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Performance of High Voltage Circuit-Breakers using C4FN gas mixture on Shunt reactor applications

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SUMMARY

SF_6-free gas alternatives in High-Voltage (HV) switchgear become more and more available with products able to reach up to 420 kV, 63 kA ratings [1] for C4FN gas mixture.
However, up to now, limited information has been released regarding the assessment of shunt reactor switching performance with SF_6-free solutions. Meanwhile, this application is seeing lately an important increase of its need at all voltage levels to ensure the grid stability following the integration of renewable power generation sources to the grid. As a result, circuit-breakers compatible with this application are frequently required and likely with an SF_6-free solution to avoid the increase of SF_6 on the installed base.

Yet, the shunt reactor performance is known as being a sensitive application with SF_6 technology. Indeed, utilities requires a circuit breaker capable of frequently switching, limiting reignitions or overvoltages which could potentially damage the nearby reactance or the apparatus overtime. This balance between a good clearance capability and a strong dielectric withstand has shown to be challenging for some switchgear. It is also important to note that for shunt reactor applications, analysis shall be carried out for each project to assess the applicability and selection of adequate circuit-breaker considering the actual site configuration and reactance characteristics.

This paper will introduce the different important points which are being assessed while selecting a circuit-breaker on a shunt reactor application with a comparison between SF_6 and C4FN gas mixture results. The comparison will be done at two different voltage and current levels: 145 kV & 245 kV with both Live-Tank (LT) and Gas-Insulated Switchgear (GIS). Additionally, the performance of the 245 kV single chamber performance extension to the 420 kV level with a double-break apparatus will be studied. The insulating gas is a C4FN/O_2/CO_2 mixture (called g^3) offers a sustainable solution for the replacement of SF_6 inside the apparatus for all voltage and current ratings while keeping scalability and equivalent performance, and footprint as in the SF_6 range. It is today the only SF_6-free solution able to replace one by one SF_6 for all applications and voltage levels.

The covered points for both gas technologies will be:

- Reignitions behaviour: reignition voltage, multiple reignitions occurrence at clearance, double reignitions
- Chopping numbers
- Parts wear

Finally, the impact of the circuit breaker design on the shunt reactor clearance application will be presented.

KEYWORDS

Shunt reactor switching, Reactance, gas-insulated switchgear, live-tank, g^3, circuit breaker, fluoronitrile, gas insulation, C4FN, environmental friendly.

1. <u>Shunt reactor application</u>

The shunt reactor application is detailed in the following international standard: IEC 62271-110 [2] (especially section 4.4), the guide IEC 62271-306 [3] (especially section 16) and the IEC 60076-6 [4] (especially annex A.1 Shunt reactor switching).

The standard IEC 60076-6 [4] deals with the reactance specifications and testing while the two others are related to the circuit breaker manufacturers side. Inside its annex A.1, a risk assessment and requirements of specific features are detailed for each voltage ratings. The following outputs can be extracted:

- Reignitions events for reactance application < 52 kV: there is no risk for the reactance
- Reignitions events for reactance application between 52 kV and 170 kV: The risk is quite minimized as the overvoltages are similar to the qualified chopped wave test
- Reignitions events for reactance application above 170 kV should always be avoided

As a result, applications above 170 kV will generally require a Control Switching Device (CSD) to perform a point on wave switching [5] to minimize the risk and voltage level of reignitions, aiming for a preselected arcing window.

This window means that over the sinewave period there is an area where the circuit breaker can clear the current without leading to severe reignitions events which could be potentially harmful for the reactance.

Thus, on the circuit-breaker manufacturer side, the standard IEC 62271-110 [2] is providing a frame to demonstrate the apparatus capacity to match the conditions met on a shunt reactor application. During these tests, the reignition-free arcing window is identified for on-site use when needed.

The type-test is separated in four different Test Duties (TD) presented in the Table 9 of the standard. For this paper, the tests have been performed on a single-phase for two different rated voltages: 145 kV and 245 kV. The chosen first-pole-to-clear factor for each application was selected as proposed by the standard [2]. Therefore, for the 145 kV, the selected configuration has been with isolated neutrals leading to a k_{pp} of 1.5 while at 245 kV, the configuration is with earthed neutrals and a k_{pp} of 1.

The following table is summarizing the different parameters for the four test-duties:

Table 1 : Details of the tested parameters for both 145 kV & 245 kV ratings presented in this paper

Test-duty	Cleared current	145 kV, k_{pp} = 1.5		245 kV, k_{pp} = 1	
		Peak voltage: u_c	Time parameter: t_3	Peak voltage: u_c	Time parameter: t_3
TD n°1	315 A	337 kV	130 µs	380 kV	167 µs
TD n°2	100 A		230 µs		297 µs
TD n°3					
TD n°4					

From the table above, for each voltage rating, there is only two circuits. The first one for the TD n°1, and then, the second for TD n°2, 3, and 4. The difference between these three test-duties remains in the sweeping of the arcing window and the filling pressure. Indeed, all test-duties are performed at nominal pressure exception made for the test-duty n°4 which is being tested at minimal pressure (TD2 vs TD4), while the TD3 is targeting specifically the “weak” point of the circuit breaker where a potential double-reignition could occur: the arcing time which led to the highest reignition voltage. This arcing time is targeting with 6 tests at its value, 6 tests with an arcing time 9° (0.5 ms for 50 Hz) shorter and 6 tests 9° longer (0.5 ms for 50 Hz).

2. Test-duty n°1 at 245 kV: 315 A

This test-duty has been performed on one chamber of the 420 kV GIS double-break (half pole testing) with the following gas mixture: 5% C4FN/13% O_2/82% CO_2. This circuit-breaker was developed during LIFEGRID project [6] that was completed in 2022 resulting in the successful development of a 420 kV 63kA circuit-breaker [1] [7]. A complete type-test as per IEC 62271-110 [2] was performed resulting in compliant results. The test results of TD1 illustrated on Figure 1 are extracted from the complete tests sequence.

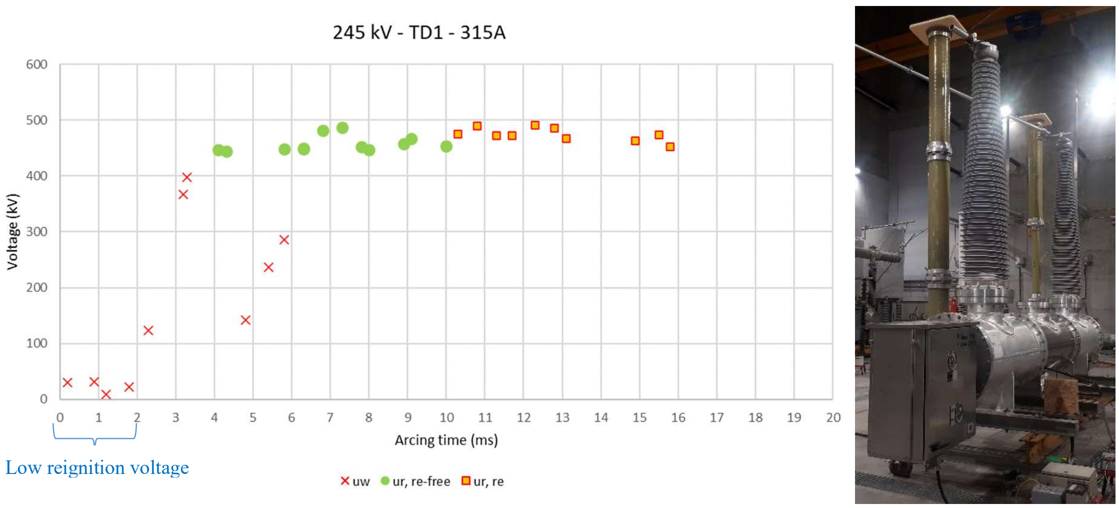

Figure 1 : Results of the TD1 results at 245 kV and picture of the 420 kV GIS double-break (C4FN based gas mixture)

The chart above will be the typical one presented inside this document for all results of Shunt Reactor type-tests, it can be read as per the following guidelines:

- The red crosses are highlighting a reignition event, then the voltage value is the u_w (voltage at reignition) and the arcing time is the location in the arcing window where the event occurred
- The green dots are demonstrating a clearance with the peak voltage of the TRV and the location in the arcing window
- The orange squares are showing the TRV peak voltage of an interruption at the second zero when a reignition occurred at the first current zero crossing. The tests have been carried out at 50 Hz, as a result, each red cross can be associated to an orange square with a time difference of approximately 10 ms (half cycle).

From the Figure 1, the shunt reactor performance for the test duty n°1 at 245 kV/315 A is giving a reignition-free arcing window between 6 and 10 ms. This range is offering an opportunity of target with a CSD between 6 and up to 12 ms (for 50 Hz) as the reignitions below 2 ms are thermal non-clearances leading to very low values of voltage transients [5]: harmless for both the circuit breaker and the reactance.

As a result, the 245 kV chamber using a C4FN gas mixture is providing an SF_6-free solution for shunt reactor performance for an application at 245 kV, and in this example with a 130 MVAR reactor.

3. Study of the performance at 420 kV: Double chamber

Half pole testing is acceptable as per IEC [1].
However, since the test duty n°1 at 245 kV / 315 A presented above was achieved, a theoretical transposition at 420 kV / 315 A for a double break is explored. The goal is to demonstrate from those 245kV test data the shunt reactor performance of a 420 kV circuit breaker having two 245 kV breaking chambers in series with grading capacitors.

To do so, a comparison of the transient recovery voltage peak (u_{trv}) across the 245 kV circuit breaker and u_{trv} across one of the chambers of the 420 kV is achieved. This recovery voltage peak is extracted from the test data (see Figure 1) in the case of the 245 kV and calculated from international standard IEC 62271-110 [2] and IEC 62271-306 [3] methodology in the case of the 420 kV. More precisely, $u_{trv\,420kV}$ is calculated from the chopping number λ and the arcing time u_a of each shot performed on the 245 kV breaking chamber.

The circuit inputs and assumptions used are as follows, and imply the circuit characteristics presented in Table 2:

- Voltage rating investigated: 420 kV
- A distribution factor of 0.55 is considered, which means that the most stressed chamber of the circuit breaker needs to withstand 55% of the voltage applied at its terminals.
- Reactance of 200 MVAR is considered leading to 315 A.
- Calculations are made on a single-phase equivalent circuit as presented Figure 2

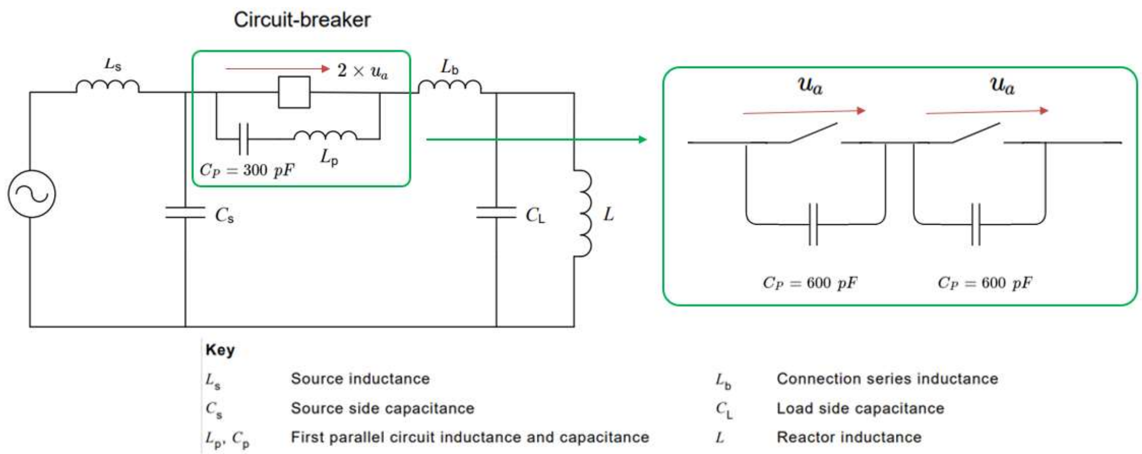

Figure 2 Single-phase equivalent circuit of shunt reactor switching. - Case of a double-chamber circuit breaker with u_a the arcing voltage of one chamber (right)

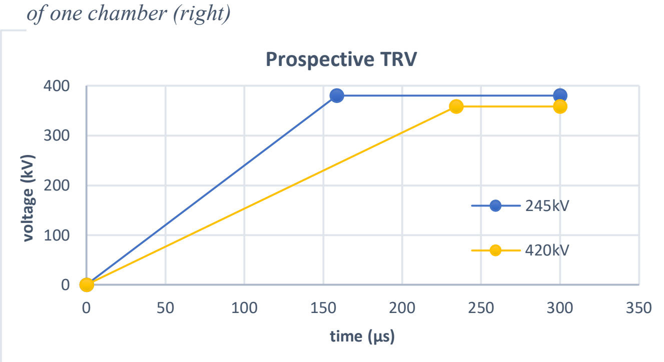

Figure 3 Comparison of prospective TRV seen by 245 kV circuit breaker and one chamber of 420 kV circuit breaker

	I (A)	L (H)	U_0 (KV)	u_c (kV)	t_3 (µs)
420 kV	274.9	2.81	188.6	358.4	234

Table 2 Summary of the characteristics of each circuit studied considering the inputs and assumptions made

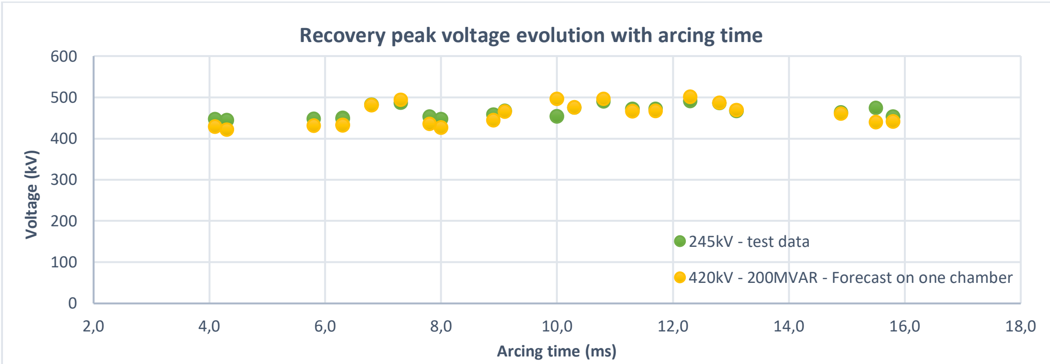

Figure 4 Comparison of u_{trv} evolution with the arcing time between 245kV test data and 420 kV forecast

Overlapping the peak transient voltages across the circuit breaker from test data (245 kV) and calculated (420kV) (Figure 4), Shunt Reactor performance would be covered on a 420 kV – 315 A double chamber circuit-breaker for two reasons:

- ✓ The slope of the prospective TRV seen by one chamber is smaller in 420 kV (<2 kV/µs) than the one seen by the 245 kV circuit breaker (<3 kV/µs) which would significantly ease the TRV withstand.
- ✓ The transient recovery voltage peak (u_{trv}) is similar (420 kV) compared to the 245 kV test results.

Overall, it can be concluded that the 245 kV performance demonstrated as per IEC 62271-110 [2] will cover the need for application at 200 MVAR for a 420 kV double break application.

4. Test-duties n°2 & 3 at 145 kV: 100 A

The performance at a lower cleared current has been as well investigated with the test-duties n°2 & 3. This time, the rating is 145 kV and was performed on a Live-Tank apparatus with the following gas mixture: 3.5% C_4FN/13% O_2/83.5% CO_2. A complete type-test as per IEC 62271-110 [2] was performed resulting in fully compliant results. The test results of TD2 and 3 illustrated on Figure 5Figure 1 are extracted from the complete tests sequence.

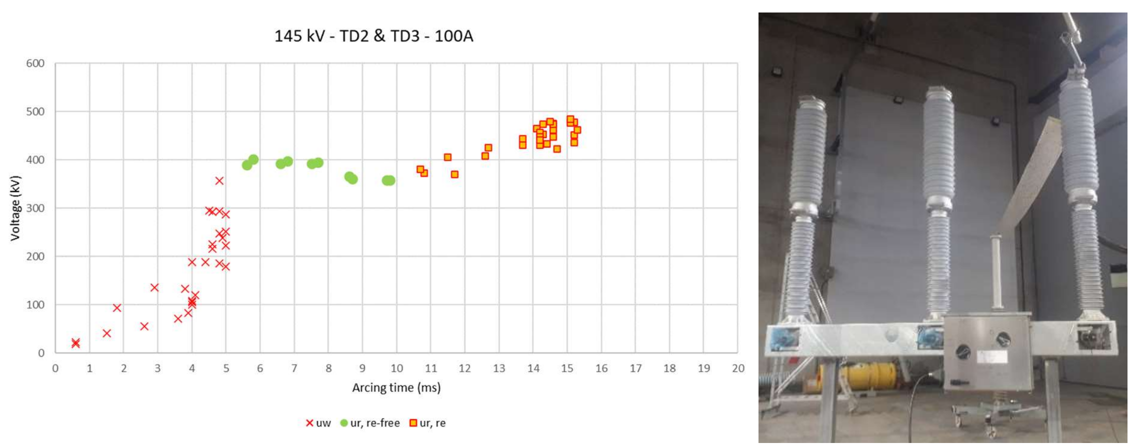

Figure 5: Results of TD2 & TD3 at 145 kV and picture of the 145 kV LT circuit breaker (C_4FN based gas mixture)

The 145 kV LT apparatus demonstrated a full shunt reactor performance for the test duties n°2 and 3 with a reignition-free arcing window between 5 and 10 ms, allowing a large opportunity of target with a CSD even if not mandatory as explained in section 1.

During the test-duty n°3, all tests have generated reignitions between 4 and 5 ms as the highest reignition voltage during TD2 was at 4.6 ms. However, none of them led to any double-reignitions nor multiple reignitions at a single current zero.

5. Comparison between SF6 and C4FN gas mixture technologies

a. Double reignitions and multiple reignitions at clearance

Yet, the results for both 245 kV and 145 kV for test-duties 1 to 3 revealed similar behavior to SF_6. This is especially the case as both apparatuses have not seen any double reignitions nor multiple reignitions at clearance demonstrating a healthy and similar behavior to what has been the standard in SF_6 for years.

b. Reignition voltage peak & chopping number

The results of the test duty n°1 on the Figure 6 are coming from the performance of a 245 kV circuit breaker which is an equivalent apparatus when compared to the chamber of the 420 kV introduced earlier. The design was adapted to g[3]. Therefore, a direct comparison can be proposed as both are modern design and equivalent for their respective technology. The reignition-free arcing windows are quite similar with a range between 6 to 10 ms. Furthermore, the overvoltages are reaching values as high as 500 kV which is about the same as what has been presented on Figure 1.

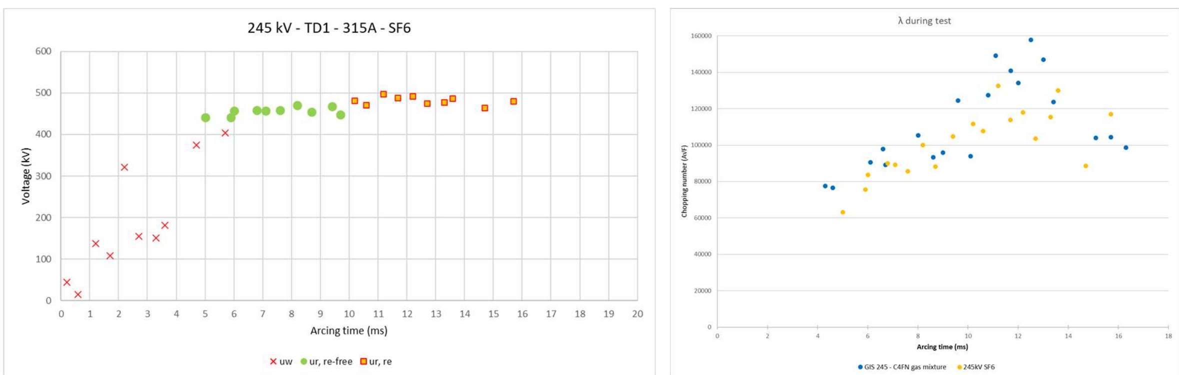

Figure 6: Test duty n°1 at 245 kV in SF_6 (left) and chopping number comparison between SF_6 and C_4FN gas mixture (right)

To be noted that the chopping number of an interrupter is an important characteristic to assess the applicability of a circuit breaker for shunt reactor applications. The chopping number between both technologies remains in the same range as presented on the right side of Figure 3. Slightly higher chopping number (~10%) may be observed with C4FN in this example but it cannot be given as a general statement as it is not always observed in all executed tests.

c. Parts wear after test

The following figures are the parts from the LT 145 kV SF_6-free apparatus (C4FN based gas mixture) which performed the whole sequence of test-duties: 1 to 4. The wear generated by the sequence is negligible and superficial with no dimensional impact as expected with the low energy of each interruption. It also does not reveal any puncture, tracking or damage on the insulating parts. Furthermore, their general design does not differ from what has been used for years with SF_6 technology and the wear aspect after breaking is similar.

Figure 7 : Tulip

Figure 8: Pin

Figure 9: Nozzle (front and back)

6. Design impact on the shunt reactor performance

a. Filling pressure: Test duty n°4 at 145 kV, 100 A

The filling pressure is an important parameter for shunt reactor applications. On one hand, the nominal filling pressure offers generally a higher TRV withstand because of the higher cooling capability of the arc blast and thanks to a higher dielectric strength related to the higher density of gas. However, in shunt reactor application, a higher filling pressure may also mean higher current chopping resulting in higher overvoltage. This is particularly true for lower current TD2-TD3-TD4 when the chopping capability has a more sensitive impact on the overvoltage. Therefore, TD1, TD2 and TD3 are performed at nominal pressure to better assess the most severe chopping conditions. TD4 is then performed at lockout pressure to assess the impact of the reduced pressure.

The test duty n°4 which has the same circuit characteristics as the test duty n°2 highlights the effect of the filling pressure on the performance. Indeed, this sequence is performed at the lockout pressure instead of the nominal previously.

Figure 10 is presenting the results obtained on the LT 145 kV during test duty n°4:

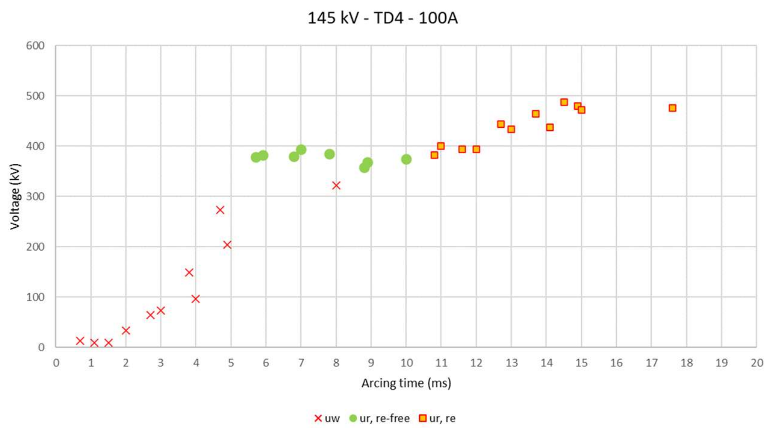

Figure 10: Test duty n°4 at 145 kV with a C4FN based gas mixture

In comparison to the results of the TD2 & TD3 presented in section 4, this time the original reignition-free arcing window (5 to 10 ms) shows an isolated reignition at 8 ms which is interrupted at the next current zero. Those results are somehow similar to what could be encountered in SF_6.

b. O_2 content

- Performance:

The gas mixture can also influence the shunt reactor performance. The following chart is presenting the result of the test duty n°2 for the LT 145 kV with no O_2 with the following gas mixture: 3,5% C_4FN / 0% O_2 / 96.5% CO_2.

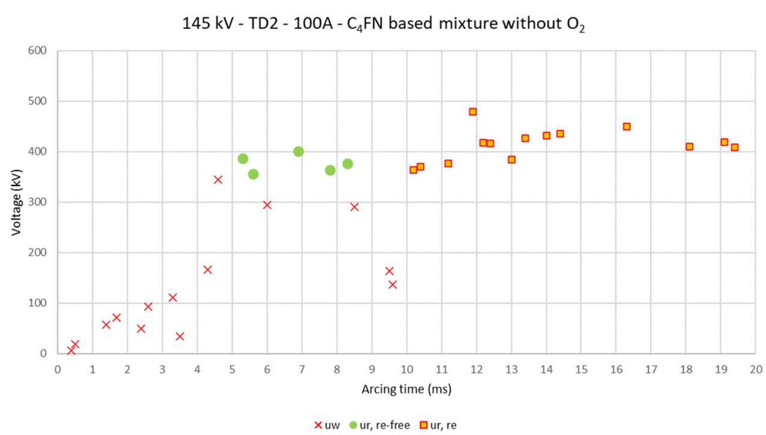

Figure 11: Test duty n°2 at 145 kV with a different gas mixture: 3% C_4FN/0% O_2/97% CO_2

As a result, the lack of O_2 decreased the performance in comparison to the results presented in section 4. This time, the original reignition-free arcing window from 5 to 10 ms is jeopardized with reignitions at 6, 8.5 and 9.5 ms. Furthermore, the ones at 9.5 ms have seen their reignition voltages being reduced around 150 kV which highlights as well that the reignition-free performance at this specific arcing time is far from the performance.

- Multiple reignitions at a single current zero:

In the case of inductive load switching the initiation of the re-ignition is a high-frequency event, which can be of a single or multiple nature and may in some cases be interrupted without power-frequency follow current.

The number of re-ignitions (at a given power frequency current zero attempt) in vacuum circuit breakers is significantly higher because of its capability to interrupt the high-frequency re-ignition current. Therefore, in Vacuum CB (VCB) inductive load switching, overvoltages can escalate to higher values than in gas circuit breaker inductive load switching [8][9]. Unfortunately, due to multiple re-ignitions, very high overvoltages can be reached causing high stress on the nearby inductance and can result in dramatic failure of the reactor. Therefore, switchgear generating multiple reignitions shall be equipped with costly surge arresters (ZnO) and RC dampers [8].

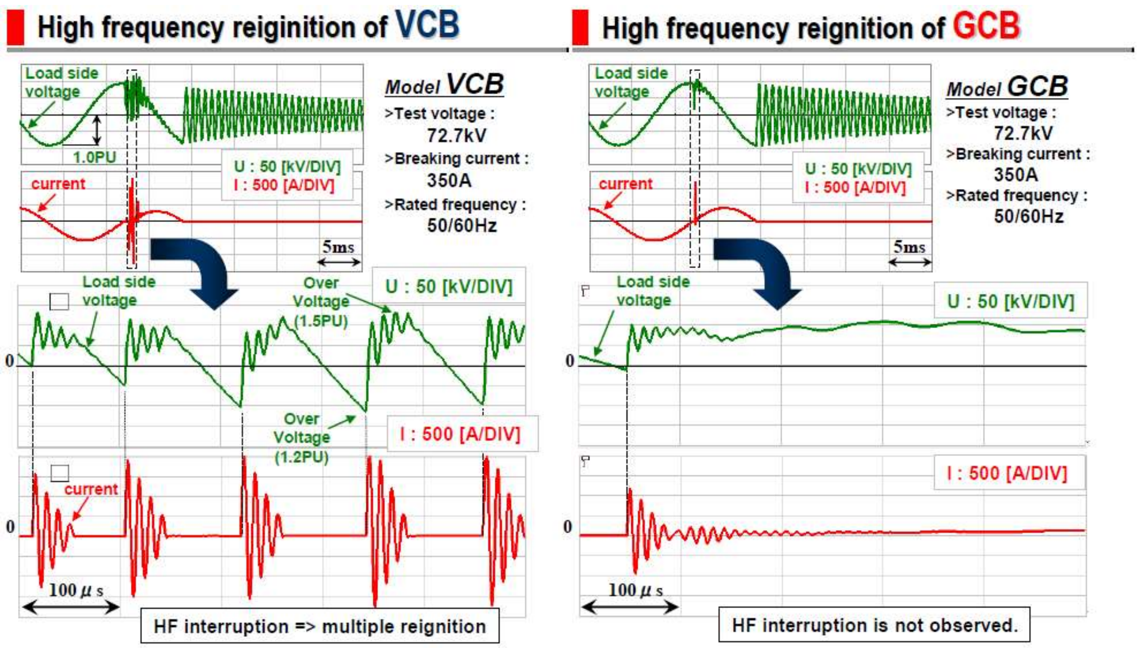

Figure 12: Example of High-frequency interruption and re-ignition observed with an 84 kV VCB (left) and an 84 kV SF_6 (right) [8]

This phenomenon is significantly reduced in gas circuit breaker using SF_6 [8] and has not been observed with C4FN mixture containing O_2 making the reignition behaviour with g^3 at much lower risk for the nearby reactor than with VCB.
It was also observed during the investigations that the absence of O_2 in the C4FN mixture can favor multiple reignitions. Therefore, C4FN circuit-breakers shall be applied for shunt reactor switching with a mixture containing O_2.

7. Applications

As in SF_6, each shunt reactor application shall be studied in order to determine whether a circuit-breaker and its corresponding characteristics is suited to be applied. The ratings of the circuit breaker, the need for control switching device and corresponding setting shall be determined by the manufacturer based on the application data. All investigations and type-tests carried out with C4FN / O_2 / CO_2 mixtures circuit-breaker have shown the potential to replace SF_6 on the grid.

8. Conclusions

The shunt reactor performances presented in this document revealed that with the SF_6-free alternative based on C4FN gas mixture, the results and the circuit-breaker behaviours were close to what have been the standards for years in SF_6.

Furthermore, it demonstrated that the shunt reactance performance from 145 kV to 420 kV is available to replace SF_6 solutions for current projects with g^3 circuit-breakers.

Finally, multiple design key elements have been identified to leverage the performance with C4FN gas mixture and equal the performance in SF_6 as from all the test-duties performed on LT, GIS and DT (not presented inside this document) apparatus. Not a single puncture or insulating part degradation have been observed after the investigations. This specific difference could find its root cause inside the gas properties of C4FN based gas mixture.

As a conclusion, C4FN / O_2 / CO_2 circuit breaker are suitable to replace SF_6 for shunt reactor switching applications.

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