

Medium Voltage Load Current Interruption in Presence of Ablating Polymer Material

Henning Taxt, *Student Member*, Kaveh Niayesh, *Senior Member, IEEE*, and Magne Runde

Abstract-- The expected abolishment of SF₆-gas in medium voltage switchgear has prompted a search for replacements for the switch types that depend on SF₆ to obtain the required capability, reliability, compactness and cost. Ablation of polymers can enhance the arc-quenching capabilities in certain electrical switch designs. Several aspects, like electric arc plasma composition, gas flow and wall stabilization must play together to obtain a successful interruption. In this paper, open and closed switch geometries and two nozzle materials (PP and PTFE) are studied in medium voltage interruption experiments. Fundamental differences in the arc-quenching process for PP and PTFE are shown. In the case of PTFE, the current interruption performance depends on gas flow resulting from the pressure built up under the high current period. In the case of PP, the gas flow plays a lesser role for the arc-quenching capability, as the interruption capability is large even in an open design with no forced gas flow around current zero. Current chopping happens a few tens of microseconds before voltage zero crossing, thereafter, a remnant conductance in the contact gap is observed, lasting for up to several milliseconds. This can be explained by an arc-to-glow transition in presence of hydrogen.

Index Terms— Ablation, Arc-to-glow transition, Current interruption, Glow discharges, Hydrogen, Load-break switch, Medium voltage, Switchgear

I. INTRODUCTION

THE switching of loads and feeders in medium voltage (MV) networks is essential to the operation of medium voltage distribution networks. Thus, MV load-break switches are abundant in networks today, and could become even more important in the future, as the complexity of distribution network operation increases. Because of the market size, there is a strong pressure to reduce cost, without compromising on reliability or compactness. In the past decades, metal-enclosed switchgear filled with SF₆ has provided a compact solution, but due to environmental concerns, manufacturers of these products are now seeking for alternative ways to achieve compact and low-cost products. One approach is to review and improve the technologies that were applied before the introduction of SF₆, one of which is the use of arc-induced ablation of polymers that release hydrogen compounds, also known as *hartgas* and wall-gassing. Some older switchgear products take advantage of the arc-quenching effect of this ablation, also in the MV product range, but there is no comprehensive publication that explains the mechanisms involved.

Nowadays, ablation of hydrogen-containing polymers is a

key element in low voltage (≤ 1 kV) switches and circuit breakers. The development of a new MV ablation switch would encompass several attractive features: environmentally friendly interruption medium, reduced requirements for puffer driving mechanism, compactness and inherent scaling of interruption capability to current amplitude. However, some challenges appear when moving the known designs towards higher voltages. A major problem seems to be a delayed contact gap recovery and consequent risk of re-ignitions, a process closely linked to the voltage rating [1, 2]. In high voltage switchgear, polymers without hydrogen is the preferred nozzle material.

The present study is set out to investigate the strong arc-quenching effect of ablation with certain polymers, and the delayed recovery that inhibits the application at higher voltages. Several studies have screened and ranked polymers and other gassing materials, for example according to their thermal interruption performance [3], re-ignition voltage [4, 5] or ablated mass [4]. However, they are mainly relevant for low voltage application, while mechanisms at higher voltages are likely to be different.

Ablation by a steady-state arc, which is relevant for the study of pressure development and material wear at all voltage ratings, has been described by several authors [6-8], but a comprehensive understanding of the rapid changes taking place around the time of interruption is lacking. One approach is modelling the decay in temperature and electric conductivity around the current zero (CZ) [9]. However, these models cannot give accurate results without the inclusion of non-equilibrium effects [10]. Because of the extreme complexity of modeling current interruption, the experimental approach is, for now, an indispensable part of switchgear development, and is the approach taken in the present study.

The experimental setup and test switch geometry are described in the following section. The main results are presented in Section III, followed by a discussion of the findings and, finally, the conclusions.

II. EXPERIMENTAL SETUP

The experiments were performed in a grid-connected medium voltage one-phase circuit for development of load-break switches, and with a moving contact configuration [11]. This setup ensures that the tests are truly relevant for commercial devices. For this particular series of experiments, the circuit parameters have been kept constant, yielding an rms

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H. Taxt and K. Niayesh are with the Norwegian University of Science and Technology, Trondheim, Norway (e-mail: henning.taxt@ntnu.no).

M. Runde is with SINTEF Energy Research, Trondheim, Norway.

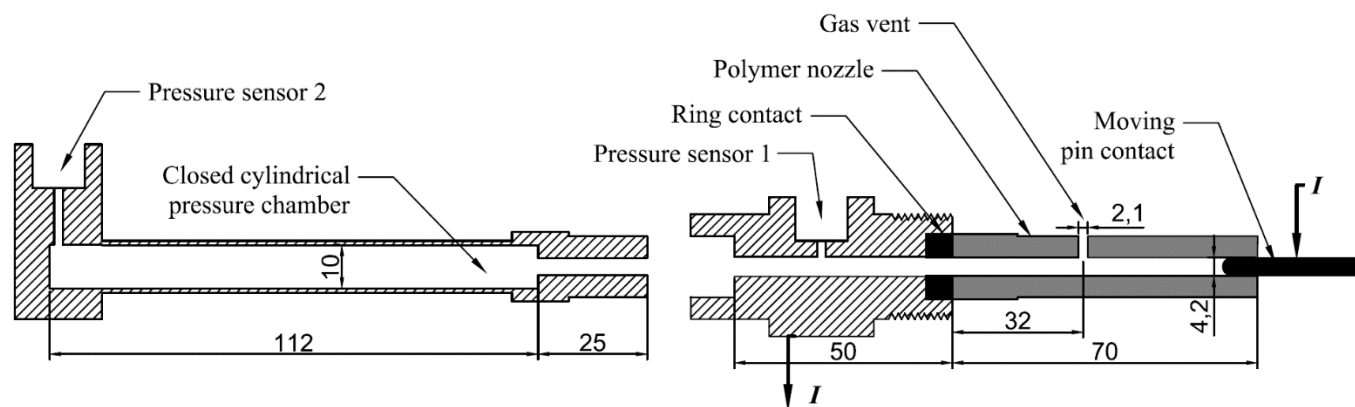


Fig. 1. The test switch with 4-mm pin contact in open position on the right hand side. The part to the left can be attached to the switch, creating a closed volume that allows for the pressure to build up on the left-hand side of the electric arc. In the open configuration, this part is removed, so pressure can not build up. The contacts (solid black) are made of copper-tungsten and the main casing and pressure chamber (hatched parts) are made of brass. Current connection points are indicated by arrows, I . Dimensions are in millimetres.

current of 200 A and a rate of rise of recovery voltage of 200 V/ μ s. The source voltage was set to 13.9 kV. For details on the circuit and the setup, see [12].

The arc voltage is measured with a parallel capacitive-resistive voltage divider. Two sensors are used to give a detailed current measurement: a resistive shunt for the range of ± 500 A, and, based on [13], a resistive shunt with bypassing Schottky diodes for the range of ± 700 mA.

Only a light-touch filtering of the measurement signal has been applied. A Savitsky-Golay filter is used to remove noise and discrete steps due to digitalization, but with a very small sliding window ($< 2 \mu$ s) to avoid blurring the fast processes around current zero (CZ). A more aggressive filtering, smoothing and time shifting of the signals could easily obscure the important current and voltage waveforms around CZ. To obtain a conductance that is real and positive, voltage and current zero crossings must coincide. Where this is not the case, it is assumed to be caused by a capacitive current contribution, so this part has been calculated and removed. Typical capacitance is in the ten-picofarad range.

Two test switches have been used, one with a 4 mm pin contact diameter, shown in Fig. 1, and another with a 6 mm pin

contact; in that case, the inner diameter of the nozzle is 6.2 mm, and the gas vent size is unchanged. The switch is designed for the sole purpose of investigating the mechanisms involved in the current interruption. Parts can be changed easily and variations in geometry can be made to investigate the influence of the different features on the current interruption. The effect of nozzle wear on voltage and current waveform was checked and shown to be negligible for the load current and number of experiments in this study. The nozzles were used for consecutive experiments. In the present study, three parameters are varied as outlined in Table I: nozzle material (polypropylene/PP and polytetrafluoroethylene/PTFE), enclosure of the arcing chamber (open and closed pressure chamber) and pin contact diameter (4 mm and 6 mm). In the case of the closed arcing chamber, the part on the left hand side in Fig. 1 is connected to the switch, and in the open case, it is removed.

Time of contact separation relative to the current waveform is varied to obtain a realistic evaluation of interruption performance and, as a result, the contact gap and pressure at current zero varies. Average contact opening speed is 3.6 m/s with minor variations; standard deviation is 0.07 m/s.

TABLE I
Summary of tested configurations and results

	Nozzle material	Arcing chamber enclosure	Pin contact diameter	Success rate	Qualitative description	Ref.
#1	PP	Open	4 mm	7/8	Current chopping around 3 A. One case of re-ignition $\sim 45 \mu$ s after CZ at electric field ~ 120 V/mm	Fig. 2a Fig. 3a
#2	PP	Open	6 mm	1/7	Current chopping around 2.5 A. Typically fails with uninterrupted post-CZ current $\sim 10^{-1}$ A until delayed re-ignition, up to several milliseconds after CZ at electric fields ranging from 116 to 264 V/mm	Fig. 4
#3	PP	Closed	4 mm	4/4	Current chopping around 3.5 A	Fig. 2a Fig. 3b
#4	PP	Closed	6 mm	1/5	Current chopping around 3 A. One re-ignition after ~ 0.1 ms and three delayed thermal re-ignitions after > 10 ms at electric fields ranging from 203 to 250 V/mm.	---
#5	PTFE	Open	4 mm	0/4	Fast thermal re-ignition	Fig. 2b Fig. 3c
#6	PTFE	Open	6 mm	0/4	Fast thermal re-ignition	---
#7	PTFE	Closed	4 mm	4/4	No current chopping, fast shift to low electric conductance	Fig. 2b Fig. 3d
#8	PTFE	Closed	6 mm	0/4	Fast thermal re-ignition	---

III. RESULTS

A summary of results, presented in Table I, shows the success rate in the different configurations, but special attention is paid to the qualitative descriptions of interruptions in PP

versus PTFE nozzles (or tubes). Fig. 2a shows typical waveforms for interruptions in the PP nozzle, with a prominent current chopping and consequent high voltage imposed on the contact gap from the network before CZ. However, from the post-arc current measurement, it is evident that the current is

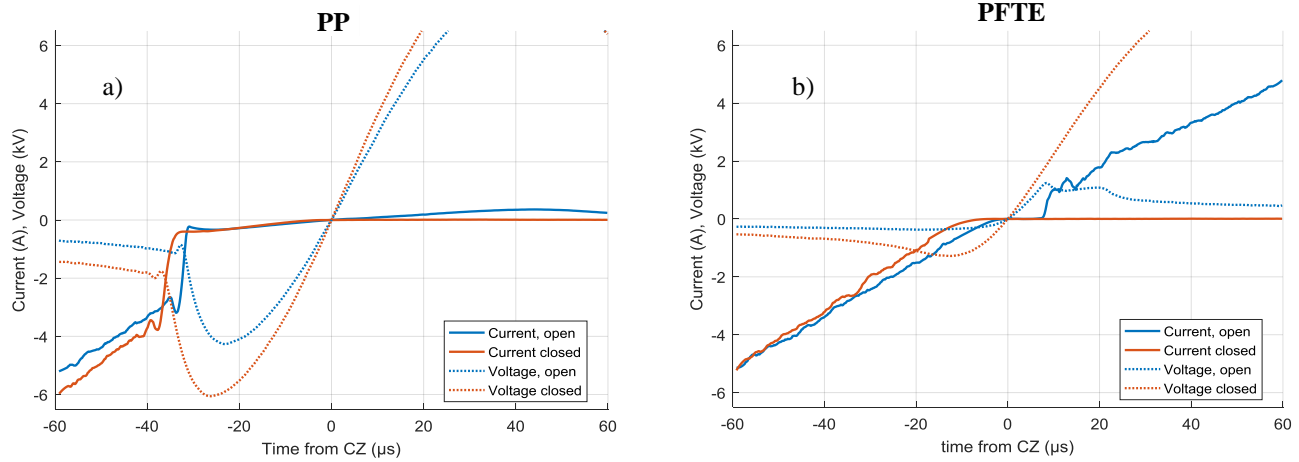


Fig. 2. Typical current and voltage waveforms for interruptions in PP nozzle (a) and PTFE nozzle (b), in the open and closed configurations with 4-mm pin contact diameter. The contact gap distance is 47 mm. In the closed case, relative pressure at CZ is 3.1 bar and 1.9 bar for PP and PTFE, respectively. Take note of the current chopping about 35 μs before CZ in the case of PP nozzle, as well as the post-arc current in the open case. The PTFE open case failed to interrupt the current.

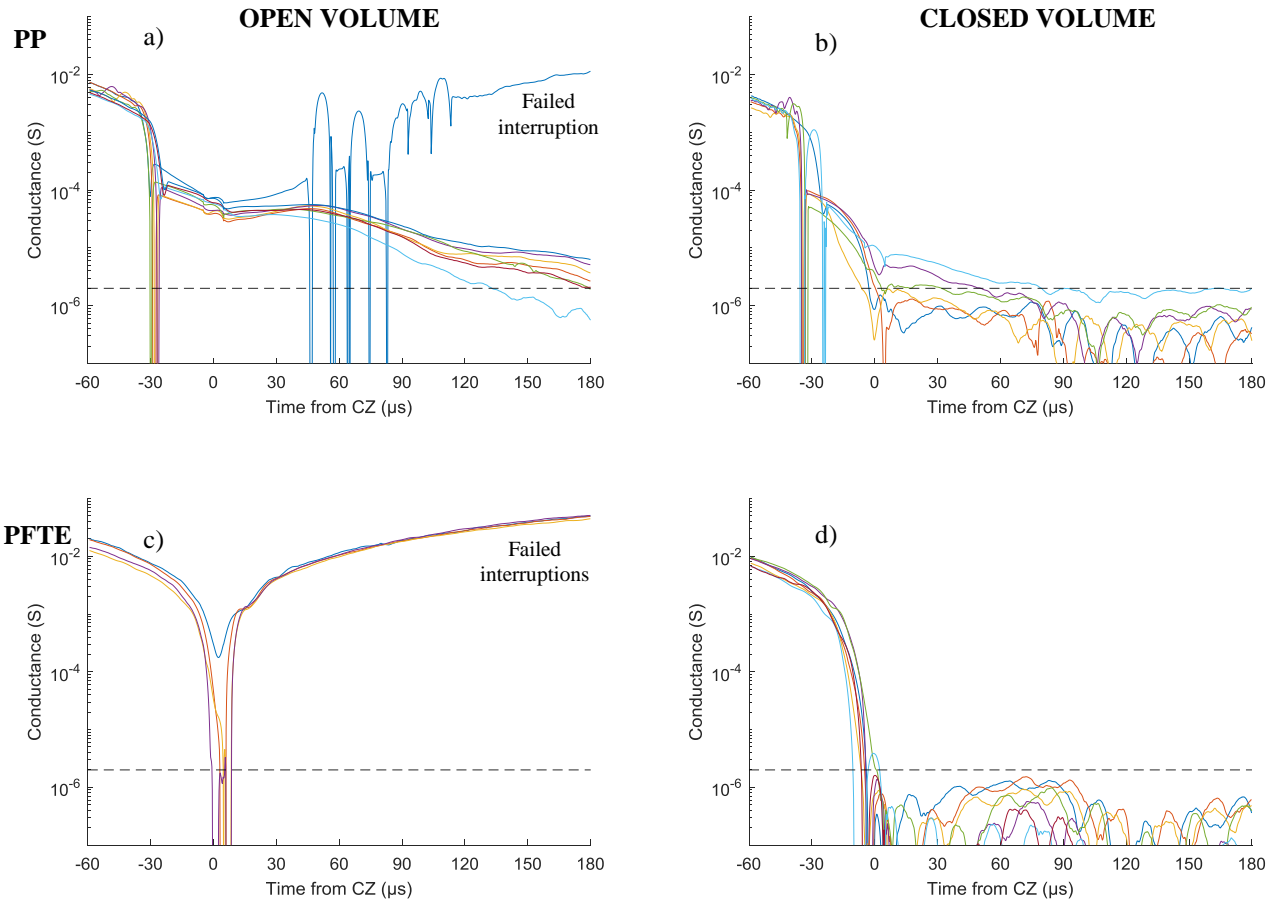


Fig. 3. Contact gap conductance around CZ for the interruption attempts with 4-mm diameter pin contact, a) PP nozzle and open volume b) PP nozzle and closed volume c) PTFE nozzle and open volume d) PTFE nozzle and closed volume. Contact distance at CZ was between 42 and 60 mm. A successful interruption is where conductance drops around CZ and stays low. Due to the current measurement resolution, the accuracy decreases at the low levels of conductance and a lowest measurable level is indicated with a dashed line in the graphs. The failed interruption in a) displays repeated re-ignitions, and a slightly different step response of the current and voltage measurement systems gives artificial conductance calculations at these instances.

not completely interrupted after this chopping. The contact gap conductance just after the chopping, that is 20 μ s before CZ, is about 10^{-4} S in the 4-mm setup, see Fig. 3a. In the 6-mm setup the conductance at this point is about 70 % higher, see Fig. 4.

Comparing the open and closed arc chambers (Fig. 3a and Fig. 3b), the conductivities 20 μ s before CZ, that is just after current chopping, are the same or slightly lower for the closed setup. However, with a closed geometry, the conductance continues to fall sharply in the period between current chopping and CZ, due to the gas flow from the closed volume, a self-blast effect. In the setup with an open geometry, there is no pressure build-up and therefore no significant gas flow after the current chopping. As a result, the conductance is changing slowly and, depending on dissipated power and cooling, is either reduced or increased. In some cases, it seems that a stable state is reached, where a small current can be maintained for tens of milliseconds, sometimes leading to a full re-ignition of the arc, as shown in Fig. 4. The current also seems to be little affected by the pin contact leaving the nozzle and moving into ambient air, as shown in Fig. 5.

The observations for PTFE nozzles are fundamentally different. Current chopping cannot be observed, and neither can the remnant conductance. In the 4-mm open setup case (Fig.

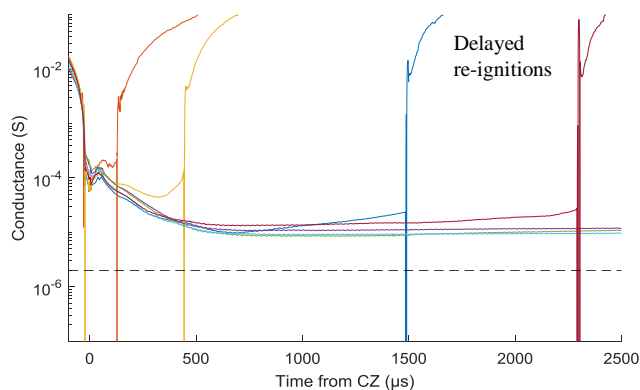


Fig. 4. Contact gap conductance around CZ for the interruption attempts with 6-mm diameter pin contact, PP nozzle and open volume. Notice the stable conductance around 10^{-5} S, and re-ignitions taking place after several milliseconds.

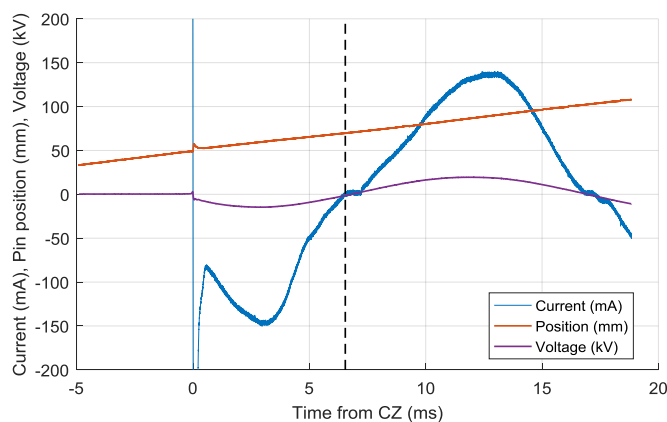


Fig. 5. Example of interruption with a 6.2-mm diameter PP nozzle and open-case showing a continued post-arc current (in milliamps and milliseconds). The vertical dashed line indicates when the moving pin contact leaves the nozzle, so after that a part of the current path is in ambient air.

3c), all interruption attempts failed, whereas all interruption attempts were successful in the closed setup (Fig. 3d). This indicates that the gas flow resulting from the pressure build-up is the main mechanism for arc extinction in the case of PTFE. The mechanism that leads to current chopping, and that makes the PP nozzle interrupt successfully even without self-blast, is not present in the PTFE case. On the other hand, when interrupting successfully, the PTFE nozzle brings the conductance faster to a lower level than is the case with PP and no stable remnant conductance is observed.

The main differences between PP and PTFE nozzles, under the given test conditions are:

- The PP nozzle was able to quench the arc in both closed and open configuration, although sometimes followed by a delayed re-ignition.
- The PTFE nozzle was only able to interrupt in the closed design.
- Conductance after arc quenching was higher with PP nozzle compared to successful interruptions with the PTFE nozzle.
- The ablated mass, measured in a sample with successful interruptions in the 4-mm setup, was 5 - 8 mg per interruption for the PP nozzle and 7 - 9 mg per interruption for the PTFE nozzle.
- Although less mass is ablated from the PP-nozzle, the average pressure at CZ in the PP-nozzle closed volume case was about 50 % higher than with the PTFE nozzle, indicating lower average particle mass in the PP vapor.

The main differences between 4 mm and 6 mm pin contacts, under the given test conditions are:

- Average contact gap conductance just after chopping in the 6-mm PP case was about 70 % higher than the 4-mm PP case.
- With PTFE nozzle, all interruptions failed in the 6-mm case, whereas all were successful in the 4-mm closed setup case.
- With the PP nozzle, average pressure at CZ in the 4-mm closed setup case, was about 50 % higher than in the 6-mm closed setup case.

IV. DISCUSSION

In literature, there has been attempts to rank materials according to their arc-quenching performance. The present study shows that such a one-dimensional ranking can obscure important information. The qualitative evaluation of the interruptions in PP and PTFE nozzles indicates that there is a fundamental difference in the mechanisms involved in the interruption for the two materials, especially when moving from low voltage and towards the medium voltage range. The proposed explanation is based on the fundamental difference in the gas properties of the vapor of PP (mainly hydrogen) and PTFE (mainly fluorine). In addition, carbon is present in the vapor of both PTFE and PP vapor, and is assumed to have no or little differentiating effects on the interruption process.

A. Glow Discharge and Arc-to-Glow Transition in Hydrogen

The effect of polymer ablation on the interruption capability has been demonstrated in several publications. In [3], it is suggested that the hydrogen content in the polymer is of importance for the interruption capability under low voltage conditions. Polypropylene, used in the present study, contains hydrogen and carbon, with an atomic ratio of two-to-one. It is fair to assume that all air originally residing in the nozzle is flushed out and that hydrogen dominates inside the nozzle volume at the time of interruption. As an example, in the setup with 4 mm pin contact, 5 mg of PP decomposed to diatomic gas would, at 3500 K and atmospheric pressure, occupy 300 times the volume inside the nozzle.

Edels and Gambling [14] have studied electric discharges in hydrogen, and their observation of an arc-to-glow transition in atmospheric pressure compares well with the current chopping that we have observed. They show that, by controlling the discharge temperature, a transition from constricted arc to a diffuse glow discharge can take place in the hydrogen arc at atmospheric pressure. This transition is explained by the steep negative slope in thermal conductivity of hydrogen with a peak at around 3800 K [15]. From high arc core temperatures, far above 5000 K, the temperature decreases as the energy input to the arc is decreased. The arc core is stable as long as the thermal conductivity is low, but when thermal conductivity starts to increase at temperatures below 5000 K, the heat conduction from the arc core to the surrounding polymer vapor accelerates, with the result that the core temperature drops by $\frac{1}{4}$ almost instantaneously [14]. This explains the sudden drop in electric conductance about 30 μ s before CZ.

After the drop, the temperature and the electric conductivity are low and more even throughout the entire volume inside the nozzle. The remnant electric conductance and the recovery voltage over the contact gap result in a glow discharge. The stability of this glow discharge can be explained by the steep positive slope of thermal conductivity just below 3800 K. Any local temperature increase is inhibited by the consequent increase in heat conduction, so a glow-to-arc transition must be preceded by a homogenous temperature increase up to 3800 K. After that, a local temperature increase will lead to instability and arc constriction.

Assuming homogenous temperature and electric conductivity inside the entire nozzle volume just after current chopping, the contact gap conductance should be proportional to the cross-sectional area inside the nozzle. The observations confirm this assertion, but with a proportionality factor less than one. The observed ratio of conductance is 1:1.7, whereas the ratio of the cross-sectional areas is 1:2.2. The deviation could possibly be attributed to effects of electrode temperature which we, from [14], could expect is likely to influence conditions around the arc-to-glow transition. The 4-mm pin contact is expected to reach higher temperatures than the 6-mm pin, because of lower mass and lower conduction cross section.

The glow state is characterized by an energy balance between the heat dissipation and the cooling or replacement of the conductive gas. The heat dissipation is a function of the recovery voltage and the electric conductance itself. The

cooling at this stage, if there is no forced gas flow, is dominated by heat conduction to the electrodes, to the polymer surface, with some polymer evaporation, and some dissipation out of the nozzle openings. This cooling is slow, as illustrated by our observation that a current of tens of milliamps can last for milliseconds and even continue after the next CZ, as shown in Fig. 5.

In [16], Maftoul et al. report on a current after arc extinction that exceeds the 10^0 - 10^2 - μ s period of a typical post-arc current, and name it 'post-recovery' current. Although differing in current rating (24 and 41 kA) and gas (SF_6), the observation of a continued current of a few tens of milliamps is similar to ours. They attribute this current to the ionic conduction dominated by S_2^+ -ions at around 2000 K. In our case, a parallel would be the conduction by hydrogen ions. In [14] it is found that for hydrogen, there is prominent deviation from local thermal equilibrium, with electron temperatures exceeding 20 000 K. That gives a degree of dissociation [17] and charge carrier density significantly higher than what would be expected from equilibrium assumptions.

To illustrate, data for equilibrium hydrogen from Yos [18] gives conductance that is two orders of magnitude lower than observed; that is assuming an isothermal volume of hydrogen at 3800 K (just after arc extinction) and atmospheric pressure. The data also shows steep reduction in electric conductivity below that temperature, about one decade per 300 K.

B. Effect of Self-Blast

By connecting a closed volume to the arc chamber, the pressure that builds up during the high current phase can be stored and used to cool the arc by self-blast around current zero. This is the mechanism to interrupt successfully with the PTFE nozzle. Self-blast also plays a role when applying PP nozzles. Because the natural cooling after current chopping is so slow, the forced gas flow is needed to replace the hot conductive gas by colder gas.

Clearly, the pressure, temperature and composition of the gas in this volume are of great significance for the interruption capability of the switch. Only the pressure is measured in this work.

C. Implications for Medium Voltage Application of Ablation-Assisted Interruption

The strong arc-quenching effect of hydrogen from certain polymers, such as PP, seems to be attractive in the development of new switch designs. However, when moving from low to medium voltage, the conductivity of the gas in the contact gap after arc-extinction becomes increasingly important. The arc-to-glow transition in hydrogen, seen when applying a PP nozzle, might be exploited in a future design, but it is not sufficient to obtain a successful interruption, as also the glow discharge must be extinguished before the gap can attain sufficient dielectric withstand strength. In some of the earlier designs it seems this has been overcome by having a separate slower switch in series, operating in air [19].

In the development of an MV ablation switch, there is in any case a range of issues that would have to be studied and dealt with. Because the current amplitude is important for

interruption performance, interruption of small currents could be difficult, and can demand for additional cooling mechanisms, such as a puffer device. The effect of material erosion is another concern.

Polypropylene (PP) is a polymer consisting solely of carbon and hydrogen. Compared to mixtures with strongly reactive gases, such as oxygen or fluorine, it allows for a high concentration of free hydrogen when decomposed. Although free hydrogen is beneficial for the arc-quenching phase of the interruption, it might not be good for the post-arc phase. A polymer with some content of such reactive elements might be beneficial for higher voltage applications; or it might even be so, that ablation of polymers with high hydrogen content is a dead end in the development of new switchgear at higher voltage ratings. However, no such definite conclusion can be drawn from this study alone, but if so, some other arc-quenching mechanism would be required, like puffer or self-blast. In that case, PTFE seems to be a good choice for nozzle material.

V. CONCLUSION

The experimental results presented in this paper, show clearly the fundamental difference of interruption in a PTFE and a PP nozzle. Where the PTFE nozzle must be accompanied by a self-blast effect to interrupt successfully, the PP nozzle produces a sharp decrease in contact gap electric conductance about 30 μ s before CZ (a current-chopping-like phenomenon), and the main electric arc is thus interrupted. However, the resulting conductance after CZ is higher than what is the case in a PTFE nozzle and, at sufficiently high recovery voltage, this leads to re-ignition of a full-blown arc. This makes a weak case for use of PP ablation at higher voltage levels, unless dealt with properly. The voltage level at which this becomes an issue is strongly geometry dependent.

VI. ACKNOWLEDGMENT

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VIII. BIOGRAPHIES

Henning Taxt received his bachelor degree in Electric Power Engineering from Sør-Trøndelag University College, Trondheim, Norway, in 2010 and graduated MSc in Electric Power Engineering from the Norwegian University of Science and Technology, Trondheim, Norway, in 2012.

He was employed in SINTEF Energy Research, Trondheim, Norway, from 2012 to 2014 working mainly on electric distribution network research. He is currently pursuing a PhD from the Norwegian University of Science and Technology.



Kaveh Niayesh (S'98-M'01-SM'08) received the B.Sc. and M.Sc. degrees in electrical engineering from the University of Tehran, Tehran, Iran, in 1993 and 1996, respectively, and the Ph.D. degree in electrical engineering from the Aachen University of Technology, Aachen, Germany, in 2001.

He held different academic and industrial positions including Principal Scientist with the ABB Corporate Research Center, Baden-Dättwil, Switzerland; Associate Professor with the University of Tehran; and Manager, Basic Research, with AREVA T&D, Regensburg, Germany.



Currently, he is a Professor with the Department of Electric Power Engineering, Norwegian University of Science and Technology (NTNU). He has been mainly involved in the research and development of high-voltage high-current systems. He is the holder of 16 patents and has more than 105 journal and conference publications on current interruption and limitation, vacuum and

gaseous discharges, plasma modeling and diagnostics, switching transients, and pulsed power technology.



Magne Runde received the MSc degree in physics and the PhD degree in electrical power engineering from the Norwegian University of Science and Technology (NTNU), Trondheim, Norway, in 1984 and 1987, respectively. He has been with SINTEF Energy Research, Trondheim, Norway, since 1988. From 1996 to 2013, he also was an adjunct professor of high voltage technology at NTNU. His fields of interest include high voltage switchgear, electrical contacts, power cables, diagnostic testing of power apparatus, and power applications of superconductors. He has been the convener and member of several CIGRÉ working groups, and authored and co-authored more than 50 articles in peer-reviewed international journals and more than 60 conference publications.