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Faculty of Electrical Engineering
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ÚSTAV VÝKONOVÉ ELEKTROTECHNIKY A ELEKTRONIKY

SWITCHING ARC DIAGNOSTICS IN DC CONTACTOR

DIGNOSTIKA ZHÁŠECÍHO POCHODU U STEJNOSMĚRNÉHO STYKAČE

MASTER'S THESIS
DIPLOMOVÁ PRÁCE

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Master's Thesis

Master's study field **Power Electrical and Electronic Engineering**

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Student: Bc. Jakub Píška ***ID:*** 186163

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TITLE OF THESIS:

Switching arc diagnostics in DC contactor

INSTRUCTION:

1. Describe principle of function for the given contactor and principle of arc quenching in this device.
2. Propose suitable diagnostics of quenching process in the contactor.
3. Identify critical phenomena during quenching process in the contactor.
4. Carry out necessary experiments and propose possible adjustments of the device.
5. Analyze the results and summarize them.

RECOMMENDED LITERATURE:

[1] Havelka, O. a kol.: Elektrické přístroje, SNTL, 1985

[2] Fendrych, M. Studium vlivu parametrů na pohyb elektrodových skvrn v modelu zhášecí komory elektrického přístroje. Brno: Vysoké učení technické v Brně, Fakulta elektrotechniky a komunikačních technologií, 2016. 84 s. Vedoucí diplomové práce Ing. Jiří Valenta, Ph.D.

[3] Boulos, M. I., Fauchais, P., Pfender, E.: Thermal Plasmas, Volume 1, Springer Science & Business Media, 1994

[4] Dědek, L., Dědková, J.: Elektromagnetismus, Vysoké učení technické v Brně, VUTIUM, Brno, 2000

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Subject Council chairman

ABSTRACT

The goal of this master's thesis was to carry out middle voltage DC contactor diagnostics with a focus on back-commutation and sticking, to propose and test alterations which would remove these negative phenomena.
The arc voltage, fast camera and pressure measurements were used to determine these effects. Changes to arcrunners and pole plates of the magnetic circuit were used to limit them.
The proposed alterations limited the time delay caused by back-commutation and thus shortened the arc transfer time.

KEYWORDS

Contactor, breaking, diagnostics, pressure measurement, fast camera, back-commutation, reignition. sticking, arcrunner, pole plate

ABSTRAKT

Cílem této diplomové práce bylo provést diagnostiku vysokonapěťového stejnosměrného stykače se zaměřením na zpětnou komutaci a lepení oblouku, navrhnout a ověřit úpravy, které odstraní tyto negativní jevy.
Měření obloukového napětí, tlaku a pomocí rychlokamery byly použity při diagnostice těchto jevů. Změny na arcrunnerech a jhu magnetického obvodu byly využity při jejich odstraňování. Úpravy na arcrunneru zmenšily skokové nárusty délky oblouku a úpravy na jhu navýšily sílu na oblouk mezi rozevírajícími se kontakty.
Navrhnuté změny na stykači snížily časovou ztrátu v důsledku zpětné komutace, a tak zkrátily čas přenosu oblouku.

KLÍČOVÁ SLOVA

Stykač, vypínání, diagnostika, měření tlaku, rychlokamera, zpětná komutace, znovuzápal, lepení oblouku, arcrunner, jho

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Rozšířený abstrakt

Cílem této diplomové práce bylo provést diagnostiku vysokonapěťového stejnosměrného stykače se zaměřením na zpětnou komutaci a lepení oblouku, navrhnout a ověřit úpravy, které odstraní tyto negativní jevy.

První kapitola se zaobírá prve obecně používanou konstrukcí stykače a následně konkrétní konstrukcí zkoumaného stykače. Hlavní důraz je přitom kladen na proudovodnou dráhu a magnetický obvod s permanentními magnety.

Následující dvě kapitoly popisují zhášení oblouku ve spínacích přístrojích a s tím spojený negativní jev znovuzápalu. Dále jsou rozebrány důvody vzniku tohoto jevu a jsou ukázány speciální případy, které se vyskytovaly ve zkoumaném stykači. Jmenovitě se jednalo o jevy zpětné komutace a lepení oblouku, které se projevují ještě během samotného zhášecího pochodu, narozdíl od klasického znovuzápalu.

Kapitoly čtyři a pět obsahují popis použitých měřicích mětod a popis prvotního měření, které sloužilo k určení možností použití daných metod. Jednalo se o měření obloukového napětí, tlaku a za pomocí rychlokamery. Během prvotních měření byla potvrzena přítomnost výše zmíněných negativních jevů a byla určena místa a časy jejich výskytu.

Kapitola šest je literární rešerše možných odstranění zpětné komutace a lepení oblouku a výběr vhodných řešení pro daný stykač.

Následující kapitola obsahuje výkresy a důvody použití jednotlivých úprav provedených na stykači, které vycházejí z předchozí kapitoly. Tyto úpravy byly provedeny na proudovodné dráze, a to na arcrunnerech a na jhu magnetického obvodu. Úpravy na arcrunnerech byly provedeny za cílem snížení výskytu náhlých nárustů délky oblouků, a s tím spjatého obloukového napětí. Změny na jhu navyšovaly sílu na oblouk v oblasti rozepínaných kontaktů.

Kapitola osm poskytuje metriky použité k hodnocení jednotlivých variant přístroje. Jedná se o čas potřebný pro transport oblouku do zhášecí komory t_1, celkový vypínací čas t_2 a časovou ztrátu v důsledku zpětných komutací t_d.

Následující kapitola devět shrnuje naměřené výsledky jednotlivých variant a popisuje postup výběru finální verze včetně kontrolního měření.

V závěru práce jsou tyto změny shrnuty včetně zkrácení jednotlivých časů, které byly použity pro porovnání. Je zde také popsán další možný postup, sestávající se z měření na jiných parametrech testovacího obvodu a měření na novém, nepoškozeném přistroji pro získání finálních dat.

DECLARATION

I declare that I have written the Master's Thesis titled "Switching arc diagnostics in DC contactor" independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the thesis and listed in the comprehensive bibliography at the end of the thesis.

As the author I furthermore declare that, with respect to the creation of this Master's Thesis, I have not infringed any copyright or violated anyone's personal and/or ownership rights. In this context, I am fully aware of the consequences of breaking Regulation § 11 of the Copyright Act No. 121/2000 Coll. of the Czech Republic, as amended, and of any breach of rights related to intellectual property or introduced within amendments to relevant Acts such as the Intellectual Property Act or the Criminal Code, Act No. 40/2009 Coll., Section 2, Head VI, Part 4.

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Contents

List of Figures

List of Tables

Introduction

The demand for increased switching capability and compactness of switching devices has been increasing. To address this, new approaches and designs are applied. But new ways to determine whether these changes bring the desired effects also have to be studied.

The reason why I chose this topic was to determine which of the wide range of applicable diagnostic methods are of use when trying to measure specific negative phenomena in a contactor. The focus of this thesis was on arc sticking and back-commutation which are both effects afflicting the arc transfer from the contact to the quenching chamber.

The first part of this thesis describes the contactor construction and phenomena accompanying the breaking of the circuit.

The second part focuses on the diagnostic methods and the preliminary measurements realized on the contactor.

The last segment gives possible alterations with a goal of limiting the negative phenomena of back-commutation and sticking. These alterations were tested and the best combination was proposed as a solution to the diagnosed problems.

1 Construction and function

As is true for all contactors, this device was built for frequent switching of operational currents. So, its construction is not that different from commonly used models at the first glance. First, the basic construction of a electromechanical contactor will be addressed and then different changes used to facilitate the enhanced demands for this product will be discussed.

1.1 Basic construction

The most common construction of a contactor uses two contact pairs and linear movement of a contact bridge facilitated by an electromagnet. The main parts of a single pole of a contactor are as follows:

- current conducting path
- contact system
- electromagnet
- arc quenching chamber
- enclosure and other insulation

All of the mentioned parts can be seen in fig. 1.1

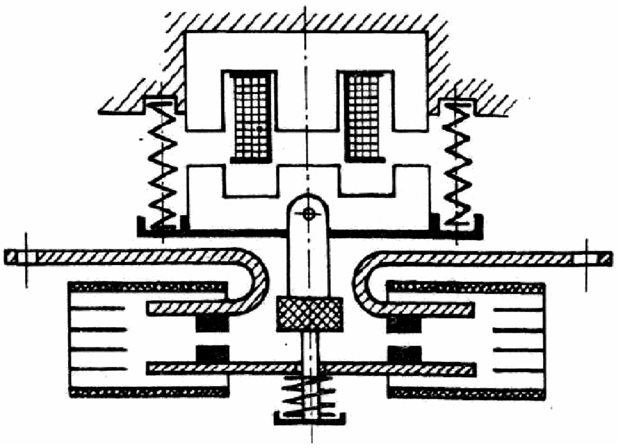

Fig. 1.1: Basic contactor construction [1]

As we can see, the current conducting path is bent and brought back under the contact system to achieve movement of the arc due to its interaction with magnetic field created by current passing through the path. The only other requirements for the path are to serve as a way to transfer heat away from the contact point, as it is the main source of heat losses, and to mechanically withstand the force generated by passing current.

Because of the gap length effectively doubled by the circuit being divided in two separate places the distance between the contacts when fully opened can be shortened. This also positively affects the electromagnet because the length of its air gap depends on the contact distance.

The innate short length of the arc, when it is ignited, is referred to as a problem of DC contactors with this topology and needs to be addressed with additional measures.[1]

The contact system apart from its duty to facilitate galvanic connection between two parts with minimal contact resistance without using excessive force has to withstand very high amount of operations both with and without load. So, the incentive on high erosion and abrasion resistance is applied more severely than on other types of switching devices.

As the contactor is a device designed for switching operational currents, the quenching chamber is not often of the same importance as in breakers where current limitation is often required. But it should be mentioned that this is not the case for the DC switching where overvoltage always needs to be created to force the current to reach zero as discussed later.[1]

1.2 Changes made

This particular contactor is being developed for application in DC traction. The main requirements are to reliably switch its rated current and to occupy as little space as possible. To tackle these demands, changes needed to be done.

First, the main difference must be mentioned and it is the addition of a new component - permanent magnets and joined yokes which serve instead of the curved current path to route the arc to the quenching chamber. This influences all following parts.

1.2.1 Current path and contacts

The current path now serves other purposes than primarily affecting the arc. It can still have a noticeable impact in the current range above 1 kA but that is only a secondary effect of the U-shaped current path.

The main objective is to allow the arc to reach a sufficient length and transfer it to the quenching plates. This is accomplished by shaping the path and adding new components to serve as arc runners.

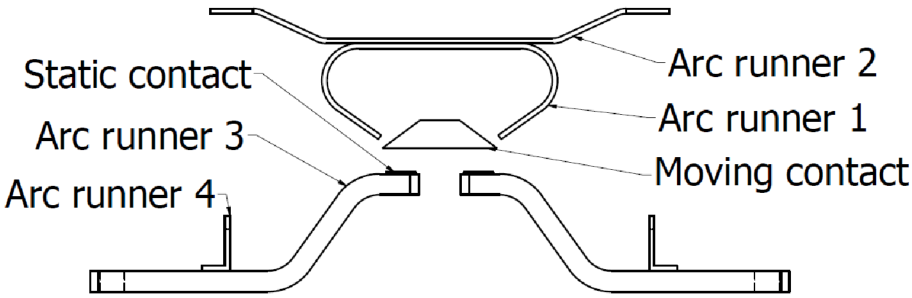

Fig. 1.2: Current path

The mechanism of arc motion begins after ignition between the static and the moving contact. After this, the lower arc roots move along the arc runner 3 and the upper arc roots move subsequently to arc runner 1 and 2. This serves the purpose of lengthening the arc while not allowing the arc roots to stay in one place to limit the arc erosion.

1.2.2 Magnetic field

The magnetic field's purpose is to force the arc to move along its designed trajectory to the quenching chamber. This is a commonly used practice and when reaching higher currents the breaking process would not be possible without it. But while most of contactors use a shaped current carrying path to achieve this, this contactor uses a system of permanent magnets and steel yokes to create the required field.

The magnetic circuit is separate for each contact gap and therefore for each arc produced.

The first version of the device used steel arc runners 1 and 2 (see fig. 1.2) and in later versions they were changed to bronze ones with identical shape.

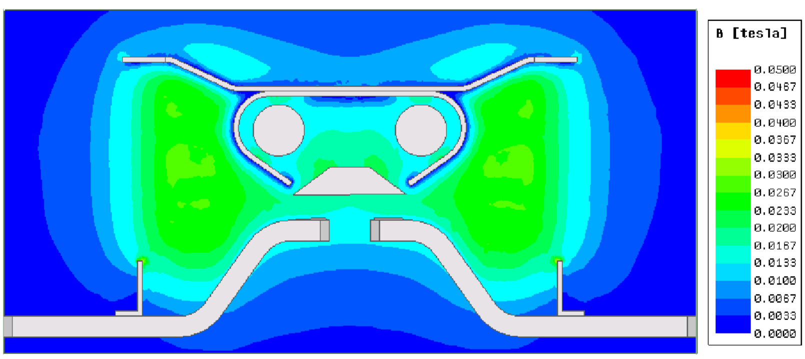

Fig. 1.3: Magnetic field distribution with steel arc runners

1.2.3 Quenching chamber

After the transfer when the stable arc is finally established, the arcrunners 2 and 4 serve as its electrodes. Both arcrunners serve as an anode and cathode due to the existence of two serial arcs.

If the arc was let burn freely with length defined only by the electrode distance, the produced arc voltage would be inadequately low and the slope of current drop would be unacceptably long. Therefore, several non-conducting plates are inserted to prolongate the arc and to drain the heat from it.

To achieve even better prolongation with constant electrode, gap length using combination of plates of different shape is used.

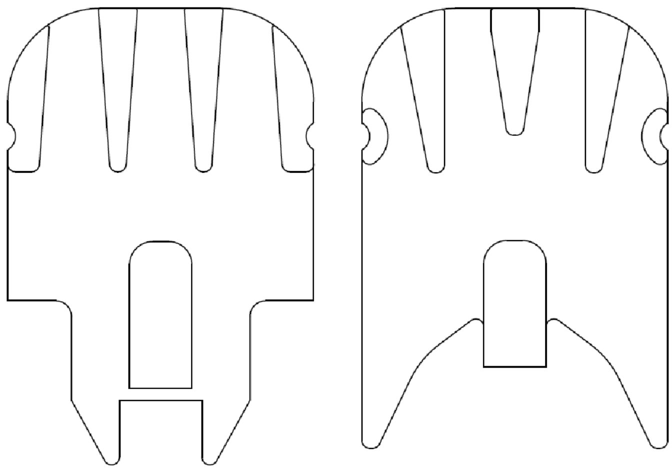

Fig. 1.4: Two types of non-conducting plates

The plates are stacked upon each other while alternating between the left and right design. The lower parts of the plates then force the arc to weave between them while the previously mentioned magnetic field still presses the arc against the top part of the plates. By this, magnetic force again bends the arc and increases its length.

The ceramic plates are commonly used in DC switching devices as they always lead to greater increase of arc voltage. But they lack the ability of steel plates to draw in the arc due to magnetic force.

In addition, the non-conducting plates made from ceramics bring the distinctive advantage of high erosion and ablation resistance in comparison to the metallic ones. While also the molten droplets of metal, which solidify on its surface, can never short-circuit the neighbouring plates and render them useless regarding dividing the arc.

2 Arc extinguishing

Although the contactor serves both for making and breaking, the breaking process is more important for the contactor construction as a whole. Therefore, it will be the primary focus. But at first, it must be established what constitutes a successful breaking of a circuit and which parameters and circumstances must be met for proper function of the contactor.

The extinguishing process consists of several parts:

- creating and burning of the original arc
- current passing through zero
- race of TRV against reignition voltage
- dissipating of heat to the surroundings

The creation of an arc and its existence will not be discussed here up to the point of first current zero.[2]

2.1 Current passing through zero

The moment when the arc current stops flowing through the circuit is also the moment when no further heat is being pumped into the plasma of the arc. The arc can cool down properly and the ions can recombine due to exchange of heat with the surroundings - at first with contacts and the current path and then to the enclosure of the contactor.

The cooling itself actually starts even before the first zero point. The arc starts cooling after achieving equilibrium between the heat losses caused by the passage of current and the heat transfer from the arc by the means of conduction and radiation.

We can fairly precisely determine when this equilibrium is reached by examining the current and voltage curves. The moment is well documented and signified by so called *minimal arc current*. After this, the current rapidly drops to zero and voltage steeply rises both due to rise of resistance of the arc caused by the starting deionization of plasma. The rise of voltage is furthermore given by the voltage surge on the circuit inductance due to the increase of $\mathrm{d}i/\mathrm{d}t$.

The minimal arc current is not a constant but is highly dependant on the construction of the contactor. The main influence on the value of the minimal current is the rate of energy losses to the surroundings. So, it can be expected that with longer lengths of the arc and better cooling the minimal sustainable current will be higher.[2]

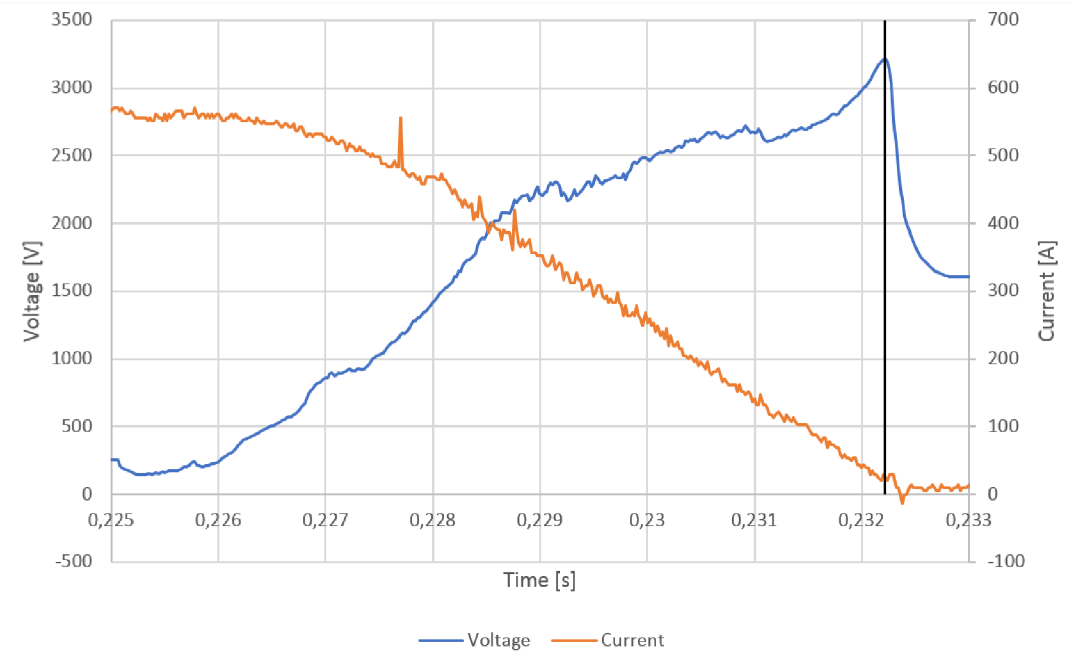

Fig. 2.1: Minimal arc current

As the fig. 2.1 shows, the minimal arc current coincides with the maximal arc voltage. So, the time of equilibrium of losses and transferred heat can be determined either by the local voltage maximum or by the change in the decline rate of the current.

The current zero occurrence depends both on the type of voltage type (AC/DC) and measures to achieve it.

The DC contactors have to decrease the current from its original value to zero by increasing the arc voltage above the supply voltage as can be seen from the following formula:

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \frac{1}{L}\left([U_c - Ri] - U_a\right) \qquad (A/s; H; V; \Omega; A; V) \tag{2.1}$$

The actual increasing of arc voltage can be done in a number of ways namely: increasing the length, cooling the arc and dividing it into several smaller arcs which uses the fact that arc voltage is not a linear function of its length to its advantage.

Alternatively, designs using totally different approaches have been made, such as superposition of high frequency current signal on top of the original one with reverse polarity of the first half-wave.[3]

AC contactors and breakers do not have to rely on these techniques to reach the current zero for it naturally occurs twice in one period of the signal. So, the only duty of the breaker is to not let the arc reignite. This is both very convenient and suboptimal because it might be needed to limit the passing current and namely

Joule integral to properly protect the device that is being switched off. When this demand arises, the steps to achieve it are the same that were already mentioned when describing the extinguishing of DC current.[2]

2.2 Race of TRV against reignition voltage

As the current and power losses in arc and electrodes go to zero, the space between electrodes changes from relatively good conductor to an insulator. Thus, the current stops flowing though the gap. As this happens, the voltage across the contact gap changes from arc voltage to *Transient recovery voltage* (TRV). This voltage impressed over the gap is not dependant on the actual switching device by a great margin. The main factors are circuit inductance, stray capacitance and residual conductance. This transient voltage has two distinct components: the power frequency one and oscillatory transient component as shown in the fig. 2.2.[2]

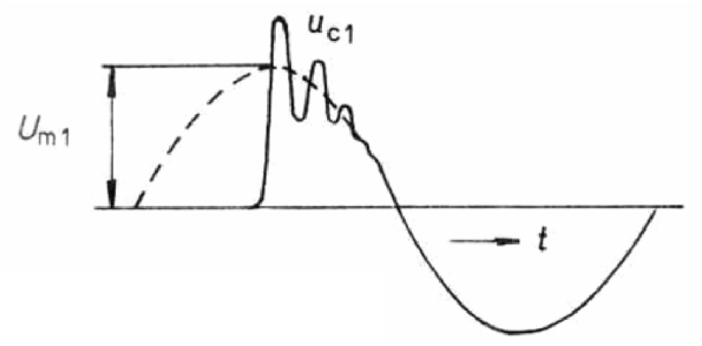

Fig. 2.2: Transient recovery voltage [1]

The power frequency component is there due to system voltage and the oscillatory is there because of the inductance and capacitance of the circuit. The oscillatory part vanishes in a few microseconds while the power frequency component continues. The frequency can be given by the Thompson's equation:

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (Hz; H; C) \tag{2.2}$$

The real system oscillatory waveform has several frequencies and cannot be summed up by the previously stated equation.[1]

While this transient voltage is impressed over the decaying plasma another voltage can be discerned - *reignition voltage*. This voltage is the maximal voltage the gap can be stressed with and not cause another arc to be ignited. If the TRV was higher than this reignition voltage at any point in time, the arc would be reestablished, current would again start to flow and the whole process would have to start anew.

This reignition voltage is very much influenced by the construction of the switching device namely the arc current before current zero, the gap length, contact material, arc chamber design and the ambient gas. But is it does not depend on the circuit parameters. During the recovery process the reignition voltage does not linearly increase with time but we can differentiate four distinct stages:

1. instantaneous recovery of reginition voltage that occurs in <1 µs
2. a slight increase in the dielectric strength followed by a plateau
3. a steady increase of reignition voltage that lasts between a few tens or a few hundred microseconds
4. the full dielectric strength of the "cold" contact gap [2]

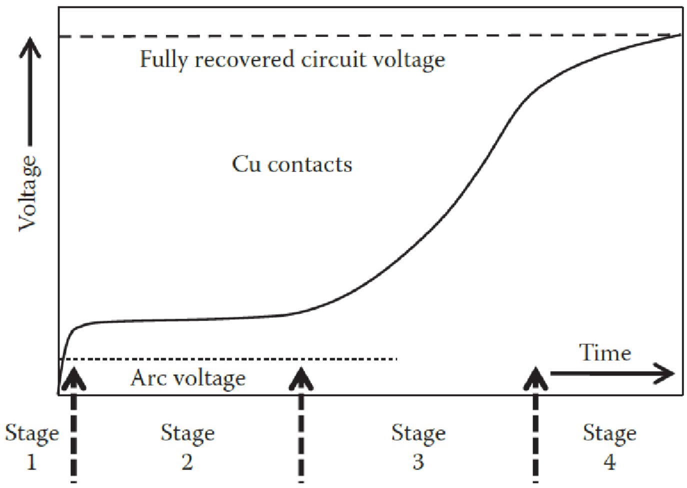

Fig. 2.3: Stages of recovery voltage [2]

2.2.1 Instantaneous recovery

At the very beginning of the first stage, the arc column is uniformly distributed between the electrodes and has not started to decay yet. But the emission of electrons is halted from the cathode and due to the voltage impressed over the gap, redistribution of particles is initiated. Let us assume that the slow moving ions can be treated as stationary. Then, the process starts with electrons in immediate vicinity of the cathode, being repelled and creating a space charge sheath about 10e-7 m wide. This sheath by itself covers approximately the first 300 V of reignition voltage for cold cathode. If the TRV is smaller than or equal to this reignition voltage then there is no voltage impressed over the rest of the arc column. In the case of TRV being higher than these 300 V then the full 300 V is covered by this sheath and only what is left affects the the plasma while electrons start to be ejected from the cathode again.

The actual reignition voltage of this sheath depends mostly on the material and temperature of contacts. And thus partially on the switching current and the construction of the device such as the size of current-carrying members as they serve as the primary way of draining the heat from the contacts.

For example Cu and Ag would have the value of initial reignition voltage close to the mentioned 300 V as they are non-thermionic emitters. But for the thermionic emitters such as W the reignition voltage drops and the greater the switching current the bigger the drop is. Simply because of the higher temperatures, which go hand in hand with higher current, the tungsten needs lesser voltage to emit electrons again.

The material properties that dictate this value of reignition voltage are many, for example density, melting and boiling point, work function, ionisation potential and thermal diffusivity.

Apart from the material of the contacts other variables influence the reignition voltage covered by cathode gap. Mainly the ability to transfer heat away from the surface of contacts, the maximal value of current and its rate of decrease.[2]

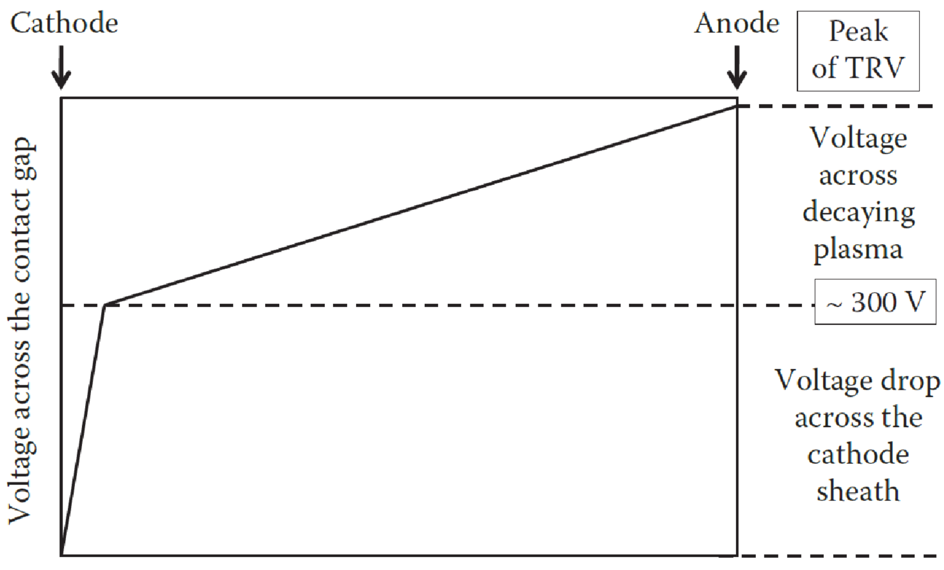

Fig. 2.4: Distribution of TRV across contact gap [2]

This effect can be again enhanced by using the same technique used for arc extinguishing. If the splitter plates from conductive material are used to generate additional cathode and anode spots, these same spots will serve as additional cathode layers and again increase the reignition voltage as they effectively serve as new contact gaps in series. The reignition voltage increase is however not proportional to the number of splitter plates used due to the electric field distribution along the contact gap.[2]

2.2.2 Arc decay

After the instant increase of recignition voltage due to creation of cathode gap there is another increase although it is not as steep. It occurs due to rapid cooling of the arc roots by axial conduction to the relatively cool contact spots. This cooling again increases the cathode layer gap additionally to increasing local resistivity.

The plateau in reignition voltage characteristics represents cooling of the arc column, deionisation and gradual decrease of arc conductivity. After the arc is cooled under approximately 2000 K the thermal ionisation due to the Sasha's equation is negligible and the voltage is uniformly distributed across the whole length of the contact gap.

The rise after the plateau is caused by the general cooling of the arcing chamber and the whole switching device.

Both of these parts depend on the construction of the device, its ability to transfer heat from both the contacts and the chamber, the type of ambient gas used and the amount of metal particles in evaporated in the gas.

After the thermal equilibrium is achieved the reignition voltage stays constant. This part is marked as stage 4 in the diagram.

The contact gap after this moment acts as a normal break in a circuit with full dielectrical strength derived from its length, shape of the electrodes and materials used for the surrounding parts.[2]

3 Arc reignition

The arc reignition is a phenomenon in which there is an additional ignition of an electrical arc after the initial one, which starts the breaking process. The arc reignition can occur in two ways:
a) After the extinguishing of the arc
b) During the extinguishing of the arc

The first one mentioned is well documented because its occurrence can often lead to failure of switching device and damage to the protected device.

The second one, while not always causing a failure, prolongates the switching time, damages the device and severely reduces the number of operations the device can successfully execute. This phenomenon is generally called *Back-commutation of the arc.*

3.1 Creation of arc reignition

3.1.1 Dielectric reignition

The dielectric reignition is the direct result of TRV reaching and acceding the recovery voltage of the gap. This process is equivalent to *Long-gap gas breakdown* with the benefit of electrons already existing in the space between the two electrodes.

The process itself is based on existence of electric field between the electrodes. If the cathode layer is not accounted for, the impressed voltage is evenly distributed along the rest of the gap length.

As there are still free electrons in the decaying arc, they are accelerated by the the electric field and can collide with atoms of the ambient gas. If the result of these collisions can reliably produce additional electrons, the number of created electrons spirals to high enough numbers to reignite the arc. This process is termed the *Townsend avalanche*. It requires the colliding electron to have energy exceeding the ionization energy of the weakest bound electron in the atom. The ionization potential of atom depends on the type of gas used and the energy of electron E_e is a function of intensity of electrical field E and distance it travels undisturbed.

$$E_e = E \cdot \lambda_e = \frac{U}{d} \cdot \lambda_e \qquad (J; V/m; m; V; m) \tag{3.1}$$

Where λ_e is *electron mean path* which stands for average distance travelled between two collisions. U and d represent voltage between electrodes and their distance respectively.

The electron mean path is a simple function of pressure with constant A.

$$\lambda_e = \frac{1}{Ap} \qquad (m; m^{-1}Pa^{-1}; Pa) \tag{3.2}$$

To discern the conditions that limit the reignition of a self-sustaining discharge the genesis of new electrons needs to be enumerated.

Let us establish a new coefficient α or the *Firts Townsend coefficient* which is a number of electrons generated by one electron if it traverses distance of one meter.

$$\mathrm{d}n = \alpha \cdot \mathrm{d}x \qquad (-; 1/m; m) \tag{3.3}$$

$$n = n_0 e^{\alpha x} \qquad (-; -; 1/m; m) \tag{3.4}$$

Where n is the number of electrons and n_0 is the original number of electrons. After deducing the number of original electrons the number of new electrons is obtained. To simplify, only simple ionizations are accounted for. In that case the number is equal to newly generated positive ions.

These ions are also propelled by the electric field and when they hit the cathode there is a chance of generating a new electron. This probability is expressed by a coefficient γ or the *Third Townsend coefficient*. By definition, if the discharge is self-sustaining, the electrons leaving cathode produced by positive ion collision need to be able to sustain them selves. Any other sources of electrons only support this process. If n_1 is declared as the number of electrons leaving cathode per second and x is established as equal to the contact gap length d, the following formula will apply.

$$n_1 = n_1 \gamma \left(e^{\alpha d} - 1\right) \qquad (-; -; -; 1/m; m) \tag{3.5}$$

The only way for this formula to apply and the number of electrons leaving cathode be different from zero is to reach the following condition.

$$\gamma \left(e^{\alpha d} - 1\right) = 1 \qquad (-; 1/m; m) \tag{3.6}$$

The coefficient α can be further expressed as a function of coefficient A, pressure, present voltage, electrode gap distance and effective ionization potential V_i.

$$\alpha = Ap \cdot e^{-\frac{AV_i pd}{U}} \qquad (1/m; m^{-1}Pa^{-1}; Pa; V; m; V) \tag{3.7}$$

If $e^{\alpha d} >> 1$, the formula can be reduced to equation 3.6. Then the new expression for α can be used.

$$ln\left(\frac{1}{\gamma}\right) = \alpha d \qquad (-; 1/m; m) \tag{3.8}$$

$$ln\left(\frac{1}{\gamma}\right) = Apd \cdot e^{-\frac{AV_i pd}{U}} \qquad (-; m^{-1}Pa^{-1}; Pa; m; V; V) \tag{3.9}$$

$$U = \frac{-AV_i pd}{ln\left(\frac{Apd}{ln(1/\gamma)}\right)} \qquad (V; m^{-1}Pa^{-1}; V; Pa; m; -) \tag{3.10}$$

The gained voltage is the minimal voltage needed to start an ignition of a discharge. This relation is referred to as the *Paschen's law*. For the purpose of this thesis, this is the voltage needed to be impressed over the body of an arc. To get the total voltage needed between electrodes voltage spent on cathode layer needs to be added.

If the function should be plotted over the product of pressure and distance of electrodes, function with single minimum would emerge. This can be qualitatively explained by the fact that with high pressure there is low electron mean path and the electrons do not achieve high enough energies and with low pressure the collisions are just too rare to start the avalanche needed to sustain this process.[2][4]

3.1.2 Thermionic and thermal reignition

While the dielectric reignition was a race between two voltages, the thermionic reignition is a race between the power losses in the remains of the arc and the heat transfer away form the plasma.

First, losses in the plasma need to be defined. If there is voltage greater than the cathode sheath drop impressed over the contact gap, there is voltage over the decaying plasma column. This column has still non-zero conductivity due to ionised particles. As a result, a post-arc current can pass through the gap and by Joule losses heat up the column. For this, the power input into the plasma depends on the source voltage, gap length, ambient gas used and the arc chamber design.

If these losses cannot be sufficiently transferred, the temperature rises and with it the conductivity which further fuels this process and will quickly lead to thermionic reignition.

But there is one more type of reignition which is not as common in switching devices but when it occurs it can lead to a total failure of the device. The therm *thermal reignition* is used to describe a phenomenon where the cathode is able to emit electrons even right after current zero. This can be the case of the electrodes reaching high temperatures while using refractory materials. But even when not using refractory materials there is the danger of this reignition if the contacts can not sink the heat effectively.[2]

3.2 Back-commutation and Sticking

As was discussed at the beginning of this chapter, there are phenomena connected to reignition even while the current is still flowing. Both of these effects cause the quenching process to take more time and cause uneven thermal stress to different parts of contact system and arc runners.

3.2.1 Sticking

When observing a switching device with magnetic blow-out the expected progression of arc movement should depend on several quantities like current, magnetic flux and fluid resistance. With this, when not accounting for turbulence the velocity of an arc should be only increasing or reaching a steady state as the forces affecting the arc reach an equilibrium.

But on the contrary to this first look, there can be a value of current which when exceeded will change the nature of arc movement. If this phenomenon appears, it is called *sticking* and it is manifested as arc stopping at one spot typically where arc runners or horns diverge or just before the arc chute with plates. Both of these spots are characterised by a steep increase of arc voltage when crossed.[2]

So, the arc is held in place by a fictional force that stems from the fact that moving in any direction would cause the arc to increase its energy.

$$F = -\frac{\partial W}{\partial x} \qquad (N; J; m) \tag{3.11}$$

The the increase in energy is twofold but both are connected to voltage increase. The first one is simply caused by a prolongation and when near metal arc chute the arc splitting and creating new anode and cathode spots. Both of these effects are demonstrated in following equation where N is the number of metal splitter plates.

$$U_a = (N+1)\left(\Delta U_A + \Delta U_C\right) + El \qquad (V; -; V; V; V/m; m) \tag{3.12}$$

Where U_a is the total arc voltage, ΔU_A and ΔU_C are anode and cathode voltage drops and l is length of arc without anode and cathode drops.

The second one is the fact that both heat transfer from the arc and energy of particles hitting the electrode spots heat up the arc root regions and in the case of cathode further increase its ability to emit electrons. This again influences the arc voltage by needing less voltage to extract enough electrons to transfer the current. This is conveyed by decreasing ΔU_C in equ. 3.12 with increasing temperature of cathode spot. Thus, when the arc is forced to move to a place with cold cathode spot the ΔU_C increases and so does entire arc voltage and with it the energy. And so, the arc displays tendency to stay in its original place.

This effect is multiplied when using arc chute due to forcing the arc to create multiple cold cathode spots in one moment. This is a major problem that needs to be addressed when using this solution for current limiting as documented in [5].

3.2.2 Back-commutation

If the arc successfully overcomes the previously mentioned hurdles on its way to quenching chamber it can face another phenomenon. When the arc voltage increases so does the voltage across the whole contact gap. If the space between electrodes does not have enough time to increase its dielectric strength by processes of recombination and heat transfer, an event can occur very similar to dielectric reignition.[2]

This effect can be enhanced by additional transfer of ionised particles from the arc by different causes like diffusion, radiation and transfer by hot gas propelled by the moving arc and reflected back by the arc chute.

The exact spot where this reignition occurs influenced by the gap length, electric field distortion by edges of the contacts and the lateral walls and the temperature distribution of the gas.[6]

When this causes a new arc to ignite on some previous position the old arc is immediately extinguished and the process of arc motion starts anew. This obviously stresses the arc runner and needlessly prolongates the breaking process. This again makes the arc voltage drop and current rise.[5]

4 Arc diagnostics

The purpose of diagnostics is to determine parameters of certain device or to observe some phenomena that can influence these parameters. By this definition, the types of tests imposed on the device vary widely depending on the used device and the information one desires to obtain.

When concerning switching devices test focus mainly on the following parts:

- switching capabilities
- material degradation and endurance
- safety

The switching process is always observed by measuring current and arc voltage on the device under defined loads. But this can be enhanced by adding fast camera, pressure sensor or measuring spectra of the arc to better understand the ongoing processes.

The material degradation and erosion concerns almost all parts of the device. Every device is exposed to thermal effects of current and arc. Some are even directly exposed to arc. Some are mechanically stressed. Some are exposed to UV radiation. All of this lowers the lifetime of the device and in the case of contacts often can lead to malfunction.

For the safety reasons, it is demanded that plasma emission cannot occur in a place occupied by operating personnel. Dangerous voltage or temperatures are restricted to places the operator cannot come into contact with.

4.1 Chosen methods

The chosen methods for measurement always depend on the phenomena one wants to observe. So, for the first test only current and arc voltage were measured. These are the easiest to implement and can always be used because there are no limitations stemming from the device construction.

After this, further needed methods can determined. In this case, the observed effect was back-commutation and sticking. To address these problems, places on arcrunners where these effects occur need to be identified. Fast camera was the method of choice for this. At first, this was not an option due to the fact that the material of enclosure did not let through any light from the arc at the used arc parameters. This was solved by using an enclosure made for the prototype of this contactor. This can bring up two influences on the breaking process. The first is the presence of another plastic in the immediate vicinity of an arc. This can alter the composition of the arc and thus its behaviour. The seconds problem is the fact that there are several minute construction differences between the used version and the prototype. This can cause improper sealing of the enclosure.

Another things needed to be investigated were the forces causing the arc movement and eventually stagnation. The pressure field was measured in three places along the arc trajectory. The possibility of substitution of the fast camera measurement by the pressure measurement for the purposes of determining the arc position was investigated.

The magnetic field was not measured but was modelled by finite element method in Ansys.

4.2 Arc voltage

When taking any measurement of a switching device the voltage and current measurements are the most widely used and easiest to implement methods. The measurement methods are commonly known and do not need to be discussed in this thesis.

What is worth discussing is the evaluation of the data gained. For the simplicity of all the following waveform diagnostics let us assume that the voltage drop across the current carrying path is negligeable in comparison to the arc voltage.

The following effects will be demonstrated on waveforms of MCCB switching short circuit current.

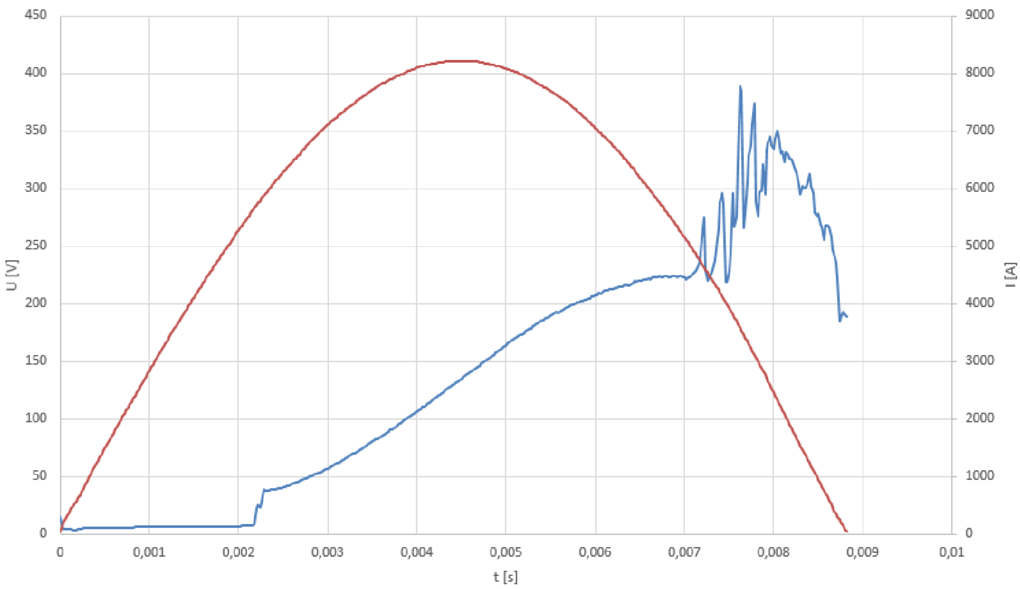

Fig. 4.1: Breaking operation voltage waveform - MCCB

Let us start in chronological order and focus on the steep rise in voltage in about 2 ms from the start. It consists of two distinctive edges. This represents the parting of contacts and ignition of the arcs. The voltage rise consists mainly of the anode and cathode voltage drops. The reason why there are the two edges is construction of this breaker. There are two pairs of contacts and due to tolerances the two contacts do not separate at the same exact moment. Therefore, separate ignitions of the arcs can be seen.

The second process after arc ignition is arc travel across the arcrunners. This can be seen in the time frame from 2 ms to 7 ms. This part is recognizable by the continual increase in voltage given by arc prolongation and cooling. In this particular case, the waveform is very smooth. This is not always the case as will be shown later. This is due to a smooth increase in arcrunner distance which translates to smooth increase in arc length and the fact that the arc is stable due to relatively short length and magnetic constriction as a result of high arc current. For this the arc is not disturbed by gas flow.

The last part from 7 ms to about 9 ms shows a distinctive increase in voltage combined with great fluctuation in the voltage value. This is a simple indicative of the arc reaching the arc chute. The arc rapidly changes its length and location of electrode spots and this causes the fast changes in voltage.

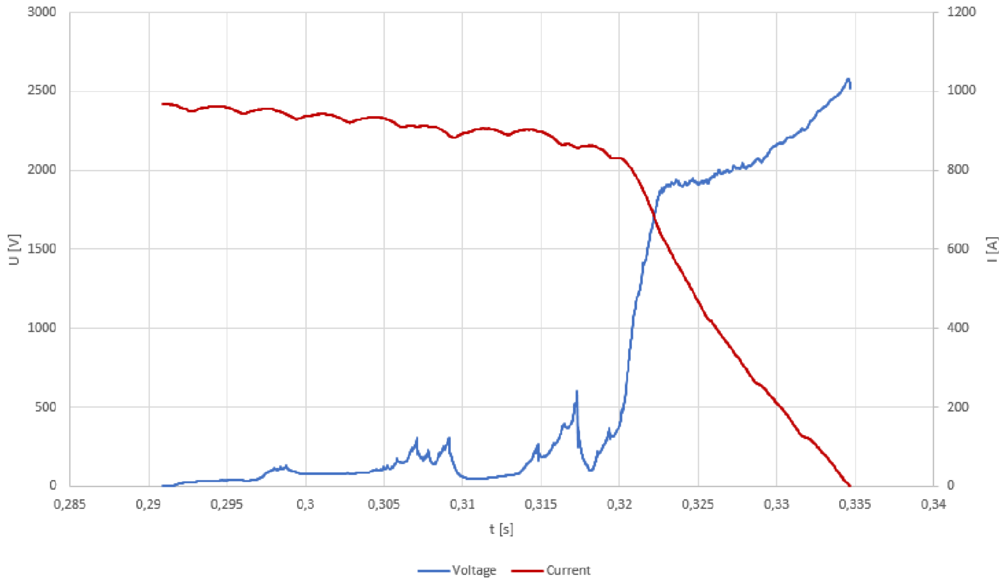

Fig. 4.2: Breaking operation voltage waveform - contactor

Figure 4.2 depicts waveform from the diagnosed contactor. By comparing it to the fig. 4.1 several differences to the MCCB can be discerned. Firstly, the voltage rise from 290 ms to 320 ms is not a smooth function as it was in the breaker. The value of voltage stagnates or rises very slowly in comparison to the MCCB for the majority of time. This long period of stagnation is intersected by a steep rise and fall in several timestamps namely 307, 309 and 317 ms. These rises indicate a quick movement of the arc along the arcrunner and subsequent back-commutation. This was validated by joined fast camera observation. The second thing to note is the voltage of the arc in the quenching chamber (about 320-335 ms). The voltage rise is far steeper and far more stable. This is due to usage of non-conducting material for the splitter plates.

4.3 Pressure

As the pressure field influences the arc movement alongside the magnetic field it is of an importance to be able to measure its distribution. For this there is a number of possible pressure sensors that can be used.

Piezoelectric principle is one of the most commonly used in pressure sensors. This principle uses the fact that some crystals are capable of producing electric charge on its surface when force is applied to the crystal. This is due to positive and negative crystal lattice elements are displaced relative to one another and as such create an electric dipole. This charge manifests several positive attributes. It is proportional to the applied force and depends only on the material used and not on the physical dimensions of the crystal. This can be used to reduce the size of sensors and increase their sensitivity by stacking multiple crystals on top of each other while connecting them in parallel. But voltage output is needed for following measuring chain the charge has to be processed by a charge amplifier to get the output voltage that matches the measured pressure.

Other principle also uses a crystal deformation but it uses the changes in its dimensions to create a variable resistor. That is called a piezoresistive sensor. By applying a constant current to this resistor a variable voltage is obtained corresponding to the measured pressure. Other material than crystal could be used. For example metal but the change of resistivity is more pronounced for semiconductors.[10]

There are other principles like the capacitive sensors which also measure the change of a property in this case capacity with pressure. The configuration often consists of two parallel electrodes with a thin gap. One of the electrodes is moving the other is static. The change of capacity is measured by making it part of a tuned circuit.

The last but not least is an optical sensor which encompasses two working principles. The first one is that the moving membrane just covers part of the light source and the light sensor registers this decrease in intensity as an increase of pressure. Other uses a configuration a moving mirror and optical path with variable length.

And by comparing the phase of the light returning to the sensor the change in the position of the mirror carrying membrane can be discerned.[11]

With such a wide array of possible sensors there is a great need to choose the one suitable for the right application.

The piezoelectric sensors are mostly suited for fast processes due to both having high natural frequency and due to the virtue of its principle drift occurrence during longer measurements without pulsations. They also have very high thermal stability which is needed for measurements in arc chamber.[10]

The piezoresistive sensors lack the downfall of an output voltage drift and as such are used for static measurements. They have very simple construction and are the most common ones. This leads to low costs and durability. But the construction carries a drawback that it is temperature dependent and its response time is about 1 ms in comparison to 1 μs of a piezoelectric.

The capacitive sensors show little temperature dependence and have a very low hysteresis. They can be also easily implemented as wireless but the main drawback is that in comparison to previous sensor these sensors have a non-linear characteristics. There are ways to compensate this but at a cost of worsening of sensitivity and hysteresis.

Optical sensors have both high sensitivity and low temperature dependence due to the measurement and reference detectors being affected equally. They are also very resilient to surrounding interference hence it uses optical signal. But their high sensitivity can be a cause of error by acoustic and mechanical vibrations of the whole sensor.[11]

Even after choosing the correct type of sensor several effects need to be addressed that can still influence the validity of the output data.

First one to mention is sensor acceleration. If the sensor is mounted in a place that can be moved, it can read this movement as a false change in pressure. This can be avoided by properly fixing the sensor and emplacing it to a place that is not prone to moving. Alas, this is sometimes not achievable in combination with the requirements on the sensor placement. If this is the case. Cross examining with other sensors placed on immovable parts and with other quantities such as arc voltage and current can help to filter out this error. Additionally, if the movement is mostly caused by the contact movement, the test can be performed without load and the data can be used for filtering.

As the sensor cannot be used alone but in a conjunction with an adapter, there is another phenomenon influencing the measurement. The sensor and adapter create a resonator and superimpose a high frequency oscillations on top of the actual waveform. But if the frequency of these oscillations is much higher than of the pressure, it can be filtered out by low-pass filter either hardware or in post-process.

Last but not least, there is a problem common to a switching device pressure measurements and it is thermal shock. This leads to pressure decrease that does not reflect real conditions. The only way to address this is to apply protective grease layer of appropriate thickness.[9]

4.4 Fast camera

Many of the previous measurements are used to assume the arc behaviour from indirect effects. The usage of fast camera provides data about actual arc movement and behaviour. This in conjunction with measurement of mechanical movement without load can bear significant insight into the inner workings of the designed device.

Both test with and without load carry their own advantages and shortcomings but both can prove invaluable as a diagnostic tools. While other methods were basically universally applicable this is often not the case of fast camera. This is caused by the simple need of a direct optical path to the spot desired to observe.

First, let us aim to investigate process which is without an arc for the majority of time. For example the dynamics of closing contacts. It is needed both to use a light source and to recapture the light. Seldom is the optical path is open and it has to be created. The simplest way is cutting open the side of the enclosure and aligning the light source with the camera and recording the reflected light. Even if there is no arc which would be affected by the pressure changes caused by the alteration of the enclosure, the natural frequency of the system can be altered and thus, for example the contact bounce can differ after this change. To counteract this, the missing part can be replaced by a translucent part to a varying degree of success. To address this disadvantage, the position of the light source can be changed. It can directly face against the camera and not capture the reflected light but the shadow cast by the observed object. A source of parallel rays of light is needed for this and in both cases the access to the contacts or any other observed part cannot be obstructed by any part that either cannot be removed or is opaque.

In case of arc measurements, the light source is not needed for every type of measurement as the arc produces light of its own. Depending on the switching load, the intensity of the arc changes and determines the measurement method. For low intensities one needs to again resort to removing a part of the device but now the replacement with translucent part is not optional. This in addition to the problems mentioned above creates the problem of adding a new type of plastics to the immediate vicinity of the arc. This can alter the transport quantities of the arc by the process of ablation. With high power arc the intensity can be high enough to radiate even through the plastic enclosure. But this is not always the case as some plastic materials can absorb the light emitted by the arc. Then even for high power arcs one needs to again resort to the first approach.

But if none of the previously mentioned methods is sufficient there is one more approach to spot the arc movement. It is based on the methods used for the movement without load but instead of using regular light source a laser light with wavelength both not emitted by the arc and not absorbed by the enclosure and a narrow band filter are used. The laser light source can again be positioned either aligned or facing the fast camera.

There are more uses for filters in arc measurement. If the arc composition is known in advance either by previous measurements or by accounting for contact and plastic materials, wavelength emitted by only one of the present element can be chosen. Thus, its distribution in arc can be observed. This finds its application for example in observing arc erosion and follow-up re-deposition of contact materials.

It is important to mention another method of an optical observation primarily used when fast cameras did not have high enough resolution. It is the usage of optical fibre arrays. Basically, a matrix of points in the enclosure could be created and the emitted light could be transfered by optical fibres to a photosensitive element which converted the photosignal to a voltage signal. From this the position of the arc may be assumed. This while only giving discrete information about the arc location can be done in great success while limiting the influencing the actual switching.[12]

For all the previously mentioned approaches, apart from qualitative evaluation, a measurement of movement based on tracking chosen points is possible while having referential dimension for each setup. This can be done in any relative position of camera and the plane in which the movement is realized. The measurement is most easily accomplished when the plane of movement is parallel to the plane of lens. This is often the deciding factor in camera placement together with limiting factors of the optical path.

5 Preliminary measurements

The goal of this thesis was to realise changes that reduce or eliminate the occurrence of sticking and back-commutation phenomena. Therefore, the time and location of their occurrence had to be determined first. This had to be done by reliable and non-invasive methods.

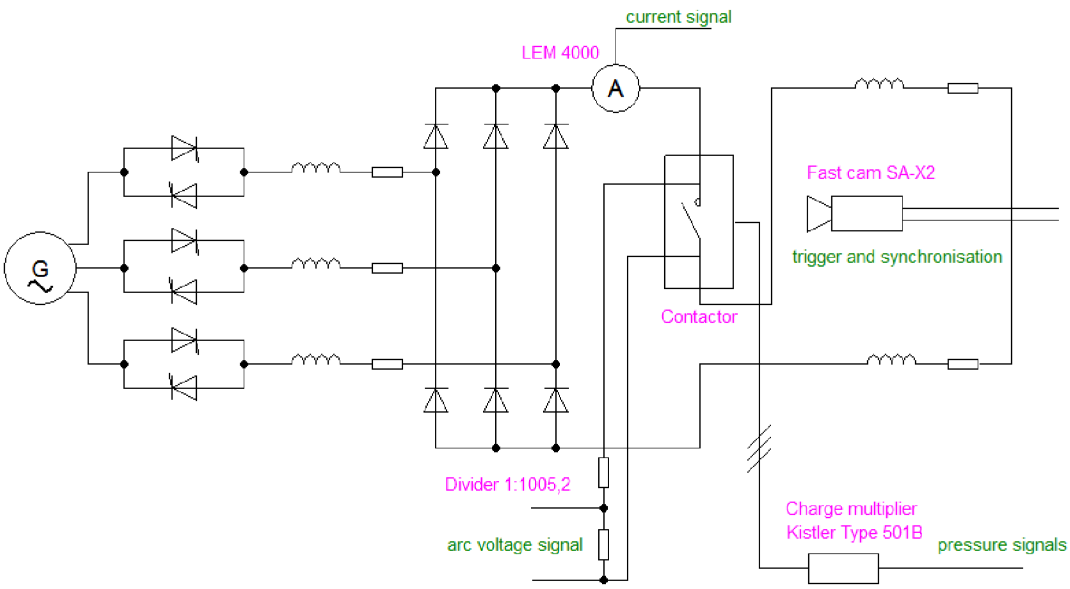

Fig. 5.1: Measurement setup

The whole setup is shown in the fig. 5.1. Not all parts were always used. But the parameters of the circuit were always the same.

The first measurements were done without fast camera due to the plastic material of the contacor sample. The contacor was tested at 1800 V of DC voltage at current 1700 A and time constant 1.51 ms. The purpose was to determine several things - if there is a relation between the pressure waveforms and voltage drops caused by the back-commutation, if there are any significant pressure gradients causing either arc stagnation or transfer of particles from the arc back to places with shorter electrode distance and thus helping back-commutation.

The second measurement was performed after acquirement of a previously used enclosure which transmits light. Thus, fast camera could be used to actually determine the places where the sticking and back-commutation occur. The contacor was tested at 2250 V of DC voltage at current 960 A and time constant 8.6 ms. To synchronise the data and reliably link the events on camera recording and voltage waveform, data card NIUSB-6361 BNC or trigger signal waveform from the system was used. The pressure was not measured this time to streamline the process.

The third measurement was a combination of the previous ones. This was to link the pressure waveforms with voltage ones while gaining more data on the problem tackled in second measurement.

5.1 Pressure measurements

The pressure was monitored in three places. Their location was determined both by separate function of each location and by limitation given by contactor construction.

The three chosen places were: at the start of arcrunner 1 (1), in the middle of the trajectory to the quenching chamber (2), at the ceramic plates (3) as shown in the fig. 5.2.

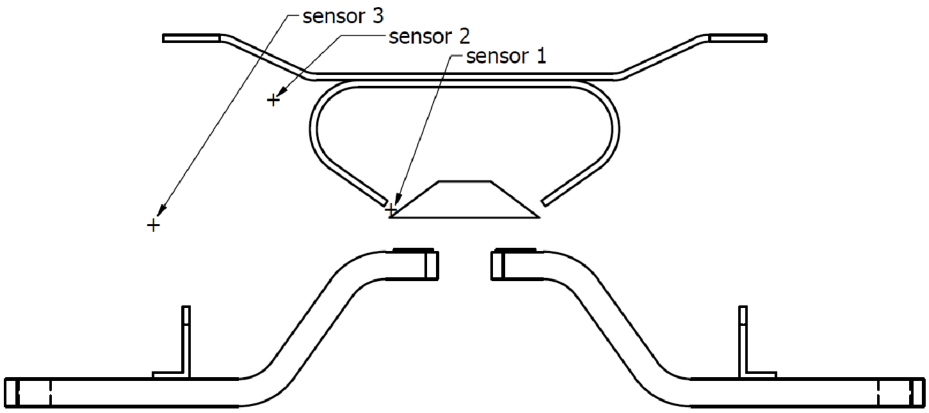

Fig. 5.2: Pressure sensor placement

Several types of pressure sensors were available. All of them were tested to select the most suitable one. All of them contained charge output which is suitable for high temperature range and dynamic measurement. All of them had sufficient pressure and temperature ranges. They used the same connection system and charge amplifier so, they were comparable.

The comparison was based on influence of mechanical vibrations. Due to the fact that the better properties like shock resistance and natural frequency the worse the linearity of the sensor is. So, the sensor with the best linearity which was not yet influenced by the mechanical vibrations was chosen.

These tests were done for sensors 603B, 701A, 601C produced by the company Kistler.

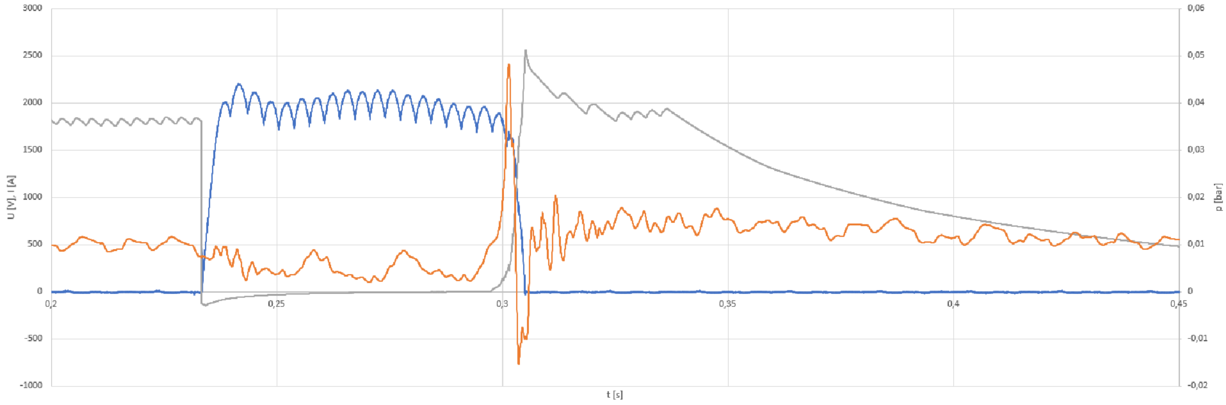

Fig. 5.3: Sensor 603B

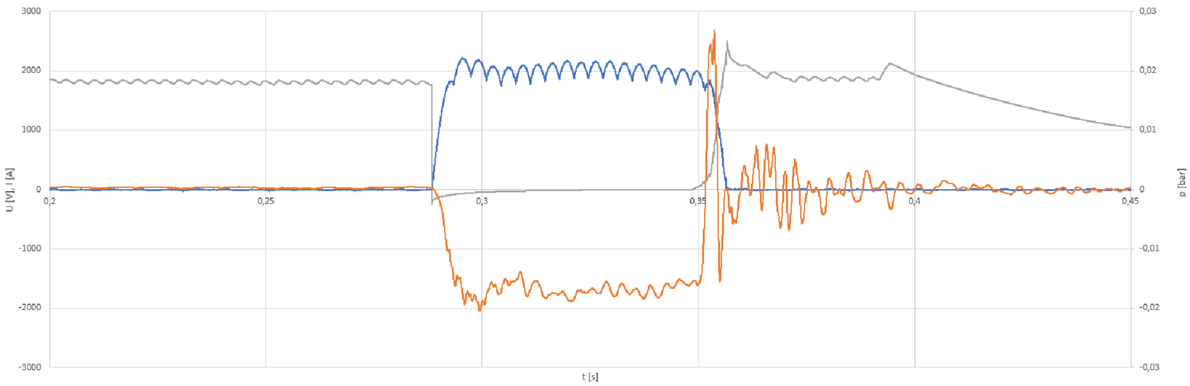

Fig. 5.4: Sensor 701A

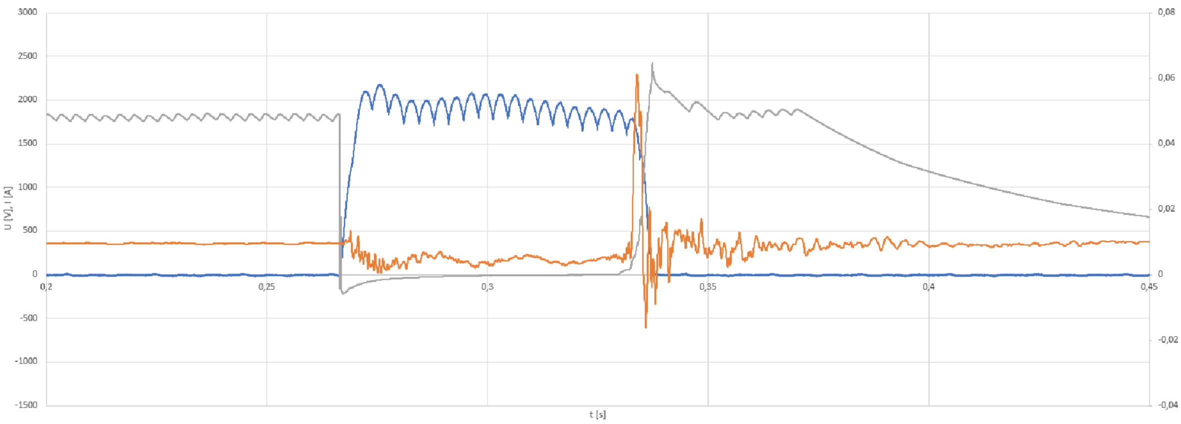

Fig. 5.5: Sensor 601C

By comparing the fig. 5.3-5.5 the impact of closing of the contacts can be observed. The sensor 701 A reads this as a change in pressure and gives output with constant offset. This was not suitable for further measurement due to the mechanical stress to the enclosure.

Both 603B and 601C do not react to this operation so severely but the change in value can be observed in both waveforms.

But the sensor 601C has much lower distortion of the signal and as such it proves to be the most suitable sensor to be used.

The sensors were then tested by switching with no load on mechanical stress and interference from the surroundings.

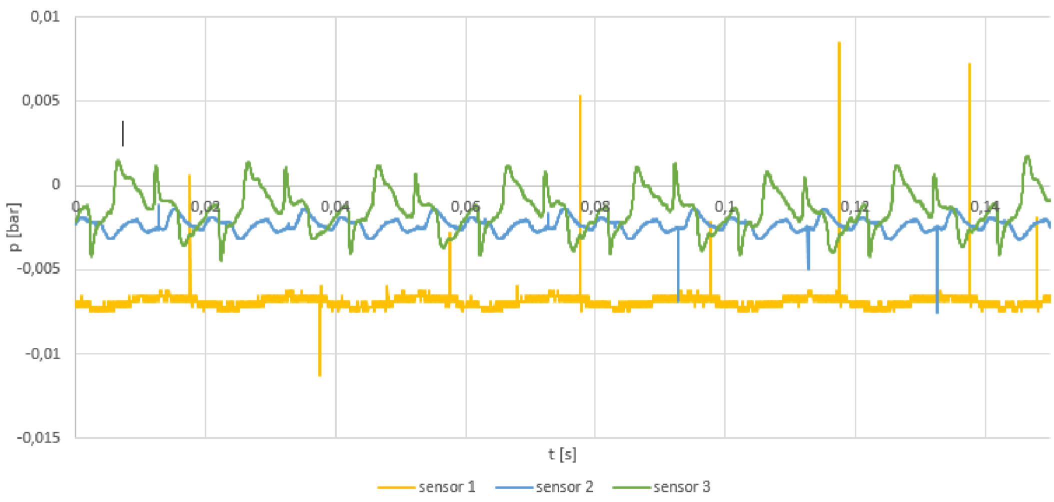

Fig. 5.6: Switching with no load

This figure shows that the mechanical impact cannot be distinguished by the sensors and that the peak-to-peak value of the interference reaches maximally 5 mbar which is about 10% of the pressure rise measured during the switching with load.

5.2 High speed camera

The high speed camera was used at first to determine the location of places where the arc sticks and where does the back-commutation occurs. This was done together with arc voltage measurement so, its changes can now be reliably described in dependence on the arc location and movement.

The process of arc movement in the chamber consisted of several phases. Some of them could be skipped whereas some of them occurred always. The sequence is listed in the order of occurrence.

- sticking in position 1
- transfer of arc root to arcrunner 1 joined with back-commutation back to the moving contact
- sticking in position 2
- quick change of arc root from arcrunner 1 to arcrunner 2 (position 3)
- quick change of the lower arc root to position near arc runner 4 (position 4) often joined with back-commutation to position 2 or 3
- slow transit to position 5

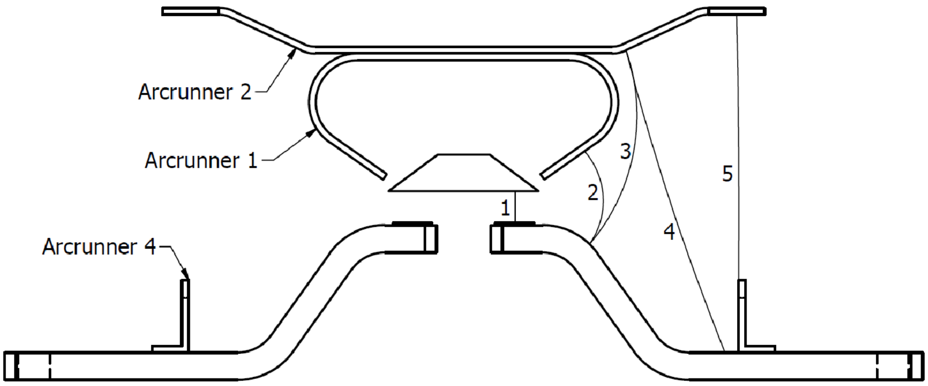

Fig. 5.7: Arc movement positions

To put these stages into perspective, the images taken by the fast camera were compared to voltage waveforms.

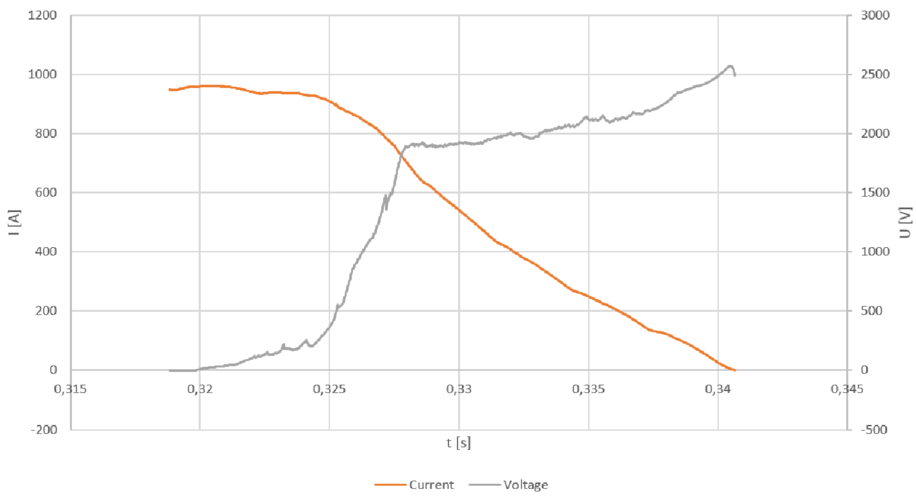

Fig. 5.8: Arc voltage and current waveforms

In the fig. 5.8, several of the mentioned stages can be discerned. A slow rise in voltage can be seen from 320 ms to 322.6 ms. This signifies that the arc is staying between the contacts. The period from 322.6 ms to 324 shows a transfer from position 1 to 2 and 3. This was accompanied by several back-commutations onto the moving contact. These re-strikes are signified by a drop in voltage. Then from 324 ms to 327.9 ms the arc is in position 4 and just slowly transfers to the position 5 and comes into contact with the ceramic plates. This is marked by a now steeper rise in voltage. This rise is again disrupted by a fall in 327 ms. This was again a back-commutation to the position 2. After that arc burns on the plates from time 327.9 ms to 340.7 ms. This is again shown as a slow rise in arc voltage.

That means it takes the arc 7.9 ms from 20.7 ms total to reach the quenching chamber. The average of these times from 20 measurements is 7.65 ms and 21.49 ms respectively. This amounts to 35% of arc time is used solely on arc movement and contributes only a little to the breaking itself.

This applies only to a fully successful breaking. But switchings can occur that proceed abnormally and the arc movement takes up to 70% of the time. These switchings, while not common, are significant contributors to the degradation of the device.

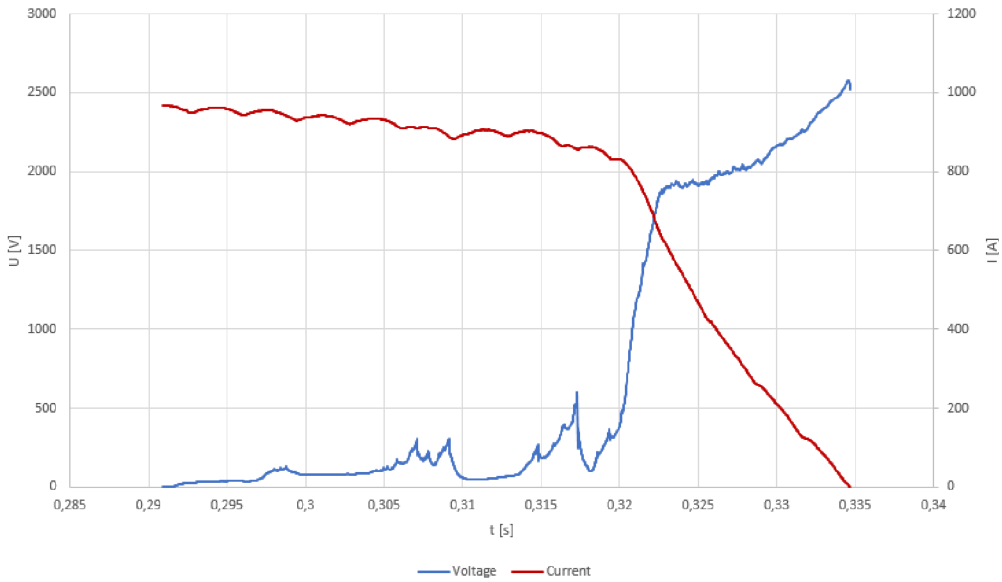

Fig. 5.9: Abnormal breaking

5.3 Combined measurement

This last test was performed to find out if it can be reliably determined where the back-commutation occurs from the pressure waveforms. The same pressure sensor position as for the separate pressure measurement was used. The time synchronisation with camera was done by reading the camera trigger as a new input signal. But the signal from the sensor no.3 was either so low that it was indistinguishable from background or was lost due to other reasons. Therefore, it was discarded.

The purpose was to provide an alternative way to determine the location of back-commutation occurrence in the case the changes to the magnetic yokes would limit our ability to observe the arc by means of fast camera. Alternatively, this approach will be useful in the final tests with enclosure which does not transmit the light.

From the performed tests it can be stated that with pressure waveforms alone nothing can be assumed about the arc position. However, in conjunction with arc voltage differences between transitions between different positions can be discerned as shown in fig. 5.7.

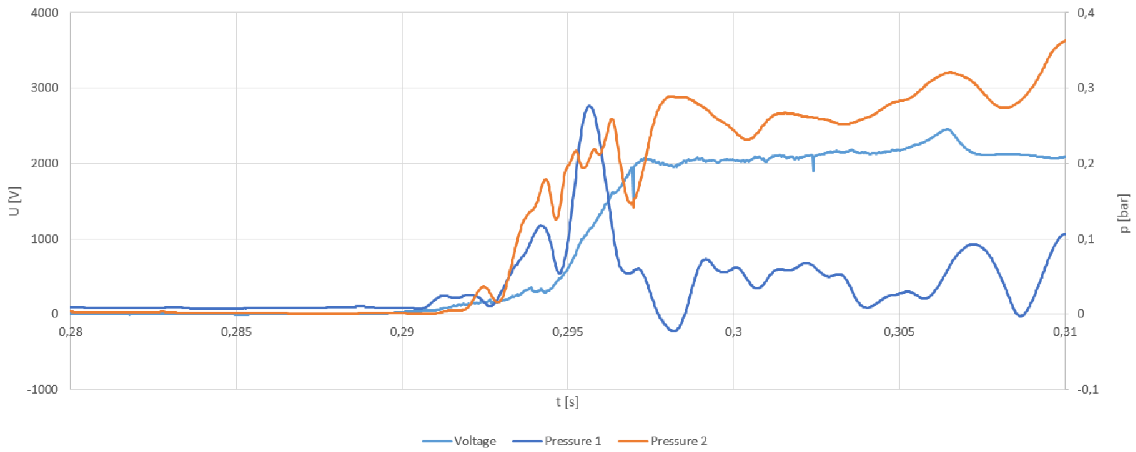

Fig. 5.10: Combined measurement

As stated before, if the time of back-commutation occurrence is to be determined the voltage waveforms need to be analyzed as described in previous chapters. Then, the pressure waveforms in corresponding time need to be observed. If the curves copy the same shape as shown in time 294 ms in fig. 5.10, the jump appeared from position 3 or 2 to position 1 and as such was detected by sensor number 1. But if the first sensor is undisturbed and only the second sensor records a change, then the back-commutation occurred between position 4 and 3. This is shown in time 297 ms in fig. 5.10.

This differentiation can be enhanced by adding pressure measurements to more places and thus having more references. But this will be done only if the opportunities to use fast camera become limited.

6 Possible solutions to back-commutation and sticking

One of the possible ways that have been used is a usage of a narrow slot or a hybrid of a slot and arch chute. This has been proven to make the transition to increased voltage smoother and gave the arc more time to adapt. Although this is also connected to lowering of the peak arc voltage it is still a good way to address this problem. There are several proposed mechanisms why it is so. The close insulator slot effectively cools the hot gas while also preventing it from moving back behind the arc. In addition, the plastic usage can serve as a gassing material to cool the gas and increase the dielectric strength of the gap. While this can be used when designing a new contactor it is highly unsuited for a small change to already existing device.[5][8]

Other possible solutions are given by [6], namely increase of recovery time. This is the time between the arc leaving a defined place and time of voltage increase due to lengthening or splitting. It has been shown that the re-strike voltage rises linearly after about 0.9 ms. This can be used in conjunction with slower arc motion to address the reignition problem without significant changes to the device. This can be done either by changing the magnetic field distribution by differently shaping the magnetic yokes or by changing the air vents to modify the aerodynamic forces influencing the arc. The magnetic field is also one of few ways to influence the sticking between the parting contacts, see fig. 6.1, where d is a contact gap length.

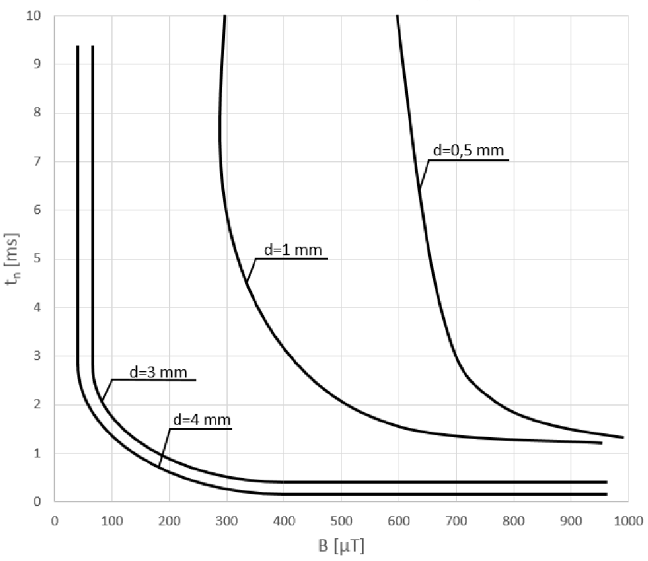

Fig. 6.1: Sticking time as a function of flux density [13]

Additionally, [6] gave other characteristics for increasing the re-strike voltage and thus preventing back-commutation. One of them is increasing the contact gap length. But the relation is highly non-linear and saturates at about 7 mm gap length. That is about half the length used so, this effect has already been fully used. Another of them is a small effect of the lateral wall distance. While slight changes to the distance could be implemented the change itself has both positive and negative effect. The closer the walls are the more effective the cooling and gassing of the insulating material is. However, at the same time the close walls distort the electric field. Other mechanism influenced by lateral wall distance is presented by [7]. They demonstrated influence of wall distance on temperature and pressure field distribution in DC CB by experiment and simulation but concluded that under 100 mm distance these effects are negligible. Even though this number will differ for every device one can argue that there is a limit to reduction of wall distance which when reached bears no more benefit. For this, change of wall distance was not considered as a primary option.

Another approach was mentioned by [8] and it is to appropriately shape the arcrunners to achieve maximally smooth increase in arc voltage to reduce the chance of back-commutation while choosing the right material. This is a sensible solution for arc runners 2-4 because a change in their shape does not need to affect other parts while the amount of material used does not change considerably. The arcrunner material used by the providing company is either steel or bronze. For further testing bronze was used to prevent the material to distort the magnetic field used to propel the arc to the quenching chamber.

As demonstrated in previous chapter, the problems of sticking and back-commutation are generally linked together. The more the arc lingers in one place the more ionised the vapours in that place become and the higher the chance of re-strike is. Also the bigger the change in voltage when moving the longer it takes for the arc to move and again the bigger the chance of back-commutation. This can be addressed by the methods mentioned above with addition of increasing the magnetic field in the places where the sticking occurs and shaping the arcrunners 2-4 are the most viable.

So, to conclude the selected changes to the contactor are:

- shapes of arc runners
- shape of yokes to influence the magnetic field distribution
- size of air vents

7 Alterations of contactor parts

The main changes were done to arcrunners 1 and 2 and pole plates 1, see fig.7.1. This was both due to the fact that according to available literature they might be suitable for addressing the back-commutation problem and changes made to them do not pose a technological problem. All these separate changes are addressed in the following sections.

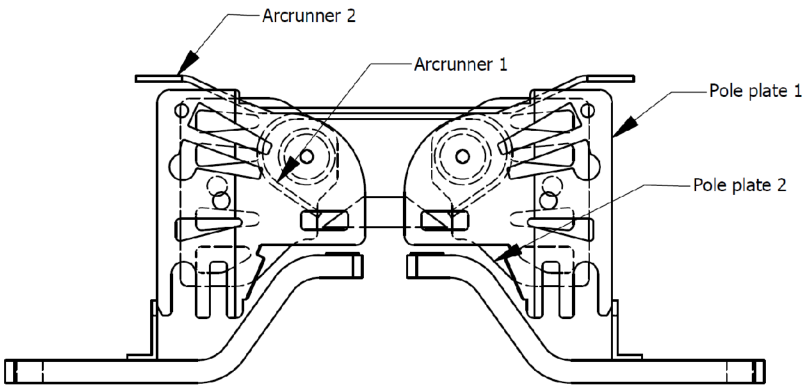

Fig. 7.1: Altered parts in a setup

7.1 Arcrunner 1

The arcrunner 1 had been modified into two versions. Both of them with the aim to shorten the sticking time between the contacts. This was done by stretching the ends of the arcrunner apart to shorten the air gap between them and the arcrunner 3 (the main current carrying path). The narrower gap makes it easier for the arc to transition from the moving contact to the arcrunner 1. On the other hand, the now lower dielectric strength of the shortened gap makes the breaking process more susceptible to back-commutation.

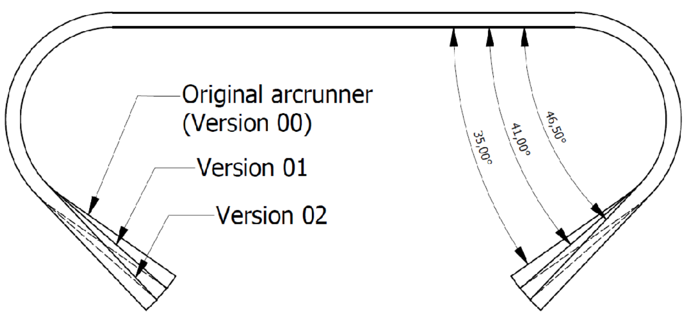

Fig. 7.2: Versions of arcrunner 1

7.2 Arcrunner 2

The most extensive changes were done to arcrunner 2 due to the fact that the gap between the arcrunners 1 and 2 is the source of most of the addressed negative phenomena. As stated before, the change in arc length should be as fluent as possible.

Apart from closing the gap, as mentioned above, it was tested whether the lateral length of arcrunner 2 has any influence on the quenching process. The idea was that better prolongation of the arc could be achieved if longer electrode was used. This was tested in version 2. However, the tests showed that the arc root position did not change. This was observed by comparing the erosion of version 1 and 2 after tests.

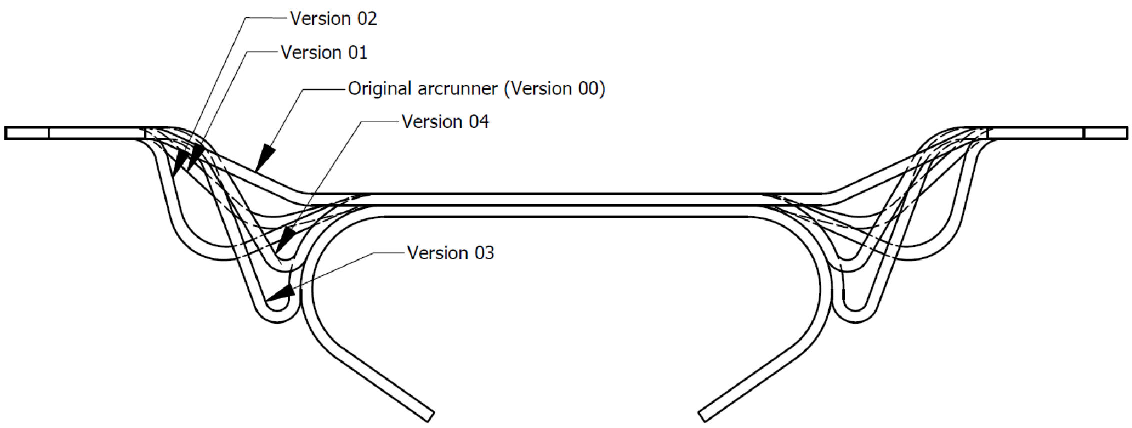

Fig. 7.3: All versions of arcrunner 2

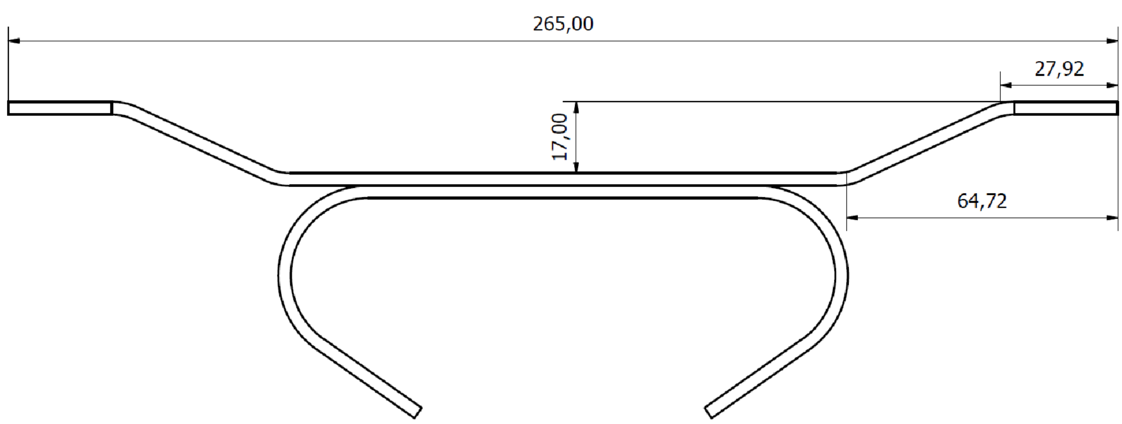

Fig. 7.4: Original arcrunner 2

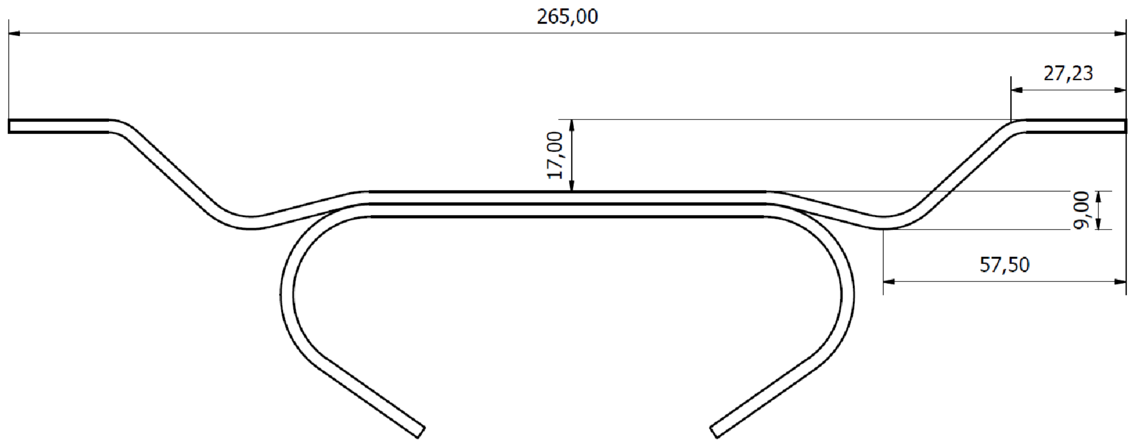

Fig. 7.5: Version 1 of arcrunner 2

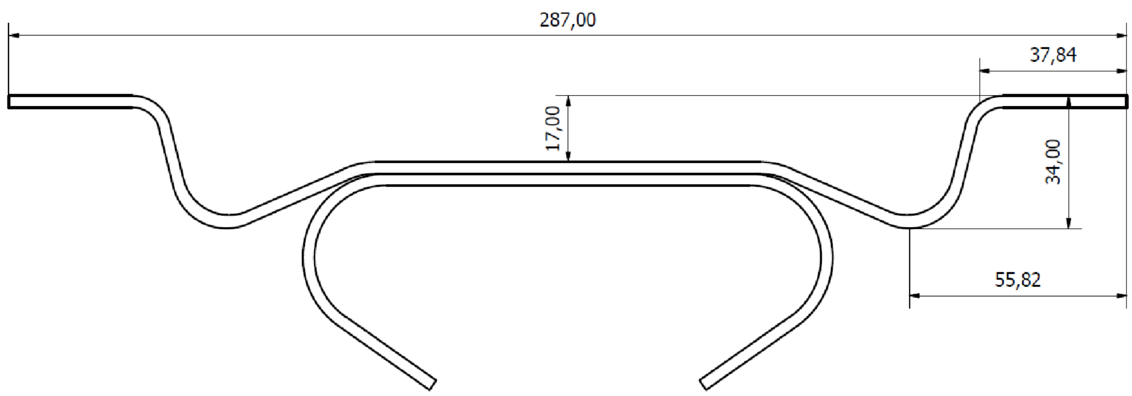

Fig. 7.6: Version 2 of arcrunner 2

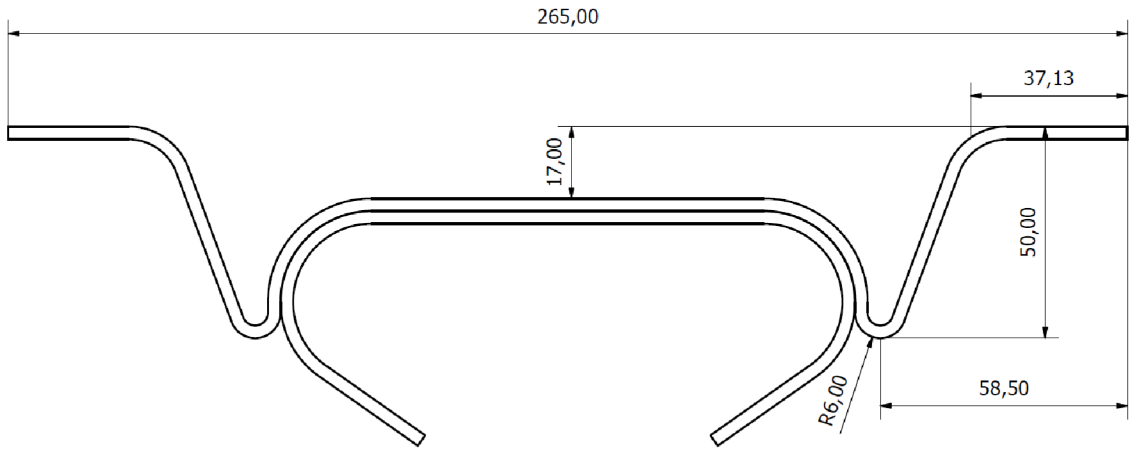

Fig. 7.7: Version 3 of arcrunner 2

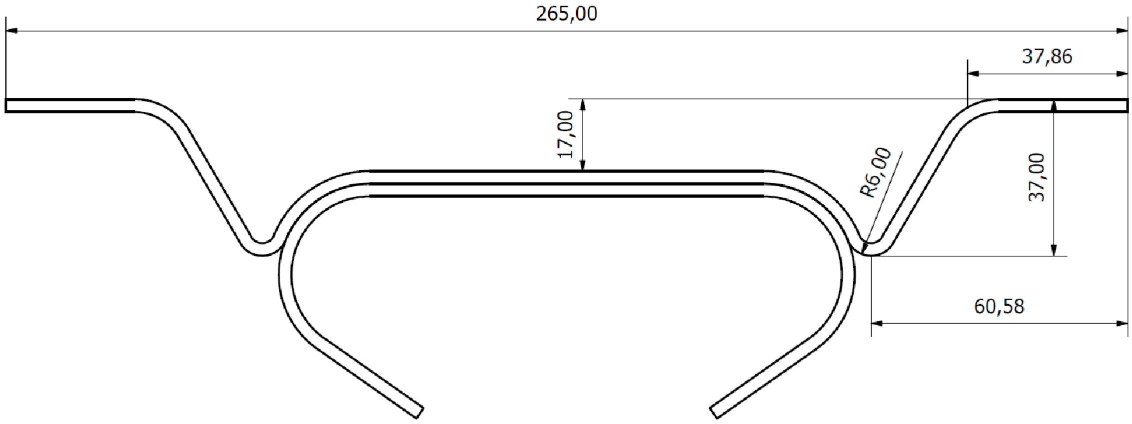

Fig. 7.8: Version 4 of arcrunner 2

7.3 Pole plates

The pole plate 1 was altered by adding two pieces in the immediate vicinity of the contacts to speed up the process of arc leaving the contacts. Version 1 was done by filling a gap in the original pole plate. Version 3 was achieved by adding a part bellow the original piece. Version 2 was a combination of the previous changes.

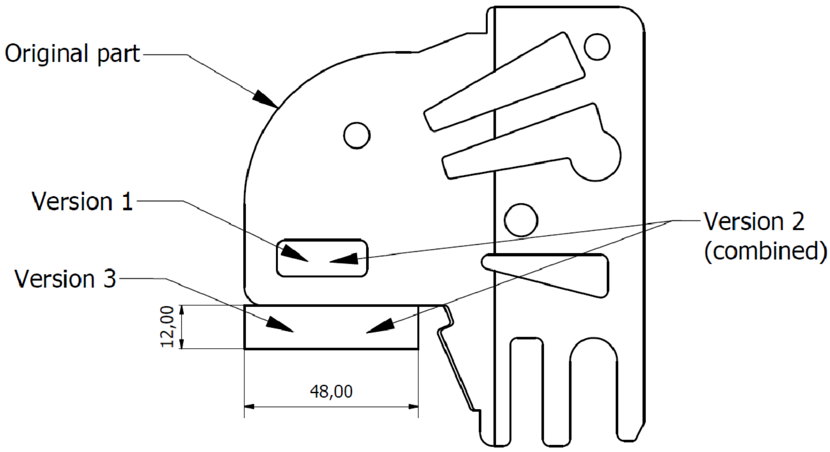

Fig. 7.9: Versions of pole plate 1

8 Methodology

All tests were done with the same setup as preliminary tests. The first series of tests was done on the prototype chamber. This brought the possibility of observation by highspeed camera. However, the chamber was becoming worn out due to ablation of plastic. This led to several test failures. For this, the serially manufactured chamber was used further on. This led to prolongation of all switching times due to the different plastic used for this new chamber.

Tests of all parts were done in series of minimally five tests. Between each test, there was a three minutes long waiting time to allow the chamber to cool down. The contactor was cooled again by pressurised air between each set of tests (different configuration) to provide comparable data.

However, even with this the new chamber also degraded over the time and the breaking performance worsened. For this, the test of original configuration with no alterations was repeated several times and the results are therefore be expressed as percentual changes in behaviour.

8.1 Measured quantities

To be able to compare the individual breakings, metrics were needed. Two primary ones were chosen. The time from separation of the contacts (rise of arc voltage) to the arc being fully transported onto the ceramic plates. The end of this period can be dicserned on voltage wavefunction as the first peak. This was confirmed by fast camera observations. This time was labeled as t_1. And time from contacts separating to current zero was labeled as t_2.

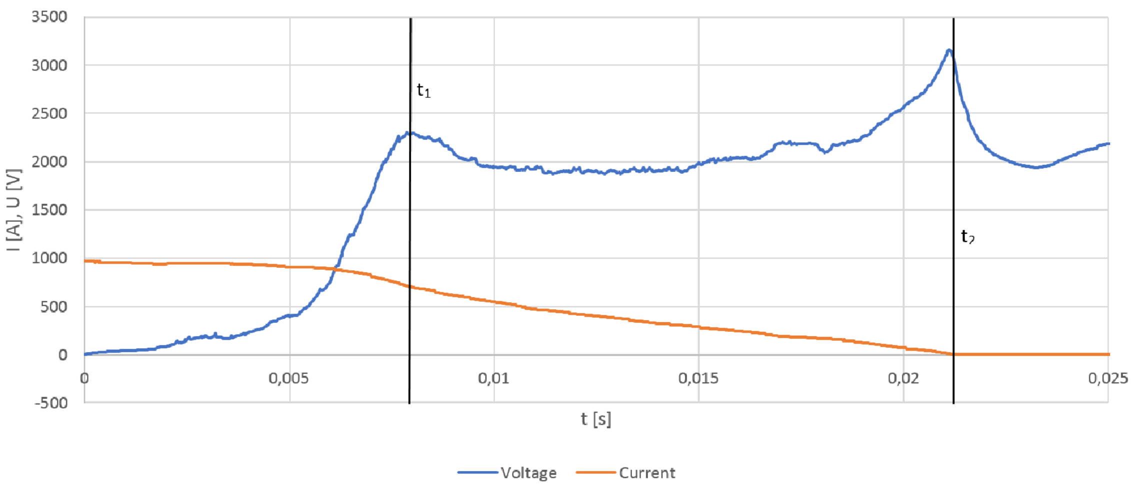

Fig. 8.1: Demonstration of t_1 and t_2

9 Measured data

In this chapter, all relevant test results are provided. Tests with no alterations are labeled "no changes". Alterations to the arcrunners are labeled AR"number of arcrunner"-"version". For example, version 1 of arcrunner 2 was labeled AR2-01. Pole plates were labeled PP-"version". If a part is missing label of a part, the part was not altered.

A worsening of the total switching time t_2 can be observed in a substantial part of the data as the number of test increased. This can be attributed to heating of the chamber.

With both prototype and the new chamber, first tests were sometimes discarded as an outliers due to impurities from assembly being burned away by the first test. These data are crossed out and are not accounted for in the averages.

9.1 Prototype chamber

test no.	t_1	t_2
1	8.00	21.28
2	9.92	22.40
3	8.16	20.88
4	6.72	20.00
5	8.64	22.32
6	6.80	20.88
7	7.04	21.28
8	6.96	22.40
9	6.64	22.00
avrg.	7.65	21.49

Tab. 9.1: No changes

test no.	t_1	t_2
1	6.42	23.86
2	7.38	23.88
3	7.44	23.90
4	7.42	24.06
5	7.20	25.54
6	8.90	28.22
7	7.66	28.58
8	7.24	30.74
avrg.	7.46	26.10

Tab. 9.2: AR2-01

test no.	t_1	t_2
1	7.54	17.14
2	7.52	18.16
3	7.76	18.06
4	9.22	18.92
5	6.92	17.58
6	9.06	20.56
7	7.04	18.66
8	7.70	19.32
9	8.56	20.04
10	8.78	20.62
avrg.	8.01	18.91

Tab. 9.3: No changes

test no.	t_1	t_2
1	7.60	29.34
2	7.42	30.36
3	7.20	33.34
4	7.20	29.02
5	7.56	30.58
avrg.	7.40	30.53

Tab. 9.4: PP-01

test no.	t_1	t_2
1	8.96	20.46
2	9.70	22.08
3	7.42	20.00
4	7.78	20.10
5	6.44	20.06
6	6.70	20.26
avrg.	7.83	20.49

Tab. 9.5: AR2-02

test no.	t_1	t_2
1	8.20	20.00
2	7.88	20.20
3	7.74	18.48
4	8.14	21.16
5	8.20	20.64
avrg.	8.03	20.10

Tab. 9.6: No changes

test no.	t_1	t_2
1	6.70	22.00
2	7.20	22.84
3	7.64	23.32
4	7.56	22.72
5	7.54	23.72
avrg.	7.33	22.92

Tab. 9.7: PP-01

test no.	t_1	t_2
1	~~13.34~~	~~24.80~~
2	7.30	21.08
3	7.14	20.54
4	7.02	21.44
5	7.00	21.42
avrg.	7.12	21.12

Tab. 9.8: PP-02

test no.	t_1	t_2
1	7.60	21.36
2	6.78	22.06
3	7.48	22.36
4	6.66	22.12
5	7.74	23.14
avrg.	7.25	22.21

Tab. 9.9: PP-03

All the alterations proved effective in shortening the travel time t_1. However, all of them suffer from prolongation of overall time t_2. This was due to lower arc voltage when in contact with the ceramic plates.

In case of altered pole plates, this can be attributed to lower magnetic field in the vicinity of ceramic plates. That led to smaller prolongation of the arc and thus lower voltage.

At this point, no arcrunner 2 had yet been chosen for further testing. However, from the three tested pole plate alterations version 2 was chosen as it had provided shortest times for both t_1 and t_2.

9.2 New chamber

test no.	t_1	t_2
1	7.92	21.28
2	7.30	22.14
3	7.48	22.84
4	7.88	23.70
5	7.68	23.16
avrg.	7.65	22.62

Tab. 9.10: No changes

test no.	t_1	t_2
1	7.56	22.38
2	7.40	23.06
3	7.70	23.54
4	6.78	22.90
5	6.67	23.62
avrg.	7.22	23.10

Tab. 9.11: AR1-01

test no.	t_1	t_2
1	6.78	23.00
2	7.38	23.48
3	7.86	23.78
4	7.06	23.42
5	7.38	25.34
avrg.	7.29	23.80

Tab. 9.12: PP-02

test no.	t_1	t_2
1	7.26	23.62
2	6.88	23.48
3	6.96	24.78
4	6.66	24.26
5	6.68	24.14
avrg.	6.89	24.06

Tab. 9.13: AR1-01;PP-02

test no.	t_1	t_2
1	6.88	22.08
2	7.88	23.22
3	6.94	21.82
4	8.86	23.94
5	7.00	22.76
avrg.	7.51	22.76

Tab. 9.14: AR2-03

test no.	t_1	t_2
1	6.68	21.74
2	6.98	22.22
3	8.08	24.86
4	7.16	24.84
5	7.12	25.42
avrg.	7.20	23.82

Tab. 9.15: AR1-02

With the new chamber, the original setup was tested again to account for the change of plastic material and minor construction details. Also, version 2 of pole plates was tested again.

Arcrrunner 1 was the focus of this group of tests. Version 1 again followed the trend of shortening the time t_1 and prolonging the time t_2. Version 2 only furthered this trend. However, it shortened t_1 by only a negligable amount but prolonged t_2 by 0.7 ms. For this, no further widening of arcrunner 1 was tested and for any further tests version 1 was used.

Also, combination of pole plate version 2 and arcrunner1 version 1 was tested. This let to further shortening of time t_1 and slight prolongation of time t_2.

test no.	t_1	t_2
1	7.14	24.58
2	7.22	24.20
3	7.62	26.54
4	7.16	26.28
5	7.36	28.26
avrg.	7.30	25.97

Tab. 9.16: No changes

test no.	t_1	t_2
1	6.52	24.90
2	6.76	25.08
3	6.76	24.38
4	7.10	26.92
5	7.54	25.26
avrg.	6.94	25.31

Tab. 9.17: AR2-03

test no.	t_1	t_2
1	7.34	23.24
2	7.14	22.68
3	7.50	23.46
4	6.52	22.78
5	6.92	23.94
avrg.	7.08	23.22

Tab. 9.18: AR2-03;AR1-01

test no.	t_1	t_2
1	~~16.68~~	~~30.94~~
2	7.28	24.10
3	6.78	24.30
4	6.88	24.56
5	6.62	25.04
avrg.	6.89	24.50

Tab. 9.19: AR2-03;PP-02

test no.	t_1	t_2
1	6.60	23.40
2	6.40	23.08
3	6.30	24.58
4	6.82	24.68
5	6.28	25.32
avrg.	6.48	24.21

Tab. 9.20: AR2-03;AR1-01;PP-02

test no.	t_1	t_2
1	7.70	23.10
2	7.36	25.02
3	7.24	24.40
4	8.26	24.94
5	7.34	24.56
avrg.	7.58	24.40

Tab. 9.21: AR2-04

test no.	t_1	t_2
1	7.70	26.08
2	6.42	26.02
3	6.30	27.08
4	7.28	28.32
5	6.32	28.08
avrg.	6.80	27.12

Tab. 9.22: AR2-04;AR1-01

test no.	t_1	t_2
1	7.06	25.34
2	6.92	24.84
3	7.06	26.30
4	6.96	24.96
5	6.96	27.16
avrg.	6.99	25.72

Tab. 9.23: AR2-04;PP-02

test no.	t_1	t_2
1	6.98	25.00
2	6.42	24.16
3	6.60	24.72
4	6.84	24.92
5	6.54	26.18
avrg.	6.68	25.00

Tab. 9.24: AR2-04;AR1-01;PP-02

In this group of tests, only AR2-04;AR1-01 and AR2-04;PP-02 performed worse than the original by any of the chosen metrics.

AR2-04 performed worse in every combination of parts than AR2-03. For this, it was discarded from further considerations.

From the combinations with AR2-03, AR2-03;AR1-01 had the shortest total switching time t_2 of 23.22 ms which is 10.6% improvement over the original version. However, AR2-03;AR1-01;PP-02 had the lowest time t_1 of 6.48 ms which is an improvement of 11.2%.

	t_1	t_2
No change	7.30	25.97
AR2-03,AR1-01	7.08	23.22
AR2-03;AR1-01;PP-02	6.48	24.21

Tab. 9.25: Comparison of the best results

9.3 Influence of back-commutation

t_2 is a necessary parameter whose value needs to be equal or lower to the t_2 of the original chamber not to worsen the switching performance of the device. However, it does not point to whether the problem with back-commutation and sticking have been addressed.

The parameter t_1, while expressing the goal of reducing the time of arc travel time, can be influenced by other phenomena apart from sticking and back-commutation (eg. by magnetic field distribution).

To check for the influence of back-commutation, delays caused by it were calculated and voltage waveforms were compared.

9.3.1 Determination of delay caused by back-commutation

The time delay t_d was defined as the time needed for the arc voltage after back-commutation to reach its original value before the back-commutation as shown in fig.9.1. The total time delay was not calculated from every drop but only from drops lasting at least 0.1 ms. This can lead to a substantial error due to the high number of small changes in voltage as the arcs transition from moving contact to the arcrunners. For this, the quantification of delay is to be used only as a comparative method between the used alterations. It needs to be accompanied by a qualitative comparison of the voltage curves.

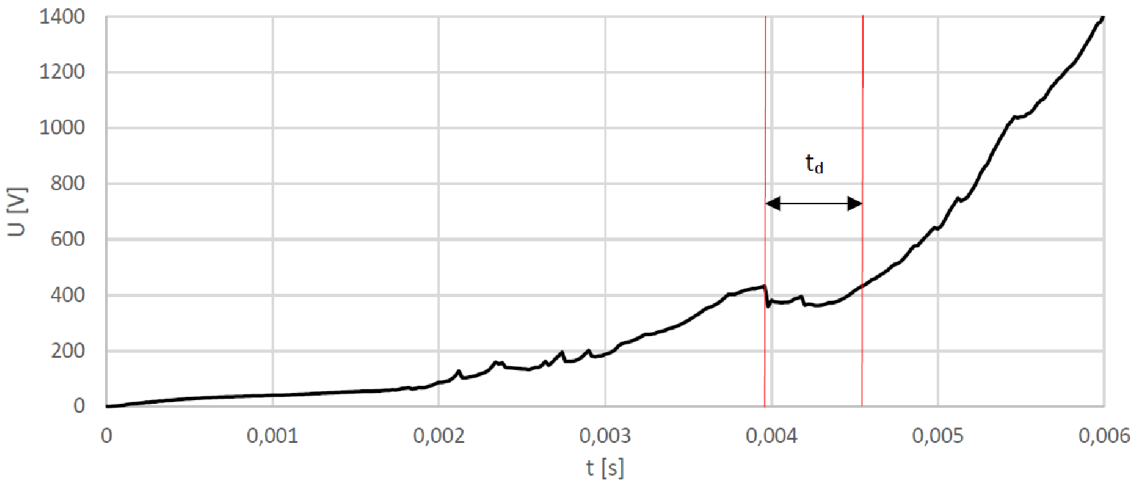

Fig. 9.1: Back-commutation delay

9.3.2 Comparison of the final versions

Although the version AR2-03;AR1-01 achieved the shortest switching times, version AR2-03;AR1-01;PP-02 had both the shortest time t_1 and time t_d. It also had the smoothest voltage waveforms during the transition period of breaking. Examples of these waveforms are provided in fig. 9.2, fig. 9.3 and fig. 9.4.

No change		AR2-03;AR1-01;PP-02		AR2-03,AR1-01	
test no.	t_d [ms]	test no.	t_d [ms]	test no.	t_d [ms]
1	0.84	1	0.40	1	1.24
2	0.78	2	0.60	2	0.76
3	1.02	3	0.40	3	1.30
4	1.72	4	0.26	4	0.38
5	1.44	5	0.96	5	0.66
6	0.50	6	0.32	avrg.	0.87
7	0.94	avrg.	0.49		
8	1.76				
9	0.92				
10	0.84				
avrg.	1.08				

Tab. 9.26: Delay times

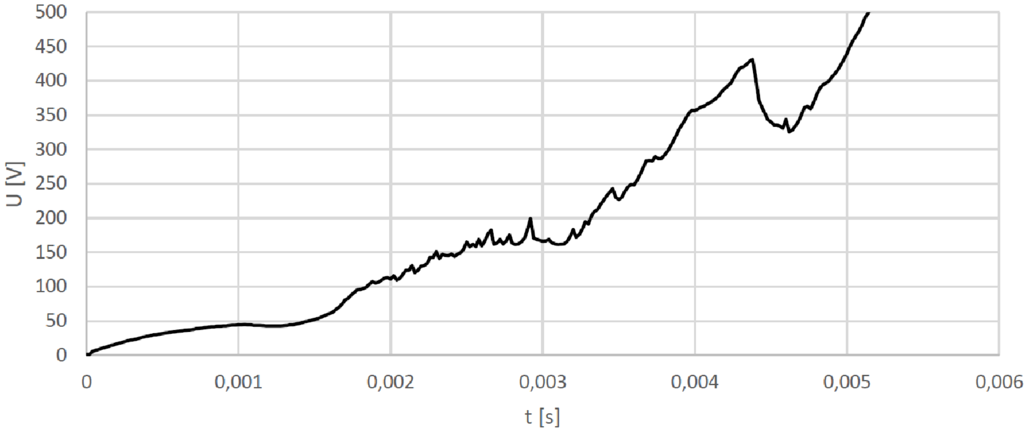

Fig. 9.2: Arc voltage - No change

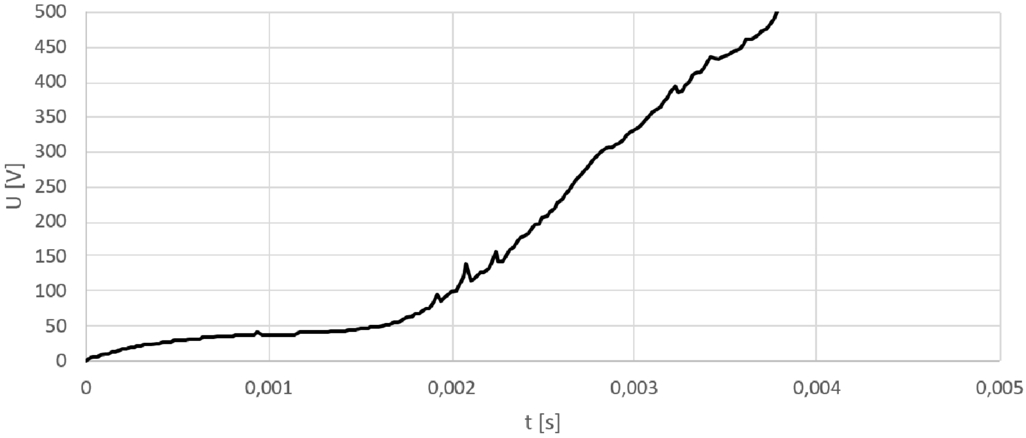

Fig. 9.3: Arc voltage - AR2-03;AR1-01;PP-02

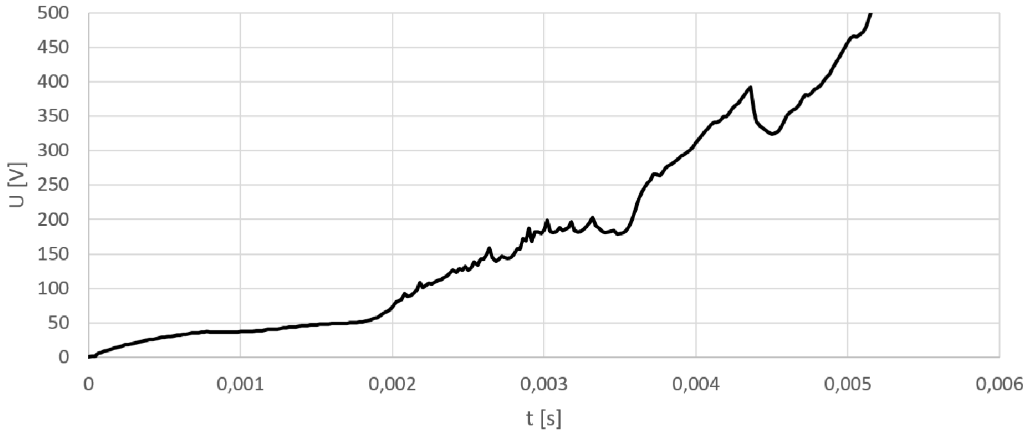

Fig. 9.4: Arc voltage - AR2-03;AR1-01

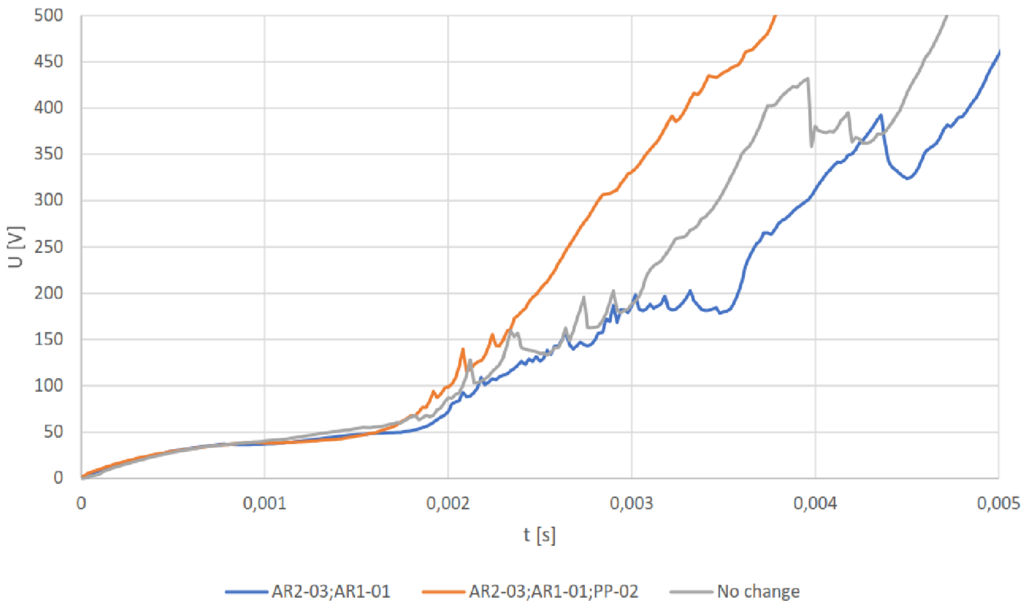

Fig. 9.5: Comparison of final versions

9.3.3 Control measurement

After the tests which compared different versions of the contactor, control measurement of only the version AR2-03;AR1-01;PP-02 and the original with no changes was carried out.

The tests were done in groups of five with five minutes between each test and cooling by pressurised air between each group. The parameters of the tests were the same as for all previous tests.

During these tests, the total switching time t_2 increased from 25 ms to values above 35 ms and in the last two tests the circuit was interrupted by the system rather than by the contactor. This was due to damage sustained by the quenching chamber over the course of the entire testing.

	No change		AR2-03;AR1-01;PP-02	
test no.	t_1 [ms]	t_d [ms]	t_1 [ms]	t_d [ms]
1	7.04	0.80	7.00	0.76
2	6.94	1.07	6.76	0.34
3	7.14	0.78	7.56	1.34
4	6.74	1.34	6.44	0.42
5	6.52	0.28	6.52	0.66
6	7.22	1.00	7.10	1.90
7	7.06	1.20	7.50	0.78
8	6.40	0.50	7.00	1.22
9	7.04	1.36	7.08	1.28
10	7.62	1.42	6.04	0.36
11	7.42	1.92	6.64	0.86
12	7.30	1.80	6.30	0.42
13	6.88	0.70	7.34	1.22
14	6.72	0.86	7.18	0.54
15	7.14	0.86	7.90	0.62
avrg.	7.01	1.06	6.96	0.85

Tab. 9.27: Control measurement

Again, the altered version has both shorter travel time and time delay due to back-commutation but because of the fact that the contactor failed to operate these tests do not bring reliable data about the improvement. For clearly determining the difference between original contator and the final version, tests on a new undamaged contactor would be needed.

10 Conclusion

After choosing appropriate diagnostic methods and examining the provided contactor, it has been concluded that the contactor's function to reliably transfer the arc from contact region to its quenching chamber is afflicted by two phenomena: sticking and back-commutation. Possible ways to address these problems were suggested while considering the limits of possible changes to the contactor.

The changes were focused on the arcrunners and pole plates of the contactor as they have the highest influence on arc mobility.

A combination of three alterations of the contactor was chosen:

- widening of the arcrunner 1 to allow easier arc transfer from the contacts
- shaping of the arcrunner 2 so the arc root transfer from arcrunner 1 to arcrunner 2 causes minimal prologantion of the arc
- changing the pole plates of magnetic circuit to increase the magnetic field in the vicinity of the contacts.

This modification limited the back-commutation both in the transition from arcrunner 1 to arcrunner 2 and during the transfer of arc onto the ceramic plates. This resulted in shortening of the arc travel time by 11.2% and the total breaking time by 6.8%.

To validate these results, final tests on a new contactor would be needed. As well as tests with different circuit parameters (current, voltage, time constant) would be needed to confirm if these alterations provide positive effect in the whole spectrum of switching currents.

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List of symbols, physical constants and abbreviations

TRV	Transient recovery voltage
i	Current
t	Time
L	Inductance
U_{c}	Source voltage
R	Resistance
U_{a}	Arc voltage
U_{m1}	Power frequency component of TRV
u_{c1}	TRV with only one frequency of oscillatory component
C	Capacitance
f	Frequency
Cu	Copper
W	Tungsten
Ag	Silver
E_{e}	Electron energy
U	Voltage
E	Electric field intensity
B	Magnetic flux density
d	Electrode distance
λ_{e}	Electron mean path
A	Electron mean path constant
p	Pressure
α	Firts Townsend coefficient
x	Distance
n	Number of electrons
n_0	Original umber of electrons
γ	Third Townsend coefficient
n_1	Number of electrons leaving cathode per second
V_{i}	Effective ionization potential
F	Force
W	Energy of the arc
N	Number of splitter plates
ΔU_{A}	Anode voltage drop
ΔU_{C}	Cathode voltage drop
l	Arc length

UV	Ultraviolet
$MCCB$	Molded case circuit breaker
$\int i^2 dt$	Joule integral
t_1	Arc transfer time
t_2	Total breaking time
t_{d}	Back-commutation delay
t_{n}	Sticking time