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A thermal analysis for a switchgear system

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Abstract

Distribution of electrical energy is important. Particularly during the management of power transmission networks, many critical systems enter the circuit and perform important functions. One of the most important of these is the high-voltage switching process, known as switch-mode operation. One of the problems that switching mechanism meets when performing its function is heat accumulation. It is imperative to examine the thermal design and consider design considerations under limited volume and special conditions. In this closed volume, the temperature values produced by these elements were experimentally measured at certain points and then these values were compared with the 3D finite volume based CFD determined values. This comparison demonstrates that the design could be based on CFD analysis values in terms of temperature appearance. This is a valuable contribution for cost minimization and optimal system design approach.

Keywords: *CFD analysis, convection heat transfer, industrial design, switchgear.*

Bir şalter sistemi için termal analiz

Özet

Elektrik enerjisinin dağıtımı önemlidir. Özellikle güç iletim şebekelerinin yönetimi sırasında, birçok kritik sistem devreye girer ve önemli fonksiyonları yerine getirir. Bunlardan en önemlilerinden biri, anahtarlamalı mod olarak bilinen yüksek gerilim altında anahtarlama işlemidir. Bir şalter sisteminin (switchgear mekanizması) işlevini yerine getirirken karşılaştığı problemlerden biri de ısı birikmesidir. Termal sorunlara yol açabilecek bu problemlerden dolayı sınırlı hacim ve özel koşullar altında termal tasarımı inceleyerek tasarım hacmini incelemek zorunludur. Bu kapalı hacimde, bu elemanlar

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tarafından üretilen sıcaklık değerleri belirli noktalarda deneysel olarak ölçülmüş ve daha sonra bu değerler 3B sonlu hacim tabanlı CFD değerleri ile karşılaştırılmıştır. Bu karşılaştırma, tasarımın sıcaklık görünümü açısından CFD analiz değerlerine dayanabileceğini göstermektedir. Bu, maliyet minimizasyonu ve optimal sistem tasarımı yaklaşımı için değerli bir katkıdır.

Anahtar Kelimeler: *CFD analizi, taşınım ısı transferi, endüstriyel tasarım, şalter sistemi.*

1. Introduction

Electricity transmission, distribution, and grid system operations require switchgears which are switching devices, to create on and off states of electrical lines. Thus, control over power flow is maintained and maintenance can be monitored. These devices can be grouped into two main categories, Gas Insulated Switchgear (GIS) and Air Insulated Switchgear (AIS). For gas insulation, in the switchgears sulfur hexafluoride (SF6) gas is used. The SF6 is stagnant and non-toxic gas. Its dielectric strength of 89 kV/cm which is three times more than air under 1 Bar air pressure. It's five times heavier (It's density at 20 ^{o}C and 0.1 MPa which is one atmosphere is ρ=6.139 kg/m^3) than air. SF6 gas also has a high heat transfer characteristic and is a non-flammable gas. Because of these exceptional properties and due to the insulating capability of pressurized SF6 gas, it is suitable for small conductor distances, therefore compact switching stations are realized by SF6 insulation. The insulating gas sulfur hexafluoride (SF6) has even higher cooling capacity as the gas pressure increases. More detailed technical specifications could be gathered from [1].

The analysis of the heat generated in the switchgear cell is a complex phenomenon and caused by the co-occurrence of convective, conductive and radiative heat transfer. However, since the heating occurs in a pressurized cell, it can be considered that the heat transfer phenomenon takes place primarily with natural convection. Permissible temperature increase for a gas insulated switching systems (GIS) has been given in related standard IEC 62271-1, [2]. Analysis methods for temperature increase during design of the GIS are very important. Computational Fluid Dynamics (CFD) is an useful tool for calculating the heat transfer and temperature rise of a power device while considering the actual geometry. Experimental investigations are also carried out to verify the calculated heat transfer of natural convection flows.

2. Literature review

There are specifications about temperature conditions and heat accumulations of switchgears in the standard of IEC 62271-1. This standard guarantee to keep safe conditions and reliability of this switching mechanism under different heating conditions. To overcome these problems, some studies have been completed and published in the literature. A brief literature review can be given as follows.
In study of Kaufmann et al., an experimental verification of convective heat transfer computation for a gas insulated switchgear has been carried out. Specifically, in the annulus of the system has been modeled with a CFD point of view and the annulus setup has also

been observed for turbulence and oscillations. Results showed that Nusselt numbers did not differ significantly between Reynolds Stress Turbulence Model (RSM) and Shear Stress Turbulence Model (SSTM). Flow oscillations have also been observed for gab-based Rayleigh numbers of $3.8x10^7$ and above. Hence, transition to turbulence regimes occurs in that range of Rayleigh number [3].

Kaltenborn and Dong examined the dynamic thermal simulation of the GIS. In this study, thermal network method approach was used. It is determined that the contacts and joints are the heat source, and the verification of the model is presented by experiments. These tests included statistical analysis of load steps, on/off states and load [4]. Singh and Summer mentioned disadvantages of the CFD analysis. These are design difficulties and the high costs of the analysis. Therefore, it is advantageous to combine CFD with Thermal Net Method (TNM) for new designs. As a result, it is stated that this combination can offer many advantages in new designs. Some valuable results have been presented [5].

This work compares some insulating properties of SF6 gas, air and N_2 gas used in the switching systems due to adverse environmental effects. It evaluates the temperature rise of alternative gases. The analysis of the switchgear mid-phase element in three different gases has been carried out. It has been reached that the temperature rise in N_2 and air is lower than the one in SF6, and air as the substitution of SF6 to be the insulating gases in switchgear is feasible [6]. Kitzrow et al. have been studied heat pipes for cooling medium voltage level switchgears. Firstly, it is stated that the generated heat can be dissipated with four different heat pipe applications. A thermal network approach is also proposed for this process. The advantages and disadvantages of the heat pipes connected to the heat generating conductors along the conductor, the heat exchanger application, the external atmosphere connection or the cabinet connection have been evaluated [7].

This study is mainly focused on CFD and experimental study of busbar heat transfer analysis. It is aimed to determine the configuration that will provide the best cooling performance by considering the different combinations and situations [8]. In the study of Gramsch et al. have been introduced a formulation of a mass transfer and a new iterative method of coupling ventilation and thermal networks [9]. In the study of Fjeld et al. experimental and CFD thermal design analysis for medium voltage switchgear is performed. The result is that the 12 kV 630 A switchgear does not exceed the values specified in the standards in the tests. It is also stated that the results of the CFD analysis are in a structure to confirm this [10].

In this study, a switchgear thermal simulation was performed and the reduction of the heating and the distribution of the generated heat were taken into account by the CFD. As a result, it has been concluded that increasing the pressure at contacts can reduce heat build-up and heat generation can be reduced by correct selection of the contact materials [11].

3. Materials and method

First of all, the model is formed in terms of heat transfer and heat accumulation. For the modelling, ANSYS Fluent CFD software is used [12]. System components and solid surroundings of the volume are modeled in 3D (Inventor software).

These parts are extracted from the whole cell volume and the volume of insulation gas is remained. In this insulating gas, some heat generating sources are designated as measured temperature values, and the values are compared to the calculated values and measured values obtained in the evaluation of data points. It is assessed whether these results ultimately confirm each other.

3.1 Fundamental equations for the mathematical model of the CFD

Heating and dissipating process is a complex physical process that combines conduction, convection and radiation, and it could be analyzed by mathematical modeling and numerical calculations. However, it is difficult to carry out this calculation because of the complicated 3D model of the switchgear and the large grid numbers in the numerical calculation.

CFD is based on the three processes of mass transfer, momentum transfer and energy transfer of fluid mechanics to establish the partial differential equations. In CFD, the solution of these equations is obtained numerically using 3D finite volume method.

Mass conservation equation:

The mass conservation or continuity equation is based on the fact that the rate of change of mass inside the fluid element is equal to the net rate of the mass flow into or out of the fluid element across its surfaces.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

where ρ is the fluid density and ν is the velocity vector.

Momentum conservation equation:

The law of conservation of momentum is also the basic law that any flow system must satisfy. Newton's second law states that the rate of change of momentum is equal to the sum of the forces on the fluid. These forces are in general surface forces and body forces. While the surface forces like pressure and viscous forces are normally considered as separate terms in the momentum equation, body forces like gravity and centrifugal forces are in general included in the source term. With this convention, momentum conservation equation in x, y, and z directions can be derived,

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u u) = \nabla \cdot (\eta \nabla u) - \frac{\partial \rho}{\partial x} + S_x \tag{2a}$$

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v u) = \nabla \cdot (\eta \nabla v) - \frac{\partial \rho}{\partial y} + S_y \quad \text{(2b)}$$

$$\frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w u) = \nabla \cdot (\eta \nabla w) - \frac{\partial \rho}{\partial z} + S_z \quad \text{(2c)}$$

where η is the dynamic fluid viscosity, *p* the pressure and *S* is the source term of force.

Energy conservation equation:
The first law of thermodynamics states that the rate of change of energy of a fluid element is equal to the rate of heat supply plus the rate of work done on the element mainly by surface forces. The energy equation expressed in terms of total specific enthalpy,

$$\frac{\partial(\rho \cdot h_0)}{\partial t} + \nabla(\rho \cdot h_0 \cdot \vec{v}) = \nabla(\lambda \cdot \nabla T) + \frac{\partial p}{\partial t} + \nabla((\tau_{ij}) \cdot \vec{v}) \quad \text{(3)}$$

where h_0 is the specific enthalpy, λ is the heat conduction coefficient, *T* is the temperature, and τ_{ij} is the viscous stress tensor.

These studies and many other studies point out that more studies should be carried on the thermal analysis of switchgears for the sake of compactness, environmental expectations and optimization of the complete system. Following part of the study is about a CFD analysis to improve the medium voltage (2500 A) GIS to improve the equipment and its design process.

4. Experimental study

A medium voltage GIS prototype has been tested to meet thermal expectations of the IEC 62271-1. Following temperatures (Table 1.) from the GIS prototype have been gathered. These temperature values have also been used for the CFD analysis.

With this prototype of the switchgear, there is no violation of the standards for the thermal expectations. However, these results are close to upper limits of the standards, because of this, thermal design of the system should be improved and some other new designs could be considered to satisfy all the expectations.

Table 1. Temperature values of the prototype in the thermal regime.

Point	X	Y	Z	Mesur	CFD	Differ.	Point	X	Y	Z	Mesur	CFD	Differ
1	187	244	-312	94,3	92,0	2,30	20	364	1331	-422	89,8	89,0	0,80
2	156	425	-273	97,3	98,0	-0,70	21	589	419	-633	93,2	88,0	5,20
3	160	779	-271	102,9	100,0	2,90	22	156	459	-633	98,3	100,0	-1,70
4	187	903	-301	95,0	98,0	-3,00	23	160	779	-627	105,5	102,0	3,50
5	533	943	-278	94,4	94,0	0,40	24	187	903	-657	100,3	100,0	0,30
6	566	1003	-326	94,3	98,0	-3,70	25	533	943	-633	97,6	94,0	3,60
7	546	1065	-326	93,3	93,0	0,30	26	560	1003	-682	97,0	98,0	-1,00
8	549	1136	-326	90,8	89,0	1,80	27	546	1065	-682	95,0	94,0	1,00
9	548	1191	-317	90,5	87,0	3,50	28	549	1136	-682	91,9	89,0	2,90
10	364	1331	-244	89,2	87,0	2,20	29	548	1191	-673	91,4	87,0	4,40
11	380	363	-448	94,1	88,0	6,10	30	364	1331	-600	89,1	88,0	1,10
12	156	475	-446	96,6	99,0	-2,40	31	38	1164	-731	55,2	56,0	-0,80
13	160	779	-449	107,9	102,0	5,90	32	38	694	-731	49,2	52,0	-2,80
14	187	903	-479	100,9	101,0	-0,10	33	-17	1317	-711	52,7	48,0	4,70
15	533	943	-456	97,2	96,0	1,20	34	-17	502	-711	42,1	40,0	2,10
16	560	1003	-504	97,3	91,0	6,30	35	700	1318	-842	51,8	62,0	-10,20
17	546	1065	-504	95,2	98,0	-2,80	36	107	227	-850	59,3	59,0	0,30
18	549	1136	-504	93,4	91,0	2,40	37	405	403	-631	93,2	88,0	5,20
19	548	1191	-495	92,2	89,0	3,20							

Figure 1 represents the prototype that has been investigated for thermal expectations. Some measured points can also be seen from the Figure 1. Figure 2 shows CFD thermal analysis model that has been used for the ANSYS Fluent. The main components can be seen in Figure 2 are conductive copper busbar, ceramic tubes and steel constructions that affect the flow of SF6 gas.

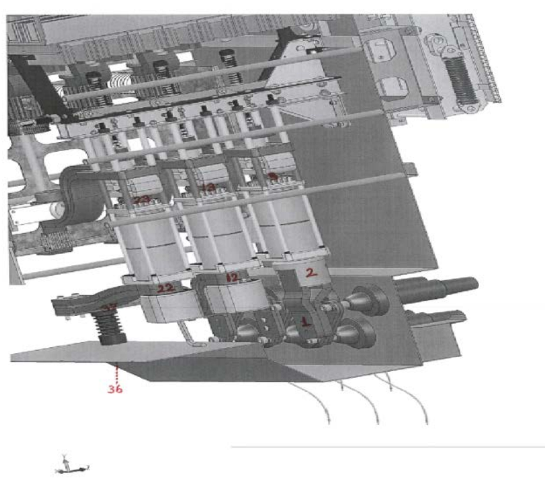


Figure 1. Inner structure of the medium voltage switchgear.

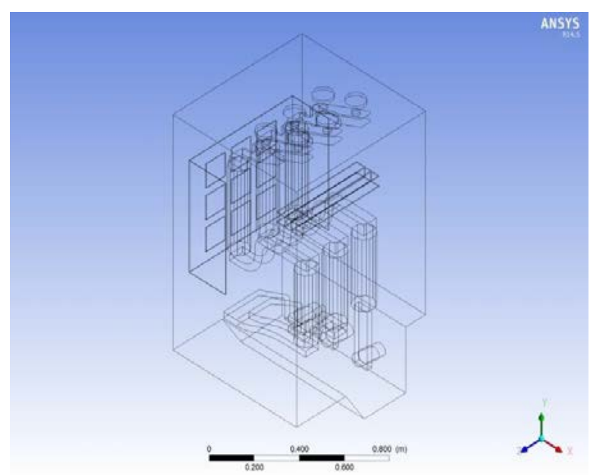
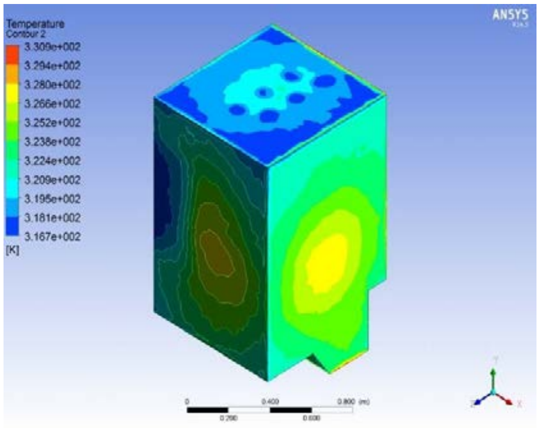
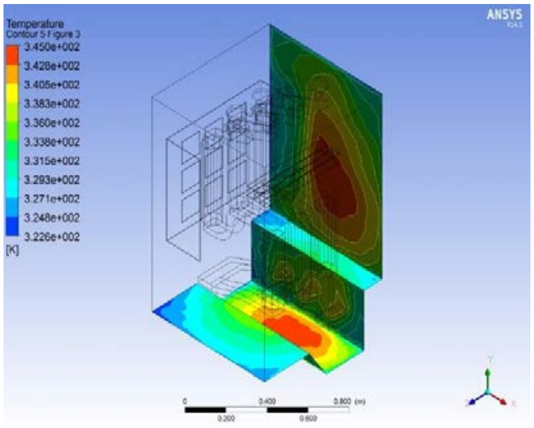


Figure 2. Model of the switchgear and its main components.

From the Figure 3a, it can be seen that the temperature distribution of the exterior walls which the maximum temperature occurs in the center of the surface. Also, Figure 3b shows the temperature distribution of the inner walls. As, it can be seen that center of the wall and the bottom of the sructure have maximum temperature values.





(a) (b)

Figure 3. Comparison of switchgear exterior and inner wall temperature gradients.

Figure 4 and Figure 5 present temperature gradients from inside of the switchgear for different horizontal cross sections.

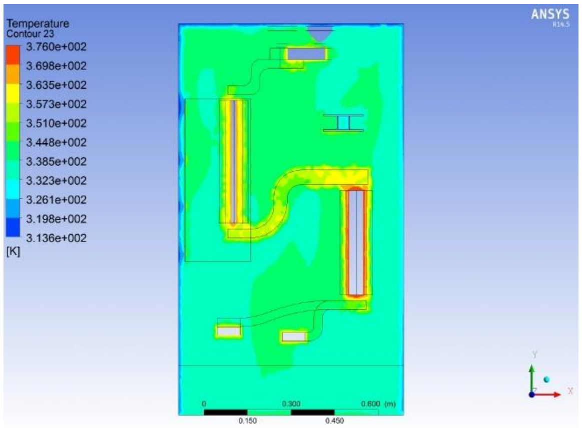


Figure 4. Switchgear horizontal (X-Y) cross section temperature gradients.

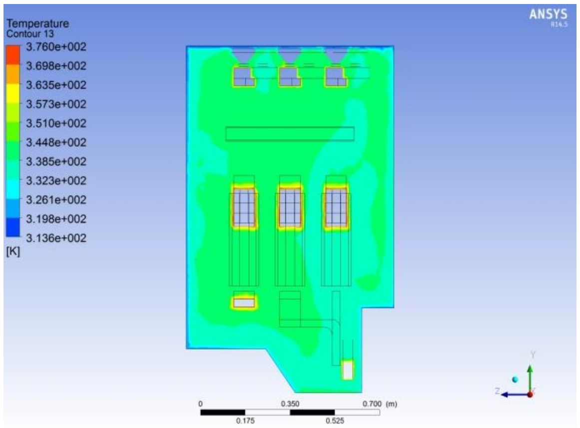


Figure 5. Switchgear horizontal (Y-Z) cross section temperature gradients.

Flow vectors can also help the design process for some improvements (Figure 6). However, flow velocity measurement is not easy task because of their small values and closed volume restrictions.

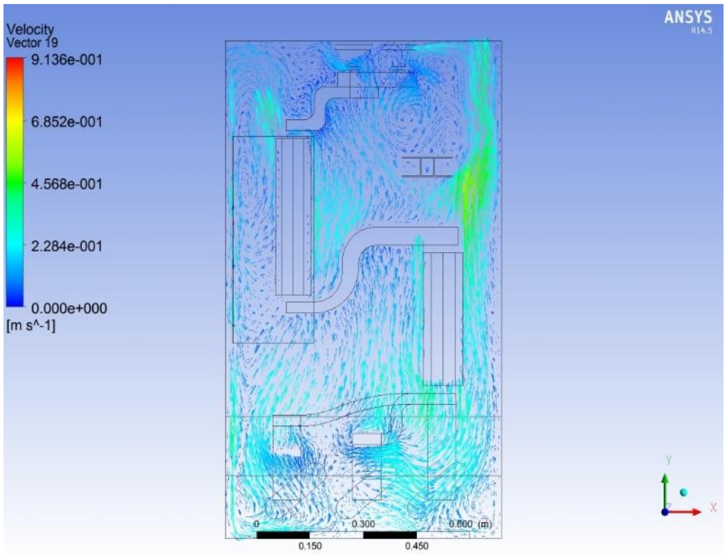


Figure 6. Switchgear horizontal (X-Y) section view of flow vectors (from the analysis).

5. Comparison

Volume of the insulating gas and general shape of the switchgear elements were modelled in Section 3. Heat generating sources are modelled as constant temperature sources and placed at appropriate locations in the model. Temperature values for the heat sources are provided by the real-world measurements of the GIS prototype. Measured points other than the heat generating locations are not used in the analysis. These points are evaluated to compare with the temperature values obtained by the CFD analysis on real world measurements. Basing on these comparisons, the success of the analysis is determined.

In this context, it is observed that the measured temperatures and determined temperatures by the CFD analysis confirm each other. This verification will allow for rapid prototyping of confirmatory test setups and a smaller number of tests rather than multiple experiments for a new product design and development.

The advantage of this assessment is that;
The design and development is quicker, more economical, and allows rapid development of multiple systems. In structural and mechanical systems, a standardized design approach consisting of analytical calculations and FEA is widely used. This successful and promising thermal analysis proves that a similar standardized approach can be used for complicated thermal designs.

6. Conclusions and further works

A good modelling and CFD analysis stage can help the thermal design of the GIS. A proper CFD analysis and its results could help to assess the design before manufacturing the GIS.

Before the experimental setup of prototype CFD and some other modelling (such as Thermal Net Modelling) could be compared for more reliable systems and their designs. CFD and other modelling approaches can optimize design stages. The overall design process of a GIS could be shortened and improved. Systems could be designed by the help of modelling and other design aids.

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