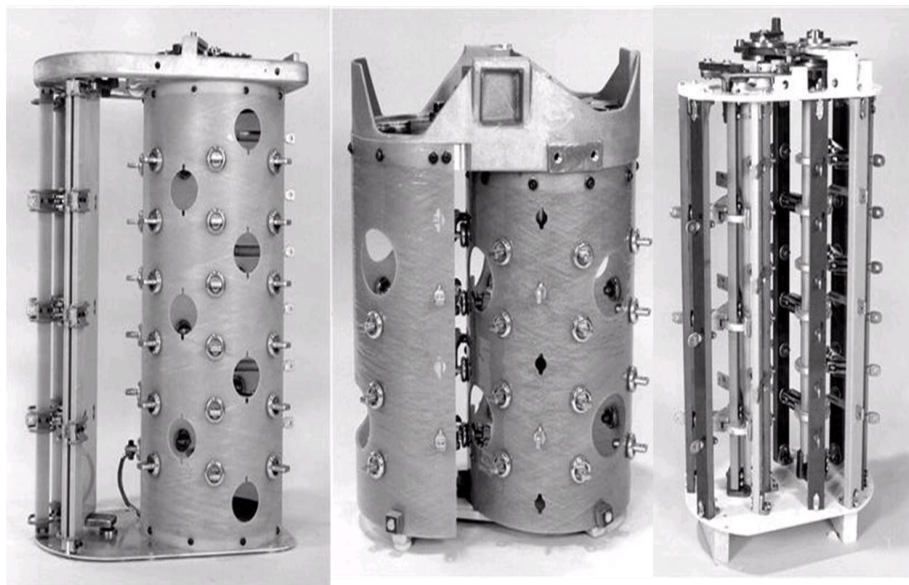


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Investigation of long-time stability Of electrical contacts

*Master of Science Thesis
In Electric Power Engineering*

Keerthana Ravechandiren

Department of Energy and Environment
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2012

Cover:
On-load tap-changers, types UCG, VUCG and UCL, with motor-drive mechanisms, types
BUE and BUL Installation and commissioning guide [1]

Master Thesis in Electric Power Engineering

Investigation of Long-Time Stability of Electrical Contacts

Keerthana Raveechandiren

Performed at : ABB Components
SE- 77180 Ludvika, Sweden

Supervisor : Niklas Gustavsson
ABB Components
SE- 77180 Ludvika, Sweden

Examiner : Tuan Anh Le
Senior Lecturer
Department of Energy and Environment
Chalmers University of Technology, Göteborg

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Department of Energy and Environment
Division of Electric Power Engineering
Chalmers University of Technology
SE- 412 96 Göteborg
Sweden
Telephone: +46-(0)31-772 1000

Investigation of Long-Time Stability of Electrical Contacts

Keerthana Raveechandiren

Abstract

In today's world, it is an undeniable fact that surplus amounts of power are being utilized for almost every domestic and industrial need. Load variation is one thing that is quite common in our scenario, wherein there is a sudden change in the required amount of power supply. To meet with such load variations, tap-changers are used in transformers which help in the regulation of the output voltage to the required levels. There are different kinds of tap-changers used depending on ratings as well as applications. These tap-changers operate by selecting different taps in a regulation winding to produce different output voltages. So they have a lot of fixed and moving contacts in them and these are the most important parts of a tap-changer that help keep them in operation.

This thesis aims to bring about a design guideline which focuses on the various parameters that affect the contacts and also the most important ones to be considered while designing a contact. An accelerated ageing test called the Hopkinson test was conducted on a tap-changer to evaluate its operation for the entire life time in the field. The wear of the contacts in the test was noted and the resistance was measured by passing a DC current through them. A list of all the possible parameters that could affect the contacts was put up and interdependency between them was found. Visual aids were formed taking three parameters at a time. COMSOL simulations were also done to find the current distribution in the contacts. Simulations were done at different rated currents and with various contact resistance values and their corresponding temperature and current density plots are shown in the report. It was determined that it was a really complicated relation to bring about between the parameters and display it as a single dimensional table.

Keywords: Tap-changer, Contact Ageing, Hopkinson test, Mineral oil, Design parameters, COMSOL, Contact Resistance, Esters, Contacts, Accelerated Ageing, Parameter table, Design of contacts

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List Of Abbreviations

OLTC	On-load tap changer
VRLTC	Vacuum Reactance Load Tap-Changer
Ag	Silver
Cu	Copper
AgI	Silver Iodide
Si	Silicon
O	Oxygen
R	Contact Resistance in $\mu\Omega$
T	Temperature
A	Area of mechanical contact in mm^2
F	Force in N
H	Hardness in N/mm^2
2a	a-spot radius in μm
K	Kelvin
C	Celcius
h	Hours
CT	Current Transformer
Ag ₂ S	Silver Sulphide
CuO	Copper Oxide

Chapter 1 Introduction

This chapter gives a basic introduction to tap-changers and voltage regulation. It defines the scope of the thesis and the structure that the report follows, explaining what is covered in each chapter and also highlights the various tasks performed in the thesis.

1.1 Purpose

The On-Load Tap-Changers (OLTCs) for power transformers are important components for an electrical network. Sudden load variations need a tap-changer for proper output voltage regulation. An OLTC failure may be due to one of the following reasons: mechanical malfunction, increased contact resistance, material failure, coking, contact wear, improper design or heavy loads [2]. An improper design may initiate fault modes.

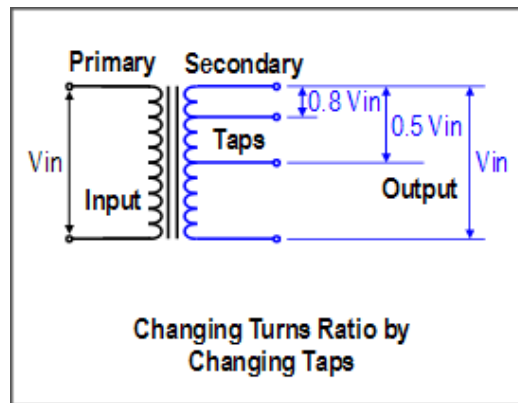


Figure 1 : Voltage Regulation

A proper guideline is required for proper designing and dimensioning of the contacts. This thesis has been focused on the study of long-time stability of electrical contacts. The idea was to study the contact theory and list out the possible parameters that need to be taken into account while designing an electrical contact. The contacts should be designed so as to have high reliability and long life for high frequency operations. Figure 1 shows the basic voltage regulation wherein the secondary regulating winding is tapped at different places to get varied output voltages according to the requirement [2].

1.2 Scope

There are tap-changers operated in different media such as air, SF₆ and oil. They are called dry and wet tap-changers respectively. But this thesis focuses on the tap-changers operated in oil and covers the most commonly used fluids such as esters, mineral oil and silicone oil.

This thesis mainly relies on an accelerated ageing test called the Hopkinson test which is only valid for liquids and the relevance of the test is mainly based on tests performed in mineral oil. So the report covers the parameters affecting the contacts of the tap-changers operating in liquids and specifically mineral oil.

The scope does not cover the tap-changers operated in air and SF6 because the designing of contacts used in these cases require different considerations and a different set of parameters to be taken into account. This forms another thesis altogether.

1.3 Structure

- Chapter 1 of this report covers the introduction part of the thesis, the scope and the basic structure of the report.
- Chapter 2 covers the literature review that was done at the beginning of the thesis work. It includes the basics required for understanding the thesis. It also explains the test methods used in the thesis.
- Chapter 3 moves on to explain the solution of the thesis. It covers the parameters considered for the formation of the Parameter table.
- Chapter 4 shows a part about COMSOL Multiphysics which was used for the simulation part of the thesis. This was done for various current values and various values of contact resistances. The materials were also varied to see how it affects the results.
- Chapter 5 depicts the results obtained from the thesis and the interdependency of the various parameters.
- Chapter 6 includes the conclusion of the report along with the future work.

1.4 Tasks

- The contact ageing test ‘Hopkinson test’ was carried out based on IEC 60214, “Tap-changers”, first edition. 2003-02.
- Primary list for the formation of a design guideline.
- Formation of visual aids representing interdependency of parameters.
- COMSOL simulation to represent the current distribution in fingers.

Chapter 2 Literature review

This chapter covers the background study made in the thesis. It includes a part about the On-load tap-changers and its various types. It focuses on topics like Ageing of Electrical contacts, Contact resistance and Hopkinson test which are the considered to be the heart of this thesis.

2.1 On-load tap-changer

A tap is a point in a transformer winding, which can be selected depending on the output voltage requirements, in order to get a variable output voltage. These devices that enable the selection of different taps so as to regulate the output voltage are called tap changers. Figure 1 shows the basic mechanism of a tap-changer. There are basically two types of tap-changers: Off-circuit or de-energized tap-changers and On Load Tap-Changers (OLTC) [3].

In off-circuit tap changers, the power to the device needs to be cut off before the taps can be changed. This is done in some low power and low voltage transformers. It is a relatively simple design [4].

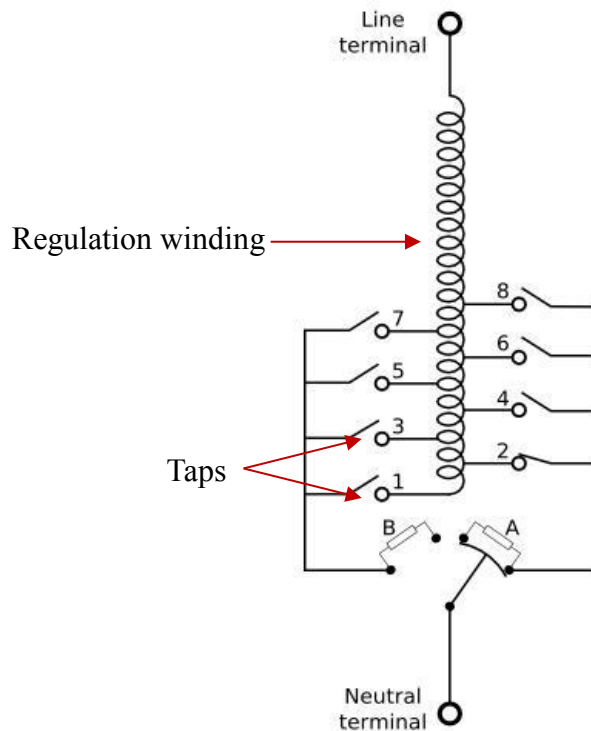


Figure 2: Basic tap-changer mechanism

In many other power transformer applications, such a power supply cut is unthinkable. So OLTC's are used prominently. This tap changer enables changing of the tap ratio without the disconnection of the load. There are many kinds of OLTC's available: mechanical, electronically assisted or fully electronic [5] [3].

ABB has been manufacturing tap-changers since 1910. There are different types of OLTC's available. There are two sub-types for these tap-changers: in-tank and on-tank. They can be kept inside along with the transformer called in-tank or outside in a separate compartment called on-tank. The placement of the OLTC in the different types is shown in Figure 3 and Figure 4.

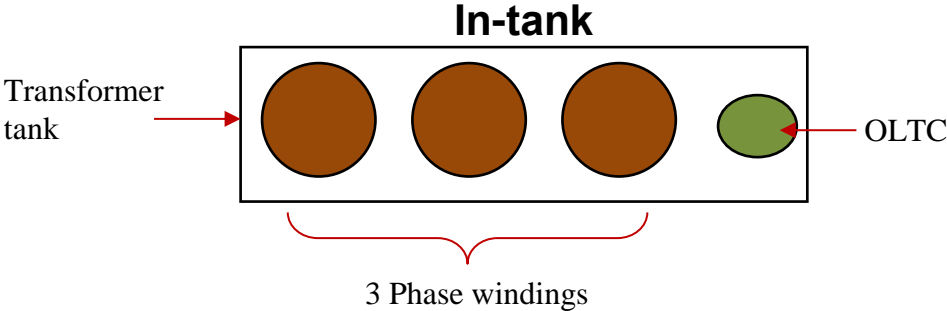


Figure 3: In-tank type OLTC

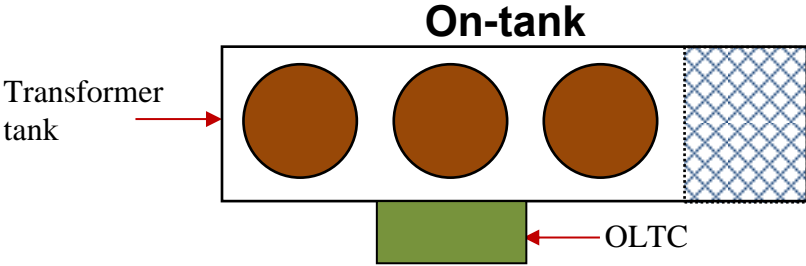


Figure 4: On-tank type OLTC

The available OLTCs are:

- In-tank types
 - UCG/VUCG
 - UCL
 - UBB
- On-tank types
 - UZ and
 - VRLTC

2.1.1 Design

There are basically two types of tap-changers: one with a diverter switch and tap selector (UC family) and one selector switch type (UB, UZ) where breaking and selecting a new tap is done in the same sequence.

During the operation of the tap-changer, arc quenching occurs which if the tap-changer is directly placed in the transformer oil, contaminates it. So the diverter switch is placed in a separate housing below which the tap selector is placed.

If the arc quenching is done in vacuum instead of oil, then it is a much cleaner operation. This is said to be the popular technology of today.

The power to operate the tap-changer is provided by a motor-drive mechanism, placed on the outside of the transformer. There are two kinds of motor-drive mechanisms provided by ABB: Type BUE2, Type BUL, Type BUF that are used with UZ. These motor-drive mechanisms are used for outdoor operation. They are connected to the tap-changers by means of drive shafts and bevel gears. Special equipment and supplements like voltage regulation systems are also provided by ABB to fulfill customer requests.



Figure 5: Type BUE [6]



Figure 6: Type BUL [6]

2.1.2 Type UCG and VUCG

These types of tap-changers come in a variety of models which can be used for almost all kinds of applications. They are called the UC types. UCG operates with arc quenching in oil and VUCG operates the same in vacuum. The vacuum technology is the one that is getting popular now because of the clean operation and ease of maintenance.



Figure 7: Type UCG

They cover up to 400kV and 500 MVA.

There is another type UCC which has a rating up to 80kV.

2.1.3 Type UCL

It is another of the UC types. This is also an in-tank type and mounted as mentioned previously. UCL is considered to be the medium size of the UC type. It ranges up to 525 kV and 1000 MVA [7].



Figure 8: Type UCL

The latest updation is the VUCL which is the vacuum type of the UCL tap-changers.

2.1.4 Type UBB

This is a unique model design for a medium size transformer with a kind of a combination of the in-tank and the on-tank. It is mounted similar to the in-tank, so called an in-tank type. But

it has features of the on-tank type. It is a compact and cost-efficient model. It can range up to 76kV and 90MVA.



Figure 9: Type UBB

A recent release is the VUBB, which is the UBB with vacuum technology. It can range up to 145kV.

2.1.5 Type UZ

This is an on-tank model. The selector switch is located in the main compartment and the motor drive mechanism is located on the outside. It is welded to the outside and supplied ready to be mounted outside the transformer tank.



Figure 10: Type UZ

It covers up to a range of 145 kV and 110 MVA. There are also types UZE and UZF that come under the UZ type.

2.1.6 Type VRLTC

The Vacuum Reactance Load Tap-changer (VRLTC) is an on-tank type tap-changer. There are three major components that make up the Load Tap changer (LTC): tap-changing components, driving and decision making components. The tap-changing components are present in an oil-filled steel tank.

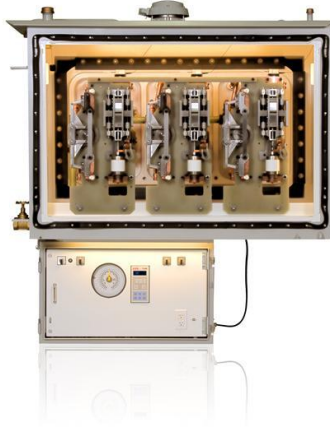


Figure 11: Type VRLTC

The driving and decision making components are present in a separate air compartment that is placed below this oil compartment. A system called the Tap Logic Monitoring System (TLMS) has been added which makes this the world's first smart grid-ready tap changer. It covers up to a range of 72.5 kV and 2500 A [8] [9].

2.2 Ageing of Electrical contacts

A contact exists whenever two materials are placed abutting one another. They may be held together by force, by cementing or by bolts and rivets. A contact is said to be an electrical one when there is a passage of current, voltage or signals [10].

The contact ageing can be defined as the changes in its performance over a period of time. It includes degradation and self-healing. Degradation increases contact resistance and self-healing reduces it. Degradation can be of two types:

1. Corrosion or oxidation
2. Relative movement of contact surfaces (by external vibrations , thermal stresses, thermal cycling or stress variation)

Self-healing events are unstable mostly and so cause eventual degradation.

There are oxides present on all industrial metallic surfaces. Depending on the alloy of the contact material, the growth rate and the thickness may vary. The development of gas films may also depend upon other factors like gas concentrations, temperature and humidity. This film layer later on causes corrosion in the contact interface.

Contacts touch each other only at few spots irrespective of their shape. These spots are called a-spots and are most susceptible to oxidation. This results in the formation of an insulating layer (surface film) which leads to an increase in the contact resistance. The phenomenon succeeding this is the increase in the temperature at the contact spots. The increase of temperature beyond the bulk temperature is called the super temperature. It can be measured by relating to the voltage drop given by the equation below:

$$V^2 = 4 * L * (Tc^2 - Tb^2) \quad (2-1)$$

where,

V is the voltage drop in volts.

L is the Lorenz constant, $2.4 * 10^{-8}$ volts²/degree K²

Tc is the super temperature of the contacts above bulk temperature in degree K

Tb is the bulk temperature of the contacts in degree K.

The super temperature increase above the bulk temperature is only in order of degrees for new contacts but ranges in hundreds of degrees for badly oxidized contacts. The further increase in oxidation restricts flow of current and also increases voltage in turn raising the resistance values. This can go up to the point of melting contacts. When the super temperature exceeds 300 degree C, then the oil cracking occurs with releasing some gases like methane [11].

The tap-changer design considerations taken into account can be classified as follows:

Electrical load: rated current, rated voltage

Mechanical load: contact force, vibrations, fretting

Environmental conditions: Ambient temperature, Humidity, Corrosive gases, Media

There are particular standards to be followed in order to design and test a connector. In the selection of materials there is a rule which says that materials should never be mixed in a connector design as it causes material migration. But in practical aspect this is not taken into account and materials are mixed in order to make a strong design.

When for example, Copper is taken into account, every parameter it has is very important. Even though it is not ideal, it reacts easily with its surroundings. In case of absence of appropriate Copper, Brass can be used. Steel is said to be avoided.

A coating material is used because it lowers contact resistance and provides protection against corrosion. There is a rule which says that both the contact surfaces of the connectors should be coated with the same coating. Silver coating is said to be practically the best till now. Gold is supposed to be even better than Silver but being more expensive it can rarely be used. Its oxide disintegrates at temperature above 180 ° C. It has lowest resistivity and highest thermal conductivity. So it is an excellent contact material. Measurement of the contact resistance is the best way of determining quality of a connector.

2.3 Electrical Contact Resistance

High current mechanical connector is defined as a separable, stationary, non-movable connection between two electrical conductors having the primary function of transmitting power. Contacts of any two surfaces occur only at a-spots, through which electric current pass from one connector component to the other. These a-spots are the basis for determining the contact resistance.

$$A = F/H \quad (2-2)$$

where,

A is area of mechanical contact in m^2

F is contact force in N

H is hardness of the material is kg/mm^2

The above equation means that the true area of mechanical contact is independent of the nominal area of contact. Holm's radius can be defined as a radius which gives a representation of the area over which electrical contact occurs. Location of a-spots within a fixed electrical contact area doesn't affect contact resistance.

The metallic surfaces are covered with oxide layer which needs to be penetrated for electrical contact. The area of true contact is a small fraction of the nominal contact area. The interface only becomes electrically conductive when metal to metal contact spots are produced. The area of electrical contact is smaller than the area of true mechanical contact. The flow of current is constricted by a-spots which reduce the volume and thus increase the resistance called Constriction resistance. It is given by

$$R = \rho/2a \quad (2-3)$$

where,

ρ is resistivity Ωm .

2a is a-spot radius in μm

The contaminant films that are present especially with large electrical resistivity increase the resistance beyond the constriction resistance. Thus the Contact Resistance becomes Constriction resistance + film resistance, which is the Total Interfacial Resistance.

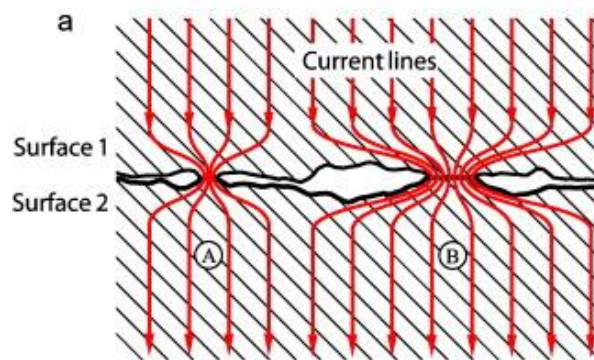


Figure 12: Constriction Resistance [12]

The constriction for the flow of the currents from one surface to the other because of the constriction resistance is shown in Figure 12.

Joule heating and power dissipation occur at a-spots. The resulting a-spot temperature is a function of the interfacial voltage drop as shown below:

$$T_{a-spot} = T_{bulk} + \sqrt{\left(\frac{U^2}{4\alpha\rho\lambda}\right) + \left(\frac{1}{\alpha}\right) - \left(\frac{1}{\alpha}\right)} \quad (2-4)$$

where

U is the voltage drop

T_{bulk} is the ambient temperature

ρ and α are resistivity at the bulk temperature and temperature co-efficient of resistivity

λ is the thermal conductivity [13].

The hottest spot in the contacts of the tap-changer usually when placed in a transformer, is exposed to a temperature of:

$$T_{sc} = T_a + T_{o/a} + T_{b/o} + T_{s/b} \quad (2-5)$$

where

T_{sc} = Contact super temperature

T_a = Ambient temperature outside of the transformer

$T_{o/a}$ = Oil rise over ambient

$T_{b/a}$ = Contact bulk conductor rise over oil temperature

$T_{s/b}$ = Contact super temperature rise over bulk temperature

2.4 Operation of Tap-changers

A tap-changer consists of two sections, the diverter switch and the tap-selector.

This is to avoid contamination of the transformer oil. The diverter switch is placed above the tap-selector and the entire unit is hung from the transformer cover. The diverter switches have resistors which act as transition impedance.

This diverter switch shown is put into a separate housing. There are two types of diverter switch: conventional type and vacuum type.

The conventional types have arc quenching in oil and the vacuum types have arc quenching in oil making the operation very clean and safe.

The tap-selector consists of various fixed and moving contacts, which are connected via current collectors to the diverter switch. The sliding of moving contacts over fixed contacts creates a kind of wiping action making them self-cleaning.

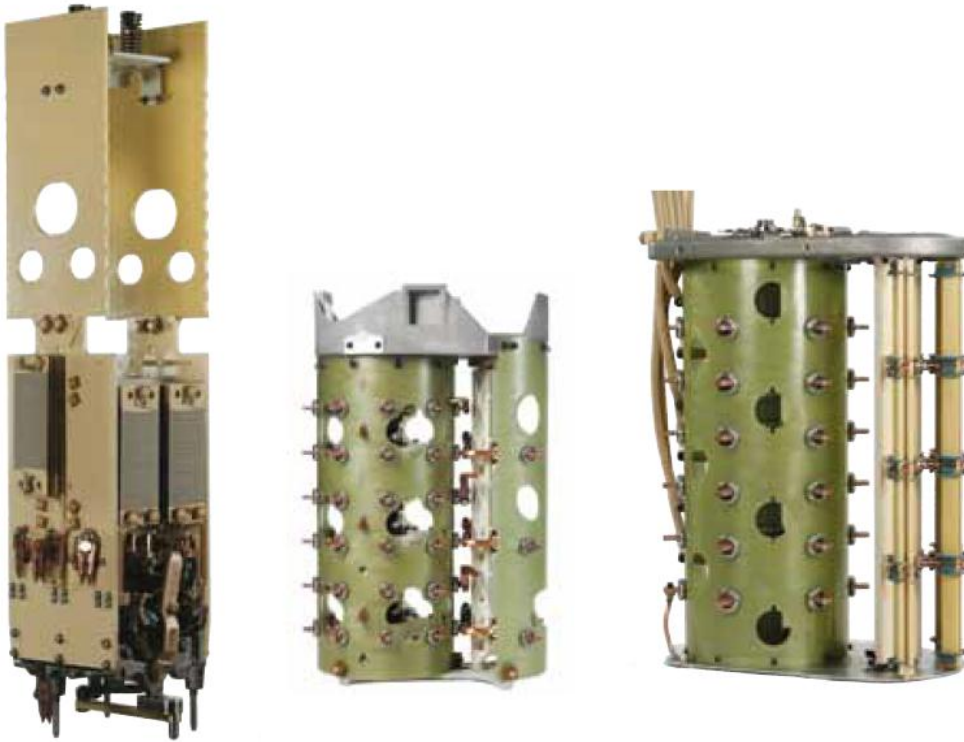


Figure 13: Diverter switch and tap selectors

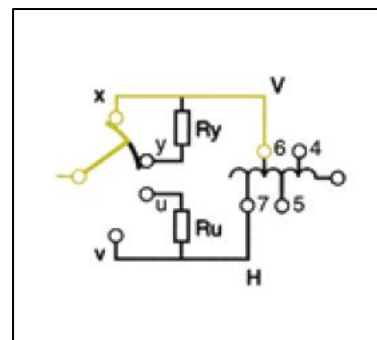
The tap-selector is responsible for the selection of the appropriate taps whereas the diverter switch does the making and breaking of current between taps.

The operation of a tap-changer is explained below with the help of diagrams from (i) to (v).

The diverter switch has two current carrying arms called x and v.

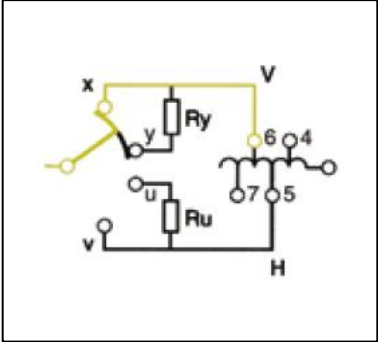
The tap-selector has two arms called H and V. The transition resistors are denoted by R_y and R_u and the corresponding transition contacts are called y and u. The switching sequence of the tap-changer from Position 6 to position 5 is as explained below.

In (i), the tap-selector arm V is connected to tap 6 and H is connected to tap 7. The load current is carried by the main contact x, because current takes the path with the least resistance.



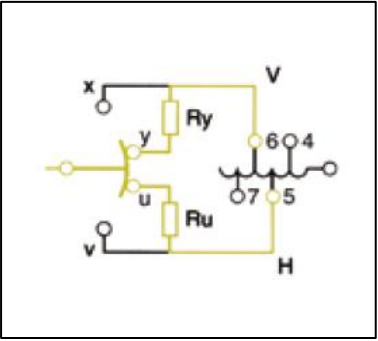
(i)

In (ii), the tap-selector arm H has moved from tap 7 to tap 5. This is the indication that the tap-changer is going to get into a new service position.



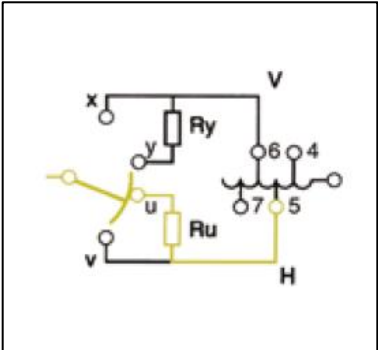
(ii)

In (iii), the main contact x has opened and now the transition contact y is connected. Now the current flow is through y and through the transition impedance Ry.



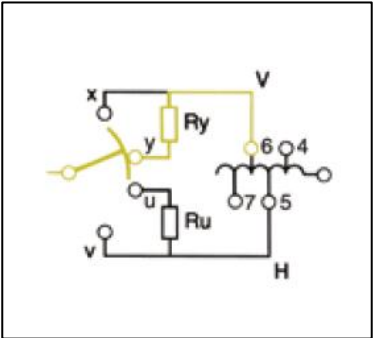
(iii)

In (iv), both the transition contacts y and u are closed. The load current now flows half through each contact. Due to the closed loop, a circulating current is generated which is limited by the two transition resistors Ry and Ru.



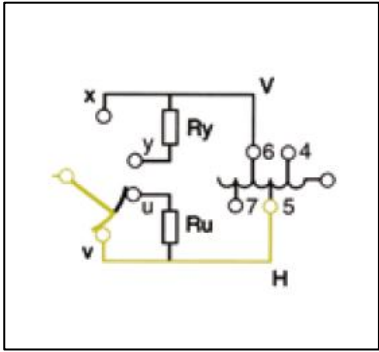
(iv)

In (v), the transition contact y is no longer connected. The load current flows through the contact u and through the transition impedance Ru.



(v)

In (vi), the main contact v is now closed and the load current flows through this contact. This is connected by arm H to tap-position 5. Now the tap-changer is in position 5. Thus a new position has been achieved [7].



(vi)

Shown above is the operation of a general type of tap-changer.

The operations vary for a conventional type from a vacuum type. But that is out of scope of the thesis, hence not covered in this report.

Chapter 3 Hopkinson Test

This Chapter explains in detail about the most important test in the thesis, the accelerated ageing test. It covers the actual testing conditions and the requirements for passing the test. A lot of reasoning is also provided for using certain conditions in the test. A section about Arrhenius equation is described which is used to validate this test.

Accelerated ageing tests are performed on products to get information on life distribution [14]. This is done by subjecting the test objects to extremely severe conditions than the normal ones. These results are extrapolated to evaluate how the object behavior will be at normal conditions. The objects can also be subjected to varied conditions depending upon their exposure in the field.

This is usually achieved at elevated values of temperature, voltage, pressure, vibrations and so on. There can also be a combination of the above parameters used. The cases which mainly use temperature to achieve accelerated ageing can be validated by using Arrhenius equation which will be explained further in this chapter. There are graphical and analytical methods of approaching this validation. More concentration will be given to the analytical method, in which, hours to failure will be plotted against temperature and thus the life performance of the test object can be evaluated [14]. There are also numerous graphical methods which are not in the scope of this thesis. Mostly, these two methods are used hand in hand in life performance evaluations.

The Hopkinson test is a contact ageing test proposed by Phil.J.Hopkinson which runs for 30 days in order to simulate 30 years of field life of the tap changer. This test is made on tap-changers to see how the contacts withstand 'coking'. The process of coking can be defined as the process of extraction of carbon from the surrounding and its deposition on a contact. In this test the test object is kept in oil at a temperature of 130 °C at a current of twice the rated value. The contact resistance measurement, done twice a day, is the one of importance in this test.

There are two criteria that need to be satisfied in order to pass this test:

1. The contact resistance should not increase more than 25% during the test.
2. The resistance value should remain stable in the test.

A complement to this rule is if the increase is above 25% but less than 100% and the standard deviation is <5% and if the contact after the test can be cleaned by maneuver of the arm one position forward or backward and back again to the contact and the resistance measured after this is < 25 % increase, then also the contact is said to be OK. This shows that the cleaning behavior of the contact is good.

The test circuit and the methodology of the test will be explained in the next section.

3.1 Test Circuit

The test circuit is as shown below in Figure 14:

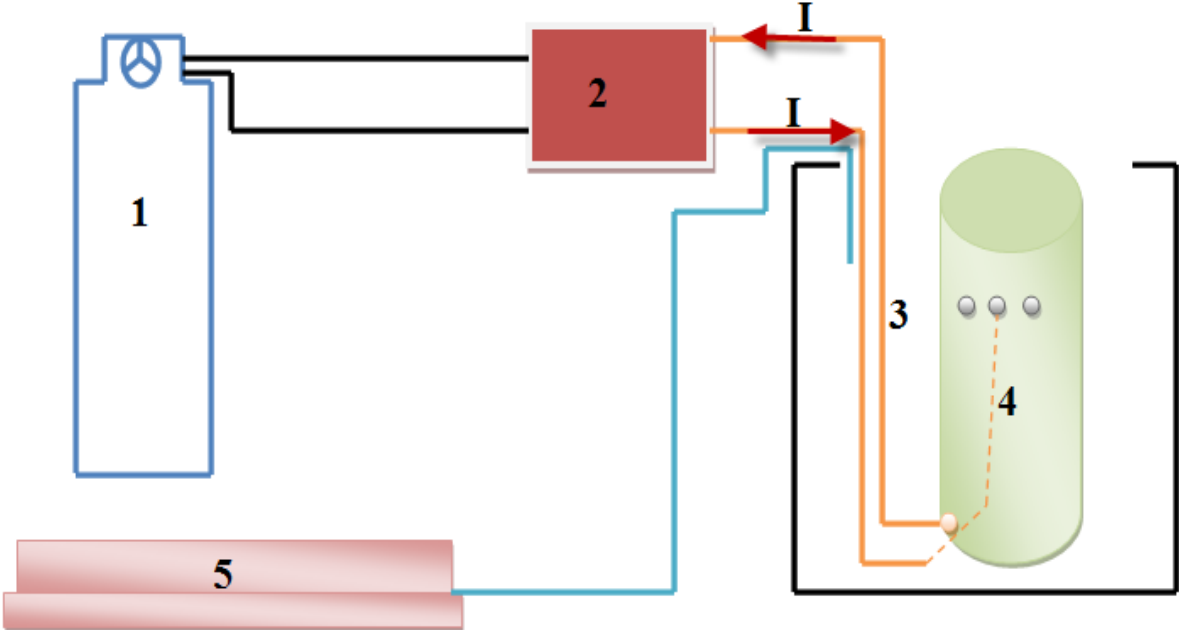


Figure 14: Hopkinson test

1. Regulating transformer
2. High current transformer
3. Test vessel with transformer oil
4. Test object
5. Heaters

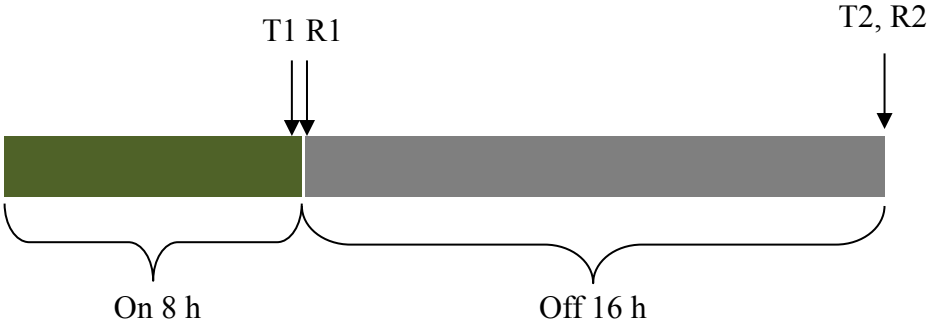


Figure 15: Temperature and Resistance Measurement times

The current is turned ON for 8 hours every day and turned OFF for the next 16 hours which is depicted in Figure 15. This cycle is repeated for 30 days. During the OFF period, the current is turned off but the heater is kept ON for the whole night and during weekends so that the oil temperature does not fall to a really low value. The temperature is measured just before the

current is switched off. The temperature is measured at various contact points by thermocouples inserted in them. Since the flash point of the oil is 140 ° C, the temperature must be kept at maximum 120 ° C over nights and weekends with the help of just the heater. On a normal weekday, twice the rated current value alone will not be enough to bring up the oil temperature to 130 ° C. Sometimes, the oil temperature just due to current can also exceed the required value. So in either case, in order to maintain the temperature of the oil around 130 ° C a heater is used.

The contact resistance is measured at the beginning and the end of the 8 hours ON period. The voltage drop across the contacts is measured and that divided by the load current gives the corresponding contact resistance value. The values are measured using a DC instrument because AC usually gives misleading values because of inductance. The method of measuring is called '4 Terminal Method'. The current level should be such that it is low enough to avoid heating and high enough to ensure accurate voltage recording. Voltage probes are placed as close as possible to the contact interface, in order to minimize bulk resistance. The equipment used to measure contact resistance is called Chance Digital Micro ohmmeter and Ultra Optec DMO 350.

5A and 100 A ratings are used to measure the contact resistance. There are five readings made in the case of each current value. The highest and the lowest values are ignored and an average of the remaining three values is taken as the respective contact resistance value. The values have to remain in the same range for both 5 A and 100 A because for different current ratings, the voltage changes correspondingly to maintain resistance.

Why 5 A and 100 A are used for measurement?

5 A is used first mainly because a lot of customers use less than 5 A for testing. While testing on the field they are not allowed to go more than 10% of the rated current of the transformer. The product should be designed in such a way that it still gives a low resistance at 5 A also.

100 A is used because the higher current will break through the oxide layer formed. So the lower current is passed first and then the higher current.

The current transformer is cut-off during the resistance measurement because then the given DC splits part through the CT and part through the tap-changer which lowers the resistance value. So the CT is cut out and the DC is only allowed to pass through the tap-changer.

The highest value of contact resistance in the contacts kept in oil, is when the oil is cooled down, because the contacts move which cause changes in the contact areas that are somewhat oxidized.

3.2 Arrhenius equation

The relevance of the Hopkinson test is by comparing with Arrhenius equation which is stated as follows: for each 10 degrees rise in temperature the speed of the chemical reaction is doubled. Many of the accelerated ageing tests are validated with the help of Arrhenius equation.

The Arrhenius equation is as given below:

$$k = Ae^{-Ea/k_B T} \quad (2-5)$$

where k = rate constant, A = pre-exponential factor, Ea is activation energy and k_B is Boltzmann's constant, T is absolute temperature in Kelvin

The above equation can also be written in the following way:

$$k = \exp Ea/k((1/T) - (\frac{1}{T'})) \quad (2-6)$$

where Ea can be found out using the following equation given below:

$$Ea = k_B (\beta') / 0.4343 \quad (2-7)$$

where,

$$B' = (T' T) / (T' - T) \log (t * / t *')$$

Using the above equations the Arrhenius relationship can be determined [14].

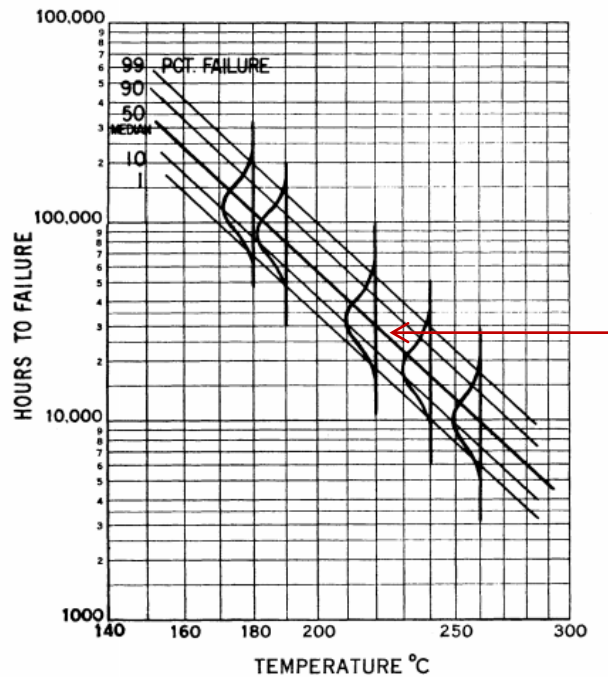


Figure 16: Arrhenius plot of the Arrhenius model

The Figure 16 depicts the relationship between the median life (50 percent failure) and temperature. This is shown by the dark line in the middle shown by the arrow.

Chapter 4 Design of the Parameter table

This chapter explains in detail the various parameters that are supposed to affect the performance of contacts over time. The parameters are also split into two conditions: design conditions and environmental conditions. These parameters are later on used to form a parameter table.

4.1 Parameters Table

A table was formed which served as a listing of all the possible parameters that need to be taken into account while designing the contacts. All the parameters that affect the performance of the contacts cannot obviously be taken into account. There are some design conditions as well as some environmental conditions. They are listed as shown below:

4.1.1 Design conditions

These are the most important parameters that should be kept in mind during the designing phase. The impact of these parameters on mainly the contact resistance was studied.

4.1.1.1 Type of oil

The oil types usually can be Natural ester, Mineral oil or Silicone. The assumption was that the contact materials are Silver plated copper against silver plated copper, Silver plated copper against plain copper and plain copper against plain copper. The results were obtained by performing functional-life test of the different material combinations in three types of oils. In the case of natural ester, it is stable for all the materials used, in terms of temperature and contact resistance [15].

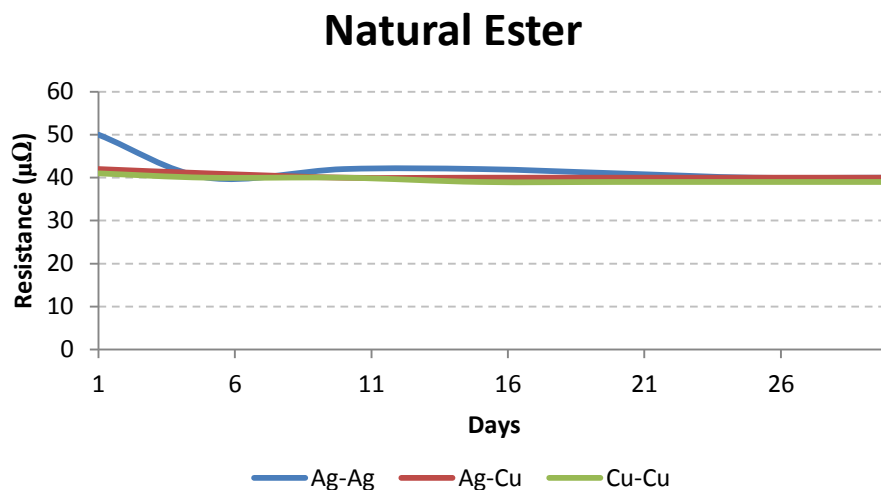


Figure 17: Contact Resistance vs number of days in Natural Ester

All types of contacts (Ag-Ag, Ag-Cu & Cu-Cu) are suitable when used in natural esters. As you can see from Figure 17, the resistances of all the material combinations revolve around 40 μΩ and so are stable. But esters are not used much because they affect the dielectric tests; they are more expensive and damage the OLTC. They have a lot of positive and negative aspects to them. But the negatives are more dominant in this case, as just replacing mineral oil by ester is never possible in a power transformer [16]. The testing of the entire insulation

system layout, modifications of the winding design and also usage of appropriate materials are essential for this replacement to happen without a problem. Some of the disadvantages and advantages are as shown below.

Disadvantages:

- Temperature range for mineral oil is from -40 ° C to +120 ° C. But for esters it is +4 C and above (because it becomes like ice cream at -4 ° C and does not melt until it crosses +4 ° C).
- Streamer propagation speed is faster in esters making esters more sensitive to sharp edges with very high local high stresses.
- Esters are more viscous which affects operation.
- They need to be preserved from oxygen because their presence destroys the ester.

Advantages:

- Being kept away from oxygen helps in the prevention of contact corrosion.
- They are natural so in turn renewable.
- They are non-flammable.

The natural esters used today are called Bio-temp and FR3. There are also synthetic esters which are used today called Midel 7131. The synthetic esters are so made that they have a property of absorbing oxygen and moisture from the surrounding which helps make the contacts resistant to oxidation.

In the case of Mineral oil, the behavior of contacts is as shown in Figure 18

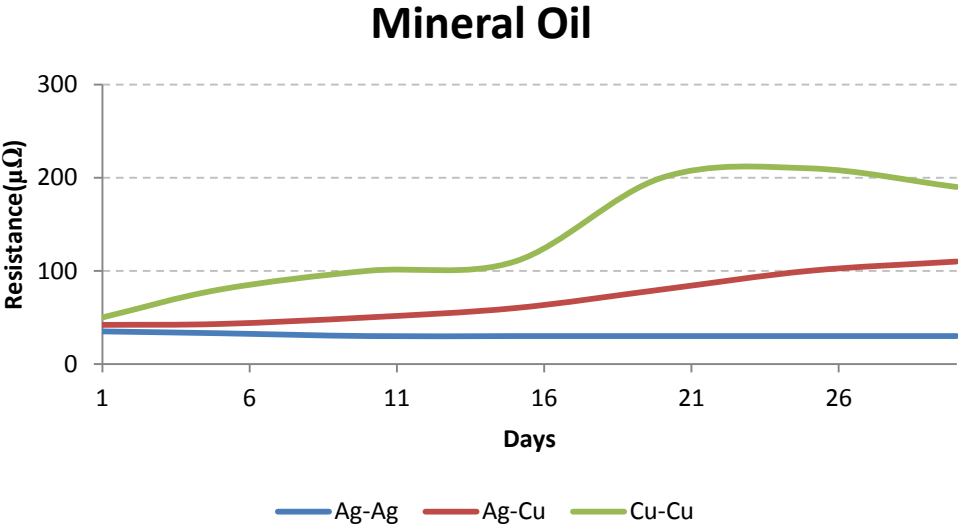


Figure 18: Contact Resistance vs number of days plot in Mineral oil

The mineral oil usually used in transformers is LC set -30°C .As the Figure 18 shows, mineral oil is stable in the case of Ag-Ag contacts but not in the case of the other two. It is especially

very unstable in the case of Cu-Cu contacts. Mineral oil is the one that is the most used in real-time tests because as mentioned previously, it has a wide operating temperature range and it is low-cost. But it also has low flash points which make them dangerous in case of high heat applications [17].

The behavior of contacts in the case of silicone oil is as shown in Figure 19

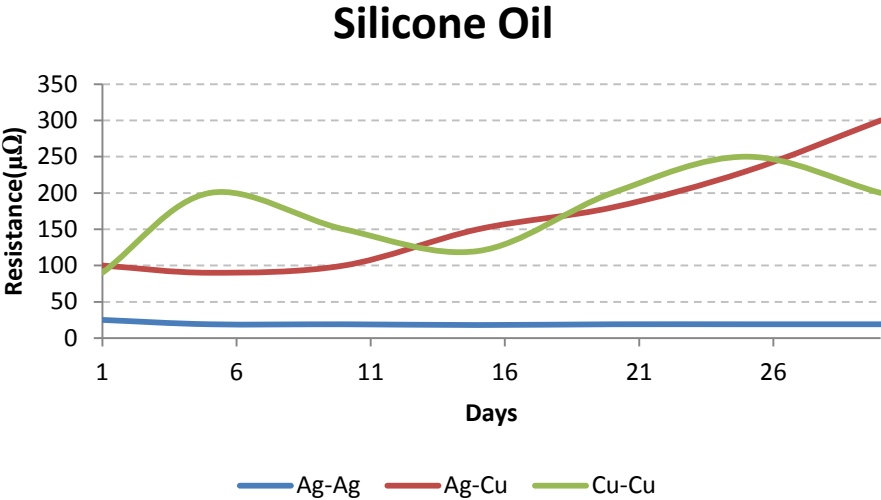


Figure 19: Contact Resistance vs number of days plot in Silicone oil

It is very clear from Figure 19, that Silicone oil is stable for Ag-Ag contacts but it is not the same for the other two contacts. Silicone oil is said to be the most aggressive of the group. It is made up Silicon and oxygen atoms alternatively (Si-O-Si-O).

So if needed to be ranked, then natural ester would be the best if not for the practical issues it has. So mineral oil becomes the one used more and last comes Silicone oil [15]. From the above shown figures it is also clear that Ag-Ag contact is a really good contact metal.

4.1.1.2 Contact geometry

There are different types of contacts used for different tap-changers depending on its design requirements. The tap-changer contacts classified based on their dimensions is as shown in Table 1.

Table 1: Contact geometry Classification

Contact Geometry	Length (L) (mm)	Breadth (B) (mm)	Height (H) (mm)	Classification
	142.5	12	8	Very long and thick
	68.3	12	8	Small and thick
	48.4	5	10.3	Small, thin and tall
	101.3	10	7	Long and thick
	93.6	8	11	Long and tall
	93.6	11	8	Long and thick
	120.58	10	7	Very long and thick
	3.1	18.7	14.8	Very small, thick and tall

The contacts can have a length of around 100mm, breadth from 5mm to 12 mm and height from 7mm to 15mm. If say for example the contact has a length of 101mm, breadth of 10 mm and height of 7mm, then it is said to be a long and thick contact.

The Figure 20 explains the flowchart for classification of contacts based on the conditions given below:

- If length and breadth are taken into consideration, then depending on the sub-conditions they satisfy, the contacts can either be Long, Very long or Small contacts.
- Similarly, if breadth and height are considered, then depending on the sub-conditions they satisfy, the contacts can either be Thick, Think, Tall or Short contacts.
- When both these conditions are combined, then the contacts can be a Long and thick contact or a Small and short contact and so on.

Current flows from outside into the contact joint and then out again which causes a force on the contacts called blow-off force. The force applied on the contacts must be such that this does not happen. This doesn't seem to have much of an impact on the contact resistance.

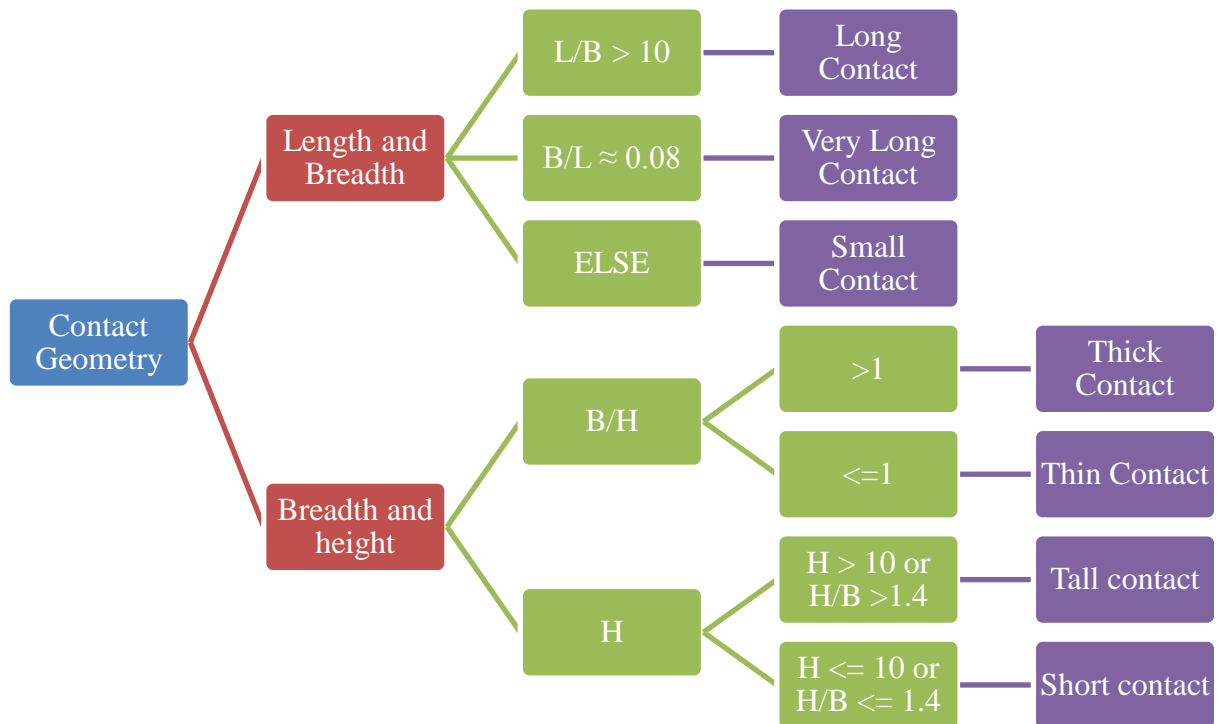


Figure 20: Flowchart for classification of contacts.

4.1.1.3 Material used

Selection of the contact materials should be generally made by first considering its adhesive properties. The best performance of contacts in the case of adhesive wear is said to be

1. Contacts should be hard so as to limit the area of initial contact
2. Have low ductility to limit junction growth.
3. Be lubricated to inhibit asperity adhesion.

Abrasive wear is directly proportional to the load and the distance slid and inversely proportional to the hardness of the material. The conditions specified above are all of a theoretical base which is in most cases contradicting to the practical applications.

The materials used for the fixed and moving contacts are usually copper with a silver padding just on the contact area. Silver is prominently used because it can be used even after formation of black Silver Sulphide (Ag_2S). The reactions of the copper are dependent on the interactions of humidity and pollutant levels.

For the contacts, assuming that the following material combinations are used: Silver-Silver, Silver-Copper and Copper-Copper. As previously stated Silver-silver combination is the most stable as it forms oxide films only if there is ozone present. These oxides are soft and also decompose above 150°C [18]. The contact resistance value is low in this combination. In the case of Silver-Copper, they are more likely to overheat. In the case of Copper-Copper, they are likely to oxidize more. In both the above combinations, contact resistance seems to rise. So Silver-silver seems to be the best combination.

Some studies have also been done on Silver iodide. They blacken when exposed to light being very light sensitive, but this coating wears off when rubbed against each other maintaining the friction to a very small value. This shows that these contacts have exactly the same electrical properties of silver along with the advantage that it has a low coefficient of friction unlike the pure silver contacts.

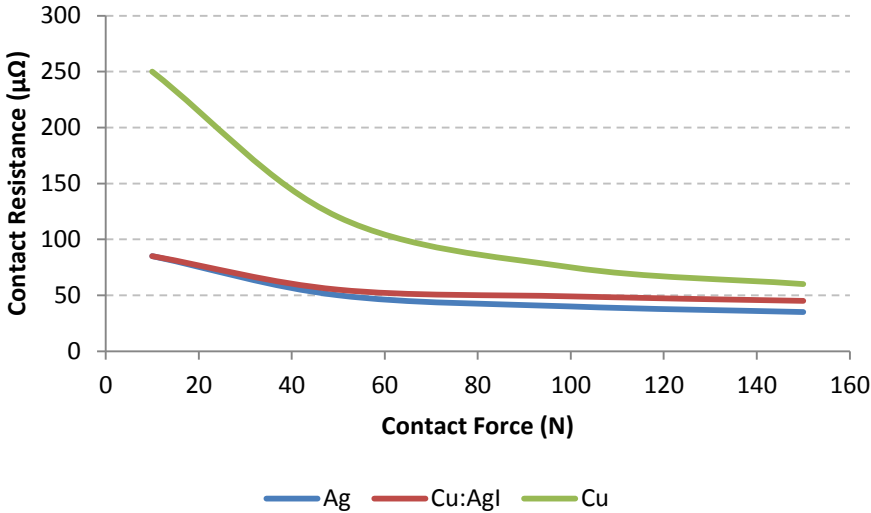


Figure 21: Contact force vs Contact Resistance in case of AgI [19]

Figure 21 shows the plot of Contact force versus Contact Resistance in AgI contacts. As it is evident from the plot, Ag seems to be the best of the three, followed by AgI and lastly by Cu. Both Ag and AgI start from a resistance of about 80 μΩ, but in the case of Cu, it starts from a value of about 250 μΩ. At 40 N, Ag has already fallen to 40 μΩ, followed closely behind by AgI. But in Cu, the resistance value at 40 N is almost 100 μΩ. So it can be concluded from this graph that Ag is the best, wherein AgI is also seems to be a good choice.

4.1.1.4 Contact Force

The selection of the contact force is based mainly on the short circuit current and also on the mechanical properties like friction to avoid too high torque for operation and also have good temperature rise properties. The current flows from outside to the contact joint and then out again which causes a force on contacts called blow-off force. There needs to be a minimum of this force applied in order to hold the contacts together.

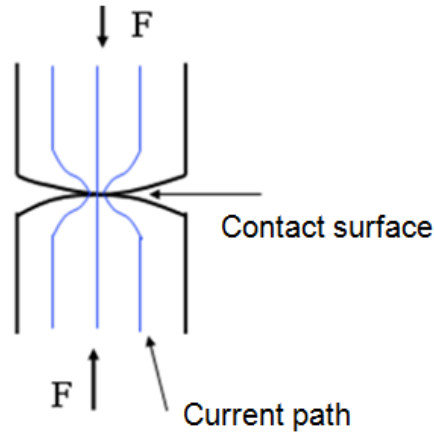


Figure 22: Blow-off force

It needs to be at least a minimum value of:

$$F_{min} = 4.45e^{-7} \times I^2 \quad (4-1)$$

where,

I is peak current in A

In the case of a parallel contact, the current flow causes a force which can be added to the contact force to know the actual force on the contacts.

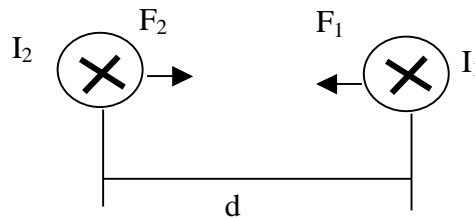


Figure 23: Attractive force

$$F = \mu_0 l \frac{I_1 I_2}{2\pi d} \quad (4-2)$$

where,

$$\mu_0 = 4\pi \times 10^{-7}$$

I_1 and I_2 are Peak current per contact in A

d is the distance between the contacts in mm

l is the length of contact in mm.

The flow of currents I_1 and I_2 in two parallel contacts that are at a distance d apart, cause a force F_1 and F_2 called the attractive forces. Since these forces help keep the contacts in place without allowing them from moving farther apart, the contact force has to be a value decided based on both the Blow-off forces and Attractive forces.

The contact resistance is said to decrease with increase in contact force because:

1. Increase of number of contacting surface asperities as surfaces brought close under more load
2. Permanent flattening of the asperities which decrease constriction resistance and so contact resistance.

The contact force usually used in sliding contacts and thereby also in the accelerated ageing tests is 40 N.

The relation between contact resistance and contact force can be given by

$$R \approx K\rho\sqrt{H/F} \quad (4-3)$$

where,

R is contact resistance ($\mu\Omega$)

K is constant ≤ 1 ,

ρ is resistivity

H is hardness of metal (N/mm^2)

F is contact force (N)

Cu Alloys

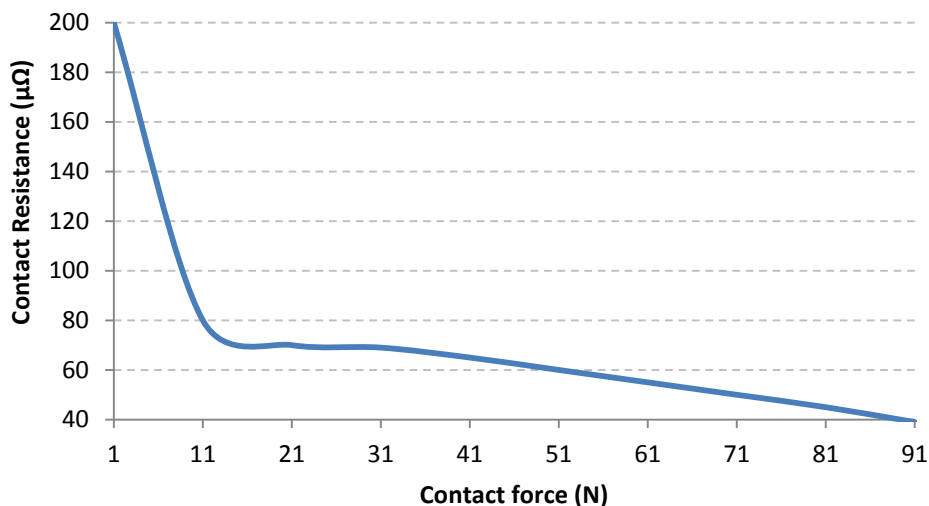


Figure 24: Contact Resistance vs Contact force [20]

Figure 24 shows a plot between the Contact force and contact resistance in the case of Copper alloys. It is evident that resistance falls with increase in Contact force. But the contact force needs to be increased to almost 90 N for the resistance to fall to 40 $\mu\Omega$.

If the copper alloy is coated with a silver plating of 6µm on both the touching surfaces, the observation in Figure 25 was obtained,

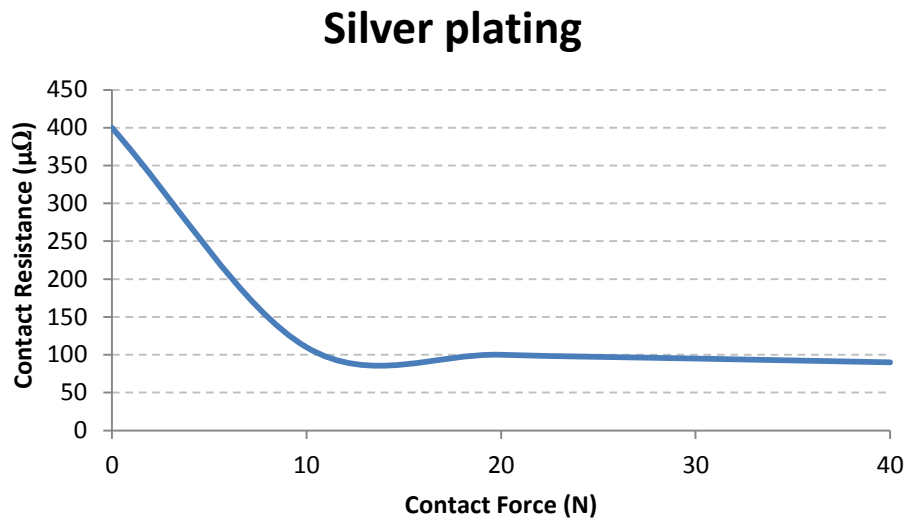


Figure 25: Contact Resistance vs Contact force [21]

It can be clearly seen that the contact resistance drops with the increase in the contact force. It is also very noticeable that a lower contact force is sufficient in the presence of silver plating.

4.1.1.5 Surface Films

The formation of thin surface films is called corrosion. There are such oxides on all industrial metallic surfaces (except gold). The type of alloy influences growth rate and thickness of oxide layer. Oxygen and other corrosive gases form a surface film of corrosive products penetrating the contact interface depending on factors such as gas concentration, temperature, humidity and various other factors. A semi-conducting oxide layer is formed below 200 degree C and above that an insulating layer of Copper oxide (CuO, black) is formed.

Contact resistance decreases due to several mechanisms such as decrease in surface hardness, large electrical conductivity, elimination of electrically insulating layered films. Conductive coatings protect contact surfaces. Contact resistance depends on electrical resistivity (ρ) and ratio of radius of a-spot and plating thickness

$$\text{Total Resistance} = \text{Spreading resistance} + \text{Film resistance}$$

There are growth of intermetallic layers formed by the inter diffusion of materials across a bimetallic interface. These phases have high electrical resistance and low mechanical strength. The growth of these layers produce material gradients characteristic by changes in micro hardness. These are caused by mechanical strains.

The order of getting visual also seems to be an important aspect for choosing the correct material. Even films that are not visual can cause insulation. Silver seems to be the best in this aspect as well as it gets visual only after 1000 Å, which is a considerable film thickness. Only

after this the contact resistance seems to rise for Silver. These films are also very soft. The thicker the film the more the resistance increases.

In the case of copper, the films get visual at a very early stage, with a much less film thickness and the contact resistance shoots up to a very high value.

Figure 26 and Figure 27 show the plots of contact resistance versus film thickness for Copper (Cu) and Silver (Ag). As seen in Figure 26, Copper gets visual much sooner than Silver. For a film thickness of 80 Å, the contact resistance has gone up to 170 μΩ. In the case of the Silver contact, it gets visual only at about 1000 Å. Even at a film thickness of 8000 Å, the contact resistance value has only gone up to 120 μΩ.

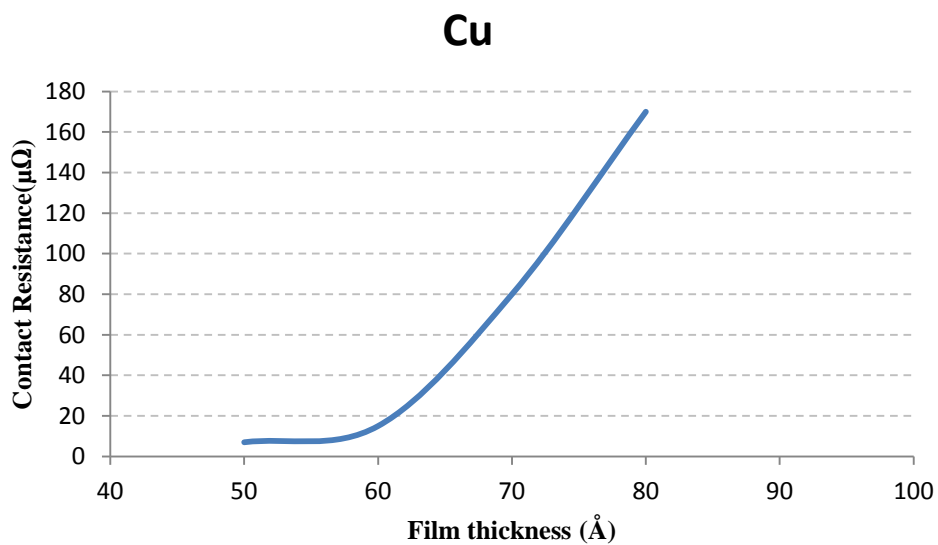


Figure 26: Contact Resistance vs Film Thickness [10]

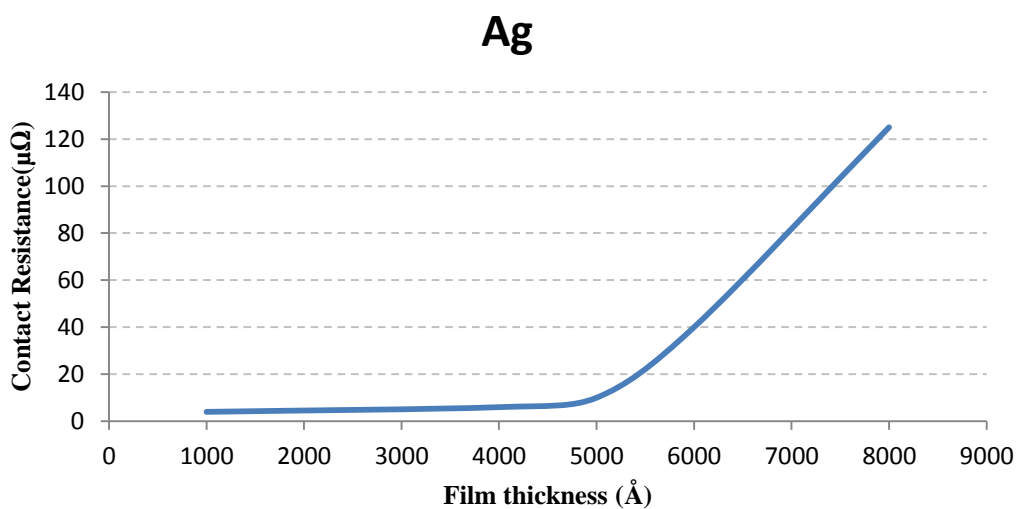


Figure 27: Contact Resistance vs Film Thickness [10]

As you can notice from Figure 26, Copper gets visual very early and attains almost 170 $\mu\Omega$ at 80 Å itself. Proper measures must be taken once these surface films get visual because they affect the operation to a great extent. In the case of Figure 27 Silver, the films get visual only after a while and even after that it can still be operated for some time without any problem because even after forming the dark oxide, the Silver is not so much of a threat to the tap-changer contacts. In this case it is clear from the silver plot, that it attains a contact resistance of 130 $\mu\Omega$ only at a film thickness of 8000 Å.

The presence of films also causes heating which increases oxidation leading to loss of continuity of current. This leads to an increase in the resistance value. Rougher the surface easier it is in breaking up the oxides on the surface.

4.1.1.6 Fretting

This is one of the contact failure processes which is also said to be small amplitude contact movement. This causes metal transfer and wear. When a force is applied to a connection due to thermal excursions, vibrations or any other means, its magnitude must be sufficient to exceed the friction between the mating contacts for fretting to occur. The coefficient of friction is 0.15-1.0.

The main factors known to affect fretting may be [10]:

- a. Contact conditions
- b. Environmental conditions
- c. Material properties and behaviour.

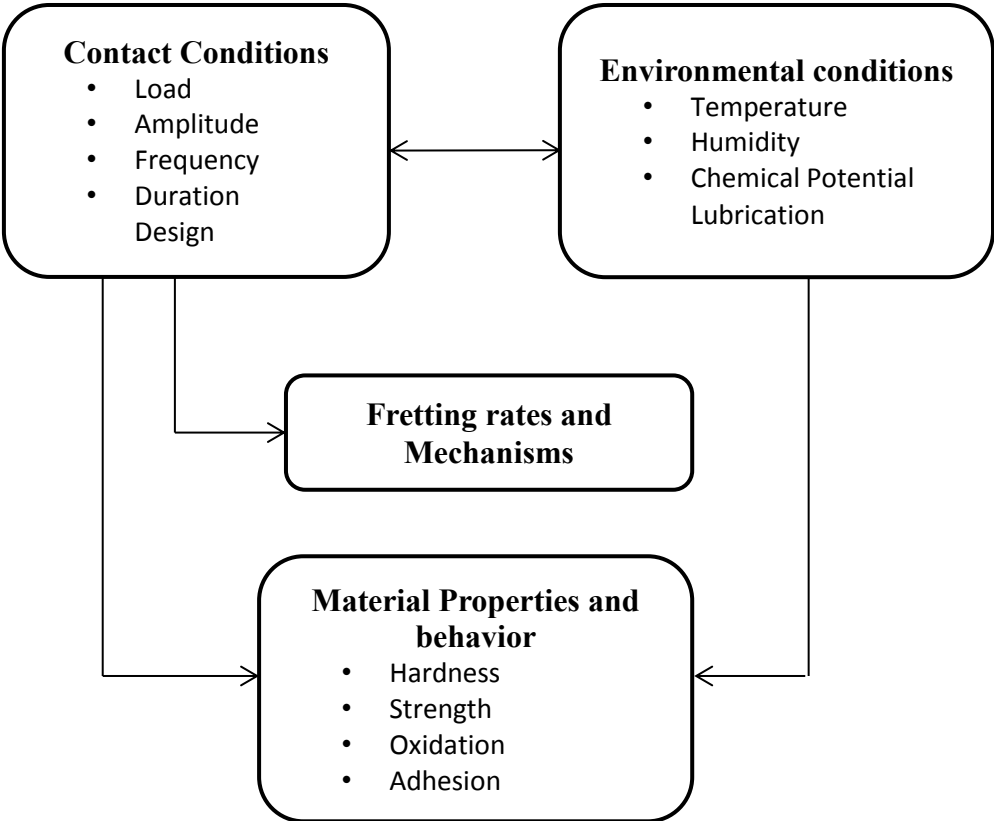


Figure 28: Factors affecting fretting [10]

When contact metal is non-noble, insulating materials appear in the contact interface. If these substances are inorganic solids, like oxides the process is called fretting corrosion. There are two aspects to electrical resistance degradation

1. Static contact resistance
2. Variability contact resistance which may reach high values during fretting.

These depend on various factors like the velocity of fretting, cycle rate, contact materials and the physical properties and thickness of the insulating layer. The lower frequency allows oxide thickens to grow more causing increase in resistance, and so reduction of contact area which in turn leads to increase of contact resistance.

Fretting to an extent causes a kind of wiping effect which causes a reduction in contact resistance. In the case of a Copper-Copper contact a similar thing happens before the contact resistance starts to increase. However fretting is not a really good thing if seen in terms of the wipe distance point of view, which suggests that reducing the fretting magnitude may significantly improve contact performance.

4.1.1.7 Current distribution in fingers

The current flow through the contacts is split through one pair of contact fingers. The ratio of this split is usually assumed to be a ratio of 60/40. This is a general assumption as it practically cannot be 50/50. The changes in values if the assumption is 70/30 or 80/20 are shown in the simulation Chapter. The current split depends on the contact resistance in the fingers. The finger which has less contact resistance allows more current to flow which leads to an increase in temperature in that contact. This leads to self-destruction of the contact over time. This is explained more in the simulations shown in the next Chapter. In some cases depending upon the rated current value the contact fingers are removed or added to withstand the current flow.

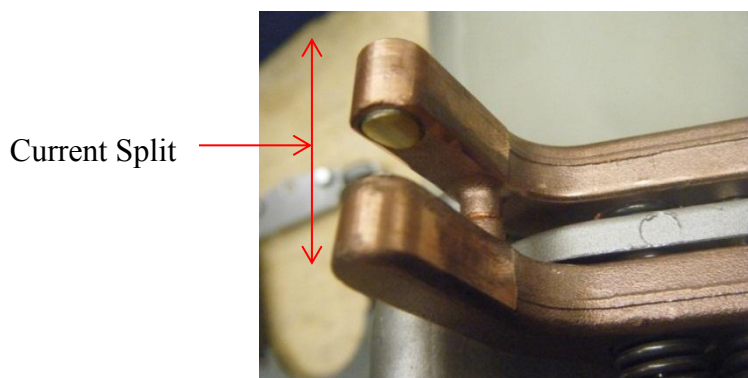


Figure 29: Current distribution in fingers

4.1.1.8 Voltage

The rated voltage of operation has some impact on the contact resistances. The contact resistance reduces when the voltage is high enough to cause fritting. Fritting can be defined as application of an electric field to the contact interface, high enough to cause electrical

breakdown for film disruption causing metal-metal contact. The electric field strength is 10^8 Vm^{-1} . Fritting causes sudden rise in current and fall of contact resistance.

But this concept is only valid in the case of low voltage applications. In the case of a Hopkinson test a high voltage is used and so is not applicable in this case.

4.1.1.9 Current

Current is a parameter that affects contacts of all types. Its presence affects the performance of contacts. The current passing through the contacts cause a temperature rise at the a-spots. This is called super temperature that is explained in the next chapter. This temperature causes

1. The viscosity of the fluid films adjacent to the a-spot to decrease
2. Increase of the evaporation of volatiles adjacent to the a-spot

These cause an increase in the a-spot area, in turn causing contact resistance to decrease. The contact voltage can be given by the constriction resistance times the current. This process leads to the decrease of the contact voltage. Further increase of the current, causes the contact voltage drop to reach a value called the melting point, where melting of asperities take place.

4.1.2 Environmental conditions

There are also some environmental conditions which need to be mentioned.

4.1.2.1 Contact super temperature

This temperature can be defined as the deviation of the a-spot temperature from the bulk contact temperature.

$$T_m - T_1 = V^2 / 8\rho\lambda \quad (4-4)$$

where,

T_m is the maximum temperature at the contact interface in degree Kelvin

T_1 is the bulk contact temperature in degree Kelvin

V is the voltage drop across the contacts in Volts

ρ is the electrical resistivity in Ωm .

λ is the thermal conductivity in $\text{Wm}^{-1}\text{K}^{-1}$

As explained in the previous chapter, this causes an increase in the a-spot area and thus a decrease in the contact resistance. This is valid for all contacts irrespective of their shape and dimension.

4.1.2.2 Humidity

Humidity is said to accelerate corrosion in mixed gas environments. It is believed that if the humidity is maintained below some critical value, corrosion will not occur. This value is called Critical humidity. But humidity alone does little to cause corrosion. But a little Cl_2 along with humidity accelerates corrosion. This causes an increase in the contact resistance.

4.1.2.3 Contaminants

The formed films are generally removed by the wiping action of the moving contacts. But, this wiped area risks direct exposure of the metals to the contaminants, leading to the formation of oxides, sulphides etc. Reactions between lubricants and the contaminants can be very severe ones. This causes an increase in the contact resistance. There are some reasons for a-spot formation [10]:

1. Metallic contact between clean asperities
2. Mechanical fracture of rigid films allowing contact
3. Expulsion of fluid films
4. Impression of hard particles to allow metal contact
5. Electrically breakdown films exposing metal areas.

The parameters that are used in the parameter table are:

- Type of oils
- Materials used
- Contact force
- Surface films and
- Current distribution in fingers.

The impact of these parameters against contact resistance is shown in the table which is displayed in the Results chapter.

Chapter 5 Simulation of Current distribution in contacts

This chapter focuses on the simulation done using COMSOL Multiphysics in order to obtain the current distribution in the contact fingers. The simulation was done at different current ratings, by variation of contact resistances and also by variation of materials.

5.1 COMSOL Multiphysics

COMSOL Multiphysics, a finite element analysis, solver and simulation software for various physics and engineering applications was used as the Simulation tool in this thesis. This software is used to do several simulations like Heat transfer, AC/DC modules, Fluid dynamics and various other physics, chemical and mechanical simulations. The models can be drawn using COMSOL or even imported from other drawing software tools like Pro-E and AutoCAD. COMSOL in fact has Live-links for MATLAB, Pro-E, AutoCAD and many other tools. In this thesis, a model of the fixed and moving contact of a diverter switch in a tap-changer was modeled in Pro-E and the model imported onto COMSOL as shown in Figure 30. This simulation was basically to see the current distribution in the contact fingers and know how it affects the resistance and temperature values [22] .

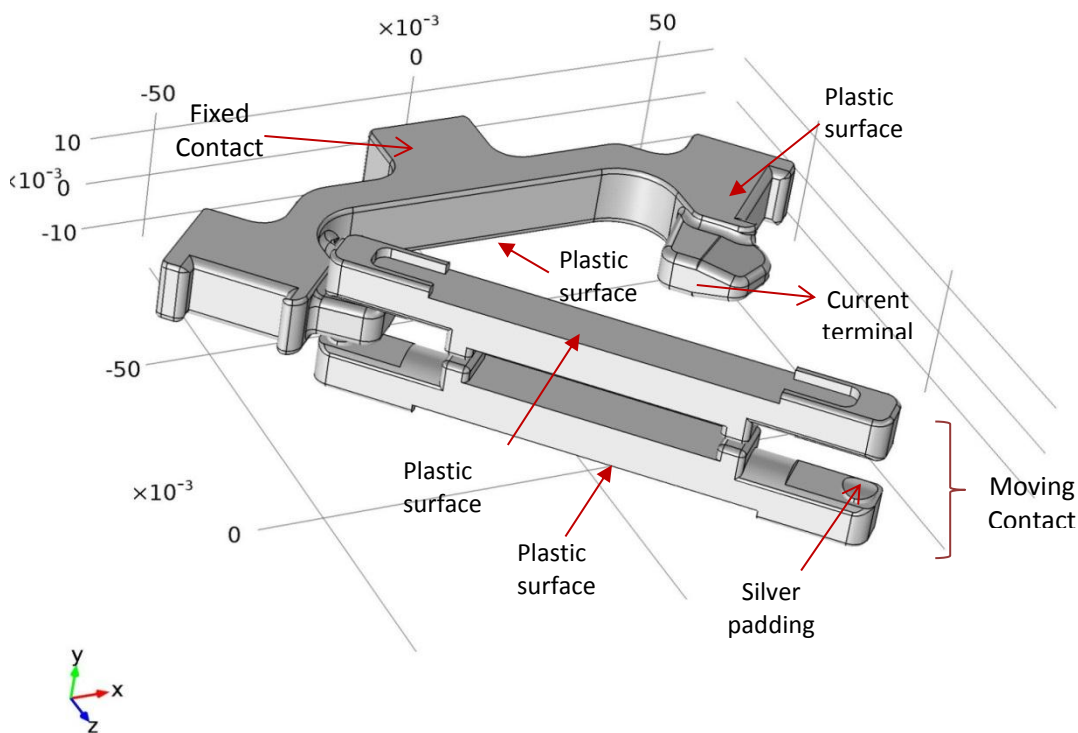


Figure 30: Pro-E Model of a fixed and moving contact.

The model dimensions were the same as in real time tap-changers. The fixed contact and the moving contacts were given Copper (Cu) as the material. The paddings were given as Silver (Ag). Since the contacts in real time are placed in a plastic housing a heat transfer coefficient

for plastic was given for the top and bottom surfaces of the fixed and moving contacts. Joule heating was done on this model. The oil temperature was taken to be 130 ° C. Contact resistance values were assumed based on the tests previously performed and contact impedances were applied to the contact surfaces of the silver paddings. For different values of current ratings and different values of contact resistances, the temperature and current density plots were formed which are displayed from Figure 32 to Figure 42.

One end of the fixed contact was taken to be the current terminal and two silver paddings on the ends of the contact fingers were taken to be the grounds. From Figure 30, the current terminal is not a particular spot but an uneven area. So the area of the particular boundary was measured and a current density applied on the surface. A normal free tetrahedral mesh as shown in Figure 31 was applied, to avoid problems in meshing because of the complexity of the model.

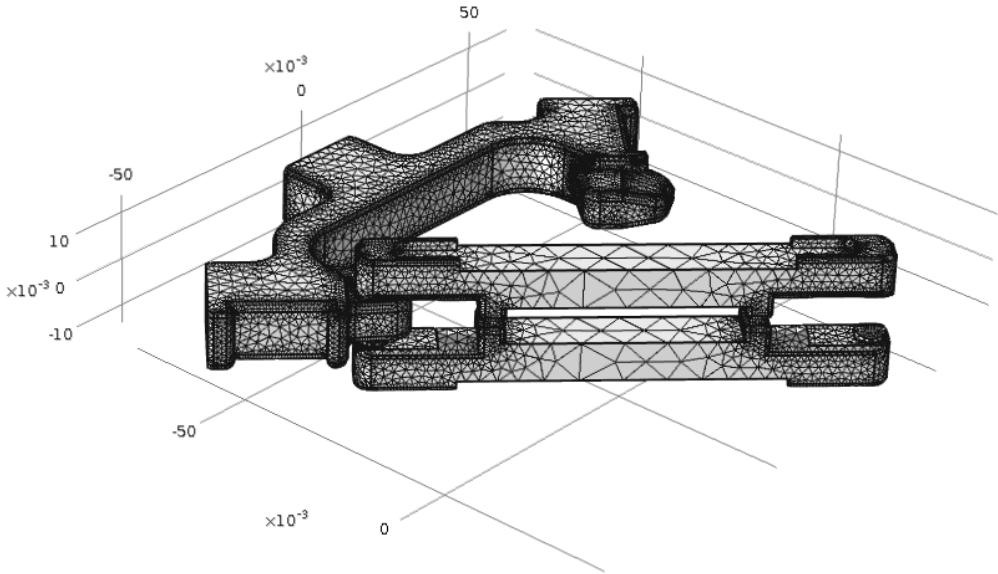


Figure 31: Meshing.

A global evaluation of the entire surface was done on the result to obtain the maximum temperature difference on the model. Surface integrations were done on the silver paddings to obtain the current density values to know the current split in the fingers. A 3D plot group was used to obtain a surface plot of the temperature difference and a streamline plot of the current density.

5.2 Current rating of 600 A

For a current rating of 600 A and contact resistance of 50 μΩ on both the contact fingers, the following temperature plot was obtained.

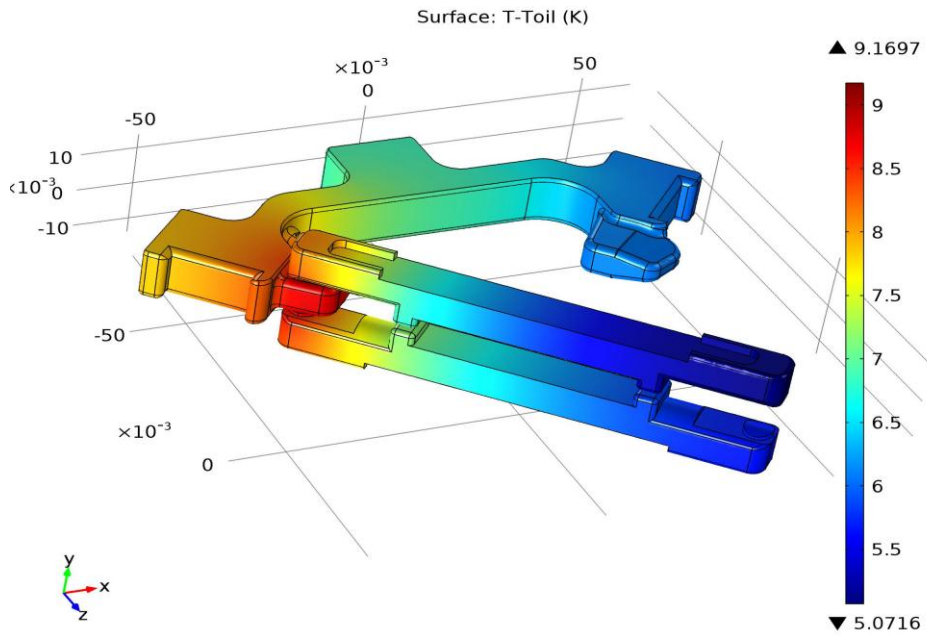


Figure 32: Temperature plot for equal resistances of $50 \mu\Omega$.

As Figure 32 shows, the temperature variations in this case can be seen from $5 \text{ }^\circ\text{C}$ to $9 \text{ }^\circ\text{C}$. The maximum temperatures can be seen around the contact interfaces, between the fixed and the moving contacts.

These variations can be seen because of the application of Joule heating mechanism to the model. In this mechanism, the flow of current through a solid with finite conductivity gets converted to heat with resistive losses in the material [22]. This is the reason why we get clear temperature variations as shown in Figure 32.

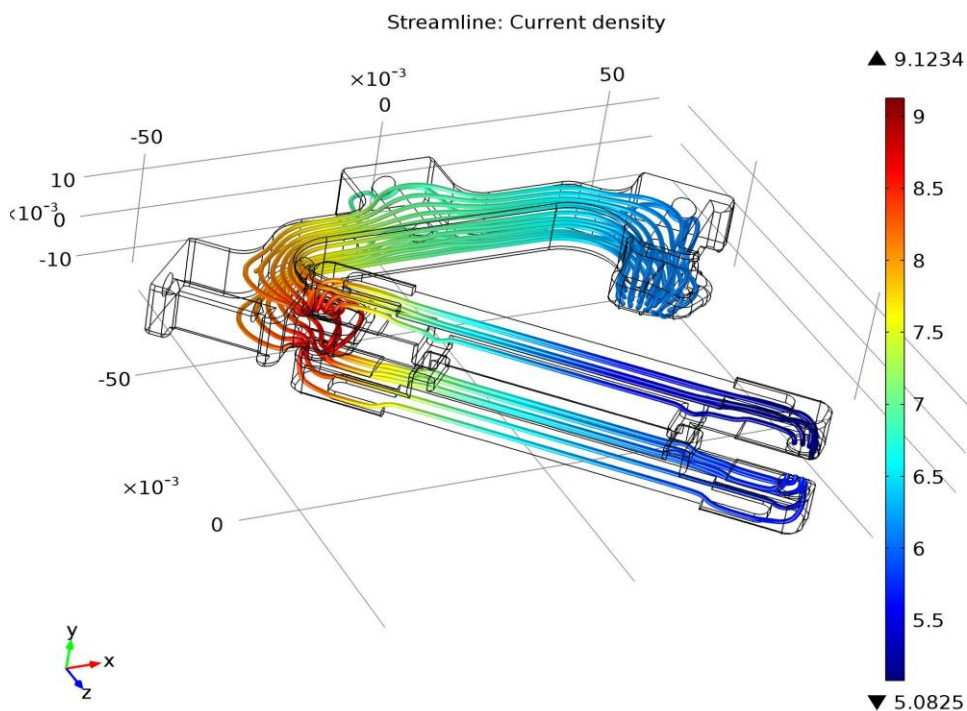


Figure 33: Current Density plot.

The streamline above shown in Figure 33 shows the current density through the model. It is very evident that the concentration of current is at the juncture of the contacts. The basic Joule heating law can be given as

$$Q \propto I^2 \cdot R$$

where Q is the heat dissipated, I is the rated current and R is the resistance at the contact. This is called Joule’s first law. Joule heating is also called ohmic or resistive heating. [23]

5.2.1 Variation of contact resistance

Since the temperature variation is of interest, the contact resistance values of the contacts were varied from 50 μΩ on both to 25 μΩ on the top contact finger and 50 μΩ on the bottom one.

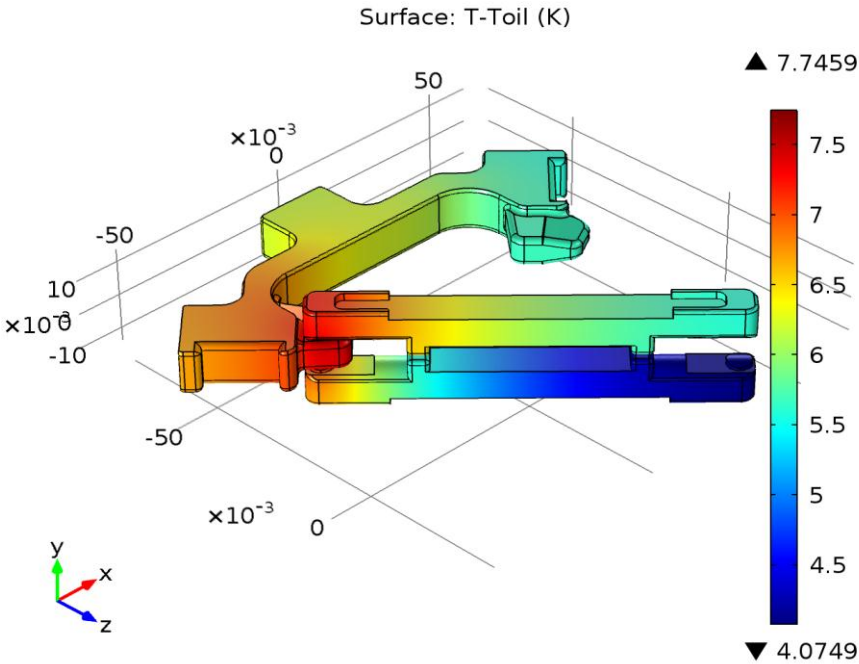


Figure 34: Temperature plot for resistances of 25 μΩ and 50 μΩ.

There is a slight variation of temperature in Figure 34 from the previous simulation result. Here the variation is from 4 °C to 8 °C.

In case of variation of resistance values then the current flowing through the fingers also vary correspondingly.

5.3 Current rating of 1300 A

For a test with rated current as 1300 A, assuming equal contact resistances as 50 μΩ the following output was obtained as shown in Figure 35.

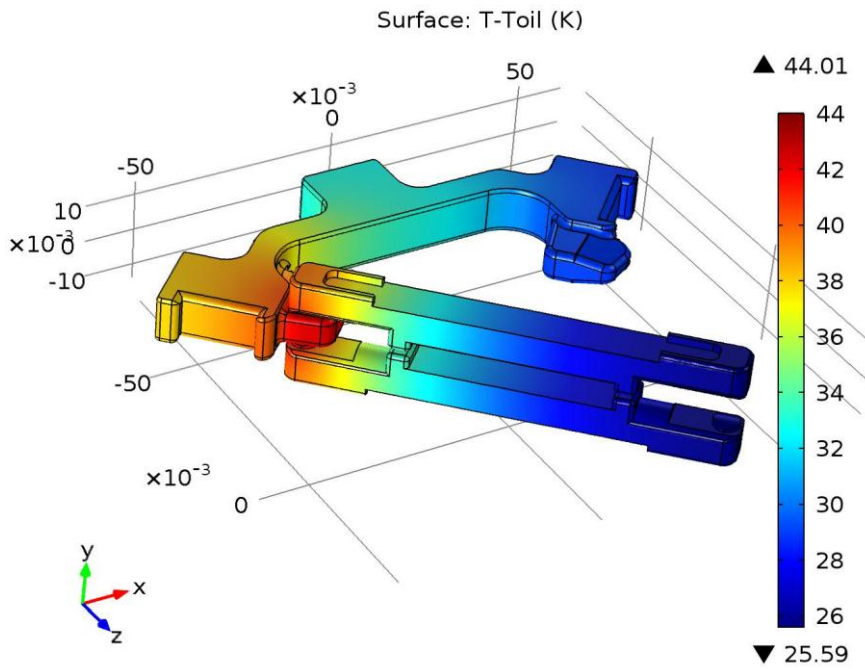


Figure 35: Temperature plot for equal resistances of 50 $\mu\Omega$.

For more information and steps of the simulation refer to the Appendices.

5.3.1 Variation of Contact Resistances

For the same ratings with a contact resistance of 50 $\mu\Omega$ and 80 $\mu\Omega$, the temperature plot and the current density plot look like as shown in Figure 36 and Figure 37.

Now the temperature variations are from 25 °C to 52 °C. This sudden increase is because of the temperature dependence on current. The current rating is now more than twice of the rating we had before, and temperature dependence is also about twice the current value.

$$T \propto I^2R \quad (4-1)$$

where T is temperature, I is current and R is contact resistance.

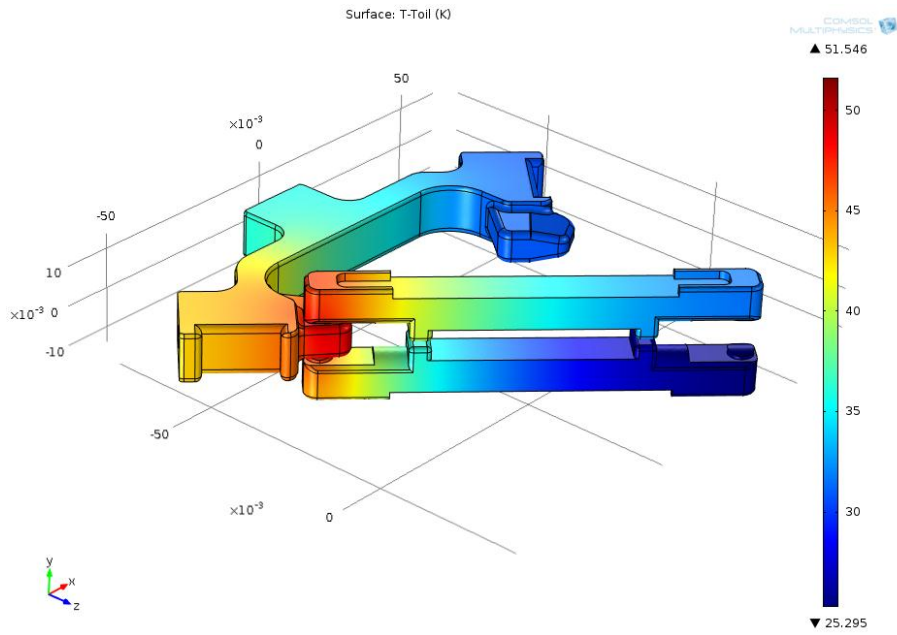


Figure 36: Temperature plot for resistances of 50 $\mu\Omega$ and 80 $\mu\Omega$.

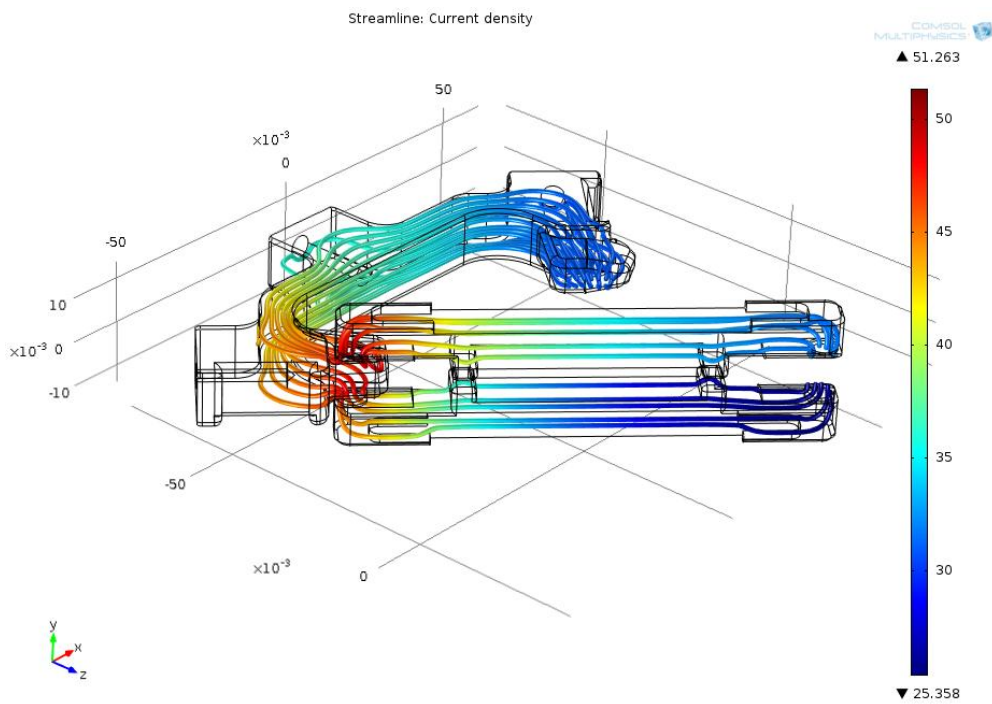


Figure 37: Current density plot.

For resistance values of 18 $\mu\Omega$ and 85 $\mu\Omega$, the current split seems to be almost 70/30 in the contact fingers, as shown in Figure 38.

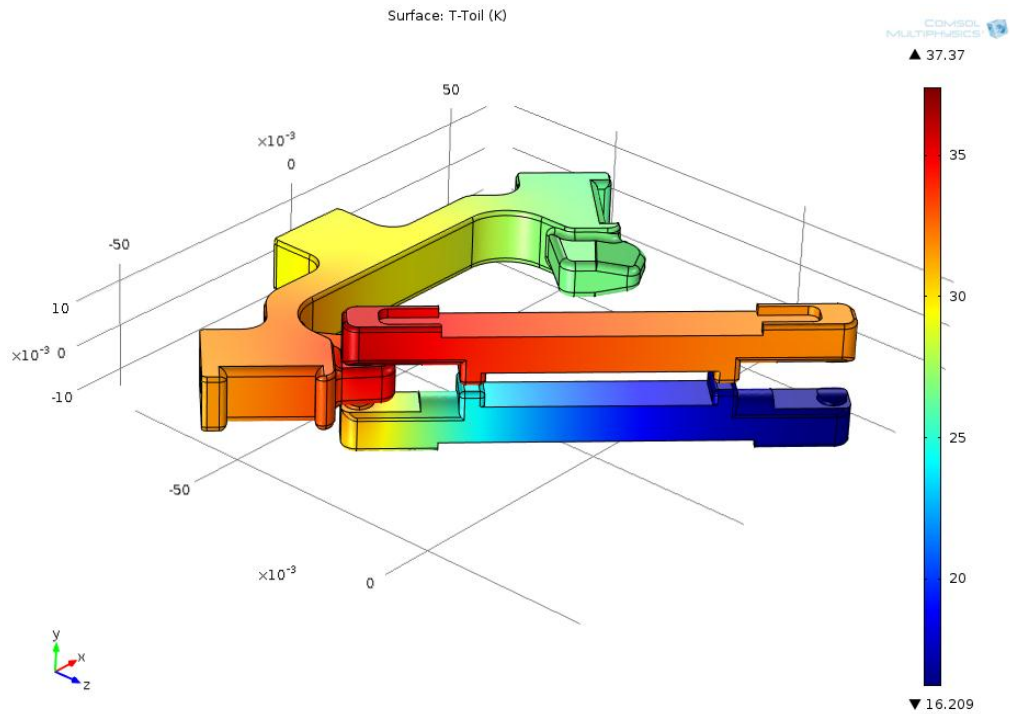


Figure 38: Temperature plot resistance values of $18 \mu\Omega$ and $85 \mu\Omega$

The current values are about 905 A and 350 A, which is almost 70/30 split of 1300 A. The maximum temperature difference is around 37.37 K.

For resistance values of $10 \mu\Omega$ and $110 \mu\Omega$, the current distribution is almost 80/20 of the rated current value as shown in Figure 39.

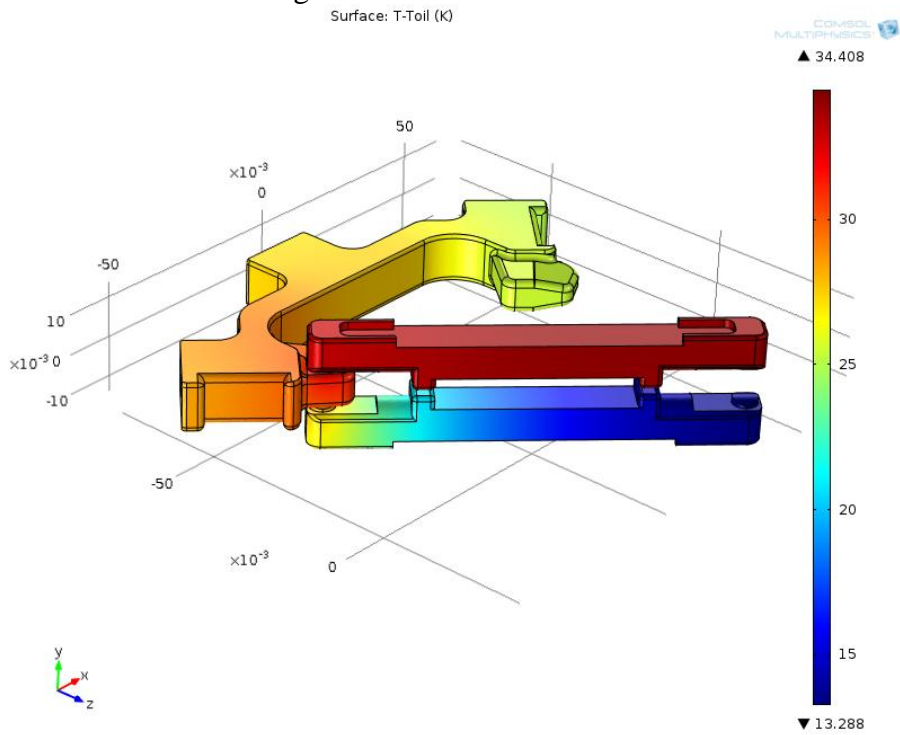


Figure 39: Temperature plot $10 \mu\Omega$ and $110 \mu\Omega$

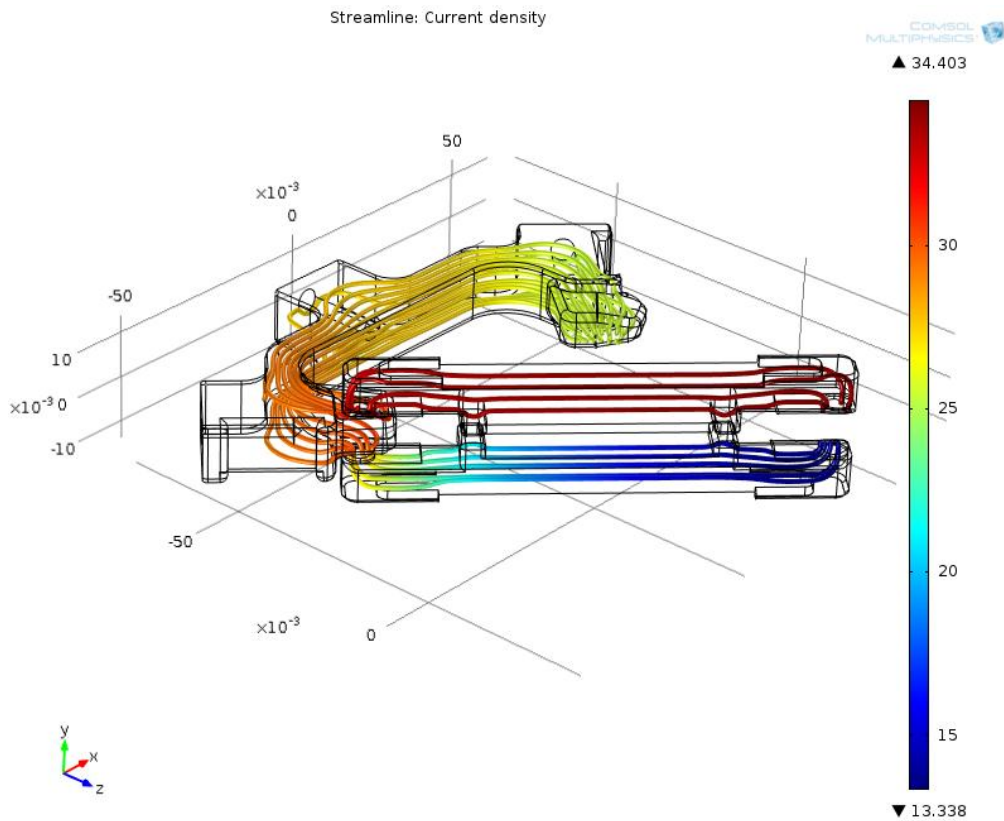


Figure 40: Current Density plot

The current split in the contact fingers are around 1000 A and 300 A which depicts an 80/20 distribution.

5.4 Variation of materials

Each material has its own material conductivity. So the contact materials were just varied in all possible combinations and simulated in order to observe the different outputs. The various combinations and results obtained are as shown below:

- When Copper was used for all the contacts and the paddings, for resistance values of $50 \mu\Omega$ and $80 \mu\Omega$, the temperature plot was like as shown in Figure 41.

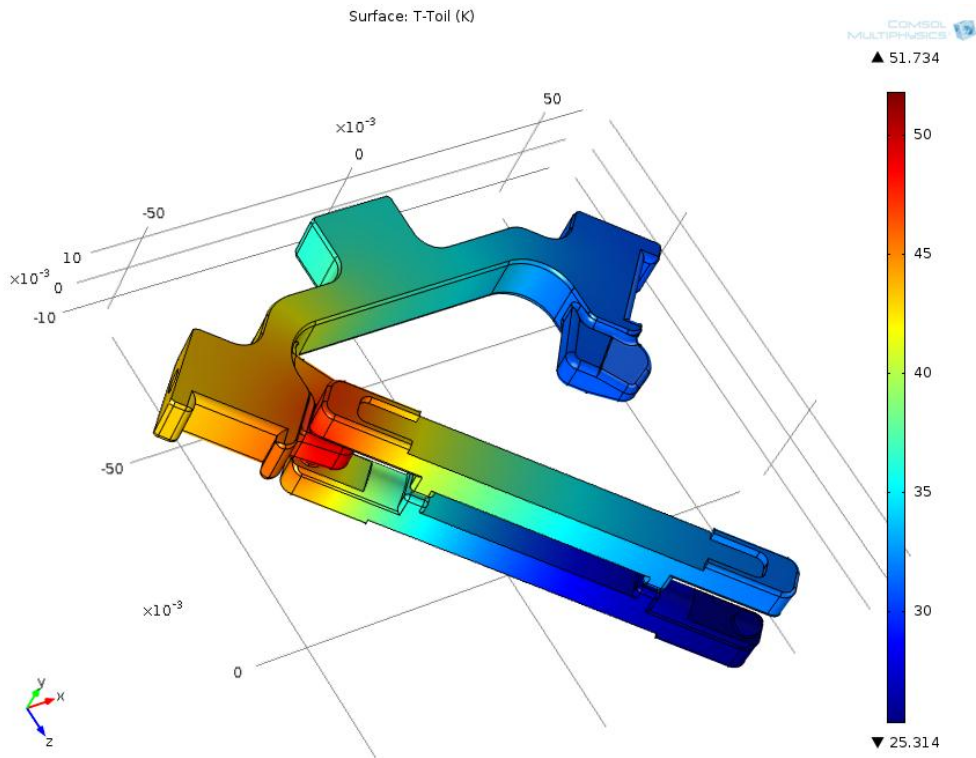


Figure 41: Temperature plot for resistances of $50 \mu\Omega$ and $80 \mu\Omega$ for Copper

- In the case where all the materials used were changed to silver and with contact resistances of $50 \mu\Omega$ and $80 \mu\Omega$, the following temperature plot was obtained.

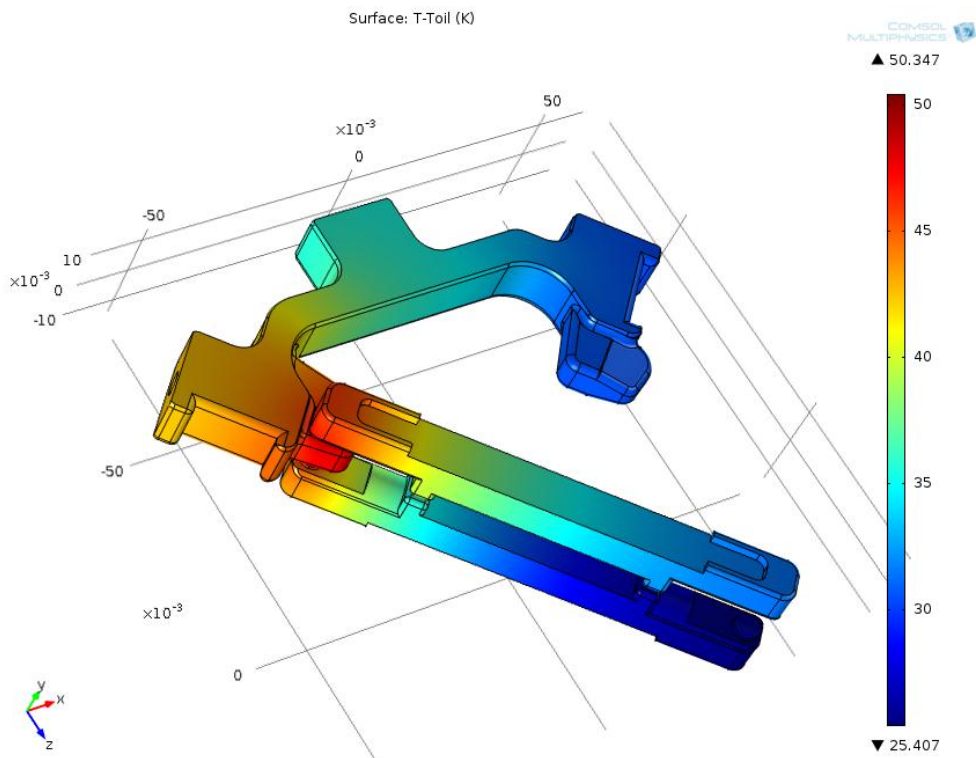


Figure 42: Temperature plot for resistances of $50 \mu\Omega$ and $80 \mu\Omega$ for Silver

From the above temperature outputs, it is evident that the temperature plots of all the three combinations of materials give almost the same kind of plot.

The only thing that seems to vary is the current split. In the case of using all copper contacts, the current split was 805 A and 495 A. In the case of all Silver contacts, the current split was 733 A and 520 A. It was also a similar split for Silver-Copper contacts. A table displaying the results of the various results is shown in the Results chapter.

Chapter 6 Results and Discussions

This chapter displays the results obtained by taking into consideration the various parameters from Chapter 4. It shows the interdependency of the different parameters in the form of a parameter table and also in the form of various visual aids. A consolidated form of the results from Chapter 5 and an example of the Hopkinson test measurements are also displayed here.

6.1 Interdependency of parameters

1. Type of oil and Material used against Contact Resistance

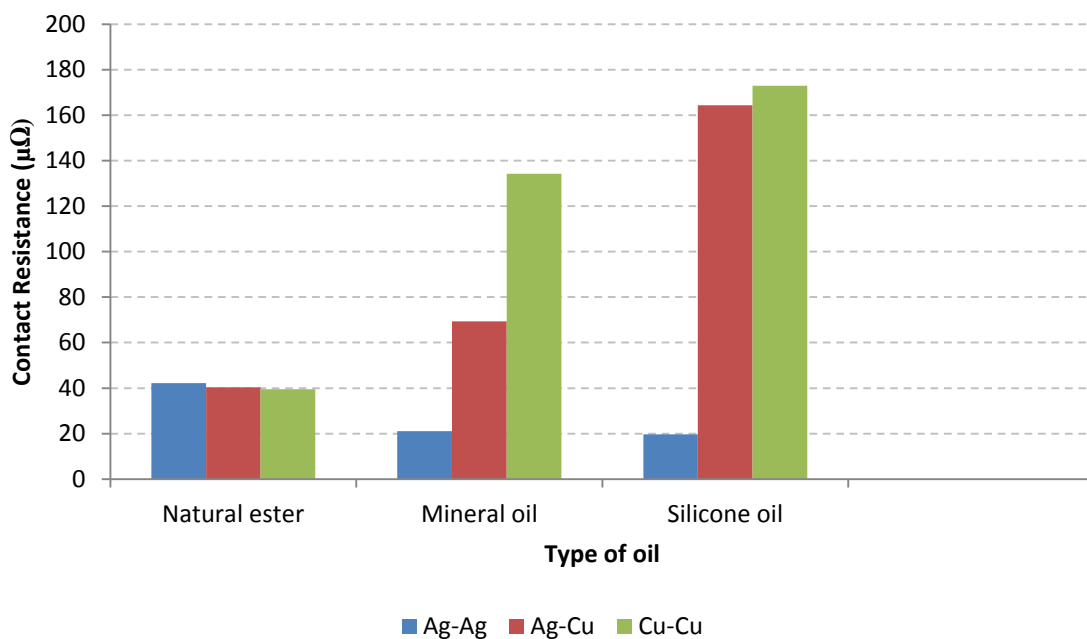


Figure 43: Contact Resistance vs Oil Type for different materials

Figure 43 depicts the results after a Hopkinson test of the various material combinations in the different oil types. It can be clearly seen that all the contacts behave very well in Natural ester having contact resistance values around 40 μΩ. In the case of Mineral oil and Silicone oil, the contact resistance varies from 20 μΩ to 130 μΩ and from 20 μΩ to 170 μΩ respectively.

Considering all the parameters explained and representing their interdependencies in a single table was not really possible since it was a very complex representation. So for the ease of understanding and visual representation, three parameters were considered as a time and their interdependencies shown from Figure 44 to Figure 49 for ease of understanding.

- Considering first the following three parameters:
 - Type of oil
 - Material used and
 - Contact force

In the case of ester, the following result was deduced:

Figure 44 depicts the dependency of the three parameters considered. It explains what contact forces are required when different material combinations are used in Natural Esters. The contact force used on a tap-changer usually depends on various other mechanical parameters and requirements. But this is just a case of determining the force value depending on the given two other parameters.

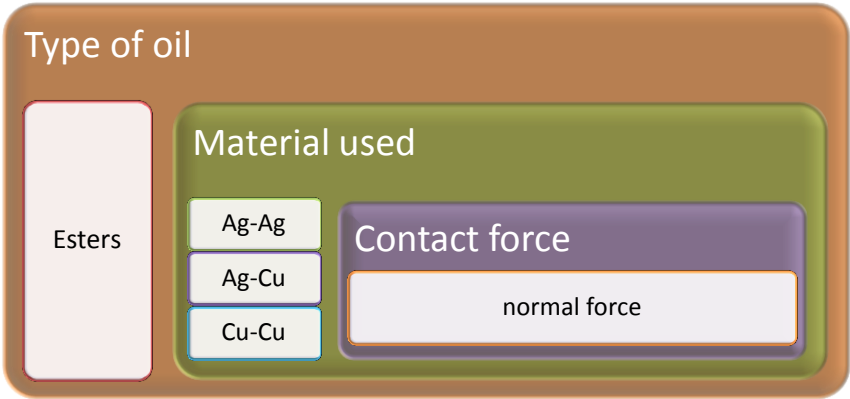


Figure 44: Relation between Types of oil, Material used and Contact force

In the above case, for any of the material combinations the resistance and the temperature will be stable. So a normal contact force of 40N is a sufficient value.

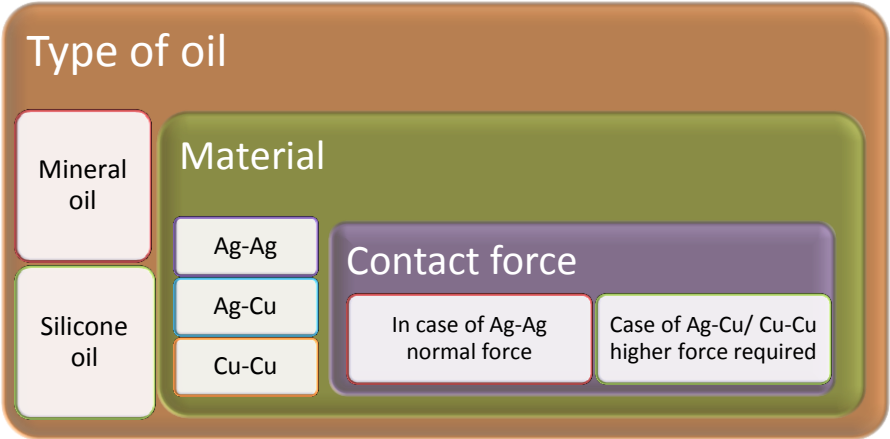


Figure 45: Relation between Types of oil, Material used and Contact force

Figure 45 shows the case of mineral oil and silicone oil, where if Ag-Ag contact is used then the contact resistance and the temperature both are stable. So like in the previous case a normal contact force is sufficient.

In case of usage of the combinations Ag-Cu/Cu-Cu contacts then the contact resistance and temperature are not stable and keep increasing. So increasing the contact force to a higher value reduces the contact resistance. This maybe a solution incase just these three parameters are considered.

- Considering the next three parameters:
 - Material used
 - Contact force and
 - Presence of Films

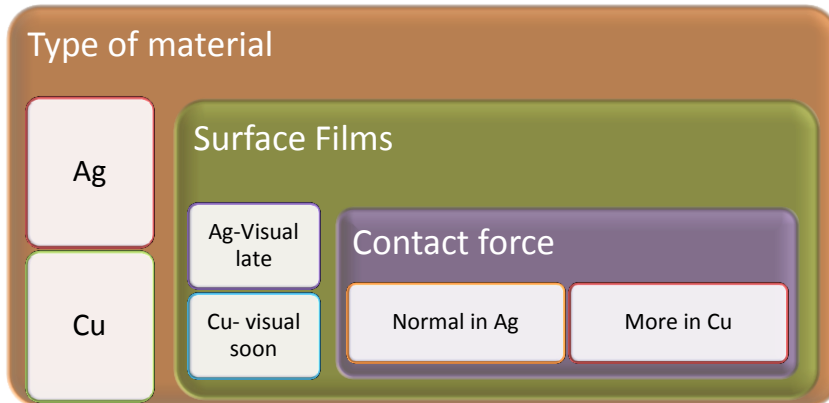


Figure 46: Relation between Material used, Surface films and Contact force

Figure 46 shows in the case of Ag contacts, the contact force is sufficient to be a normal value as stated previously. The surface films in this case get visual only at a later stage after about 1000 Å after which the contact resistance increases. Even after the formation of oxides they can be used longer, as the Ag₂S that is formed does not affect operation for some time.

In the case of Cu contacts, the films get visual at a much earlier stage. As soon as they get visible, the Cu₂O that is formed starts causing lot of problems in the operation as the contact resistance starts increasing. So the contact force needs to be more in this case so that the contact asperities increase.

- Considering the next three parameters:
 - Contact Force
 - Films
 - Fretting

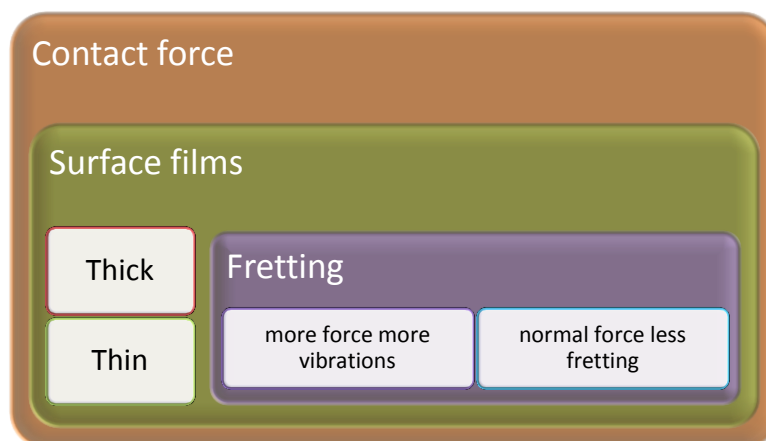


Figure 47: Relation between Fretting, Surface films and Contact force

In case the contact force is too less, then it may not have any wiping action on the contacts and this will encourage the formation of a thicker oxide layer. In this case, then application of more force may also lead to vibrations and so fretting as shown in Figure 47.

In the case of a thin surface film layer, then with application of normal contact force, a good wiping action is sufficient to make the contacts clean without causing fretting.

- Considering the next three parameters:
 - Materials used
 - Conductivity
 - Super Temperature

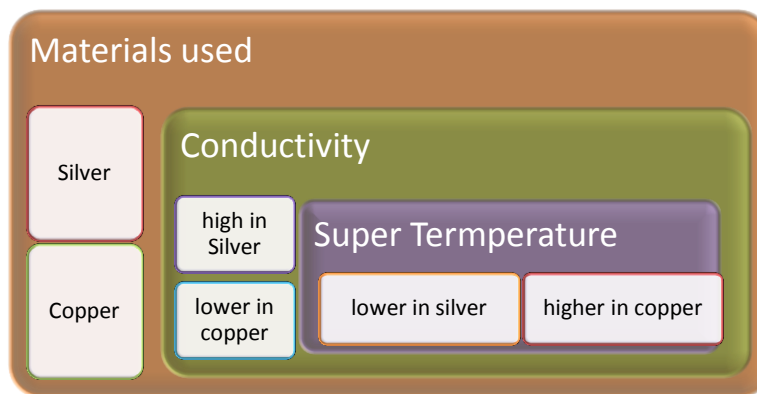


Figure 48: Relation between Materials used, Conductivity and Super temperature

In case Silver contacts are used, they have a high thermal conductivity as shown in Figure 48. Based on the equation shown in the Environmental parameters section, it can be said that the Contact Super Temperature will be a low value.

In case of Copper contacts, they have a thermal conductivity that is lower than Silver. So they will have a Super Temperature of a higher value.

- Considering the last set of three parameters:
 - Rated current
 - Temperature
 - Surface films

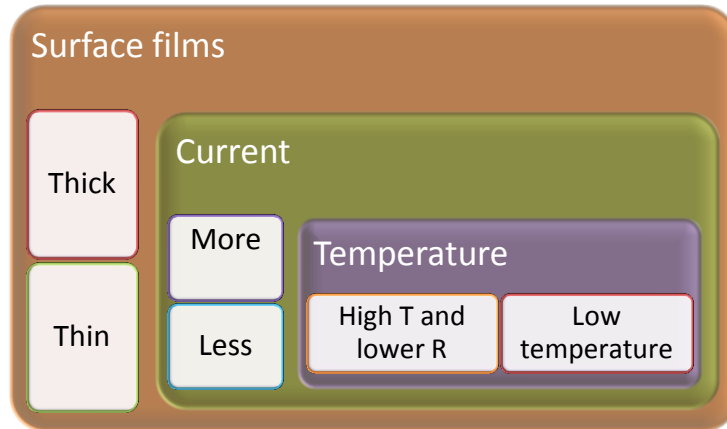


Figure 49: Relation between Surface films, Current and Temperature

Figure 49 shows that in the case of thick surface films, high currents need to be passed to break through the thick oxide layer. This in turn causes the temperature to go very high which reduces the contact resistance as well.

In the case of thin surface films, a lower current is sufficient and so the temperature and contact resistance values are quite stable.

6.2 Parameter table

The following table is just a representation of the most important parameters against contact resistance:

Table 2: Parameter Table

Parameters		Contact Materials used			Contact Resistance
		Ag-Ag	Ag-Cu	Cu-Cu	
Type of oil	Natural Ester	Good	Good	Good	Maintains $40\mu\Omega$
	Mineral oil	Good	Ok	Bad	Value goes up to $140\mu\Omega$
	Silicone	Good	Bad	Bad	Value goes up to $180\mu\Omega$
Contact Force		Normal value	Normal value	A high value required to pass a test	Increasing force enhances penetration of insulating layers and decreases resistance.
Surface films		Don't easily get affected.	A lot more probable to form oxides	Should be really careful as it forms oxides fast.	Thicker the film more insulating it gets.

<i>Current distribution in fingers</i>				Higher current split through a finger is mainly the reason of low resistance.
--	--	--	--	---

This table does not accommodate all the parameters explained in Chapter 4, because of the complexity of the resulting display.

6.3 Simulation table

From Chapter 5, the results from the various simulations were compiled into Table 1 for ease of understanding and reference.

Table 3: Current distribution in fingers with different contact resistances

Contact Resistance on finger 1 ($\mu\Omega$)	Contact Resistance on finger 2 ($\mu\Omega$)	Current in finger 1 (A)	Current in finger 2 (A)	Maximum temperature variation ($^{\circ}\text{C}$)
50	50	625	625	44
18	85	905	350	37.37
10	110	1000	300	34.4

The table shows the contact resistance values which gave a current distribution of 50/50, 60/40 and 70/30 distributions. It also shows the maximum temperature variation obtained in the respective simulation.

When the materials were changed the following results were obtained:

Table 4: Current distribution in fingers with different material combination

Material combination	Current in finger 1 (A)	Current in finger 2 (A)	Maximum temperature variation ($^{\circ}\text{C}$)
Silver-Silver	733	520	50.35
Silver Copper	733	520	51.5
Copper-Copper	805	495	51.7

As can be seen from Table 4, the current distribution and the maximum temperature variation in each case of material change is shown. It is very evident that there is not much change in the temperature in all the three cases. With respect to current distribution, the split is just the same in the case of Ag-Ag and Ag-Cu, but only varies for Cu-Cu.

6.4 Hopkinson Test Results

In this test, as mentioned earlier in the Chapter 2, the temperatures are measured in the morning before turning on the current and in the afternoon before turning off the current. Table 5 shows examples of the readings on various contacts measured with the help of thermocouples on various parts of the contacts.

Table 5: Contact Temperature measurements

	Time	Contact 1 (°C)	Contact 2 (°C)	Contact 3 (°C)	Contact 4 (°C)	Contact 5 (°C)	Contact 6 (°C)
Morning	07:00	136,1	134,3	134,7	137,3	138,1	136,5
Afternoon	15:00	137,3	135,8	136,1	138,6	139,4	137,8

The contact resistances were also measured twice a day during the temperature measurements. In the morning just before turning on the current and in the evening just after turning off the current to the test circuit, the resistances were measured digitally using a measuring instrument.

Table 6 shows examples of resistance values measured during the day at two values of DC currents, 100 A and 5 A. These DC currents were passed through three different contact regions. That is the reason for the presence of three readings of both 100 A and 5 A.

Table 6: Contact Resistance measurements

	Resistance at 100A ($\mu\Omega$)	Resistance at 100A ($\mu\Omega$)	Resistance at 100A ($\mu\Omega$)	Resistance at 5A ($\mu\Omega$)	Resistance at 5A ($\mu\Omega$)	Resistance at 5A ($\mu\Omega$)
Morning	89,30	13,70	168,80	120,00	14,50	158,90
Afternoon	97,60	13,80	175,60	181,20	4,90	100,70

These are just imaginary values and should not be considered to be values in reality.

This test is has several shortcomings as well. The different types of oils used influence the result in several ways. Since there is no specification of the type of oil used in any standard, the results are very varying. For the very specific results, a very clear standard needs to be mentioned specifying the exact test conditions.

Chapter 7 Conclusion and Future Work

This chapter shows the various conclusions obtained from the thesis and also the vast scope for future work in this area.

7.1 Conclusion

As the results show clearly, a table of the most important parameters that should be considered while designing a contact was brought up. But this also showed that this is a very complex relation to bring about with a lot of parameters depending on each other. This brought about a multi-dimensional matrix that was very difficult to display. Hence the visual representation of the dependence of three parameters on each other was done.

It was also very evident that Natural esters are really good, but not used so much because of their temperature range and also because of their high cost. Silver contacts were found to be the best used material in the designing of contacts till now. Silver iodide is also an upcoming material with properties exactly like Silver and also with a lower co-efficient of friction.

The simulations showed the temperature plot over the contacts and the current distribution in the fingers. A table summarizing the results was shown in the previous chapter. This showed the variation of temperature along the contact fingers with change in resistance and change in material.

7.2 Future Work

The results obtained in this thesis are more of a theoretical base, by going through reports of tests that have been previously done and studying various other materials. Some suggestions for future work could be:

- To carry out tests of these results and have a match to check the validity of the results.
- Test to investigate the influence of contact temperature on the stability in the Hopkinson test.
- There may also be so many other parameters influencing the design. They may also be added on to the result table.
- As far as COMSOL is concerned, a model with different number of contact fingers can be modeled to know how the number of contact fingers affects the values. Cooling conditions can also be included in the model to see how that influences the results.

Appendices

Joule heating COMSOL Simulation

A. 1 Global Definitions

a. Parameters 1

Name	Expression	Description
Rc1	75e6[ohm]	Contact point resistance
Rc2	50e6[ohm]	Contact point resistance
Toil	273.15 + 130[K]	Temperature of the oil
hoil	210[W/m ² /K]	Heat transfer coefficient of oil
Itot	1300[A]	Rated Current
hplas	40[W/m ² /K]	Heat transfer coefficient of plastic
Ain	4.596e5[m ²]	Area of the current input
Jin	Itot/Ain	Current density
Ac	1.755e5[m ²]	Area of the silver padding
rhos1	Rc1*Ac	Impedance
rhos2	Rc2*Ac	Impedance

A. 2 Model 1 (mod1)

a. Definitions

Variables 1a

Name	Expression
I1	intop1(jh.nJ)
I2	intop2(jh.nJ)
Iin	intop3(jh.nJ)
I1rel	I1/Iin
T1max	maxopUp(T - Toil)
T2max	maxopDown(T - Toil)

Name	Expression
Tmax	maxop1(T - Toil)
V1	V/Ain

b. Model Couplings

Maximum 1

Coupling type	Maximum
Operator name	maxop1

Integration 1

Coupling type	Integration
Operator name	intop1

Integration 2

Coupling type	Integration
Operator name	intop2

Integration 3

Coupling type	Integration
Operator name	intop3

Maximum 2

Coupling type	Maximum
Operator name	maxopUp

Maximum 3

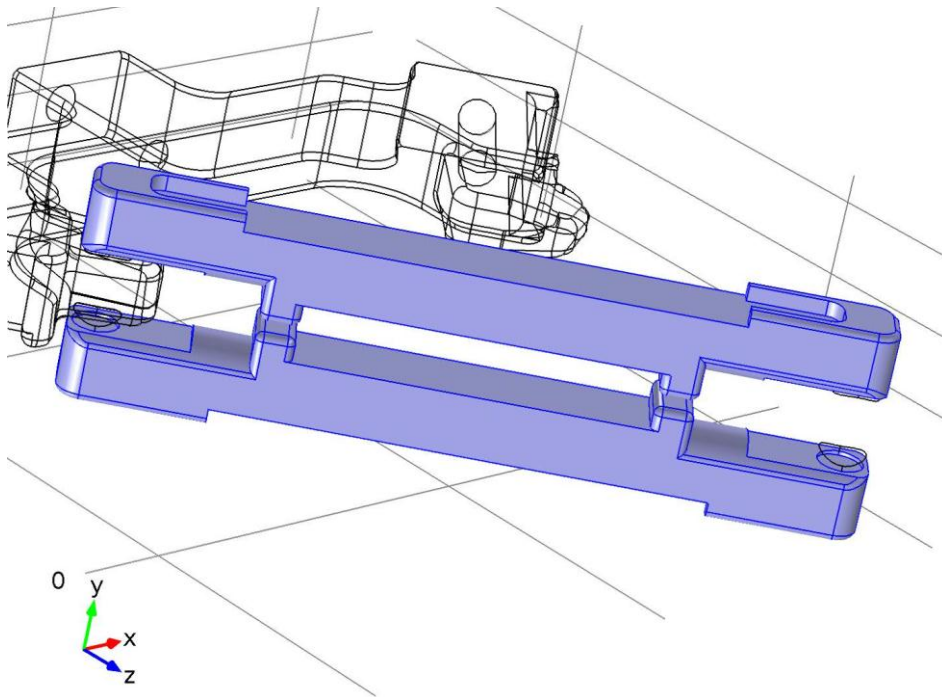
Coupling type	Maximum
Operator name	maxopDown

Units

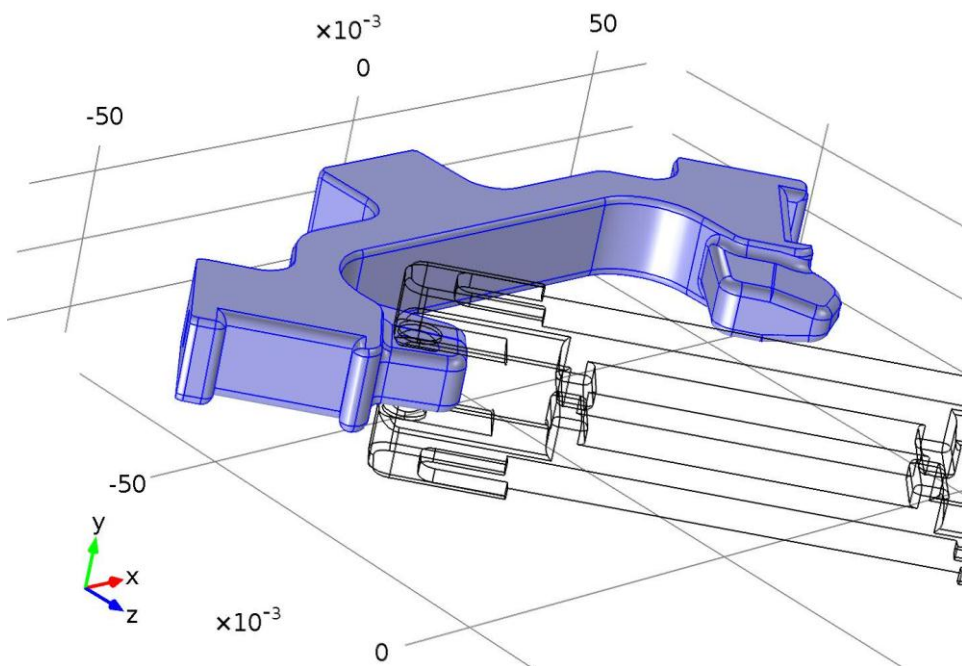
Length unit	m
Angular unit	deg

c. Materials

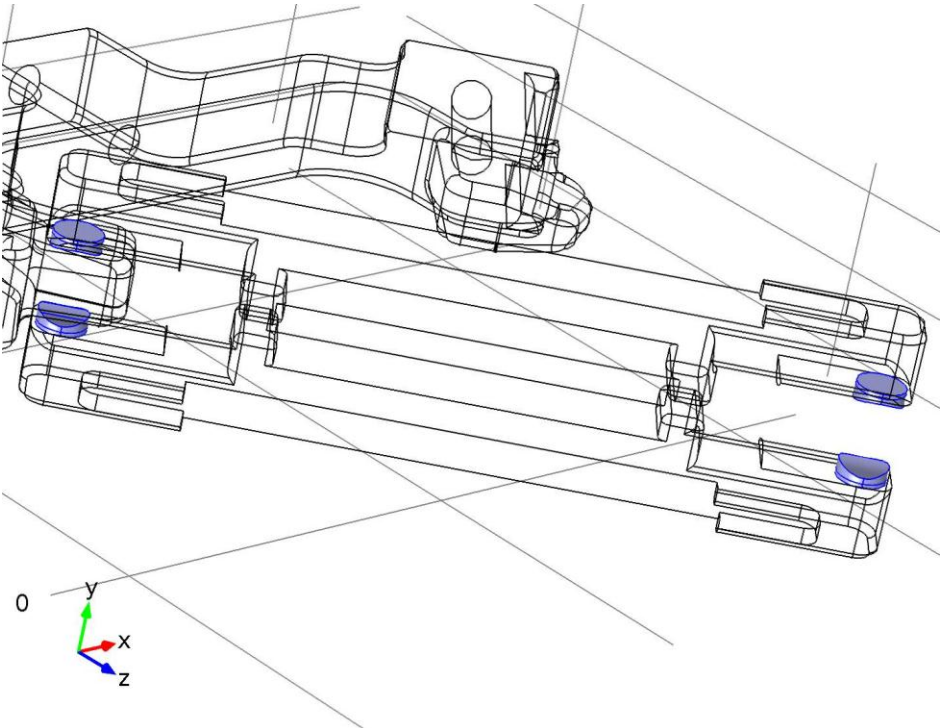
Copper (moving contact)



Copper (fixed contact)



Ag(silver pads)



d. Joule Heating (jh)

Features

Joule Heating Model 1
Electromagnetic Heat Source 1
Boundary Electromagnetic Heat Source 1
Electric Insulation 1
Thermal Insulation 1
Initial Values 1
Ground 1
Heat Flux 1
Heat Flux 2
Heat Flux Plastic
Normal Current Density 1
Contact Impedance 1
Contact Impedance 2

A. 3 Study 1

a. Stationary

Mesh selection

Geometry	Mesh
Geometry 1 (geom1)	mesh1

Physics selection

Physics	Discretization
Joule Heating (jh)	Physics

A. 4 Results

a. Data Sets

Solution 1

Selection

Geometric entity level	Domain
Selection	Geometry geom1

Solution

Name	Value
Solution	Solver 1
Model	Save Point Geometry 1

b. Derived Values

Global Evaluation 1

Data

Name	Value
Data set	Solution 1

Expression

Name	Value
Expression	maxop1(T - Toil)
Unit	K
Description	maxop1(T - Toil)

Global Evaluation 2

Data

Name	Value
Data set	Solution 1

Expression

Name	Value
Expression	Jin
Unit	A/m ²

Surface Integration 3

Data

Name	Value
Data set	Solution 1

Expression

Name	Value
Expression	-jh.Jy
Unit	A
Description	-jh.Jy

Surface Integration 5

Selection

Geometric entity level	Boundary
Selection	Boundary 330

Data

Name	Value
Data set	Solution 1

Expression

Name	Value
Expression	jh.Jy
Unit	A
Description	Current density, y component

Table 43

Global Evaluation 1 (maxop1(T-Toil))

maxop1(T-Toil) (K)
50.46455

Table 44

Surface Integration 1 (jh.nJ)

Current density, y component (A)
467.56452

Table 45

Global Evaluation 2 (I1)

Jin (A/m ²)
2.82855e7

Table 46

Global Evaluation 3 (T1max)

Table 47

Surface Integration 2 (V/Ain)

in (V)	V/Ain/Iin (Ω)	V/Ain/Iin (Ω)	V/Ain (V)	V/Ain/Itot (Ω)	V/Ain/Itot (Ω)
0.03231	5.38497e5	5.38497e5	299.25003	0.49875	0.49876

Table 48

Surface Integration 2 (V/Ain/Itot)

V/Ain/Itot (Ω)
7.85408e6

Table 49

Surface Integration 3 (V/Ain)

-jh.Jy (A)
537.93036

Table 50

Surface Integration 4 (jh.Jy)

-(jh.Jy) (A)
713.90574

Evaluation 3D

Interactive 3D values

Evaluation 3D

x	y	z	Value
0.02173	0.01022	0.0288	5.64829
0.02632	-0.0069	0.03339	4.10935
-0.03562	0.00997	-0.02854	7.24173
-0.03614	0.0123	-0.03528	39.88718
-0.03614	0.0123	-0.03528	39.88718
-0.03562	-0.0063	0.0358	41.38638
0.03623	0.0055	-0.03519	41.59569
-0.02719	0.00311	-0.03987	40.78472
0.03572	0.00543	-0.0357	41.68208

Table 51

Global Evaluation 4 ()

Table 52

Surface Integration 5 (T)

Current density, y component (A)
714.37382

References

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