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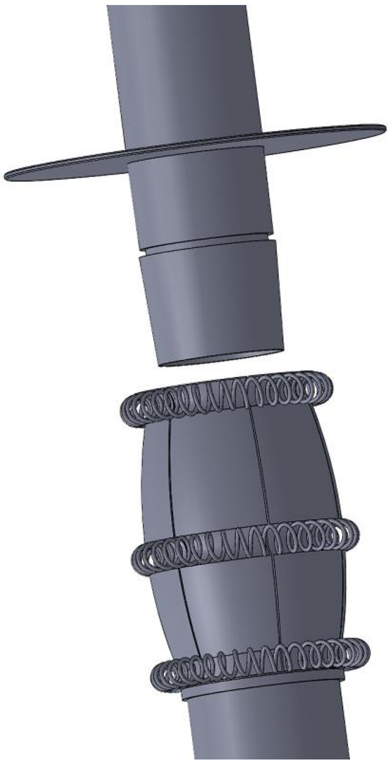
Master's Thesis 2019

Electrical power engineering

# Improving the design of MV load-break switch contacts



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**Summary:**

The breaking of currents either during maintenance, faults, or overload is common in load-break switches. Because switches are usually placed before critical installations it is important that their designs implementations are done in a manner that upholds fault tolerance. In efforts to achieve this, a fault tolerance design for switches, this project explores the ways through which an MV load-break switch contact can be improved. Specifically, this research will focus on design implementations of ratios between contact and bulk resistance. Secondly, it will explore the impact of contact force on both friction and resistance. As such, this project will go a step further and look at the influence of surface lubrication on both friction and resistance. By understanding the implication of these three factors, the project shall be in a better position recommend improved design characteristics of a tulip contact.

Finally, yet importantly, in order to affirm any findings of an improved MV load-break switch contacts design, this project will review operation theories that govern this type of switches. Through this approach, this study will present appropriate and measurable recommendations for an improved design of an MV load-break switch such as an increase of a-spots by higher contact force.

# Preface

This report is the result of the master's thesis "Improving the design of MV load-break switch contacts". The report is part of an ongoing research project between the University of South-Eastern Norway (USN) and ABB in Skien, Norway.

I would like to thank the supervisors, Elin Fjeld and Wilhelm Rondeel, for their time and valuable help during this period.

Wilhelm is an institution, and I sometimes wonder whether he carries an electrical contact in his pocket. His knowledge and interest for the subject is captivating.

Porsgrunn, 14.05.2019

Espen Thøgersen

# Contents

# Nomenclature

$SF_6$ – sulfur hexafluoride

V- voltage
kV-kilovolt

A – ampere

AC- alternating current
DC- direct current

Ω - Ohm
mΩ – milliohm

µm – micrometer
mm – millimeter
m - meter
$mm^2$ - square millimeter

g – gram

N – newton

C1 – contact point 1
C2 – contact point 2

# 1 Introduction

This chapter presents the project background, the load-break switch and the objects and structure of this report.

## 1.1 Background

Similar to electrical networks, distribution networks have switchgears typically in a range of 11-22 kilo volt. The switch is usually placed before critical installations, like transformers. Transformers present a classic case of the operation of switchgears. When faults, overloads or maintenance occur, the switch activates and break the current. Figure 1-1 below illustrates a typical ring-network on distribution level. In this illustration there are two kind of switches, load-break switch and circuit breaker. The report focusses on the load-break switch. The difference between those two kinds, is that the load-break switch is operated when the fuses are activated, or an operator manually operates the switch. A circuit breaker is an electronic switch that both work if overload or short-circuit. A fuse in this case only works as a short-circuit protection, that are placed together with the load-break switch.

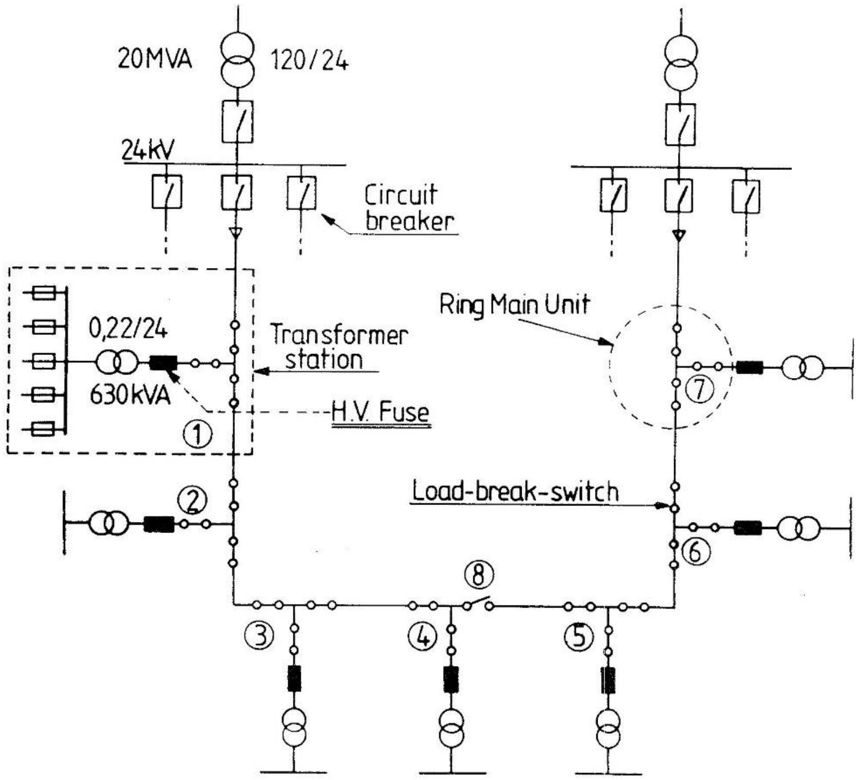
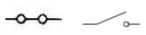



Figure 1-1: Illustration of a ring-network on distribution level [1]

 Transformer, typical in Norwegian distribution network 12/24[kV] to 415/230[V].

 Switches – load-break switches.

As shown in the figure above, even with a fault or having maintenance on a line/cable that connects the transformers, it is still non-critical since there is a 2-way flow. The switches make this possible.

There are different types of switchgears which are categorized in different ways. Voltage level is one of the ways of categorizing switchgears. The three different voltage levels are [2];

- Low voltage < 1 [kV] AC
- Medium voltage 1 – 35 [kV] AC
- High voltage > 35 [kV] AC

Switchgears can also be categorized based on the insulation medium inside them. Typical types of insulation mediums are $SF_6$-gas, oil, air or vacuum. This to make switchgears more compact, but also the isolation medium improves the capability for arc quenching and gives better thermal properties [2].

This report, however, does not focus on isolation medium.

The tulip contacts analyzed in this report have a rated current of 630 [A] and are used – or designed for a medium voltage switchgear. The tulip contacts have a transition between the fingers and the male electrode, and this resistance is higher than the bulk and the transition at the lower part of the fingers to the electrode. More about this is later chapters. The resistance in these contact points and the friction separating the male part from the female is important to get as low as possible, because of heat generation and friction-wear and tear. This to increase the lifetime of the contact.

Table 1-1. Tulip fingers

| | Tulip 1 | Tulip 4 | Tulip 3 |
|---|---|---|---|
| **Number of fingers** | 6 | 6 | 12 |
| **Thickness of fingers** | 3.0mm | 2.5mm | 3.0mm |

The tulip contacts that is analyzed in this report has the same design except thickness of the fingers and that Tulip 3 -the fingers are split in half.

## 1.2 Objectives

The objectives are drawn from the task description found in appendix 1, which states;

“A test stand for friction and resistance measurements is available in the high current laboratory. Different designs of tulip type open/close contacts with a rated current of 630 A are to be tested. Some preliminary test results, from an earlier student’s project, is available as a project report.

A systematic analysis of the characteristics of different executions of tulip contacts is to be made. Some of the topics to be analyzed include:

- The ratio between contact resistance and bulk resistance for different designs.
- The influence of contact force on resistance and friction.

- The influence of surface lubrication on resistance and friction.
- Make a proposal for possibly improving the characteristics of the tulip contact."

## 1.3 Report structure

Chapter 1: Introduction

Gives a short introduction to the topics of this report.

Chapter 2: Theory

A presentation of the theories used in this report.

Chapter 3: SolidWorks

The chapter makes a scrutiny of the SolidWorks software.

Chapter 4: Method

The chapter begins by a system description then proceeds to present the method and equipment of measurement.

Chapter 5: Results

In this section, the result of the report is displayed

Chapter 6: Calculations

Calculation of friction coefficient contact pressure/force and bulk resistance are displayed.

Chapter 7: Improving the design for lowering resistance in open/close contact.

By altering the scape of tulip contact no. 1, for improving the resistance in C2.

Chapter 8: Discussion

In this section the results found in this report is discussed.

Chapter 9: Conclusion

In the last section of this report a conclusion of the discussion will be presented.

# 2 Theory

In this chapter, the theory used in this report is presented. First a short description of a typical commercial tulip contact design is presented, followed by a presentation of the physics of resistance and contact pressure.

## 2.1 Tulip design

There are many different tulip contact designs in the market. The figure below shows a picture of one of them. The contact is built up by fingers (tulip fingers), springs and staring-brackets to keep the fingers in position. The springs create pressure on the electrode when the contact is in a closed-position. This contact is “movable” as the parts is not welded or casted in any way. The contact has two movable parts, the contact arm, and the fixed contact.

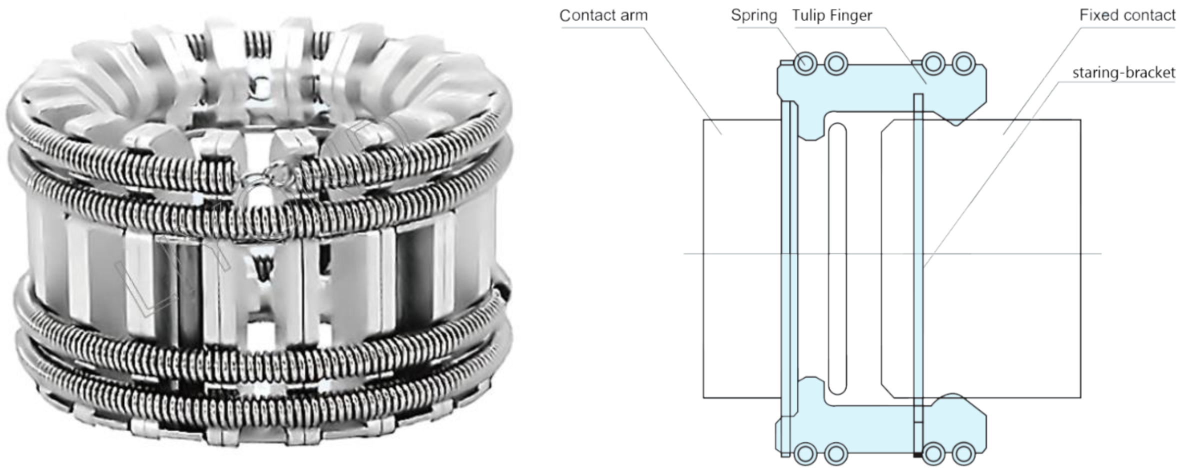



Figure 2-1: Illustration of a tulip contact. [3]

Current flows through the fixed contact (male electrode), the tulip fingers (bulk) and contact arm. The bulk resistance (fingers) and the contact resistance from the two contact points comprises the total resistance of the tulip.

Figure 2-2 shows a tulip contact where the fingers are a part of the lower electrode. That means the contact has one movable part, the male electrode.

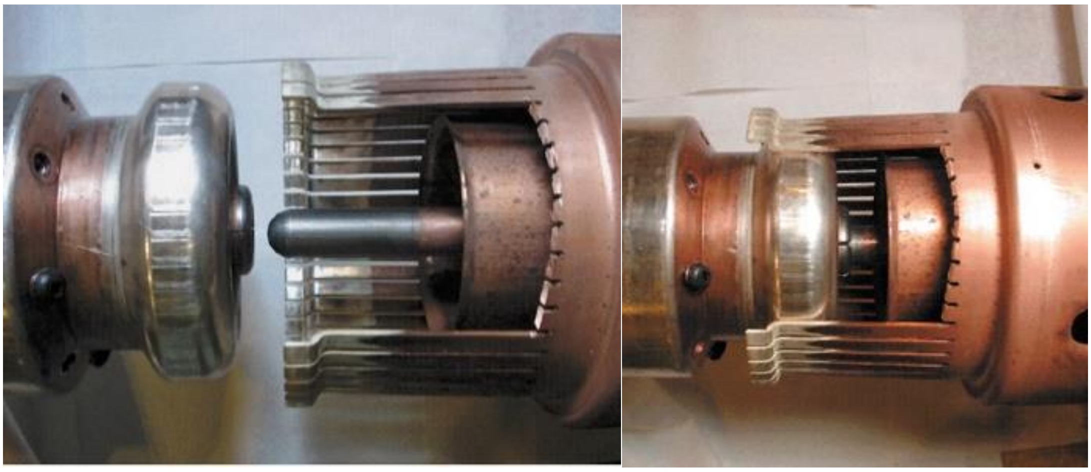


Figure 2-2: Illustration of a tulip contact in an open- and closed position. [4]

## 2.2 Bulk resistance

There is electrical or ohmic resistance in any bulk or wire, made of copper or other metal that conducts electricity. The resistance is calculated by the formula;

$$R = \frac{\rho \cdot L}{A} \tag{2.1}$$

Where;

R – Electrical resistance [Ω].

ρ – Electrical resistivity [mΩ/$mm^2$].

A – Cross sectional-area [$mm^2$].

L – Length of the conductor [m]. [5]

The resistance depends on the electrical conductivity of the metal and the cross sectional-area of the conductor. Copper and silver have high conductivity.

## 2.3 Contact resistance

When two or more pieces of metal are pushed together to create an electrical contact, an ohmic resistance occurs at the point of contact between any of the two metals – or in the transition from metal one to metal two.

By studying the Figure 2-3 below, the roughness on microscopic level accounts for the rough surface area. As a result, the current will pass through the actual contact point, called a-spot or a-spots. [6]

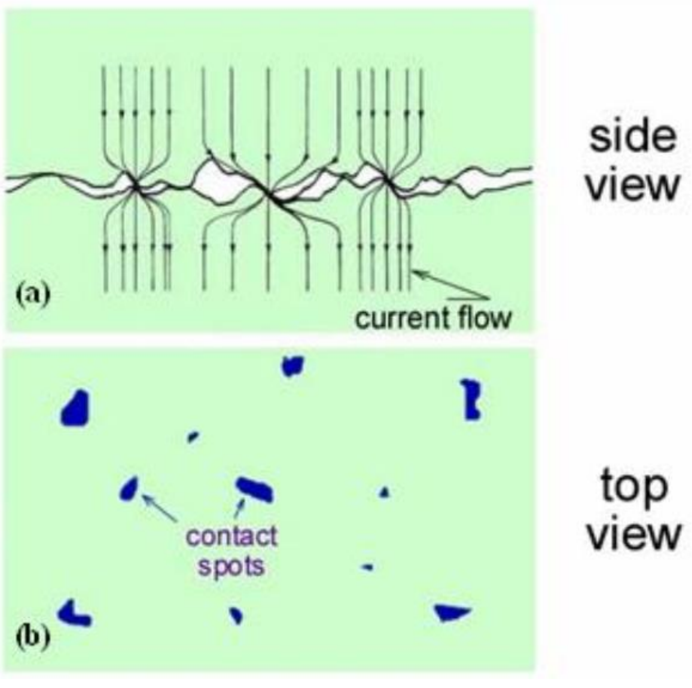



Figure 2-3: (a) Schematic diagram of a bulk electrical interface. (b) Spots in blue represent true contact area. [6]

If the metal in the contact is the same, the ohmic resistance in these a-spots can be calculated by the formula;

$$R_c = \frac{\rho}{2a} \tag{2.2}$$

Where;

$R_c$ – is the contact resistance or constriction resistance.

ρ – is the electrical resistivity of the metal.

a – is the a-spot (contact spot) radius.

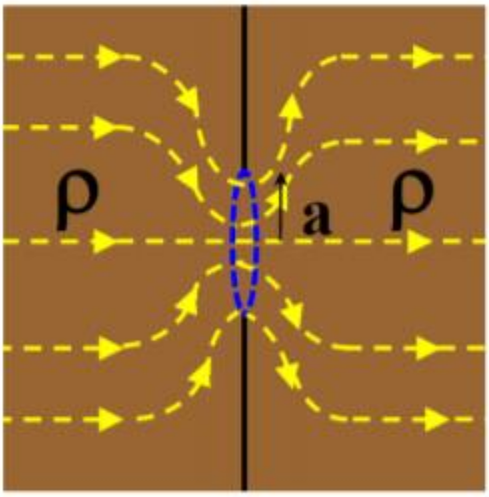



Figure 2-4: a-spot model of a circular constriction between two contacting members. [7]

**Note: The formula only applies when there is no film of contact degradation between the two metals.** [8]

The resistance in the constriction in determined by applying the formula for copper-copper interface;

Table 2-1: Ohmic resistance of a circular constriction in a copper-copper interface. [8]

| *a*-Spot Radius (μm) | Constriction Resistance (Ω) |
|---|---|
| 0.01 | 0.88 |
| 0.1 | $8.8 \times 10^{-2}$ |
| 1 | $8.8 \times 10^{-3}$ |
| 10 | $8.8 \times 10^{-4}$ |

From the table, it can be observed that the resistance of an a-spot with a radius of 1μm is approximately 10 mΩ – The electrical resistance is very small. Further, looking at power-losses;

$$P_c = I^2 \cdot R_c \tag{2.3}$$

With a current of 100[A] and an ohmic resistance of 10mΩ, the power-loss is calculated as 100[W]. This energy is transformed to heat. It is important to have as many a-spots as possible to lower the heat generation in these a-spots. This to not damage the metal.

## 2.4 Thin film contact resistance

Degradation of the contact point stems from loss of a-spots. The losses may be result from mechanisms such as oxidations, galvanic corrosions, and mechanical vibrations, fretting wear or dirt over time. The electrical resistance caused by this thin layer of film increases the ohmic resistance in the contact point.

Generally, the cracks in the film depends on the thinness of the film and the pressure compressing the two metals together.

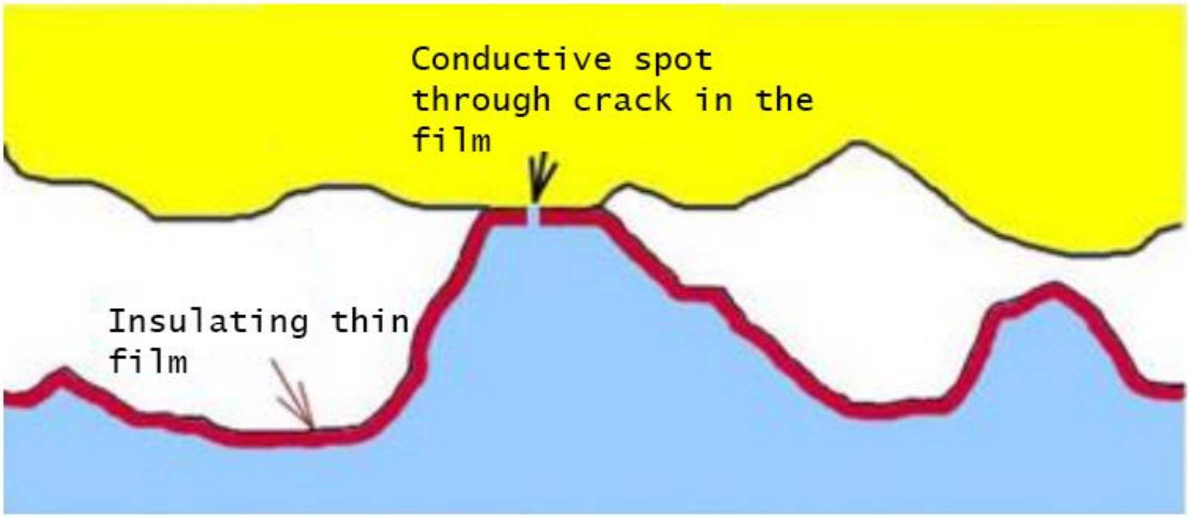



Figure 2-5: Schematic view of a contact spot with one surface covered with a thin electrically-insulating layer. [6]

Since there is an importance to reduce the friction between the fingers and the male electrode in the tulip contact, a film or lubrication might be used for lowering the friction. The lubrication result in a thin film between the metals and might result in loss of a-spots.

## 2.5 Lubrication

Lubrication is a friction-reducing film added between the surfaces. There are many different types of lubrication, for different applications. One type is grease used on fixed contact for protection from oxidation and corrosion. For lubrication on a tulip contact, this can be used for lowering the friction when separating the female part from the male electrode.

The negative affect is that this create a film between the metals and result in increased ohmic resistance. The lubrication used should have high electrical conductivity.

## 2.6 Contact pressure

Since the a-spots are much smaller than the apparent contact area, a-spots can support local mechanical pressures that are larger than the yield strength of the materials in contact. This pressure causes permanent deformation of the contact asperities depending on their mechanical hardness. As the contact force increases, the Hertz stress (highly localized stress created by contact) also increase. This means that the contact area will yield, expand, and result in an increase of a-spots. The Figure 2-6 illustrates how the compression of the electrical contact creates more and wider a-spots. This deformation of contacting asperities allows an evaluation of contact resistance. [8]

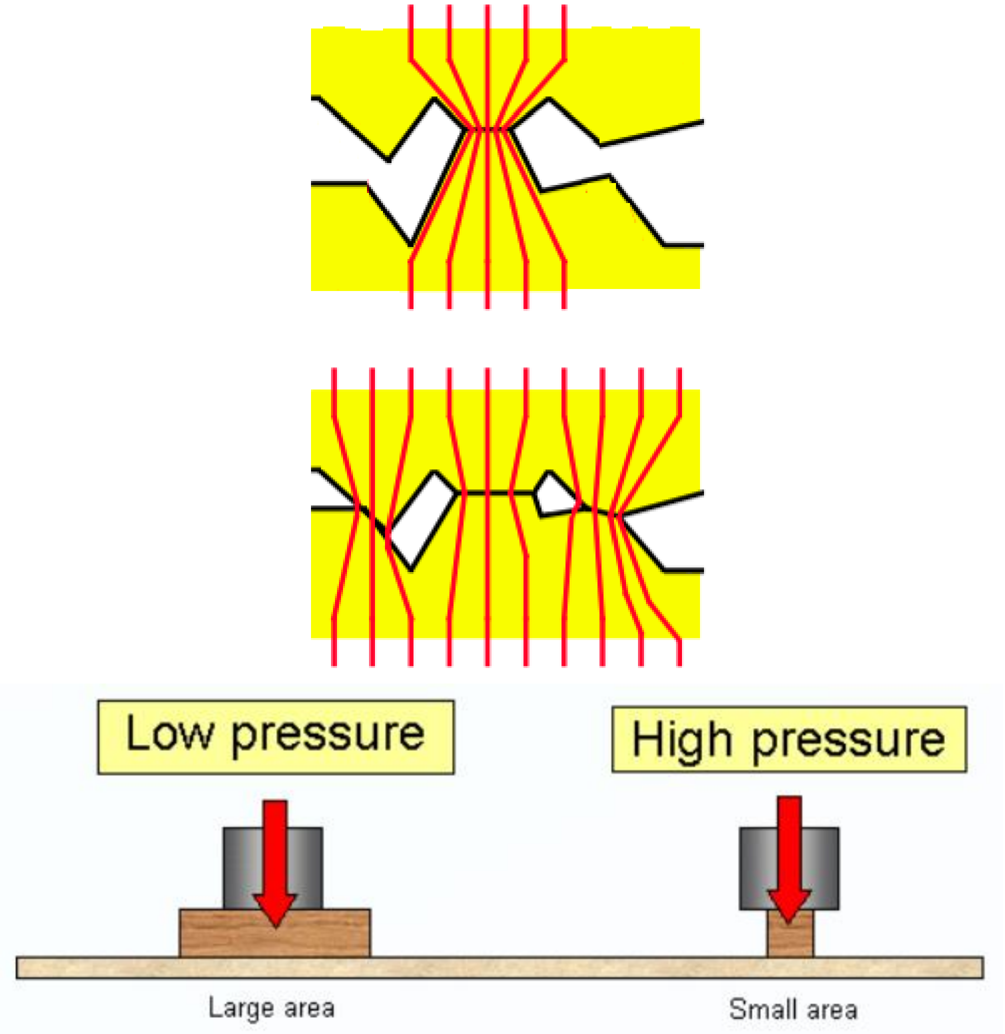



Figure 2-6: Effect of increased force on constriction resistance. [9] [10]

In the tulip contact there are springs to create this contact pressure. The springs press the fingers to the male electrode and decrease the resistance since increase of a-spots. This results in of this, is that the friction will increase.

The figure below shows that the resistance in the transition from metal one to metal two, will decrease when the pressure is increasing. So, in a tulip contact, by increasing the spring force the resistance will be lowered.

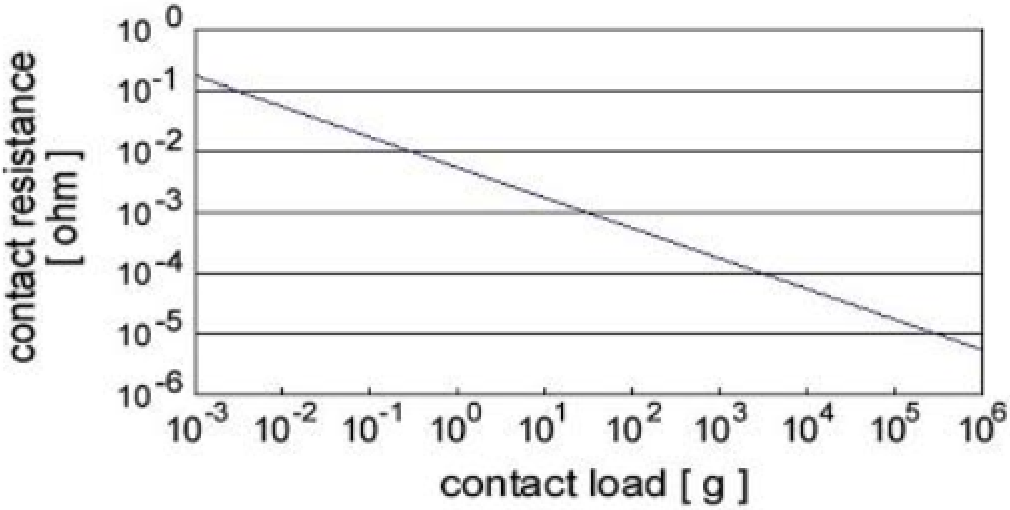



Figure 2-7: Contact resistance versus contact pressure for a copper contact. [6]

## 2.7 Plating

Plating is often used in making electric contact switches. One of such is plating copper with silver. Silver material is not suitable to use alone as silver is more susceptible to degradation in the presence of sulphurous vapor. When platted with silver, the resistance in the contact point decrease since silver conduct electricity better and has a high temperature limit of 105°C. Silver is also softer than copper. This result in an increase of a-spots when increasing the contact pressure.

The silver plating used in the switches is composed to 0.03-0.15 % of the total contact, which enhances the creep strength and prevents the melting of the plating at high temperatures or significant compromise to electrical conductivity. [8]

## 2.8 Friction

During a push or a pull on an object, as illustrated in Figure 2-8, there is a frictional force in the opposite direction. Based on the velocity of motion, there are two types of friction: static and dynamic friction. From the illustration in the figure 2-8 below, to pull out the male electrode, the force applied must overcome the dynamic friction to set the electrode in motion.

Figure 2-8: Illustration of frictional force by open a tulip contact.

$F = \mu \cdot N,$ Where F is the force, µ is the friction coefficient and N is the normal force.

# 3 SolidWorks software

SolidWorks is a software, probably most used by mechanical engineers to draw and design parts. The software has functions like find cross sectional-area.

When designing a tulip contact with a various shape of the fingers, the cross sectional-area varies. After the design, the user can find the area using the steps illustrated in Figure 3-1 below.

SolidWorks has also been used to draw most figures or illustrations of tulip contacts in this report.

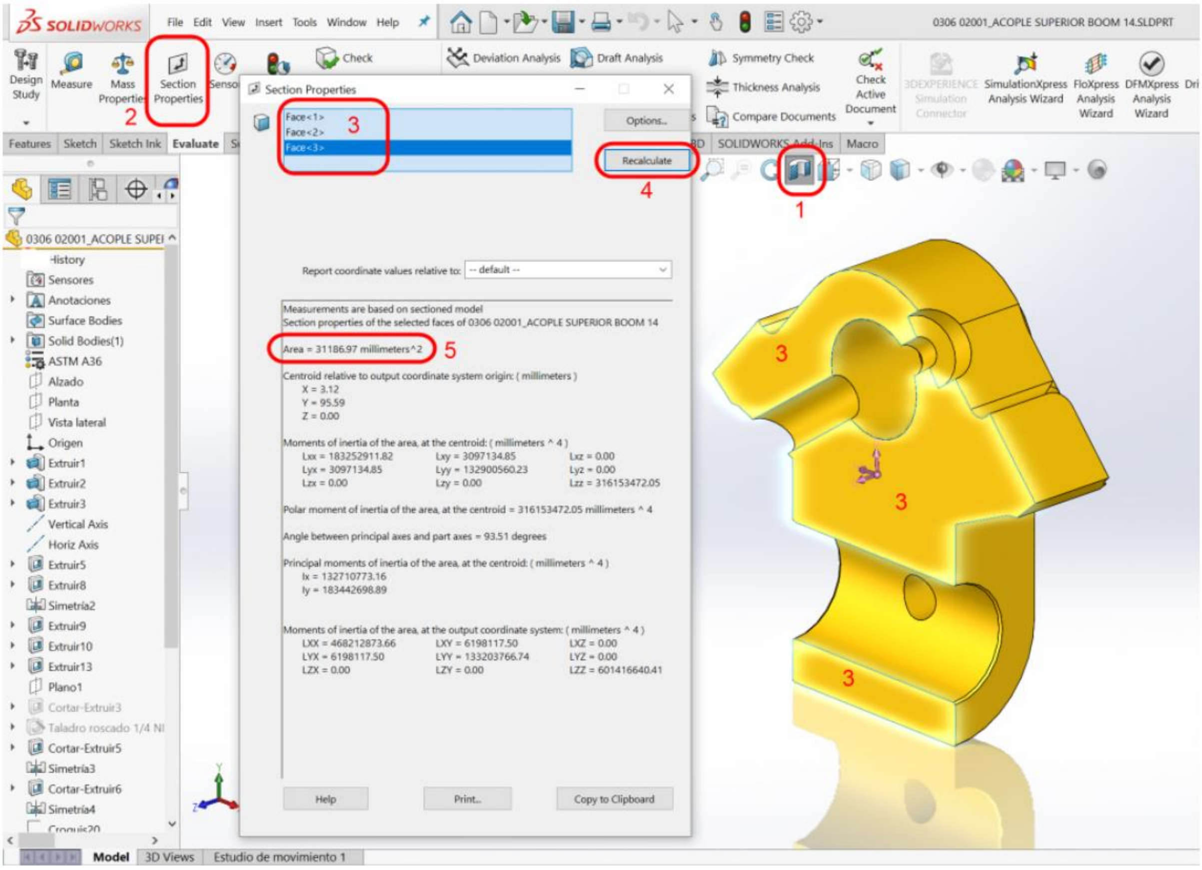



Figure 3-1: Finding cross sectional-area in SolidWorks. [11]

# 4 Method

In this chapter, the design of a typical tulip, its components and assemblage will be described. Further, the equipment used and theory relevant to the measurements and the analysis will be discussed before presenting how the experiments are conducted.

## 4.1 Tulip design

During this project three different tulip contacts have been analyzed. The three tulips have the same design but tulip 3 has sliced fingers and one has thinner metal (fingers). With sliced fingers the pressure from the spring get more linear distributed and an increase of a-spots.

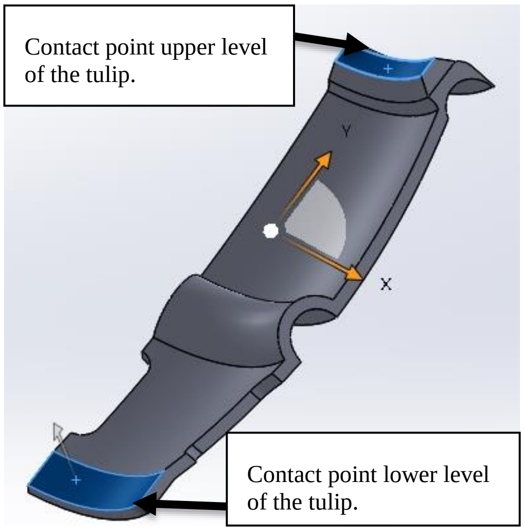



Figure 4-1: Illustration of a tulip-finger.

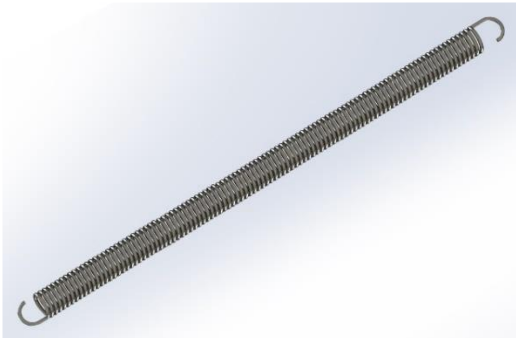


Figure 4-3: Illustration of the spring.

The spring is used to apply pressure on the contact points.

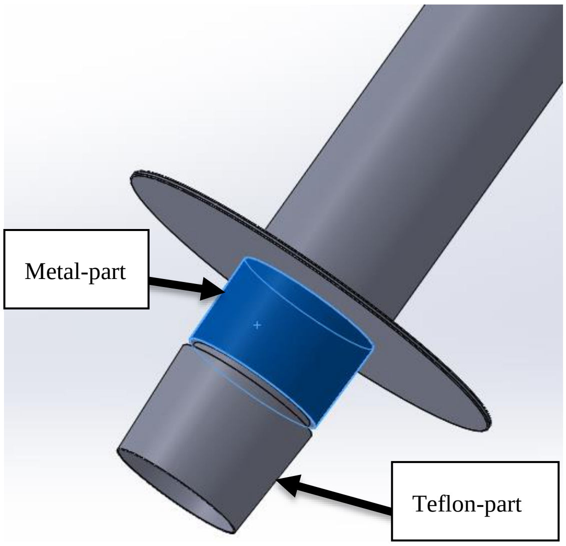



Figure 4-2: Illustration of upper-level conductor.

The upper contact point for the finger is placed on the cylindrical-shaped conductor.

Figure 4-4: Illustration of lower-level conductor.

The lower contact point for the finger is placed on the cylindrical-shaped conductor.

The assembly of the tulip contact can be illustrated as shown below.

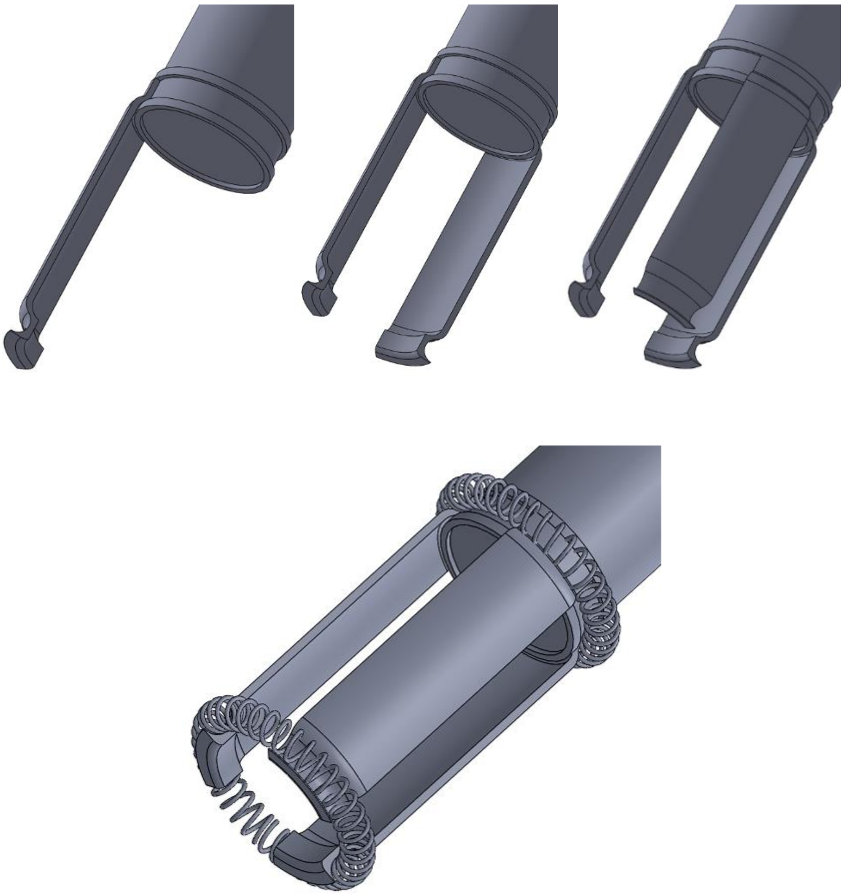


Figure 4-5: Illustration of assembling a tulip contact.

## 4.2 Equipment used

The equipment used in this project to measure the tulip contacts is shown in Table 4-1 below.

Table 4-1: Table for Equipment used

| | | |
|---|---|---|
| Grossen Matrawatt multimeter High Resolution TRMS system |  | Accuracy for DC-voltage 60[mV] ± 30[µV] |
| Probe clamps |  | |
| Current source:<br>Hilkar AK23 |  | 100 [A] DC |
| Sauter FK-500 Force gauge for simple measurements |  | Maximum 500[N] |
| Sauter TVL Manual test stand |  | |

**Note: All the photos in the upper table are illustrations.**

## 4.3 Friction measurement

The metal surface has some irregularities, a phenomenon which has a substantial influence on the frictional force. When the object is at rest, it is referred to as static friction. Interface of an object in motion is called kinetic or dynamic friction. The dynamic friction across the tulip contact was one of the primary targets in this examination. To define the contact force and friction, a test stand with a Sauter FK-500 is installed. The test stand includes a base plate, scale in mm/inch and a driving mechanism, for altering the vertical length between the base plate and the Sauter FK-500.

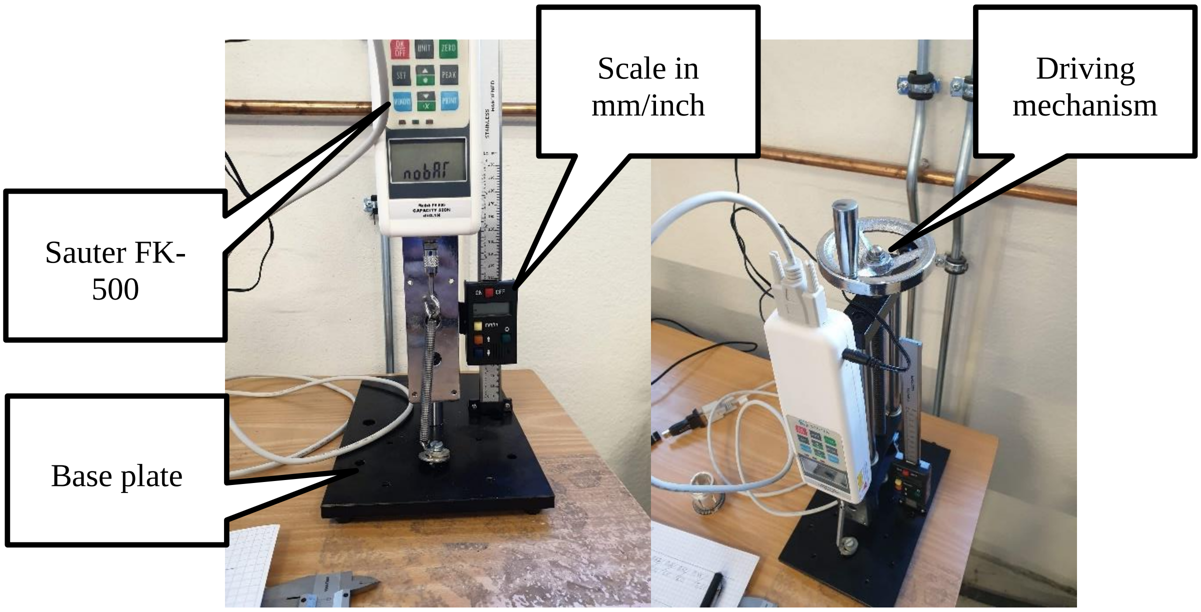



Figure 4-6: Illustration of a spring in the test stand.

The test is run by mounting the female part of the contact in the base plate and the male connected in the Force gauge. As the male contact is pulled out of the female contact, by rotating the driving mechanism, the force gauge records measurements of the force applied. The Sauter FK-500 gives data in newton depending on time.

To separate the contact from closed to open position, the force applied is measured.

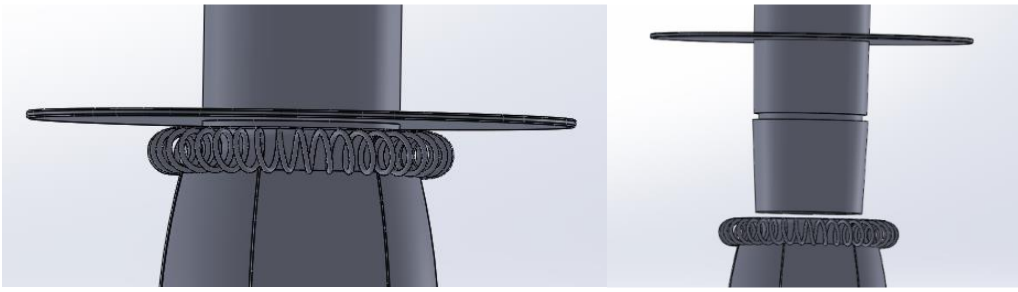


Figure 4-7: Illustration of closed and open tulip contact.

The same measuring procedure will be done on the spring. By stretching the spring by the same distance as the spring is when in a closed position as shown in Figure 4-7, the tension force in the spring is reviled. This allows for the determination of the contact pressure between the fingers and the male electrode – through calculations. Since the springs are elastic, their length increases when stretched and the force used to stretch it will increase.

### 4.3.1 Lubrication

Lubricants is applied between the fingers (bulk) and the male electrode (C2). This to reduce the friction experienced when separating the contacts. Lubrication may affect the resistance in the contact-area since this creates a thin film (from theory chapter), this is revealed by measurement. The difference in the force needed to separate the contacts will be observed by repeating the test with the lubricant applied.

## 4.4 Resistance measurement

From resistance perspective, a tulip contact contains a bulk and two contact points (as already shown in Figure 4-1). The resistance in the contact points are determined by the surface-area, the cleanliness of the surface, the number of actual points of contacts (a-spots) and the pressure generated by the spring. These variables make theoretical calculations very complex and require microscopical analysis.

The resistance in the fingers (bulk) are unproblematic to find, since there are a few variables which are also predictable. Finger-resistance are determined by the material and the cross-sectional area (Further calculations are shown in the calculation chapter).

**For physical resistance measurements, the metal, over time, will be heated when connected to the current source. When a metal is heated, its resistance increases. In this report, however, temperature changes are not considered.**

$$R = R_{ref}\left[1 + \alpha\left(T - T_{ref}\right)\right](4.1)$$

*Where;*

*R: Conductor resistance at temperature "T".*

*$R_{ref}$: Conductor resistance at reference temperature,$T_{ref}$.*

*α: Temperature coefficient of resistance for the conductor material.*

*T: Conductor temperature in degrees [°C].*

*$T_{ref}$: Reference temperature that α is specified at the conductor material.*

According to the website "All about circuits" the temperature coefficient for copper at 20[°C] is 0.004041. [12]

**By increasing the temperature from 20[°C] to 50 [°C], the resistance will increase by 12.1 [%].**

One of the main objectives of this report was to find the contact resistance in the point between the finger and the male electrode. To achieve this, a stand of a wooden board with two clamps, one to hold the female, and one to hold the male electrode are used.

Figure 4-8: Wooden board for measurement.

To measure the different parts of the contact, the tulip is divided into three parts: the bulk (fingers), contact 1 (C1) and contact 2 (C2). C2 is the contact between fingers and the male electrode.

To find the resistance of the tulip contact, the contact is connected to a 100 [A] DC-source. Then the voltage-drop is measured by the multimeter. The measuring points are shown in Figure 4-11.

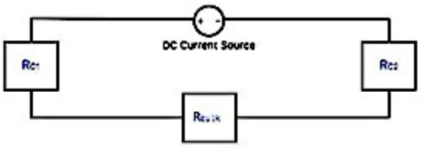



Figure 4-9: Block diagram of the tulip contact.

Figure 4-9 illustrates the electrical diagram of the tulip. There is the contact 1 (C1), the bulk (fingers) and contact 2 (C2) between the fingers and the male electrode.

When finding the different overall voltage-drops in the tulip contact, ohms law is applied to find the resistance.

$$R = \frac{\Delta U}{I} \quad (4.2)$$

Where $\Delta U$ is the voltage-drop and $I$ is the current. $R$ represents the resistance.

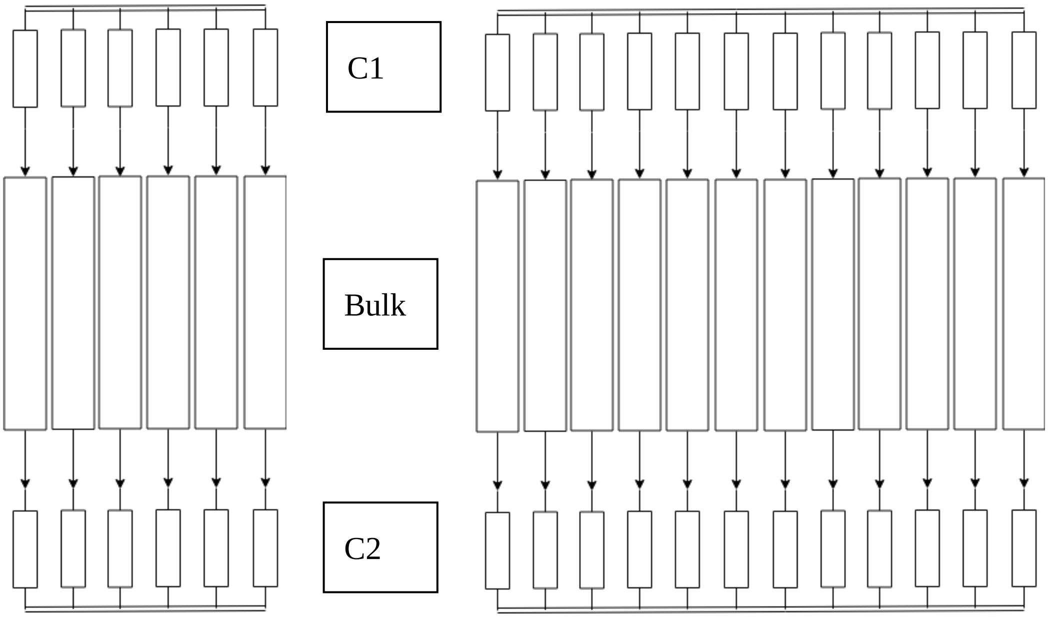



Figure 4-10: Diagram of the two tulip contacts.

Figure 4-10 shows a schematic diagram of the tulip contact. Tulip contact number 1 and 4 is represented to the left, and tulip number 3 is represented to the right, with fingers split in half.

Tulip 1 and 4, have 6 fingers. Tulip 3 has 12 fingers.

When doing the resistance measurement, the resistance in each contact point has some deviation. This because the a-spots may vary from finger to finger. Since the resistance – or voltage-drop vary the current through each contact point may vary. So, the current distributed, is not the same overall the contact.

Regarding the number of a-spots, in the transition from finger to electrode – the resistance is determined by factors like number of a-spots. One finger has at least one a-spot, so by cutting the fingers in half or increasing the number of fingers there should be an increase of a-spots.

The resistance ratio between bulk and contact points in a tulip contact will be an important factor to see which one is most proper to improve.

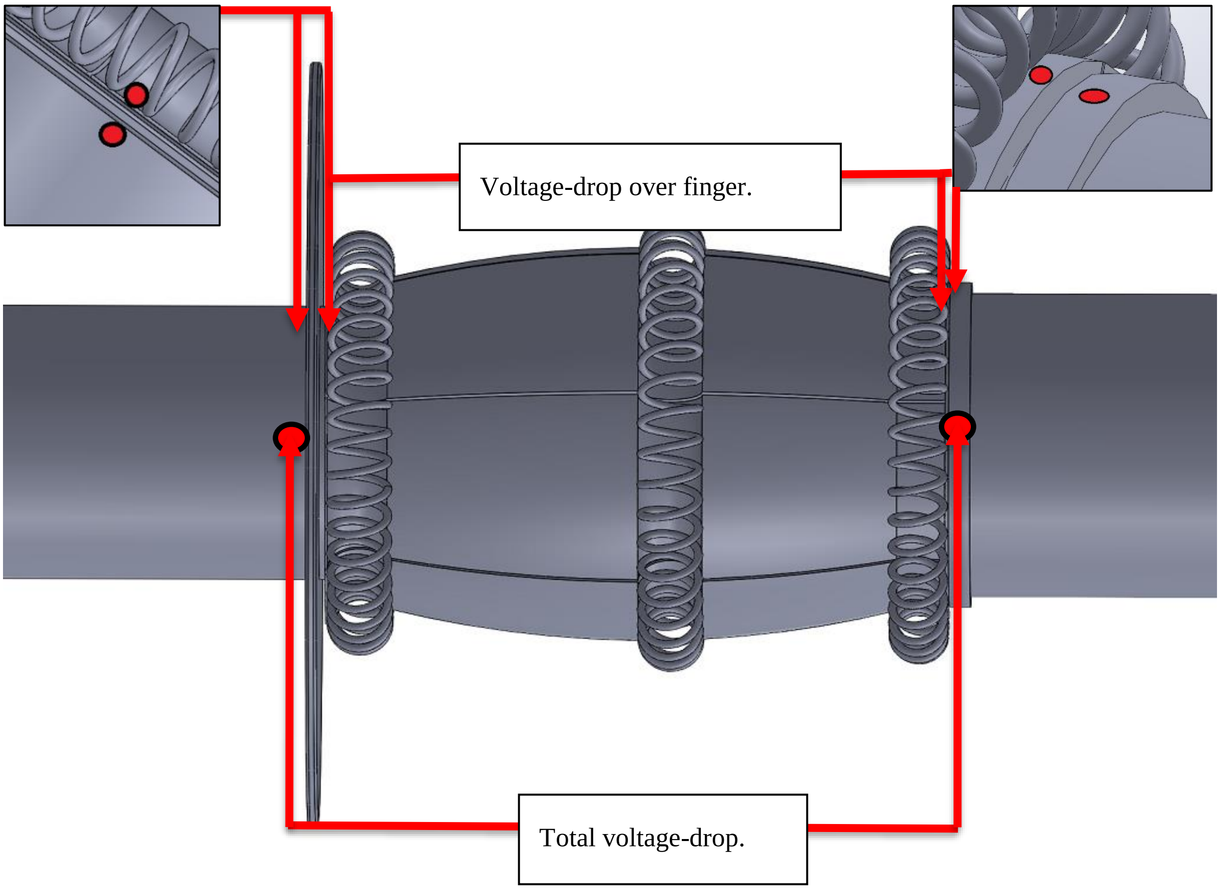



Figure 4-11: Illustration of measuring-points.

Current (100[A, DC]) flows through the tulip contact, and probes, one red, one black, is connected to the contact. This is called the four-probe method.

Measurement of contact 1 (C1), is conducted by putting the probes at the corner and to the right as shown in

Figure 4-11. The multimeter is showing the voltage-drop.

Measurement of bulk (fingers) is done as illustrated in

Figure 4-11.

Measurement of contact 2 (C2) is done by putting the probes at the left corner as shown in

Figure 4-11.

## 4.5 Contact area

A blue marker can be used to try detecting contact area between two metals. In this report, the YETI blue marker has been used to this.


Figure 4-12: Male contact and blue marker

The blue marker is painted with a pencil on the male electrode. A maker can be obtained from a dentist office or a dentist supplier.

# 5 Result

In this chapter the results of the measurements are shown. The contact force measurement from separating the contacts, the measurements for voltage-drops for the different tulip contacts and the contact points.

## 5.1 Tulip contact

Three different tulip contacts have been tested and analyzed. The three tulips, denoted tulip 1, 4 and tulip 3, are of the same design with a slight difference in the fingers – tulip 3 has sliced fingers. Tulip 4 has slightly thinner fingers, 2.5mm, instead of 3.0mm. The prototype-contacts are developed at ABB, and they are non-commercial. These are to be used in a MV switchgear at distribution level.

Table 5-1: Number of fingers.

| | | Tulip 1 | Tulip 4 | Tulip 3 |
|---|---|---|---|---|
| **Number of fingers** | | 6 | 6 | 12 |

## 5.2 Friction measurement

The graph in *Figure 5-1* illustrates the force applied to separate the tulip contact. The function represent force [N] depending on time[s]. As described in the method, the tulip contacts are measured in the test stand, with a driving mechanism. When the user rotates the wheel, the force is increased. An interesting relationship between the tension of spring and the force applied separating the contacts is observed in the peak values.

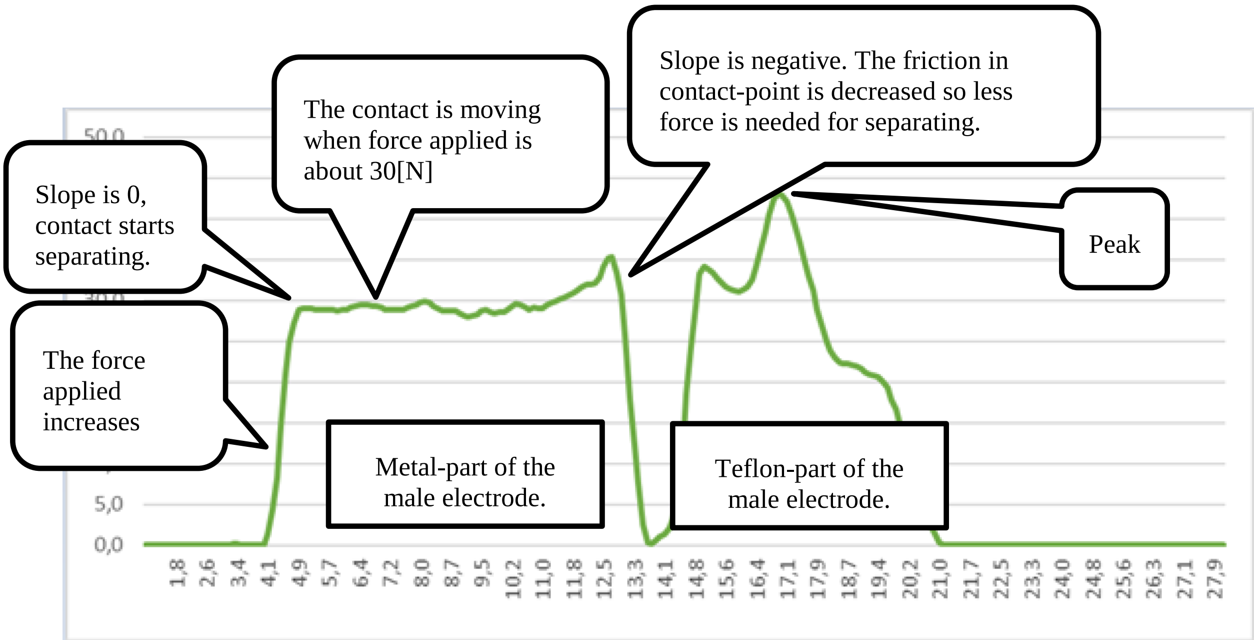



*Figure 5-1: Illustration of force-separation graph*

When the contact is moving or separating, the graphs slope is 0 or negative. The reason is that when moving or separating an object, there must be a force applied. As the force applied increases, the slope is greater than 0, and when the object starts separating or moving, the force stabilizes.

**Force applied for separation -From closed- to open position**

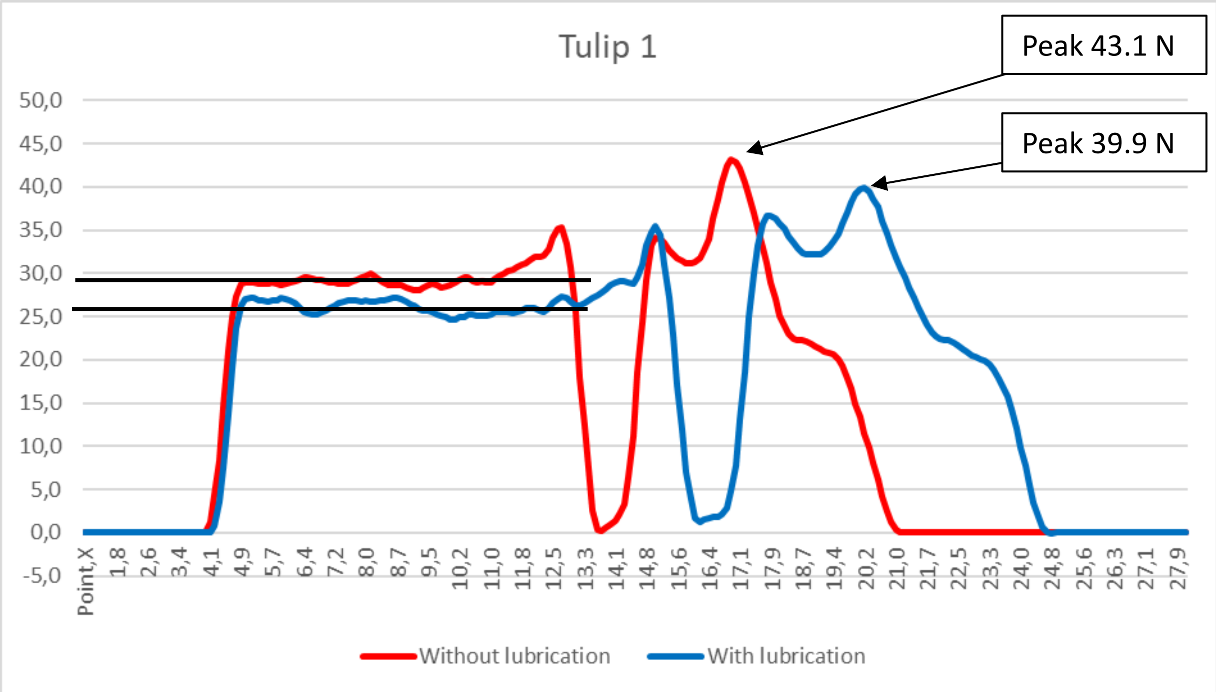



Figure 5-2: Force-graph -Tulip 1.

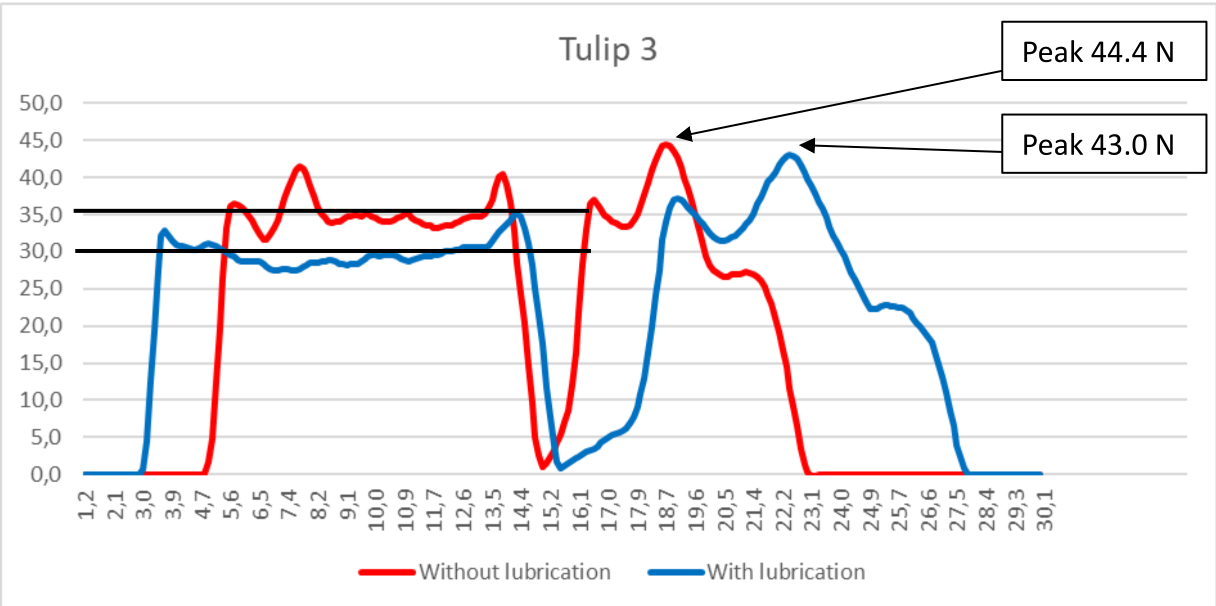



Figure 5-3: Force-graph -Tulip 3.

From Figure 5-2 and Figure 5-3, an application of a force of 0 up to about 30 [N] sets the contact, or male electrode into motion. The pattern is the same for every test, but for tulip 3 without lubrication there are some irregularities. This situation can be explained with irregularities in the metals. When the surface has irregularities, the force changes with the changes in the friction coefficient. When the graphs in the middle, drops to 0, is then the transition from metal to Teflon starts.

The reason that the graphs is not parallel, or have equal time-span is that, as mentioned, the x-axis represents time. When the operator uses the driving mechanism, the time or speed of altering this wheel will be different each time.

*Table 5-2: Result of force measurement.*

| | Tulip 1 | Tulip 3 |
|---|---|---|
| **Without lubrication [N]** | 29 | 35 |
| **With lubrication [N]** | 26 | 30 |
| **Reduction [%]** | 24 | 17 |

**The values from Table 5-2 are average from the measurements. For peaks, or variance look at Figure 5-2 and Figure 5-3. The average values are taken from the graphs at the metal part of electrode.**

*Table 5-3* shows the measurement from the spring-test. This force represents the tension in the spring.

*Table 5-3: Spring data*

| Tulip | Spring length (resting)[mm] | Spring length (tension)[mm] | Force of spring[N] |
|---|---|---|---|
| **1** | 92 | 119 | 51.7 |
| **3** | 92 | 119 | 52.6 |

This data may be used to calculate the contact pressure between the fingers and the male electrode.

## 5.3 Resistance measurement

The resistance is determined by applying the four-probe method. The tulips that are analyzed are Tulip no. 1 and 3. For measurements on Tulip no. 2, 4 and 5, the previous report from a project group at USN may be further studied. In appendix 2 the results for that report are presented.

*Table 5-4: Results from measurements: tulip 1.*

| Tulip 1 | Without lubrication | With lubrication |
|---|---|---|
| **C1 [μΩ]** | 4.81 | (4.81) |
| **Finger [μΩ]** | 5.69 | (5.69) |
| **C2 [μΩ]** | 9.00 | 12.82 |
| **Total [μΩ]** | 18.74 | 23.27 |
| **C1+Finger+C2 [μΩ]** | 19.50 | 23.32 |
| **Deviation [%]** | 4.00 | 2.14 |
| **Difference from C1 and C2 [%]** | 87.11 | 266.53 |
| **Increase with lubrication C2 [%]** | 42.44 | |

As the Table 5-4 shows, there is a deviation in measured total resistance obtained by adding C1-, C2- and bulk resistance together. This deviation is about 4 percent, but lower with lubrication. Ideally, there should be 0 deviation. Some of the factors accounting for this deviation include error in the physical measurements and some changes due to heat generation. As earlier described, small changes in heat, will result in changes in the resistance. There is an increase in C2 resistance with- and without lubrication of 42.44 percent. This can be explained by the thin film between the metals which result in the reduction of a-spots.

The difference in C1 and C2, is that C2 has an increase of the resistance of about 87 percent (without lubrication). That is a vast increase in the resistance for making C2 to an “open-close-slide”-point. **NB! C1 never lubricated.**

*Table 5-5: Results from measurements tulip 3.*

| Tulip 3 | Without lubrication | With lubrication |
|---|---|---|
| **C1 [μΩ]** | 4.71 | (4.71) |
| **Finger [μΩ]** | 4.08 | (4.08) |
| **C2 [μΩ]** | 6.84 | 10.12 |
| **Total [μΩ]** | 16.20 | 19.32 |
| **C1+Finger+C2 [μΩ]** | 15.63 | 18.91 |
| **Deviation [%]** | 3.64 | 2.17 |
| **Difference from C1 and C2 [%]** | 45.22 | 214.86 |
| **Increase with lubrication C2 [%]** | 47.95 | |

As the *Table 5-5* shows, there is a deviation in measured total resistance obtained by adding C1-, C2- and finger- resistance together. There is an increase in C2 resistance with- and without lubrication of 47.95 percent. **NB! C1 never lubricated.**

The difference in C1 and C2, is that C2 has an increase of the resistance of about 45.22 percent – which is about half the value from tulip 1. Therefore, it can be concluded that sliced fingers give reduction in C2.

When measuring tulip 3, the fingers were not equally distributed as Figure 5-4 shows.

Figure 5-4: Illustration of non-equally distributed fingers.

Table 5-6: Comparison measurement for tulip 1 and 3.

| C1+Finger+C2 [μΩ] | Tulip 1 | Tulip 3 |
|---|---|---|
| **Without lubrication** | 19.5 | 15.63 |
| **With lubrication** | 13.32 | 18.91 |

By splitting the fingers in an equal position with a gap between the fingers.

Figure 5-5: Illustration of equally distributed fingers.

Table 5-7: Result for equally distributed fingers.

| Tulip 3 | Before | After |
|---|---|---|
| **C2 [µΩ]** | 6.84 | 6.95 |
| **Deviation [%]** | +1.61 | |

By equally distribute the fingers, the resistance had an increase by 1.61 percent.

## 5.4 Contact area in tulip 1

To show where the fingers and the male contact have their contact-points, a blue marker from YETI was applied on the male contact.


Figure 5-6: Male contact with blue marker

The pictures below show the contact-point on the fingers that is in contact with the male contact when the tulip is in a closed position.

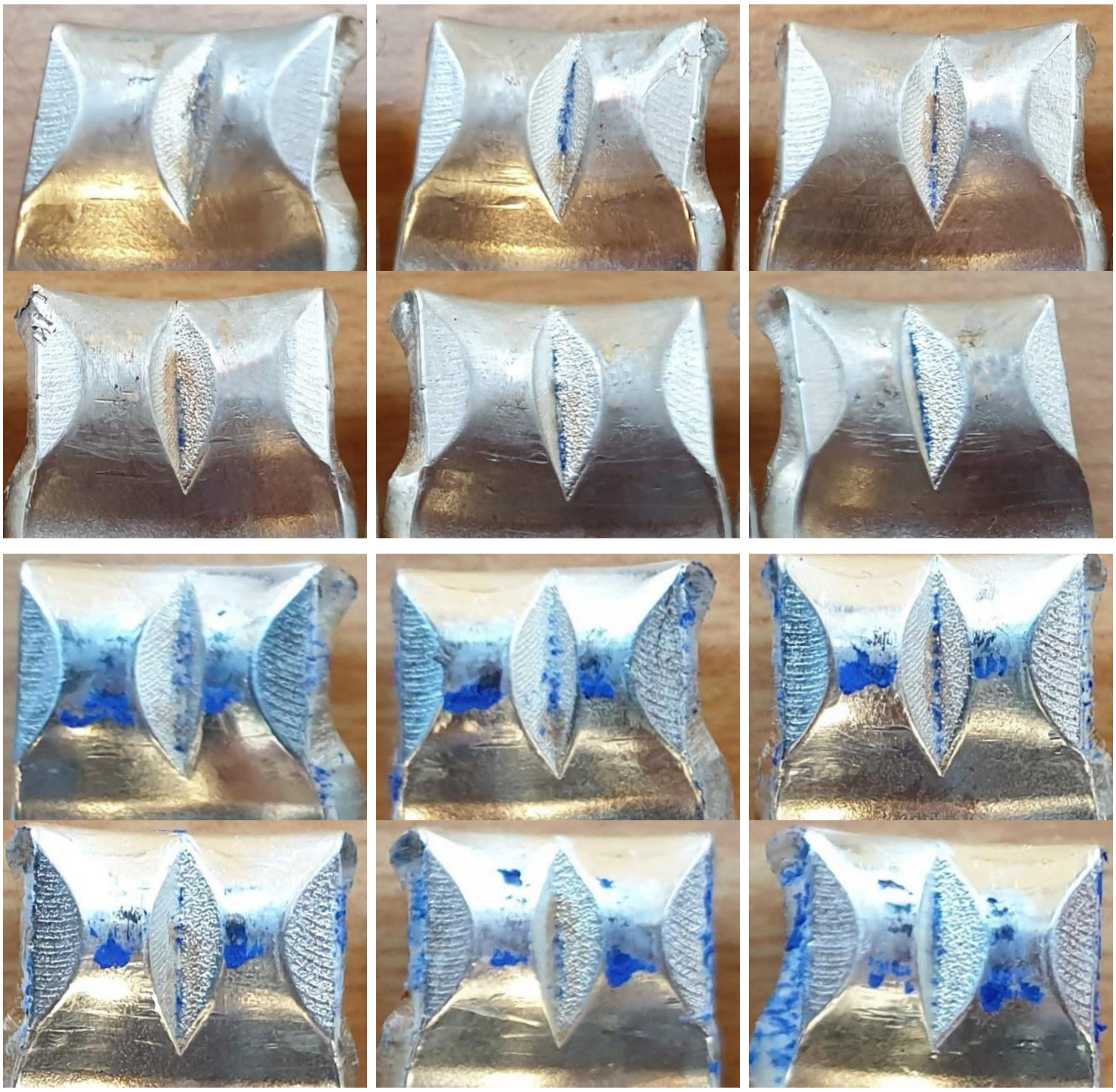


Figure 5-7: Contact-point without and with blue marker.

As Figure 5-7 shows, the blue represents the contact points between the two metals. There is some area which are “clean”, and which have no contact. On average, there are about 1-3 contact points between the metals. Ideally, the whole area should be in contact to minimize the resistance. Greater area means less resistance.

## 5.5 Increasing the contact force

To improve the conductivity in the contact-points, force is applied to the spring to create pressure between the finger and the male electrode. This will result in an increase of number of a-spots, and the resistance will be decreased. Because of this, the friction separating the contact will increase.

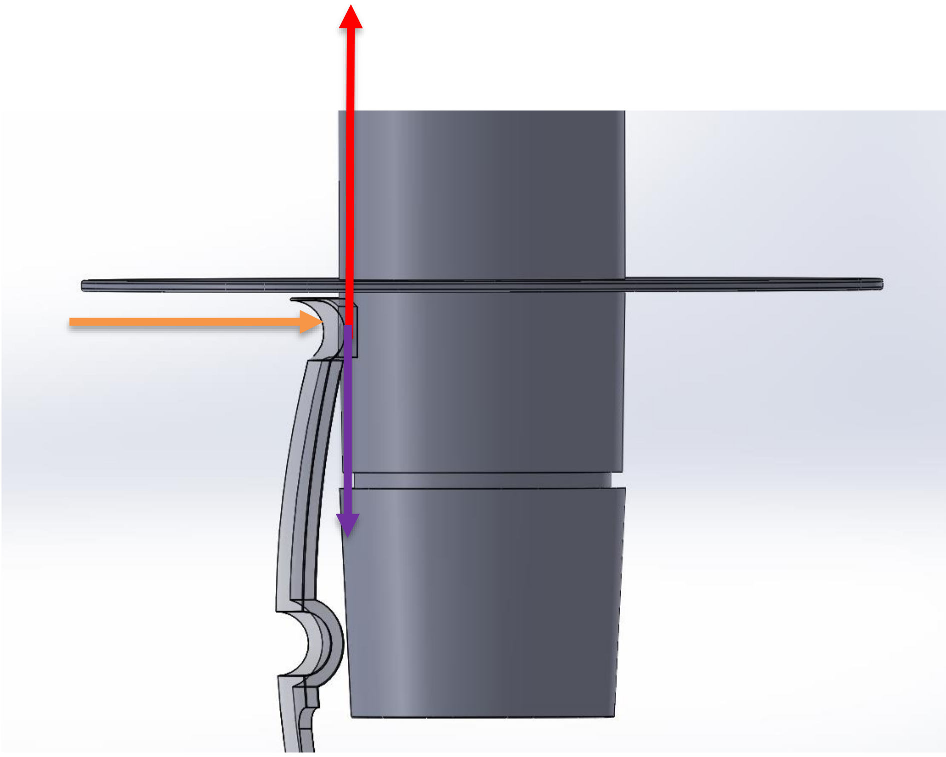


Figure 5-8: Illustration of forces interaction on upper level contact-area.

Where;

Red arrow represents the drag-force applied to separate the contact.

Green arrow represents the force delivered by the spring to make pressure on the contact-area.

Purple arrow represents the force of friction.

For this experiment -Tulip number 4 has been used. This tulip has the same design as number 1, but the thickness of the metal fingers is less, 2.5mm. For increasing the pressure between the fingers and the male electrode, plastic has been used to put between the spring and the fingers (bulk). First a measurement without any plastic, original shape. Then putting 1mm plastic sheet in-between, then a 2mm plastic sheet.

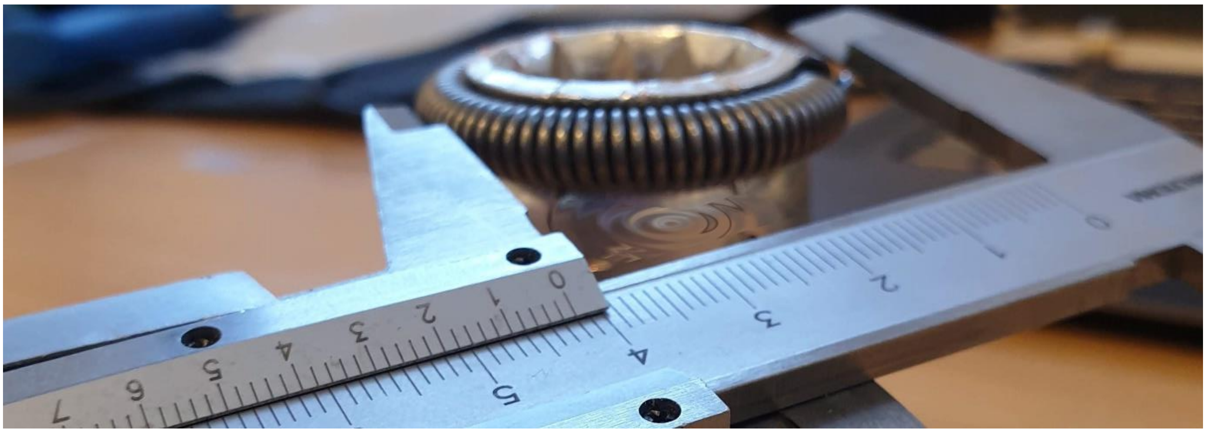


Figure 5-9: Measuring the tulip spring.

By measuring the spring on the tulip, there will be a different in the measurement when putting the plastic sheet in position.

Figure 5-10: Measuring the tulip spring with plastic between spring and fingers.

Figure 5-10 the spring get more stretched and increase the pressure on the fingers. This results in an increased contact force, and as the theory explains, there should be an increase of a-spots.

Table 5-8: Spring data when altering the pressure.

| Tulip 4 | Before modification | 1mm plastic sheet | 2mm plastic sheet |
|---|---|---|---|
| **Spring length (tension)[mm]** | 117.4 | 120.57 | 123.72 |
| **Spring Force[N]** | 39.4 | 46.4 | 52.0 |
| **Contact Force [N]** | 25.08 | 29.54 | 33.10 |

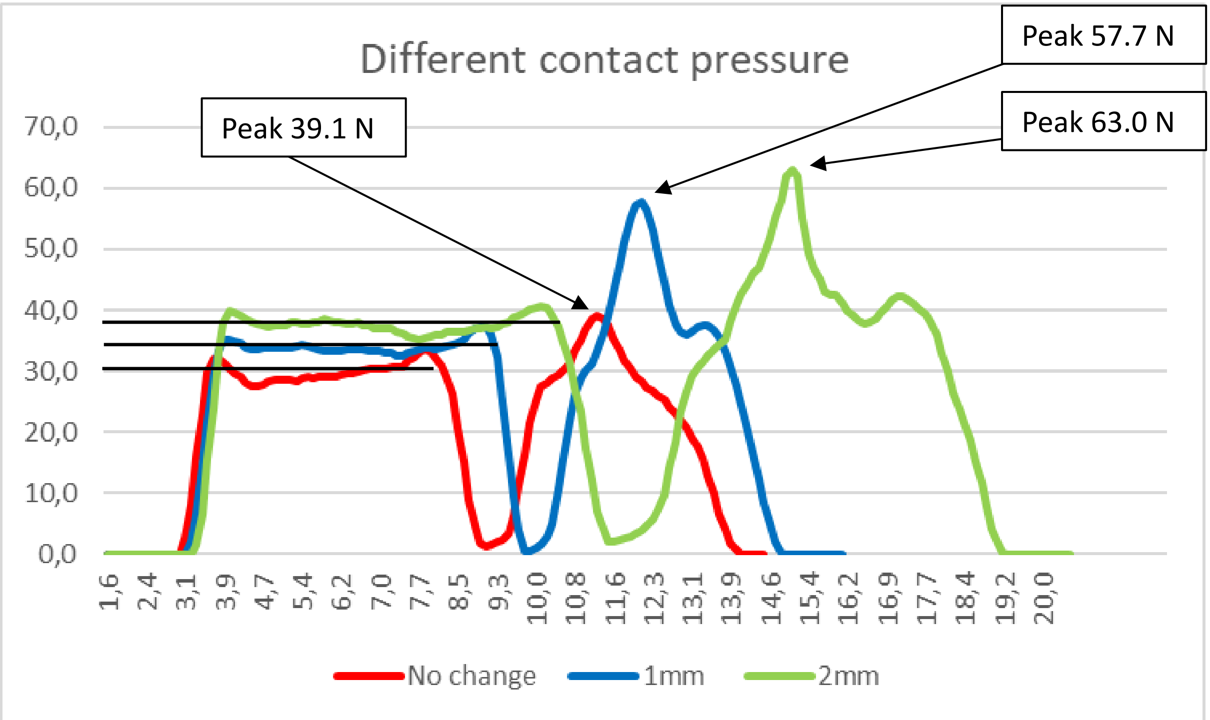



Figure 5-11: Different contact pressure.

Table 5-9: Average force measurement from Figure 5-11.

| | Before modification | 1mm plastic sheet | 2mm plastic sheet |
|---|---|---|---|
| **Without lubrication [N]** | 30 | 35 | 39 |

**The values from Table 5-2 Figure 5-11 are average from the measurements. For peaks, or variance look at Figure 5-11.**

Table 5-10: Resistance measurement from increased contact force.

<table>
<tr><th>Tulip</th><th>No change</th><th>1mm</th><th>2mm</th></tr>
<tr><td>C1 [μΩ]</td><td>6.88</td><td>(6.88)</td><td>(6.88)</td></tr>
<tr><td>Finger [μΩ]</td><td>5.77</td><td>(5.77)</td><td>(5.77)</td></tr>
<tr><td>C2 [μΩ]</td><td>6.00</td><td>5.77</td><td>4.40</td></tr>
<tr><td>C1+Finger+C2 [μΩ]</td><td>18.65</td><td>18.42</td><td>17.05</td></tr>
<tr><td rowspan="3">Difference in C2[%]</td><td colspan="2">-3.99</td><td></td></tr>
<tr><td></td><td colspan="2">-8.04</td></tr>
<tr><td colspan="3">-36.36</td></tr>
</table>

From the theory part the resistance in the contact-point will decrease when the contact pressure increases. This is shown in this chapter. When the contact force increases from 25.08 to 33.10 the force needed for separating the contacts increase from 30 to 39 [N]. So, by applying more contact pressure, the separating of the contact requires more force.

When the contact pressure is improved the resistance in the transition from bulk to the male electrode is reduced. In this case from no change to 2mm plastic sheet, it was reduced by 36.36 percent.

The theory part explains that when increasing the contact pressure, there will be an increase of a-spots. Silver is softer than copper, and this means that the contact area will yield, expand, and result in an increased contact area.

The contact force is calculated by using the formula for contact force in the calculation chapter.

**NOTE: The resistance in C2 is lower than Tulip 1. The male electrode is silver plated in this case.**

# 6 Calculations

In this chapter a theoretical approach is used to calculate the contact force and friction coefficient, and to determine the resistance in the bulk of the tulip fingers.

## 6.1 Contact force and friction coefficient

To calculate the contact force and friction coefficient, following formula can be used:

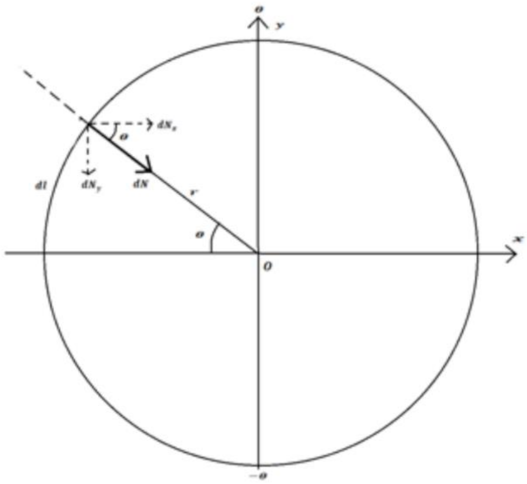


Figure 6-1: Derivation of the frictional force acting in the tulip

$$dN_r = \left|\overrightarrow{dN_r}\right| = F_a \cdot \frac{dl}{\pi R} = F_a \cdot \frac{R \cdot d\theta}{\pi R} = F_a \cdot \frac{d\theta}{\pi}$$

Where $dl = R \cdot d\theta$

$$N_r = \int dN_r = \int_{-\theta}^{\theta} F_a \cdot \cos\theta \cdot \frac{d\theta}{\pi} = \frac{F_a}{\pi} \cdot \int_{-\theta}^{\theta} \cos\theta \cdot d\theta = \frac{2}{\pi} \cdot F_a \cdot \sin\theta$$

With using; $\theta = \frac{\pi}{2}$, total radial force:

$$N_r = \frac{2}{\pi} \cdot F_a \cdot \sin\frac{\pi}{2} = \frac{2}{\pi} \cdot F_a$$

The normal force N on the surface of the electrode may be written as:

$$N = N_r = \frac{2}{\pi} \cdot F_a$$

Where $F_a$ is the force from spring. [13]

Table 6-1: Calculation of contact force.

| Tulip | Contact force[N] |
|---|---|
| **1** | 32.91 |
| **3** | 33.49 |

Further, the calculation of the friction coefficient:

From theory part:

$$F = \mu N$$

$$\rightarrow F = \frac{2}{\pi} \cdot \mu \cdot F_a \rightarrow \mu = \frac{F\pi}{2F_a}$$

Where F is the force separating the contact, and $F_a$ is the force from spring.

From the Table 6-2 and Table 6-3, the friction coefficient can be calculated. The lower the coefficient, the lower frictional force.

Table 6-4: Calculated friction coefficient.

| Tulip | Force from spring [N] | Force, separation. Without lub. [N] | Calculated friction coefficient |
|---|---|---|---|
| **1** | 51.7 | 29 | 0.88 |
| **3** | 52.6 | 35 | 1.05 |

## 6.2 Calculating the bulk resistance

From theory part:

$$R_{finger} = \frac{\rho \cdot l}{A} \quad (6.1)$$

Since the fingers has holes, the physical measurement would be complicated. Then it's easier to take the measurement without taking the holes into consideration. *Resistivity coefficient (ρ) for copper, annealed 0.0172* [14]

Table 6-5: Calculated resistance by hand measurement.

| Tulip | Length[mm] | Width[mm] | Thickness[mm] | Cross-sectional area of the fingers [$mm^2$] | Calculated resistance [μΩ] |
|---|---|---|---|---|---|
| **1** | 51 | 15 | 3.0 | 45.0·6 | 3.25 |
| **3** | 51 | 7.5 | 3.0 | 22.5·12 | 3.25 |

### 6.2.1 Calculating with SolidWorks

Since the tulip fingers have a shape that the cross-sectional area is changing, a drawing will be better for calculating the cross-sectional area. By using SolidWorks to find the cross-sectional area, as described in the theory chapter.

Table 6-6: Calculated resistance using SolidWorks

| Tulip number | Cross-sectional area of the fingers [$mm^2$] |
|---|---|
| **1** | 31.8 |
| **3** | 14.7 |

Tulip 1:

$$R = \frac{0.0172 \cdot 0.051}{6 \cdot 31.8} = 4.60\mu\Omega$$

Tulip 3:

$$R = \frac{0.0172 \cdot 0.051}{12 \cdot 14.7} = 3.98\mu\Omega$$

Deviation might be not 100 % accurate drawings in SolidWorks.

Table 6-7: Comparison with calculated and measured resistance.

| Tulip | Hand calculated resistance [μΩ] | Calculated from SolidWorks[μΩ] | Measured resistance [μΩ] |
|---|---|---|---|
| 1 | 3.25 | 4.60 | 5.69 |
| 3 | 3.25 | 3.98 | 4.08 |

# 7 Improving the design for lowering resistance in open/close contact.

From the result chapter, the resistance in C2 is the most dominant one. One of the measures for improving the resistance in the contact point between the male contact and the fingers is through increasing a-spots. Using a double-sided tape, attach wet sandpaper on the electrode, then gently sand the fingers the contact points will increase.

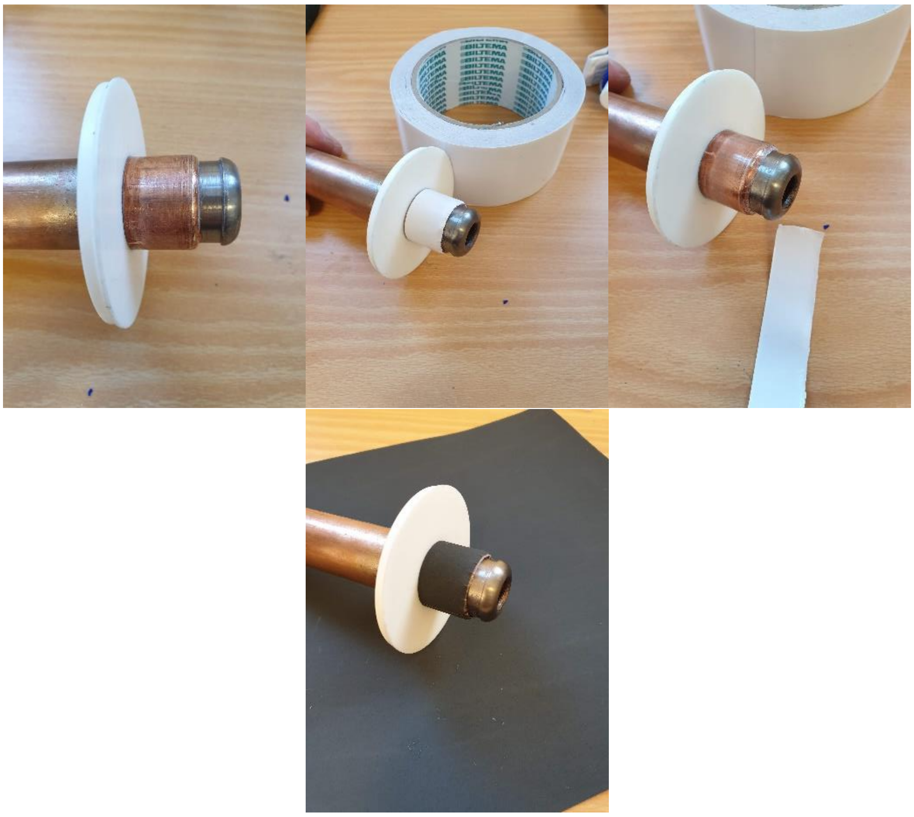
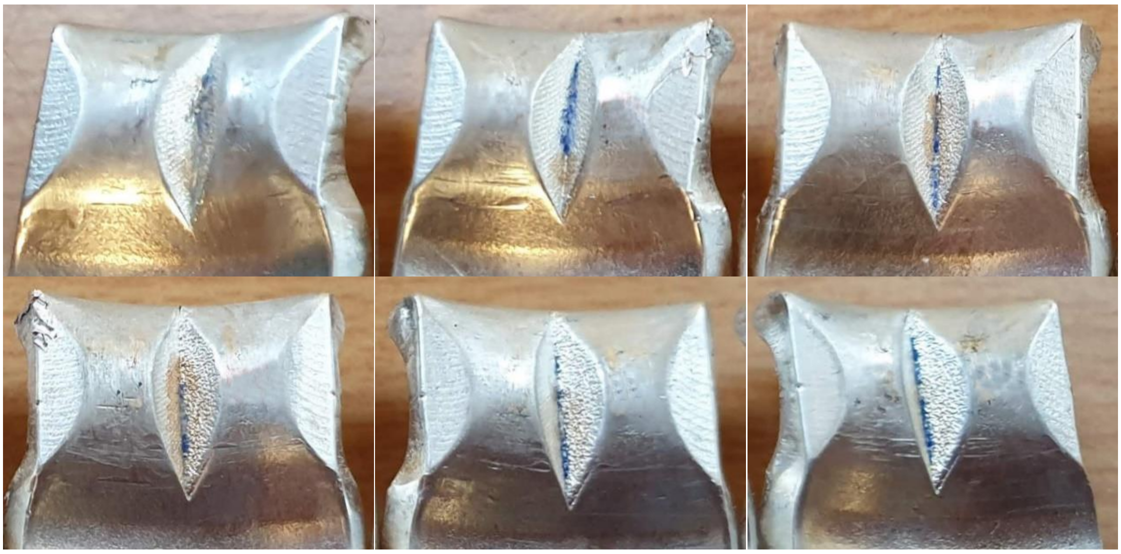


Figure 7-1: Illustration of sanding the contact-area.

The contact is placed under water and smoothly sanded by rotating the male electrode in the closed position. This method will smooth the surface on the fingers.

Before sanding:



After sanding:

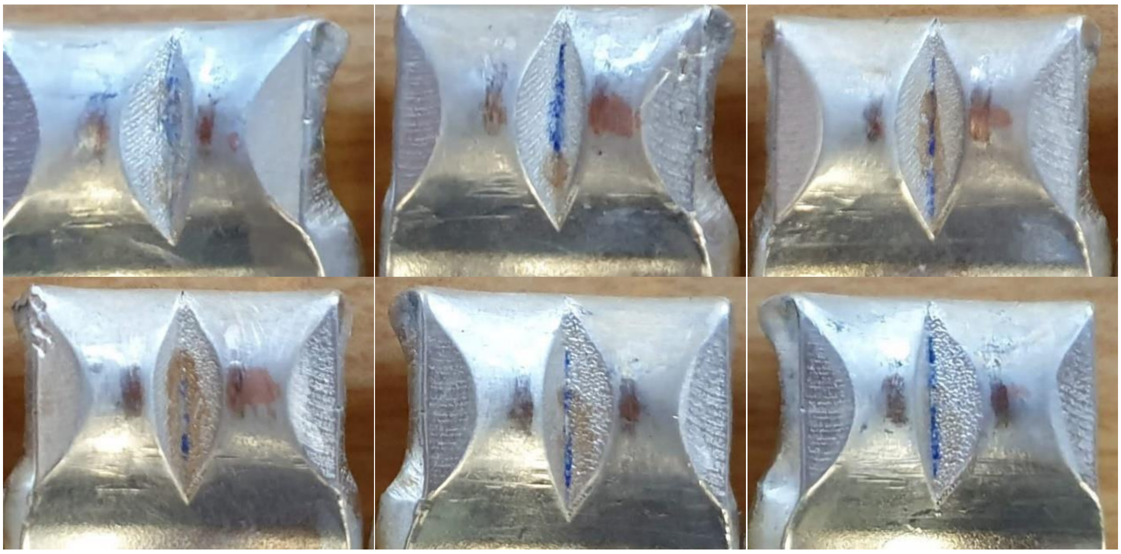
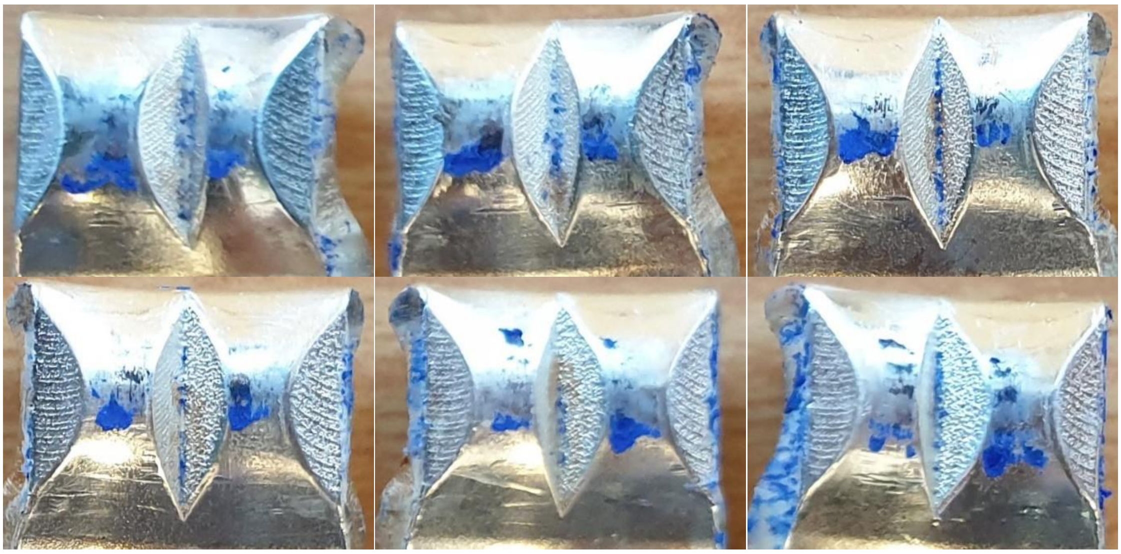


Figure 7-2: Contact surface before and after sanding (modification 1).

After sanding the fingers, the silver layer has been removed on some spots. This results in an increase of the resistance since the silver has better contact properties, it is softer than copper and less oxide.

Blue marker before sanding:



Blue marker after sanding:

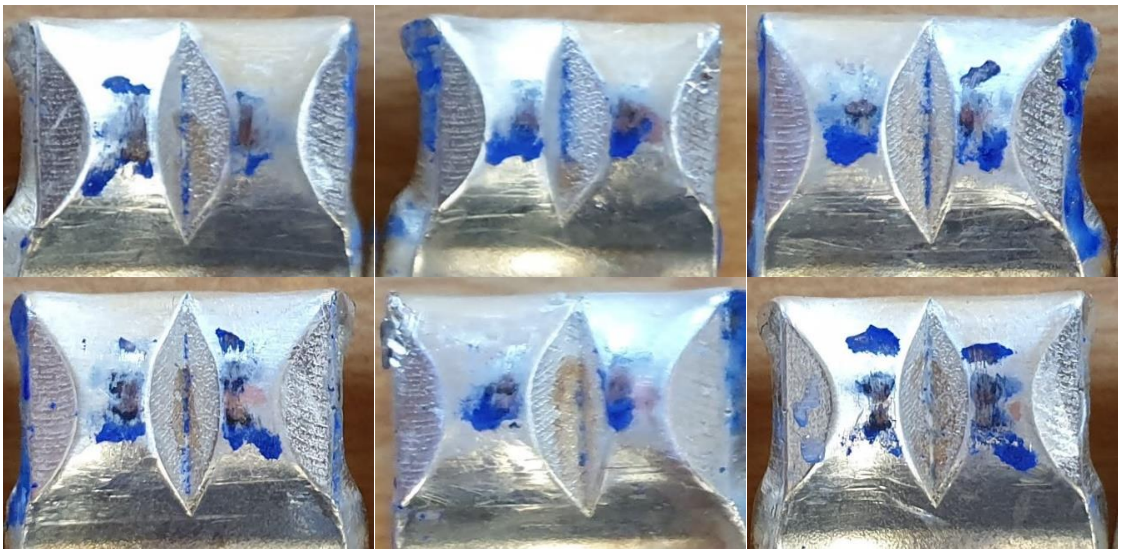


Figure 7-3: Contact-points after modification 1.

It is not easy from the Figure 7-3 to tell if there is an increase of the “blue” or not, but in some of the fingers the increase in contact can be observed.

Table 7-1: Result after modification 1.

| Tulip 1 (Without lub.) | Before modification | After modification 1 |
|---|---|---|
| **C2 [µΩ]** | 9.00 | 8.13 |
| **Improvement [%]** | - 10.70 | |

The resistance was decreased by 10.70 percent as a result of the increase in a-spots and a smoother surface.

With more sanding, the copper becomes more visible as the silver is removed in the process.

Modification 2:

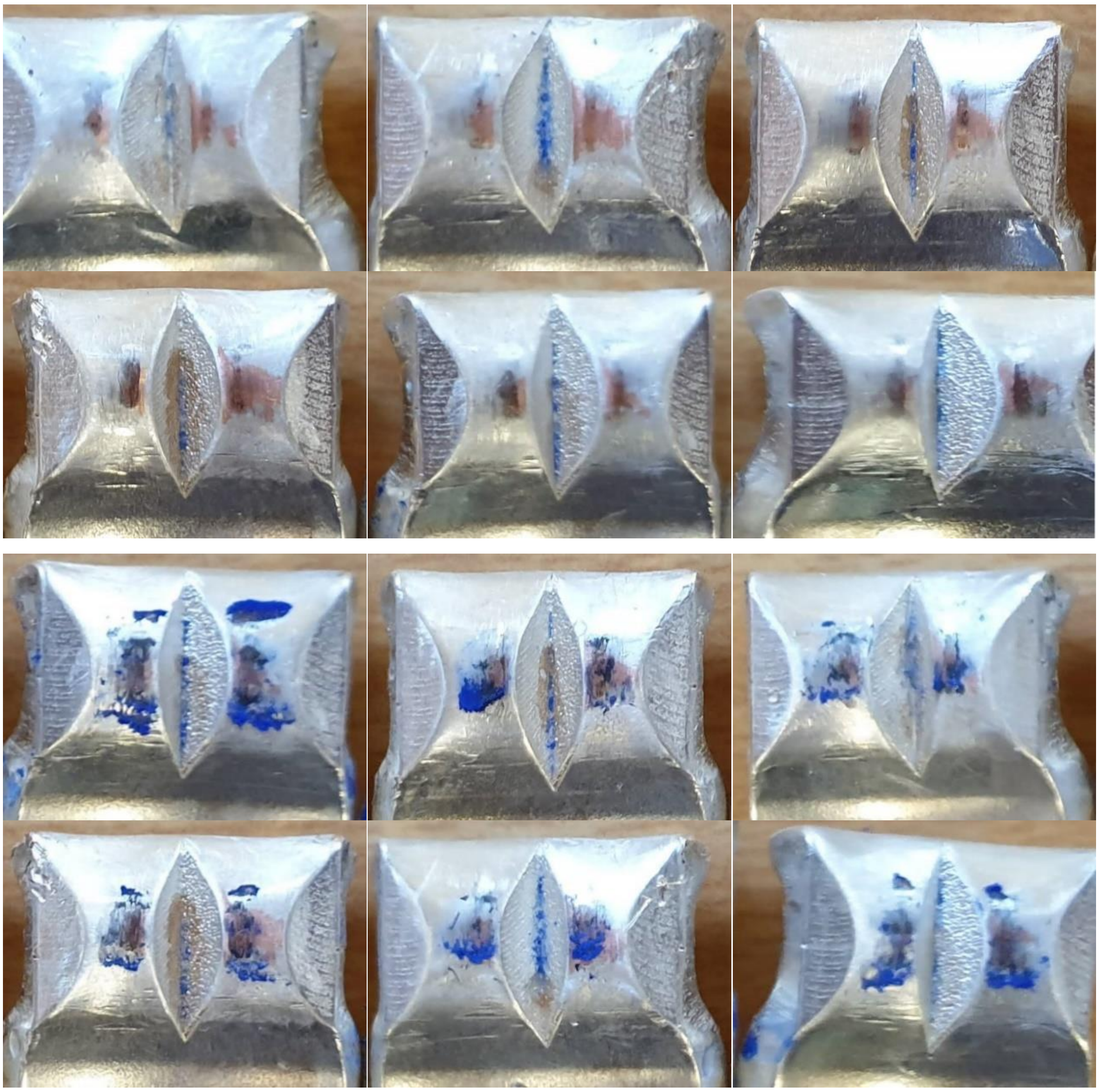


Figure 7-4: Contact-points after modification 2.

Comparing modification 1 to 2, a reduction is observed. Also, as mentioned earlier, the copper is more visible.

Table 7-2: Result after modification 2.

| Tulip 1 (Without lub.) | Before modification | After modification 1 | After modification 2 |
|---|---|---|---|
| **C2 [μΩ]** | 9.00 | 8.13 | 10.54 |
| **Improvement [%]** | | +29.64 | |

The resistance was increased by 29.64 percent.

# 8 Discussion

In this chapter, the result presented in chapter 5 (Results) and chapter 6 (Calculations) will be discussed. Also have the modification to improve the tulip contact 1 will be discussed.

When doing the friction test, in the test-stand, the male electrode and the female contact may have an angular orientation. This might result in incorrect data when separating the contacts. When carrying out measurements, there should be a “peak” or a “spike” in the graph, right before the contact starts separating. To separate the tulip contact, force was applied by rotating the driving mechanism by hand. The contacts were measured by test stand for several times.

It was observed that the resistance measurements were unstable, if the contact was not mounted to the wooden board. When mounted, the resistance measurements were stable. The difference in measurements of C2 (transition from bulk to male electrode) is mostly caused by different number of a-spots. One of the reasons is the different pressure magnitude on each finger as applied by the spring. Pressure is possibly not linearly distributed on each finger.

By applying lubrication, the resistance increases by 40-50%. From the theatrical framework, it was stated that a film between the metals causes reduction in the number of a-spots and results in increased resistance as the friction went down. As a result, lubrication not a viable recommendation for the contacts.

Heat generation, and heating of the metal change electrical resistivity as shown in the method chapter. There was also evidence of heating when the contacts were felt by hand. Heating of conductors results in increase in resistance, which inhibits conductivity.

The contact region was indicated of a blue color by applying the blue marker. Results showed that some areas had no contact since they were clear. The number of contact points on the metals depend on factors such as the force applied by the spring and the nature of the contact surfaces. The distribution of a-spots is a measure of theoretical ohmic resistance, but since it is impossible to determine their area and hence relative distribution was used to make judgments. The blue spots were a measure of the contact area distribution on the contacts.

In the pressure analysis, it was found that an increase in pressure led to a reduction in resistance from the bulk to the male electrode. It is hypothesized that when the pressure is increased in the presence of a silver-coated male electrode, the contact area will yield, leading to expansion, and a consequent increase in a-spots.

The effect of the property of the material used was also significant in the analysis. It was determined that a material that underwent permanent deformation when force was applied would increase the contact between the fingers and the male electrode, which could consequently increase the a-spots. Resistance would decrease as a result. The analysis show that silver metal is used to make the male electrode since it undergoes permanent deformation more efficiently as compared to copper.

There is a relationship between pressure and the resistance at the different contact points. An increase in pressure reduces resistance from the bulk to the male electrode. However, more and more force will be required in the separation of the contact points. Consequently, the improved pressure leads to an increase in the number of a-spots. This is a result of differences in the tensile strength between copper and silver. It is hypothesized that when the pressure is increased in the presence of a silver-plated male electrode, the contact area will yield, leading to expansion, and a consequent increase in the a-spots.

The male electrode and the finger tulips were never 100% compact as shown by the blue markings on the electrode. When the surface was polished through sanding, the distribution of the blue marks increased. It can be interpreted that the sanding led to an increase in the a-spots as reflected in the resistance values. Sanding removed the rough surface layer which was decreasing the a-spots. The analysis revealed that resistance decreased by 10.7% owing to the smoothing.

# 9 Conclusion

The result from the project confirms that the electrical contact resistance, frictional force and the tension of the springs is all connected. These relationships are either direct or inverse. For instance, resistance and contact pressure are inversely related. By increasing the contact pressure with a more tensed spring, will lower the resistance, but also increase the friction open/close the contact.

A tulip contact with sliced fingers or an increased number of fingers, will lower the friction and resistance in the contact area since there will be an increase of a-spots.

By applying a blue marker at the male electrode, are a diffuse way to discover the contact area.

Sanding the fingers at the contact area, might be a good way to lower the resistance, but should be done in controlled way with an accurate method.

From the findings, by applying lubrication the number of a-spots decreases, result in higher resistance, and the friction separating the contacts decreases.

Since the resistance in the contact point between fingers and male electrode are much greater than the bulk or in the C1, by reducing the resistance in C2 will be the most efficient one.

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# Appendices

Appendix 1 **Task description.**

Appendix 2: **Measurement from report N. Thapa, R. Lid and S. Rasmussen, "Measurement of electrical resistance and friction for tulip contacts," Porsgrunn, 2018.**

Appendix 3 **Measurements used in report (Confidential).**

Appendix 1

University of
South-Eastern Norway

# FMH606 Master's Thesis

**Title**: **Improving the design of MV load-break switch contacts**

**USN supervisor**: Wilhelm Rondeel and Elin Fjeld

**External partner**: ABB

**Task background**:

A high voltage switch always requires the use of an open/close contact. The design of these contacts will always be a trade-off between *contact resistance* and *friction*. A low contact resistance in closed position is desired to limit the temperature rise at load currents. This might be ensured by applying a high contact pressure. However, a high contact pressure implies higher friction during opening and closing of the switch. During a development project, it is important to understand how the contact shape, contact pressure and surface conditions affects the contact resistance and the friction for different contact designs. Another important factor is the relation between bulk resistance and contact resistance, the latter depending on the real electrical contact area between the different parts.

**Task description**:

A test stand for friction and resistance measurements is available in the high current laboratory. To be tested are some different designs of tulip type open/close contacts with a rated current of 630 A. Some preliminary test results, from an earlier student project, is available as a project report.
A systematic analysis of the characteristics of different executions of tulip contacts is to be made. Some of the topics to be analysed:

- The ratio between contact resistance and bulk resistance for different designs.
- The influence of contact force on resistance and friction.
- The influence of surface lubrication on resistance and friction.
- Make a proposal for improving the characteristics of the tulip contact, like altering the shape and the number of tulip fingers, and if possible check the effect of the change by measurements.

**Student category**:

EPE students

**Practical arrangements**:

Different tulip contact designs are provided by ABB.
A high current source (AC and DC) is available in the High Current laboratory of USN.
In addition to the aforementioned test stand for friction measurements, the necessary instrumentation for the resistance measurements is available.

**Signatures**:

Supervisors (date and signature):

12/4-19      12/4-19

Student (date and signature):

1/2-19

## Appendix 2

For calculations, the cross-section area of different tulip bulk is dependent by the resistivity of the material, length 0.0179[Ωm/mm2] and 0.03 [m] respectively.

*Table 1: Tulip 1st measured and calculated resistance $R_{c1}$, $R_{bulk}$, $R_{c2}$, and $R_{total}$*

| **Tulip 1** | Average voltage For all finger (A to E) for Tulip 1 [mV] | Current Applied Tulip 1 [A] | Measured Resistance [μΩ] | Calculated Resistance[μΩ] R=ρ *l /A | Cross section Area [mm2] |
|---|---|---|---|---|---|
| ***Rc1*** | 0,60 | 99,60 | 6,02 | | |
| ***Rbulk*** | 0,2 | 99,80 | **2,00** | **1,15** | 465,15 |
| ***Rc2*** | 0,974 | 99,80 | 9,76 | | |
| ***Rtotal*** | **1,48** | 99,70 | 14,84 | | |

*Table 2: Tulip 2nd measured and calculated resistance $R_{c1}$, $R_{bulk}$, $R_{c2}$, and $R_{total}$*

| **Tulip 2** | Average voltage For all finger (A to E) for Tulip 2 [mV] | Current Applied Tulip 2 [A] | Measured Resistance[ μΩ] | Calculated Resistance[μΩ] R=ρ *l /A | Cross section Area [mm2] |
|---|---|---|---|---|---|
| ***Rc1*** | 0,23 | 99,50 | 2,31 | | |
| ***Rbulk*** | 0,23 | 99,80 | **2,30** | **1,22** | 440,60 |
| ***Rc2*** | 2,40 | 99,90 | 23,99 | | |
| ***Rtotal*** | **2,53** | 99,50 | 25,43 | | |

*Table 3: Tulip 3rd measured and calculated resistance $R_{c1}$, $R_{bulk}$, $R_{c2}$, and $R_{total}$*

| **Tulip 3** | Average voltage For all finger (A to E) for Tulip 3 [mV] | Current Applied Tulip 3 [A] | Measured Resistance[ μΩ] | Calculated Resistance[μΩ] R=ρ *l /A | Cross section Area [mm2] |
|---|---|---|---|---|---|
| ***Rc1*** | 0,46 | 99,50 | 4,59 | | |
| ***Rbulk*** | 0,24 | 99,11 | **2,40** | **1,10** | 490,09 |
| ***Rc2*** | 0,67 | 99,50 | 6,73 | | |
| ***Rtotal*** | **1,53** | 99,70 | 15,35 | | |

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*The University of South-Eastern Norway takes no responsibility for the results and conclusions in this student report.*

*Table 4: Tulip 4th measured and calculated resistance $R_{c1}$, $R_{bulk}$, $R_{c2}$, and $R_{total}$*

| Tulip 4 | Average voltage For all finger (A to E) for Tulip 4 [mV] | Current Applied Tulip 4 [A] | Measured Resistance [μΩ] | Calculated Resistance[μΩ] R=ρ *1 /A | Cross section Area [mm2] |
|---|---|---|---|---|---|
| *Rc1* | 0,84 | 99,80 | 8,40 | | |
| *Rbulk* | 0,31 | 99,23 | **3,11** | **1,22** | 440,60 |
| *Rc2* | 1,41 | 99,90 | 14,11 | | |
| *Rtotal* | **2,50** | 99,65 | 25,09 | | |

*Table 5: Tulip 5th measured and calculated resistance $R_{c1}$, $R_{bulk}$, $R_{c2}$, and $R_{total}$*

| Tulip 5 | Average voltage For all finger (A to E) for Tulip 5 [mV] | Current Applied Tulip 5 [A] | Measured Resistance [μΩ] | Calculated Resistance[μΩ] R=ρ *1 /A | Cross section Area [mm2] |
|---|---|---|---|---|---|
| *Rc1* | 0,52 | 99,80 | 5,16 | | |
| *Rbulk* | 0,36 | 99,23 | **3,59** | **1,22** | 440,60 |
| *Rc2* | 0,89 | 99,90 | 8,89 | | |
| *Rtotal* | **1,87** | 99,65 | 18,77 | | |

*Table 6: Rtotal and Rsum*

| Tulip number | Rtotal [μΩ] | Rsum= Rc1 + Rbulk +Rc2 [μΩ] |
|---|---|---|
| 1 | 14,84 | 16,93 |
| 2 | 25,43 | 27,52 |
| 3 | 15,35 | 12,42 |
| 4 | 25,09 | 23,73 |
| 5 | 18,77 | 15,27 |

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## Appendix 3 Measurements used in report (Confidential).

Five different tulip contacts have been tested and analyzed.

The tulip number 1 and 4 has the same design, and tulip number 2 and 5 has the same design. The different is the thickness of the fingers.

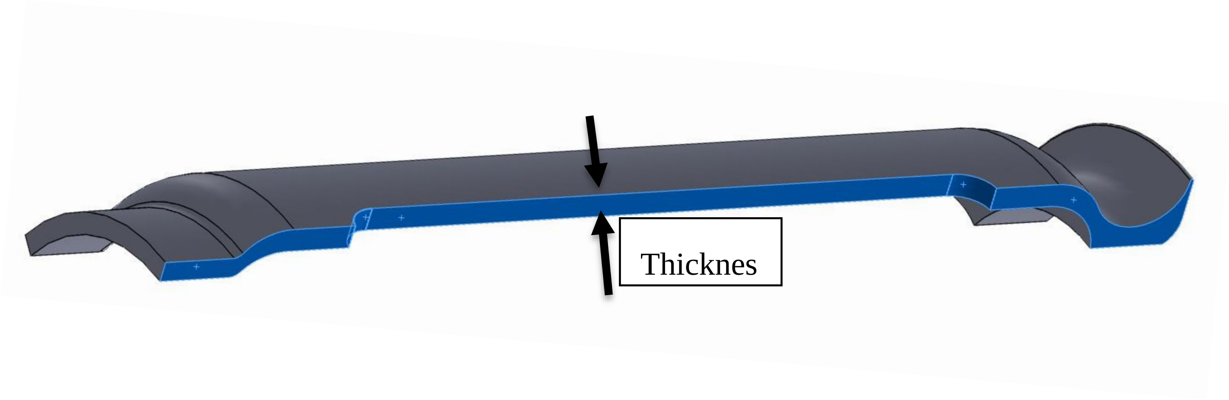


Figure 0-1: Illustration of finger-thickness

| Tulip number | Length [mm] | With [mm] | Thickness [mm] |
|---|---|---|---|
| **1** | 51 | 15.7 | 3.0 |
| **2** | 51 | 15.7 | 2.5 |
| **3** | 51 | 8.0 | 3.0 |
| **4** | 51 | 15.7 | 2.5 |
| **5** | 51 | 15.7 | 3.0 |

### The design of tulip number 1 and 4

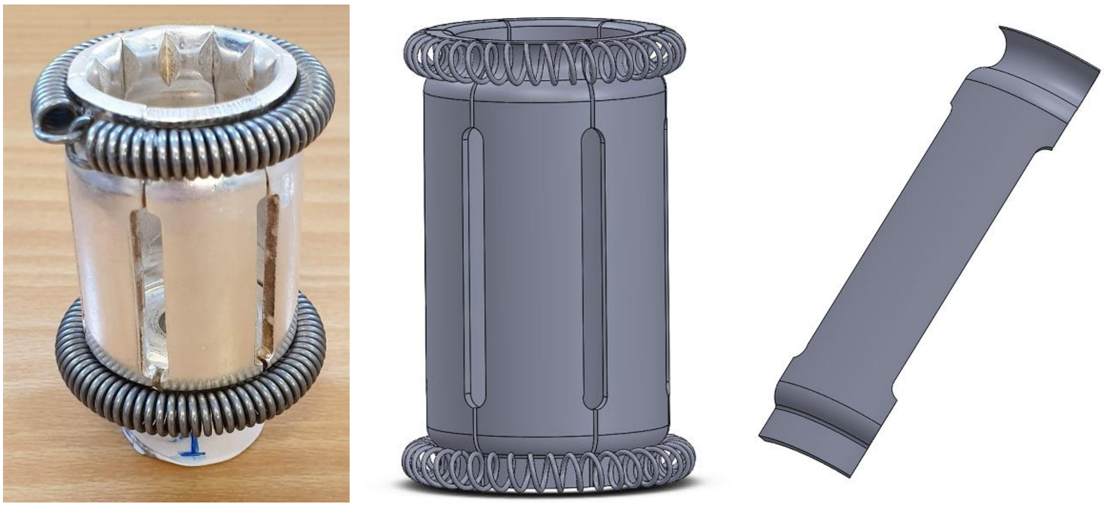

Figure 0-2:Illustration of tulip contact 1 and 4.

## The design of tulip number 3

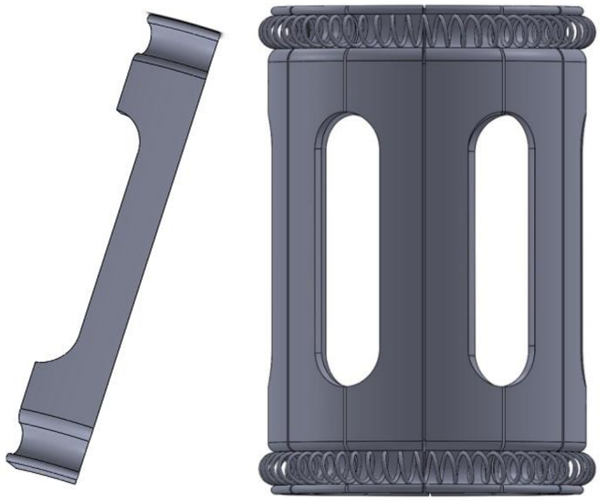

Figure 0-3: Illustration of tulip contact 3.

## The design of tulip number 2 and 5

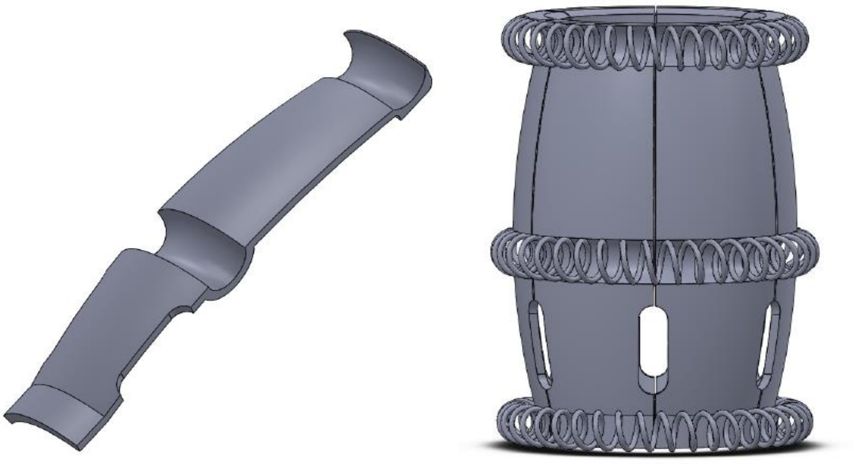

Figure 0-4:Illustration of tulip contact 2 and 5.

## Numbers of fingers

| Tulip number | Number of fingers |
|---|---|
| 1 | **6** |
| 2 | **6** |
| 3 | **12** |
| 4 | **6** |
| 5 | **6** |

# Measurements -Voltage-drop

## Without lubrication

| Tulip 1 | Finger 1 [mV] | Finger 2 [mV] | Finger 3 [mV] | Finger 4 [mV] | Current [A] | Average voltage [mV] | Resistance [µΩ] |
|---|---|---|---|---|---|---|---|
| **Finger** | 0.57 | 0.53 | 0.57 | 0.53 | 96.6 | 0.55 | 5.69 |
| **C1** | 0.45 | 0.55 | 0.41 | 0.45 | 96.6 | 0.47 | 4.81 |
| **C2** | 0.86 | 0.81 | 0.97 | 0.84 | 96.6 | 0.87 | 9.00 |
| **Total** | | | | | 96.6 | 1.81 | 18.74 |

| Tulip 3 | Finger 1[mV] | Finger 2 [mV] | Finger 3 [mV] | Finger 4 [mV] | Finger 5 [mV] | Finger 6 [mV] | Finger 7 [mV] | Finger 8 [mV] | Current [A] | Average voltage [mV] | Resistance [µΩ] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Finger** | 0.5 | 0.34 | 0.38 | 0.28 | 0.54 | 0.38 | 0.40 | 0.40 | 95.5 | 0.39 | 4.08 |
| **C1** | 0.48 | 0.39 | 0.45 | 0.70 | 0.28 | 0.36 | 0.45 | 0.46 | 95.5 | 0.45 | 4.71 |
| **C2** | 0.74 | 0.65 | 0.68 | 0.70 | 0.62 | 0.59 | 0.73 | 0.52 | 95.5 | 0.65 | 6.84 |
| **Total** | | | | | | | | | 95.5 | 1.56 | 16.20 |

**With lubrication**

| Tulip 1 | Finger 1 [mV] | Finger 2 [mV] | Finger 3 [mV] | Finger 4 [mV] | Current [A] | Average voltage [mV] | Resistance [μΩ] |
|---|---|---|---|---|---|---|---|
| **C2** | 1.18 | 1.28 | 1.23 | 1.28 | 96.7 | 1.24 | 12.82 |
| **Total** | | | | | | 2.25 | 23.27 |

| Tulip 3 | Finger 1[mV] | Finger 2 [mV] | Finger 3 [mV] | Finger 4 [mV] | Finger 5 [mV] | Finger 6 [mV] | Finger 7 [mV] | Current [A] | Average voltage [mV] | Resistance [μΩ] |
|---|---|---|---|---|---|---|---|---|---|---|
| **C2** | 0.97 | 0.87 | 0.97 | 0.63 | 1.03 | 1.29 | 1.08 | 96.8 | 0.98 | 10.12 |
| **Total** | | | | | | | | | 1.87 | 19.32 |