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Load Current Interruption in Air for Medium Voltage Ratings

Thesis for the degree of Philosophiae Doctor

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Preface

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List of publications

I. Erik Jonsson and Magne Runde, *Medium Voltage Laboratory for Load Break Switch Development,* Proc. Int. Conf. on Power Systems Transients, Vancouver, July 2013, paper nr. 351.

II. Erik Jonsson, Nina Sasaki Aanensen, and Magne Runde, *Current Interruption in Air for a Medium Voltage Load Break Switch,* IEEE Transactions on Power Delivery, In press 2014.

III. Erik Jonsson and Magne Runde, *Interruption in Air at Different Medium Voltages Switching Duties,* Submitted to IEEE Transactions on Power Delivery.

IV. Erik Jonsson, Magne Runde, Gustavo Dominguez, Andreas Friberg, and Erik Johansson, *Comparative Study of Arc-Quenching Capabilities of Different Ablation Materials,* IEEE Transactions on Power Delivery, vol. 28, no. 4, Oct. 2013.

V. Gaute Gjendal, Erik Jonsson, and Magne Runde, *Ablation Assisted Current Interruption in a Medium Voltage Load Break Switch,* Submitted to Int. Conf. on Electrical Contacts, June 2014.

Contributions of individual authors for each publication

I. Erik Jonsson planned the laboratory circuit and designed the circuit components. Realization and building of components was done by Erik Jonsson. Erik Jonsson wrote the manuscript with support from Magne Runde.

II. Erik Jonsson planned the experiment and designed the test breaker and measuring circuitry. Erik Jonsson and Nina Sasaki Aanensen carried out the experiments. Erik Jonsson wrote the manuscript with support from Magne Runde.

III. Erik Jonsson planned and carried out the experiment. Erik Jonsson wrote the manuscript with support from Magne Runde.

IV. Erik Jonsson planned the experiment together with Gustavo Dominguez and Andreas Friberg. Erik Jonsson carried out the experiment in collaboration with Gustavo Dominguez, Andreas Friberg, and Erik Johansson. Erik Jonsson wrote the manuscript with support from Magne Runde.

V. Erik Jonsson planned the experiment. Erik Jonsson and Gaute Gjendal carried out the experiments. Erik Jonsson and Gaute Gjendal wrote the manuscript with support from Magne Runde.

Abstract

Load break switches (LBSs) are common inside metal clad switchgear assemblies where space is a limiting factor. SF_6 is usually used in this application due to its superior electrical characteristics, but is unfortunately also a strong greenhouse gas. Therefore development of new products, utilizing air which is an environmental friendly alternative, is in progress. Since air has much lower dielectric strength than SF_6, the main challenge with this is therefore to reduce the size. Compact SF_6 products have created a retrofit market, and in many existing installation sites larger products will not fit.

Current interruption is a complex process and depends on several parameters, and it is not straight forward to optimize the design of a medium voltage (MV) switch. Numerical simulation which is a common for product development in other areas is difficult for this application. Due to the long dominance of SF_6 products, little research has been published about the design criteria for LBS technology in air.

The scope of the thesis covers current interruption of MV LBSs in air with respect to various design parameters, such as nozzle geometry, nozzle materials, gas flow, and contact movement. Both gas blow-assisted current interruption (associated with puffer breakers) and ablation-assisted current interruption are addressed.

The material in the nozzle can enhance the interruption capability. Such a nozzle material is called ablation material. When the arc is burning close to the surface of an ablation material, gas is evaporated which cools the arc. This technology is used to some extent for low voltage switchgear, but much less for higher voltages. The objective is therefore to investigate the potential of this technology for the MV LBS application.

All work is done experimentally with similar test conditions as are used for product type testing. A direct powered MV laboratory and a test switch are built. The test switch is designed particularly for parameter studies.

The result from air blow experiments reveal the minimum upstream pressure drop required for current interruption for various basic nozzle geometries, and at different contact positions. One study is particular relevant for the 24 kV / 630 A class, and it is found that 0.25 - 0.3 bar upstream pressure drop appears to be a threshold value for successful interruption.

It is also presented how the minimum upstream pressure drop varies for different MV LBS ratings. The results show that the needed pressure drop is approximately proportional, both towards the current and towards the rate of rise of recovery voltage. This investigation is made so that the majority of all MV LBS ratings (7 - 52 kV and up to 900 A) are covered.

From the ablation experiments it was found that high content of hydrogen in the ablation material is favorable for enhancing the current interruption capability. In a comparison experiment between different polymers, polypropylene shows best interruption capability. This material was therefor applied as ablation material in the test switch, and tested in the MV laboratory. The results reveal high capability to interrupt the thermal phase (over the needs for most MV LBSs), but also that the transient recovery voltage several milliseconds after current zero often leads to dielectric re-ignition. This is opposite to a puffer breaker where the thermal interruption instead appears to be the crucial part.

Contents

1. Introduction

This thesis is about current interruption for medium voltage (MV) load break switches (LBSs) in air. Two breaker design principles are considered; gas blow (also called puffer) interruption and ablation-assisted interruption.

Load break switches have existed for a long time and are widely applied in medium voltage distribution networks, typically for voltages in the 6 - 36 kV range. An LBS is less powerful than a circuit breaker (CB) and in most cases interrupts currents up to 1 kA. Designing an LBS in air is not necessarily difficult, but to be competitive it is essential to develop compact designs, which is far more challenging.

Environmental demands for replacing sulphur hexafluorine (SF_6) in metal enclosed switchgear with air, or another non-greenhouse gas, have opened the way for further developments. LBSs are often integrated parts in such switchgear assemblies, comprising several MV components. SF_6-usage over a long time (allowing for very compact designs) has created a situation where the market now hardly accepts products that require more space. Today's air-filled alternatives are therefore not competitive, and further development towards more compact solutions is crucial.

Vacuum switches (which are also compact) can be used in this application, but at a much higher cost. It would be better to either develop more compact puffer switches or ablation-assisted breakers. Ablation technology is common for low voltage (less than 1 kV) products, and has a relatively high level of ability to interrupt current. However, when used in MV products, this technology has difficulties with dielectric stresses directly after current interruption, especially when considering the demand for compact designs.

Further development of puffer switches is basically an optimalization of old technology, while using ablation technology involves more fundamental research. However, little information about design parameters for MV LBS is published. This is primarily because current interruption is extremely difficult to simulate by numerical computer modeling. Experimental testing is necessary, which is challenging from economical and practical points of view. Most development work has been retained by manufacturers, and no systematic parameter studies have been published.

Current interruption is a complex process and the interruption capability of a breaker depends on many parameters. The present investigation takes an empirically approach. A large portion concerns designing a test switch and a laboratory circuit for this purpose. The advantage of this approach is that all results are representative to real current interruption situations in the MV distribution system.

Initially, an introduction to current interruption and LBS technology is given. In Chapter 4 the scope of the research is explained, and the method is described and compared to alternative approaches. The results are published in five papers, attached in Chapter 5. The first paper is about the laboratory circuit (developed and used for the experiments). The second and third papers present parameter studies and discuss design criteria for MV puffer LBS. The last two papers are about ablation-assisted interruption in an MV application. The final Chapter gives a summary of the results and conclusions together with remarks about suggested future research.

2. Current Interruption

This section is an introduction to current interruption. The intension is not to give a full overview of the involved physics, but to introduce and briefly discuss the most relevant topics in this field.

The content is kept on a general level and if no other reference is given, similar information can be found in many published books [1] - [5].

2.1 The Interruption Process

2.1.1 Basic Concepts

At system voltages above about 1 kV, current interruption involves several technical difficulties. With increasing voltage and increasing current, a breaker becomes more and more technically advanced. However, the basic concepts and different stages of the interruption process are common to all MV and HV switchgear.

Fig. 2.1 shows the voltage and current waveforms from a current interruption. The upper graph shows the 50 Hz source voltage, the current and the voltage between the contacts (blue curve) named TRV. In the instant of contact opening an electrical arc instantly ignites between the separating contacts, which conducts the same current as before. The plasma in the arc conducts current well and has a voltage drop (called arc voltage) typically around a few hundred volts. The arc therefore only affects the amplitude of the current to a minor extent. In the example, contact opening happens around time -3 ms, but cannot be seen in the upper graph in the figure since the arc voltage is too small compared to the system voltage.

At the natural current zero (CZ) crossing (at time zero in the figure) the arc extinguishes and the current is interrupted. The contact voltage now rapidly builds up towards the source voltage, and in this period is called the transient recovery voltage (TRV). In this case it takes about 10 ms until the TRV has died out and the voltage between the contacts becomes the same as the source voltage. The form of the TRV is determined by the properties of the power circuit.

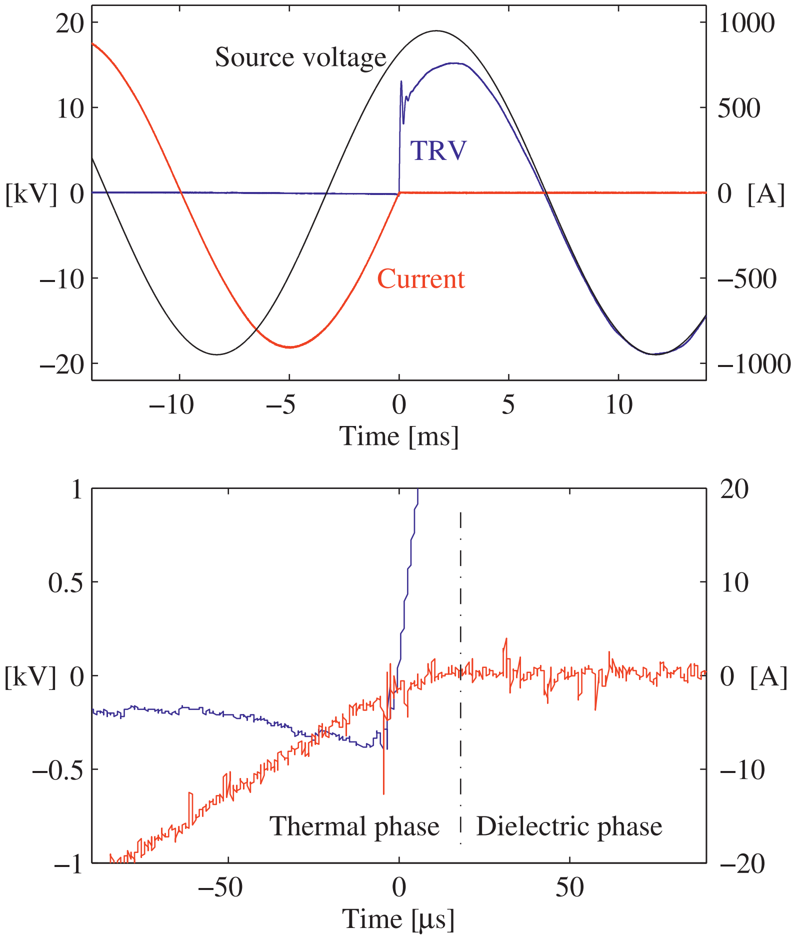

Figure 2.1: Voltage and current curves from a current interruption experiment. The upper graph shows the system voltage (black line), current (red line) and the voltage between the contacts (blue line), called arc voltage before CZ and TRV after CZ. The lower graph shows the time interval close to CZ. The dash-dot line indicates approximately when the thermal phase goes over to the dielectric phase of the current interruption.

The interruption process can be divided into two stages; the thermal phase and the dielectric phase. Just before the current reaches zero the arc voltage increases to its highest amplitude, here to about -400 V. At the same time as the arc voltage collapses the current starts to deviate from its original curve and smoothly decreases towards zero. This part of the interruption and a short time span directly after CZ is called thermal interruption. When there is no longer any moving charges between the contacts, the dielectric phase of the interruption starts. In this case this transition takes place somewhere between 15 and 20 μs after CZ, which is typical for a MV circuit at normal load conditions.

2.1.2 Thermal Interruption

The thermal phase is about quenching the arc. An electric arc consists of plasma which is ionized gas with a large amount of charged particles. Plasma conducts current very well when it is hot, but when the temperature is under a certain level the ionized atoms or molecules start to recombine, the number of free charge carriers decreases and eventually the gas becomes insulating. For air this transition temperature is around 5000 K [5]. The temperature in the arc is a result of input power, size of the arc and the efficiency of the cooling gas flow.

An MV switch can never avoid that an arc ignites and creates plasma. However, every time the current naturally crosses zero the injected power into the arc also comes down to zero, and during a short period of time the breaker has the chance to remove the hot gas and interrupt the current. This is normally done by strong blowing on the arc (or using vacuum technology, discussed further in Section 3). In other words, the thermal phase of current interruption is a competition between the power circuit which feeds the plasma with energy and the breaker that cools the plasma. Only during a short period when that current passes zero the switch has a chance to win this competition. This is the reason why interruption an high voltage DC circuit (where no current zero crossings exist) with conventional breaker technology becomes almost impossible.

The arc can be considered as a resistive circuit element with strongly temperature dependent resistivity. When the current approaches zero and the arc temperature decreases the resistivity increases and the arc becomes an active circuit element which affects the current. In addition, the arc voltage cannot change instantly because of parallel damped capacitive circuit elements. Therefore, the waveforms of the arc voltage and current close to CZ are a result of both the plasma and circuit properties.

The thermal phase does not end exactly at CZ. After CZ a small current called post arc current is present for a maximum of a few tens of microseconds, due to the drift of free charge particles in the rapidly cooling plasma. These drifting particles are accelerated by the increasing TRV and inject thermal energy into the gap which slows down the recombination of the plasma. Usually the post arc current only lasts for a few microseconds, which depends on the breaker and circuit characteristics.

2.1.3 Dielectric Interruption

After post arc current the dielectric phase begins and the TRV continues to increase over the contact gap. A new ”race” is created and if the switch does not manage to increase its dielectric strength faster than the electric field increases by the TRV, an electric flash-over will re-ignite the arc. In a gas blast breaker this is a matter of quickly replacing the hot and contaminated gas after the thermal interruption, with cold clean gas.

The separation distance the contacts have reached when interruption takes place is crucial for the dielectric phase. It is the maximum electric field strength (which often occurs at the tip if the pin contact) which can ignite an electric streamer and cause a flash-over between the contacts. The maximum electric field strength depends primarily on the TRV and contact position, but also on the contact geometry, nozzle geometry and nozzle material.

For an MV LBS the contact speed is typical 5 mm/ms, which means that the contact only moves 0.5 mm during time plotted in the lower part of Fig. 2.1. The opening time of a breaker is not synchronized with the current waveform, and the first CZ comes at any contact distance up to 50 mm (half period is 10 ms at 50 Hz). Therefore the switch has to be designed so it can interrupt the current also at the second and third CZ after contact separation.

In general, the moving contact should reach its fully open position in about 30 to 40 ms, and the breaker has to blow and cool the arcing zone during this entire period. This means that the interruption can happen at the first, second or the third CZ after contact separation, and that at least the third CZ, take place in a position where it is possible to also withstand the TRV.

2.2 Switchgear Gases and Pressure Dependency

The sections above have discussed current interruption from a general perspective that is relevant for any gas. However, the properties of the gas strongly influence the interruption capability for a given switch design. The difference between the best available gas, SF_6, and relevant alternatives like air, CO_2, or nitrogen is large, and results in very different switchgear designs [6] - [10].

There are many electrically insulating gases or gas mixtures, but not all of them are suited for current interruption. One review article from 1997 by Christophorou, Olthoff, and D. Green gives a comprehensive and thorough introduction to gases for switchgear [11]. A good gas for a breaker needs to have the following characteristics:

- High dielectric strength which is important to avoid dielectric re-ignition during the interruption process. In particular, it is important with high dielectric strength in inhomogeneous fields as well as when mixed with a small amount of conducting particles. These conditions occur after the current interruption. Gases that have this ability have high electronegativity, that is a high probability to capture an accelerating electron by negative ionization and have low probability (low ionization cross-section) for losing an electron (positive ionization) from the impact from fast moving electrons or charged particles. Both these properties reduce the risk of initiating a breakdown.

- Quick chemical recombination. In the electric arc the molecules are in the plasma state, dissociated and ionized, and when the temperature decreases during the interruption, it is important that the molecules quickly recombine to the original molecules without producing any byproducts. Stable gases of high symmetry, in particular those containing fluorine recombine fast.

- High thermal conductivity. A gas can have high thermal conductivity due to two effects. One way is having many light and movable molecules like hydrogen, which creates an efficient convection. The other way is having large molecules, with high internal heat capability (many vibration modes). This would be the same at saying "fewer molecules contribute to the cooling but more heat is removed by each of them".

- Thermodynamic stable, high vapor pressure and low condensation temperature. (Particularly important for usage in arctic regions with low ambient temperatures.)

- Chemically stable, not reactive with nearby materials. This includes both direct reactions, as well as acting as a catalyzing agent.

- Environmental friendly (low global warming effect), not toxic or explosive.

Unless global warming was an issue, SF_6 would be an obvious choice when considering the above properties. No other gas with better properties has been or is likely to be found [11]. However, since SF_6 also is the strongest greenhouse gas we know of (20 000 times more powerful than CO_2) it is unwanted. Other good candidates (which also contain fluorine) like CF_4 are also known for high global warming potential. The power engineering industry is now competing to find as good a candidate as possible without this environmental drawback. For some applications we might have to accept SF_6, with strong restrictions regarding handling of the gas, but in most cases the goal is clearly to find alternatives. Using mixtures of gases where a smaller part could be SF_6 has been discussed. This has given good results, but is hardly a satisfactory solution to the problem [11]. To narrow the question down to gases for metal enclosed LBS assemblies dry air or CO_2 remain interesting alternatives. Resent research shows that CO_2 has slightly better properties than air [6], but air has its obvious advantage when it come to practical considerations.

Increasing the gas pressure improves the dielectric strength (Paschen's law), but also the current interruption capability. For high voltage circuit breakers this effect is frequently used. However, for smaller and cheaper products for the MV market, this possibility is limited. These products are filled and sealed by the producer and not at the installation site. The pressure can be increased up to 1.3 bar, but if this pressure is exceeded the product needs to be treated as a pressure vessel. Safety limitation regarding transportation and installation, excludes using higher pressure from an economical reason.

3. Medium Voltage Switchgear Technology

This section provides as an overview of the existing technologies which are relevant in the context of this thesis.

A load break switch (LBS) or load breaker is a device that can interrupt the current under normal load conditions. Higher currents or voltages that occasionally occur, e.g. short circuit current and overvoltages cannot be interrupted with a load breaker switch. Breakers that are designed for this purpose are called short circuit breakers or just circuit breakers (CB).

LBSs and CBs are designed for all voltage and current classes. The rating system for breakers, like many other power components, is divided into low (up to 1kV), medium (1 - 52 kV) and high voltage products (over 52 kV). In addition to this, breakers are also divided into current classes, indicating the maximum current which can be interrupted.

The majority of LBSs are rated for currents less than 1000 A and have a relatively simple arrangement for quenching the arc and interrupting the current.

3.1 Puffer Breaker

Puffer breakers are by far most common type of MV LBS on the market. Several different versions exist but all have the common feature that the breaker compresses a gas volume which is released through a nozzle towards the arc during operation. Fig. 3.1 shows a typical puffer breaker. This device has a rotational movement where a rotating shaft both separates the contacts and pushes up a piston which creates a gas flow out of the nozzle (the white part in Fig. 3.1). Other devices can have a linear movement instead.

Most puffer LBSs are made for an open air environment but also more compact designs exist that are made for metal enclosed switchgear assemblies.

Central design parameters for any such device are the upstream pressure difference (the pressure drop through the nozzle during operation), the nozzle dimensions and the speed of contact movement. In addition, there are several possibilities regarding contact designs and the choice of materials of contacts and nozzle.

Most breakers have two sets of contacts. One set is called the main contact (usually made of silver plated copper), which carries the current when in a closed position and the other set is the arcing contacts which only carry the current a short period during switching. The arcing contacts can withstand the heat from the arc much better than the main contacts, and are often made of tungsten alloyed with either copper or silver.

Figure 3.1: Example of common puffer LBS from ABB. (Courtesy of ABB, www.abb.com.)

3.2 Vacuum Breakers

Vacuum breakers are completely different than puffer switches, and the current interruption is essentially achieved simply by separating contacts inside a small evacuated chamber. The plasma in the electric arc here entirely consists of evaporated metal atoms from the contacts, which recombines rapidly by itself after CZ.

The design of these breakers can be described as a porcelain cylinder with vacuum inside, where two plate contacts can be separated with a comparable small distance (in the range of a centimeter). In vacuum this is enough, and the arc is quenched by itself. The movable contact is mounted into the porcelain cylinder with a metal bellow keeping the interior sealed from the ambient atmosphere.

Current interruption in vacuum is a well established technology, primarily developed for CB. Vacuum breakers are also used as LBSs because of their very compact design. However, for the MV LBS market this technology is expensive.

Further development of vacuum breakers seems to have slowed down, both regarding technical performance and production cost.

3.3 Breakers for Metal Enclosed Switchgear

In the distribution grid, metal enclosed or metal clad MV switchgear are common (where the cabinet itself is grounded). Fig. 3.2 shows a product example. Inside such a metal cabinet several types of switches like LBSs, disconnections and earth switches are usually installed. The advantage is that different kinds of insulating gases can be used and that all the high voltage parts are safely shielded.

Figure 3.2: Example of SF_6 filled metal enclosed MV switchgear assembly. Here the LBS is the vacuum type, but SF_6-puffer breakers are also common in this application. (Courtesy of ABB, www.abb.com.).

For metal enclosed switchgear, usually found indoors where space is limited, SF_6 has been the preferred filling gas and interrupting medium. The entire cabinet is then filled with SF_6 which also allows for tight and compact design. The cabinet is usually pressurized to 1.3 bar, which improves the dielectric strength of the gas and thereby makes it possible to reduce the size. The LBS can be of different types. In SF_6 and at the lower MV ratings, the LBS design can be as simple as just separating the contact without active cooling. For the higher voltages, from about 24kV and up to 52 kV, both vacuum and puffer LBSs are common. LBSs intended as a part of metal enclosed products have to be compact and are more challenging to design than the larger open air products.

Using a vacuum breaker (which usually has higher interruption capability than needed for the application), is the most expensive solution but also the most compact. As in the example in Fig. 3.2, a vacuum breaker (as LBS) is chosen due to the small available space (white porcelain component, left part in the figure).

3.4 Usage of Polymer Ablation

Ablation of polymer close to the arc (which can enhance the current interruption capability) is mainly used for low voltage breakers. For MV applications, ablation is today used in combinations with the puffer principle. However, polymer ablation without a puffer arrangement may become a growing technology for MV applications.

When polymers are exposed to the intense heat of an electric arc the surface starts to evaporate. The vaporized atoms enhance the convection process which increases the heat dissipation from the arc. In this context, the gassing polymer is normally referred to as an ablation material. In an ablation breaker the contacts are separated between surrounding ablation polymer which generates a quenching effect on the arc.

Since the evaporation rate increases with increasing current, there is certainly a potential to interrupt the current in a MV LBS applications. The main problem is to avoid dielectric re-ignition.

For a puffer switch the gas flow continues after CZ and during the TRV period. However, for an ablation switch the gas convection slows down when the current goes to zero. Too much of the hot and soot contaminated media can easily remain, and the dielectric strength is not building up fast enough. Therefore the use of ablation material is more common for low voltage circuit breakers (which experience high current but much lower TRV).

Another concern with ablation-interruption is soot contamination on surrounding surfaces, degrading the performance after many interruptions. This could in particular be problematic if ablation-interruption would be applied in MV metal enclosed switchgear assemblies.

In the literature no information about the geometrical design of MV ablation LBS is found. However, much work is published about the ablation-properties of many different polymer materials. An experimental screening of gassing and arc extinction properties of a large number of polymers was published as early as in 1982 [14]. More contemporary experimental investigations [14] - [22] and theoretical work [23] - [28], provide details concerning various aspects of arc behavior and current interruption in the presence of gassing polymers.

3.5 Contemporary LBS Development

The task to find environmental friendly alternatives to SF_6 is now in progress, where the development of new and more compact LBS solutions is particularly important, which is emphasized in recent publications [12, 13].

Making an MV air LBS is not necessarily very difficult. (Air blast circuit breakers for much higher ratings were made for more than 50 years ago.) The challenge is to make it compact enough to fit metal enclosed products like the one in Fig. 3.2. The market is reluctant to accept products with larger sizes, than today's metal enclosed switchgear. Many such indoor SF_6 installations are today in service and replacing them with larger cabinets would in many cases involve extensive rebuilding. To be competitive with new products this retrofit market has to be considered, which introduces major technical difficulties. The half-way solution is to fill the cabinet with air for example, and use a vacuum LBS. A more favorable solution would be designing a more compact air-puffer LBS.

About 40 to 50 years ago, SF_6 became the preferred gas for medium and high voltage metal enclosed switchgear. Therefore little research during this period has addressed load current interruption in air for MV.

In the past decades, most research publications on current interruption deal with short circuit currents (tens of kiloamperes), in the transmission grid (hundreds of kilovolts). Specific publications about design parameters for compact LBS in air have not been found.

Consequently, as a basis for designing compact and inexpensive MV puffer LBSs, research on the fundamentals of current interruption in air is necessary. The key issues include understanding the contributions from the multitude of factors and phenomena at work as the arc quenches, such as the air blow (volume, mass, velocity, duration, pressure drop), contact movement (velocity, travel distance), nozzle design (geometry, material) under various switching duties (current amplitude, recovery voltage characteristics).

Vacuum or oil LBSs are not likely to be developed much further, but ablation breakers are still in an early development stage. This is certainly an interesting area for further research, which could allow for a technology shift. An ablation breaker can potentially be very cheap to manufacture. At the present there is not enough published research about how to utilize the ablation principle in an MV application and several questions have to be investigated. Fundamental work is still to be done with respect to material properties and regarding the design issues in an MV LBS application.

4. Scope of Work and Method

4.1 Scope of Research and Limitations

This thesis is an experimentally study of current interruption in air with respect to the MV LBS application. Primarily the puffer technology is considered but ablation assisted current interruption is also addressed.

A secondary objective is to design and build a direct powered laboratory circuit (comparable with IEC prescribed type test conditions), especially suitable for the research and development of MV LBSs.

For the gas blow current interruption principle, the research focuses on voltages in the range 7 to 52 kV and for currents in the range 300 to 900 A, and with respect to the following parameters:

- Upstream pressure drop through the nozzle.
- Influence of contact position for the current interruption capability.
- Basic nozzle dimensions; length and diameter.

For the ablation assisted current interruption, the work is divided into two central tasks:

- Study current interruption capability with respect to material properties of the ablation material.
- In an MV test switch, investigate the technical potential and difficulties using ”ablation-interruption” in an MV LBS (not in combination with a puffer mechanism).

4.2 Method

For the experiments an MV laboratory circuit and a test switch were built. Fig. 4.1, shows the MV circuit used for all current interruption experiments, except the test performed for the comparison of different ablation materials.

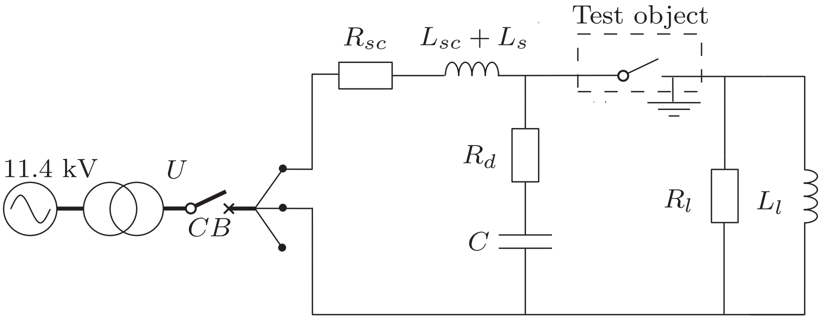

Figure 4.1: The single phase high voltage test circuit. The circuit breaker (CB) is controlled from the laboratory and connects and disconnects the test circuit from the power source.

The circuit is similar to a test laboratory for product type test, decribed by IEC [29]. The circuit is direct powered by the 11 kV distribution grid and via a laboratory transformer the circuit voltage can be varied. The main advantage of using a direct circuit is obviously that it provides the same current interruption conditions as in reality. The alternative would be to use a so-called synthetic circuit, where one part generates the relevant current and a different circuit stresses the test switch with a voltage peak directly after CZ. This is a well established technique for testing of HV CB [30].

For the MV LBS rating it is still possible to use a direct powered circuit because it does not disturb the power grid too severely. The drawback is that the current and TRV characteristic cannot be chosen independently of each other as in a synthetic circuit. However, the new laboratory circuit was built with particular attention to this issue, allowing the current and TRV to be tuned more freely compared to other existing MV test laboratories.

A test switch designed for parameter studies was built, shown in Fig. 4.2. The contact geometry, shown in Fig. 4.3, is in the same size range as that of commercially available MV LBSs. The contact movement and gas blow characteristics can be varied independently of each other. The pin contact moves linearly and with constant velocity. The nozzle can easily be changed and several geometries can be applied.

When performing an interruption experiment the test switch is first closed manually and the spring is compressed (part no. 6 in the figure). In the closed position an electromagnet holds the pin contact in position inside the tulip contact, where it also plugs the outlet of the pressure vessel. When the current in the magnet is turned off the spring drive mechanism rapidly pulls the pin contact out, and the compressed air in the vessel starts to blow out through the nozzle. The upstream pressure through the nozzle can be set to any value up to several bars with high precision. The size of the vessel is large enough to apparently maintain the same upstream pressure during the short period of time an interruption experiment lasts. The test switch is optimal for investigating the magnitude of the minimum needed upstream pressure for a specific interruption case.

The control signal to the trigger mechanism (electro magnet) is synchronized with the source voltage. This in combination with the precise mechanical operation of the switch, makes it possibly to perform repeated and similar tests, or systematically change the contact position at CZ for an experiment.

The mechanical function of the test switch proved to be very reliable, and at the moments around 4000 interruption experiments have been performed with it. The contacts (made of CuW) and nozzle were replaced many times but the rest of the switch remains apparently without wear.

The same test switch was also used for the MV ablation experiments. The nozzle was replaced by a different set-up and no active blowing from the pressure vessel was used.

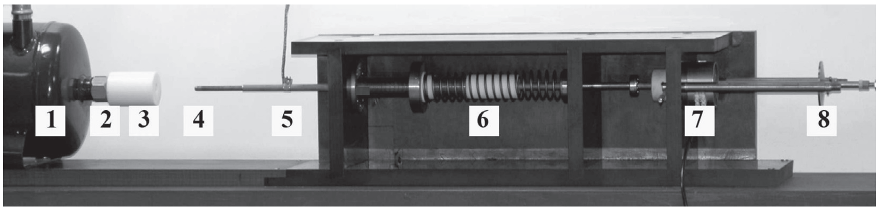

Figure 4.2: The test switch. The picture shows the entire test rig in fully open position. The numbered parts are; 1. Pressure vessel (connected to the high voltage supply circuit), 2. Tulip contact, 3. Nozzle, 4. Pin contact, 5. Connection to load circuit, 6. Spring drive mechanism, 7. Electromagnet (release mechanism), and 8. Plate for the electromagnet and connection point position transducer (outside the in picture to the right).

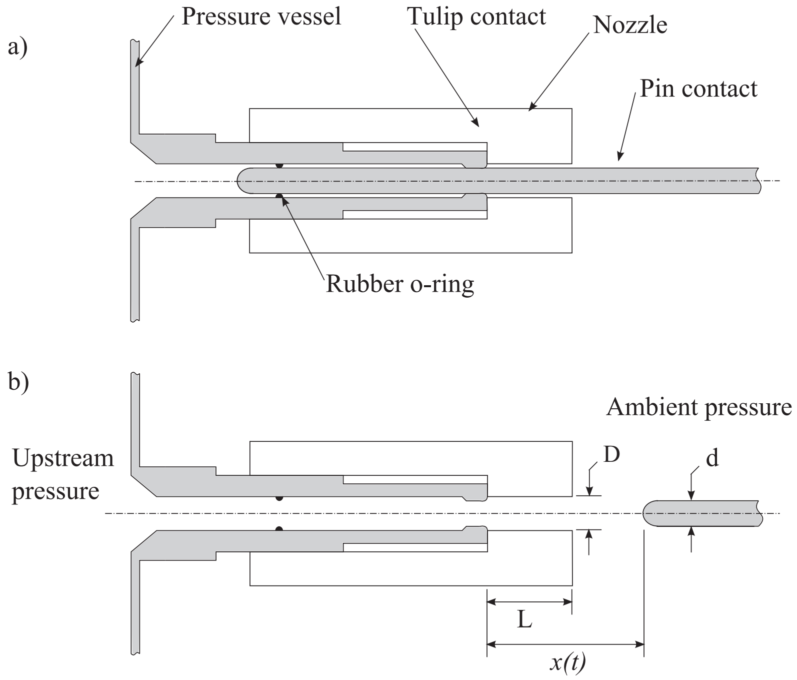

Figure 4.3: Cross-section drawings of the contact and nozzle area; a) in closed position and b) when the pin contact is moving, about halfway to fully open.

4.3 Experimental Testing or Numerical Modeling

For some aspects of circuit breaker development, computational modeling is an alternative to experimental testing. For investigating mechanical properties and electrical field calculations modeling is useful, but regarding the arc behavior, in particular close to CZ, it becomes complicated.

However, also for the current interruption, there are several simulation approaches which correspond to reality to a different degree. These can be divided into two categories; physical models and black box models (more advanced black box models are sometimes instead called parameter models).

At the first thought, a high voltage breaker has a simple mechanical design which should be possible to simulate with a physical model. The problem is the arc, and how to simulate the rapid transition from plasma to insulating gas in a realistic way. The arc conductivity has to change about 15 orders of magnitude in a few microseconds if the current is to be interrupted. This comes down to a matter of simulating the local arc temperature, which is cooled in a nozzle with a strong gas flow, often in the range up to sonic speed.

A complete physical model would include a large number of differential equations, considering conservation of mass, conservation of momentum and conservation of energy [5]. In particular the equation for energy conservation has several challenging features.

The Joule heating around CZ is very complex to describe. The arc resistivity depends on the properties of the plasma, where each type of molecule and atom has temperature dependent dissociation and recombination reactions. In addition, at low currents close to CZ, the arc resistance is no more a negligible circuit element, and will change the current waveform. Moreover, when the cooling of the arc (in a turbulent gas flow) also has to be considered, it is easy to understand why modeling all these processes becomes difficult.

Even if all physical equations could be inserted correctly into a model, a numerical simulation problem would arise instead. It is likely that such a model would take too long to run. At present, no such physical model exists and experimental testing in a relevant power circuit remains the only reliable method.

However, there are also black box models that use relatively simple mathematical equations to connect the arc conductivity with measurable parameters. These can be seen as development tools, and are used in combination with experiments. The reason for using such models is to obtain a better understanding of the arc behavior and reduce the number of expensive experimental tests. The latter are particularly important for the highest rated CBs, where testing is technically complicated.

There are many such models, but the most common approach is to use a combination of the Cassie model and Mayr model. The Cassie model is suited for the high current phase at (temperatures over 8000 K) while the Mayr model is suited for lower currents close to CZ. There is a lot of information about these methods in the literature [1] - [5].

For this PhD project an experimental approach was chosen. For the MV LBS ratings, the sizes of both test objects and the laboratory circuit are manageable. Therefore, handling the parameter studies by performing a large number of tests (without black box modeling) was found to be the most straightforward approach. This gives reliable results, while the main drawback is the practical issues concerned with maintaining the experimental equipment.

5. Publications

The research in this thesis is given in five papers. This chapter starts with a short introduction which connects each paper the scope of the thesis. Each paper can be read independently, but the presented order aids the readability. After the introduction, the papers are inserted (without changing the original format).

Paper I

Medium Voltage Laboratory for Load Break Switch Development

Erik Jonsson and Magne Runde

Proc. Int. Conf. on Power Systems Transients, Vancouver, July 2013, paper no. 351.

Establishing a new laboratory for the testing of MV switchgear was the starting point of the research. The new circuit offers significant opportunities for testing with different currents and TRVs, covering most interruption situation for MV LBSs. The laboratory components are designed for tuning the impedance values in small steps and in a wide range.

The paper describes the properties of the circuit and how to find combinations of currents and TRVs when planning test programs for a switch. It also discusses the design of the individual high voltage components in the circuit. The laboratory is designed to offer similar test conditions as the IEC prescribed type tests, for any MV rating (7.2 - 52 kV) and up to 1 kA.

Paper II

Current Interruption in Air for a Medium Voltage Load Break Switch

Erik Jonsson, Nina Sasaki Aanensen, and Magne Runde

IEEE Transactions on Power Delivery, In press 2014.

One of the most common MV LBS ratings is 24 kV at 630 A, and this was chosen for the initial experimental series. The aim was to get basic knowledge about how the interruption capability is related to basic nozzle dimensions, contact movement and the gas flow through the nozzle. (Relevant for a puffer LSB design.)

The test switch and measuring equipment were built and used for a large number of tests. The results show a clear connection between interruption capability to upstream pressure and nozzle geometries.

Paper III

Interruption in Air for Different Medium Voltages Switching Duties

Erik Jonsson and Magne Runde

Submitted to IEEE Transactions on Power Delivery

This paper is a continuation from paper II. Here the interruption capability was studied for different currents and TRVs. The geometrical parameters regarding the nozzle and contacts were unchanged and also the contact movement was kept as equal as possible for every test. For every circuit situation several series at different upstream pressure drops were performed.

A large number of experiments were performed, and the results show the critical minimum upstream pressure drop as a function of current and TRV steepness. The nine different circuit settings in the experiment were chosen so that almost all MV LBS ratings up to 52 kV and current up to 900 A were covered.

Paper IV

Comparative Study of Arc Quenching Capabilities of Different Ablation Materials

Erik Jonsson, Magne Runde, Gustavo Dominguez, Andreas Friberg, and Erik Johansson

IEEE Transactions on Power Delivery, vol. 28, no. 4, Oct. 2013.

Evaporated material from a nearby polymer influences the interruption performance of a switch in a positive way. This has been utilized for low voltage switchgear, not much for higher voltage switchgear.

This paper was intended as a starting point toward using these so-called ablation materials for MV LBSs. Four different plastic materials were tested in a capacitive discharge circuit which generated large currents, but with lower transient recovery voltage compared to the test conditions for MV switchgear. This comparison experiment gave clear results, and the most promising material was chosen for subsequent experiments the MV test switch.

Paper V

Ablation Assisted Current Interruption in a Medium Voltage Load Break Switch

Gaute Gjendal, Erik Jonsson, and Magne Runde

Submitted to Int. Conf. on Electrical Contacts, June 2014.

As a continuation from paper IV, the current interruption ability of polypropylene (PP) is investigated in the MV LBS. PP plates were positioned on both sides of the arc. The main difference to the experiment in paper IV was a far more severe TRV from the direct powered MV circuit, as well as a realistic contact movement.

The experiments demonstrate the potential and difficulties with applying ablation technology for MV products. This investigation gives promising results, but it also reveals that further work is required, in particular regarding the dielectric properties.

Paper I

Medium Voltage Laboratory for Load Break Switch Development

Erik Jonsson and Magne Runde

***Abstract*—A new, directly powered laboratory for studying current interruption in medium voltage load break switches has been designed, built and tested. Since the current amplitude and the initial part of the transient recovery voltage (TRV) in general are found to be the most important factors for whether an interruption will be successful or not, the test circuit has been made with this in mind. It is demonstrated that the TRVs up to the first peak voltage of the so-called ”mainly active load current duty” of the IEC 62 271-103 standard can be accurately replicated for all voltage classes from 7.2 to 52 kV by using a relatively small and inexpensive 600 kVA laboratory transformer delivering 6.9, 12, 13.8 and 24 kV. Test currents span from 400 to 1 250 A (only to 630 A for the lower voltage classes). The values of the inductances, resistances and the capacitance of the test circuit are adjustable over a wide range, as this is required to achieve such a great versatility. The laboratory is well suited for empirical investigations of interrupting capabilities of switchgears, for example by varying one factor (rate of rise of recovery voltage, TRV amplitude, current amplitude, point on wave, etc.) at the time, while keeping the others constant.**

***Keywords*: Load break switch, switchgear, medium voltage laboratory, transient recovery voltage, IEC type test.**

I. INTRODUCTION

CURRENT interrupting tests constitute an important part of the process of developing and qualifying new high voltage switchgear designs and products. Such tests require extensive laboratory facilities and are time consuming and expensive, in particular when considering equipment for high ratings. Consequently, the tests are often focusing strongly on the type test requirements specified in the standards, and to a lesser extent aiming at fully understanding the behavior of the device.

Investigating and in detail exploring the interrupting capabilities of a switchgear require a test facility that can vary the most important circuit parameters over a rather wide range. The essential parameters in this context are the current levels and the transient recovery voltage (TRV), in particular the TRV steepness immediately after the arc has been extinguished and the current is interrupted. Such investigations may give a better understanding of the properties and behavior of the device, and identify critical features for further design improvements.

For studying current interruption in high voltage circuit breakers the amplitudes of the currents and voltages involved are often so large that in most cases so-called synthetic test circuits have to be applied [1]. The supply current and the recovery voltage are here generated by two separate circuits. Due to this, synthetic circuits normally provide great flexibility, but careful timing is necessary for generating a realistic TRV during the crucial thermal interruption part, i.e., in the first tens of microseconds after current zero.

Such difficulties do not arise if the test circuit is directly powered from the grid. Hence, for testing switchgear of more modest current and voltage ratings, a directly supplied test circuit is a better option. The device is then subjected to stresses of a nature exactly as in service.

The present paper describes a directly powered laboratory for research on load current interruption at the medium voltage (MV) level. MV load break switches typically have interrupting capabilities up to around 1 kA and are installed in large numbers in distribution networks [2]. It will be shown that by carefully selecting the parameter ranges for the inductances, resistances and capacitance of the test circuit, a very flexible and versatile laboratory can be obtained with a reasonably rated and not too expensive power transformer.

Only the initial part of the TRV is addressed, as re-ignition at a later stage usually is less of a problem for MV load break switches [3], [4]. The International Electrotechnical Commisson (IEC) type test conditions for ”mainly active load current duty” [5] form the basis for the laboratory layout. It will be demonstrated that the first few hundred microseconds of the TRV for all IEC voltage classes from 7.2 to 52 kV for a wide range of currents can be generated by using one transformer delivering 6.9, 12, 13.8 and 24 kV.

Initially, the circuit providing the considered IEC test duty is analyzed, and the TRVs are determined for the different voltage classes. Then follows a description of the design of the laboratory components, including their parameter ranges. Finally, measurements confirming that a wide range of TRVs can be achieved this way are shown.

This new laboratory is located at the Norwegian University of Science and Technology in Trondheim, Norway.

II. ANALYSIS OF THE IEC 62 271-103 MV STANDARD

The MV load break switch standard issued by IEC [5], prescribes several test duties, including rated load current

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interruption, closing at full short circuit current, as well as dielectric withstand test for open position. Moreover, some load break switches are designed for special purposes, and special type tests exist for these cases. However, for the vast majority of load break switches, the mainly active load current duty is the dimensioning current interruption test. The associated test circuit is defined by the following requirements [5]:

- The test circuit should consist of a supply circuit and a load circuit.
- The load should contain a resistor and a reactor in parallel. The impedance of the load should have a power factor of 0.7±0.05.
- The supply circuit should contain a resistor and a reactor in series. The impedance of the supply circuit should be 15±3% of the total impedance and have a power factor less or equal to 0.2.
- The prospective TRV should have a peak value U_c with a time coordinate t_3, specified for each rated voltage.

Fig. 1 shows the test circuit according to the requirements. The implications of the first three requirements are clear, while the last one needs some elaboration.

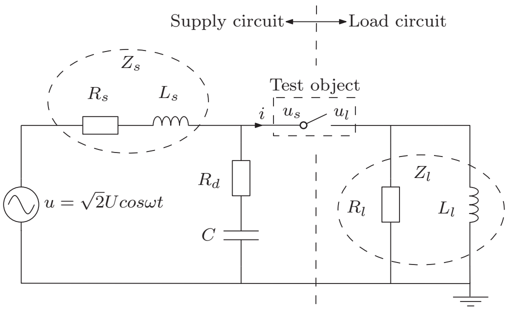

Fig. 1. Single phase circuit for IEC "mainly active load current duty". The voltages at the terminals of the test object are referred to as u_s (supply side) and u_l (load side).

Define the supply impedance as $Z_s = R_1 + jX_1$ and the load impedance as $Z_l = R_2 + jX_2$. The following set of equations can then be established with basis in the requirements listed above.

$$\begin{cases} (R_1+R_2)^2+(X_1+X_2)^2 = |Z_{tot}|^2 \\ \sqrt{R_1^2+X_1^2} = 0.15\cdot|Z_{tot}| \\ \cos\left(\arctan\frac{\mathrm{X}_1}{\mathrm{R}_1}\right) = 0.2 \\ \cos\left(\arctan\frac{\mathrm{X}_2}{\mathrm{R}_2}\right) = 0.7, \end{cases} \qquad (1)$$

where $Z_{tot} = Z_s + Z_l$.

For a three phase test the supply voltage u should be the rated voltage. For a single phase circuit the first-pole-to-clear factor of 1.5 needs to be included, and the supply voltage becomes the rated voltage multiplied by $(1.5/\sqrt{3})$.

For rated voltage and current of 24 kV / 630 A, (1) has the solution

$$R_1 = 0.99\ \Omega, X_1 = 4.84\ \Omega, R_2 = 20.5\ \Omega,_2 = 20.1\ \Omega.$$

In a 50 Hz system the values for the circuit components then become

$$R_s = 0.99\ \Omega, R_l = 40.7\ \Omega, L_s = 15.4\text{ mH}, L_l = 129.4\text{ mH}.$$

In order to comply with the IEC requirements for the TRV, the supply side of the circuit must also have a capacitor and a damping resistor. The damping resistor can be placed in series (as in Fig. 1) or in parallel with the capacitor. Most commonly used is the series damped circuit since the resistor then experiences much less ohmic dissipation. The series damped case gives a steeper start of the TRV, and the current interruption becomes slightly more difficult compared to the parallel damping case. In the present work only the series damped case will be considered.

The shape of the mainly active load type test TRV is not explicitly specified in the standard, but is defined by means of the prospective TRV. (The prospective TRV is the resulting TRV when the load is short-circuited.) It is not practical to adjust the prospective TRV using full rated voltage, since the resulting current and TRV will exceed the rating of the switch and the other test circuit components. Hence, normal procedure is to scale down all voltages when tuning the supply circuit parameters to obtain the prescribed prospective TRV. Alternatively, the circuit impedances can be determined by numerical simulations, here done with ATPDraw.

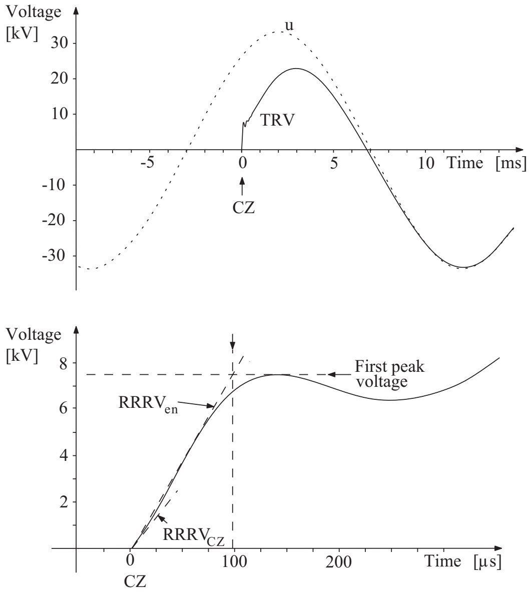

Fig. 2. Voltage waveforms from a typical 24 kV single phase mainly active load type test. Time t = 0 corresponds to CZ and current interruption. The lower part shows the first 350 μs of the TRV.

Fig. 2 shows the supply voltage and the simulated TRV for a successful 24 kV single phase type test. For more exact characterization of the initial part of the TRV, two additional parameters are also presented; the envelope rate of rise of recovery voltage (RRRV$_{en}$) and the initial rate of rise of recovery voltage (RRRV$_{CZ}$). The latter is the tangent of the voltage curve at current zero (CZ).

For the 24 kV voltage level, the IEC standard specifies that the prospective TRV should have a first peak voltage of U_c = 41 kV with a time coordinate t_3 = 88 μs. The values for the capacitor and the damping resistor yielding this voltage waveform can be calculated or experimentally determined by an iteration process to C = 0.147 μF and $R_d = 216$ Ω.

As can be seen in Fig. 2, with the load connected the resulting first peak voltage for the type test is about 7.6 kV which corresponds to 19% of the prospective value, since 85% of the source voltage is now over the load. The resulting TRV is the difference between the supply and load side voltages, but in the beginning the supply side dominates and the load side only contributes with a relatively slow exponentially decaying voltage. The shift of the time coordinate from 88 to 96 μs is mainly a consequence of changing the power factor from about 0.2 to 0.7, affecting the location of the CZ relative to the source voltage.

The same procedure is carried out for other voltage classes, and the results are given in Table I. The first peak voltages for the prospective TRV and the TRV with load are referred to as U_c and U_c', respectively. The same notation is used for the time coordinates t_3 and t_3'.

For a load break switch the thermal phase (first microseconds after CZ) usually poses the most difficult part of the interruption. Thus for more precise description of the stresses, the values for both RRRV$_{en}$ and RRRV$_{CZ}$ are included in Table I.

TABLE I
TRVs for IEC Mainly Active Load Type Test Duty

Rated voltage [kV]	Prosp. TRV [5] U_c [kV]	t_3 [μs]	TRV (with load) U_c' [kV]	t_3' [μs]	RRRV$_{en}$ [V/μs]	RRRV$_{CZ}$ [V/μs]
7.2	12.3	52	2.1	56	38	34
12	20.6	60	3.6	65	55	50
24	41	88	7.6	96	80	72
36	62	108	12.0	116	103	93
52	89.2	138	18.5	152	123	111

All values in Table I are calculated for a current of 630 A, but other currents yield nearly identical results. Hence, the TRVs of the values in the table apply for all relevant current ratings.

III. Laboratory Circuit for Switchgear Development

A. Testing with Reduced Supply Voltage

In total 13 different MV classes, from 3.6 to 52 kV, are listed in the IEC standard. Providing type test conditions for only the five classes of Table I is in itself demanding for a laboratory, typically requiring a large, flexible and thus expensive transformer solution.

Furthermore, the IEC mainly active load type test requires a low impedance at the supply circuit side. For the 24 kV / 630 A example above, the supply side inductance should be 15.4 mH. This value also includes the inductive part of the short circuit impedance of the connected power system, of which the leakage inductance of the test transformer constitutes a major part. (The resistive part of the short circuit impedance is negligible in this context.) To be able to deliver a sufficiently large current for type testing of the important 24 kV / 1 250 A class load break switch, an even lower supply side inductance of around 8 mH is required. Again, this is not easily achieved, and adds on to the cost and complexity of the test transformer.

Simpler solutions can be obtained by taking advantage of the fact that the stresses occurring during the first few hundred microseconds after interruption are decisive for whether an interruption will be successful or not. Thus for switchgear development purposes it is largely sufficient to carry out tests with the correct current and the correct "IEC TRV" up to the first peak voltage, see Fig. 2. If the TRV is as defined by the parameters of Table I for the considered test voltages, the stresses on the device during these critical parts of the interruption are almost identical to the type test stresses. The shape and amplitude of the recovery voltage later on is of considerably less importance as dielectric re-strikes milliseconds after CZ is a rare occurrence in MV load break switches.

An important implication of this approach is that the supply voltage of the test circuit can be reduced compared to that of the true type test conditions. Furthermore, a higher test transformer leakage inductance can be accepted, and these factors substantially bring down investment costs.

For creating a wide range of test conditions, the circuit components need to have sufficiently wide tuning ranges. In addition, a detailed understand how the various components affect the TRV is required to fully exploit the potential of the laboratory.

B. Creating Different TRVs

Even though the test circuit only contains six impedances it is not straight forward to analytically derive the relationships between the circuit parameter values and the resulting TRV waveform and current amplitude. However, by understanding a few basic principles of the circuit behavior, the desired TRV can relatively easily be found after a few iterations.

At the moment of interruption, u_s and u_l (see Fig. 1) are the same and given by the voltage division between Z_s and Z_l. The supply side is a damped series RLC circuit. After the arc has extinguished the supply side terminal experiences a voltage step, and u_s starts a damped oscillating around the supply voltage u. The load side voltage u_l decays exponentially. Fig. 3 shows both u_s and u_l after CZ.

The first peak amplitude and the steepness of the TRV are primarely related to the following three parameters:

- The voltage step U_{step} (see Fig. 3).
- The frequency of the supply side oscillation.
- The damping of the supply side oscillation.

The voltage step U_{step} is determined by the supply voltage, the voltage division between load and supply side, and the

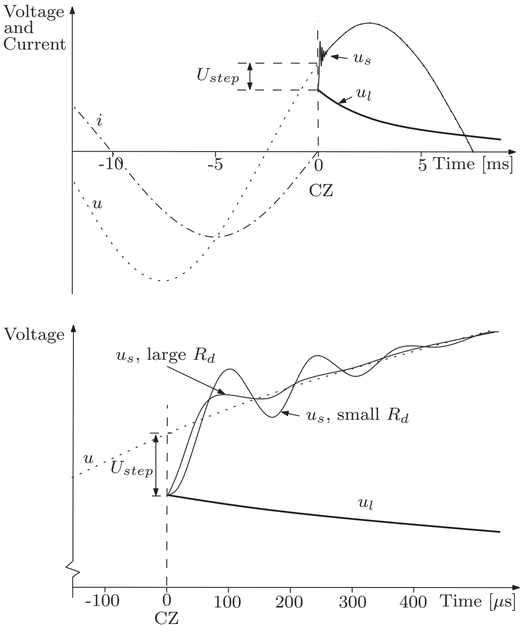

Fig. 3. Typical current and voltages during a current interruption. The two contributions to the resulting TRV, u_s and u_l are shown separately. U_{step} is the voltage across the supply side impedance at CZ. The lower graph shows the first part of the TRV and the effect of changing the damping resistance.

phase angle. Changing the ratio between load and supply side impedances changes U_{step}, and thus also the TRV amplitude.

From the general theory of a damped oscillation the frequency of the supply side oscillation is given by

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{L_s C} - \left(\frac{R_d}{2L_s}\right)^2}. \quad (2)$$

The minute contribution from R_s is here neglected.

Unless the circuit is over-damped the first term of (2) is dominating over the second. Since the value of the capacitor can be adjusted without significantly changing the current through the test object, this is a convenient way of changing the time coordinate and frequency of the TRV.

Adjusting the damping has several effects on the TRV. For example, when increasing R_d the first peak voltage U_c' decreases, the time coordinate t_3' decreases, and the initial part becomes steeper, as shown in Fig. 3.

IV. BUILDING THE LABORATORY

With basis in the considerations above, a laboratory for MV switchgear development was designed and built. The three phase laboratory transformer is directly powered from the 11.4 kV distribution system in the area, but the secondary side test circuit is only for single phase experiments. Fig. 4 shows the circuit diagram where the short circuit resistance R_{sc} and inductance L_{sc} of the test transformer and the external network are drawn together with the circuit components. The resistance R_s of Fig. 1 should be small and is not critical for tuning the TRV. In the realization of the test circuit R_s is simply taken as the short circuit resistance R_{sc}. (That is, R_{sc} is not a physical component.)

The operating mechanisms of both the laboratory circuit breaker (CB) and the test object have installed equipment for synchronizing the contact opening with the supply voltage. This makes it possible to control the contact position at the moment of current interruption and thereby efficiently study the effects of different arc lengths and arcing times.

For simplifying the TRV measurements the ground point is located at the load side terminal of the test object. This does not influence the TRV since the neutral point of the transformer is floating.

Even though it is not the objective to perform IEC type testing, it is still advantageous to have a laboratory transformer with a low leak inductance, as this gives greater flexibility for making different TRVs. The thermal rating of the transformer, on the other hand, is less of a concern as typical current interruption tests only last a few power cycles. A three phase 600 kVA transformer with a low short circuit impedance, providing 6.9, 12, 13.8 and 24 kV was designed, built and installed. Although being a customized device, the size and cost of this test transformer is small compared to what would be needed for a transformer able to power a full IEC mainly active load test duty.

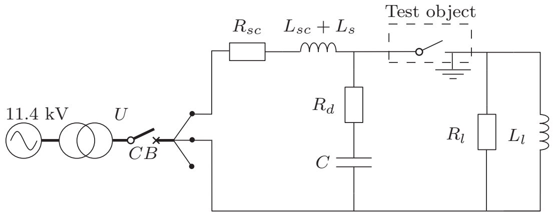

Fig. 4. Laboratory circuit diagram. The short circuit inductance L_{sc} and resistance R_{sc} are drawn as circuit components. Several disconnectors and earthing switches installed for personnel safety reasons are omitted from the diagram.

To generate the correct current amplitudes and the associated TRVs corresponding to a wide variety of IEC MV test levels, the components of the test circuit need to be adjustable over a wide range and with fairly small steps. Table II lists the ranges and resolution of the resistances, the inductances and the capacitance of the laboratory components.

TABLE II
LABORATORY COMPONENTS VALUES

	Symbol	Range	Step lenght
Load reactor	L_l	30-390 mH	1 mH
Load resistor	R_l	5-95 Ω	0.5 Ω
Supply reactor	L_s	0-70 mH	1 mH
Capacitor	C	0-9.676 μF	2 nF
Damping resistor	R_d	0-1 000 Ω	5 Ω

The reactors and resistors are all designed and built in-house, whereas the capacitor unit is assembled from commercially available devices. Obviously, the main challenges are to allow for fine tuning of the component values over a wide range, and at the same time avoid excessive dielectric stresses or excessive ohmic heating in any part.

The load reactor L_l consists of two separate air core coils connected in series, one with nine coarse steps of 30, 70, 110, ... 350 mH and one with 40 fine steps of 1 mH each. The two coils are about 0.6 m in diameter and 1.7 m tall, and are shown in Fig. 5.

The supply side reactor L_s is also made up by two coils in series. These have similar design as L_l, but are only about 1 m tall.

The coils are wound with a 2.1x4.5 mm cross section copper wire, in total about 5 km for all four coils. The wire is insulated with two layers of polyamide film, giving a partial discharge tolerant insulation up to stresses of 10 kV between neighboring turns. The copper wire is wound in 3-5 cm deep and 2.5 cm wide slots machined into a thick-walled polyethene pipe.

The coils are designed to not heat up more then $15°$C during an interruption experiment of 1 250 A lasting for ten power cycles. For improving the mechanical strength and integrity, the windings are impregnated with glass fibre reinforced epoxy.

Fig. 5. Load reactor (in the 390 mH setting). The left coil is for coarse tuning and the right coil for fine tuning.

The load resistor R_l is shown in Fig. 6. It consists of 82 resistance elements, stretched up in a 4x2x1 m large frame, made of a non-flammable material. This component also has two sections connected in series, one for coarse and one for fine tuning.

Each resistance element consists of two equally long, parallel FeCrAl wires, of diameter in the range of 2-4 mm. These are wound as two springs, with opposite winding directions, one placed outside the other and with glass fiber fabric between. This design gives virtually no inductance. In the middle of each element a pipe of pressed mica provides structural support and restricts sideway movements.

With a current of 1 250 A for ten power cycles some of the resistance elements heat up $150°$C. Substantially higher temperatures, probably up to around $1000°$C, can be handled in a safe manner. This permits repetitive usage without too long cooldown times.

The damping resistor R_d is also made of FeCrAl wires. The current through this component is never exceeding a few ampere over a few milliseconds, making it much smaller than the load resistor.

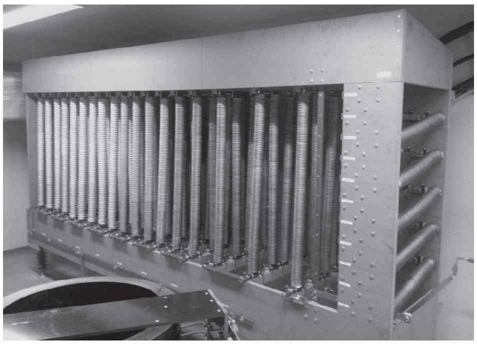

Fig. 6. Load resistor.

The capacitor is assembled from 13 commercially available capacitors with the following values: 2, 4, 8, 16, 32, 64, 100, 150, 300, 600, 1 200, 2 400 and 4 800 nF. These can be connected in parallel in any combination, giving values from 2 nF up to almost 10 μF.

V. RESULTS

Fig. 7 shows corresponding TRV and current waveforms obtained from a current interruption test replicating the initial and most important part of the 24 kV / 630 A IEC mainly active load current duty. An interval of some 400 μs around CZ is included. Since the supply voltage is only 13.8 kV, the shape of the TRV is similar to the type test conditions only for about the first hundred microseconds after interruption. The TRV is here nearly identical to the simulated waveform of Fig. 2 and well within the 3% margins given in the standard.

By changing the transformer setting and adjusting the parameter values of the test circuit components, the initial part of the TRV has been tuned to replicate 12 different IEC test conditions. As shown in Table III, voltage classes from 7.2 to 52 kV are included, each with two or three current ratings. The output voltage of the transformer and the associated short circuit inductances and resistances are listed in the table, as are the set values for the test circuit components. Finally, the last five columns of Table III list the measured current amplitude and the characteristic parameters of the resulting TRV. Comparing these numbers with those presented in Table I demonstrates that it is possible to obtain a wide variety of test conditions this way. The results in Table III are merely examples; the TRV of any other intermediate current and voltage values can certainly also be achieved.

The short circuit impedance of the different voltage settings in the transformer limits the current to around 700 A for 7.2, 12 and 24 kV levels. For the higher voltage levels, the current can be varied in the range 400 to 1 250 A, while

TABLE III
CIRCUIT SETTINGS AND MEASURED CURRENT AMPLITUDES AND TRV CHARACTERISTICS

Rated values		Transformer parameters			Circuit component values					Measured current and TRV characteristics				
Voltage [kV]	Current [A]	U [kV]	L_{sc} [mH]	R_{sc} [Ω]	L_s [mH]	L_l [mH]	R_l [Ω]	C [nF]	R_d [Ω]	I [A]	U_c' [kV]	t_3' [μs]	RRRV$_{en}$ [V/μs]	RRRV$_{CZ}$ [V/μs]
7.2	400	6.9	1.5	0.5	5	72	21	126	150	398	2.09	55	38	38
	630	6.9	1.5	0.5	3	47	13	208	150	625	2.20	57	39	39
12	400	6.9	1.5	0.5	8	79	18	108	35	403	3.61	66	55	44
	630	6.9	1.5	0.5	5	45	12	182	35	632	3.57	65	55	46
24	400	13.8	10	1.0	15	138	36	74	250	410	7.49	97	77	68
	630	13.8	10	1.0	7	86	22	102	200	634	7.50	92	83	71
36	400	24	25	2.8	14	225	63	64	100	399	11.51	119	97	62
	630	24	25	2.8	0	143	42	80	200	638	11.52	112	103	81
	1250	13.8	10	1.0	5	40	18	230	150	1 271	11.95	116	103	93
52	400	24	25	2.8	39	240	51	62	350	398	18.60	149	125	98
	630	24	25	2.8	17	134	30	100	250	632	18.47	149	124	91
	1250	13.8	10	1.0	13	94	16	250	150	1 240	18.50	154	120	99

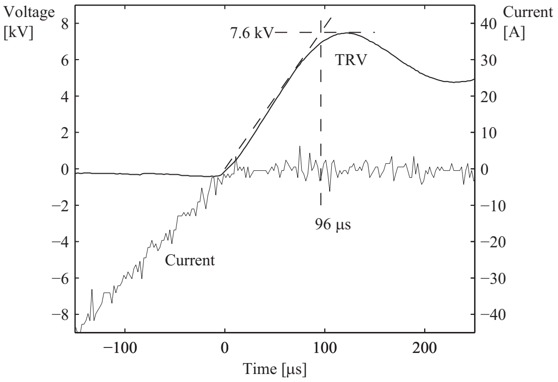

Fig. 7. Unfiltered measurement data of current and TRV during a successful load current interruption test. The sampling frequency is 5 MHz. The amplitude and the time coordinate of the first voltage peak of the TRV correspond to the values resulting from the IEC test requirements for the 24 kV / 630 A case, see Table I.

complying with the type test TRV requirements up to the first peak voltage.

VI. DISCUSSION AND CONCLUSION

Design, building and testing of a directly powered new MV laboratory devoted to current interruption research and development on load break switches have been described. It has been demonstrated how the initial and crucial part of the TRV of the considered type test duty for load break switches rated from 7.2 to 52 kV can be generated with a modestly rated test transformer, provided that the values of the inductances, resistances and the capacitance of the test circuit can be varied over a wide range.

The flexibility of the laboratory also makes it well suited for parameter studies and more fundamental investigations of current interruption at the MV voltage level. For example, a test series where the rate of rise of the recovery voltage just after current zero crossing is gradually increased while the current is kept constant, can provide information about the interrupting capability of a switching device and identify crucial design parameters. Similarly, tests where the current is increased in small steps while keeping the TRV unaltered may also give insight into basic aspects of arc quenching, and thus contribute to improving and optimizing a MV switchgear.

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Paper II

Current Interruption in Air for a Medium-Voltage Load Break Switch

Erik Jonsson, Nina Sasaki Aanensen, and Magne Runde

***Abstract*—The current interrupting capability of a load break switch (LBS) depends on many design parameters, such as contact and nozzle geometry, contact movement, and gas flow. For developing more compact gas blow LBSs for air, it is necessary to find design recommendations where each parameter is addressed individually. In this paper, a current interruption test switch is built for this purpose. The interruption tests are conducted with a directly powered high-voltage circuit. The result shows the minimum gas flow required for current interruption for various basic nozzle geometries and at different contact positions. The study is particular relevant for the 24 kV/630 A class, and it is shown that 0.3 bar upstream pressure appears to be a threshold value for successful interruption. Some conclusions are also applicable for other medium-voltage ratings. An LBS should be designed so that at least one current zero crossing comes outside the nozzle when the switch is still blowing with full strength.**

***Index Terms*—Air, current zero, load break switch, medium voltage (MV), puffer breaker, switchgear, thermal interruption.**

I. INTRODUCTION

LOAD BREAK switches (LBS) are widely applied to medium-voltage (MV) distribution networks. An LBS is less powerful than a circuit breaker (CB) and interrupts currents up to approximately 1 kA [1]. The most common types have a gas blow arrangement (usually called puffer) to quench the arc, but vacuum devices also exist.

LBSs are often an integrated part of a metal enclosed or metal clad switchgear assembly consisting of several MV components. The filling gas is air or SF_6, sometimes pressurized for improving the current interruption performance and increasing the dielectric strength, allowing for more compact switchgears.

From an environmental perspective, air-filled switchgear is preferred over SF_6 products, but air has poorer dielectrical and current interrupting performance than SF_6. Although the capabilities can be improved by increasing the filling pressure, air-insulated switchgear tends to become substantially larger than when using SF_6. Hence, to make air-filled switchgear competitive, optimizing the design with regard to size becomes crucial.

Little is published about the design of LBSs using air as an interrupting medium because SF_6 technology has dominated the marked for metal-enclosed switchgear. The current interruption capability depends on many design parameters, such as gas flow, contact separation speed, geometry, and choice of materials for the nozzle and contacts.

This paper reports on an experimental study of current interruption in air. A test switch is built, and nozzle geometry, air flow, and contact movement are systematically varied. The test circuit is based on the so-called "mainly active load test duty" for 24 kV/630 A class of LBSs, as prescribed by the International Electrotechnical Commission (IEC) [2].

The purpose of this paper is to investigate in a quantitative manner how some of the aforementioned parameters influence the interrupting capability. Such knowledge is expected to be valuable for developing competitive and compact air LBSs.

Initially, the test setup and procedure are descried. Then results from 580 interruption tests with five different nozzle geometries are presented, determining the minimum air flow required for successful interruption.

II. EXPERIMENTAL

A. Test Switch

Fig. 1 shows the test setup and Fig. 2 the contacts and nozzle arrangement in detail. The contacts are made of an arc resistant copper-tungsten alloy, whereas the nozzle is made of polytetrafluorethylene (PTFE). The contact pin is 6 mm in diameter and penetrates 60 mm into the female or tulip part in closed position. Five nozzles with various lengths L and inner diameters D were tested. The parts have a simple, axisymmetric design and are easy to replace.

The test setup uses a spring mechanism to open the contact. After the spring has been charged an electromagnet holds the movable contact in place until the control current in the magnet is interrupted. This way of releasing the pin contact is reliable and precise. Moreover, the contact opening can be synchronized with the voltage waveform making it possible to predetermine the contact gap x (see Fig. 2) when the first current zero (CZ) crossing occurs.

The force provided by the spring, and thereby the contact velocity, can be adjusted by changing the compression of the spring. The spring accelerates the pin contact for the first 60 mm, that is exactly until the pin and tulip separate. From then on the pin moves with almost constant velocity. Arcing wear causes some variation in the friction, yielding some randomness in the contact movement. It is found that the contact position at the first CZ can be preset with an accuracy of within ±5 mm.

A reservoir of compressed air provides the air blow during interruptions. When the switch is in closed position, the contact pin plugs the air outlet. As the pin leaves the tulip contact during

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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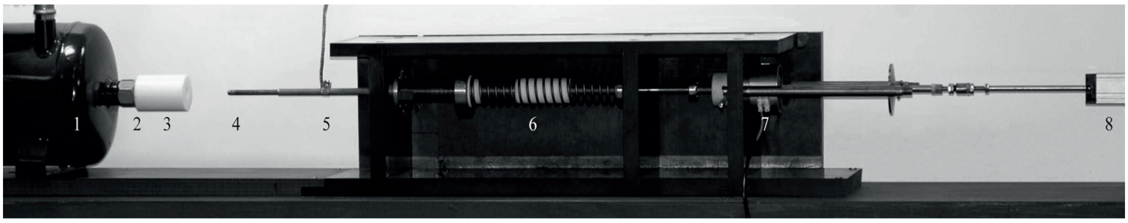

Fig. 1. Test switch. The numbered parts are 1. Compressed air reservoir (connected to the high-voltage supply circuit), 2. Tulip contact, 3. Nozzle, 4. Pin contact, 5. Connection to load circuit, 6. Spring drive mechanism, 7. Electromagnet release mechanism, and 8. Position transducer.

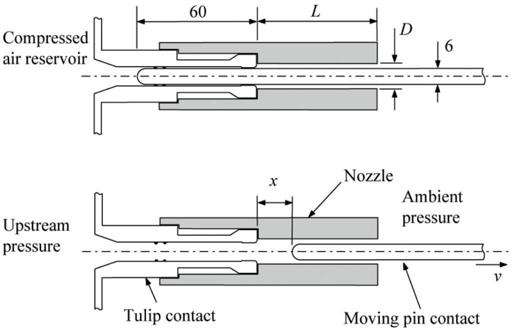

Fig. 2. Axisymmetric contact and nozzle geometries in closed position (upper drawing) and shortly after opening (lower drawing). L and D are the length and inner diameter of the nozzle, respectively. The contact position is x. Dimensions are in millimeters.

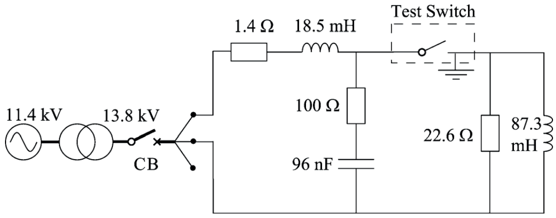

Fig. 3. High-voltage test circuit. The impedances of the system and transformer are incorporated in the component values shown. The circuit breaker (CB) is controlled from the laboratory and connects and disconnects the test circuit from the power source.

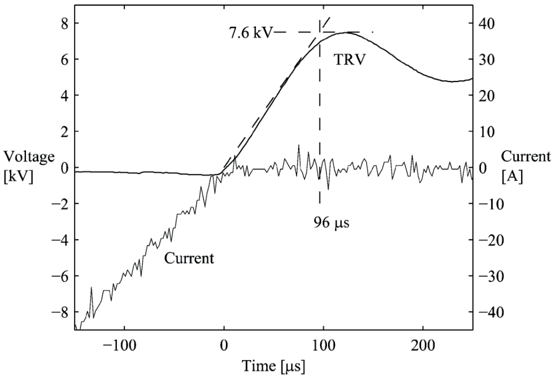

Fig. 4. Typical unfiltered measurements of current and TRV from an interruption experiment. Only a 400 μs time interval near CZ is included. The 7.6 kV amplitude and 96 μs rise time are the parameter values defined by the IEC for the 24 kV/630 A class.

opening, compressed air is released through the nozzle and blows on the arc. The volume of the air reservoir is sufficiently large for the pressure drop through the nozzle, usually referred to as upstream pressure, to remain virtually constant during the few power cycles an interruption lasts. By changing the air pressure in the reservoir, different air flow rates are obtained.

This setup allows for current interruption experiments for different nozzle lengths and inner diameters, while varying the contact velocity, upstream pressure, and position of the first CZ independently of each other.

B. High Voltage Circuit

Fig. 3 shows the high-voltage circuit used for the interruption tests. The circuit is a single-phase version of the "mainly active load test duty" type test of the LBS standard issued by IEC. The component values are set to give a transient recovery voltage (TRV) that in the first and critical 100 μs is nearly identical to that specified by the standard for the 24 kV/630 A class. (As shown in a separate paper [3], the initial part of the TRVs for the entire MV range of LBSs can be created with a source voltage of only 13.8 kV.) Hence, the present experiments primarily address the thermal phase of the current interruption process. Dielectric re-strikes are hardly a concern for typical LBS designs.

The circuit is grounded on the load side of the test switch, which is possible since there is no other grounded point on the secondary side of the laboratory transformer. The TRV between the contacts is measured with a capacitive voltage divider and current with a Hall effect current transducer. A second voltage divider with a range only up to 350 V is used to accurately determine when the CZ occurs. A resistive transducer to the far right of the test switch in Fig. 1, measures the position of the moving contact as a function of time. All these measurements are transmitted via optical fibers and fed into an 12 bit resolution transient recorder with a sampling frequency of 5 MHz. The static pressure in the air reservoir is measured with a high precision (accuracy better than 0.01 bar) pressure sensor before each test.

C. Procedure

Initial tests with different upstream pressures using a $L = 30$ mm long and $D = 9$ mm wide nozzle indicated that an upstream

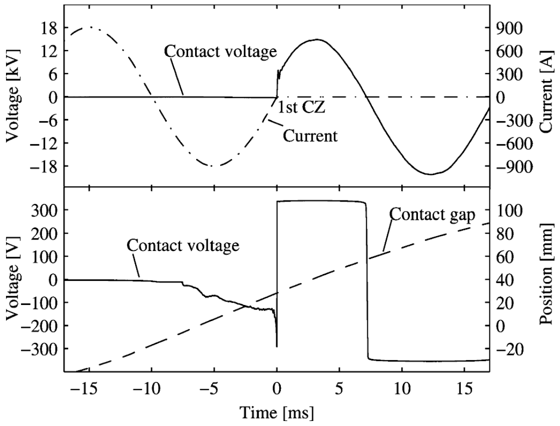

Fig. 5. Contact travel curve and current and voltage waveforms for a typical example of a successful interruption where the arc is quenched and current interrupted at the first CZ after contact separation. The contact voltage measurement in the lower graph is obtained with a voltage divider that has a limited range; it saturates at voltage amplitudes of around 350 V.

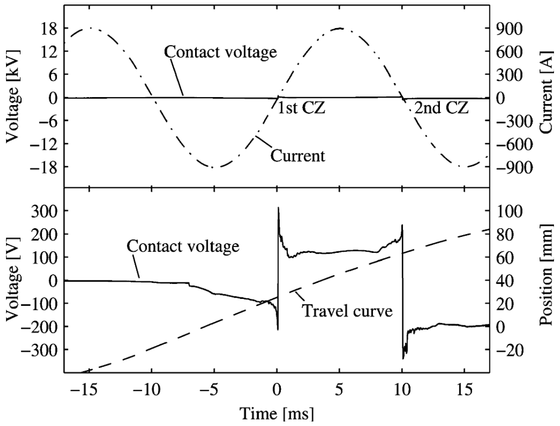

Fig. 6. Contact travel curve and current and voltage waveforms for a typical example of a failed interruption where the arc re-ignites both after the first and second CZ.

pressure in the range 0.2–0.4 bar was needed for successful interruption. Therefore, the systematic investigation started by using this nozzle size and 0.3 bar upstream pressure. In subsequent test series nozzle lengths of $L = 15$ mm and $L = 60$ mm with diameters of $D = 9$ mm were applied. For $L = 30$ mm test series with two other diameters, $D = 8$ mm and $D = 10$ mm, were also run.

For each upstream pressure 20 interruption tests were performed. The release of the pin contact was synchronized with the current waveform and evenly distributed over the 10 ms long time span of a half cycle. With a contact velocity of around 5 mm/ms, this results in a fairly even distribution of the contact position at the first CZ, in the range 0–50 mm.

For each nozzle size the upstream pressure was increased in steps of 0.05 bar, staring from 0.3 bar. This procedure continued until no further improvement of the current interruption capability was observed. After this, the upstream pressure was decreased below 0.3 bar, until all interruption attempts failed.

A failed interruption causes substantial more contact and nozzle wear than a successful one. Therefore, the test series with higher upstream pressure were carried out first, keeping the nozzle and contacts close to original condition longer. The nozzles were not replaced. The surface of the contact was regularly inspected and smoothened with a fine sandpaper.

III. RESULTS

A. Examples of Measurements From Typical Experiments

Fig. 4 shows measured current and TRV waveforms from a 400 μs long time interval around CZ from a typical interruption experiment. IEC specifies that for the 24 kV/630 A case the first peak of the TRV should have a rise time of 96 μs and an amplitude of 7.6 kV. As can be seen, this requirement is met.

Figs. 5 and 6 present data recorded from typical successful and failed interruption experiments, respectively. The upper part of the figures shows the voltage across the contacts and the current, whereas the lower part contains the contact travel curve (i.e., the pin contact position as a function of time) and the contact voltage recorded with a different voltage divider, measuring only from -350 to $+350$ V. The time axis is adjusted so that $t = 0$ corresponds to the first CZ after contact separation. The figures show that the pin contact in these cases separates from the tulip contact at about $t = -7$ ms as an arc voltage starts to build up. At $t = 0$ when the first CZ occurs and current is interrupted in the case shown in Fig. 5, the contact gap is 27 mm. In the case of the successful interruption, it can be observed that the contact voltage immediately after has a first peak as specified by the standard (shown in Fig. 4).

In Fig. 6 the arc re-ignites both at the first and second CZ, and current continues to flow. The amplitude of the arc voltage is between 100 and 200 V for most of the time after the failed interruptions, somewhat larger in the second half cycle since the arc length increases.

B. Interrupting Capability at Different Contact Positions and Upstream Pressures

In Fig. 7, the results of a large number of interruption tests with different nozzle lengths (the parameter L in Fig. 2) are presented, as a function of the contact position (the parameter x in Fig. 2) at CZ for different upstream pressures. Fig. 8 shows similar plots, but with the nozzle inner diameter (the parameter D in Fig. 2) being varied. Note that both figures contain the results for the L = 30 mm and D = 9 mm experiments, so these are for the sake of comparison shown twice.

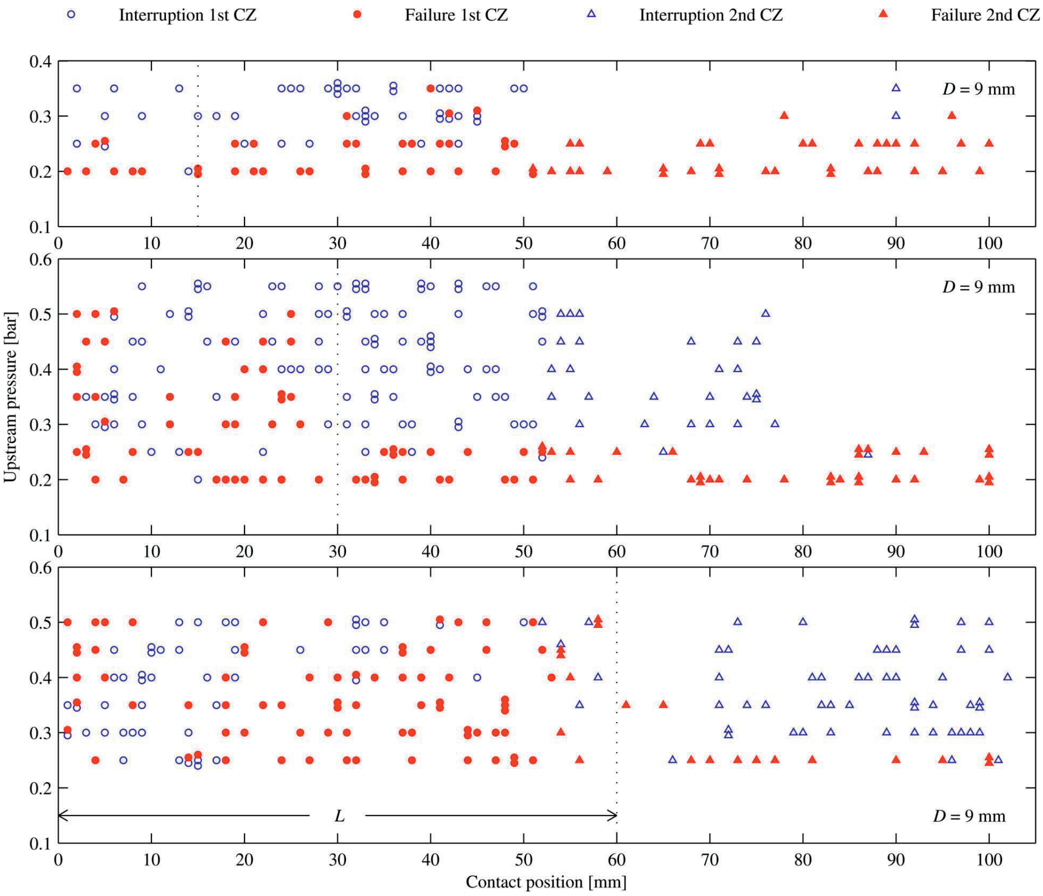

Fig. 7. Results from current interruption experiments with different upstream pressures and for nozzle lengths of 60 mm (lower), 30 mm (middle) and 15 mm (upper), as indicated with the dotted lines. The nozzle inner diameter is in all cases 9 mm. The outcome of every interruption attempt, successful or failed, both at first and second CZ, are included and plotted as a function of the contact position. When two or more experiments happened to occur at the same pressure and contact position, some of the symbols are for reasons of clarity shifted a little in the vertical direction.

In both Figs. 7 and 8 a successful interruption is marked with an open symbol in blue, and an interruption failure with a filled red symbol. Circular symbols are for the first CZ and triangular symbols for the second CZ. Each current interruption experiment can thus have three different outcomes:

- Successful interruption at first CZ. Marked with an open blue circle.
- Failed interruption at first CZ, then successful interruption at second CZ. Marked with a filled red circle and an open blue triangle separated by approximately 50 mm (contact speed is around 5 mm/ms and the CZs are 10 ms apart).
- Failed interruption at both first and second CZ. Marked with a filled red circle and a filled red triangle separated by approximately 50 mm.

Hence, each test series of 20 shots gives 20 circles and as many triangles (filled and unfilled) as there are filled red circles.

It is clear from these experiments that the interruption capability is better outside the nozzle. This is particularly evident when considering the middle and lower parts of Fig. 7. For upstream pressures of 0.3 bar or greater, all the filled red circles signifying failed interruption at first CZ are here located to the left of the dotted line indicating the nozzle length. The same applies for the upper curve in Fig. 8. Above a certain upstream pressure, interruption failures occur almost only when the CZ comes while the contact pin is still inside the nozzle.

For the 60 mm long nozzle some of the second interruption attempts (i.e., at the second CZ after contact separation) take place while the contact pin is still inside the nozzle. Several of these fail, as indicated with the filled red triangles between $x = 50$ and $x = 60$ mm in the lower part of Fig. 7. However, for the majority of the tests the second CZ comes when the contact pin is outside the nozzle (i.e., for $x > L$), and these do in nearly all cases result in successful interruption as long as the upstream pressure is above a certain level.

The magnitude of the upstream pressure is obviously crucial to the interrupting capability of this setup, and of far greater importance than the length and inner diameter of the nozzle. For upstream pressures of 0.3 bar and above, the chances for a suc-

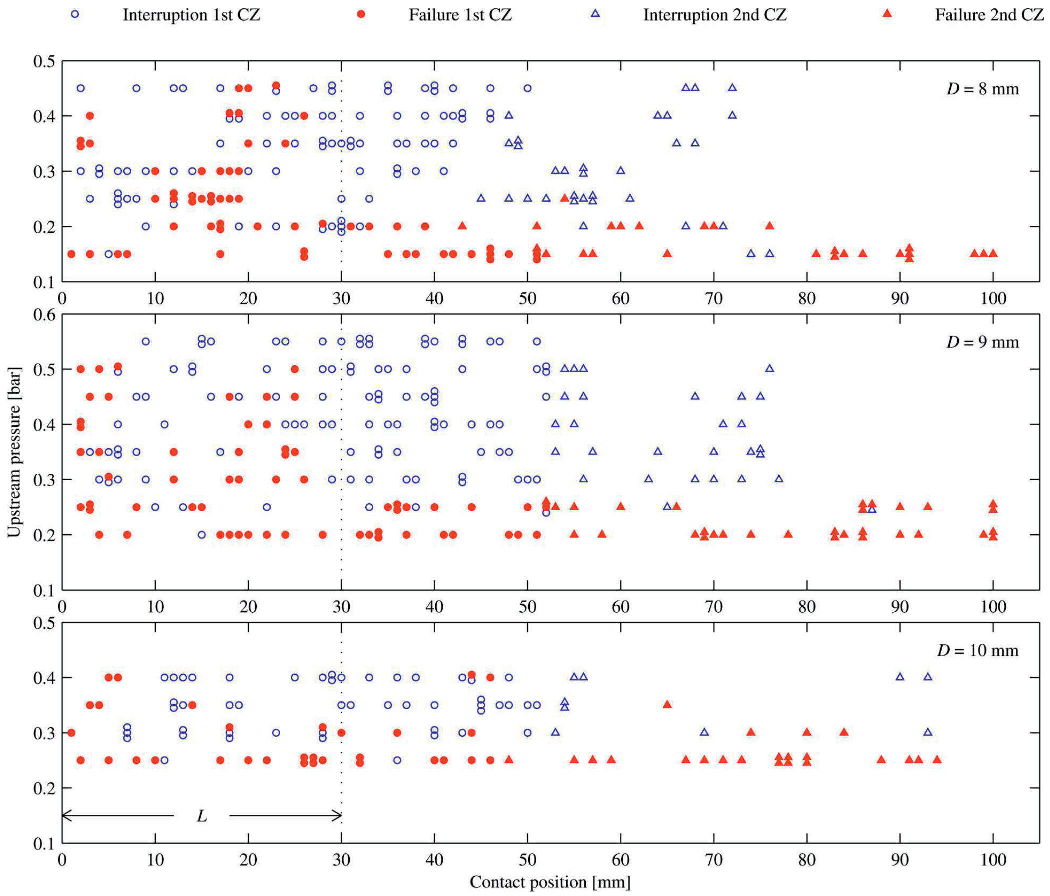

Fig. 8. Results from current interruption experiments with different upstream pressures and for nozzle inner diameters of 10 mm (lower), 9 mm (middle) and 8 mm (upper). The nozzle length is in all cases 9 mm, as indicated with the dotted lines. The outcome of every interruption attempt, successful or failed, both at first and second CZ, are included and plotted as a function of the contact position. When two or more experiments happened to occur at the same pressure and contact position, some of the symbols are for reasons of clarity shifted a little in the vertical direction.

cessful interruption in the first or second CZ are good as long as at least the second CZ comes when the pin contact is outside the nozzle. Otherwise the nozzle length seems to be of minor importance. Reducing the inner diameter of the nozzle from 10 to 8 mm appears to improve the interrupting capability somewhat. These findings are further illustrated in Fig. 9 which shows the percentage of successful interruptions for the 20 tests that were carried out for each nozzle length and diameter combination. An interruption test is here considered successful irrespective of whether the current was interrupted at the first or second CZ.

Again, the interrupting capability obviously depends greatly on the upstream pressure and to a much lesser extent on nozzle length and inner diameter, even though a narrower nozzle brings some benefits at low upstream pressures. An excessive nozzle length is however not a good solution as even a high upstream pressure some times gives failed interruptions if both first and second CZ occur while the contact pin is inside the nozzle. This comes out in Fig. 9 as success rates for the $L = 60$ mm tests of only 90–95 %, even at high pressures.

Dielectric re-ignitions were never observed in this investigation. Unsuccessful interruptions were always characterized by current starting flowing again within a few microseconds after CZ, signifying that a thermal re-ignition occurred. Successful interruptions were observed even for contact gaps as small as 2 mm. With the first peak amplitude of the TRV of 7.6 kV (see Fig. 4) this means that the average electric field across the gap reached as high value as approximately 3.8 kV/mm, without causing a re-ignition of the arc.

IV. DISCUSSION

The contact velocity during opening of a LBS is related to the type test requirements. These include withstanding a lightning impulse across open contacts. For the 24 kV level this typically implies that the gap across fully opened contacts must be in the range 100–150 mm for air insulated devices installed in metal enclosed switchgear. Moreover, a typical LBS is designed to interrupt the current in the first or second (or sometimes third) CZ, and at the latest when the contacts are approaching the fully

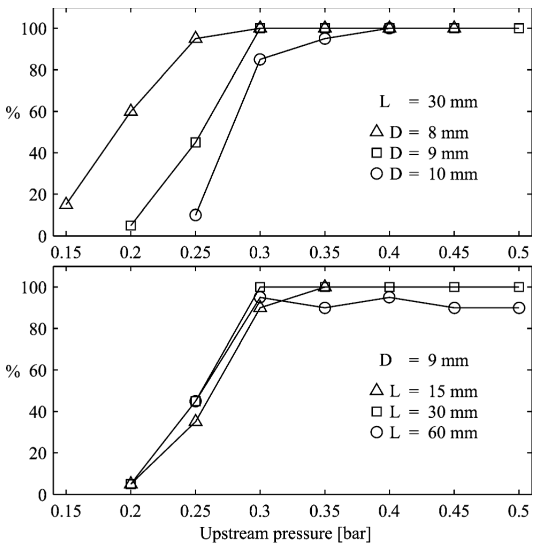

Fig. 9. Percentage of successful interruptions as a function of the upstream pressure for all test series.

open position. This infers a contact velocity during opening of typically 4–5 mm/ms. Hence, the contact travel characteristics of the test setup are comparable to that of real devices.

Concerning nozzle and contact geometries, the test switch is of a very simple, axisymmetric design, but still having the most important features of typical commercial devices, including using a PTFE nozzle and copper-tungsten contacts. The arrangement for generating the air flow, on the other hand, is completely different from commercially viable solutions. Often a piston and cylinder system is applied. However, for investigating the effect of a different air flow the used setup appears to be well suited.

As shown from the experiments the interruption capability is unpredictable if the pin contact is still inside the nozzle. The reason for this is probably that the air stream then is partly blocked by the pin contact. But once the pin moves out from the nozzle the flow rate will increase. However, it is still puzzling that the probability for interruption is not much increased when the upstream pressure is increased from 0.3 and to 0.5 bar, if only comparing when the pin in still inside the nozzle.

For upstream pressures lower than 0.3 bar, the smaller nozzle diameter performs better. The air stream is for all nozzle dimensions in this study limited by the 6 mm wide tulip contact. Without an arc, the flow rate and maximum flow speed will mainly be determined by the tulip dimension, since this is the most narrow part of this setup. For that case a 6 mm wide nozzle will then best keep up the speed of the air, while the larger the nozzle becomes, the slower the air will flow through the nozzle. However, when an electric arc is present, the nozzle part will to larger extent limit the air flow, and the discussion about air speed and flow rate through the system becomes more complex. A too wide nozzle will lead to lower air speed and creating too much space for the air to pass around the arc, not cooling it efficiently. On the other hand, a too narrow nozzle will not necessarily perform well either, since the arc then might clog the air flow. Therefore, the nozzle diameter needs to be carefully selected.

Changing the tulip diameter will have a large effect on the air flow through the nozzle. Both the speed of the air and the amount of air passing the nozzle per time unit are expected to be important for the interruption capability. Therefore, a continuation from the present study would be to investigate the influence of the contact diameter, and in addition with different nozzle shapes.

The TRV generated by the test circuit complies well with the type test requirements for the first hundred microseconds, but deviates considerably later on. The reason is essentially that a 13.8 kV and not a 24 kV voltage source is used. This is however not expected to influence the results. If an interruption fails, it does so in the thermal recovery part, long before the first peak of the TRV. A 24 kV source gives a maximum recovery voltage of around 33 kV, not 19 kV as in the present 13.8 kV circuit, but this maximum occurs several milliseconds after the interruption. For the second and critical CZ, the contact gap has then reached at least 50 mm, giving an average electric field of no more than 0.7 kV/mm, and consequently, no risk of a dielectric re-ignition.

In conclusion, the results obtained with the simple test switch and the applied high-voltage circuit are assumed to provide clues about critical design parameters for a MV LBS operating in air. In a commercial LBS the puffer arrangement needs to be carefully designed to provide a sufficient upstream pressure. Knowing the magnitude of the minimum upstream pressure may simplify the development of an LBS, and in particular reduce the need for electrical tests during the design phase.

V. CONCLUSION

The main findings from this parameter study of interruption of 630 A at 24 kV in atmospheric air using a simple test switch are as follows.

- The main challenge is to avoid thermal re-ignition immediately after CZ. Dielectric re-ignition is less of a concern.
- For the investigated contact and nozzle geometries, an upstream air pressure of at least 0.3 bar is crucial for obtaining a good interrupting capability.
- The interruption performance is not very sensitive to the length and inner diameter of the nozzle for this type of design.
- The length of the nozzle and contact pin velocity should be so that the second CZ after contact separation always comes when the contact pin is outside the nozzle.

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Erik Jonsson, photograph and biography not available at the time of publication.

Nina Sasaki Aarensen, photograph and biography not available at the time of publication.

Magne Runde, photograph and biography not available at the time of publication.

Paper III

Interruption in Air for Different Medium Voltage Switching Duties

Erik Jonsson and Magne Runde

***Abstract*—Air is an environmentally benign alternative to SF_6 for use in medium voltage load break switches. A simple, axisymmetric test switch has been used for empirical studies of the thermal phase of current interruption in atmospheric air. The purpose is to quantify how the pressure drop across the nozzle influences the interrupting capability at different rate of rise of the recovery voltages (RRRVs) and with different current amplitudes. Tests with pressure drops in the range 0.1 - 1.1 bar, RRRVs of 40, 80 and 160 V/μs, and currents of 300, 600 and 900 A were carried out. In general, the current that can be successfully interrupted is proportional with the pressure drop. Likewise, a steeper RRRV requires a proportionally higher pressure drop for the interruption to be successful. For compact air load break switches for the important 24 kV / 630 A class, it seems sufficient to provide a pressure drop of around 0.25 bar lasting for at least 20 ms to comply with the ”mainly active load” test type requirements.**

***Index Terms*—Current interruption, thermal interruption, medium voltage switchgear, load break switch, current zero, puffer, air**

I. INTRODUCTION

COMPARED to circuit breakers, load break switches (LBSs) are less powerful and are only intended to operate up to rated load conditions. In medium voltage (MV) distribution networks such devices are common, and numerous different types, designs and ratings exist. The majority of LBSs are rated for interrupting currents less than one kiloampere and have a relatively simple arrangement for creating sufficient cooling to quench the arc.

Metal enclosed or metal clad MV switchgear assemblies usually contain LBSs. Space is constrained, and SF_6 has thus been the preferred filling gas, due to its superior dielectric and current interruption properties. However, due to its high global warming potential, there is a strong demand for replacing SF_6. Air (or synthetic air) and CO_2 are two relevant alternatives. Their properties have been compared with SF_6 by many authors [1]-[6]. The obvious drawback with both these gases is the poorer current interruption capability, resulting in physically larger products for the same ratings, as well as more powerful gas blow arrangements. Hence, there is an obvious need for further improving LBSs with regards to size when using alternative gases like air or CO_2 [7]. Another alternative for a compact LBS is using vacuum breakers, but the cost becomes substantially higher.

The gas blow arrangement and nozzle design are crucial for the switching performance. A common solution is to link the contact movement with a piston that compresses a gas volume and is generating a gas flow for quenching the arc, a so-called puffer design. A central concept for any such device is the upstream pressure, which is the pressure that generates the gas flow through the nozzle during operation [8].

Little is found in the literature about design criteria for LBS regarding upstream pressure and geometrical dimensions of nozzle and contacts. For high voltage circuit breakers, in contrast, the relations between current, RRRV and critical flow rate through the nozzle have been the subject of several investigations [9], [10]. It is not straightforward to extrapolate these findings down to MV switchgear.

For the ratings concerned here, experience shows that the thermal interruption phase is the crucial part. Consequently, the gas flow during the last 100 μs before current zero (CZ) and the first tens of microseconds after CZ, is decisive for the interruption capability [11], [12]. The degree of difficulty is determined by the current amplitude (or more precisely its time derivative just before CZ) and the rate of rise of the recovery voltage (RRRV) [9]. The latter is in this work taken as the average steepness of the transient recovery voltage (TRV) in the first 20 μs after CZ.

If the arc is quenched and thermal re-ignition does not occur, the risk of having a dielectric re-strike later on is in general low in MV LBSs [11]. Consequently, dielectric re-strikes are not considered nor discussed any further in the present work.

A previous study addressed thermal interruption capability in air under different upstream pressures, nozzle geometries and contact movement for a certain MV LBS switching duty [11]. In the present work nozzle geometry and contact movement are kept the same, while the RRRV is set to 40, 80 and 160 V/μs and currents of 300, 600 and 900 A are applied. These settings cover the stresses specified by the International Electrotechnical Commission (IEC) for the thermal part of the interruption of the ”mainly active load” duty of the LBS type test for the entire MV range, i.e., 7 - 52 kV [13].

The upstream pressure of the air is varied over a wide range. A specially designed test switch is used, and all tests are performed in a directly powered MV laboratory. The purpose of the investigation, comprising about 400 tests, is to determine the required air flow - in terms of upstream pressures - for successful interruption under the considered currents and RRRVs. Such knowledge is useful when designing air LBSs.

Initially, the test switch, the test circuit and the procedures are briefly described.

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II. EXPERIMENTS

A. Test Switch

Fig. 1 shows the geometry of the contacts and nozzle area of the test switch. The upper part of the figure displays the switch in closed position, and the lower part in almost fully open position.

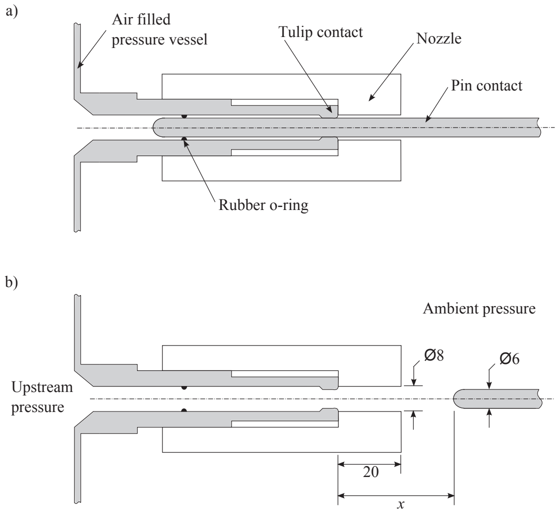

Fig. 1. The axisymmetric contact and nozzle geometries in closed position (a) and after opening (b). Grey parts are electrically conducting materials, and the white is PTFE. The outer parts on the pin and tulip contacts are made of arc resistant copper tungsten alloy. The time dependent contact position during operation is x. Dimensions are in millimeters.

The contacts are made of an arc resistant copper-tungsten alloy, whereas the nozzle is made of polytetrafluorethylene (PTFE). A pressure vessel with compressed air provides the air blow during interruptions. When the switch is in closed position, the pin contact plugs the air outlet. As the pin leaves the tulip contact during opening, compressed air is released through the nozzle and blows on the arc. The volume of the air reservoir is sufficiently large for the pressure drop through the nozzle (the difference between upstream pressure and ambient pressure) to remain virtually constant during the few power cycles an interruption lasts. By changing the air pressure in the reservoir, different air flow rates are obtained.

The operational force on the pin contact is provided by a spring. The compression of the spring can be adjusted and thereby also the velocity of the pin. The spring accelerates the pin contact the first 60 mm while the pin is still in contact with the tulip contact. From then on, as the contacts separate, the pin moves with almost constant velocity, typically around 5 mm/ms. The switch operation is synchronized with the supply voltage waveform, which allows for predefining the contact position at the first CZ, with reasonably good accuracy.

B. High Voltage Circuit and Measuring Equipment

Fig. 2 shows the high voltage circuit used for the interruption tests. The circuit is a single-phase version of the ”mainly active load test duty” type test of the LBS standard issued by IEC [13]. The circuit is grounded on the load side of the test switch, which is possible since there is no other grounded point on the secondary side of the laboratory transformer. The TRV is measured with a capacitive/resistive voltage divider and current with a Hall effect current transducer, both measuring with better than 1% accuracy. A resistive transducer measures the position of the moving contact as a function of time. All these measurements are transmitted via optical fibers and fed into a 12 bit resolution transient recorder with a sampling frequency of 5 MHz. The static pressure in the air reservoir is measured with a high precision (accuracy better than 0.01 bar) pressure sensor before each test.

In Fig. 3 waveforms from a typical experiment are shown. In this example, the current is interrupted and the steep TRV arises between the open contacts, shown in the upper part. In the lower part the pin contact traveling curve together with the voltage across the contacts are shown. This latter voltage measurement is done with a second voltage divider which only measures between -350 V and 350 V. As can be seen, the contact separates and the arc ignites approximately 8 ms before the first CZ. Moreover, the contact position x (see Fig. 1) is 30 mm when the current is interrupted.

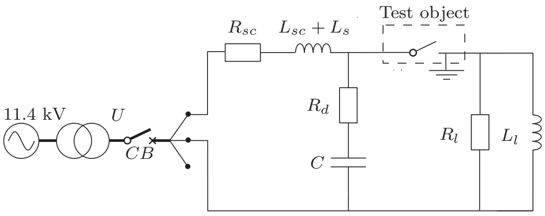

Fig. 2. The high voltage test circuit. The 11.4 kV voltage source is a high power MV distribution net. The short circuit impedances of the power system, R_{sc} = 1 Ω and L_{sc} = 8 mH are incorporated in the circuit diagram. The circuit breaker (CB) is controlled from the laboratory sequencer and connects and disconnects the test circuit from the 11.4 kV net.

More detailed information about the properties of the circuit, and how to set the different TRVs can be found elsewhere [14].

C. Circuit Settings

To investigate the minimum required upstream pressure at various currents and RRRVs, interruption experiments with three different currents, 300, 600 and 900 A, and three different RRRVs were carried out. For each current, C and R_d were adjusted until the RRRV in the crucial first 20 μs became 40, 80 and 160 V/μs respectively. Fig. 4 shows the initial parts of the TRVs of the nine circuits, and Table I lists the corresponding circuit component values.

The intention was to find circuit settings with linearly rising TRVs, which could be described with a single RRRV value, in the relevant time interval. This was done by carefully tuning the impedance values in the circuit, first by using a simulation tool (ATPDraw), and second by testing in the laboratory until a satisfactory result was found. As can be seen in Fig. 4, the shape and rate of rise of the recovery voltages are fairly similar for the three currents.

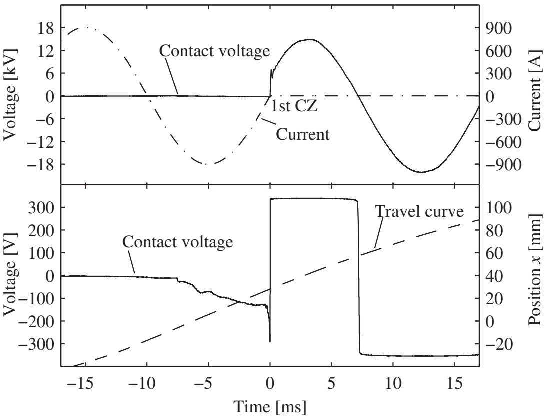

Fig. 3. Contact travel curve and current and voltage waveforms for a successful interruption where the arc is quenched and current interrupted at the first CZ after contact separation. When the contact position x crosses 0 mm, the contacts separates from each other and the arc voltage start to build up. Time is set to zero at the first CZ.

TABLE I
CIRCUIT PARAMETERS AND RESULTING CURRENTS AND TRVS

Circuit component values						Current and TRV	
U [kV]	L_s [mH]	L_l [mH]	R_l [Ω]	C [nF]	R_d [Ω]	I [A]	$RRRV^{(*)}$ [V/μs]
6.9	38.7	180.2	15.1	250	213	300	40
”	”	”	”	62	347	”	80
”	”	”	”	18	589	”	160
13.8	20.3	107.0	17.6	432	100	600	40
”	”	”	”	230	250	”	80
”	”	”	”	30	350	”	160
13.8	12.5	38.7	11.6	672	70	900	40
”	”	”	”	314	175	”	80
”	”	”	”	48	297	”	160

$^{(*)}$Approximate values. See the measured curves in Fig. 4.

D. Procedure

In a previous study of MV load current interruption using essentially the same experimental setup it was found that the interruption capability was largely unaffected by the position of the pin contact, as long as it was outside the nozzle (corresponding to $x > 20$ mm in Fig. 1) [11]. If the first CZ came inside the nozzle the switch easily re-ignited, but had a second and much better chance at the second CZ 10 ms later which then came outside the nozzle. (The contact pin travels about 50 mm during a half cycle.) Moreover, if the switch failed to interrupt when the first CZ came well outside the nozzle, it was unlikely to interrupt also at the second CZ.

Consequently, for determining interrupting capability at different currents and RRRVs, which is the aim of the present study, it is sufficient to only consider cases where the first CZ takes place outside the nozzle. Little new information is obtained by also including the second CZ outside the nozzle in the investigations. (Either the switch has already interrupted or it has failed and is likely to fail for a second time.)

Hence, in the tests the contact movement was set to always start at the same point on the voltage waveform and at a point giving the first CZ outside the nozzle. The actual pin contact position at CZ was in each test accurately determined from the current waveform and the travel curve. A scatter of around 10 mm was observed, attributed to inaccuracies in the contact release mechanism and to some differences in the contact movement friction. Only tests where the CZ occurred in the interval from $x = 30$ mm to $x = 45$ mm (see Fig. 1) were included in the subsequent analyses. Hence, by discarding experiments where CZ occurred outside of this interval, it is believed that a sufficient clearance (10 mm) from the nozzle was obtained, and secondly, that interruptions at the second CZ outside the nozzle ($x > 50$ mm) were excluded.

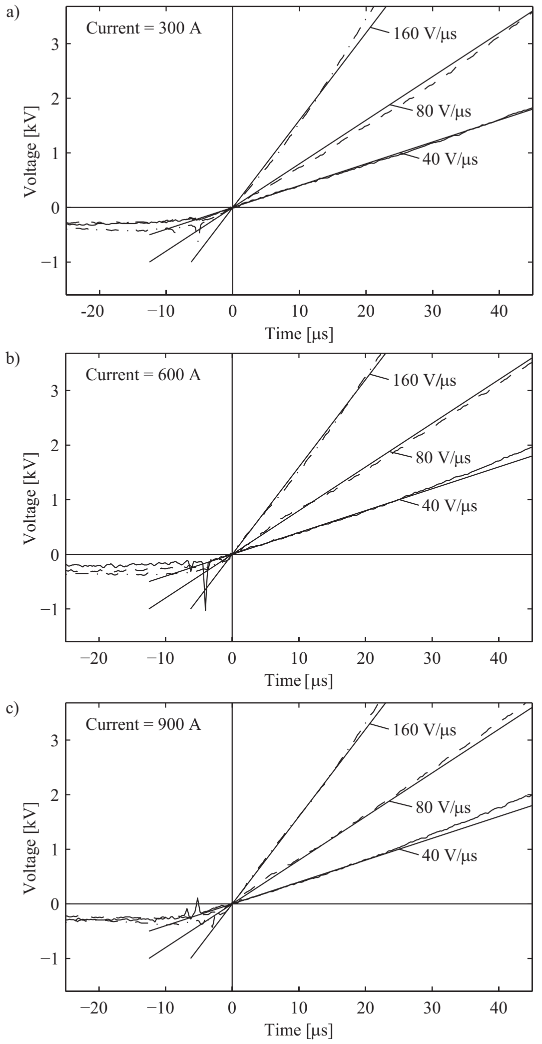

Fig. 4. Measured TRV curves for the nine different circuit settings presented in Table I. Only the relevant time range of the TRV for thermal interruption close to CZ is shown. In a) the current was 300 A for all three TRV curves and in b) and c) 600 and 900 A, respectively. The straight lines indicate the constant RRRVs of 40, 80 and 160 V/μs, for easy comparison with the measured TRV curves.

An advantage of only studying interruption in this interval is that the arcing time for experiments where the interruption fails can be limited. When doing many tests with the same setup evaporation of nozzle and contacts may become a problem. If both the first and second CZ outside the nozzle were included in the study, the wear rate would more than double. Thus, to reduce wear, the laboratory circuit breaker was set to trip a few milliseconds after the first CZ outside the nozzle.

Between each test the contacts and nozzle were taken apart and inspected. The tip of the pin contact and the surface of the tulip contact were polished with a fine sandpaper, and the nozzle was replaced approximately every 30 tests. The PTFE nozzle appeared clean after each test but the arc evaporated some polymer. This could mostly be seen close to the tulip contact where the nozzle diameter typically had increased by 1 mm before it was replaced. At the outlet region of the nozzle less material evaporated.

For each of the nine circuits the interruption experiments started with a few pre-tests in order to obtain a rough estimate of the upstream pressure where some tests will fail and some succeed. At this pressure the first series of 10 interruption tests was carried out. The upstream pressure was then increased in steps until 10 out of 10 tests became successful, and then afterwards decreased until less that 3 out of 10 succeeded. The difference between each tested pressure was 0.03 bar for the series with pressure drop below 0.3 bar, 0.05 for the intermediate series and increased to 0.1 bar for the highest current and steepest TRV.

III. RESULTS

Fig. 5 shows the experimental results, that is, the number of successful interruptions in each test series of 10 as a function of current, RRRV and pressure drop. (Note the different scale on the vertical axes.) The overall result is, as expected, that interrupting capability increases with increasing pressure drop, and that the interruption becomes more demanding as the recovery voltage becomes steeper and at higher currents.

The effect of varying the upstream pressure is quite dramatic. With a RRRV of 40 V/μs an pressure drop somewhere between 0.09 and 0.12 bar is necessary to securely interrupt 300 A, whereas interrupting 900 A bar requires 0.30 - 0.35 bar.

For the 300 A and 600 A series the transition from all failed to all successful interruptions is quite narrow. Thus some kind of a threshold or critical pressure drop seems to exist in these cases. For example, at 300 A and 160 V/μs a modest increase from 0.21 to 0.27 bar increases the success rate from nil to 10 out of 10.

The 80 and 160 V/μs experiments with 900 A show a wider transition. In these series two interruptions were successful at 0.3 and 0.6 bar, respectively, but a full 10 out of 10 success rate was not obtained until the pressure drops were almost doubled. Since this was a new trend, not seen at the lower currents, two extra series were run at 900 A and 80 V/μs, confirming the results. One extra series at 0.4 bar for the 900 A and 40 V/μs experiment was also added and confirmed a similar trend as for that lower currents.

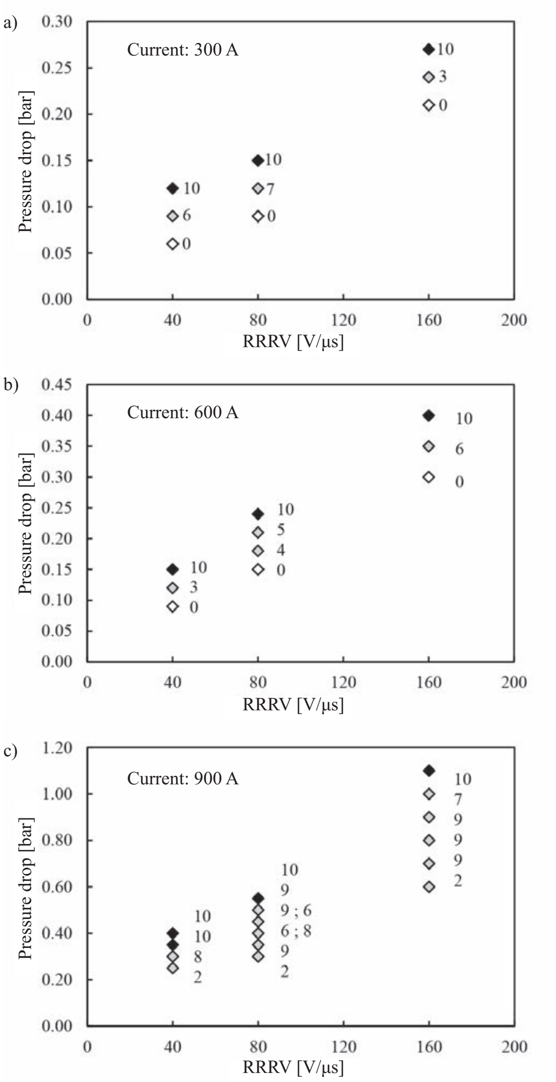

Fig. 5. Results from interruption experiments, a), b) and c) show the 300 A, 600 A and 900 A series, respectively. For every tested upstream pressure, 10 experiments were performed. Beside each symbol the number of successful interruptions is given. Black filled symbol means all experiments were successful, white all failures and grey means something in between.

For all series the assumption that only the shape of the TRV in the first 20 μs is important for these kind of experiments proves to be true. For all the failed tests at all the nine different circuits, the TRV collapsed within the first 10 μs, and the current then increased rapidly to its original sinusoidal curve form.

IV. DISCUSSION

Evaporation of the PTFE caused the nozzle diameter to increase somewhat during the experiments. However, the nozzles were frequently replaced, and there are no indications that a new nozzle performed differently from that being replaced. Hence, it seems unlikely that nozzle wear influenced on the results. The same applies for the contacts. Some arc erosion was observed, but the contacts were carefully cleaned and their surface condition remained essentially constant. The dimension changes were minute.

Whether a current interruption is successful or not depends on a multitude of physical parameters and experimental conditions, of which many are subjected to large statistical variations. Hence, the reproducibility of current interruption experiments is in general poor, and results often scatter substantially. In the present work 10 tests were done for each parameter set. From a statistical perspective this is not much. However, when considering the outcome of the entire test program, the results appear consistent. None of the 37 series yielded results in disagreement with the rest. There are no obvious peculiarities. A clear pattern of how the amplitude of the pressure drop affects the interrupting performance emerges.

Fig. 6 summarizes the findings by showing the required pressure drop for 10 successful interruptions as well as estimated 50% probability curves for the three different currents. All three parameters considered: current, RRRV and pressure drop are clearly of great importance.

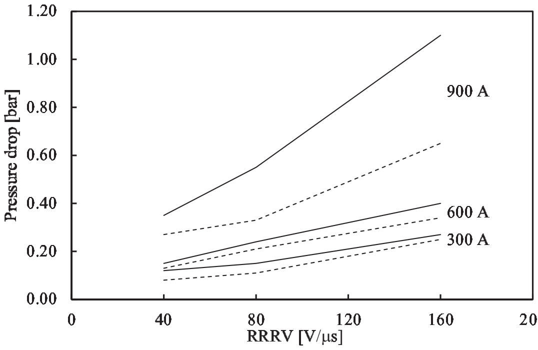

Fig. 6. The solid lines show minimum pressure drop required for 10 successful interruptions (out of 10 tests) as a function of RRRV for three different currents. The broken lines under each solid line are the estimated 50% probability curve for interruption for each current. The curves are based on the results presented in Fig. 5.

Whether a thermal re-ignition occurs is to a great extent believed to be determined by a race between heat generation and cooling in the contact gap in the immediate vicinity of CZ. Most of the cooling power is here provided by cold air blown into the contact gap. To the first approximation, the air mass, volume and speed are proportional to the pressure drop, as is the cooling power.

Concerning heat generation in the contact gap, the situation differs before and after CZ. Before CZ the arc is burning and the heating power is the arc voltage multiplied by the current. If the arc voltage is assumed constant, the heat generated before CZ becomes proportional to the current and arcing time. Consequently, increasing the pressure drop is expected to lead to a similar increase in the cooling power and thus also in the current that can be interrupted, all other factors kept constant.

After CZ the arc has quenched, but a small residual current, the so-called post arc current is flowing for a short while, presumably several microseconds. Hence, the heating power is now the TRV multiplied by the post arc current. Assuming that the post arc current is constant, the heating power at any instant is proportional to the TRV at that instant, and thus to the RRRV. Again, and by taking an approach analogous to that of the situation before CZ, increasing the RRRV is expected to require a similar increase in the pressure drop to successfully interrupt a certain current.

The outcome of the experiments is in reasonable agreement with these very simplified descriptions. As can be seen from Fig. 6, the current that can be interrupted is approximately proportional with the pressure drop, and secondly, a steeper RRRV needs a correspondingly higher pressure drop.

The relation between the interruption capability and pressure drop has be studied for circuit breakers. Various empirical relationships on the form $di/dt \propto p^{k_1}$ and $RRRV \propto p^{k_2}$ have been proposed. For high currents (requiring pressure drops over 10 bar) $k_1 = 0.5$ is reported, but for the present ratings no such data has been published [1], [15]. For k_2 values are given in the range 0.8 - 1.2 [10], but again, this values concern high voltage circuit breakers.

If a similar approach is applied here, k_1 around 0.8 and k_2 around 1.2 fit reasonably well with the results. For low current and RRRV values this empirical method becomes problematic. Below a certain current no pressure drop is needed regardless of the RRRV. Similarly, at any given current, if the RRRV is below a certain value no active blowing is necessary to interrupt. For the present data a linear relationship seems to describe the interruption capability in a better manner.

In the 300 and 600 A cases it is found that only a modest rise in pressure drop is decisive for whether none or all 10 interruptions become successful. For the 900 A series with RRRVs of 80 and 160 V/μs this transition extends over a wider range. From the first interruption is observed and until all 10 are successful, a doubling of the pressure drop is necessary. This is so also for the series at the lowest pressure drops, but here it is believed to just be a result of large percentage changes between each tested pressure.

These observations leave the impression that the test switch design and dimensions are better suited for interruption of 300 and 600 A than for 900 A. At higher currents the arc cross section becomes larger, and clogging may limit air flow and cooling, thereby reducing the chances for a successful interruption. Increasing the overall dimensions of the nozzle and contacts would probably make the 900 A performance more predictable.

The "mainly active load" test circuit specified in the IEC standard gives different RRRVs for the different voltage classes, spanning from approximately 35 V/μs for the 7.2 kV class to around 120 V/μs for the 52 kV class [13]. (The RRRV is not explicitly given in the standard, and some freedom as to how the test circuit is made causes some variations in the RRRV.) The range of RRRV included in the present work thus covers the entire MV range of this part of the type test.

Also the range of the test currents included should be relevant, at least for LBSs for use in metal enclosed switchgear. These typically have current ratings up to 630 A. Some free-standing primary LBS are rated for higher currents, up to a few kiloamperes and thus beyond what is dealt with here.

The test switch deviates in many ways from typical commercial LBS designs. Instead of using a puffer arrangement to generate the air flow, a constant pressure reservoir is applied. Moreover, the dielectric design is clearly not optimized. On the other hand, the materials used in nozzle and contacts are the same as in commercial devices, as are the contact speed and travel distance.

All matters considered, it is believed that this simple axisymmetric test switch can provide clues about how the air pressure drop through the nozzle influences the interrupting capability of a compact LBS subjected to RRRVs typical for the type test; at least for currents up to the 630 A class and in a 1 bar ambient. Such generic knowledge is useful when designing commercial devices, and may reduce the need for expensive development tests in high voltage laboratories.

An interesting continuation of this work would be to analyze in more detail how the tulip contact and nozzle diameters affect the interrupting performance at different current and RRRV ratings. By changing these dimensions and doing more interrupting tests, it may - for example - be possible to clarify whether it is the amount of air blown onto the arc that matters most, or the air speed.

V. CONCLUSION

A simple, axisymmetric test switch has been used for empirical studies of the thermal phase of interruption of MV load currents in atmospheric air. Over most of the considered current, RRRV and pressure drop ranges, it is found that to the first approximation:

- The current that can be successfully interrupted increases proportionally with the pressure drop through the nozzle during opening.
- A steeper RRRV requires a proportionally higher pressure drop for the interruption to be successful.

For compact air LBSs for the important 24 kV / 630 A class, it seems sufficient to provide an pressure drop of around 0.25 bar lasting for at least 20 ms to comply with the "mainly active load" test type duty requirements specified by the IEC.

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Paper IV

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Paper V

Ablation-Assisted Current Interruption in a Medium Voltage Load Break Switch

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Abstract

Near an electric arc some polymers, known as ablation materials, change the properties of the arcing medium in a beneficial manner. The interruption capability for current interruption improves by increasing the pressure and the heat dissipation from the arc. The present paper studies medium voltage (MV) current interruption by ablation. In an MV test laboratory, current interruption experiments are carried out with polypropylene (PP) ablation plates. Both the current and transient recovery voltage are varied. The results reveal that the PP ablation has the potential to interrupt the thermal phase for all tested currents, up to 800 A. The dielectric strength in the arcing zone after the thermal phase is however poor, and dielectric re-strikes easily occur, causing the interruption to fail.

1 Introduction

Polymers that are exposed to the high temperatures of a nearby electric arc will decompose and release gases. The gases and vapours may change the properties of the arc. In switching equipment this can be used to improve the interrupting performance by selecting polymers that significantly increase the pressure and the thermal conductivity of the arcing medium at high temperatures. In such a context the polymers are usually referred to as ablation materials. In particular, a large release of hydrogen gas has been found to be a favourable property, presumably due to the good thermal conductivity of hydrogen [1] - [3].

Ablation materials are used in the walls of the arcing chamber of many low voltage breakers, but are far less common in medium and high voltage switchgear designs.

At the medium voltage (MV) level, typically 6 - 36 kV, load break switches (LBSs) in series with fuses are extensively used as an inexpensive alternative to circuit-breakers. The majority of LBSs are rated for currents less than one kiloampere. For devices installed in metal enclosed switchgear units, SF_6 has been the preferred interrupting medium (at least when disregarding the considerably more expensive vacuum interrupters).

This may change. From an environmental perspective it is clearly desirable to avoid using SF_6. Air, which is an obvious alternative, has poorer arc quenching properties and lower dielectric strength than SF_6, so air breakers become substantially larger in size. Hence, to make an air-filled LBSs compact and competitive, the design must be carefully optimized. Developing and including new features and working principles may be necessary. Introducing ablation materials has the potential to bring significant benefits, and is among the options that should be pursued.

A previous study indicated that polypropylene (PP) may be a feasible ablation material [3]. In a simple experimental setup an arc was ignited in a gap between fixed copper contacts, and two polymer plates were placed parallel to the arc, one on each side. The arc was quenched and the current was interrupted at its zero crossing. When using PP plates 2.7 times higher currents could be interrupted than when using plates of polytetra-fluoroethylene (PTFE), which is a polymer largely unaffected by arcs.

The present study is a continuation of this work. The parallel plate geometry of the ablation plates is kept, but now the initial part of the transient recovery voltage (TRV) and current amplitude are systematically varied over a range corresponding to what a typical MV LBS experiences.

Initially, the test switch, the laboratory setup and the experimental procedures are described. Then the results from 50 interruption tests are presented and discussed.

2 Experimental

2.1 Test Switch

An MV test switch is used for the experiments, see **Figure 1.** It is designed for both gas blow assisted interruption experiments and for interruptions with ablation. For a gas flow experiment, the gas flow comes from a pressurized vessel (filled to desired upstream pressure before the operation). Therefore the switch can also be operated without gas blowing.

For the present experiment an ablation setup is used instead of a nozzle. **Figure 2** is a photo of the ablation arrangement and the two contact members. Two ablation plates of PP (one on either side of the arcing area) are positioned with an 8 mm gap in between. The plates are square with a side length of 122 mm. However, as shown, only the length L_l (70 mm) of the plates is exposed to the arc. The pin contact is 6 mm in diameter and when the switch is fully open, the pin contact stops 125 mm (55 mm outside the ablation plates) away from the tulip contact. A holder of PTFE and two spacers keep the ablation plates in position.

When the test switch is in the closed position, the pin contact penetrates the tulip contact and simultaneously also plugs the outlet of the gas vessel. Both the tulip contact and the pin contact are made of arc resistant copper-tungsten alloy.

A spring drive mechanism provides the force needed to pull the contacts apart. By changing the compression of the spring, the velocity of the pin contact can be varied. The mechanism accelerates the pin rapidly while it is still gliding outwards inside the tulip. At the time the contacts separate, the speed is about 5 m/s and remains constant during the rest of the movement.

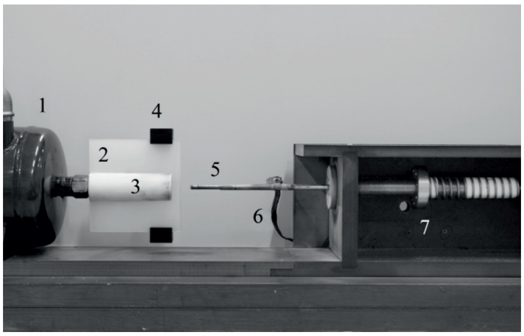

Figure 1. Central part of the test switch. The numbered parts are: 1. Compressed air vessel (connected to the supply side circuit), 2. Ablation plates, 3. Plate holder, 4. Spacer, 5. Pin contact, 6. Connection to load side of the circuit, 7. Spring drive mechanism.

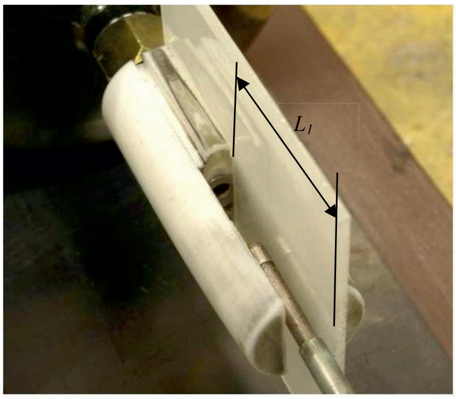

Figure 2. Ablation plate arrangement. One of the two PP plates is here removed to better show the arcing area between the plates. The pin contact is here about half way out on its travel path. The tulip contact is seen in the middle (pressed into the PTFE plate holder).

When the spring is charged an electromagnet holds the pin contact in place until the control current in the magnet is interrupted. The switch operation is synchronized to the supply voltage waveform. For example, the contact travel curve can be controlled such that the first current zero (CZ) crossing after contact separation takes place when the pin contact has reached 15 mm (within a few millimetres of accuracy). This makes it possible to repeat similar experiments many times.

2.2 High Voltage Circuit

The circuit, shown in **Figure 3**, is supplied from an 11.4 kV distribution grid, and for this case the circuit voltage *U,* is set by the laboratory transformer to 6.9 kV. The circuit breaker (*CB* in the figure) is used to connect and disconnect the power into test circuit. If the test switch fails to interrupt during an experiment, the circuit breaker is set to interrupt 20 ms afterwards. (Several disconnectors and earthing switches are omitted from the diagram.)

The circuit is similar to an MV LBS type test circuit ("mainly active load test duty"), prescribed by the International Electrotechnical Commission (IEC) [5]. The right-hand side contact (the pin contact in this case) is grounded to simplify the measurements of the TRV and the current. (This is possible in a single phase circuit and since the neutral point of the transformer is on a floating potential.) The voltage across the contacts is measured by a capacitive/resistive voltage divider and the current by a Hall effect current transducer. Measurement signals are transmitted via optical fibres into a transient recorder with a sampling frequency of 5 MHz.

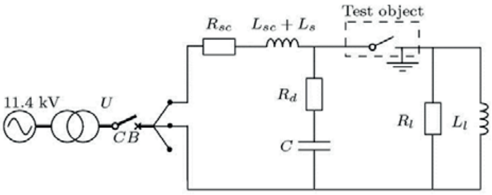

Figure 3. Single phase MV test circuit used for the experiments. The diagram shows the main parts of the power supply connection and the circuit impedances.

2.3 Circuit Interruption Characteristic

If a circuit interruption is simulated by a numerical circuit program (like ATPDraw) as an ideal switch, and compared to a real current interruption experiment, it will not exactly show the same result. The current will be almost the same, but the TRV will look somewhat different [4]. This has to do with the arc voltage and its interaction with the circuit, which varies for different LBS designs.

For IEC type tests, the TRV is not explicitly specified in the standard. The circuit is instead prescribed by the result from a low voltage test method of the circuit (the prospective TRV) [4]. However, since puffer and vacuum switches totally dominate the LBS market, the measured

TRV from a puffer or vacuum interruption (these two alternatives give similar TRVs), is often said to be the TRV associated to that specific type of test circuit.

For ablation-assisted interrupting, the interaction with the arc is different. Compared to a circuit simulation of an ideal switch, the measured TRV from an ablation experiment appears to be significantly easier. This means also that if the same circuit is interrupted with a puffer breaker or with an ablation breaker, the measured TRV (and arc voltage) will not be the same. As will be shown in the result section, the first peak of the TRV can be as much as 50% lower with an ablation breaker. This causes problems when comparing and characterizing the switching duties of the circuit.

For the present ablation experiment each circuit is first interrupted by a puffer breaker. From this test, the measured TRV together with the current, are used to describe the interruption characteristics of the circuit. This way it is possible to compare the presented ablation results, both to well-known type test conditions and to other puffer experiments.

Two parameters are used to describe the TRV shape: voltage of the first peak (U_p) and the envelope time (t_p). The rate of rise of recovery voltage (RRRV) is calculated as U_p / t_p. **Figure 4** shows current and voltage curves around CZ (at time equal zero) and how these two parameters are found.

Figure 5 shows the entire TRVs for different test circuits. Since the same system voltage is used for all circuits, the TRVs have similar shape, apart from the very first part. However, as a consequence of adjusting the first peak voltage, the phase angle of the current also changed. Therefore the CZ comes a bit later (related to the system voltage) for the circuits with higher first peak voltages.

2.4 Procedure

For every interruption experiment the test switch is given three chances (that is three CZs after contact separation) to interrupt the current before the circuit breaker disconnects the circuit. The third CZ always happens after the pin contact has reached its end position.

The outcome from a current interruption experiment is either success or failure. Therefore, the circuit parameters needed to be changed gradually, to make the test circuit more difficult or easier to find the interruption limits.

The ablation interruption study constitutes of two parts. In the first part, interruption tests with currents of 200, 400 and 800 A are performed. For each current, TRVs with three different first peak voltages; 2, 4 and 7 kV are tested, all with the same envelope time of 50 µs. For each such circuit setting four interruption tests are performed. However, if the test switch fails in all four interruption attempts, for instant with peak voltage of 4 kV, the 7 kV setting is not tested for that current.

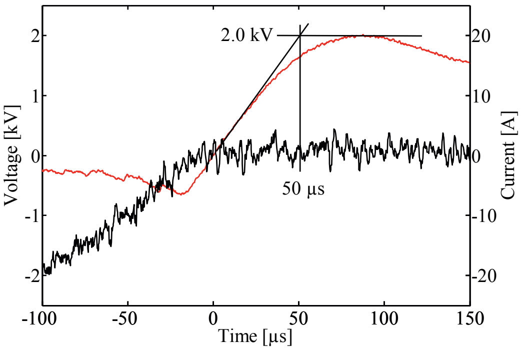

Figure 4. Typical current and voltage measurements around CZ (from a gas blow interruption). The red curve shows the contact voltage (called TRV after CZ at time 0), and the black curve is the current. Here the circuit gives a TRV with first peak voltage U_p = 2 kV and envelope time t_p = 50 µs.

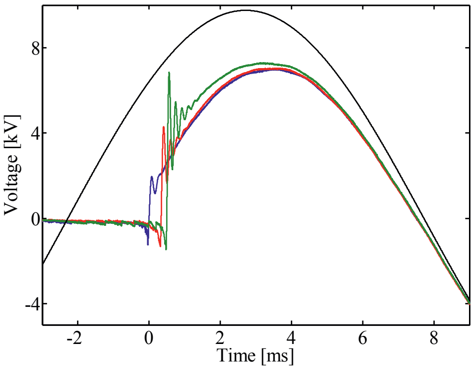

Figure 5. Shape of the TRVs for the different circuits used in the experiments. The black curve is the source voltage. After about 10 ms all three TRVs follow the same curve as the source voltage.

New ablation plates are used for every test, and the contacts are frequently cleaned and polished to maintain identical test conditions.

In the second part, the current is 400 A for all tests, and TRVs with different envelope times are tested. The first peak voltage is now kept constant at 4 kV. The first series is made with an envelope time of about 300 µs, followed by a series with gradually shorter envelope times until none of the four attempts are successful.

In addition, a contamination (reproducibility) experiment is made. A circuit with 180 A current, envelope time of 14 µs and with first peak voltage of 3 kV is used. Ten interruption tests are performed in a sequence with the same ablation plates. Between each test, one of the plates is photographed to show the degree of contamination (primarily by soot from burned polymer). The circuit is chosen such that it is likely that the current will be interrupted with clean plates, but still with some risk of failure.

Circuit Interruption Characteristic				Circuit Component Values					
I [A]	U_p [kV]	t_p [µs]	RRRV [V/µs]	L_s [mH]	L_l [mH]	R_l [Ω]	C [nF]	R_{sd} [Ω]	Results
	Part I								
200	2.0	50	40	10.1	155.1	40.0	80	198	4/4
200	4.0	50	80	23.2	131.9	34.0	32	297	2/4
200	7.0	50	140	38.7	151.7	17.1	16	494	0/4
400	2.0	50	40	4.92	71.5	21.6	126	150	4/4
400	4.0	50	80	13.5	65.8	17.1	72	297	0/4
800	2.0	50	40	1.91	27.7	14.1	148	120	0/4
	Part II								
400	4.0	308	13	7.86	76.0	18.6	2400	25	3/4
400	4.0	235	17	9.53	72.6	18.1	1200	50	1/4
400	4.0	174	23	11.4	69.2	17.6	600	100	1/4
400	4.0	100	40	11.4	69.2	17.6	182	125	0/4

Table 1. Circuit Settings and Interruption Results

3 Results

3.1 Interruption Capability

All interruption tests are summarized in **Table 1**, including the circuit interruption characteristics, values of the circuit components and the interruption results. The result column lists the number of successful interruptions out of four attempts. The table is divided into two parts, corresponding to the procedure explained above.

The results are that the circuits with first peak voltage of 2 kV, envelop time 50 µs, and up to 400 A are interrupted. For the circuit with 200 A current, the 4 kV peak voltages seem to be on the interruption limit for the switch. The data also indicate that circuits with longer envelope times are easier to interrupt (for the same first peak voltage and current).

The failed interruption experiments contain further information about the interruption capability. **Figure 6** presents current and voltage measurements from a failed interruption, here with 800 A current and with a first peak voltage of 2 kV. As can be seen, the current was almost interrupted in this example.

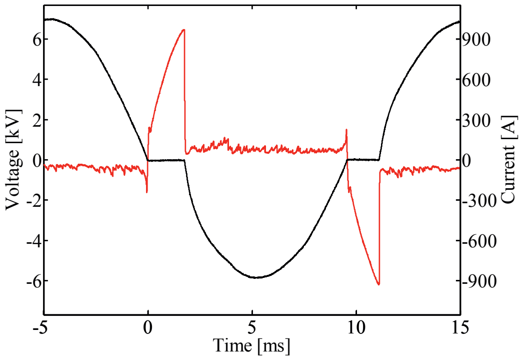

Figure 6. A failed current interruption experiment. The current is the black curve and the voltage between the open contacts is the red curve.

Exactly where on the TRV curve re-ignition may occur varies from time to time. However, all interruption failures in this study are due to dielectric re-ignition. For the circuit with the 7 kV first peak voltages, re-ignition occurs on the way up to the first peak, but it was still a dielectric failure. For almost all cases, the re-strike takes place somewhere between 4 and 6 kV.

3.2 Arc-Circuit Interaction

The ablation interruption process affects the arc voltage and thereby also the beginning of the TRV. When the arc voltage is increased, less voltage is left to oscillate on the supply side of the switch at the moment of current interruption. Due to this, also the first peak voltages in the beginning of the TRV will be lower [4].

In **Figure 7**, two interruption experiments of the same circuit are compared, one with gas flow from the pressure vessel, and one with the ablation arrangement. With the ablation setup, the arc voltage (before CZ) is almost 4 times larger, and consequently the first peak voltage becomes lower.

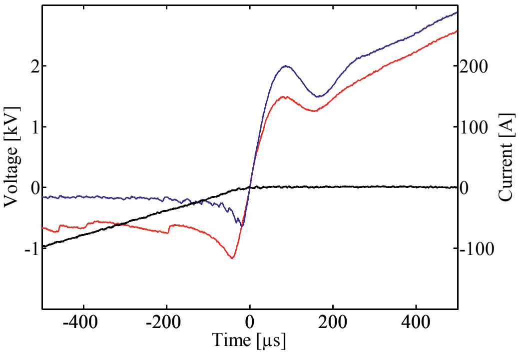

Figure 7. TRVs from the same circuit, interrupted both with gas flow (blue curve) and ablation (red curve). The current is apparently identical (a small difference can be found if the region around CZ is compared in detail).

The arc voltage also depends on the current, which is particularly obvious when the current is low. In **Figure 8**, the ablation interruption measurements from three circuits with different currents are compared. The 200 A current experiment gives a much larger arc voltage, compared to the 400 and 800 A experiments. However, for the same circuit the arc voltage can vary from time or time, but not as much as the difference between the curves in the figure.

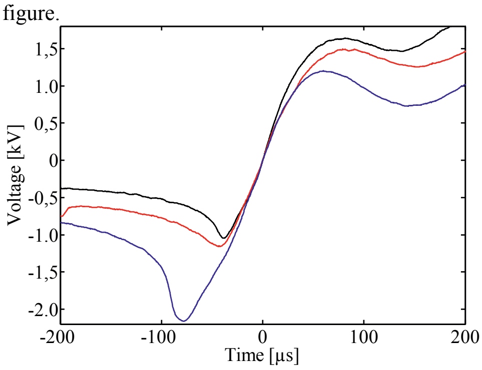

Figure 8. Contact voltages for three different ablation interruption experiments. The blue voltage curve refers to a 200 A circuit, the red to a 400 A and the black to an 800 A circuit. With gas flow interruption, all these voltage measurements would become lower (in absolute value) and also be more similar to each other.

3.3 Soot Contamination

The result from the soot-contamination experiment is shown in **Figure 9**. The plates become contaminated rapidly and the colour changes from semi-transparent to almost black during the ten interruption tests.

Out of the ten interruptions tests, no. 5 and no. 8 failed. This is not a clear trend, and it is not possible to determine if the risk for interruption failure increased during the tests.

4 Discussion

The main objective was to investigate the potential of using ablation-assisted current in an MV LBS application. The results show an impressive ability to interrupt the thermal phase (synonymous with quenching the arc). However, the ablation setup had difficulties with the TRV, which often re-ignites the arc. A solution to this problem could be to re-design the geometry of the ablation zone, and separate the contacts further apart. Therefore, ablation-assisted interruption seems to be a promising alternative for the MV LBS market.

This is the first published study about ablation interruption made with an MV type test circuit. Therefore the procedure, choice of geometry of the ablation area, and choice of test circuits are more or less a "best guess". However, considering the total outcome of the test programme, the results seem consistent and applicable within the scope of the study. None of the tests gave any unexplained issues which do not fit with the overall picture, and the results are a good starting point for further research.

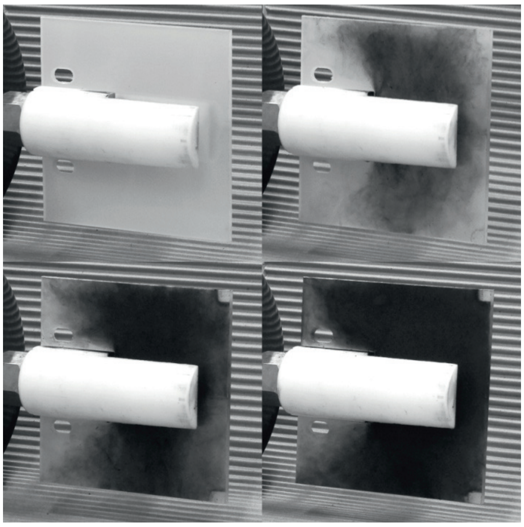

Figure 9. The same ablation plate, after 0, 3, 6 and 10 interruption tests. One of the two plates in the setup is removed when photographing to show the same side of the plate that was exposed to the arc during the tests.

Considering only the thermal interruption phase, polymer ablation appears to significantly increase the interruption capability. With increasing currents the polymer also ablates more and more, and the quenching ability appears to be self-regulating.

The RRRV at CZ does not seem to influence the result in this study. The limit for the thermal interruption capability has not been reached in the tests. Performing interruption tests with even higher currents and also varying the RRRV more are needed to determine the thermal interruption capability further. Also lower currents should be tested, since the ablation process might need some minimum current to actually start to influence the arc. Therefore an ablation switch might have difficulties interrupting smaller currents than in this study.

For ablation-assisted interruption the problems start a while after CZ, when the TRV reaches a critical amplitude. The ablation rate of polymer will rapidly decrease after the current is interrupted, and hot and contaminated gas remains in the arcing zone. Considering an experimental series with different currents, it appears that the dielectric strength builds up more slowly after CZ for increasing currents.

If ablation is considered for MV LBS, the dielectric properties in the arcing zone after current interruption need to be investigated more. Here, increasing the travel distance of the contacts or changing the geometry of the arcing area in some way could be considered and this may result in a satisfactory performance. The material properties might also be important for the dielectric recovery of the arcing zone. PP was chosen for this study since it gave the best current interruption performance in a comparison test [3]. That test was performed with very low TRV and high currents. Possibly a different conclusion will be reached regarding preferred material properties, if a more difficult TRV is used when comparing polymers.

To understand the arc-circuit interaction better, the current shortly before and after CZ has to be analysed in more detail. By measuring the currents in the arc, and in the capacitor branch of the circuit, better understanding could probably be achieved.

The soot experiment with only 10 interruptions was too short to yield a clear conclusion. However, considering how black the plates became before the last interruption, it was surprising that it managed to interrupt. This suggests that soot on surfaces of the plates does not influence the risk for dielectric re-strikes very much. This should be studied by prolonging the same type of test, but here there should be a larger number of interruptions until failures come more frequently.

5 Conclusion

The main findings from this work are as follows:

- The ablation test switch interrupts the thermal part of the current interruption to an impressive degree. This satisfactorily covers the need of what is typical for an MV LBS.
- The main problem is to avoid subsequent dielectric re-ignition. The present test switch has problems to withstand voltages higher than 4 – 5 kV.
- Compared to gas flow interruption, the ablation process greatly affects the arc voltage and thereby also the initial part of the TRV. It is important to pay attention to this when comparing ablation experiments with puffer LBS tests.

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6. Summary of Results and Conclusions

6.1 MV Laboratory Performance

A direct powered MV laboratory has been designed, built and tested. The test circuit is similar to a laboratory for a product type testing but more optimized for current interruption research and development on LBSs. The initial and crucial part of the TRV can be adjusted in a large range. The laboratory can imitate product type tests, rated from 7.2 to 52 kV, for any current up to about 1 kA.

The flexibility of the laboratory also makes it well suited for parameter studies. It permits investigations of current interruption, where both the current and TRV can be varied with high precision. For example, a test series can be performed where the rate of rise of the recovery voltage (RRRV) can be varied while the current is kept constant. Or similarly, tests can be done where the current is increased in small steps while keeping the TRV unaltered.

The circuit has proven to be robust, and at present is used for over 4000 current interruption experiments.

6.2 Gas Blow Current Interruption

The extensive experimental survey covers a great part of all MV LBS ratings. The results indicate that the current interruption capability increases almost proportionally with increasing pressure drop through the nozzle (at least up to 600 A). Likewise, increasing the RRRV requires a proportionally higher pressure drop for interruption.

The results in Fig. 6.1, shows the required upstream pressure drop at different RRRVs and currents (which directly can be compared to different product type test conditions, voltage and current ratings). This type of information is particularly useful for product development, both for developing completely new designs or when improving an existing LBS.

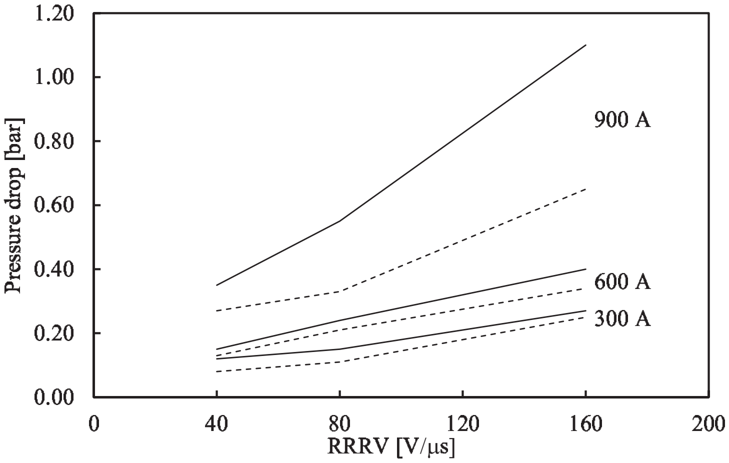

Figure 6.1: The solid lines show minimum upstream pressure drop required for 10 successful interruptions (out of 10 tests) as a function of RRRV for three different currents. The broken lines under each solid line are the estimated 50% probability curve for interruption for each current.

The dielectric phase of the interruption is not a large problem in an MV puffer LBS. If the cooling air flow is strong enough to interrupt the current and avoid thermal re-ignition immediately after CZ, the following TRV will most likely not lead to dielectric breakdown and arc re-ignition. This is true for all experiments presented here, which cover most of the MV switching duties. However, current interruption in series with a fuse, will lead to a more difficult TRV and possibly cause dielectric breakdown. Further investigation of this particular case is suggested for future studies.

The length of the nozzle and pin contact velocity should be so that the second CZ (after contact separation) always occurs outside the nozzle. The shortest tested nozzle in any of the experiments was 20 mm, and no beneficial effects were found by having a longer nozzle. The nozzle should be tight around the pin contact (at least if only considering current interruption and not the closing operation). The results regarding 24 kV and 630 A, reveal that less upstream pressure is needed when the nozzle diameter was decreased from 10 to 8 mm, with a pin contact diameter of 6 mm. Further work has to be done on different nozzle shapes and contact diameters but the presented results give some basic clues about how the nozzle best could to be designed.

Although these results are specific for the present setup, the test switch geometry is believed to be relevant. For an optimal contact nozzle geometry it is likely that slightly lower pressure drops could be sufficient. However, the trend for the upstream pressure drop when changing the current and TRV is believed be the same.

Compared to commercial puffer LBS designs, the test switch has a different air flow characteristic. A puffer device compresses the gas using a piston, and the upstream pressure will increase during the contact movement. Therefore, when using the results from the test switch, some caution is necessary. However, in a such situation designing the puffer arrangement is to some extent reduced to a mechanical problem (where enough upstream pressure drop should be produced during the period over at least two CZs).

The main conclusions are:

- A steeper RRRV requires nearly a proportionally higher pressure drop for the interruption to be successful.
- The current that can be successfully interrupted seems to increase almost proportionally with the pressure drop through the nozzle during opening (at least in the range up to 600 A).
- The main challenge is to avoid thermal re-ignition immediately after CZ. Dielectric re-ignition is less of a concern.
- In particular, for the IEC prescribed type test at 24 kV and 630 A, an upstream pressure drop in the range 0.25 to 0.3 bar is sufficient.
- The interruption performance is not very sensitive to the length and inner diameter of the nozzle for this type of design.
- The length of the nozzle and contact pin velocity should be so that the second CZ after contact separation always comes when the contact pin is outside the nozzle.

6.3 Ablation Assisted Current Interruption

The interruption capability of four different ablation materials is compared and the experiments show that PP interrupts almost 2.7 times higher current than polytetra-fluoroethylene (PTFE, which almost gave the same result as without an ablation material). Polycarbonate (PC) and Polymethyl methacrylate (PMMA) had similar performance, and had a interruption capability in the range 2.2 to 2.3 times higher than PTFE. The tests were performed in an open arc quenching assembly, but the presence of ablation polymer significantly enhances the current interruption capability.

The results indicate that high content of hydrogen in the ablation material is favorable. PP generates the highest number of atoms per ablated polymer mass among the tested polymers. PP has one of the highest percentages of hydrogen atoms in the polymer compared to any other material. This is believed to be the main reason to why PP has the best interruption properties among the tested materials. It is also important that the evaporation is homogeneous (e.g. leaving a flat and smooth surface after the arc interaction), giving the same starting point for the next current interruption. Producing as little soot particles as possible is also important for the same reason. It is not realistic to totally avoid the production of soot particles when a carbon-hydrogen based polymer is exposed to an arc. However, among the different tested materials in this study, PP and PMMA are apparently equal, while PC produces much more soot.

From the ablation-assisted interruption tests with the MV test switch, it was found that PP plates nearby the arc gave high capability to interrupt the thermal phase (over the requirements for many MV LBS ratings). In contrast to a puffer design (where the thermal interruption was the crucial part), here the problem starts during the dielectric phase. The current was always interrupted for a while, but often followed by a dielectric breakdown several milliseconds after CZ (usually in the voltage range around 5 kV).

Around CZ where the current is interrupted the evaporation from the ablation plates rapidly slows down. A combination of the remaining hot gas after the arc and soot particles from the ablation, is believed to cause the dielectric problems.

The ablation process increases the arc-voltage to values that are several times higher compared to the gas blow interruption tests. The gases from the ablation seem to push the arc sideways and making it longer. This can to some extent explain the increased arc-voltage, but the difference can also be a result of changing the gas content in the arcing area. This is a topic to be investigated further.

For the tested geometry, the switch can possibly pass the IEC prescribed type tests, in range up to 7.2 kV system voltage. By simply scaling up the dimensions of the switch, it is likely that higher voltage rating will also be possible. Further research is needed about the dielectric recovery after current interruption, where both material properties as well as the geometrical design should be considered.

The main conclusion from the material investigation are:

- Even for an open arc quenching assembly with static electrodes, the presence of ablation polymer enhances the current interruption capability to an impressive degree.

- From a large number of experiments, with pristine conditions in each test, PP interrupts almost 2.7 times higher current than PTFE. PC and PMMA have more similar performance, in the range 2.2 to 2.3 times higher than PTFE.
- High content of hydrogen combined with a clean and complete ablation process are favorable properties for a polymer ablation materials.

From the MV ablation tests the most important finding are as follows:

- A remarkable high ability to manage the thermal phase of the current interruption process is observed.
- There is a poor dielectric recovery after thermal interruption, which often leads to dielectric breakdown and re-ignition of the arc.
- The results indicates that PP ablation plates (applied as in the performed experiments) can interrupt a test circuit with about 7 kV system voltage and 400 A (IEC product type test, "mainly active load current test").
- By increasing the size of the arcing area (primarily longer contact separation) the test switch will probably interrupt more difficult TRVs and at higher currents.

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