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Research on the Application of Multi-Physics Field Coupling Simulation in the Analysis of Temperature Field of 500kv GIS Circuit Breaker

Abstract: - Gas insulated switchgear (GIS) is a crucial part of any electrical infrastructure. Overheating the conductor on the GIS busbar would reduce the effectiveness of the insulating gas and shorten the life of the device. We then maximize output by fine-tuning the busbar's rotation angle, central distance, and conductor thickness. Dependable electrical systems always include gas insulated transmission lines (GIL) and gas insulated switchgear (GIS). Because of their reduced total cost and greater efficiency in terms of both space use and power transmission, GILs are gradually replacing conventional overhead lines for long-distance, high-power transmission. The reliability of GIL performance and the ease with which designs can be optimized necessitates research into their power loss and temperature profiles. The study found that the maximum temperature and power loss variances were approximately 70% attributable to differences in conductor thickness. By employing the aforementioned combination method (A1, B5, C5), energy consumption and thermal load in the GIS can be reduced. The research also shows that SF6 gas retains its outstanding insulating capacity after undergoing structural optimization. The calculation of the gas breakdown margin demonstrates this. In conclusion, the results of this study contribute to the understanding of heat transmission in three-phase GIS busbars and their optimization and engineering. Examining the temperature field of 500kV GIS circuit breakers, it highlights the value of multi-physics field coupling simulations in improving the reliability and performance of power system components, especially GILs. This is done so that power system components are more reliable and run more efficiently. Optimal heat transmission and other design considerations for three-phase GIS busbars are the most important takeaways from this research.

Keywords: Gas insulated switchgears (GIS); Multi-physics field coupling simulation; Temperature field analysis; Power loss density; Gas Insulated Transmission Lines (GIL)

1. Introduction

The IEC risk evaluation standard is connected to the safe functioning of gas insulated switchgear (GIS) (1). In the field of engineering that deals with power transmission and transformation, gas-insulated switchgear is an essential component. In research that was carried out in 2020, it was discovered that the functional dependability of a GIS could be improved by lowering the working temperature of the busbar and measuring its temperature with a higher degree of precision (2). Keeping the temperature of the busbar lower is one way to cut down on power losses in GIS systems and lower overall energy consumption. A magnetic-thermal coupling finite element methodology was proposed as a method for predicting the growth in busbar temperature (3). Experiments have shown that this method, which generates heat in the busbar by relying on the loss detected in the magnetic field analysis, is effective. Then the method of finite elements was applied to the process of developing a multi-physics coupled GIS busbar model (4). An electromagnetic-flow-thermal coupling model was used for the research that was conducted on the thermal properties of the GIS busbar (5). When the researchers changed the conductor and enclosure sizes, one of the things they did was monitor the increase in temperature of the busbar. It was suggested that changing the design of the busbar conductor by incorporating slots into the conductor as a means of enhancing the heat flow within the GIS (6). As a direct consequence of this, the conductor reached a maximum temperature that was 4 K lower than before. In their 2017 study, Wu et al. proposed an innovative method for the design of busbars that takes into account the SF6 gas breakdown criterion. This approach was developed with the intention

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of keeping a comfortable buffer zone between the temperature of the busbar conductors and the operational environment at all times.

To achieve the objectives of this work, a finite element model of a 252-kilovolt, three-phase, common-box GIS busbar has been constructed. The results of heat radiation are factored in at this stage. Knowing whether or not the busbar will fail is crucial for safety reasons. Since optimal GIS busbar design and GIS heat transfer calculations involve coupling many different physical domains, this study has the potential to set a new standard in the field.

2. Literature Review

Power transmission and transformation engineering relies on gas insulated switchgear (GIS) reliability and safety. Both the reliability and performance of the GIS busbar are significantly impacted by the ambient temperature. In order to improve GIS security and reduce inefficient energy consumption due to power losses, it is essential to carefully measure and reduce the busbar's temperature rise.

In order to calculate the temperature of the busbars, this technique depended on the losses that were uncovered by analysis of the magnetic field. The proposed method was validated through experiments. In order to examine how load current, ambient temperature, and wind speed affect temperature distribution across a region, a multi-physics coupled GIS busbar model was developed using the finite element method (7). The causes of the GIS busbar temperature differential were investigated. Another researcher employed a model of electromagnetic-flow-thermal coupling to investigate the GIS busbar's thermal properties (8). They monitored how much the busbar heated up in response to varying conductor and enclosure diameters in order to improve future designs of GIS busbars. To increase heat transfer in GIS busbars, researchers suggested slotting the conductor (9).

A unique method for the design of busbars was proposed (10). Their research brought to light the importance of giving early attention to the thermal performance and insulation needs of GIS in order to ensure the systems' ability to work in a secure and efficient manner. In the process of estimating the temperature rise and distribution of GIS busbars, the finite element approach and multi-physics coupling have made significant progress; however, there has been relatively little effort done to optimize the temperature rise. For the purposes of analysis, a finite element model of a three-phase common box GIS busbar operating at 252 kilovolts is developed. Temperature, velocity, and breakdown margin distributions are able to be determined with a high level of accuracy as a direct result of the model's incorporation.

The optimization of GIS busbar temperature rises and power loss has a number of practical benefits, two of which are the improvement of heat transfer efficiency and the design of the busbars. By using multi-physical field coupling and advanced numerical methodologies such as the finite element method and Taguchi optimization, scientists are able to learn more about the thermal behavior of GIS busbars and zero in on the important design elements that effect temperature increase and power loss. In addition, scientists are able to learn more about the thermal behavior of GIS busbars. The proposed research intends to further our understanding of how to improve the thermal performance of GIS busbars by making use of multi-physics field coupling simulations and optimization approaches. This will hopefully allow us to develop better solutions. It offers a comprehensive method for studying the effects that different operating conditions have on GIS busbars in terms of temperature distribution, power losses, and breakdown margin. Because of the findings of this study, it will be possible to build designs for GIS busbars that are both more dependable and efficient, which will ultimately lead to improved performance and longer lifespans for the associated devices. The results of the literature review indicate how important it is to accurately calculate and optimize the temperature rise in the GIS busbars. Previous research has looked into a variety of aspects pertaining to GIS busbars, including their thermal properties, design optimization, and multi-physics field coupling. It is necessary to do additional research in order to fill in the knowledge gaps and develop innovative strategies for improving the thermal performance of GIS busbars. Combining optimization techniques with multi-physics field coupling models is what the proposed research will do to fill this gap in knowledge.

Engineers who work on the transmission and transformation of electric power rely significantly on gas insulated switchgear (GIS) to maintain the dependability and safety of their networks (11). The performance of GIS busbars and the length of their lifespan are both greatly influenced by the temperature at which they are operated.

Temperature increases on the busbars can reduce the effectiveness of the insulating gas, endanger the life expectancy of the equipment, and create a potential for fire. This underlines how important it is to do a precise analysis and then re-adjust the temperature field of the GIS busbars. The results of various experiments demonstrated that this technique is both effective and trustworthy (12). By calculating the anticipated increase in temperature, operators and designers are able to maintain a safe operating temperature for the busbars while the busbars are in use.

An analysis of the distribution of busbar temperatures was carried out. As a result of their investigation into the factors that influence temperature dispersion over GIS busbars, they came to the conclusion that certain characteristics are important for thermal management. It is necessary to have a comprehensive grasp of these components in order to realize improvements in the design and functionality of GIS busbars in a number of applications.

In their study on the heat dissipation of GIS busbars, researchers made use of a model that incorporated electromagnetic-flow-thermal connection (13). While the conductor and housing diameters were being adjusted, the temperature of the busbar was monitored. According to the findings of their research, the utilization of geometrical components throughout the design process is absolutely necessary for efficient heat dissipation and temperature regulation. Changing the sizes of the busbars in the machine can reduce the amount of heat generated and assure consistent functioning. The researchers (2016) came up with an innovative method to improve heat transfer in GIS busbars by modifying the shape of the conductor and adding slots (14). According to the results of their research, making these alterations has the potential to bring the conductor's maximum temperature down and increase the rate at which heat is dissipated. Due to the increased surface area that was available for convective heat transfer, the thermal performance of the upgraded busbar design was significantly improved. This research contributes to the progress of busbar design with regard to the dissipation of heat and the cooling of electrical components. Researchers developed a new technique that is based on the SF6 gas breakdown criterion in order to reduce the temperature of the busbar conductor while still providing an appropriate breakdown margin (15). This was accomplished by designing the busbar in such a way that the criterion would be satisfied. The breakdown margin plays a significant role in ensuring that the gas maintains its insulating properties. When designing the standards for GIS busbars, researchers emphasized how important it was to strike a balance between the requirements for thermal performance and insulation. When doing so, they made sure to take into account both the breakdown margin and the temperature rise. Because of this comprehensive method, the thermal behavior of the apparatus can be improved, and its safety and dependability may be ensured.

Even though we have made tremendous strides in our comprehension of the temperature field and thermal behavior of GIS busbars, we still have a way to go before we can determine the best temperature at which to operate the busbars in order to limit the amount of power that is lost. In the course of this investigation, we construct a finite element model of a 252 kV three-phase common box GIS busbar. This model takes into consideration the complex interactions that occur between electromagnetic fields, heat transmission, and fluid movement.

This investigation makes use of the Taguchi method in order to improve the thermal efficiency of the busbar. The Taguchi technique is an efficient optimization tool that can be used to cut down on wasted heat and other forms of energy loss (16). The goal of this endeavor is to find the busbar design characteristics that have the largest impact. It is essential to optimize the design of the busbar in order to minimize energy waste, keep operating temperatures at a safe level, and achieve the highest possible level of heat transfer efficiency.

This study fills a hole in the literature by integrating simulations of multi-physics field coupling with optimization approaches. Specifically, this study aims to do this by enhancing the thermal performance of GIS busbars. This information contributes to our understanding of how varying loads influence the operating temperature, power loss, and safety margin of GIS busbars. As a result of this study, GIS busbar designs will become more effective in terms of performance, energy efficiency, and durability.

In conclusion, the research highlights how important it is to conduct an accurate analysis and make any necessary adjustments to the temperature field of the GIS busbars. Investigations have been conducted into a wide variety of topics, some of which include magnetic-thermal coupling, multi-physics coupling, geometrical optimization, and breakdown margin. More research is required to achieve a deeper comprehension of the subject matter as well as the creation of strategies that are more effective in terms of maximizing the thermal efficiency of GIS busbars. In order to reduce power losses and enhance busbar reliability in GISs, the suggested study makes use of multi-physics field coupling simulations, finite element analysis, and the Taguchi approach. This study will be highly helpful to engineers, operators, and academics who are interested in increasing the efficiency and dependability of power systems in GIS busbar design and operation.

3. Methodology

3.1. Physical Model

The research object is a 252 kV three-phase common box GIS busbar (17). To summarize, the busbar has been flattened out into a two-dimensional representation. Figure 1 illustrates its physical model as well as its dimensions.

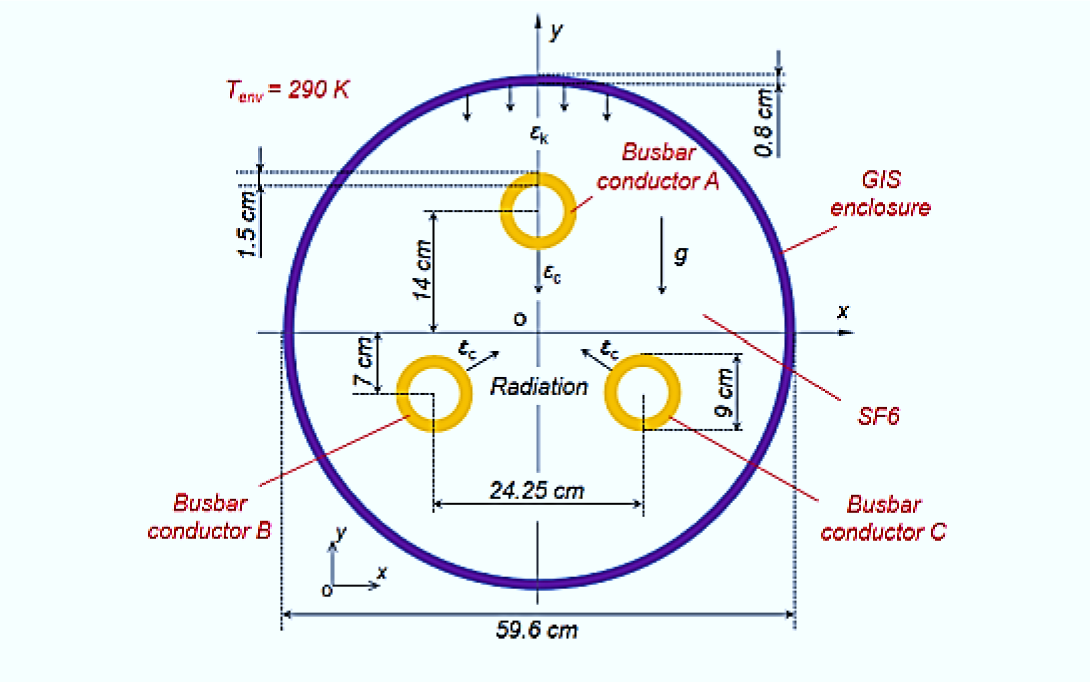


Figure 1 – Physical Model of GIS Busbar

Temperature affects SF6 gas and busbar conductors. Eqs. (1) and (2) indicate SF6 gas's specific heat capacity and thermal conductivity. Multiple studies confirmed this (18). SF6 gas has a Sutherland constant S of 110.55 K, while air at room temperature has a Tenv of 290 K.

(1) $c_{p,sf6}(T) = -2 \times 10^{-3} \times T^2 + 2.4 \times T + 123.4$

(2) $\gamma_{sf6} = 0.01206 \times (T/T_{env})^{1.5} \times ((T_{env} + S)/(T + S))$

According to the equation (3), the electrical conductivity of busbar conductors is denoted by the numeric value 2 (T).

(3) $\sigma(T) = 1/p_0(1 + \alpha(T - T_{ref}))$

3.2. Calculation Methods of Control Equations

The conductors and enclosure make up the solid domain, while the SF6 gas makes up the fluid domain in the GIS model's breakdown. The electromagnetic-heat coupling in the solid domain is represented by equations (4) through (6). The magnetic loss equation (Eq(5)) is the link between equation 4 and 5.

(4) $\nabla.(\gamma(T)\nabla T) + Q_e = 0$

(5) $Q_e = Q_{rh} + Q_{ml} = \frac{1}{2}Re(\vec{J}.\vec{E}) + \frac{1}{2}Re(j\omega\vec{B}.\vec{H})$

(6) $-\omega^2\gamma\vec{A} + j\omega\sigma(T)\vec{A} + \nabla \times \left(u^{-1}\nabla \times \vec{A}\right) = 0$

The electromagnetic field's constitutive equations are shown in (7-9).

(7) $\nabla \times \vec{A} = \vec{B}$

(8) $\vec{E} = -j\omega\vec{A}$

(9) $\vec{B} = u\vec{H}$

(10) $\vec{J} = \sigma(T)\vec{E}$

COMSOL finite element analysis software's thermal properties of SF6 gas interconnect the equations 11, 12 and 13. Equations (11)–(13) define the fluid domain's connected heat-flow dynamics.

(11) $\nabla_{\vec{V}} = 0$

(12) $\mathrm{P(T)}(\,\vec{v}.\nabla T) = \nabla.[\left(\frac{\gamma(T)}{c_p} + \frac{u_t}{\sigma_T}\right).(\nabla T)]$

(13) $p\,(T)(\,\vec{v}.\nabla_{\vec{v}}) = -\nabla p + \nabla.[(u(T) + u_t)(\nabla_{\vec{v}} + (\nabla_{\vec{V}})^T$

In which the thermal conductivity, measured in watts per meter-Kelvin, is denoted by (T); Thermal radiation from the GIS housing to the busbar conductors transfer heat. The k and c bands have 0.85 radiative emissivity. When Tenv is 290 degrees Kelvin, heat transport along the outer wall of the GIS enclosure is natural convection outside a horizontal cylindrical wall. The MUMPS solver in COMSOL Multiphysics 5.2 solves the governing equations for the current inquiry.

3.3. Model Validation

When using the multi-physics direct coupling approach, which requires an extraordinarily significant amount of memory resources, having a mesh that is too fine renders calculation unfeasible. The current research analyzed the effectiveness of four different grid configurations. There are 6000, 7754, 10064, and 13132 grids in each of the four sets, making the total number of grids 13132. It is required to perform a verification of the calculation model and procedure in order to guarantee the reliability of the simulation. The verification process makes use of the three-phase common box GIS heat transfer model (19). The frequency of the alternating current is set at sixty hertz, and the rated current is three thousand amperes. The findings indicate that the method of calculation and the calculation model utilized in this study can be trusted.

4. Results and Discussion

Here, we apply numerical modeling and the Taguchi method to determine the optimal design parameters for a 252 kV three-phase GIS busbar with a 3150 A. We perform this to get the best configuration for a three-phase GIS busbar operating at 252 kV. Each of the three conductors is spinning at the same rate, where (d0) is the distance between the conductor's center and the GIS's center, and () is the conductor's thickness. Each optimized parameter can be placed into one of Table 1's five classes.

Table 1 – Optimized Parameters

Optimized Parameter	Symbols	Level				
$\emptyset$	A	0	25	40	55	70
d_0	B	70	90	110	130	150
φ	C	6	11	16	21	26

If each variable is factored in independently, the total cost of the analysis quickly becomes rather large. There should be 25 distinct simulations. Use the maximum temperature (Tmax) to determine the signal-to-noise ratio (SNR). SNR averaged over all occurrences where the optimized parameter (, d0,) was utilized is the value of the performance statistic (PSi,j). The PSi,j values optimized by changing the parameters are listed in Table 2. When

PSi,j is larger, the maximum temperature or power loss is minimized, as indicated by the negative number in the SNR calculation process.

(14) $R_1 = \max(PS_{ij}|j = 1,2,3,4,5)$

(15) $CR_i = R_i / \sum_i^3 R_i$

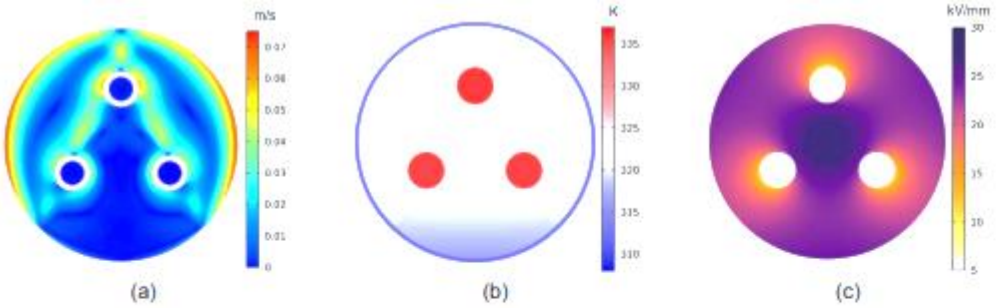
Table 2 – Performance Statistics

Target	Optimized Parameter	Psi.j						
		Level 1	Level 2	Level 3	Level 4	Level 5		
T_{max}	A	-257.4	-255.7	-252.9	-251.6	-259.6	0.11	6.9%
	B	-256.5	-254.3	-255.5	-253.3	-253.1	0.22	22.5%
	C	-255.6	-252.2	-257.12	-255.2	-250.2	1.31	69%
Q_h	A	-278.8	-276.1	-278.2	-279.1	-289.3	0.59	6.8%
	B	-276.3	-275.3	-273.6	-275.5	-285.4	1.59	21%
	C	-273.4	-273.6	-274.9	-279.8	-279.2	6.06	66.4%

Table 2 demonstrates that the conductor thickness is responsible for determining both the Tmax and Qh We will be able to construct a three-phase GIS busbar of superior quality if we take conductor thickness into consideration. We are able to reduce the peak temperature by 21.5 percent and the power loss by 20.7 percent if we calculate the optimal distance in the center, which we will refer to as d0. It is adaptable to your specific requirements due to its high degree of flexibility. Temperature and loss are only marginally impacted when the conductor is rotated; the difference is less than 10%.

According to level 1 of parameter A's best performance data, the maximum temperature (Tmax) is lowest when the rotation angle is zero. Level 5 has the best B and C values. Thus, (A1, B5, C5) has the greatest ability to lower the GIS busbar's maximum temperature while staying within the study's restrictions. Table 3 shows the GIS power loss density (Qh) for the unoptimized structure (=0°,d0=140 mm,=15 mm), SF6 gas average velocity (Uave), and busbar maximum temperature (Tmax). Gravity and confinement create a vertically symmetrical flow field. The flow field's peak velocity is on both sides of the wall. Contrary to symmetrical heat distribution, busbar conductor A has the highest temperature. The auxiliary areas of the three busbar conductors have the lowest breakdown margin when an electric field is strong and SF6 gas is flowing. Electric fields cause this.

Figure 2 – Simulation results of GIS



After optimization, you can achieve the following results, as shown by contrasting them with those achieved before optimization. The distribution rules for the breakdown margin, temperature field, and flow field (1) have not altered.

Table 3 – Comparison

Conditions	U_{ave}	T_{max}	Q_h	E_{min}
Ɵ=0, do=130mm	0.012	339.5	742.2	7.66
Ɵ=0, do=150mm	0.031	321.1	467.3	5.08

5. Conclusion

Data acquired before and after using Taguchi optimization to the design of a three-phase GIS busbar is compared. This is done in order to ascertain the optimal result. Below, in chronological order, are the most important findings: The maximum temperature and the amount of power lost by the GIS are both affected by a number of factors. Differences in conductor thickness account for almost 70% of the influence, whereas center distance accounts for 20% and rotational angle accounts for less than 10%. While the insulating qualities of the SF6 gas were not changed, the maximum temperature was reduced by 9.56 degrees Kelvin and the power loss density was reduced by 158.42 watts per cubic meter (21.7%). It is possible that the results do not precisely reflect reality due to the inherent simplicity of the physical model employed in the article; nonetheless, the results can still be used as a reference for improving the design of a three-phase GIS busbar system. This possibility remains even if the article's findings can serve as a guide for improving the design of a three-phase GIS busbar system. Including contact resistance in further versions of the GIS busbar model may prove useful. It would be possible to more accurately predict the maximum temperature and power loss.

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