ECO-EFFICIENT PUFFER-TYPE LOAD BREAK SWITCH FOR MEDIUM VOLTAGE APPLICATIONS

Elham ATTAR
ABB – Norway
elham.attar@no.abb.com

Magne SAXEGAARD
ABB – Norway
magne.saxegaard@no.abb.com

Maik HYRENBACH
ABB – Germany
maik.hyrenbach@de.abb.com

Pouria HOMAYONIFAR
ABB – Norway
pouria.homayonifar@no.abb.com

Tor BRATSBERG
ABB – Norway
tor.bratsberg@no.abb.com

Ole GRAUHAUG
ABB – Norway
ole.granhaug@no.abb.com

Nina STØA-AANENSEN
SINTEF – Norway
nina.stoa-aanensen@sintef.no

Erik JONSSON
SINTEF – Norway
erik.jonsson@sintef.no

ABSTRACT

In the recent years, significant efforts have been made to develop SF_6-free switchgears to reduce the use of greenhouse gases in the electrical industry. Up to now, vacuum switching technology is being used as the possible solution in SF_6-free load break switches (LBS) and thereby most of the efforts have been focused on dielectric and thermal challenges.

This paper presents the next generation of SF_6-free load break switches based on a puffer interrupter technology for medium voltage (MV) application. In puffer-type switches, the interrupting capability depends on the contact geometry and the gas flow pattern. In general, replacing SF_6 with alternative gases reduces the interruption performance, due to the poorer arc-quenching properties and dielectric strength.

The presented arrangement of flow pattern around the arcing zone, called stagnation-point flow, enables a significantly better thermal interruption performance in SF6 alternatives. After thermal interruption, the weak dielectric strength of both cold and hot zones may cause re-strikes. Therefore, innovative solutions have been implemented to tailor the flow pattern of the hot gas to prevent arc re-ignition. Although interruption capability is the main challenge, the functionality of a new LBS also relies on optimized dielectric and thermal design.

This paper summarizes different challenges in developing the new LBS module with references to both simulations and full-scale tests. The LBS panel comprises a puffer switch for current interruption and a knife switch for earthing function. The interrupter works in either synthetic air for 12 kV or AirPlus^{TM}, i.e., a mixture of synthetic air with $C_5F_{10}O$ fluoroketone (C5-FK), for 24 kV applications. This switch is a cost-effective and easily operated alternative to the LBSs using vacuum interrupters for load current switching application. The new LBS panel meets the same technical requirements as the corresponding SF_6 product with the same physical outer dimensions.

INTRODUCTION

Environmental concerns related to the greenhouse effect of SF_6 are promoting a new generation of gas-insulated switchgear (GIS) based on environmentally friendly insulating gases. Until now SF_6-free gas insulated switchgears have used vacuum interrupters for switching, and therefore the main challenges when utilizing the new eco-friendly gases have been related to dielectric and thermal issues inside the switchgear [1, 2].

Load break switches are widely utilized in medium voltage secondary switchgears, assigned with the task of switching load currents in the range of 1-1250 A_{rms}. Conventional LBSs for 36 kV or higher typically use a so-called puffer interrupter to quench the arc. The puffer interrupter (Figure 1) consists of a compression chamber and an interruption chamber. The principle of operation is to "blow out" the arc by using the over-pressure generated by compression of the gas obtained by the piston movement. The compressed gas is released to the arcing zone and it cools the arc ignited between the arcing contacts. The arc is extinguished at the first current zero (CZ) crossing if sufficient cooling and contact distance is achieved to withstand the transient recovery voltage. SF_6 bears an extremely good switching capability due to its intrinsic capability to both cool the arc and quickly restore the insulation level after the switching event. Replacing SF_6 with eco-efficient alternatives reduces the interruption performance of the puffer interrupter both in the "thermal" and "dielectric" phases, due to the poorer arc-quenching properties and dielectric strength of alternative gases.

This paper summarizes possible solutions for achieving compact LBSs for eco-efficient alternatives while maintaining the established ratings and footprint of SF_6 GIS. The solutions and results presented here are applicable for 12 kV LBS in dry air and 24 kV LBS in a mixture of synthetic air with C5-FK called AirPlus^{TM}.

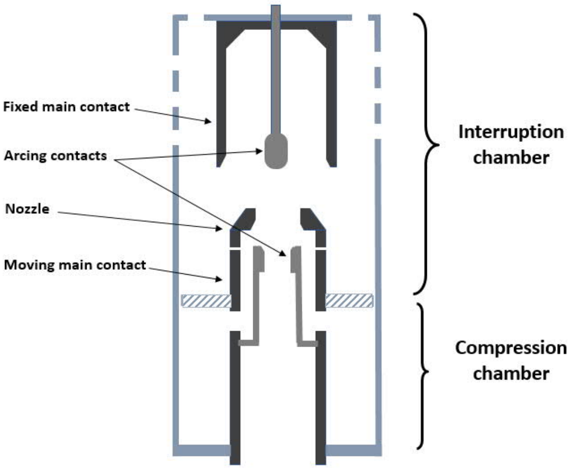

Figure 1. Schematic drawing of the gas puffer interrupter.

CURRENT INTERRUPTION PRINCIPLE

Thermal interruption

During the opening operation of a switch, the piston attached to the moving contact compresses the gas which results in an over-pressure in the compression chamber and at the same time the arcing tulip contact is pulled away from the arcing pin which consequently generates an arc. The arc is initiated and heats the gas, which partly "clogs" the critical cross-section of the nozzle, resulting in even higher pressure in the compression volume. Eventually, the pressurized gas from the compression volume blasts into the arcing zone and helps to extinguish the arc. The arc extinction should preferably occur at the first CZ crossing, and therefore enough gas pressure is needed to blow out the arc. As a part of the solution, customized ports are inserted around the arcing zone in which blowing fresh gas through the nozzle replaces the hot gas quickly. Many parameters of the puffer design influence the gas flow and pressure build-up in the system and will result in different interruption capabilities. In this switching device, the gas is used as both an arc interrupting and a dielectric medium.

The specific arrangement of the flow pattern in arcing zone significantly improves the interruption performance. Different topologies of the flow around the arcing zone are shown in Figure 2. The common flow pattern utilized in SF_6 MV puffer interrupters is denoted as "simple flow". Here, the gas flows straight through the moving contact and nozzle system toward the fixed contact. Experiments with a simple flow puffer interrupter in different gas pressures and loads have indicated that the interruption performance of this typical puffer design is not sufficient for SF_6-free MV application [3]. The puffer-type switch developed for air and AirPlus therefore requires significant improvement in interruption performance.

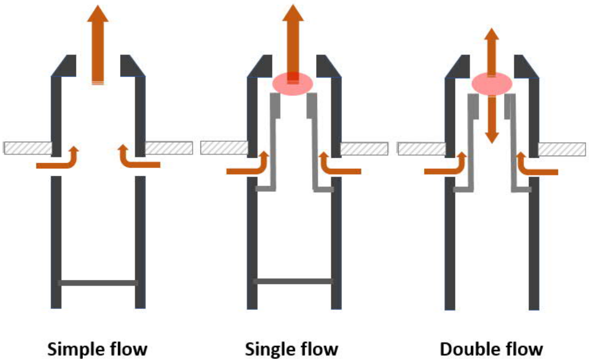

Figure 2. The simple flow and the stagnation-point type flow called single/double flow.

Two alternative designs in Figure 2 were also explored. The "single" and "double" flow designs both feature a "stagnation point" (highlighted by a red cloud in Figure 2), found to improve the interruption performance significantly for air and AirPlus compared to the "simple flow" design. A stagnation point is a point in a flow field where the local velocity of the fluid becomes zero and all the kinetic energy is converted into pressure energy. The stagnation-point type of flow is commonly utilized in high voltage circuit breakers, but no applications is known for commercial MV LBS.

Dielectric re-strike

The dielectric phase, characterized by a residual current close to zero and a time scale of ~10-100 µs after CZ, may still generate re-strikes because hot gas and vapor generated by the burning arc remains around the contacts. This mixture of hot gas and metal vapors reduces dielectric strength compared to the cold insulation gas, and when the transient recovery voltage increases, re-strikes may take place within or away from the original plasma channel. To quantify robustness of the switch, regular experiments were conducted at different development stages. An example of such a test is depicted in Figures 3 and 4, where interruption in air was failed by dielectric re-strike.

In addition to full-scale experiments, CFD modelling is the main tuning tool in the development phase for both root cause analysis and sensitivity analysis of new switchgear design concepts. Figure 5 illustrates the cloud of accumulated hot gas around the contacts in the "double" flow design for two different arcing times. The ideal situation would be to push this hot gas away from the moving main contact. It is important to tailor the flow pattern of the hot gas generated during the interruption event in such a way that re-ignition in the dielectric phase is prevented.

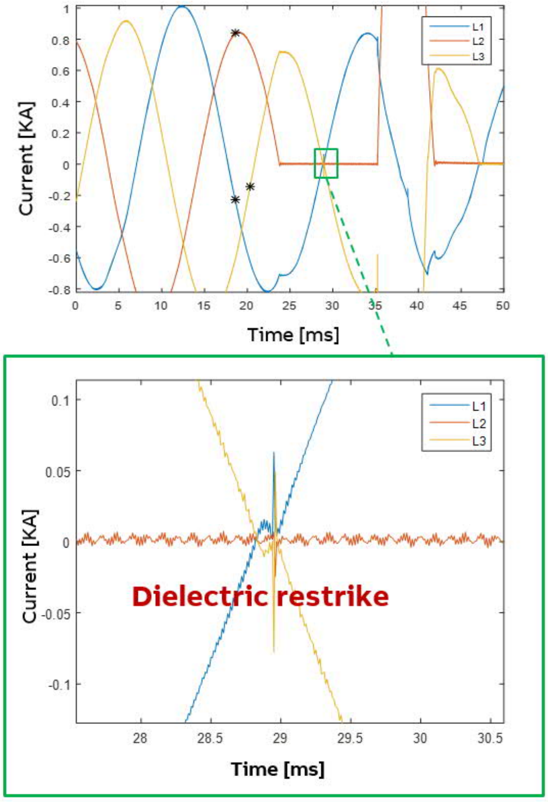

Figure 3. Sample current curves from a failed interruption experiment in air due to re-strike.

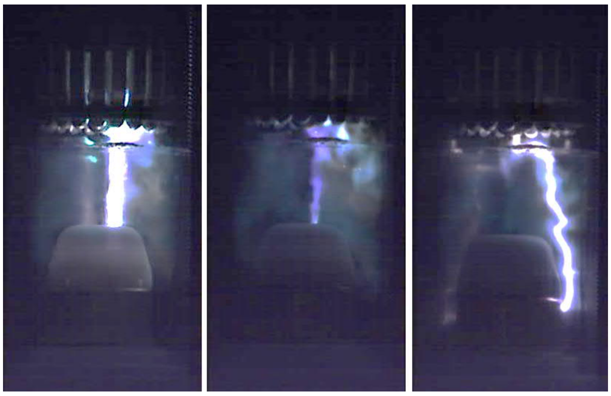

Figure 4. Hot cloud from the arc settling around the moving main contact which resulted in re-strike to the main contact.

The flow pattern is controlled by utilizing one or more of the following design elements. The fixed arcing contact (arc pin) is split, and the fixed main contact, made of multiple contact members with pressure-release openings. The gas outlets should be large enough to avoid the hot gas flowing towards the main contact. Any change in the contacts should not sacrifice the needed cross-section of main current path.

Figure 6 presents the effect of the pin split together with the openings on the main contacts on the local temperature distribution just after CZ. The detected effects in simulations have been observed in experiments as well. Beside mentioned parameters, it has been seen that inserting some holes in the piston helps pushing hot gas around the moving contact and thus improves dielectric recovery even more. This option should not weaken the pressure build-up in the compression chamber.

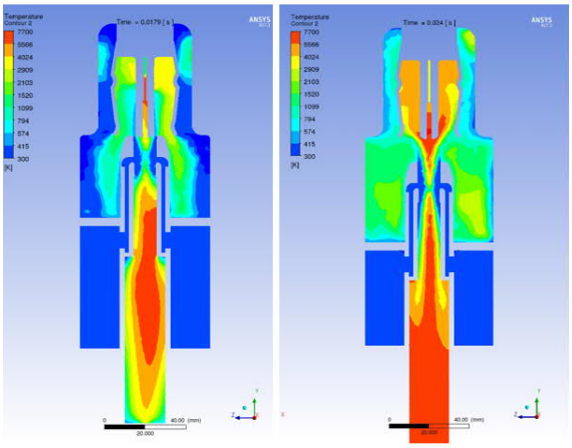

Figure 5. Temperature distribution just after CZ crossing. To the left, arcing time = 5.25 ms and to the right, arcing time = 13.3 ms.

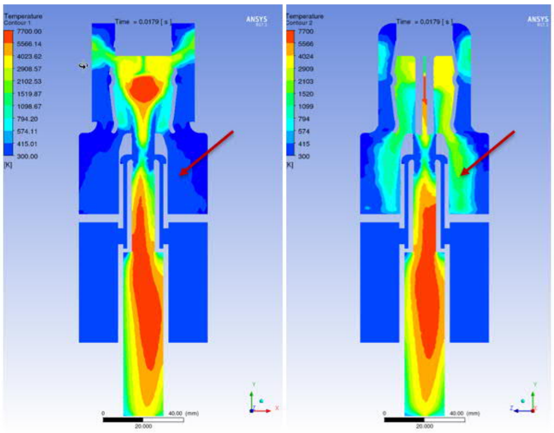

Figure 6. Temperature distribution for two perpendicular cross sections just after CZ.

In the double flow concept, at the stagnation point, the gas accelerates to different directions and the outlet at the end of the tube releases the hot gas from arcing zone effectively. The effect of discharge port at the end of the tube, which is the difference between single flow and double flow, on the amount of accumulated gas around the moving contact is presented in Figure 7 by CFD models. The double flow design reduces the amount of hot gas around the moving main contact which helps to avoid re-ignition in the dielectric phase in eco-efficient alternatives.

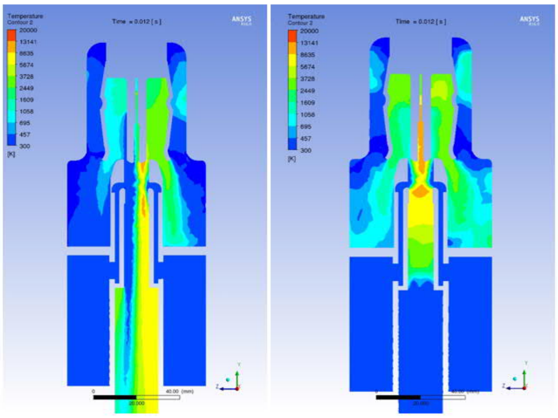

Figure 7. Effect of the outlet at the end of the tube on the accumulated hot gas around the main contact just before current zero (left: double flow, right: single flow).

DIELECTRIC DESIGN

Although the dielectric withstand strength of the selected AirPlus composition for ring main unit (RMU) application is almost half of SF_6 [3], the footprint of the switching unit should be kept equal to conventional SF_6 units. Therefore, a substantial effort has been done to reduce the electric field stress at components to compensate the high effective ionisation coefficient of AirPlus [3]. This action has made parts very smooth and in other words, converted them to field shields (Figure 8). Novel designs have been implemented to overcome high stress regions at triple points, where conductive solid, insulating solid and insulating gas meet. Finally, the sophisticated design fulfilled all dielectric requirements based on common standards such as IEC 62271-1[4].

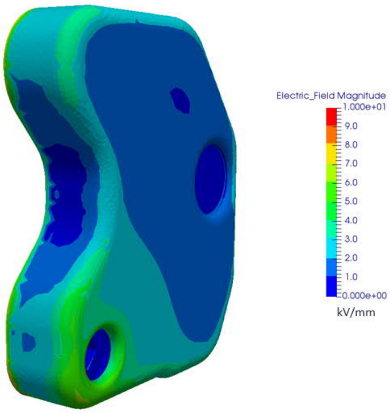

Figure 8. Simulated electrical field stress of housing of interrupter assembly.

By implementing some openings on the field controllers around the interruption chamber, the hot gas, vapors and exhaust generated during the arcing event is transported away from regions with high electrical field stress (Figure 9), which not only helps to cool down the switch, but also helps to maintain the dielectric strength of the gas at the needed level between phases.

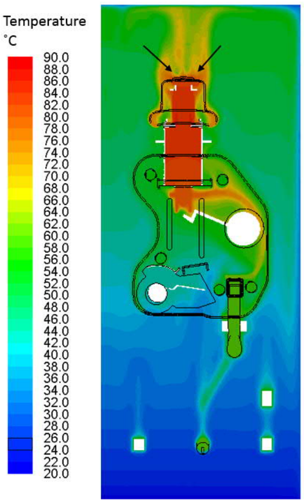

Figure 9. Gas temperature distribution shows the effect of adding the openings on the upper field controller

FULL SCALE EXPERIMENTS

Full-scale interruption experiments based on the double flow concept were conducted according to the "active load" test duty of the IEC standard for a rated voltage 12 kV in air and 24 kV in AirPlus gas mixture at nominal current of 630 A [5, 6]. In the first prototype (loop 1 presented in Figure 10) filled with AirPlus, it was observed that the interruption performance dropped with time, and the frequency of successful interruptions at the first CZ decreases over the 100 operations due to the decrease of pressure build-up in compression chamber.

Figure 10. First prototype was successfully tested for 100 interruptions in loop 1

This prototype has been also successfully tested for "switch-fuse" transfer current according to the IEC standard [7] for 24 kV/780 A in AirPlus. The switch-fuse test duty is challenging due to the much higher rate of rise of recovery voltage compare to the "active load" test duty.

In the next step (loop 2) modifications has been included to reduced friction and increased velocity to achieve a higher and steady pressure build-up and improve the hot gas sweeping. The effect of such fine tunings is shown in Figure 11. These optimizations led to a switch that interrupts mostly at the first CZ and only about 20% of the shots interrupted at second CZ after contact separation.

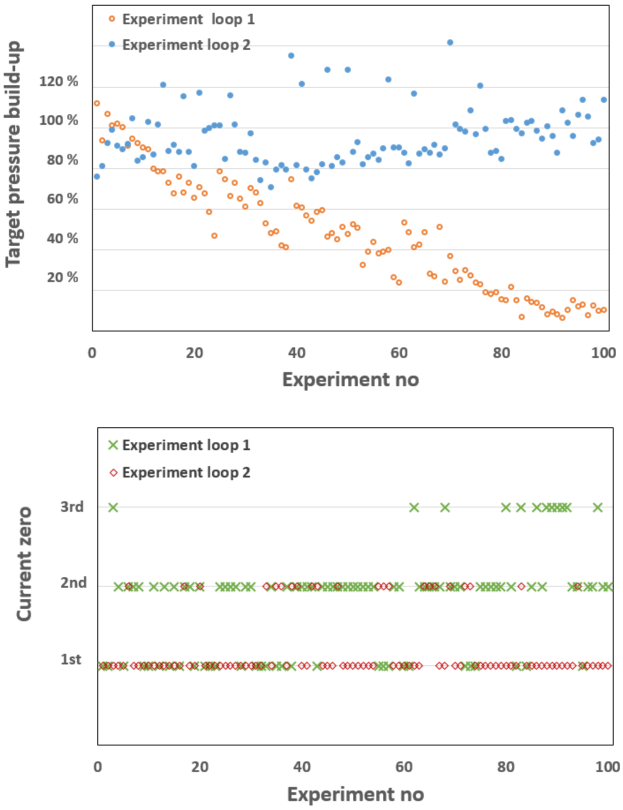

Figure 11. Pressure build-up in compression chamber (at contact separation) and interruption performance for 100 make-break operations (loop 1 vs loop 2).

The chemical decomposition of AirPlus, due to low-current arcing for the switchgear equipped with molecular sieve has been explored earlier [6]. The 100 successful interruptions have been repeated in a switchgear without a molecular sieve bag (loop 2), and the test results indicated only trace amounts of fluoroketone decomposition products and no toxic by-products (Table 1).

The zeolite drying agent placed in the GIS can absorb some of the decomposition products; for example, Hexafluoropropene - C_3F_6 is not presented in the gas sample from the GIS equipped with the drying bag.

Table 1. Substances detected in gas samples Chromatogram (GC-MS) from the AirPlus GIS with/without the molecular sieve after 100 interruptions of 630 A at 24 kV.

RT [min]	Chemical Name	Formula	GIS without Molecular Sieve	GIS with Molecular Sieve
1.564	Air O_2/N_2 and CO		✓	✓
1.65	Tetrafluoromethane	CF_4	✓	✓
2.036	Carbon dioxide	CO_2	✓	✓
2.11	Hexafluoroethane	C_2F_6	✓	✓
3.361	Octafluoropropane	C_3F_8	✓	✓
4.027	Hexafluoropropene	C_3F_6	✓	
4.778	Decafluorobutane	C_4F_{10}	✓	✓
5.392	2H-Heptafluoropropane	C_3HF_7	✓	✓

CONCLUSION

Puffer interrupters, which use the gas blast produced by the relative movement of the moving and fixed contacts, are widely used in SF6 switchgears due to their compact size, simple structure and excellent interruption characteristics. In a puffer switch, the interrupting capability depends on the interaction between arc, gas properties, flow pattern, pressure build-up and geometry. The stagnation-point type of flow is improving the interruption performance compared to simple flow in non-SF6 gases. The performance of a new interrupter design is successfully examined for "active load" test duty at 12 kV in air and "active load" and "switch-fuse" test duties at 24 kV in AirPlus, a mixture of dry air and C5-FK. This switch, which is a cost-effective and easily operated alternative to the LBSs using vacuum interrupters, has paved the way for the next generation of environmentally friendly RMU.

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