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ARC EXTINCTION WITH NITROGEN AT 1–40 BAR$_{ABS}$ IN A PUFFER-LIKE CONTACT CONFIGURATION

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Abstract. To develop cost-efficient subsea switchgear for large sea depths, the extinction of arcs under high filling pressures must be understood. In this work, arc-extinction experiments have been performed with a puffer-like contact configuration using nitrogen at different filling pressures as the current interruption medium. The main finding is that, for the given contact configuration, the current interruption capability was lower at 20 and 40 bar$_{abs}$ than at 1 and 10 bar$_{abs}$. While higher pressures result in higher cooling flow rates and longer flow times given the same puffer volume, compression spring and nozzle geometry; it does not necessarily improve the arc-extinction capability. This is probably because higher filling pressures increase the arc voltage and total energy dissipated in the arcing zone. Because the filling pressure greatly influences the flow characteristics, the puffer design should be optimized for each pressure level.

Keywords: Current interruption, subsea switchgear, medium voltage, high-pressure nitrogen.

1. Introduction

Today, switchgear is typically based on vacuum technology or gas-filled devices (e.g., SF_6 or emerging environmentally friendly SF_6-alternatives) with filling pressures up to around 10 bar. The shift towards green energy sources, such as offshore wind, has moved the electrical grid farther off coast. Floating wind farms that are placed at locations with water depths up to several hundred meters are already installed and planned [1, 2]. In the future, substations will be put on the seabed due to the high costs of floating substation platforms. To realise subsea substations, the switchgear must be placed in an environment with high ambient pressure. One alternative is to use the same switchgear technology as on land, but this requires addition of costly parts such as pressure-compensated connectors/penetrators and compartments. The other, and probably more cost-efficient, option is to have the same filling pressure in the switchgear as the ambient sea-water pressure. To realise this technology, the characteristics of high-pressure arcs and arc extinction must be understood.

Previous work has investigated the arc voltage of a free-burning arc as a function of nitrogen filling pressure (1–100 bar$_{abs}$) and contact-gap size (5–30 mm) for current amplitudes up to 450 A (190–950 Hz) [3]. The results showed that increasing the nitrogen filling pressure from 1 to 40 bar$_{abs}$ caused an almost threefold increase of the arc voltage. The arc-voltage characteristics for wall-restricted arcs, both thermal interruption capability and dielectric recovery rates in the contact gap after short (0.5–2.6 ms) current half-cycles, have also been published [4–9]. Moreover, dielectric recovery and arc characteristics in high-pressure (supercritical) CO_2 have been studied [10].

This paper reports on current-interruption experiments with a puffer-like contact configuration and nitrogen as the current interruption medium. In contrast to previous work [3–8], an upgraded test circuit with a current waveform close to 50 Hz is used. The current interruption capabilities at nitrogen filling pressures of 1, 10, 20 (subcritical) and 40 bar$_{abs}$ (supercritical state) were compared, using the same contact configuration and puffer design. The goal of the study was to obtain some first puffer design rules for high nitrogen filling pressures. A total of 90 current interruption tests were carried out.

2. Test Circuit, Contact Configuration and Test Procedure

The test circuit is shown in Fig. 1 and consists of a charging section, a capacitor bank, a discharge section, and the main circuit. The main circuit consists of an inductor (L), responsible for generating a 50 Hz current (damped oscillations), the puffer-type test device and a transient recovery voltage (TRV) circuit. Initially, all switches (S) are open. Then, S_{charge} is closed so that the capacitor bank, C_{bank}, can be charged to the desired voltage by the HVDC source. When the charging is completed, S_{charge} is opened, thus disconnecting the HVDC source from C_{bank}. Next, S_{CB} is closed and the energy stored in C_{bank} is released through L to the main circuit. A 25 µm diameter copper ignition wire has been placed between the contacts (through the nozzle) to ensure that an arc is initiated and current starts to flow. After the current is interrupted, either by the test object or after 80 ms, S_{dis} is closed to ensure that the current is interrupted and that any remaining charge in C_{bank} is discharged. The circuit parameter values are listed in Table 1.

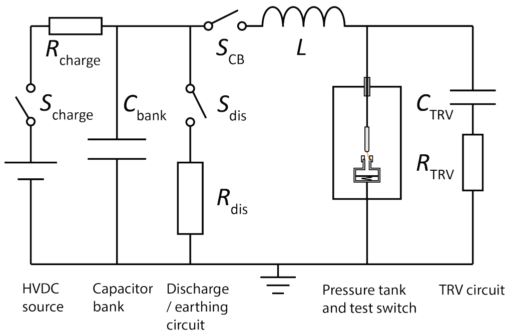

Figure 1. The test circuit.

Circuit parameter	Symbol	Value
Charging resistor	R_{charge}	$220\,\Omega$
Capacitor bank	C_{bank}	$0.167\,\mu\mathrm{F}$
Main inductance	L	$59.7\,\mathrm{mH}$
TRV capacitor	C_{TRV}	$0.94\,\mathrm{nF}$
TRV resistor	R_{TRV}	$600\,\Omega$
Discharge resistor	R_{dis}	$73.3\,\Omega$

Table 1. Circuit parameter values

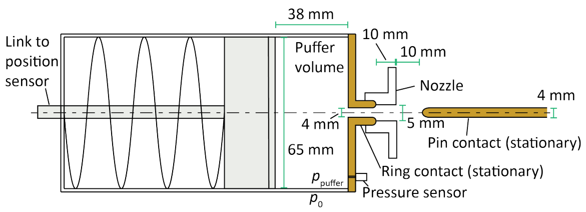

Figure 2. The puffer-type contact configuration. The nozzle was made of polytetrafluoroethylene (PTFE), and the contact material was copper tungsten (CuW, 20/80).

The test device is a puffer-type construction and is shown in Fig. 2. It consists of a puffer volume, a spring, contacts (ring and pin), and a nozzle. The entire test device is placed inside a pressure tank, where the nitrogen pressure can be regulated from a control room. The ring and pin contacts are stationary, i.e., the contact gap is fixed. The cooling nitrogen flow is created by a piston in the puffer that moves towards the ring contact. Before each experiment, the spring is charged manually and held in place by an electromagnet. During an experiment, a triggering signal causes the spring to release at a pre-determined time. The signal is given 40 ms later for 20 and 40 $\mathrm{bar_{abs}}$ filling pressures than for 1 and 10 $\mathrm{bar_{abs}}$, as the piston moves slower at higher pressures. When the spring releases, the puffer volume is compressed and nitrogen is blown through the ring contact and nozzle onto the arc.

To ensure that the gas inside the tank is $> 99\%$ nitrogen, the tank is flushed with 10 $\mathrm{bar_{abs}}$ nitrogen before it is refilled to the desired pressure level. (Flushing is performed twice for the 1 $\mathrm{bar_{abs}}$ tests). The pressure in the tank, p_0, is measured with a static pressure sensor, and the interruption experiment is carried out as soon as the pressure settles at the desired value. During a current interruption test, the current flowing through the inductance L and the test switch (current through C_{TRV} and R_{TRV} are ignored) and the voltage drop across the contacts (the arc voltage and the transient recovery voltage (TRV)) are recorded. Moreover, the over-pressure in the puffer volume compared to that in the rest of the pressure tank ($p_{\mathrm{puffer}} - p_0$) is recorded using a pressure sensor, and the puffer movement is recorded using a position sensor. The sensors, signal transmitters and oscilloscope are listed in Table 2.

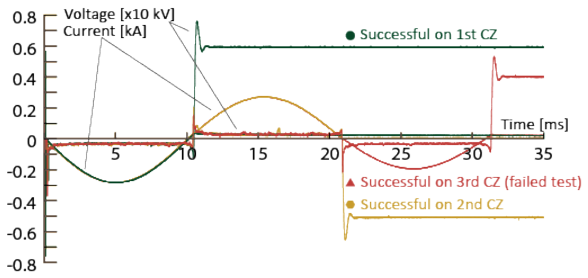

Figure 3. Examples of a successful interruption at the first CZ, at the second CZ, and a failed interruption (interrupted at 3rd CZ).

What	Type/sensor
Current	Pearson current monitor 301X
Voltage	North Star HV probe PVM-3
Piston position	Novotechnik TR-0050
Puffer pressure	KULITE XCL-100-25PSID
Static pressure	Tecsis DMT02 ATEX E114X
Fibre links	TTI Model LTX-5510R ST
Oscilloscope	Tektronix MSO2024

Table 2. Sensors and measurement equipment

The current interruption tests are done at varying gas pressures and capacitor bank charging voltages, while the contact configuration and circuit parameters are kept constant.

3. Results

There are three outcomes of a current interruption test. The first is successful interruption, where the current is interrupted by the test switch and no re-strikes occur after the first current half cycle. The second outcome is "successful interruption at 2nd current zero (CZ)". If the current is not interrupted within the first two half cycles, the test is considered a failed interruption.

Fig. 3 shows examples of these three outcomes at 20 $\mathrm{bar_{abs}}$ nitrogen filling pressure and 7 kV charging

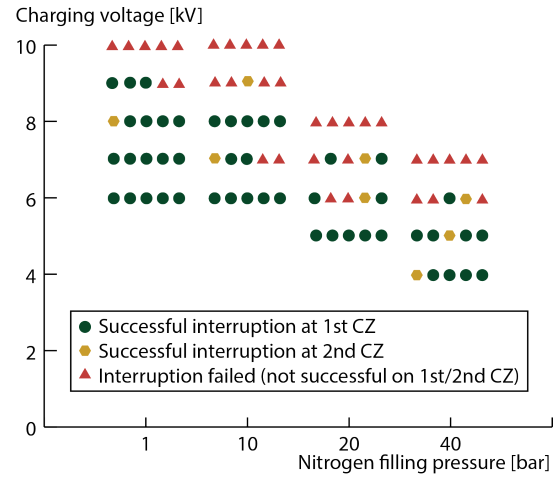

Figure 4. Outcomes of all tests. The coloured symbols (green, yellow and red) represent successful, successful at 2nd half cycle and failed interruption.

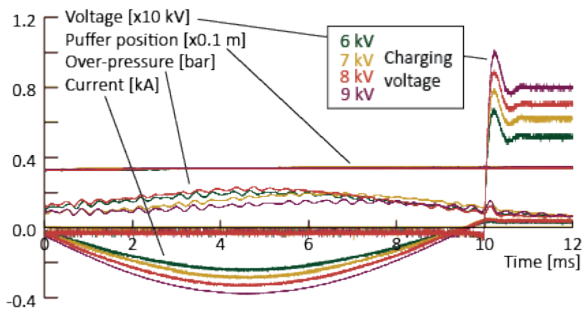

Figure 5. Resulting current and TRV for different charging voltages with 1 bar$_{abs}$ nitrogen filling pressure.

voltage. By comparing the current amplitudes of the first, second, and third half cycles, it is clear that the current is damped due to the losses in the arcing zone. The same is true for the TRVs, so the TRV peak is higher the earlier the current is interrupted. The steady-state voltage across the contacts after interruption corresponds to the remaining energy in the capacitor bank.

A diagram with outcomes of all tests is shown in Fig. 4. Five tests were performed for each charging voltage and filling pressure. Overall, lower nitrogen filling pressures (1 and 10 bar$_{abs}$) seem to have higher interruption capability than higher filling pressures (20 and 40 bar$_{abs}$).

Higher charging voltage results in increased current, a higher rate of rise of recovery voltage (RRRV), and a higher TRV peak. Fig. 5 shows examples of successful interruption tests with 1 bar$_{abs}$ filling pressure for charging voltages in the range 6–9 kV. Table 3 lists the resulting currents, TRV peaks and RRRVs for all charging voltages in the first and second current half cycle.

The TRVs and RRRVs are not available (N/A) for cases where no successful interruptions occurred. Moreover, some variations in currents and TRVs oc-

Charging voltage [kV]	Current peak [A]	TRV peak [kV]	RRRV$_{env}$ [V/µs]
	First current half cycle		
10	428–436	N/A	N/A
9	378–380	10.2	81.5
8	330–332	8.7–8.9	70.7–76.5
7	284–288	7.6–7.9	61.2–64.1
6	238–248	6.2–6.6	48.9–54.3
5	196–200	5.2	43.4–46.4
4	148	4.1	39.1
	Second current half cycle		
10	394–412	N/A	N/A
9	356–378	9.0	66.3
8	320	8.2	63.9
7	269–278	6.4–6.7	52.8–53.3
6	219–224	5.4	42.0–45.8
5	172	4.2	35.2
4	132	2.8	27.2

Table 3. Charging voltage and resulting current and TRV. N/A indicates that no data is available.

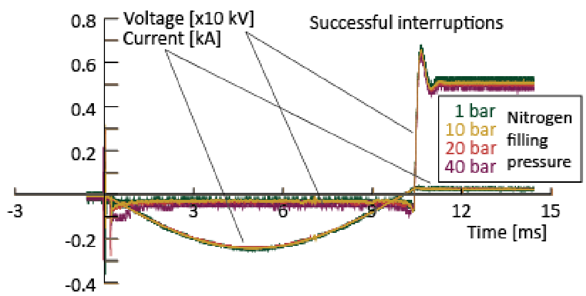

Figure 6. Successful interruptions for different filling pressures. All tests were performed with a charging voltage of 6 kV, resulting in a current peak of 240 A and a TRV first peak of 6.3–6.4 kV.

cur due to differences in the arc voltage at different filling pressures. Fig. 6 shows an example of how the different filling pressures result in slightly different TRVs.

Table 4 lists the arc energy (current multiplied with the arc voltage integrated over time) for the first current half cycle for all charging voltages and nitrogen pressures (one out of the five tests per case was randomly chosen). In general, the energy dissipated in the arc increases with increasing filling pressure and with increasing current.

The piston is moved by the same spring and spring energy, independent of the nitrogen filling pressure. Thus, the piston velocity and pressure profiles vary with filling pressure. Fig. 7 shows pressure curves and puffer positions for different nitrogen filling pressures obtained in "dry tests", i.e., without charging the

Charging voltage [kV]	Nitrogen filling pressure (abs)			
	1 bar	10 bar	20 bar	40 bar
10	82 J	102 J	–	–
9	70 J	91 J	–	–
8	59 J	83 J	69 J	–
7	49 J	48 J	58 J	88 J
6	42 J	40 J	51 J	73 J
5	–	–	55 J	58 J
4	–	–	–	45 J

Table 4. Cumulative arc energies in the first current half cycles.

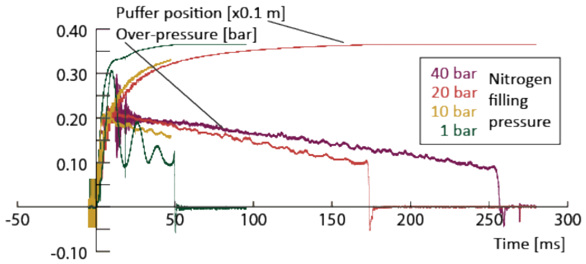

Figure 7. Piston movement and puffer over-pressure as a function of time for all filling pressures (no current). Due to flawed oscilloscope setting, parts of the trace at 10 bar is missing. Due to noise, the piston position for 40 bar was not recorded properly.

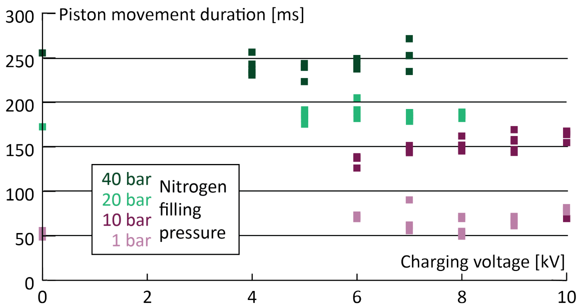

Figure 8. The time from the piston starts moving until it reaches its end point during current interruption tests for all filling pressures and charging voltages.

capacitors. The piston takes approximately 50 ms to reach its end position when the tank pressure is 1 bar_{abs}, whereas it takes more than 250 ms at 40 bar_{abs}. The maximum over-pressure is comparable (0.2 bar) for all filling pressures, except at 1 bar_{abs}, where oscillations result in maximum over-pressure of 0.3 bar_{abs}.

Fig. 8 shows the piston-movement duration for all filling pressures and charging voltages. As was seen for the no-current cases (Fig. 7), higher filling pressures increase the time it takes for the piston to reach its end position. It is also observed that the charging voltage does not significantly affect the piston movement at a given pressure (no clogging effect).

4. Discussion

4.1. Arc extinction at different filling pressures

Typically, current interruption is more difficult for higher currents (higher di/dt before CZ). Moreover, higher dU/dt after CZ (and how high the voltage becomes) reduces the chance of successful interruption. In the experiments conducted in this work, the current and TRV were varied simultaneously and not independently. It is therefore not obvious what caused a failed interruption. Still, all unsuccessful interruptions were thermal failures (right after CZ, where heat from the arc still remains in the arcing zone) and not dielectric re-strikes (some milliseconds after CZ), which indicates that either the high current or a steep RRRV caused the failures, and not the TRV peak value.

As seen in Fig. 4, the best interruption performance was observed for nitrogen filling pressures of 1 and 10 bar_{abs}, whereas 40 bar_{abs} resulted in the lowest interruption capability. The over-pressure generated in the puffer is determined by the spring force, the area of the piston, the filling pressure, the outlet diameter, and possibly other factors, such as clogging effects of the arc. At higher filling pressures, the same over-pressure is achieved with less piston movement than at lower filling pressures. Indeed, the measurements showed (see Figs. 7 and 8) that the piston movement was slower in the case of high filling pressures compared to lower ones, whereas the maximum over-pressure was around 0.2 in all cases (except for the 1-bar case, where oscillations occurred). However, the piston velocity at 1 bar_{abs} is not 40 times higher than at 40 bar_{abs}, which means that the cooling mass flow rate is higher for higher nitrogen filling pressures. Still, the interruption capability becomes lower with increasing nitrogen filling pressure. The velocity of the cooling flow may be of importance, which is higher at 1 bar than 40 bar with the specific puffer and contact configuration.

The arc voltage may also influence the arc extinction process. Given the same contact gap and arc current, the arc voltage increases with increasing filling pressure. This has also been observed in previous studies (see e.g., [3]). The arc energy becomes approximately 1.7 times higher when the filling pressure is increased from 1 to 40 bar_{abs} with the same current (see Table 4). Moreover, the energy dissipated in the arc for 1 bar_{abs} nitrogen and a charging voltage of 9 kV is comparable to the arc energy for 40 bar_{abs} with a charging voltage of 6 kV. Consequently, more heat needs to be removed from the arcing zone in the case of high filling pressures, which could partly explain why interruption appears more difficult for higher filling pressures, at least when only considering the thermal interruption phase.

4.2. Puffer design for high filling pressures

One way to improve the interruption capability of a puffer-type switch filled with high-pressure nitrogen is to replace the spring with a stronger one. This will increase the allowed over-pressure and the resulting cooling flow. However, increasing the spring force will also increase the interruption capability at 1 bar_{abs}, and not necessarily change the relative interruption capability at different filling pressures.

When the dimensions of the test switch for this work was decided, the test tank size and pressure build-up at 1 bar_{abs} were important factors. With limited space for a spring-driven puffer, a small ring contact diameter was chosen to obtain some over-pressure in the puffer volume. The puffer empties in 50–70 ms, which is a suitable cooling flow duration. The same is not true when the filling pressure is increased to 10, 20 or 40 bar_{abs}: Here, the cooling flow lasts up to 250 ms, much longer than needed. To improve the switch design for higher pressures, a larger outlet area should be used (larger ring-contact inner diameter). If chosen correctly, this results in higher mass flow rates and better cooling, and presumably an improved interruption capability.

4.3. Further work

In the future, a similar study should be be conducted with larger contacts. The ring contacts should be dimensioned so that the puffer piston takes 50–100 ms to complete its movement for both 10 bar, 20 bar and 40 bar nitrogen filling pressures (absolute). These contact sizes should also be tested at all pressures, to obtain a complete comparative study for a range of contact dimensions.

Other gases should also be tested for a wide range of filling pressures. Little work has been done on current interruption in CO_2 at pressures >10 bar_{abs}. Further work should also investigate moving contacts with no ignition wire, and possibly also different gas-flow concepts that could be more beneficial for constricted arcs. This will bring such test-switch experiments closer to "real" switchgear designs.

5. Conclusion

Current interruption tests were carried out for a puffer-type test switch filled with nitrogen at 1 bar, 10 bar, 20 bar and 40 bar absolute. The range of tested currents were 150–400 A (at 50 Hz), with TRV peaks of 4–10 kV and RRRVs of 18–48 V/µs. The main findings are:

- The current interruption capability was lower for 20 and 40 bar_{abs} nitrogen filling pressure than for 1 and 10 bar_{abs}.
- As expected, the arc voltage increases with filling pressure. The energy dissipated between the contacts during the first half cycle for 1 bar_{abs} filling pressure and a current peak of 380 A is comparable to that of 40 bar_{abs} and a current peak of 240 A (approximately 70 J arc energy).
- For the same puffer volume, compression spring and outlet-hole geometry, increased nitrogen pressure results in higher cooling flow rates and longer flow times. However, this does not improve the interruption capability.

To better determine interruption capability for high nitrogen filling pressures, other puffer switch designs should be tested.

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