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COMPARATIVE TEST PROGRAM FRAMEWORK FOR NON-SF_6 SWITCHING GASES

OKVIRNI PROGRAM ZA UPOREDNA SKLOPNA ISPITIVANJA ZAMJENSKIH GASOVA ZA SF_6

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Abstract: In recent years, significant achievements have been made with respect to the development of SF_6-free gas insulated substations (GIS). In parallel, the interest in installing SF_6-free GIS by utilities increased steadily and tenders for new substations or upgrades, which regularly also include alternative technologies. The excellent performance of SF_6 was unequivocally accepted by all vendors and users so that the community became used to single technology solutions. This is no longer the case with alternative gas mixtures, and multiple technological solutions are available. However, from the present body of literature it is not possible to make a full and comparative evaluation of different alternative gas switchgear, i.e. circuit-breakers and disconnectors. Thus, the High-Voltage Laboratory of ETH Zürich started investigations and measurements of basic experiments that allow an unbiased comparison of properties of alternative gas mixtures relevant for switching. The two main purposes of these investigations are to define a set of measurements that allow an estimation and comparison of switching performance with different gas mixtures, independent of a specific interruption nozzle geometry, drive system, electrostatic design, and other design specific features, and to perform (some of) these measurements comparing pure SF_6, with air, pure CO_2, CO_2/O_2 mixture, and further specific gas mixtures that are currently proposed by manufacturers for SF_6 replacement. The basic analysis behind the definition of measurements will be given in detail and the design principles of the chosen test devices and the derived test currents and diagnostics will be introduced. Test results themselves will not be given, rather they will be the subject of separate future publications.

Keywords: gas circuit breakers, current interruption performance, SF_6 alternatives

Sažetak: Posljednjih nekoliko godina napravljena su značajna postignuća u razvoju metalom oklopljenih postrojenja (MOP) sa zamjenskim (alternativnim) gasovima za SF_6. Paralelno, porastao je interes za ugradnju MOP-ova sa SF_6 alternativama i tenderi se redovno nadograđuju tako da uključuju i tehnologije sa SF_6 alternativama. Odlične karakteristike SF_6 gasa su nedvosmisleno prihvaćene od svih dobavljača i korisnika tako da je energetska zajednica naviknuta na postrojenja koja koriste istu tehnologiju. Ovo nije slučaj sa SF_6 alternativama gdje postoji više tehnoških rješenja. Međutim, iz postojeće literature nije moguće napraviti potpunu i uporednu ocjenu različitih sklopnih aprata (prekidači, rastavljači) koji koriste SF_6 alternative. Stoga, Laboratorija visokog napona sa ETH Cirih je započela istraživanje i mjerenja u osnovnim eksperimentima koji omogućavaju nepristrasnu usporedbu karakteristika alternativnih gasnih mješavina relevantnih za sklapanje i prekidanje struja. Dvije glavne svrhe ovog istraživanja jesu definirati skup mjerenja koja će dozvoliti procjenu i usporedbu sklopnih karakteristika različitih gasnih mješavina, neovisno o specifičnoj geometrije mlaznice, pogonskom mehanizmu, izolacijskim karakteristikama i drugim karakterističnim odlikama prekidača, i sprovesti (neka od) ovih mjerenja poredeći SF_6 gas, sa zrakom, čistim CO_2, CO_2/O_2 mješavinom, i drugim specifičnim gasnim mješavinama koje su trenutno predložene od strane proizvođača kao zamjena za SF_6. U radu je detaljno prikazana osnovna analiza koja stoji iza definicije mjerenja te su predstavljeni principi konstrukcije odabranih ispitnih uređaja, izvedenih ispitnih struja i dijagnostike. Sami rezultati ispitivanja nisu dati u radu, već će biti predmet zasebnih budućih publikacija.

Ključne riječi: gasni prekidač, karakteristike prekidanja struje, SF_6 alternative

INTRODUCTION

In recent years, significant achievements have been made with respect to the development of SF_6-free gas insulated substations (GIS). This includes the compartments with insulating duties, such as gas insulated busducts/lines (GIL), but also those with switching duties, such as disconnectors and circuit breakers. In parallel, the interest in installing SF_6-free GIS by utilities increased steadily and tenders for new substations or upgrades, which regularly also include alternative technologies. Several pilot installations around the world have been built, and announcements have been made for SF_6-free GIS up to the 420 kV level.

The excellent performance of SF_6 was unequivocally accepted by all vendors and users so that the community became used to single technology solutions. This is no

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longer the case with alternative gas mixtures, and multiple technological solutions are available. Depending on the users' objectives and preferences, different technical solutions may seem beneficial. Amongst these criteria are the minimum operating temperature, size and footprint, ease of gas handling, the global warming potential (GWP) of the chosen gas mixture or the total environmental footprint assessed in the form of a life-cycle-analysis, and last but not least, local legislation and taxes. From all these criteria, the insulation and switching performance stand out as they constitute the necessary basic requirements. Users thus typically try to perform a comparative study of the switching capabilities of the different solutions within their requirement specifications.

A recent summary on the existing know-how with respect to switching performance, based on publicly available results, was written in 2017 [1]. Since then, more publications have been issued, but the situation did not change fundamentally. The body of literature on switching in non-SF_6 gases is predominantly presented by manufacturers. The investigations are typically performed in example of a switchgear that is derived from the manufacturers SF_6 portfolio (e.g. [2], [3]) and (naturally) not all details are fully disclosed. Based on the present body of literature it is not possible to make a full and comparative evaluation of different alternative gas switchgear, i.e. circuit-breakers and disconnectors.

Thus, the High-Voltage Laboratory of ETH Zürich proposed to start "investigations and measurements of basic experiments that allow an unbiased comparison of properties of alternative gas mixtures relevant for switching". Here, "basic experiments" refers to the fact that the investigations shall be performed under realistic stresses, but not on real breakers and not with type-test conforming test circuits. "Comparison" refers to the plan that empirical experimental investigations shall be performed to show differences, but that it is not necessarily the goal to explain these differences. "Properties relevant for switching" indicate that basic dependencies shall be studied, but direct switching performance shall not. The object of the investigations is "alternative gas mixtures", which in the present context is CO_2 as the base gas, mixed with varying content (≤ 10%) of C_4F_7N and $C_5F_{10}O$, plus Oxygen to minimise the negative effect of gas decomposition. Air and SF_6 are investigated for comparison. These gases are the ones currently proposed by manufacturers as alternatives to SF_6 in real applications.

To go beyond the state-of-the-art and to be of a practical relevance for users, focus is also laid on "unbiased" investigations. For this, the freedom of academic research at a technical university is combined with a wide basis of financial supporters, backed with suggestion of tests by a group of switching experts.

Currently, 18 representative utilities and manufacturers financially support these activities. The following two main purposes of these investigations can be stated:

1. To define a set of measurements that allow an estimation and comparison of properties relevant for switching with different gas mixtures, independent of a specific interruption nozzle geometry, drive system, electrostatic design, and other design specific features. These properties can be used by manufacturers in the design and dimensioning processes of their equipment and by the user to identify the optimum technology for their purpose and portfolio.
2. To perform (some of) these measurements comparing pure SF_6 with synthetic air, pure CO_2, CO_2/O_2 mixtures, and further specific gas mixtures that are currently proposed by manufacturers for SF_6 replacement.

The gas inner circle of the Current Zero Club [4] supports this initiative by using its expert know-how to recommend how such tests could be performed and what issues have to be considered.

The present contribution will introduce this comparative switching initiative. The basic reasoning behind the definition of measurements that allow a design independent investigation, and comparison will be given in detail. Moreover, the design principles of the chosen test devices and the derived test currents and diagnostics will be introduced. Test results themselves will not be given, rather they will be the subject of separate future publications.

1. PROPOSAL OF TESTS

Switching devices need to be able to cope with a large number of different switching duties and to be able to interrupt very low and very large currents. The switchgear design is thus a compromise between all the requirements and the designer needs to consider a large number of (partially conflicting) phenomena. A selection of the most important switching duties and the related proposal of tests relevant to investigate the switching performance of novel non-SF_6 gas mixtures are given in this section. We will exclude the voltage withstand requirement in open position, which is, again, design-specific and mainly related to the cold gas electric strength.

1.1. Small current switching

Switching small capacitive and inductive currents are standard duties when disconnecting equipment from the power network and thus occur regularly. The current interruption itself is not challenging, as the current amplitude itself is rather small (typically in the range of a few ten to some hundred Ampère only). On the contrary, current interruption before a natural current zero crossing (called "current chopping") can occur if the powerful gas flow acts too strongly on the small current arc, which can lead to overvoltages across inductive network components. And when the current is interrupted prematurely with small contact opening gaps in the interrupter, restrikes can occur and lead to large transient switching overvoltages. Current chopping is a very design-specific phenomena and thus cannot be meaningfully addressed

by the present study. The question of restrike is mostly a question of the electric withstand strength of the gas gap between the electrodes and can be dimensioned based on breakdown tests in cold gas configurations. This is very important, but also not part of the present investigation. Comparative studies in this field are, for example, performed by the Cigre Working group D1.67. These results have already been applied in WG A3.41 in the context of preparing capacitive switching tests.

Transferring load currents in substations is also a very common switching duty that is typically performed with disconnectors. This is possible with disconnectors, as transferring a current requires only to counteract a small inductive voltage during the current transfer process, in contrast to load current interruption which counteracts the full system voltage. Figure [5] shows us that the current transfer is successful if the arc voltage is larger than the inductive voltage drop across the transfer loop. As disconnectors typically follow very simple designs, a parameter relevant for bus transfer switching is thus the arc voltage in an unblown setup as a function of arc length, current amplitude and background gas pressure for the various gas mixtures. This test is planned to be performed within the scope of this project.

1.2. High-current interruption (thermal phase)

The process of high current interruption is typically divided into two parts. First, the thermal phase where the hot plasma is cooled down to temperatures at which it is no longer conducting and electrons are either attached or recombined with positive ions, and second, the dielectric phase in which the temperature in the former arcing region is further reduced and the gas particle number density increased so that the voltage withstand strength is sufficient to withstand the transient recovery voltage.

To optimize the thermal interruption performance, manufacturers combine several design features such as the geometric design of the arcing chamber, travel curve of the contacts and backheating caused by nozzle ablation. As this design optimization is explicitly excluded from the present study, it is proposed to measure in a decaying arc the voltage and the extinction peak, the arc conductance decay, post arc current and thermal recovery (in terms of maximum di/dt at given du/dt after current zero, or in terms of maximum di/dt and du/dt with constant $Z = 450\ \Omega$). Ideally, this is done in an axially blown setup with simple orifice and at constant pressure levels a few milliseconds before and after current zero. The gas blow should be with cold filling gas only, unaffected by any ablated nozzle and contact material. In addition, the determination of black-box arc model parameters (in particular the “thermal inertia”) would be useful as well. This would help to predict the effect of changes in the external electric circuitry (e.g. grading capacitors) on the interruption capability. The influencing parameters that are independent of design specific optimizations are the blow gas pressure (absolute and relative to filling pressure) and the gas mixture. Questions of particular interest are does the background gas, which dominates the mixing ratio, also dominate the thermal interruption performance, and does the switching performance increase with increasing percentage of a strongly attaching gas, and if yes, does it increase linearly or non-linearly. Additionally, oxygen is admixed to reduce the negative effects of gas decomposition during arcing and its role during the thermal phase needs to be investigated.

To summarize the requirements for a thermal interruption test device: i) simplest possible nozzle design, ii) gas flow from “cold” gas without ablated nozzle material, iii) the blow gas pressure level and ratio can be varied over a large range below and above sonic speed, iv) the blow gas pressure should be constant for a few ms around CZ and v) copper vapour must be avoided in the arcing zone.

1.3. High-current interruption (dielectric phase)

After the arc region has been cooled down sufficiently to suppress the post current-zero current flow (the thermal phase), the transient recovery voltage builds up across the breaker contacts. The maximum voltage during this TRV can reach levels up to twice the peak system voltage within a few 100 μs. The limiting location inside the interrupter in this test is typically the region of maximum E/N. The electric field distribution E is exclusively controlled by design specific parameters such as the contact shape and the travel curve, which is clearly outside the scope of this project to investigate. To be able to withstand the electric stress given by this design, the particle number density N needs to be as high as possible, i.e. the pressure should be high and the temperature low. The remaining important parameter that is not design-specific is the electric withstand strength of warm/hot gas as a function of temperature. While it is a very important and required gas characteristic, it will not be investigated in this study for reasons of time.

1.4. Interrupter wear during current interruption

Inevitably, the arcing contacts will erode under the influence of arcing. In SF_6, the ablation rate is found to be a function of the current amplitude and arcing time. In alternative gases, one measurement indicates significant differences in electrode (tulip) erosion with varying oxygen contents [6]. If this is to be confirmed in future tests, it would represent an important characteristic that influences circuit breaker wear and thus poses a requirement specification to the designer. As gas flow can influence the wear, e.g. by blowing off a liquid pool of molten material, contact erosion is preferably investigated in a setup with free burning arcs. If this type of measurement is prepared in advance, contact wear can be measured in parallel to all other experiments. First, one needs to enable easy contact removal from the setup to determine weight and size before and after the experimental campaign. Second, the currents and voltages during the test need to be measured exhaustively and accurately to be able to determine the total charge transfer and energy input.

Then, the contact erosion behaviour can be evaluated without extra experimental effort using the tests tailored and conducted for other purposes.

Many gases do not recombine to the original molecule after decomposition during arcing. This is particularly important in case reactive or even toxic components would form, or in case one of the molecules with low concentration is affected, which has a dominant role in the electric withstand strength. The decomposition rate is thus also an important life-time determining parameter that needs to be known to the designer.

In literature, linear decomposition rates of e.g. $C_5F_{10}O$ in CO_2/O_2 were reported ranging by more than an order of magnitude from 0.14 mol/MJ [7] to 2.1 mol/MJ [8]. Even though this linear law is only a first order approximation, it is not clear why such extremely different decomposition rates have been found. This needs to be investigated, understood, and reliable models with predictive strength for other conditions need to be developed. Fortunately, similar to the above mentioned experiments for contact erosion rates, these measurements can also be done in parallel to anyhow ongoing tests, if regular gas samples for analysis are taken or mobile analyser devices are directly attached to the experiments and regularly used.

1.5. Internal arc test

The event of an internal arc in a sealed compartment of GIS will lead to pressure rise resulting in high mechanical (and high local thermal) stress. The pressure rise is a result of released arc energy, evaporation of contact material and exothermic chemical energy being released. In the event of enclosure burn-through or activation of protection device (rupture disc), gas contaminated with arc products will be released from the enclosure. Therefore, the standard prescribes an “internal arc resistance test” where the arc is initiated in the smallest compartment of gas-insulated switchgear.

Due to the different thermodynamic properties of different gases/mixtures, pressure rise under the internal arc will be different. In addition, the arc voltage itself most likely depends on the gas mixture as well as the energy released by an exothermic reaction. A possible motivation for comparative study here is to investigate to what extent the properties relevant to the internal arc of non-SF_6 gases are defined by the background gas, and if potentially tests can be performed with the background gas alone. However, these tests are beyond the scope of this project.”

2. TEST DEVICES

In order to perform the measurements, suitable test devices are required. With the argumentation outlined above, there needs to be one configuration with unblown arcs and one with axially blown arcs.

2.1. Unblown Arcs

As stated above, the requirement formulated for a test device with unblown arcs is to be able to measure the arc voltage as a function of arc length, current amplitude and background gas pressure for the various gas mixtures. As free burning arcs are known to fluctuate strongly, a large number of repetitions need to be performed and the results analysed with statistical methods. Designs with static contacts and ignition wires are thus excluded as performing the experiments would be too cumbersome and tedious. The test device for this set of experiments is thus designed with two moving pin contacts, for which the maximum contact separation can be adjusted in the range up to approx. 100 mm. The current amplitude can either be stationary or slowly varying, i.e. on a timescale much lower than typical thermal arc time constants. A schematic and a photo of this test devices are shown in Figure 1.

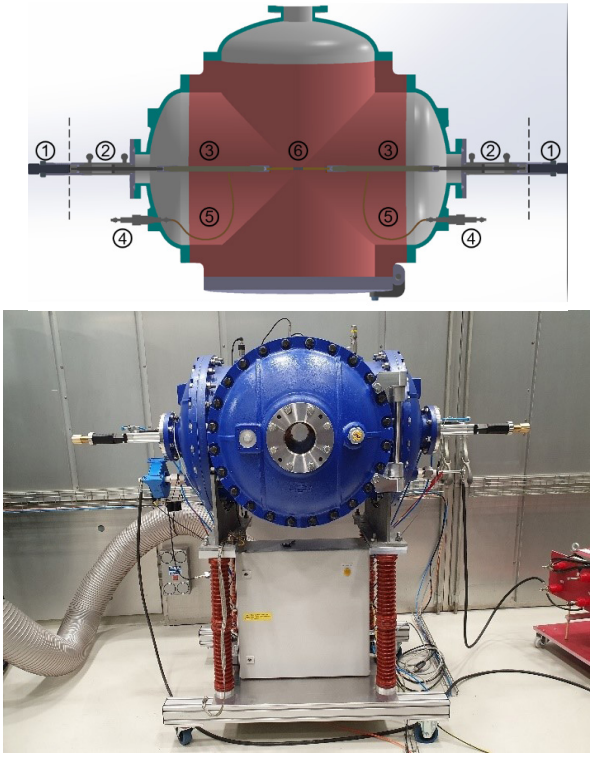


Figure 1: Schematic of one side (top) and photo of the entire unblown test device (bottom). 1: stroke regulation, 2: drive, 3: insulating rod, 4: current feedthrough, 5: flexible current connection, 6: pin contact.

It is recommended to use standard W/Cu (80/20 wt%) *contact material* and the influence of metal vapour in the arc needs to be considered and investigated. Disconnectors can be found with various contact shapes; we opted for pin contacts with spherical tips.

A sufficiently large gas volume is a very important requirement. This ensures, on the one hand, that the pressure build-up during the test, and from test to test, is kept reasonably low. On the other hand, the gas mixing ratio is only slightly affected by the inevitably occurring gas decomposition. The decomposition is an unsolved question itself and could be investigated in parallel.

2.2. Axially Blown Arcs

In literature, three principal types of test devices can be found for arc investigations: two-pressure devices, those with pressure build up by a compression volume, and by pure backheating. In real circuit breakers, the last two principles are combined, but, as mentioned above, this leads to design specific optimizations and these should be explicitly excluded from this comparative study. Pure backheating devices are also not considered here; mainly because the pressure build-up strongly depends on the gas itself and the nozzle geometry, as the nozzle vapour could change the interruption performance, and also because of its cumbersome operating and maintenance requirements. Thus, two-pressure and puffer devices are considered and compared. Two-pressure devices have been used by researchers to study SF_6 in the 1970's and 1980's, e.g. [9]. Here, gas stored in a high pressure reservoir is expanded into a low pressure tank via a nozzle in which the arc is burning. Their main advantage is that the blow gas pressure in the upstream and downstream region can be set independent from the test current and from the contact movement; it is thus completely independent from any specific designs.

In addition, the pressure and the pressure ratio can be varied over a large range and the gas temperature before the experiment is clearly defined by the laboratory temperature. However, due to adiabatic expansion, the blow gas temperature reduces during the experiment, which can lead to unrealistic conditions. The exhaust volume should be very large so that the downstream pressure increase is minimized. In the context of experimenting with novel SF_6 replacement gas mixtures, the main disadvantage is the high static pressures that occur during the gas compression. Most of the novel compounds to be investigated have a high boiling point and liquefaction could occur. Thus, the mixing ratio of the blow gas could change in between experiments due to the required gas handling. The maximum theoretical blow gas pressures are limited and an additional uncertainty is introduced during gas handling and compression. The achievable pressure range is limited and considered too small for the gases to be investigated in the present study.

In contrast to this, the above mentioned main disadvantages of two-pressure devices can be avoided by using puffer type pressure build-up. Here, a volume is compressed by an operating mechanism during the contact motion and arcing phase and the overpressure is generated only when needed. Thus, the blow gas temperature is close to ambient temperatures. However, in classical puffer designs the pressure build-up is a function of the travel speed, piston area, contact stroke and current amplitude. As a design specific pressure build-up should be avoided, a tailor-made experimental device is required. A scheme and a photo of the developed test device is shown in Figure 2. The basic idea of this special device is to use an oversized drive system that guarantees a constant travel curve under all test conditions. The puffer volume is oversized as well and equipped with an adjustable overpressure relief valve. This way, a constant pressure is ensured under all conditions, for all gases; the pressure level itself can be adjusted by adjusting the pre-tensioning of the spring.

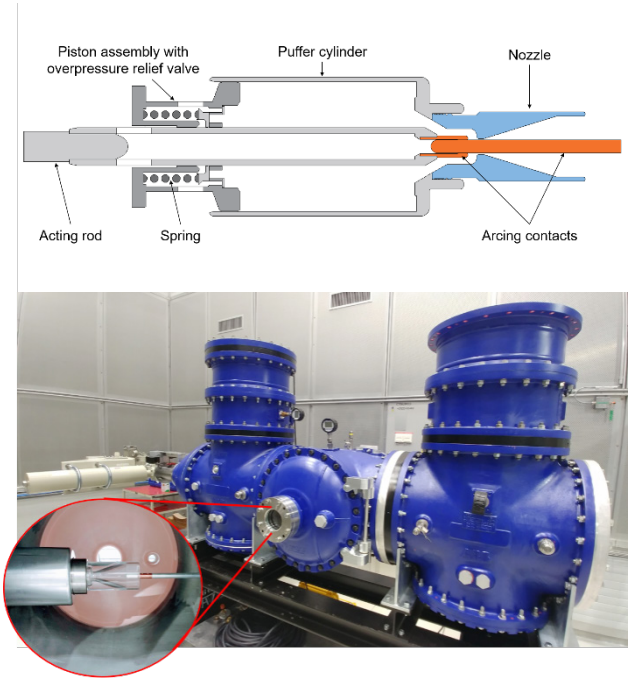


Figure 2: Schematic of the nozzle and puffer region (top) and photo of puffer breaker (bottom).

A remaining (small) disadvantage is that the downstream pressure is equal to the filling pressure and as some mass is required in the puffer to be compressed, the minimum downstream pressure is limited. Overall, an experimental interrupter with tailor-made gas compression seems to be the most favourable option and is thus used in the present project.

Backheating and nozzle clogging must be avoided. As both phenomena depend on the relation of a nozzle cross section to current, the nozzle size should be appropriately chosen for the maximum current level. The length of the nozzle throat should be as short as possible. In addition, metal vapour in the arcing zone must be avoided to measure the gas specific properties only. Thus, a double-flow configuration and possibly even hollow pin contacts are favoured. Low current testing is also possible, which leads to low gas decomposition and low nozzle/contact erosion and therefore, a larger number of tests is possible without revision and/or gas exchange. The smallest nozzle cross section should be as simple as possible (simple orifice) and deep shock and flow separation must be avoided in the diverging part of the nozzle. In addition, a simple nozzle, contact and flow configuration with constant pressure and stable axially symmetric arcs around current zero makes it easier to model the interruption process; maybe even with 1D tools.

In the following list, specific details of the design relevant issues are given:

The thermal interruption performance is a function of the *upstream pressure* and of the pressure ratio between the upstream and downstream region [9], [10], [12]. In the test device the upstream pressure should thus be easily and reproducibly adjustable so that the thermal interruption

performance can be studied in detail. The minimum required upstream/downstream pressure ratio that ensures sonic flow conditions in the nozzle throat can be calculated for a given nozzle geometry assuming isentropic flow conditions of a perfect gas from, e.g. equation (5.60) in [11]

$$\frac{p_{up}}{p_{throat}} = \left(\frac{\gamma+1}{2}\right)^{\gamma/\gamma+1} \quad (1)$$

For SF_6 this minimum pressure ratio is ~ 1.7. As the values of the ratio of specific heats γ for air and CO_2 are higher than that of SF_6 (γ_{air} ~ 1.4 and γ_{CO2} ~ 1.28), the required pressure ratio is slightly higher as well and ~ 1.8. Thus, the upstream pressure should be in a realistic range of about 1…1.5 MPa. Cold flow simulations should be used to help determine the pressure differences and it must be checked under which conditions condensation might occur (which must be avoided as much as possible).

The *downstream/exhaust pressure* (filling pressure) is recommended to be at 0.5 MPa for the upstream pressure range of 1…1.5 MPa in order to enable sonic flow conditions and isolate most of the downstream arcing region from the possibility of shocks.

For the same reasons as with the unblown arc setup, it is recommended to use standard W/Cu (80/20 wt%) *contact material*. Using standard material also enables using standard *contact shapes*. Main concern is the uniform flow field and avoiding gas blocking and metal vapour removal. Mechanical and endurance questions are secondary.

Similarly, ablated *nozzle material* in the blow gas may influence the interruption performance, but should be of smaller significance with the suggested large nozzle cross section. Also material compatibility is of lower concern for short testing durations of weeks. Thus, the material can be chosen by availability or further requirements, e.g. transparency in case of direct arc observations.

The electrode *gap length* should be in the range of 50…100 mm, no further electric requirement (BIL level) is relevant.

The nozzle and flow design should guarantee sonic flow in the nozzle throat only and have a nozzle with small diverging angle of < 15° to prevent shock formation. The annular gap between plug and nozzle should be ≥ 1 mm.

And last but not least, the overall *tank volume* ("exhaust") should be sufficiently large. To allow for 10 % decomposition during one experiment of 50…100 shots (assuming 30 kJ per shot, a decomposition rate of 0.5 Mole/MJ and 10% admixture at 0.5 MPa total pressure, typically), a volume requirement of 375…750 litres can be calculated. For this, the pressure rise during the shot should be small (≤ 40 mbar) and there would be little influence on the pressure ratio of compression volume to exhaust volume.

3. TESTING AND PARAMETERS

As the experiments aim for basic tests, the test circuits do not need to be compliant with IEC. Nonetheless, the stresses should be realistic, which requires a certain minimum current and voltage amplitude, as well as stored energy in the test circuit.

For the thermal interruption performance tests, established injection circuits can be used, e.g. the ones of Weill-Dobke type as shown in Figure 3. The choice of parameters can be adjusted to the test device, cf. e.g. [12], and parameters like arcing time or current shape don't have to reproduce short-circuit currents from networks. The high-current phase is emulated by an *LC*-discharge circuit (L_{HC} and C_{HC}) that is activated with a making switch SM. The element size is chosen to deliver the desired peak current with the required arc duration. To prolong the arcing time without increasing the peak current, we plan three parallel *LC*-circuits that can be triggered independently from each other. Shortly before the final current zero of the high-current phase, the high-voltage injection circuit is triggered with a spark gap (SG). The main current path is decoupled with the auxiliary switch S_A. The size of the elements is selected to achieve the desired current slope d*i*/d*t* shortly before and voltage rate-of-rise d*u*/d*t* after current zero. Particular attention needs to be paid to the charging voltage and duration of voltage application of the injection circuit in order to minimize the arc-network interaction and to ensure that the slope of current before and rate-of-rise of voltage after current zero is constant ("stiff circuit"). We aim to test with peak currents of up to 7.5 kA with 10 ms half-wave duration and need a charging voltage of up to 5 kV in the high-current circuit. The desired current slope from the injection circuit is up to 20 A/μs with 0.5…2 ms duration. In contrast to type tests, the current slope before CZ of the high-current phase does not have to match with the one from the injection circuit. The TRV-shaping elements are chosen to result in a 450 Ω surge impedance and a time delay of < 100 ns. The charging voltage of the injection circuit is up to 50 kV.

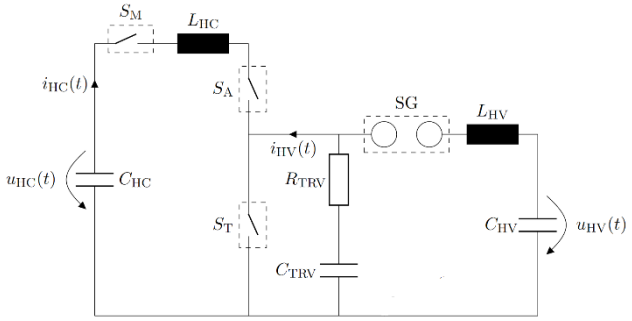


Figure 3: Synthetic test circuit to investigate the thermal interruption limit performance.

Quantities to be measured in these tests are the conductance decay before CZ, the arc voltage ("extinction peak"), and the post-arc currents after CZ. Again, the contact wear and gas decomposition are parameters that should be monitored in parallel.

For the test with free burning arc, no such established test circuits exist. In the past, sources based on short-circuit generators or resonant circuits have been used. To overcome the limitations imposed by these circuits, the HVL of ETHZ has developed a power electronics based flexible pulsed current source with which arbitrary current shapes of up to 3 kA and 50 kA/ms can be generated at a driving voltage of up to 3 kV [13]. The single line diagram of a single module is shown in Figure 4.

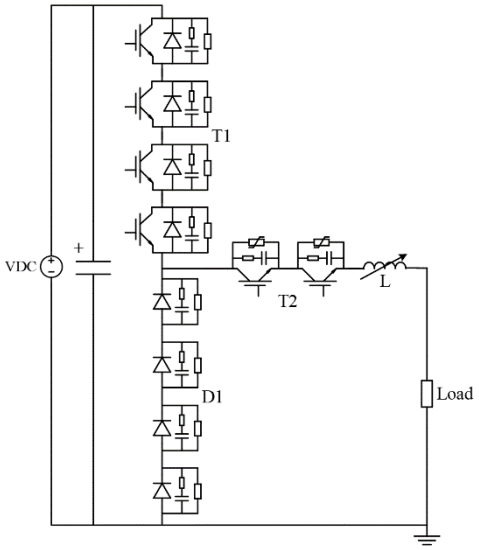


Figure 4: Pulsed current source equivalent diagram.

An example of a test current optimized for the unblown tests is shown in Figure 5. A first phase of constant low current is set during contact opening. The use of ignition wires can be avoided (to enable a large number of tests) and the energy input to the experiment (contact ablation and gas decomposition) is mainly limited to the phase of high current once the full contact opening is established.

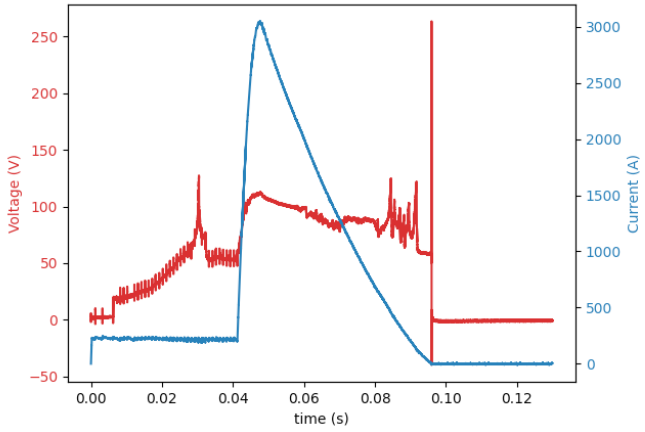


Figure 5: Example current trace for unblown setup.

Also for future tests beyond the scope of the present investigation, this source in combination with the two test devices offer great potential for unique measurements. By superimposing slowly varying (quasi-stationary) currents with steep gradients (spikes or steps), also the thermal arc time constant can be determined at any given current level and any given blow conditions [14].

4. OUTLOOK

The topic of this publication is the preparation for investigations and measurements of basic experiments that allow an unbiased comparison of properties of alternative gas mixtures relevant for switching. A specific set of measurements that allow an estimation and comparison of switching performance with different gas mixtures, independent of a specific interruption nozzle geometry, drive system, electrostatic design, and other design specific features is proposed. The physical background and motivation for these defined measurements are given in detail, together with design principles for test devices, test currents and diagnostics. The focus is on unblown arc experiments and the thermal interruption phase of short-circuit current interruptions. The tests are now started and their results will be presented in future publications.

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REFERENCES

[1] M. Seeger, et al., Recent development of alternative gases to SF_6 for switching applications, Cigre Reference Paper 291, 2017. https://e-cigre.org/publication/RP_291_1-recent-development-of-alternative-gases-to-sf6-for-switching-applications

[2] P.C. Stoller, C.B. Doiron, D. Tehlar, P. Simka, N. Ranjan: Mixtures of CO2 and C5F10O Perfluoroketone for High Voltage Applications, IEEE Trans. on Dielectrics and Electrical Insulation 24(5), 2712-2721, 2017

[3] S. Silvant, et al: Detailed analysis of live tanks and GIS circuit breakers using a new environmental friendly gas, Proceedings of the Cigre Session, A3-114 (2016)

[4] http://currentzeroclub.org/gas-circle/

[5] A. Ritter and C. M. Franck: Prediction of Bus-Transfer Switching in Future HVdc Substations, IEEE Transactions on Power Delivery 33(3), 1388-1397, 2018
[6] A. Majima, T. Uchii, T. Yasuoka, T. Inoue, D. Schiffbauer: Properties of CO_2/O_2 gas mixture as an alternative medium for gas circuit breakers, International Conference on Gas Discharges and their Applications, 367-370, 2018
[7] B. Radisavljevic, et al.: Switching Performance of alternative gaseous mixtures in high-voltage circuit breakers, 20th International Symposium on High Voltage Engineering, Buenos Aires, Argentina, 2017
[8] M. Sato, et al.: Interrupting performance of circuit-breakers with SF6 and SF6 alternatives, CIGRE – AORC Technical Meeting Kanazawa, Ishikawa, Japan, 2020
[9] W Hermann, U Kogelschatz, K Ragaller, E Schade: Investigation of a cylindrical, axially blown, high-pressure arc, J. Phys. D: Appl. Phys. 7, 607-619, 1974
[10] G. Frind: Experimental Investigation of Limiting Curves for Current Interruption of Gas Blast Breakers, in Current Interruption in High-Voltage Networks, Springer New York, 1978
[11] Philip A. Thompson: Compressible-fluid dynamics, McGraw-Hill, New York, 1972
[12] P. C. Stoller, M. Seeger, A. A. Iordanidis, G. V. Naidis: CO2 as an Arc Interruption Medium in Gas Circuit Breakers, IEEE Transaction on Plasma Science 41(8), 2359, 2013
[13] A. Ritter, L. S. J. Bort, C. M. Franck: Five Years of Pulsed Current Testing for HVDC Switchgear, IEEE International Conference on High Voltage Engineering and Application (ICHVE), 2016
[14] L. S. J. Bort, T. Schultz, C. M. Franck: Determining the time constant of arcs at arbitrary current levels, Plasma Physics and Technology 6(2), 175–179, 2019

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