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CONTRIBUTION OF THE LIQUID PHASE ON DIRECT CURRENT INTERRUPTION BY A FORCED FLUID FLOW

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Abstract. The rising amount of medium voltage direct-current systems requires novel solutions for DC switching. The interruption of direct-currents is accomplished by enforcing a current zero, which can only be achieved when the arc voltage of the switching device raises above the grid voltage. On way to achieve this, is to force the arc into narrow channels by an imposed fluid flow. The increasing arc voltage than not only depends on increased cooling due to phase change but also on the mechanical elongation of the arc enforced by the fluid stream. Hence, the interaction of the fluid flow and the arc should be studied in more detail. For this, the switching characteristic of selected dielectric liquids are examined. Using a self developed setup, direct-current interruptions at a constant voltage of 10 kV were carried out. Our results indicate, that the process of enforcing a current decay strongly depends on the mechanical resistance of the liquids to deform under the pressure of the electric arc.

Keywords: mvdc interruption, dc switching arc in liquids, current limiting, arc cooling by liquid.

1. Introduction

The increasing usage of direct current in medium (MVDC) and high voltage (HVDC) energy distribution provides new challenges for the electrical equipment. Especially switchgear design is one of the key obstacles due to the required direct current interruption. With direct currents a current zero crossing does not naturally appear hence AC switchgear technologies are not capable of high voltage direct current interruption [1]. To overcome the lack of a current zero (CZ), commonly synthetic oscillating networks in parallel to the main switching path are used. Technically, it is also possible to build up a voltage drop by an electric arc (or semiconductor circuits) along the current path higher than the driving voltage thereby forcing the current to zero, hence it is also called current limiting. But, due to the required high arc voltages, this is usually considered non-practical [2]. However, it was first shown by Gerdien [3], that an electric arc, immersed in a steady flow of water, does have a much higher power dissipation rate compared to ambient air. This was later picked up by Ann [4] who used a forced oil flow perpendicular to the electric arc showing the rapid increase to very high arc voltages (∼ 70 kV) by quickly increasing the arc length.

Based on the idea of increased arc voltages due to a forced fluid flow of a dielectric liquid, we want to further explore this possibility of MVDC current interruption. For this, a low inertia mass, hence fast, contact mechanism was designed and the switching behavior of liquids with high molecular hydrogen content but different molecular constitution is investigated. We are considering synthetic oil (Shell Diala S4) and synthetic ester (Midel 7131) as representative liquids here. Furthermore, particular attention is targeted on the fluid flow of the liquid phases.

As there are no common grid voltage levels in application, our research work is based on the distribution grid levels proposed by Cigré [2]. We are working on an application of nominal power limited DC sources in the context of multi terminal MVDC grids (10 kV, up to 1 MW), were all electrical components are attached to the DC link by power converters. AC-side feed through fault currents are not considered here.

2. Theoretical considerations on liquid arc cooling

As an electric arc is an ionized gas (plasma), to initiate it within a liquid, there has to be vapor (gas) generated first. The heat provided by the current carrying metal vapor arc occurring after contact separation, acts on the surrounding liquid. With this, the boundary layer of the liquid gets heated to the boiling point and then vaporized. To vaporize the liquid, thermal energy is not used to heat the liquid but to overcome the intermolecular interactions, which is characterized by the enthalpy of vaporization (Δh_v), given in Tab. 1.

	Shell Diala S4 [5]	Midel 7131 [6]
Δh_v	$55.2\,\mathrm{kJ\,mol^{-1}}$	$80.3\,\mathrm{kJ\,mol^{-1}}$

Table 1. Enthalpy of vaporization

Due to the steep temperature gradient in the vapor, radiation is almost completely absorbed within the vapor and the mass transfer from liquid to vapor can be approximated by linear heat conduction ($\mathbf{q} = -k\nabla T$) at the boundary by

$$S_q = -\dot{m}_{\mathrm{lv}}\Delta h_{\mathrm{v}} = \nabla \cdot (\mathbf{q}_{\mathrm{v}} - \mathbf{q}_{\mathrm{l}}) \tag{1}$$

or

$$\dot{m}_{\mathrm{lv}} = -\dot{m}_{\mathrm{vl}} = \frac{\nabla \cdot (k_{\mathrm{l}}\nabla T_{\mathrm{l}}) - \nabla \cdot (k_{\mathrm{v}}\nabla T_{\mathrm{v}})}{\Delta h_{\mathrm{v}}} \tag{2}$$

the sum of the heat taken by the liquid ($k_{\mathrm{l}}\nabla T_{\mathrm{l}}$) and the amount of heat reaching the phase boundary through the vapor ($k_{\mathrm{v}}\nabla T_{\mathrm{v}}$), see also Fig. 1.

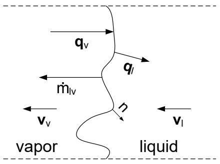


Figure 1. Liquid-vapor phase boundary

In case the liquid is in motion ($\mathbf{v}_{\mathrm{l}}$), the generated vapor carries on the specific impulse of the liquid phase

$$\frac{\dot{\mathbf{p}}_{\mathrm{l}}}{|\dot{m}_{\mathrm{lv}}|} = \mathbf{v}_{\mathrm{l}} = \mathbf{v}_{\mathrm{v}} = \frac{\dot{\mathbf{p}}_{\mathrm{v}}}{|\dot{m}_{\mathrm{vl}}|} \ . \tag{3}$$

3. Test and measurement setup

3.1. Electrical Test Circuit

Testing HVDC/MVDC switchgears proves to be much more difficult in comparison to HVAC switchgears, as the required test circuit needs to provide high voltage and high current at the same time, leading to exceptionally high testing power. So, to overcome this, a synthetic test circuit as in Fig. 2 was built. It uses a pulse forming network (PFN) consisting of a lattice configuration of capacitors (C_0) and inductors (L_0). A detailed description can be found in [7].

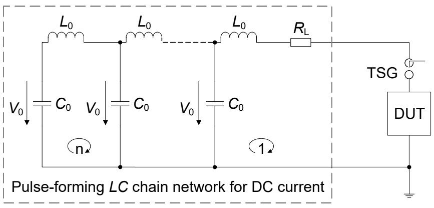


Figure 2. High voltage test circuit for direct current pulses

The capacitors are charged to the test voltage (in our case $V_0 = 10\,\mathrm{kV}$) and then the PFN is discharged into the device under test (DUT) by the triggered spark gap (TSG). When the load resistance (R_L) is matched to the line impedance of the PFN ($Z_0 = {}^{L_0}\!/_{C_0}$), the PFN will provide a direct current pulse of about 1000 A in amplitude and 25 ms in duration.

3.2. Test Setup

Based on Eq. (3) it is necessary to guide the fluid flow towards the electric arc, instead of separating electrodes within a liquid flow. Furthermore, the velocity needs to be rather high to reach the very high arc voltages required for high voltage direct current interruption by current limiting [4]. So, in our test setup a modified pneumatic piston pump is used to accelerate the liquid. The pneumatic piston is precharged to a certain pressure and equipped with an electrically triggerable lock mechanism. Due to this lock mechanism, the acceleration of the pneumatic piston is only limited by the mass inertia of the piston itself and the mass of the fluid filling of the switching apparatus. So, a constant flow velocity of the liquid can be reached relatively fast and the fluid flow sustains for some 10 ms. As the liquid is assumed to be incompressible, a high fluid flow velocity is generated by reducing the cross section of the cylindrical channel of the piston pump, see Fig. 3. The position of the piston along its axis is tracked by a laser triangulation sensor. With this, the volumetric flow of the liquid can be calculated.

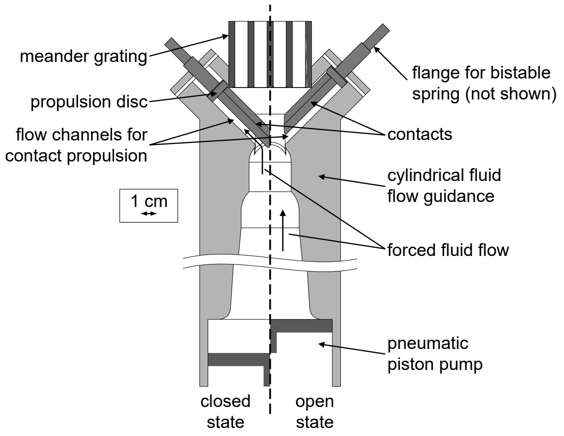


Figure 3. Cross section view of the direct current interruption apparatus

Above the piston pump, contacts are arranged in a 90° V-shape, so that they form a divergent electrode arrangement utilizing the Lorentz force to move the arc upwards once the contacts separate. They are initiated by the fluid flow itself, hence there is a flow channel underneath the contacts, guiding the fluid flow on a propulsion disc mounted on the contacts. Once the contacts start to move, they overcome the tension of a bistable spring attached to them.

To achieve a rapid increase of the arc voltage, the length of the arc column needs to rapidly increase to. This can preferably be achieved by forcing the arc into narrow channels because the length increase is then double the physical movement of the arc. Here, we use a meander grating made of polymer (POM) with a number of six vents. Each 5.2 mm in width and 7.5 mm in depth. The dimensions are chosen, so that a maximum fluid flow velocity of about $25\,\mathrm{m\,s^{-1}}$ is not exceeded.

4. Results

For the purpose of this evaluation, only successful current interruptions are considered here. For each parameter set, a total of ten measurements were conducted.

4.1. Arcing time

In case of DC switching, the switchgear must force the current to zero by itself. So the time to CZ is of great significance. In our case the time is defined by contact separation and current zero, hence, we treat it as arcing time.

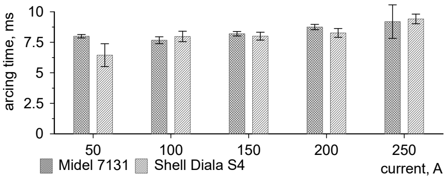


Figure 4. Arcing time in different liquids

Fig. 4 provides the arcing times for different direct current (I_{DC}) interruptions in the chosen liquids. It can be determined, that with increasing direct current, the arcing time slightly increases. This is to be expected, as the magnetic energy stored in the grid, which has to be depleted to reach CZ, increases with increasing direct current ($W_{\mathrm{mag}} \sim I_{\mathrm{DC}}^2$). Comparing the liquids, it is important to point out, that there are no relevant differences in the arcing times for comparable currents. So, bearing in mind, that current carrying is mainly handled by free moving electrons, the chemical composition of the vapor phase and plasma does not change the arc duration.

4.2. Arcing energy

As there is no parallel commutation path in case of current limiting switching, the input power of the electrical source needs to be taken over by the arc. As instantaneous power is time variant, it is difficult to compare. Instead the power integral, or arcing energy should be considered as parameter for arc cooling of the extinction media. Lower values are favorable here, as they indicate a more rapid current limiting combined with a steeper arc voltage increase.

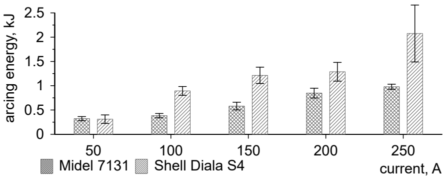
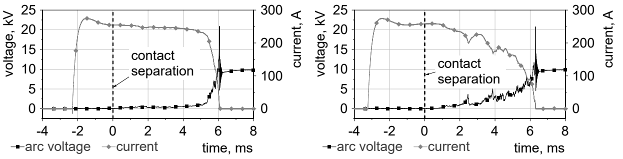


Figure 5. Energy inducted into the liquids by the electric arc

Evaluation of the arcing energy in Fig. 5 shows an increase with current, which is to be expected due to the increasing magnetic energy stored. But, there is a considerable difference in arcing energy for the different liquids, of which the values for Shell Diala S4 are about 60 % to 100 % higher than for Midel 7131. So, the current limiting capability of Shell Diala S4 is noticeably lower, as can be seen in Fig. 6.



(a) Midel 7131 (b) Shell Diala S4

Figure 6. Exemplary measurements for 250 A *DC interruption*

4.3. Required liquid volume for arc extinction

The efficiency of the liquids to extinguish an arc can be determined by the amount of liquid required to force the current to zero. This volume can be calculated from the displacement of the moving piston.

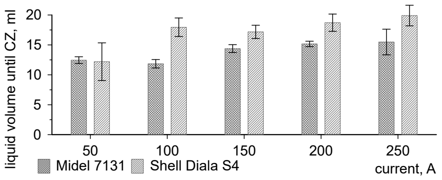
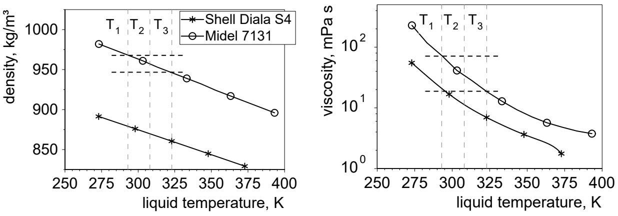


Figure 7. Required liquid volume for arc extinction

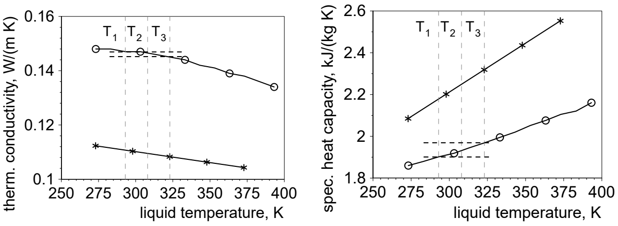
Fig. 7 shows the liquid volume displaced by the piston pump until CZ is reached for different currents. In accordance with the arcing time (Sec. 4.1), the liquid volume also slightly increases with current. However, comparing the liquids, there is a significant higher volume of Shell Diala S4 required to extinguish the arc than of Midel 7131, which correlates to the increased arc energy. Taking the similar arcing times into account, this higher liquid volume equals an increased fluid flow velocity of about 10 % to 20 % for Shell Diala S4, of which an increased current limiting effect would be assumed. As the displaced liquid volume is a mechanical parameter of the fluid flow, it can not be linked to the external grid or the plasma properties of the electric arc.

4.4. Measurements at elevated temperatures

Due to numerous varying material characteristics of the two liquids, the results of the previous measurements are not easily traced back to any them. So, to separate the varying chemical constitution of the liquid and vapor phases from macroscopic material properties, measurements of only one liquid (Midel 7131) were carried out at various temperatures of the liquid phase. With this, the chemical composition and properties of the vapor/plasma phase are not changed, however the flow characteristics of the liquid phase can be governed. The temperatures are chosen, so that basically only viscosity is changed to the value of the oil used here, see fig. 8.



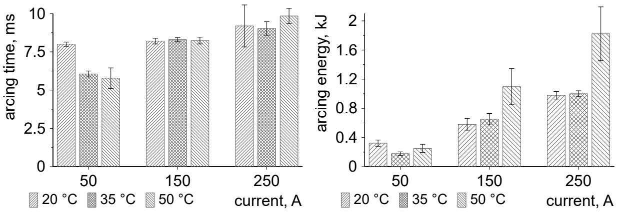
(a) Transport properties



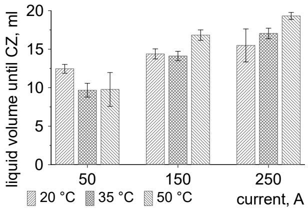
(b) Thermodynamic properties

Figure 8. Temperature dependence of the material properties of the liquid phases [8, 9] ($T_1 = 20\,°\mathrm{C}$, $T_2 = 35\,°\mathrm{C}$, $T_3 = 50\,°\mathrm{C}$)

The analysis of the measurements at elevated temperatures in Fig. 9 indicate, that the change of the arcing parameters from 20 °C to 50 °C equals the measured differences of synthetic oil and synthetic ester (of the specific types used here) in Fig 4, 5 and 7.



(a) Arcing time (b) Arcing energy



(c) Liquid volume

Figure 9. Arcing parameters at elevated temperatures of the liquid (Midel 7131)

The results can be interpreted under the assumption of incompressibility of the liquid phase, which then acts similarly like a moving solid on the arc. Especially, when the mechanical resistance to deformation of the liquid (viscosity) is high (see Midel 7131). Forcing the flow perpendicular to the arc means, the arc represents a flow resistance. So, a lower viscosity liquid can more easily bypass the arc, thus requiring more liquid to elongate, cool and extinguish the arc. When the liquid bypasses the arc, it creates flow turbulence of the vapor/plasma phase thus raising the arc voltage. However this turbulence is associated with partial dielectric breakdowns, as can be seen by the voltage spikes/current dips in Fig. 6b. So the ability of the liquids to elongate the arc and thus limit the direct current reduces with decreasing viscosity.

5. Conclusions

Medium voltage direct current interruption can be reliably conducted by current limiting, utilizing a forced liquid flow of dielectric liquids. However, there are distinct differences in the extinction performance of the liquids, of which synthetic ester (Midel 7131) and synthetic oil (Shell Diala S4) were compared. Despite similar arcing times, the required liquid for arc extinction and the energy turnover are significantly increased with Shell Diala S4. To exclude the effect of different chemical compositions, measurements with Midel 7131 at elevated temperatures of the liquid phase were carried out, so to basically only change the viscosity of the liquid phase. Decreasing the liquid viscosity of Midel 7131 to a value comparable to Shell Diala S4 at 20 °C by raising the liquid temperature to 50 °C, leads to increased arcing energy and liquid volume for arc extinction. The values are then very similar to Shell Diala S4 at 20 °C. With this, fluid flow and material properties of the liquid phase should be considered as major contribution to successful current interruption.

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