt{E_{dx}^2 + E_{dy}^2 + E_{dz}^2} \quad (1)$$

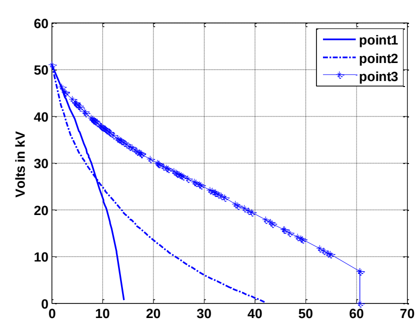

Figure 3. The voltage levels of points 1, 2, and 3 with respect to arc length for Phase A

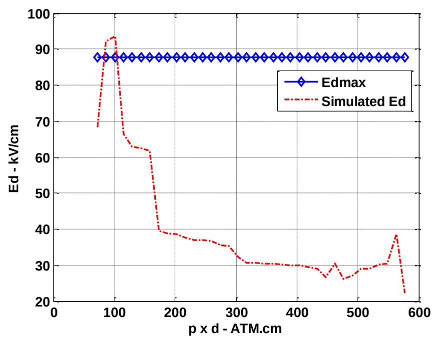

Figure 4. Simulated electric field for point 1 for Phase A

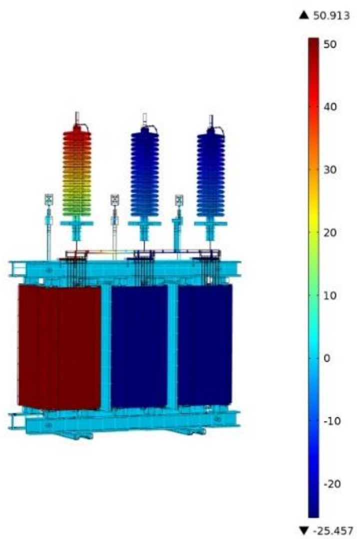

Figure 5. Potential distribution inside the tank in kV

Potential distribution is given in Figure 5. Tank, upper cover and R410A gas units are hidden to see the details of voltage variation inside the tank.

Analysis Under Lightning Impulse Voltage for 50 kVA R410A GIT

In this particular example, it is assumed that Phase B is exposed to lightning over voltages during the normal operating condition as seen in Figure 6.

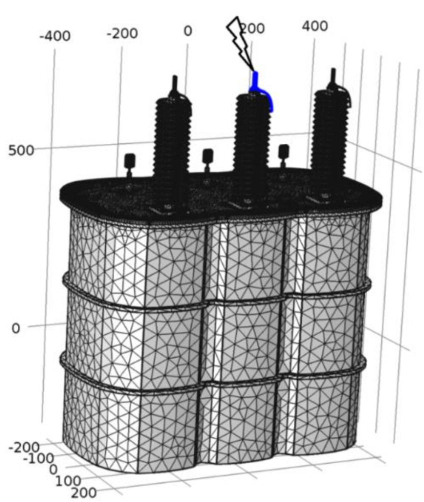

Figure 6. Transformer under lightning voltage during normal operation (according to IEC 660076-3)

Figure 7 shows the electric potentials of all the windings at the time of peak voltages.

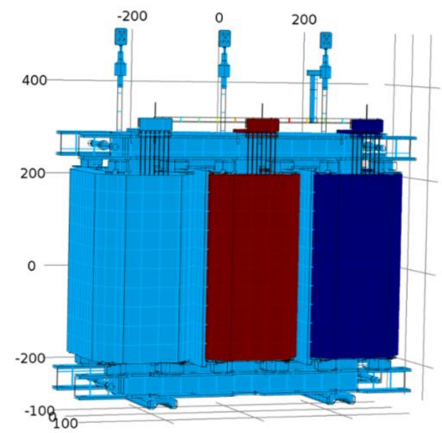

Figure 7. Surface graph of peak electric potentials during lightning impulse

Heat Analysis of 50kVA Distribution Transformer

Economic impact on the operation of distribution transformers is of vital importance for power networks. Thermal aspect, among other operational status indicators, plays an important role because it is directly related to the life (aging) of the transformer. An unwanted outage of transformers may cause loss of profits and lead to power quality problems [10]. 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 R410A GIT is also performed on the 2-D model (Figure 8). The simulation includes the non-isothermal flow of R410A 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 R410A. Low-voltage windings are assumed to operate on rated load (50kVA with 0.9 power factor) and modeled as heat sources. They transfer heat from the source to the R410A gas (conduction heat transfer). Then, convection heat transfer drives the R410A gas inside the tank 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, R410A gas is heated and its density, viscosity and pressure changes inside the tank. The performance curves are used to obtain the temperature dependent variables of R410A gas (Eq. 2–5).

Thermal conductivity, k [mW/(m*K)]

$$k = 0.004244T^2 + 0.01767T + 12.61 \quad (2)$$

Heat capacity at constant pressure, Cp [kJ/(kg*K)]

$$C_p = (-1.049E-7)T^3 + (2.772E-6)T^2 - 0.001708T + 1.915 \quad (3)$$

Density, ρ [kg/m^3]

$$\rho = 41.91\exp(0.0244T) - 12.53\exp(0.00895T) \quad (4)$$

Dynamic viscosity, μ [mPa*s]

$$\mu = (8.489)T^2 + 0.005353T + 12.63 \quad (5)$$

In (4–7), **T** is temperature in K, $p0$ is the initial R410A gas pressure, and M_{R410A} is the molar mass of R410A where 72.585 (kJ/kg).

Eq. 2–5 are simply fitted according to minimum RMS error. The LV winding as a heat source is in a rectangular shape, neglecting any internal effects inside it.

The non-isothermal flow in the R410A is given in (6).

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

$$\rho g\frac{d\rho}{dt} + \nabla.(\rho \mathrm{u}) = 0 \quad (6)$$

where ρ is the density, u is the velocity (m/s), μ is the dynamic viscosity, p is the R410A gas pressure (Pa) and g is the gravity constant (m/s^2).

The conductive and convective heat transfer inside the R410A is given in (7).

$$\rho C_p\frac{dT}{dt} + \nabla.(-\mathrm{k}\nabla \mathrm{T}) = -\rho C_p u.\nabla \mathrm{T} + P_{total} \quad (7)$$

where P_{total} is the total rated power of R410A GIT.

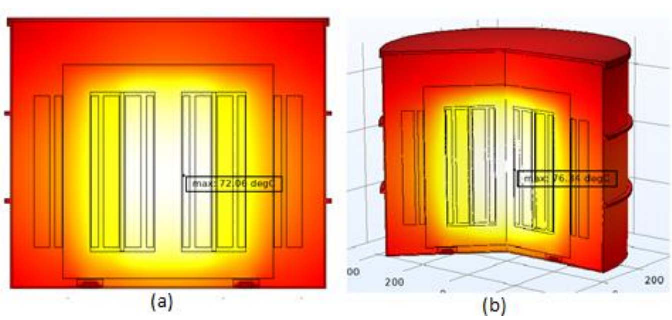

Figure 8. Temperature distribution (hot points) inside the tank. (a) 2D and (b) 2D axial symmetry analysis

Hot spot temperature is calculated as 72.06℃ for 2D analysis and 76.34℃ for 2D axial symmetry analysis in Figure 8.

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 handles the opportunity of gas-insulated distribution transformers in the theoretical study describing the flow behavior of fluids (R410A, air and transformer oil). R410A is used for insulating material inside the tank. Electrostatic analysis is performed on 3-D models, whereas the heat analysis is achieved on the 2-D models due to heavy computational burden. Finite element method with the associated dynamic equations is used for both electrostatic and heat analysis.

The computer simulations presented by the authors are believed 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.

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