DIELECTRIC AND THERMAL CHALLENGES FOR NEXT GENERATION RING MAIN UNITS (RMU)

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ABSTRACT

Environmental concerns related to the greenhouse effect of SF_6 have driven changes to take place in the power distribution industry. This paper discusses the main challenges for next generation medium voltage (MV) ring main units (RMU) using new technologies and materials with reduced environmental impact. Market requirements are going in the direction of equal or even higher technical ratings for new products. Replacing SF_6 with any other insulation gas in RMU requires innovative solutions to be implemented. A key challenge is to be able to maintain the outer physical dimensions of the unit, as this imposes strict conditions on the dielectric and thermal performance.

Dielectric design of SF_6 free RMU targets the distribution of electrical fields within the unit, aiming to reduce the field strength of weak points to compensate for the reduced dielectric strength of alternative insulating gases. Key parameters for optimization include choice of insulating materials, geometrical shape of conducting surfaces and definition of conductor/insulator interfaces. Thermal design is further critical due to the lower thermal properties of alternative insulating gases. Computational Fluid Dynamics (CFD) analysis is used to understand and optimize the temperature distributions inside the switchgear. Simulation results are validated by temperature rise tests in full scale prototypes.

The main functionality of next generation RMU relies on optimized dielectric and thermal design in order to provide a cost efficient and reliable unit. In this paper a selection of techniques are discussed with references to both simulations and full scale tests based on the challenging boundary condition of keeping the same physical dimensions as an existing SF6 product.

INTRODUCTION

Environmental concerns related to the greenhouse effect of SF_6 are promoting a new generation of power products based on more environmentally friendly insulating gases.
In medium voltage network components such as the ring main units, SF_6 serves both as an electrical insulator and a thermal conductor. Currently, no alternative gas has been found that exhibits the excellent dielectric and thermal properties of SF_6. Several gases have been explored, but many tend to suffer from high liquefaction temperature or reduced dielectric strength (see e.g. [1]). From an environmental perspective, dry air is one of the most desirable alternatives.

Market requirements are further going in the direction of equal or even higher technical ratings for new products with the stringent requirement of no changes to the physical dimensions of the unit. Optimizing the dielectric and thermal design to comply with these requirements are identified as the key challenges with the development of the next generation RMU.

This paper summarizes the thermal and dielectric methods and possible solutions for achieving compact switchgear while maintaining the established ratings used in SF_6-insulated RMU when replaced by dry air.

DIELECTRIC DESIGN

In terms of dielectric performance, replacing SF_6 with dry air in a ring main unit causes a drastic reduction in the withstand voltage level due to the reduced insulation level of dry air relative to SF_6. The only possibility to compensate for this is to reduce the maximum electrostatic fields inside the unit to a level below the critical limit for discharge. The strict conditions of maintaining the physical dimensions of the unit typically prevent simply increasing electrode separation distances. Thus, careful optimization through a combination of techniques is required.

The challenge may be appreciated by considering e.g. the withstand voltage of the disconnector in a 12 kV RMU. Replacing SF_6 bar with dry air at similar pressure causes the withstand voltage to drop with up to 50%. It follows that while the type tested SF_6 unit will pass the standard lightning impulse test (BIL) with good margins, the air filled unit will fail if same design would be used. This challenge must be resolved with careful optimization of the dielectric design of the RMU.

A general approach is given by considering the breakdown mechanisms in gases. The inception of a self-propagating electron avalanche, known as a *streamer* is required for a discharge to occur. In the limit of weakly non-uniform fields and short electrode separation distances, the streamer may cross immediately from one electrode to another and create a discharge. The withstand voltage (U_w) is therefore given by the streamer inception voltage (U_{si}), which may be determined from the "streamer criterion" [2]. However, for larger electrode separation and strongly non-uniform fields, the applied voltage must also be able to support the propagation of the streamer across the gap. The critical voltage for streamer propagation (U_{prop}) has been determined empirically for needle-plane arrangements in air [3] and found to scale linearly with electrode separation. Consequently, we may state the following "design rules":

a. For short electrode distances and weakly non-uniform fields, U_w may only be increased by increasing U_{si}
b. At larger electrode distances and strongly non-uniform fields, U_w may be increased further by increasing U_{prop}.

The degree of field uniformity (η) is a key parameter. It is typically defined as the ratio of the average electric field to the maximum field observed between electrodes:

$$\eta = E_{mean} / E_{max} \quad (1)$$

E_{mean} is given by the voltage drop divided by electrode separation distance. Turning this around, one can also see that $1/\eta$ corresponds to the effective "field enhancement factor". It is clear that increased field uniformity is a driving optimization criterion, as increased η tend to increase the inception voltage and consequently the withstand voltage of the electrode configuration.

In practice, η and U_{si} may be increased by reducing the maximum electrostatic fields at the electrode surfaces. Common methods for achieving this are:

- Increase the electrode separation.
- Reduce sharp features and edges
- Increase radiuses of rounded surfaces
- Limit the number of high field points, such as triple junctions

As for streamer inception, streamer propagation is prevented by increasing the separation between the electrodes. Another option is to increase the effective streamer path by inserting insulating barriers, but care must be taken to ensure that the charge transferred to the barrier by the first streamer does not create the condition for a second streamer on the other side of the barrier [3]

For the next generation RMU, the environmental impact and carbon footprint can be seen to be lowered directly through an optimization of dielectric design, as summarized in figure 1.

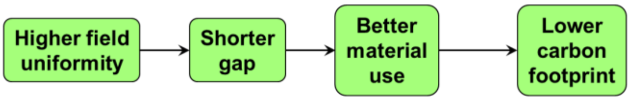

Figure 1: Synergy of field uniformity with sustainability

By utilizing the general design criteria described here, techniques such as shielding, barriers and "triple point" evaluations are often the given solution on a specific design challenge.

Dielectric design example

An example of the application of these principles is the dielectric optimization of a typical 3-position disconnector- and earthing switch used in a 12 kV compact RMU. Electrostatic simulations were performed with the ABB in-house simulation tool Polopt that solves the Poisson equation with the indirect boundary element method [4]. The potential distribution and resulting electrostatic fields of the disconnector are shown in figure 2.

The tip of the two knives is clearly identified as the critical points (dielectric "hot spots"), where the surface electric fields are as high as ~ 10 kV/mm. Because of the short distance to the ground electrode, U_w is estimated with U_{si}.

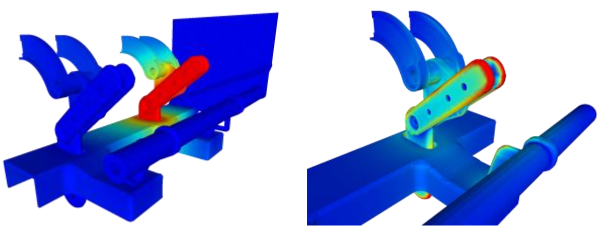

Figure 2: Simulated potential and electric field distribution of a 3-position disconnector and earthing switch in a 12 kV RMU. Color scale ranges from blue (minimum) to red (maximum).

A common solution to this design example is found by adding a field distributor to the tip of the knives, as outlined in figure 3. This increases the effective radius seen by the voltage gradient and the maximum field strength is reduced by as much as 50%. Even though the separation distance between the high voltage knives and the ground electrode is reduced, the condition for streamer inception is raised by approximately 160% due to the reduced surface field strength. This example demonstrates how a rather complex geometry may be optimized with powerful tools as well as smart design criteria's to find simple sustainable technical solutions.

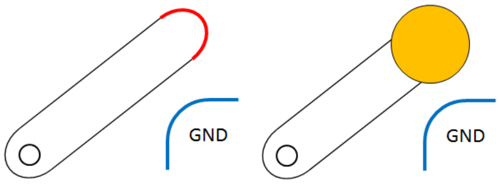

Figure 3: Schematic of the simulated field of the original and modified disconnector switch knives

THERMAL DESIGN

One of the main challenges of designing MV RMU is to satisfy the requirements of the temperature rise test. In a standard temperature rise test as specified in IEC62271-1, the rated current at rated frequency in case of alternating current, is applied to the switchgear continuously, and the temperature of the components is measured separately until steady state conditions are reached. The steady-state temperature rise in all of the components should be within the permissible limits, as specified by the standard.

In order to improve the thermal performance of the switchgear, first of all it is necessary to analyze it from a thermodynamic point of view. The switchgear can be considered as an enclosure with a series of elements generating heat and able to dissipate heat to the surroundings. The elements generating heat inside the enclosure exchange heat between themselves or other elements (conduction and radiation), with the gas inside the enclosure (convection).

The structure of each element, its material and assembly design inside the switchgear introduces a heat transfer system which influences the temperature field. In particular, the different arrangements of the assembly result in changes in heat generation pattern and consequently lead to new temperature field equilibrium.

The main focus areas for RMU redesign are: decrease of the ohmic heat losses and increase of the heat dissipation. Decrease of heat losses by for example reducing number of interfaces, right material selection, plating of contact surfaces and increasing the conductor cross section or decreasing the length of the conductor. Increase of the heat dissipation by optimizing the design related to heat convection, conduction and radiation inside and outside of the switchgear encapsulation. For these purposes parts, components and assemblies are arranged in such a way that the natural free convection is optimized, by adding openings on the pole houses (figure 4) or increasing the free space around all live parts (for an example using the slim support brackets). In addition busbars are arranged somehow to improve the effective surface.

To enhance the heat conduction dissipation, emphasize is put on the choice of materials, optimization of dimensions and reduced of the number of interfaces. For example, the pole house cover is in particular made of a good heat conductor, which is connected to the current path for maximizing the effect of heat conduction. For optimizing the radiation heat transfers the inner walls of the pole house do have a rough surface that is considered and utilized, together with possibility of painting or coating of inside as well as outside encapsulation walls. All above mentioned methods are considered for thermal design of the next generation of RMU.

CFD Simulation

The CFD simulation has been utilized for thermal design optimization of next generation RMU filled with dry air. Most of the heat generated in the switchgear is accumulated in the pole house. To increase the cooling of pole house, it is important that a good circulation of air is generated and maintained by introducing thoroughly dimensioned holes.

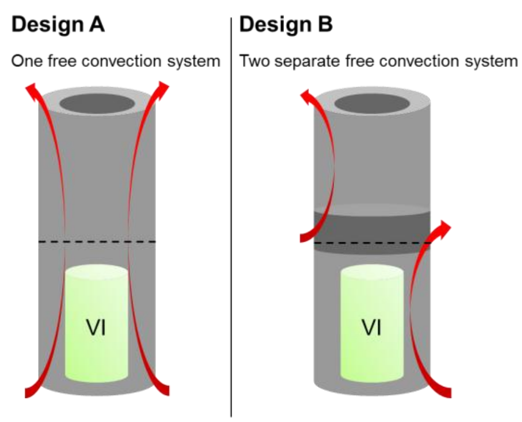

Figure 4: two different designs for free convection system in a typical switch pole house that encloses a vacuum interrupter (VI)

The position of the ventilation openings on the pole house is important to enhance the "chimney" effect. The CFD model has been used to compare two different designs of the openings in the pole house (figure 4). Design A is considered with one free convection system with openings on top and bottom and design B with two separate free convection systems with openings in the mid height as well as openings on top and bottom.

Using design B with openings in the middle results in lower gas velocity in the pole house (figures 5). From the simulation results it can be concluded that any openings at mid height can reduce the "chimney" effect, thus causing a reduction of the buoyancy movement

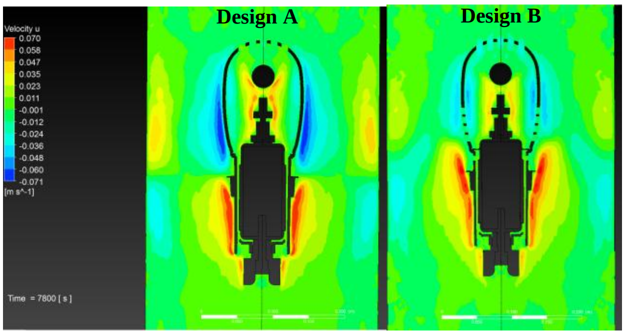

Figure 5: Velocity fields for two different designs show a better "chimney" effect in design A

The full scale simulation of the whole RMU has been performed by using Ansys Fluent commercial code with two different designs, the original design and the modified design. Physical phenomena such as heat generation, heat conduction, convection, radiation and turbulence were taken into account.

The main differences between the original and modified design were using silver platted bus bars with enlarged cross section and thicker flexible connectors in modified case.

According to the simulation results, these two designs led to two different temperature distributions with hot spots in different positions. In the original design hot spots appeared at flexible - bus bar connection and in the modified design hot spots were on the knives. The numerically predicted hot spots are similar to the experiment results obtained from temperature rise tests for the original and the modified designs. It was also proven that applying parts and connections with lower resistances may significantly decrease temperatures for the modified design.

CONCLUSION

The dielectric and thermal challenges associated with replacing SF_6 as an insulating medium with other, more environmentally friendly gases can be solved with careful optimization based on powerful simulations tool, deep empirical knowledge as well as a combination of technologies. Through examples of dielectric optimization and thermal design, it has been shown that the next generation RMU can obtain the compactness of current SF_6 filled units. This compactness is also utilized in a broader perspective, by using a combination of materials as well as the more environmental friendly insulation gas dry air to correspond to the overall sustainability approach.

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