LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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Electrical Engineering

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NEW CONTACT DESIGN CONCEPT FOR LOW-VOLTAGE SWITCHES

Examiners: Professor Juha Pyrhönen, LUT
Martti Taimisto, ABB

ABSTRACT

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New contact design concept for low-voltage switches

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M.Sc. (Tech.) Martti Taimisto, ABB

The purpose of this thesis is to find factors and suggest solutions to improve the long-term thermal and electrical stability of ABB's AC switch-disconnectors. The challenges are found and solution are proposed in the area of the contact design, surface treatment and arc interruption, regarding the switch thermal stability. Tests are made to verify the proposed solutions. In the switches, high temperature rise is caused by the formation of insulating layers on the contacts. It is because of the lubricant burning, the contact's surface wearing, and arcing near the contacts. It is found out that a high thermally stable lubricant can keep the temperature-rise value low. The wearing of the contacts can be decreased by its design modification. Decreasing the arc energy during the contact breaking would decrease the temperature rise of the contacts. Solid lubricant as a contact plating has shown low temperature-rise by decreasing the wearing of the contact surface.

Acknowledgement

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1 Introduction

The increase in customer demands for higher reliability and cost effectiveness is becoming a big challenge for switch manufacturers worldwide. Industries are trying to reduce cost by employing more cost effective solutions without compromising its efficiency. This trade-off between cost-reliability can be realized through size reduction and ensuring long-term thermal stability of switches.

The application of switches is mainly in low-voltage power distribution and motor control units. These switches can handle both resistive and highly inductive load conditions and are available for a wide range of application for both AC and DC.

The question of this thesis is “How long-term thermal stability of low voltage electrical switches is affected by contact design, surface treatment and arc interruption?” Thermal stability is an ability of a switch to remain in its thermal limits specified by the standards.

In switch operations, one of the main challenges is the low thermal stability of lubricant used between contact surfaces. The lubricant upon burning forms a layer of high resistance polymer resulting in a high operating temperature during current flow. Thermal stability of a lubricant is dependent on its chemical composition. Today, a number of lubricants which offer excellent properties are available on the market.

The contact design is very crucial to avoid contact wearing[1] phenomenon during contact closing. This gradual wearing increases the resistance across the contacts and thus increasing temperature rise.

During contact making an electric arc, which depends on the rated values, increases the contact wearing. Similarly, an electric arc during contact breaking generates a high temperature around the contacts depending on the arc energy. This temperature increase makes contact surfaces more reactive towards environmental stresses. Due to this, a corrosive layer is deposited on the contact surfaces. This increases the contact resistance and further raises their temperature beyond allowable limits. The rate of developing these layers depends on the time and temperature.

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[1] In this thesis, by contact wearing specifically means mass loss from the contact surface at the main-area (Ref: figure 3.3).

The effect of a corrosive layer is less prominent when copper contacts are coated with silver. Similarly, lubricants are applied to keep contacts' surface from building corrosive layers and reduce wearing. But, burning of a lubricant due to arcing causes exponential temperature rise.

Apart from these there are a number of other factors which affect the thermal stability of switches e.g. contact material, switch mechanism, contact design, surface treatment, lubricant thermal stability, arc interruption etc. However, in this thesis focus is kept on contact design, surface treatment and arc interruption.

For this, analysis and evaluation of the existing switch has been performed and solutions are proposed based on shortcomings found out in the existing solutions. For the testing and data analysis, E03[2] switch configuration for OT630, OT400, and OT1600 has been selected with line-to-line voltages range of 400-690V. Furthermore, the tests are performed in accordance with IEC 60947-1 and IEC 60947-3 standards. The operational performance tests were conducted on proposed solutions and results have been discussed.

1.1 Structure of Thesis

In chapter 2, a brief theory about the parameters related to the switch thermal stability in the area of contact design, surface treatment and arc interruption are discussed. In chapter 3, for each area, analysis and evaluation of challenges in the existing switch solutions are performed. In chapter 4, solutions are proposed in order to improve the switch thermal stability, in reference to the challenges explained in chapter 3. Tests performed for verification of these solutions are explained in chapter 5. Test results and their analyses are provided in chapter 6. At the end, conclusion of the thesis is provided in chapter 7.

Figure 1.1 illustrates the structure of the thesis.

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[2] E03: Three pole switch (IEC) where the operating mechanism is located at the left end and three poles on the right side.

Chapter 1: Introduction

- Problem defination.
- Scope.
- Thesis structure.
- Product overview.

Chapter 2: Theory

- Contact design: parameters explanation.
- Surface treatment: parameters control selection of contact grease and plating.
- Arc interruption: parameters affecting contact degradation.

Chapter 3: Existing solutions

- Analysis and evaluation of existing solution (on the basis of previous tests)

Chapter 4: Proposed solutions

- Possible solutions are proposed to improve shortcomings in the existing solutions.

Chapter 5: Testing

- Test procedure explanation.
- Contact design test.
- Surface treatment test.
- Arc interruption test.

Chapter 6: Results and Analysis

Chapter 7: Conclusion

Figure 1.1 : *Structure of the thesis.*

1.2 Product Overview: Switch-Disconnector

Switch-disconnector is a combination of switching and disconnecting functions mainly used as a main switch in low-voltage switchgears, motor control centers and for isolation of loads during maintenance. It can make, break and carry currents under normal, specified overload and abnormal circuit conditions. At open position it complies with the requirements stated for a disconnector [1].

The structure of a switch consists of one operating mechanism and two, three or four switching poles based on its application. The operating module provides a mechanism for making and breaking of electrical contacts present in the switching module.

Figure 1.2 *ABB switch-disconnector OT630E03.*

Switches can be built in different configurations depending on the position of operating module: in the middle or, at complete left or right. Power cables are connected at the terminals visible on both sides of the switching poles.

In switches, knife contacts are used as electrical contacts, which provide good contact stability during short-circuit conditions. These can be further categorized as fixed or moving contacts. The fixed contact is of knife shape, whereas the moving contact has two parallel bars, which at the closed position cover the fixed contact knife on its both sides. In this way, a large contact area can be utilized for the conduction of the nominal and overload currents. A schematic diagram of the contact structure can be seen in figure 1.3

In order to minimize the surface friction between the contacts during operations grease is applied on both fixed and moving contacts. Grease sticks on the contacts due to its surface tension and provides lubrication during the lifetime of the switch.

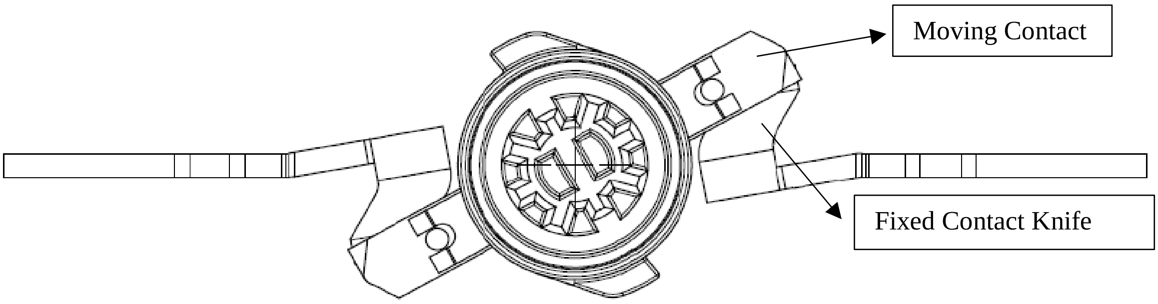


Figure 1.3 *Fixed parts on the left and right. Moving part in the middle. The contacts are closed in clockwise direction and are opened in anti-clockwise direction. [11]*

Electrical contacts are made of oxygen-free highly conductive copper (OFHC) also known as Electrolytic Tough Pitch (ETP) copper. It is high quality copper commonly used in electrical applications. Its oxygen content is less than 0.005% of mass. Copper is soft, malleable and ductile metal with high conductivity and excellent weldability.

Copper is very active towards environmental corrosion, therefore contacts are electro-plated with silver. Silver is a ductile and noble metal; it is fairly stable towards environmental corrosion, and it has high thermal and electrical conductivity.

2 Theory

In this chapter brief theory of parameters which affects switch thermal stability is explained. The thermal stability of switches is affected by the type of contact design, surface treatment and arc interruption. Following in this chapter, each of these parameters are discussed in details.

2.1 Contact design

The flow of current through contacts causes a temperature rise in switches in accordance with Joule heating phenomena. High value of a temperature-rise decreases the power capacity of a switch. For safe operation of switches, thermal limits outlined by standards e.g. IEC 60947-1 and IEC 60947-3 are employed throughout life cycle of switches.

Temperature rise in the switches is mainly attributed to increased resistance in current flow through a switch. In this regard, it is an important parameter which can be minimized to increase thermal stability. A contact resistance consists of two parts: (1) bulk resistance and (2) constriction resistance.

The bulk resistance is due to resistivity of the material and geometry of electrical contact. Whereas, the constriction resistance is due to surface roughness of the contact surface, this constricts current flow, as shown in figure 2.1.

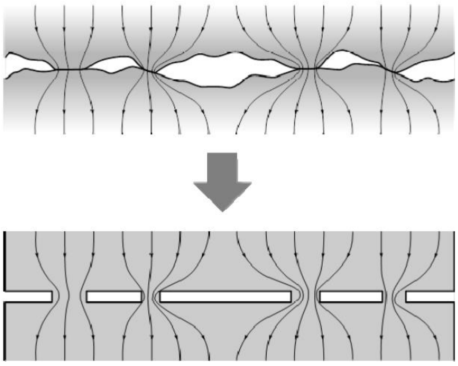


Figure 2.1 *Schematic diagram of contacts constriction [14]*

In contact design process, contact resistance can be minimized by three parameters as: (1) contact design, (2) contact force and (3) contact material. In this thesis we will explain parameters related to the first two only.

2.1.1 Contact force

An increase in contact force decreases the contact resistance. It is because of elastic and plastic deformation of the contact surface which increases the area between the contacts. The relation between contact resistance and contact force is explained as under (2.1a & b). [2]

$$R_{\mathrm{c}} = \frac{\rho}{2}\sqrt{\frac{\pi H}{F}} \tag{2.1 a}$$

$$R_{\mathrm{c}} = aF^{-n} \tag{2.1 b}$$

Where, F is contact force [N], ρ is resistivity [Ωm] and H is hardness of a material [Nm^{-2}], $'a'$ is a y-intercept of a straight line curve and ‘n’ is slope of the curve.

The selection of an optimum value of contact force during design stage is an important task. It is a tradeoff between contact resistance and contact wearing. Its value is evaluated on the basis of: (1) number of operations, (2) short-circuit current value, (3) minimum contact bouncing during closing operations, (4) contact material and (5) contact design.

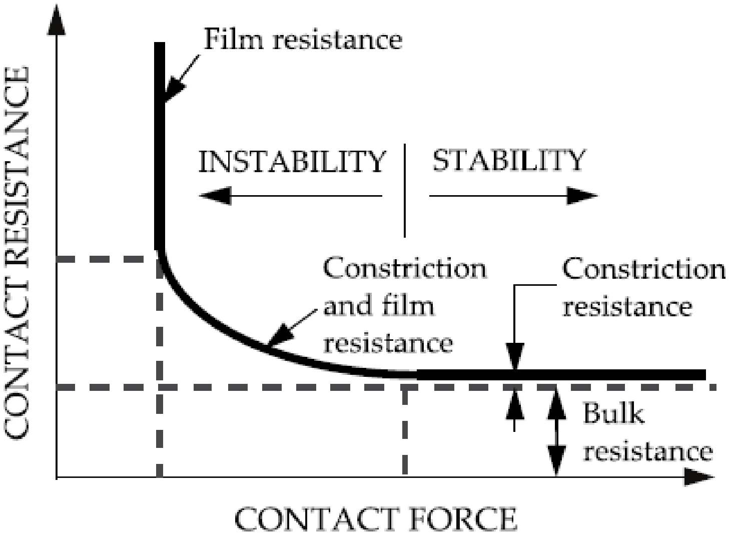


Figure 2.2 *Relation of contact force and contact resistance [15]*

While selecting a value for contact force, it should be high enough to achieve low contact resistance while staying stable during its lifecycle. Figure (2.2) shows relation between contact resistance and contact force. At lower values of contact force, the value of contact resistance moves from stable to instable after few operations due to the stress relaxation and mass loss at the contact's surface.

The contact force is also affected by the change in material properties (elastic modulus, yield strength, plastic limit, and stress relaxation) as a result of electrical and mechanical wearing.

2.1.2 Joule heating and temperature rise

In the presence of contact resistance, heat generated due to current flow can be calculated by the Joule heating formula, as shown in equation (2.2). It can be understood as, when a RMS current I flows through a resistance R during time t then the Joule heat loss will be. [3]

$$Q = \int_t I^2 R(t)\mathrm{d}t \tag{2.2}$$

In equation (2.2), I remains constant at a closed switch condition, $R(t)$ depends on the quality of a connection between contacts and bulk resistance, and t is the current flow time. The maximum temperature T_{Max} at contact peaks due to surface roughness (as shown in figure 2.3) can be calculated by using the voltage drop at the contacts:

$$T_{\mathrm{Max}}^2 = T_0^2 + U^2/4L \tag{2.3}$$

Where, T_0 is ambient conductor temperature, U is the voltage drop, and L is the Lorentz constant ($2.45 \times 10^{-8}\ \mathrm{V}^{-2}\mathrm{K}^{-2}$). [2]

The temperature-rise due to the contact resistance depending on the thermal conductivity 'k' and electrical resistivity 'ρ' of a contact material can be measured as: [2]

$$\Delta T = \frac{U^2}{8\rho\kappa} \tag{2.4}$$

Both equations, (2.3) and (2.4) can be used to measure the temperature rise, whereas the equation (2.3) is independent of the material properties.

The heat generated by high temperature spots on the contact surfaces cause the heat flow to the adjacent metal conductors, hence stabilizing its temperature at a high value from its initial value depending on the heat flow rate.

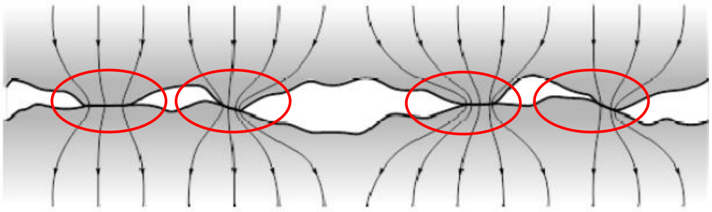


Figure 2.3. *Schematic diagram of contacts interaction. Red circles are contacts peaks or a-spots. [14]*

The heat flow due to the temperature difference and its cross-sectional area S can be find as:

$$Q = -kS\frac{\partial T}{\partial x} \tag{2.5}$$

The heat is generated because of the bulk resistance of the conducting parts and is removed via conduction, radiation and convection. On the contact surfaces in figure 2.3, heat transfer is mainly due to conduction. It is because of the distance between the two surfaces is very small, therefore the heat flow due to conduction will dominate.

The increase in contact resistance can be identified through temperature rise, which entails contact degradation or fault in the contact design [4]. For well-designed contacts, the value of contact resistance remains fairly stable throughout their lifecycle.

The trend of the contact failure with time depending on current rating can be seen in figure 2.4. The value of the contact resistance is sharply increased, which leads to an increase in the Joule heating, as current value is increased for a device (rated at 100A). Increase in current value decreases its lifetime. The sharp increase of the contact resistance along with current flow causes a thermal runaway of a switch and results in its failure.

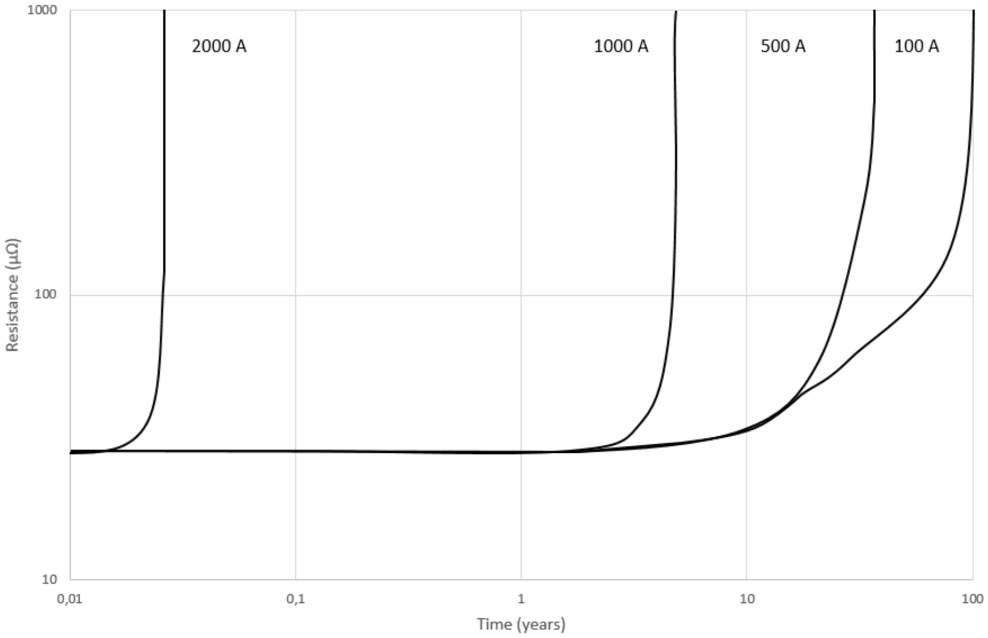


Figure 2.4*. Variation of contact resistance as a function of time for different current values. [2, p. 256]*

Reliability of electrical contacts

The lifetime of a switch is inversely proportional to the square of contact resistance at a new condition. The higher the value of initial contact resistance is, the shorter will be its lifetime be. [5]

$$Contact\ liftime \propto \frac{1}{(R_i)^2}$$

It can be seen in figure 2.2 that the bulk resistance is approximately equal to the switch initial contact resistance. Therefore, in case of a high value of the bulk resistance, a small increase in the constriction resistance because of the switch operations will cause a thermal runway.

2.1.3 Surface friction

The mechanical wearing of contacts also increases the contact resistance due to mass loss effect. During switching, surface of contact get degraded due to friction between contact surfaces. Thus contact force may be evaluated keeping in view the cofficient of friction of material being used.

Frictional force between the contact surfaces can be calculated by equation shown below:

$$F = \mu F_{\mathrm{n}} \tag{2.6}$$

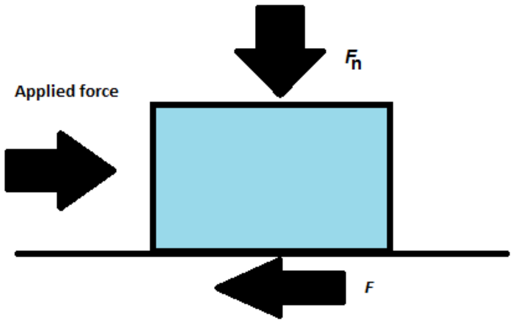


Figure 2.5. *Friction force acted on a block due to the normal force and surface roughness.*

where μ is coefficient of friction, F_{n} is normal force, and F is force due to friction.

Because of surface friction, two forces act on the contact: insertion force and extraction force. Insertion force acts during contact making, whereas extraction force during contact breaking (as shown in figure 2.6). In order to overcome insertion force, more torque is required for proper contact closing followed by high extraction force to open it.

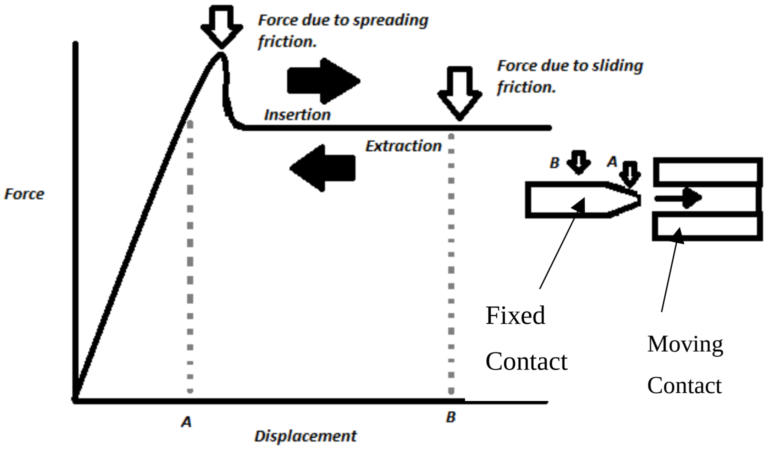


Figure 2.6. *Insertion and extraction forces faced by a sliding contact during making and breaking operations.*

2.2 Surface Treatment

This subchapter is further divided into two sections: (1) contact lubrication and (2) contact plating.

2.2.1 Contact Lubrication

Lubricants are applied on the electrical contacts to minimize mechanical wearing caused by surface friction and to avoid environmental corrosion, thus, improving contact functionality and its lifetime. A good lubricant should remain stable during the switch lifetime and operable on switch thermal limits.

Lubrication decreases the insertion forces by forming a thin coating on the contact surface, therefore, keeping the contact resistance low and stable. Contrary to this, lubricants also have high dielectric strength and, therefore, their application on the contacts increases the contact resistance depending on their thickness. Also, lubricant delays the contact corrosion rate to a certain point, but cannot completely prevent it. It is important to consider that lubricant may or may not affect the switch's performance, but in case of an unstable contact lubricant it can cause overheating.

Furthermore, development of lubricants with exceptionally long-term thermal stability and corrosion resistance is both a complex and expensive process. [6] For switches, grease as a lubricant is preferred in contact lubrication because of its high surface tension.

Lubricant types

a) Grease: Greases are composed of three elements: base oil (75-95%), thickener (5-20%) and additives (0-15%). Long-term thermally stable contact greases are mainly formed by using synthetic lubricant as a base oil because of their high thermal stability. A comparison between different base oil can be seen in figure 2.6a. Thickener is selected based on the application e.g. solid lubricant as thickener in order to provide high wear resistance. The behavior of a grease varies depending on its chemical composition, manufacturing process, and additives. Figure 2.6b illustrates different combinations of contact greases.

b) Synthetic lubricant: Polyphenyl ether (PPE) and Perfluorinated Polyether (PFPE) are categorized as synthetic lubricant. They are available in liquid form, but can be converted into grease by adding suitable thickener and additives. They have a high thermal and chemical stability, very low vapor pressure, minimal coefficient of friction, very low pour point and very good viscosity index. Besides, they have high consistency and resistance towards environmental contamination.

c) Solid lubricants: Graphite, Molybdenum-disulphide and PTFE (Polytetrafluoroethylene or Teflon®) are common as solid lubricants. These are available in powdered forms which are added in the base oil during grease manufacture.

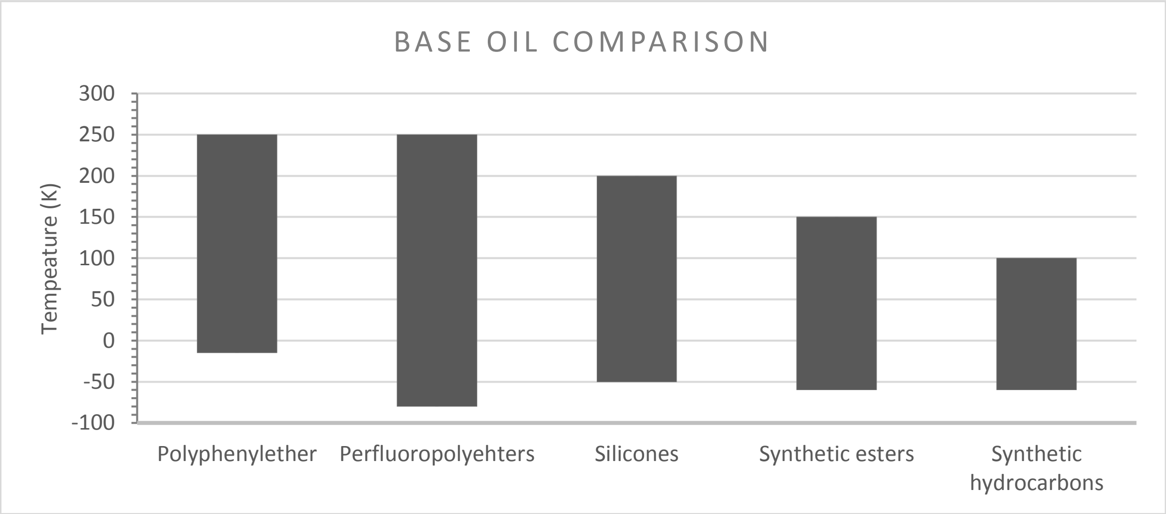


Figure 2.6a: *Comparison of contact greases base oil and their temperature ranges (K). [18]*

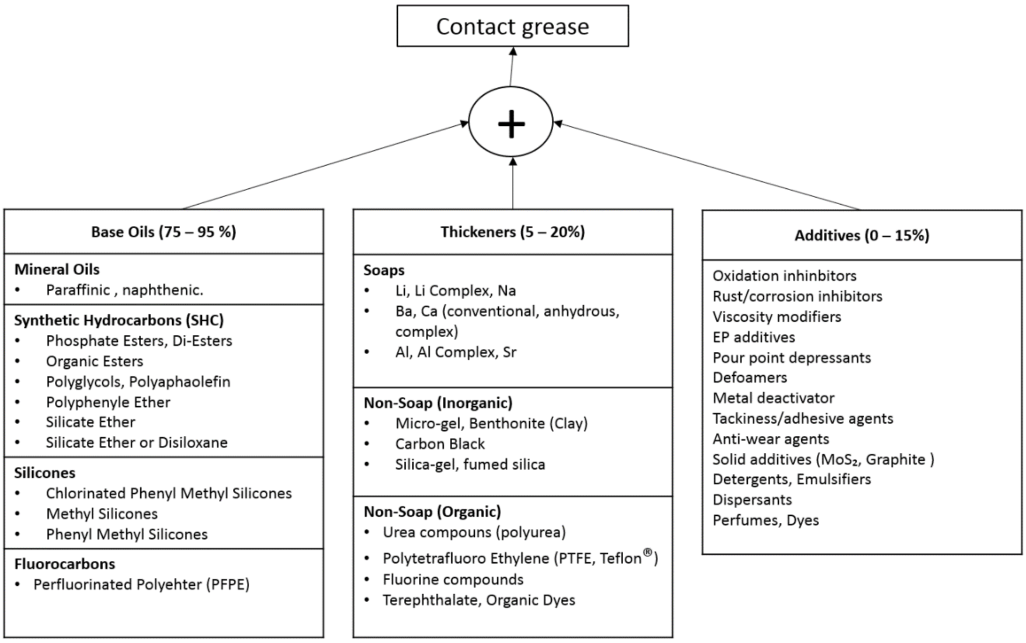


Figure 2.6b: *Different combinations of the greases. [6]*

Requirements for contact grease

In table 2.1, for the switch applications, the desired characteristics, which decide the selection of the contact grease; and the device parameters which affect the performance of grease are shown.

Table 2.1: Desired characteristics for selection of grease and device parameters, which affect contact grease performance.

	Selection of grease	**Device parameters**
1	Long term thermal stability	Contact design
2	low and stable contact resistance	Contact force
3	Decrease surface friction and abrasive wear	Rated value of current and voltage
4	Compatible with metallic and plastic parts	Operating temperature
5	Consistency on the contacts	Environmental conditions
6	--	Contacts and plastic materials

Lubricant degradation

The presence of a high temperature, mechanical stress and dust particles both metallic and plastic generated during the switch operation, causes a change in the chemical composition of the contact grease. It gets softer and appears dark.

At the contact surface, a lubricant face four aging mechanism, which fastens the oxidation rate of the lubricant, as: (1) evaporation, (2) surface migration, (3) polymerization (oxidation) and (4) degradation.

The surface migration and degradation are mainly due to mechanical losses caused by the removal of grease due to contact sliding and wiping or due to wear debris that carries it away. Evaporative loss occurs if the lubricant has a high vapor pressure at normal and elevated temperatures. A thermally non-stable lubricant gets oxidized and changes into a thick hard film of a polymer, which results in decreases in the contact area and an increase in the contact resistance.

Lubricant behavior during current flow

The thermal stability of a lubricant is its behaviour during a current flow known as under charged condition (figure 2.7). Due to current constriction, high current density causes high temperature spots on contact surfaces. The high temperature and current density lead to dielectric breakdown of the contact grease and changes its chemical composition leading to premature failure of grease. [7]

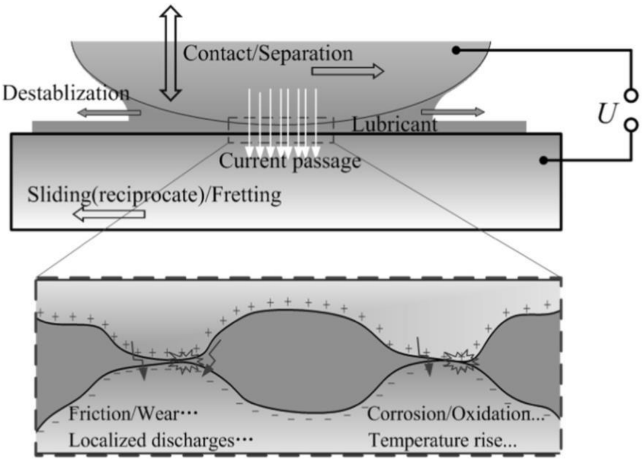


Figure 2.7. *The behaviour of a lubricant under charged condition.*

2.2.2 Contact Plating

The purpose of a contact plating is to save contact material from developing any electrically insulating layers i.e. oxides and corrosive layers. The contacts are plated with a material whose oxide layers can be easily removed. The oxides of silver can be easily removed.

Copper is sensitive towards the environmental corrosion and its corrosive layers have fast growth rate. In the presence of air, it forms a semi-conductive oxide layer (Cupric oxide CuO, $\rho = 1 - 10\ \Omega\text{m}$) at the temperature below 200°C and at the temperature above 200°C it forms an insulating layer (cuprous oxide (Cu_2O), $\rho = 4.5 \times 10^3\ \Omega\text{m}$ at 100°C).

Following graphs (figure 2.8 & 2.9) show contact resistance as a function of a film thickness on the silver and copper contacts. In silver, the contact resistance starts increasing after 1000 Å (significant thickness) and its value is 120 μΩ at 8000 Å. In case of copper a film thickness of 80 Å can cause the contact resistance of value 170 μΩ.

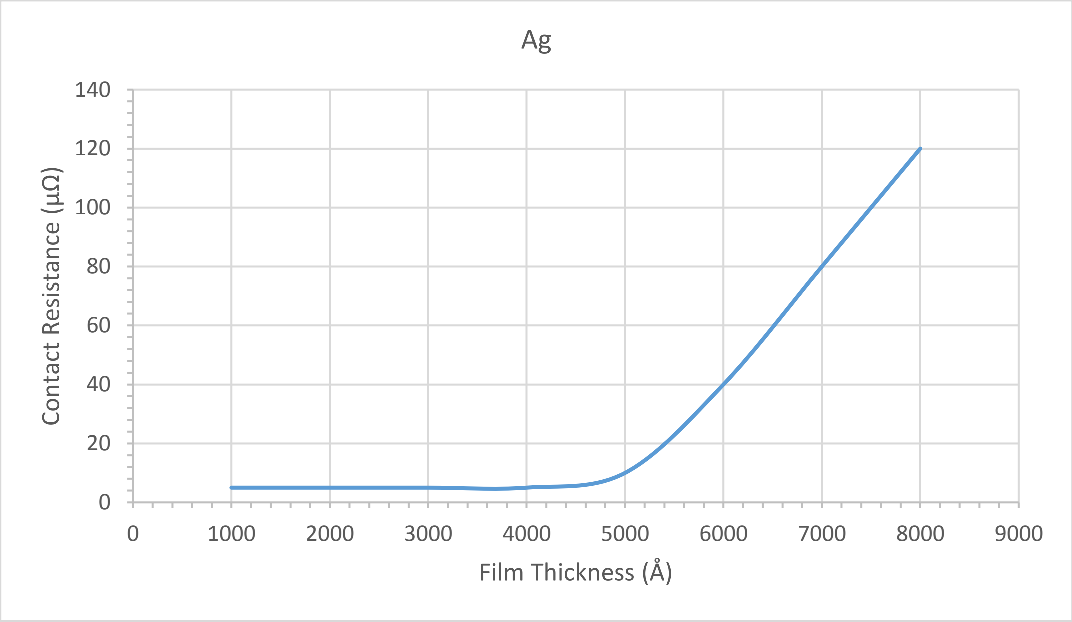


***Figure 2.8:** Contact resistance as a function of film thickness (Å) for silver contacts. [9]*

Silver is a ductile, malleable, and highly electrical and thermal conductive material. It belongs to the noble metals therefore it is less reactive towards the environmental corrosion. It has low value of surface hardness thus high value of surface friction, which can be controlled by use of lubricant. In figure 2.10, a stable value of the contact resistance is achieved by plating a copper alloy with silver plating of 6 μm thickness.

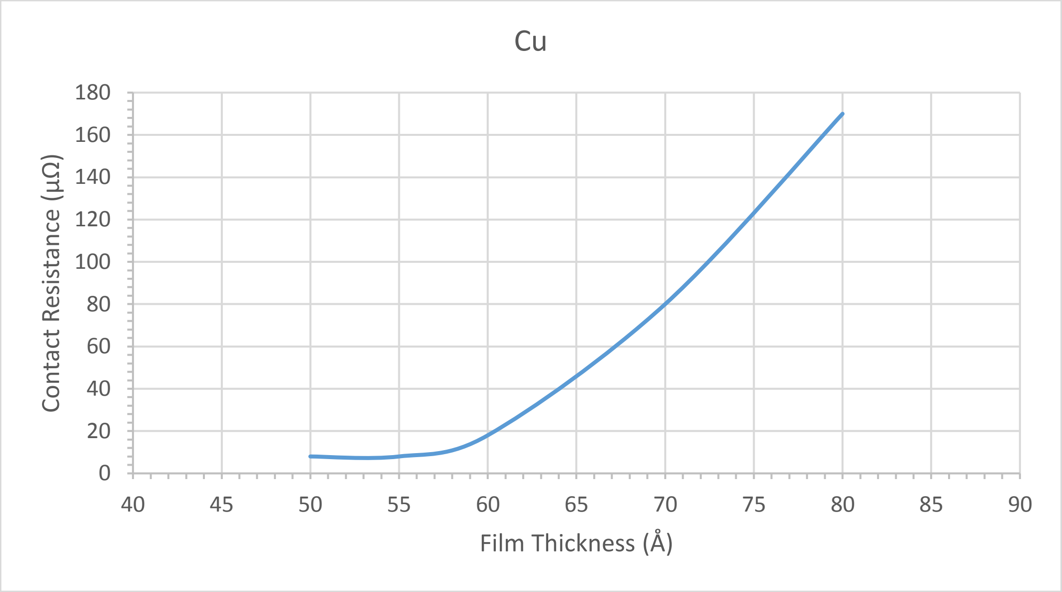


Figure 2.9: *Contact resistance as a function of film thickness (Å) for copper contacts. [9]*

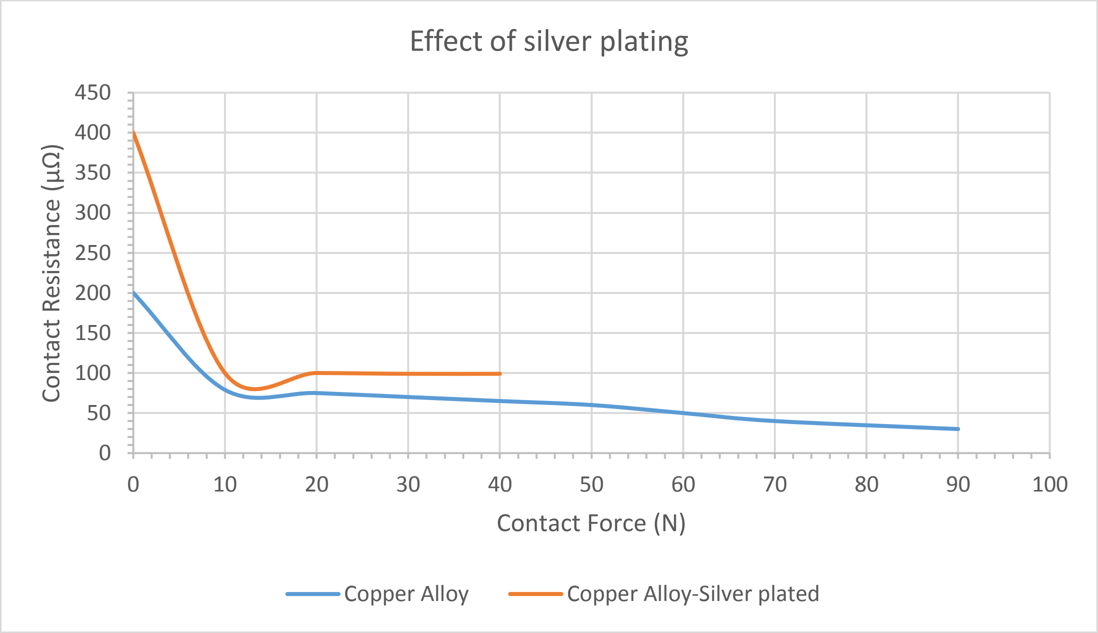


Figure 2.10: *Comparison of contact resistances of copper alloy without and with silver plating (6 µm) as a function of contact force. [19] [20]*

Silver in the presence of a corrosive environment forms silver sulphide Ag_2S, sulphur chloride AgCl, silver oxide Ag_2O and silver carbonate (Ag_2CO_3). These corrosive layers on the contact surfaces affect the contact resistance value depending on their value of resistivity and temperature dependency.

The behaviour of a silver plating against the corrosion can be explained by dividing it into two cases as: (1) Environmental corrosion, and (2) Operational corrosion.

Environmental corrosion

In environmental corrosion, corrosion of electrical contacts without current flow (switch open condition) is discussed.

The corrosive environments for silver corrosion are**:** [8]

- Sulphur mainly comes from hydrogen sulphide and sulphur dioxide. Their sources are: organic decay, combustion of sulphur based fuels, process and manufacturing of wood pulp, refineries, sewage plants, steel mills, and high sulphur packaging materials.
- Chlorine comes from hydrochloric gas along with other chloride containing compound as NaCl etc. Manufacturing of plastics, insecticides, incineration of garbage, plating, and galvanizing operations releases chlorine gas.
- Ozone and peroxides are produced by the reaction of oxygen and nitrogen oxides, which are mainly produced during internal combustion engine.
- The presence of humidity in an environment causes dissolving of corrosive elements more easily and speeds up the corrosive behaviour.

Silver does not oxidize in a normal atmosphere. Sulphur, chlorine, ozone and humidity in the atmosphere make silver react to form films as oxides, sulphides, and chlorides. These surface films are non-conductive.

Silver corrosion during field applications are mainly silver sulphide and/or silver chloride. Silver sulphide is a soft and semi-conductive layer at normal temperature, which can be easily removed by the contacts’ sliding action. Its corrosion rate increases linearly with time and is not self-limiting. Whereas, silver chloride is a non-conductive and hard to remove from the contacts’ surface. It is less often present on the contact surface, but its presence sharply increase the contact resistance value.

At room temperature silver forms silver sulphide in the presence of free sulphur or hydrogen sulphide (H_2S) . Thickness of silver sulphide layer depends on the concentration of sulphur and humidity. It has a high resistivity at room temperature. The resistivity decreases at a high temperature. Its resistivity at room temperature is in the range of 1 Ωm to 20 Ωm. At higher temperature (above 200 ℃) its electrical conductivity increases rapidly. [8]

Silver forms silver chloride in the presence of chlorine gas in the environment. In the presence of ozone at the room temperature silver forms silver oxide but its oxides are not thermally stable above 150 ℃. [9]

Operational corrosion

In the operational corrosion, corrosion of the electrical contacts during current flow (switch closed condition) is discussed.

During switching operations, presence of electric arc during current making or breaking causes a high temperature around the contacts. This makes contacts reactive to environmental gases. The compounds formed on contact surface also depends on the composition of an electric arc and contact material.

Silver in the presence of an electric arc and air forms silver oxides and silver carbonates. The thickness of these layers is a function of temperature and time. The presence of these layers can create challenges for the switch thermal stability. The corrosive layers of silver become unstable at the temperature above 300 ℃, which makes the contact resistance value unpredictable [8]. The corrosive layers of silver are normally formed when contacts are cooling down after interrupting an electric arc.

Copper in the presence of an electric arc and air gets oxidized. Its corrosive layers are also a function of temperature and time. It also forms oxides, chlorides and sulphides depending on the environment. The corrosive layers of copper are highly resistive, thermally stable, and hard to remove from the contact surface during the contact operation. The oxides of copper are more thermally stable (melting temperature > 1000 ℃) as compared to the silver oxides.

In figure 2.11, test results of an aging test are shown in which the thickness of oxide layers on the copper contact is measured at three different conditions with a same sample. It can be seen that the oxidation rate is increasing with time and temperature.

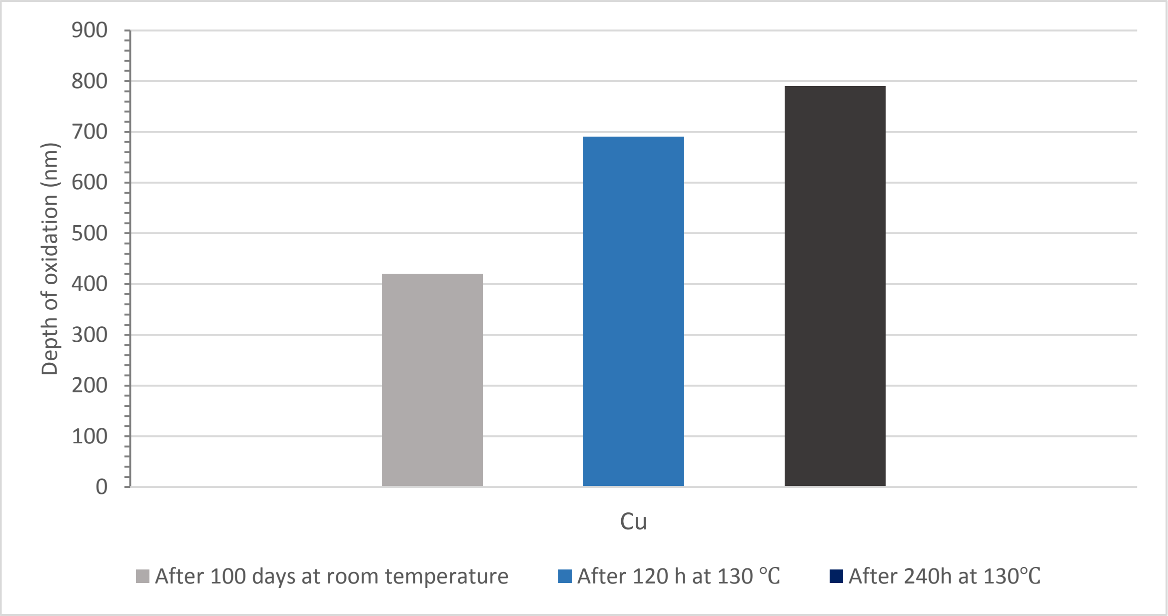


***Figure 2.11** Thickness of oxide layers on a copper sample as a function of time and temperature [10]*

The interaction of an electric arc with the contact surface forms different compounds, which is mainly dependent on the environment, as shown. A general phenomenon of forming possible corrosive layers on the contacts' surface can be understood by figure 2.12.

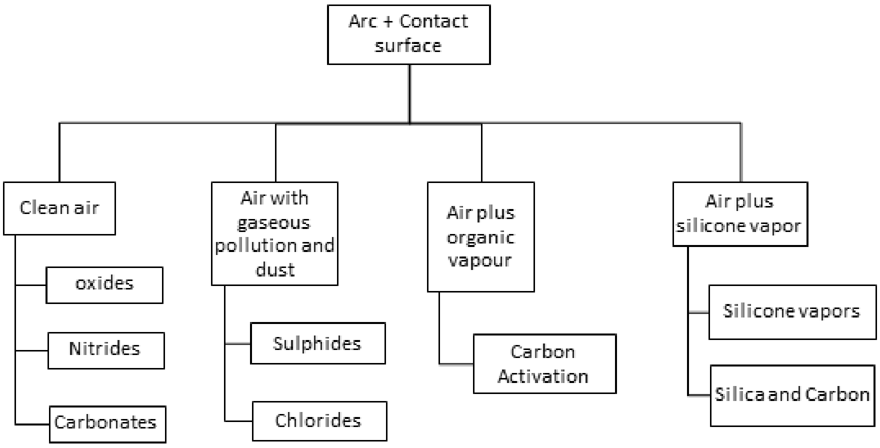


***Figure 2.12** Possible interaction of electrical contacts and the ambient air during arcing [8]*

Silver behaves differently in case of short or metallic arc (< 1-3 ms) and long arc or gaseous arc (> 3 ms). The switching operations in which an electric arc sustains for a long time, both silver oxide and silver carbonate are formed. In figure 2.13, the relationship between the silver carbonate on the contacts' surface and the contact resistance is shown. In the graph, those points where the contact resistance is showing peak values, the switch has interrupted long arcs. Whereas, those points in which the contact resistance has low value, the switch has interrupted short arcs.

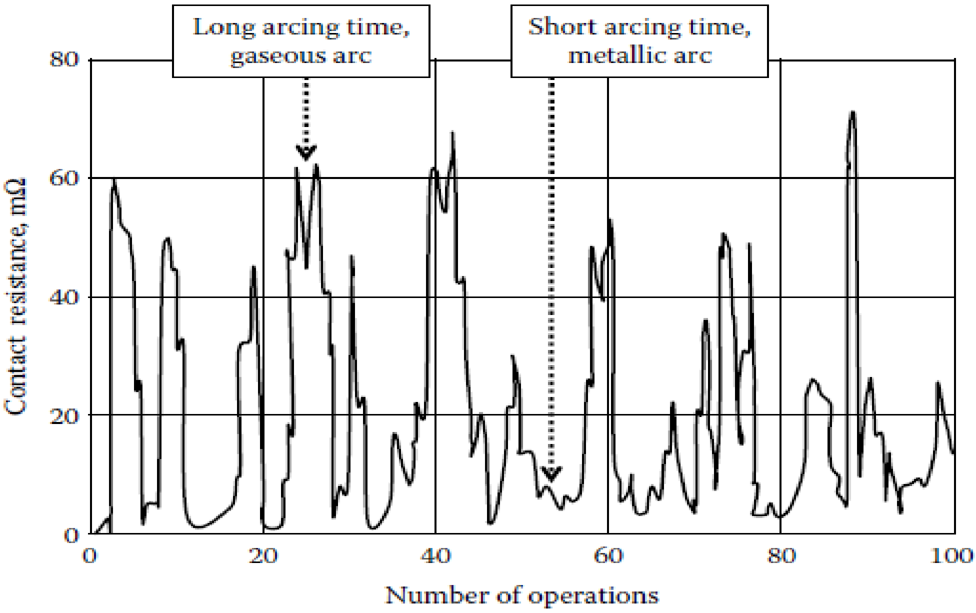


Figure 2.13 *Effect of long and short arc on the contact resistance of silver contacts*. [8]

This difference in the contact resistance value is because of the presence of the silver carbonate on the contacts' surfaces. In case of long arcs, the contact silver has reacted with CO_2 in air and has formed silver carbonate. In case of short arcs, high density of silver vapor is present in an electric arc, which avoids formation of silver carbonate and evaporates existing silver carbonate. Hence, value of the contact resistance is decreased.

Surface films and behavior of contact resistance

The exact behavior of the contact resistance in the presence of the surface films is very complex to explain. This can be seen in figure 2.14, as the behavior of the contact resistance in the presence of surface films is depending on different electrical and mechanical factors.

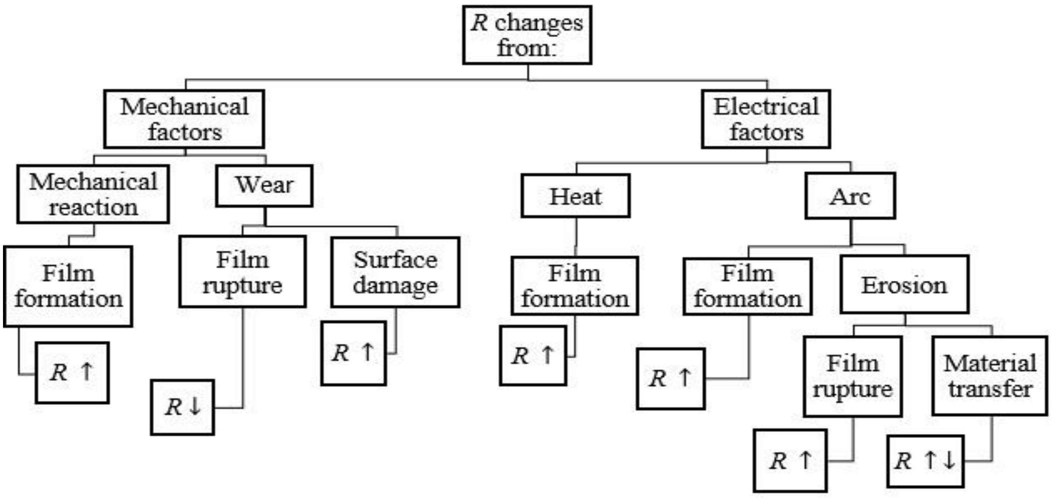


Figure 2.14 *Effect of electrical and mechanical factors on the contact resistance R.* [8]

The surface films formed on silver surface will not affect contact performance in presence of a high contact force. The importance of the contact force in relation to surface films is further explained in figure 2.15. As the surface films thickness is increased, more contact force is required to keep contact resistance in stable region [10].

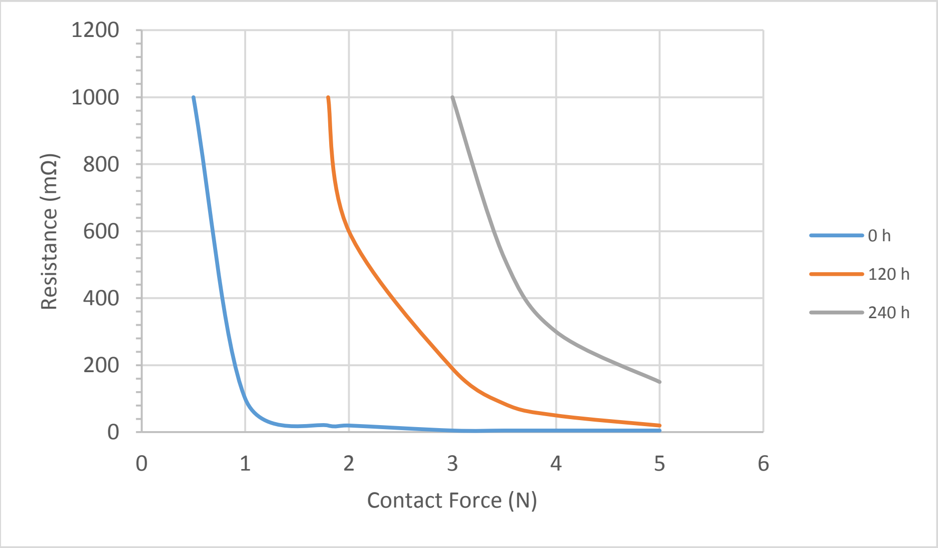


Figure 2.15 *Influence of annealing of electrical contact of copper material at 130 ℃ [10]*

Silver plating thickness

An increase in silver-plating thickness decreases environmental corrosion on electrical contacts. Figure 2.16 shows test results measured to check effect of corrosive layers for various thickness of silver plating on copper substrate. It was found that contact resistance decreases with an increase of the contact plating thickness as it lessens build-up of corrosive layers.

Contrary to this, decrease in contact plating thickness causes corrosion of substrate material through pores (pore corrosion) on plating layer. Thus, increasing contact resistance value.

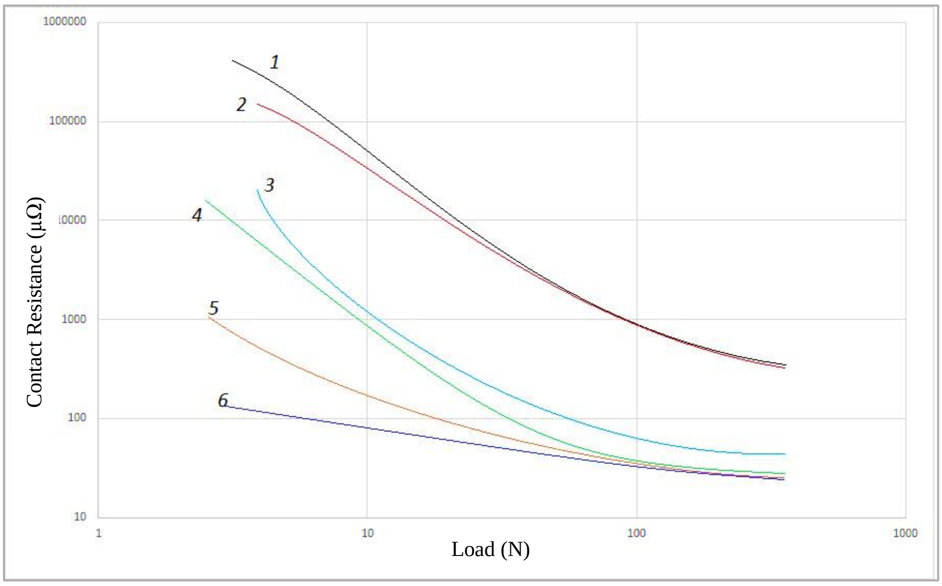


Figure 2.16 *Contact resistance as a function of contact force (Load (N)) for samples with different silver plating thickness.* 1: Ag (1µm), 2: Ag (2 µm), 3: Ag (4 µm), 4: Ag (8 µm), 5: Ag (16 µm), 6: Ag (16 µm) *without exposure. [16]*

However, with increase silver-plating thickness, the material becomes more susceptible to sulphur corrosion. Figure 2.17, shows concentration of elements found on surfaces of contact samples tested in figure 2.16. It can be seen that, with increasing plating thickness, the percentage of sulphur on contact surface increases.

Effect of plating resistance

Generally, for contact plating, material with low resistivity is preferred as different values of resistivity of plating material affect the contact resistance and create power losses.

In figure 2.18, samples with contact plating of different material with varying plating thickness are shown. It shows that Tin (Sn) having higher resistivity value than substrate (Copper) offers more contact resistance with increasing plating thickness. Whereas, contact resistance of silver decreases since its resistivity is lower than copper’s resistivity.

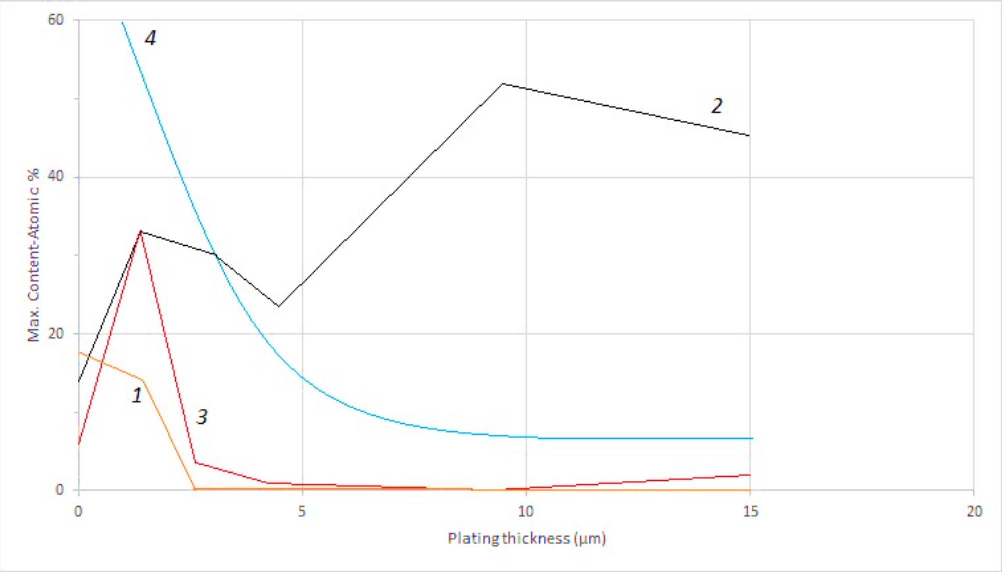


Figure 2.17 *Maximum concentration percentage of different elements on the contact surface as a function of Ag plating thickness.* 1: Oxygen, 2: Sulphur (S), 3: Chlorine (Cl), 4: Copper (Cu). *[16]*

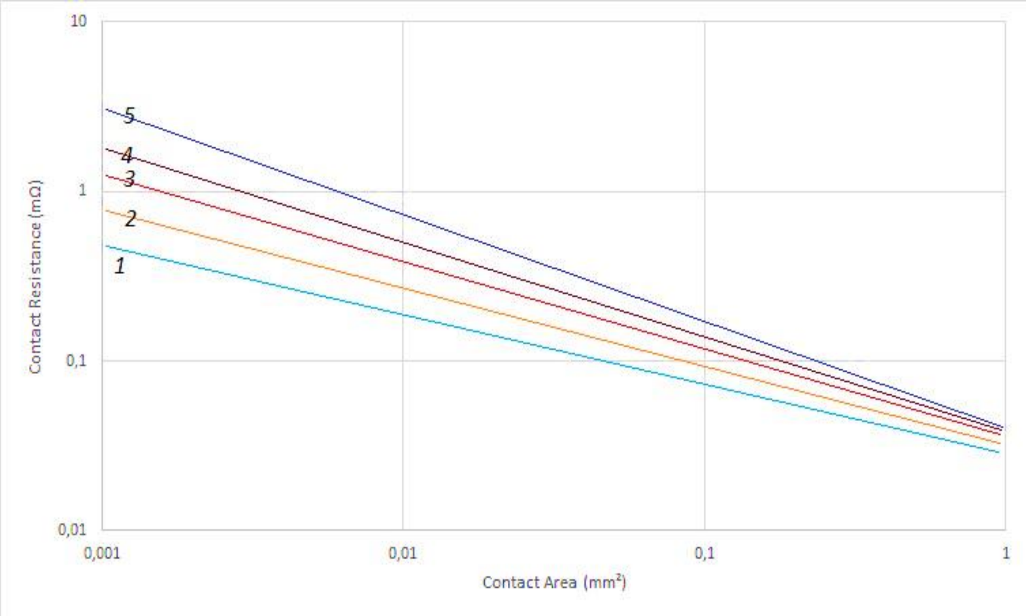


Figure 2.18 *Contact resistance as a function of contact area for different plating material and thickness is shown.* 1: Ag (6 µm), 2: Ag (2 µm), 3: No-plating, 4: Sn (1 µm), 5: Sn (5 µm). *[20]*

2.3 Arc Interruption.

In this sub-chapter, the arc-energy-caused degradation of electric contact, and how it affects the switch thermal stability are explained.

The presence of an electric arc between contacts causes thermal stress. It affects a contact surface by creating grooves, ridges and vaporization of contact material. High temperature at a contact surface speeds up aging of contact by increasing chemical reactivity and corrosion. It is further accelerated by mechanical stresses during switching operations.

The mass loss Δm (material evaporated and particles ejected) from the contact surface is a function of the power input P as:

$$\Delta m = f(P) \tag{2.4}$$

Total power input can be calculated with the current flow and the arc voltage during current breaking operations. The relation between mass loss rate because of current flow only, can be understood with:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = k_1 I^{1.6}\ (\mu\mathrm{gs}^{-1}) \tag{2.5}$$

In (2.5), m is the material loss and k_1 is the slope constant. The value of k_1 depends on the contact material. For copper its value varies from 2.4 ($I < I_{\mathrm{tr}}$) to 36 ($I > I_{\mathrm{tr}}$). Whereas, the value of the exponent can vary in the range of 1.6 to 3.7. [8]

It was found out in research [11], that at low current values (for $I_{\mathrm{tr}} < 800\mathrm{A}$), the main wearing of contact areas is mainly due to the mechanical operations, whereas for higher current values ($I_{\mathrm{tr}} > 800\mathrm{A}$) it is mainly due to the arcing stress and current flow. In figure 2.19, a test result is shown, performed on different samples of OT400E03 at different current values. The value of current was increased from $0.5I_{\mathrm{e}}$ to $8I_{\mathrm{e}}$, and the contact wear was measured. Cubic curve fitting was done on results calculated for mass loss in relation with applied current. At $I = 0.79$ kA, the experimental values deviate from the predicted ones because after this point the wear significantly increased as a function of increasing current value.

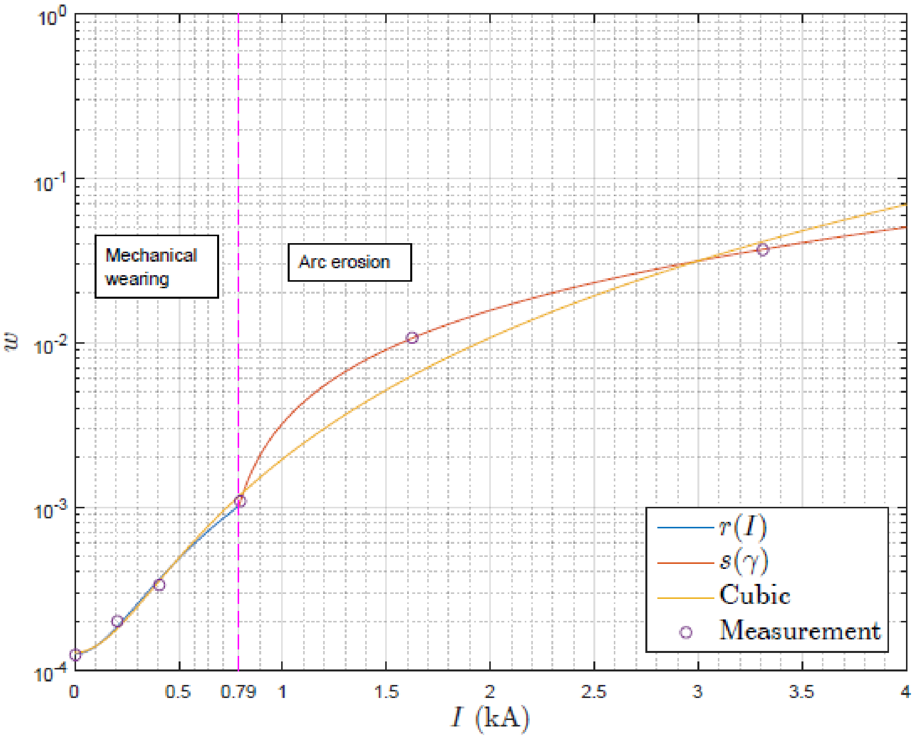


Figure 2.19 *The aging curve of OT-switch between relative wear (w) and rated current is shown. The threshold value of current is shown at* I_{tr}=0.79 kA. *r(I) and s(γ) are the curves drawn from the data points. Cubic curve is the predicted curve. [11]*

The energy generated due the presence of arc between contacts can be calculated via arc energy as:

$$E_{\mathrm{arc}} = \int_{t_{\mathrm{i}}}^{t_{\mathrm{e}}} U_{\mathrm{arc}}\, I_{\mathrm{arc}}\, \mathrm{d}t$$

where t_{i} and t_{e} are the arc ignition and extinguishing times, U_{arc} and I_{arc} are the values of voltage and current across contacts during the presence of arcing between contacts. The energy generated due to arc energy is absorbed by the arcing plates, air, and contacts.

Figure 2.20 shows cumulative arcing time as a function of switch operations number. Also the high temperature generated as a result of arcing alters the material properties of contact, as a result minimum arc voltage and current value decreases.

Arc energy is directly related to the arc time as:

$$E_{\mathrm{arc}} \propto t_{\mathrm{arc}}$$

In order to minimize arc effects, arcing plates are used. They extinguish an arc by elongating and cooling it. Each arcing plate provides a voltage drop of approximately 20 V [8]. Arc breakup capacity increases with addition of arc plates but it also increases arc energy and magnetic field density between contacts. Therefore, selection of the optimal number of arc plates is very important for arc interruption and avoiding arc erosion.

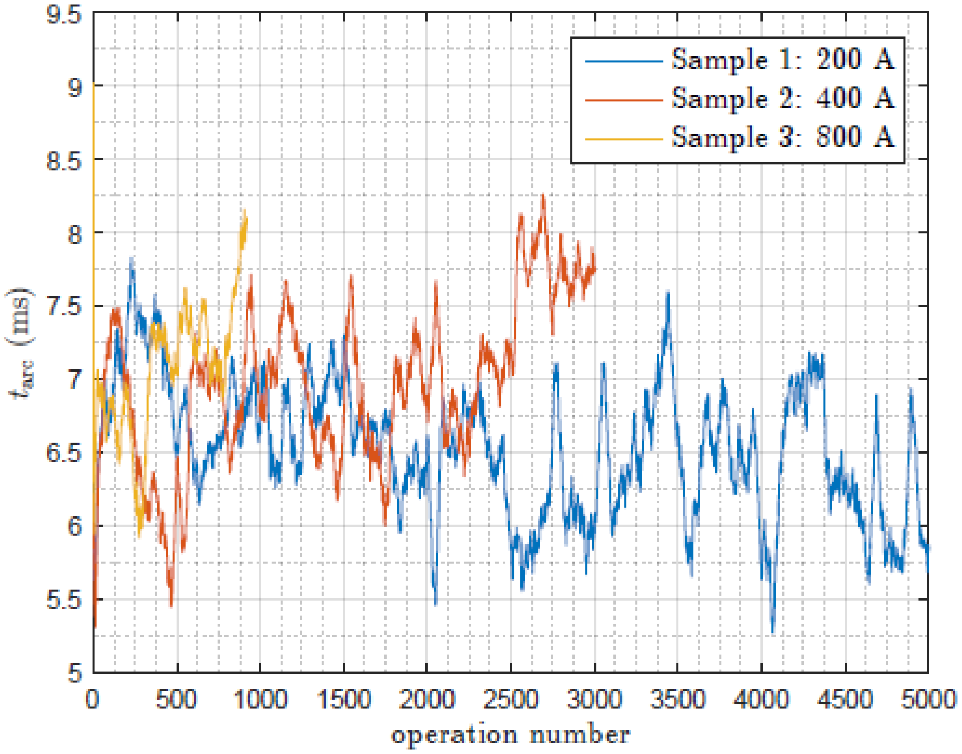


Figure 2.20 *The arcing time of OT400 switch at current values of* 200A, 400A *and* 800A. *[11]*

3 Existing solutions

The issue of long-term thermal stability in the switch arises mainly because of two main reasons.

1. Poor connection between the moving and fixed contacts due to increase of gap between their surfaces as a result of mass loss. The development of the contact deterioration can be seen in figure 3.1 (from left (new switch) to right (worn out switch)), whereas arrows are showing the contact closing operation from the mid position to the final position.

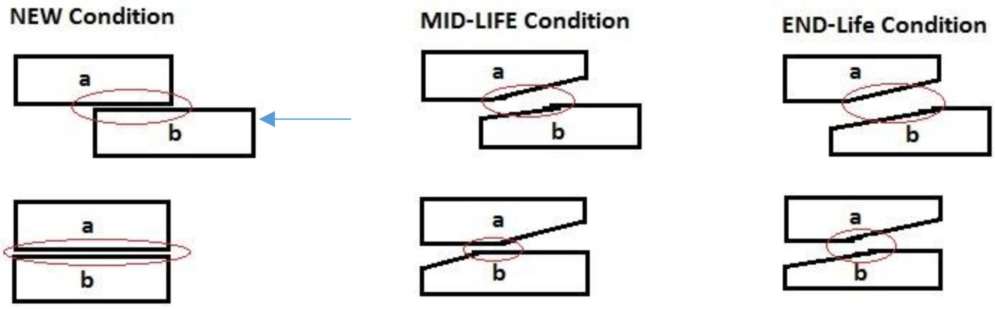


Figure 3.1 *The process of contact's mass loss with switching operations. The symbols "a" and "b" are denoting fixed and moving contacts which are moving horizontally with respect to each other. The red circle is showing the possible contact area between the contacts. The top row shows contacts half closed. The below row shows contacts at their final position. The blue arrow shows moving contact direction.*

2. Corrosive layers i.e. burnt lubricant, oxides, carbonates etc. are formed due to high temperature, which decreases current conduction area between the contacts, as shown in figure 3.2.

Figure 3.2 *Carbonisation and polymerization of a the lubricant on the contact surface after 200 operations*

The existing solutions in the field of contact design, surface treatment and arc interruption are elaborated below.

3.1 Contact design

A well designed contact offers a high electrical and thermal conductivity, high resistance towards mechanical and electrical wearing and a low cost during its lifecycle. These benchmarks are used to judge the performance of the contact design.

1. In switches with current ranging from 160A-800A, fixed contact consists of a single knife as shown in figure 3.3.
2. For the current range from 1250A - 4000A, the fixed contact with two or more parallel contact knives are used, as shown in figure 3.4. At higher currents, parallel combination of knives helps in dividing current value reducing contact blow force ($F_\mathrm{B} \propto I^2$).

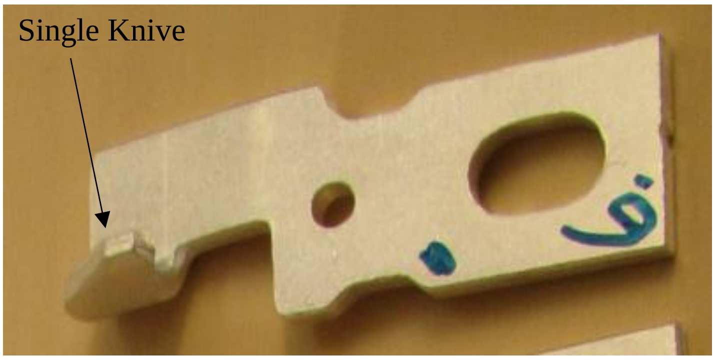


Figure 3.3 *Fixed contact design for current range (*160A *to* 800A*)*

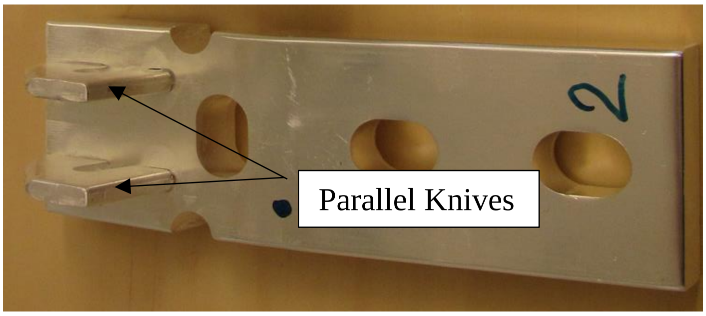


Figure 3.4 *Fixed contact design for current range (*1250A *to* 4000A*)*

The contact knives perform function of both arcing and main contacts as shown in figure 3.5. Proper designing of an arcing contact area aids moving of arc away from the main area.

In the switches, the contact force decreases with operations due to surface relaxation and contact wearing in the presence of an electric arc along and high contact closing force. The possible factors, related to the contact design, which are causing these challenges are described below.

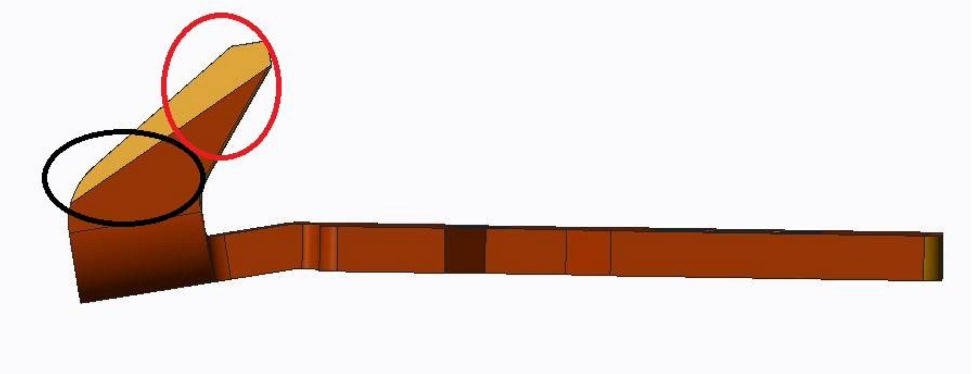


Figure 3.5 OT630 *fixed contact. Black circle indicates the main contact area. Red circle is showing the arcing contacts. The orange coloured area is a chamfered area.*

3.1.1 Impact-line to main-contact-area distance

In the contact making operations, the line of impact on the fixed & moving contact is very close to their main contact area (figure 3.6). Therefore, with operations the main-area on the both moving and fixed contact starts shrinks increasing resistance. The contacts are shown in figure 3.6. The chamfer provided at the impact line of the fixed contact has a high angle and a short chamfer length. Hence, the impact force on the contacts is high.

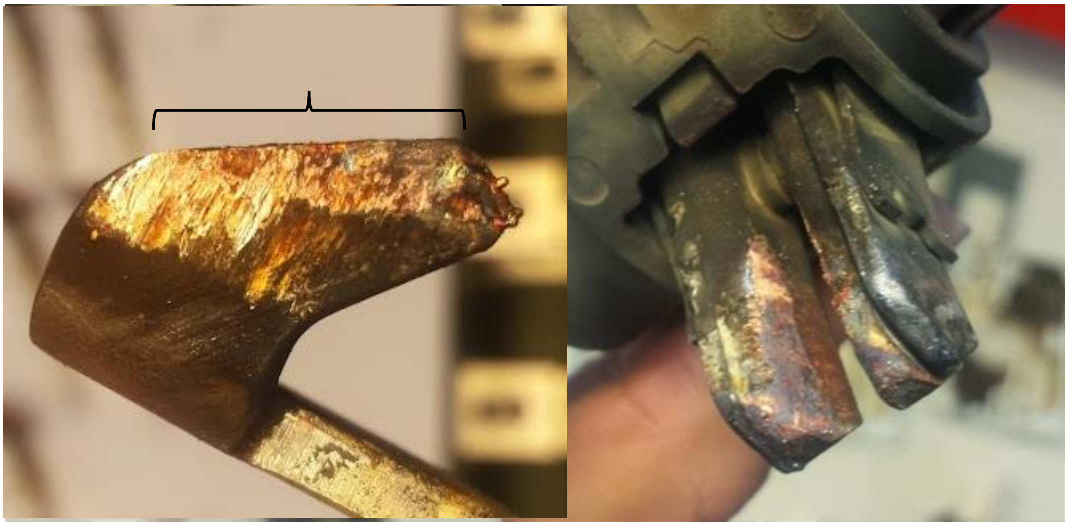


Figure 3.6 *Left: Eroded fixed contact after electrical operations. Line of impact is shown by a round bracket. Right: Eroded moving contact terminals.*

3.1.2 Degradation due to Initial and final point

In making or breaking operations, the initial and final overlapping area where fixed and moving contacts meet is small (shown in figure 3.7). This results in a high current density and contact melting due to high voltage drop during contact making. Comparatively, contact wearing is higher in case of making than breaking due to high inrush of currents in response to inductive loads.

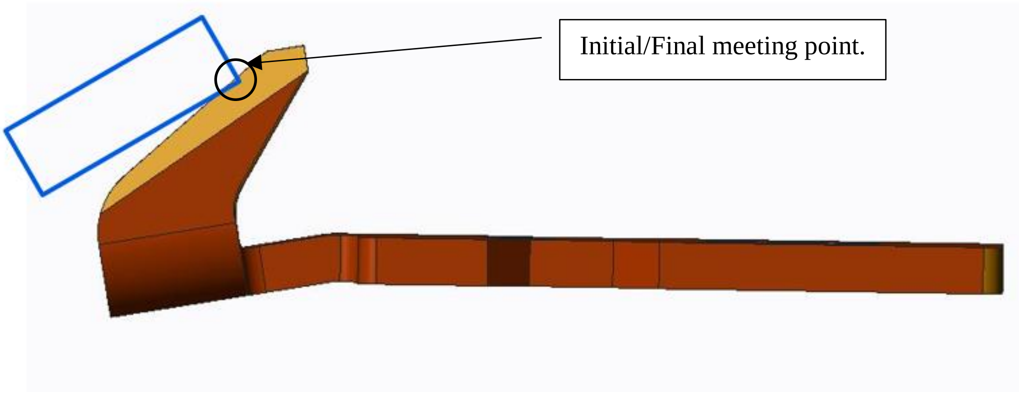


Figure 3.7 *Blue rectangle showing moving contact. The initial and final point of contact is shown between contacts*

3.1.3 Impact point shifting

This factor is caused in result of the combined effect of factor 3.1.1 and 3.1.2, explained above. The point of the first contact or impact point between the moving and fixed contacts shifts with the operations (as shown in figure 3.8).

The arc produced during the making operations is also shifted from the position ‘a’ to ‘b’, closer to the main-area. In the same, during the breaking operations an electric arc will

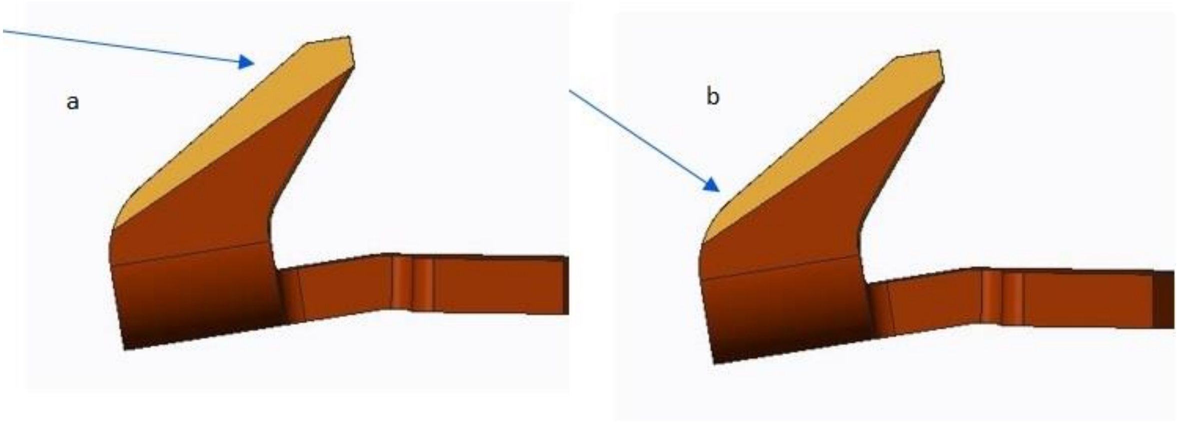


Figure 3.8 *Left* (a) *at the start of operations. Right* (b) *at the end or later operations.*

generate from the position ‘b’ and then move towards the position ‘a’. Consequently it will sharply increase the wearing of the main-area of the contact due to arcing effects

3.1.4 Irregular current flow

This issue arises due to sticking of burnt lubricant on main-area of contacts during early switching operations, which increases resistance. Therefore, in early making operations current conduction between fixed and moving contacts takes place mainly in the region from rectangular area as shown in figure 3.9 (a). Whereas, in the later operations it mainly takes place from area shown by rectangle in figure 3.9 (b).

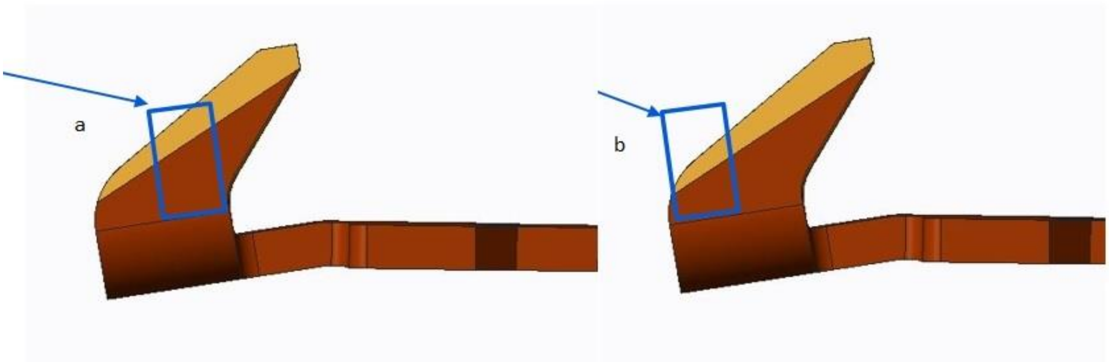


Figure 3.9 *Left* (a) *Current conduction during the early current making operations. Right* (b) *Current conduction during the later operations in current making.*

This leads to incapacity to utilize whole contact area for conduction, until burnt lubricant is removed.

3.1.5 Determination of optimum wiping area

The contact’s surface wiping is one of the main benefit in using knife type contacts (sliding contacts) as shown in figure 3.10. It helps in removing the corrosive layers from the contact surface. However, a small wiping area may result in in-efficient corrosive layer removal.

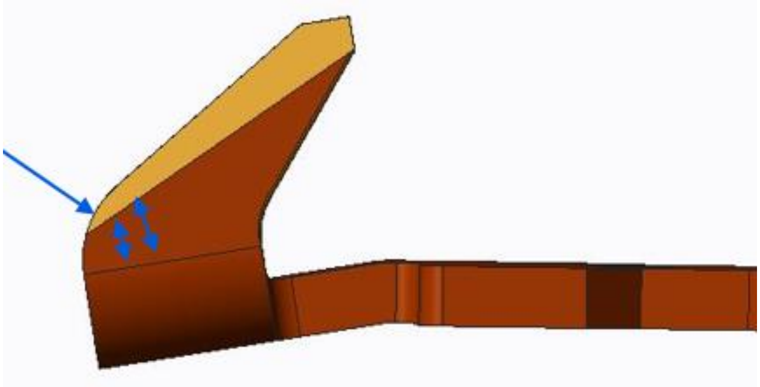


Figure 3.10 *Double headed blue-coloured arrows showing the available wiping area. Single arrow head showing the location of wiping area.*

3.1.6 High contact closing force

High contact closing force produces large insertion force on the contact surface, which leads to mass loss from a contact's surface, as shown in figure 3.11. This also increases the bouncing amplitude of a contact upon making leading to short arcs. Surface friction along with improper chamfer (high angle and small chamfer length) requires high contact closing force.

Figure 3.11 *Eroded contact of* OT400 *after* 2000 *operations.*

3.1.7 Metallic dust

During switching metallic dust is generated because of mechanical wearing of contacts, and presence of molten metal in the electric arc. The molten metal in the arc splashes on the contacts surface and get bonded on it when the arc is being extinguished (figure 3.12). This leads to surface wearing of the contacts as more switching operations are performed.

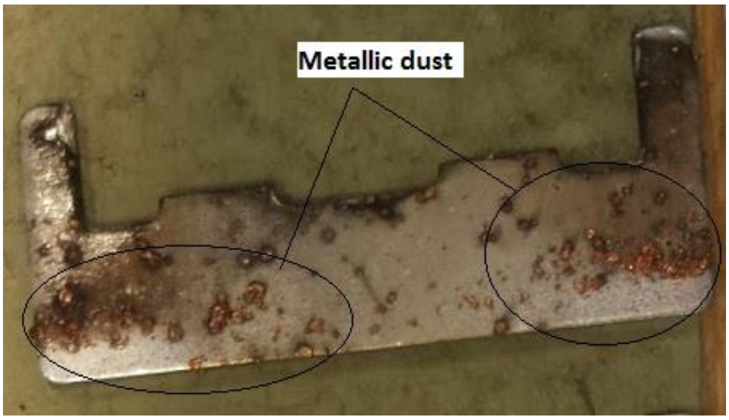


Figure 3.12 *Black circles are showing metallic dust (molten metal) sticks on the arcing plate surface after having extinguished an electric arc*

3.1.8 Friction due to long arc runner

Electric arc is driven away from the main contact area through contact shape arc runner. While, on other hand, it also increases surface friction value due to the distance moving contact has to travel to reach main area, as shown in figure 3.13.

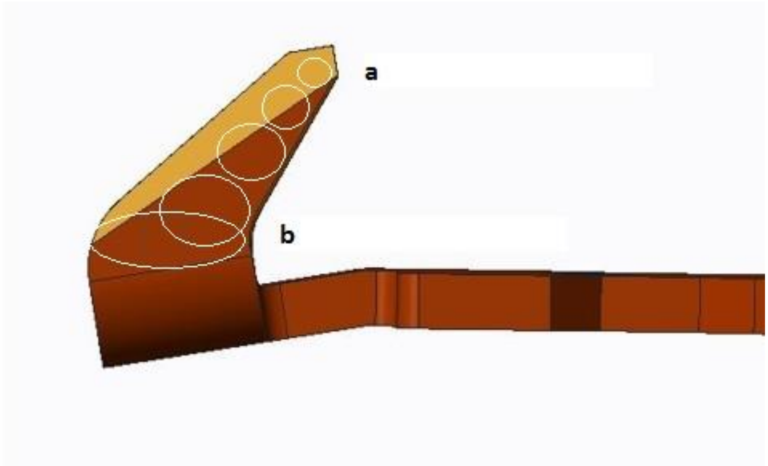


Figure 3.13 *Increase of contact area from point "a" to"b". White circles showing increase of contact area.*

3.2 Surface treatment

In this sub-chapter, the existing solutions, which are used as the surface treatment technology in the ABB switches. The possible factors, which are causing detrimental effect on the switch thermal stability are identified.

3.2.1 Contact lubrication

In switches lubricant A is used as a lubricant between the contacts. Its operating temperature range is in between $-50\,°\mathrm{C} \leq T \leq 120\,°\mathrm{C}$. It is a grease type lubricant consisting of synthetic hydrocarbon oil as a base oil and barium complex soap as a thickener.

For contact grease, long-term thermal stability of a lubricant is the main challenge. Less thermal and oxidation stability of a lubricant, as shown in figure 3.2, decrease switch thermal stability by increasing the contact resistance.

Following are the possible factors, which affect stability of a lubricant.

Degradation due to Metallic dust

Metallic dust produced during switching operations get immersed in the lubricant applied on the contacts (shown in figures 3.14 & 3.15). It decreases the thermal stability of a lubricant due to decrease in its dielectric strength and making it conductive. It also degraded lubrication ability of lubricants.

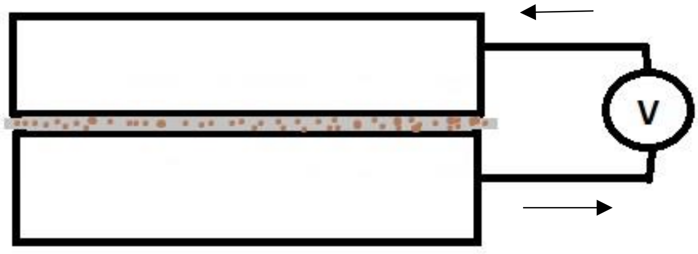


Figure 3.14 (a) *Contacts at the closed position is shown. Lubricating film is shown by the grey coloured layer. Brown dots are showing metallic dust immersed in the lubricating film.*

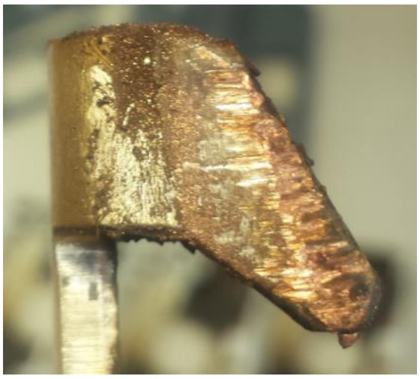


Figure 3.15 *The fixed contact of OT400. Metallic dust on the contact surface can be seen.*

Degradation of Lubricant due to oxidation

The presence of high temperature around electrical contacts, which exceeds the temperature limits causes evaporative loss and oxidation of lubricant.

In oxidation, a polymer surface is formed due to lubricant burn-up. In addition, carbon produced during arcing also accelerates lubricant oxidation.

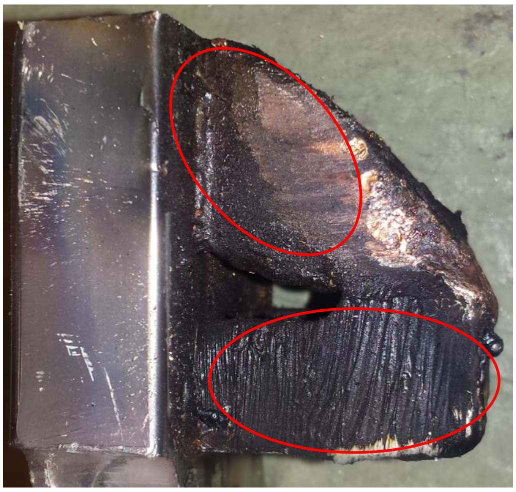


Figure 3.16 *Fixed contact of* OT1600. *Red circles are showing polymerized and carbonised areas.*

Lubricant degradation due to Surface pockets

In contact wearing, surface pockets are produced due to mass loss (figure 3.17), which during operations traps lubricant. The flow of current through these pockets causes high current density at these points leading to quick burning of the lubricant.

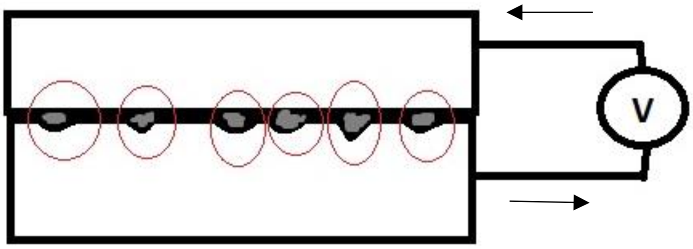


Figure 3.17 *Schematic diagram of contacts at the closed position. Red circles are showing the grey-coloured grease trapped in the pockets generated on the contact surface.*

Lubricant drop point

During operations, surface tension and viscosity properties of lubricant changes as contact temperature exceeds drop point of the lubricant. Therefore, the lubricant loses its consistency on contact surface and it drips off (shown in figure 3.18).

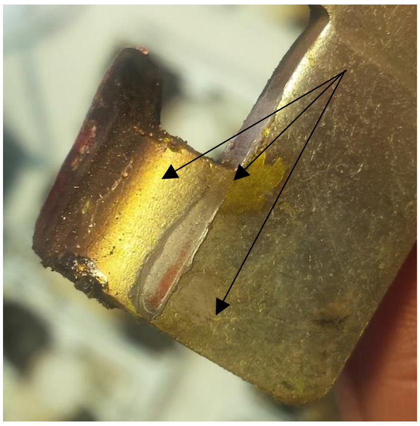


Figure 3.18 *The fixed contact of* OT400. *Arrow heads are showing dropping of the grease.*

Challenges due to increase of Surface roughness

The increase of surface roughness due to mechanical operation makes it difficult to remove the burnt lubricating layer on the contact surface, as shown in figure 3.19. This results in increase of the contact resistance.

Figure 3.19 *The fixed contact of* OT400*. Black areas showing burnt lubricant trapped in degraded contact surface.*

3.2.2 Contact plating

The idea of contact plating is to reduce the contact resistance due to formation of corrosive layers. Contact plating significantly reduces the contact resistance making contacts more thermally stable. However, there are also challenges faced in its implementation.

Low wear resistance

One of the major issues of plating is that it tends to wear-off during its lifecycle exposing substrate to the environment. One of the commonly used plating material is silver, which offers low contact resistance. It is a ductile material with low surface hardness value and high friction coefficient (μ_s = 1.4) thus requires high contact closing force during making operations, as shown in figure 3.20. This causes fast degradation of contacts' surface. In addition, silver has low melting temperature, therefore shows poor behaviour under electric arc.

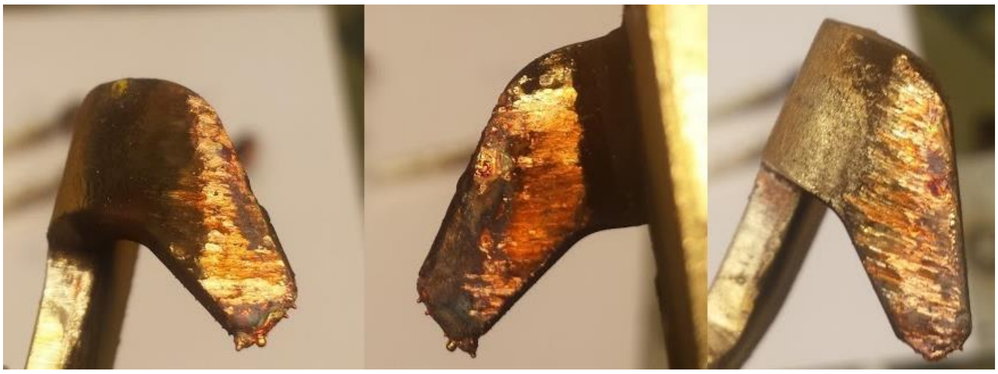


Figure 3.20 *Contact wearing of* OT400 *with no-grease* 2000 *operations.*

3.3 Arc Interruption

The switches during current breaking generate electric arc, which is extinguished by the arcing plates (figure 3.21). Arcing plates are made of iron and coated with zinc. Their main purpose is to generate a magnetic force (Lorentz force), which moves the arc away from the contacts and help in cooling it down via arc elongation process.

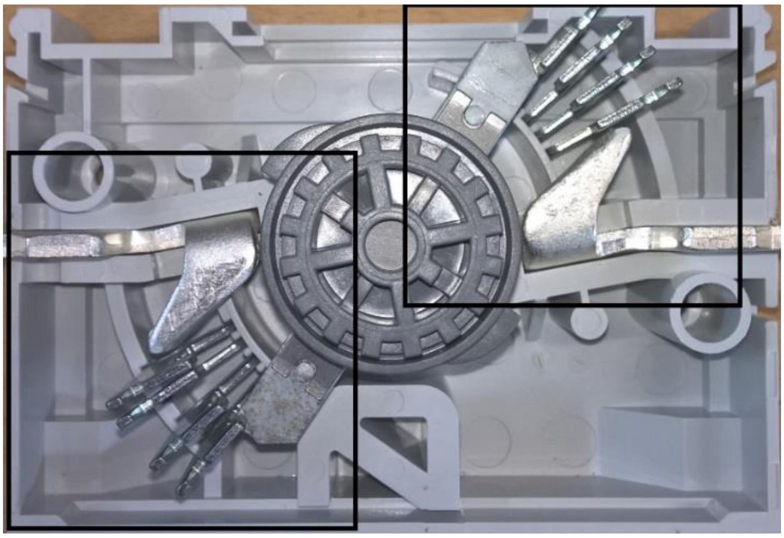


Figure 3.21 *A Switch module of* OT630. The rectangles are indicating four arcing plates per gap between contacts.

A space with exhaust is provided at the backside of the arcing plates as shown in figure 3.22. It is for the hot gases accumulated during current breaking and decreasing their pressure by removing them via exhaust. The exhaust also provides direction to the gas flow, which helps in directing an electric arc away from the contacts and can be easily extinguished.

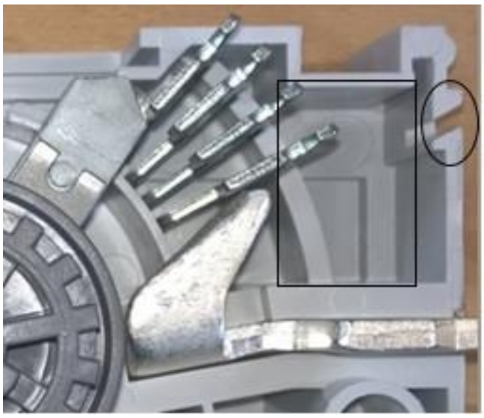


Figure 3.22** Rectangle shows space area. Circle shows exhaust**.

The angular distance between the inner points (double headed arrow, figure 3.23) of the fixed and moving contacts at the open position is about 15°, whereas, the linear distance between them is about 18mm (thick black line, figure 3.23).

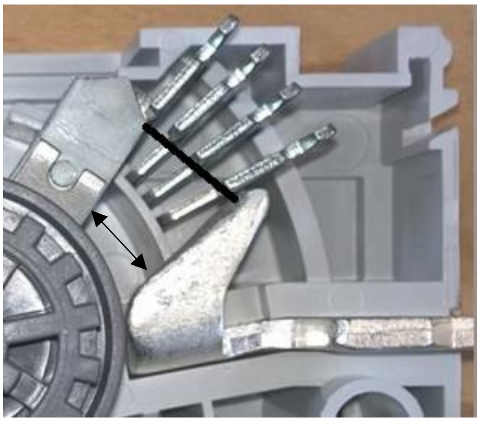


Figure 3.23 Double arrow head gives angular distance between contacts. The black line shows the points from where distance is measured.

The moving contacts are supported by a plastic roller as shown in figure 3.24. The rotational motion of the moving contacts helps in shifting arc easily from the contacts to the arcing plates.

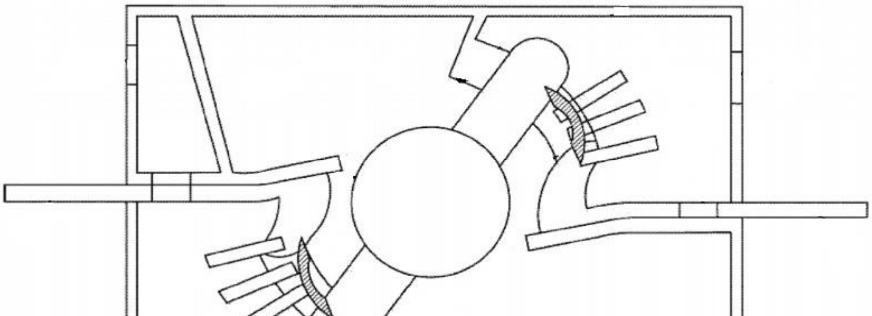


Figure 3.24 *A simplified schematic diagram of* OT630 *switch. The thick grey curve between contacts is indicating arc between contacts.*

3.3.1 Challenges in Arc interruption: Contact Erosion

The energy produced during arcing increases the mass loss of contacts. In the present switch design, arc is generated between the contacts, as shown in figure 3.24, therefore arcing effect on the contact surface is prominent. It is desired that the arcing plates should pick an arc from the contacts and extinguish it in fast, therefore arcing stress on contacts can be minimized.

The arc point during contact breaking is shown in figure 3.25. The fixed contact guides the arc to arcing plates. Arcing plates are placed near the contact, so it can easily pick the arc from it and keep the arc not burning in between the contacts. Whereas, it also increases the arcing effects on the contacts surface.

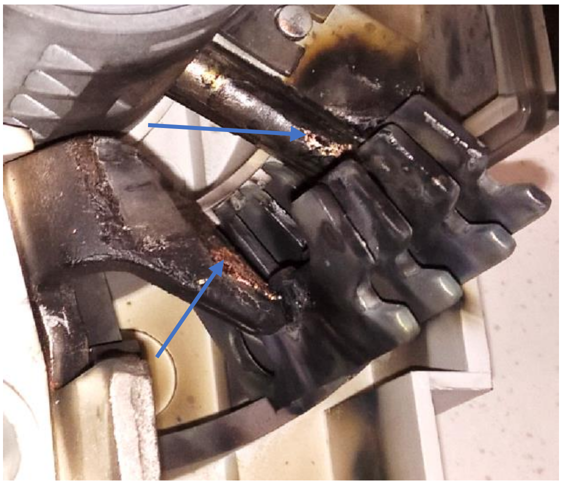


Figure 3.25 *Blue arrow heads are showing points on the contacts where contacts are melted due to arc generation.*

In figure 3.26, the direction of arc movement on the contacts during breaking operations is shown and the point of arc picking by an arcing plate is also shown via red arrow. The red circle is showing the arcing effect on the iron plate above the moving contact.

Figure 3.26 *White arrows pointing the arc movement during contact breaking. Red arrow pointing damage of arcing plate due to arc picking and the same effect is encircled by a red circle.*

4 Proposed solutions

In this chapter, solutions are proposed for contact design, surface treatment and arc-interruption in response to the shortcomings explained in chapter 3.

4.1 Contact Design

In this sub-chapter design modifications in the fixed and moving contact are explained, which can possibly minimize the contact wearing during switching. With the help of drawings, a clear picture about the approach is explained.

Sections 4.1.1 and 4.1.2 are related to a modification in the fixed contact and 4.1.3 is related to a modification of the moving contacts. Only 4.1.2 will be tested in this thesis time period, other modifications will be tested in the future.

4.1.1 Impact-line to main-contact-area

The solution in this section addresses the issue mentioned in the chapter 3.1.1. The geometry of the fixed contact's knife is modified in order to reduce wearing during making operations.

These changes are made in two steps. In the first step, offsetting of the line of impact from the main area is done. In the second step, a knee is provided approximately in the middle. New chamfered surface with less slope is provided. The scheme is shown in figure 4.1. The purpose of extending the main area in the outward direction is to minimize the degradation of the main area due to impact.

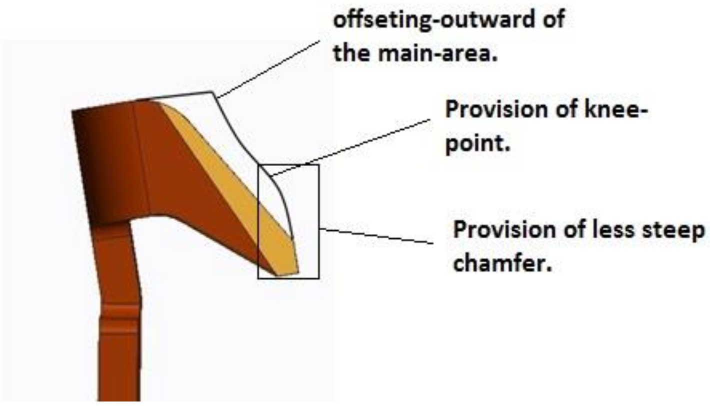


Figure 4.1 *The fixed contact of* OT630. *The black curve is showing the idea of the suggested solution*.

The addition of more material because of the knee-shaped design will help in utilizing more overlapping area between the fixed and moving contacts during their initial and final contact points. Therefore, the value of current density as compared to the existing design will decrease and less degradation during the contact making will happen.

A chamfer with a smaller slope angle and larger length (compared to the existing design) will aid in decreasing the contact wearing as a result of impact force.

The importance of the chamfer in decreasing the impact force is more clearly explained by mathematical derivations.

Mathematical derivation

The energy possessed by the moving contacts during contact closing is equal to the kinetic energy due to its velocity:

$$E = {}^{1}\!/_{2}\, mv^2 \tag{4.1}$$

As the moving contacts hits the fixed contact, the kinetic energy is converted in to frictional work. The work is equal to the product of impact force (*F*) and distance covered to compensate the impact force (*d*).

$$W = Fd \tag{4.2}$$

At the point of impact, kinetic energy is transformed in to the work, therefore from here we can get the relation of the impact force as a function of distance (*d*) as:

$$ {}^{1}\!/_{2}\, mv^2 = Fd \tag{4.3}$$

$$F = {}^{1}\!/_{2d}\, mv^2 \tag{4.4}$$

The distance (*d*) intended to cover by the impact force *(F)* as explained above is usually provided as a chamfer at the fixed contact interface. Therefore less damage to the interface of both moving and fixed contacts would occur.

The range angle at which the chamfer will be provided is $0 \leq \alpha \leq 90°$. The angle of chamfer is important for proper utilization of the chamfer length in order to decrease contact wearing and for smooth operations. The function of the chamfer is to save the contacts from wearing during the contact making operations.

In figure 4.2, a simplified picture of the situation when the moving contact makes impact on the fixed contact and move against it is shown. The moving contact is shown by a blue box, which is being driven against the chamfer of the fixed contact by force (F). Spring force (F_s) acting on the moving contacts is supposed constant. Forces acting on the block mass are shown. The force (F) is driving the block up to the height of the chamfer, which is also creating impact on the fixed contact because of the angle (α). Force (N) is acting on the blue box as a reaction to force because of its weight. The coefficient of friction between surfaces is ‘μ’.

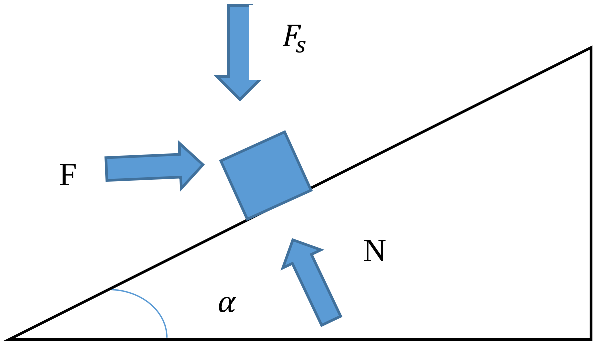


Figure 4.2. *A rectangle block is moved up to the slope.*

Balance equations (4.5) and (4.6) for the forces acting downward and rightwards are derived by the translation of vectors in figure 4.2.

For downward: $$F_s - N\cos\alpha + N\mu\sin\alpha = 0; \tag{4.5}$$

For rightward: $$F - N\sin\alpha + N\mu\cos\alpha = 0; \tag{4.6}$$

Solving the equation (4.5) and (4.6) for N, and then substituting the value in the either of equation will give:

$$F - F_s\left(\frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha + \mu\sin\alpha}\right) = 0 \tag{4.7}$$

The maximum and minimum values of the applied force (F) is dependent on the F_s and the factor (eq. 4.8).

The trend of the factor (eq. 4.8.) with different values of slope angle ($0° \leq \alpha \leq 90°$) is increased exponentially with the increase in value of '$\propto$' as shown figure 4.3 (μ = 0.1).

$$\left(\frac{\sin\alpha + \mu\cos\alpha}{\cos\alpha + \mu\sin\alpha}\right) = 0 \tag{4.8}$$

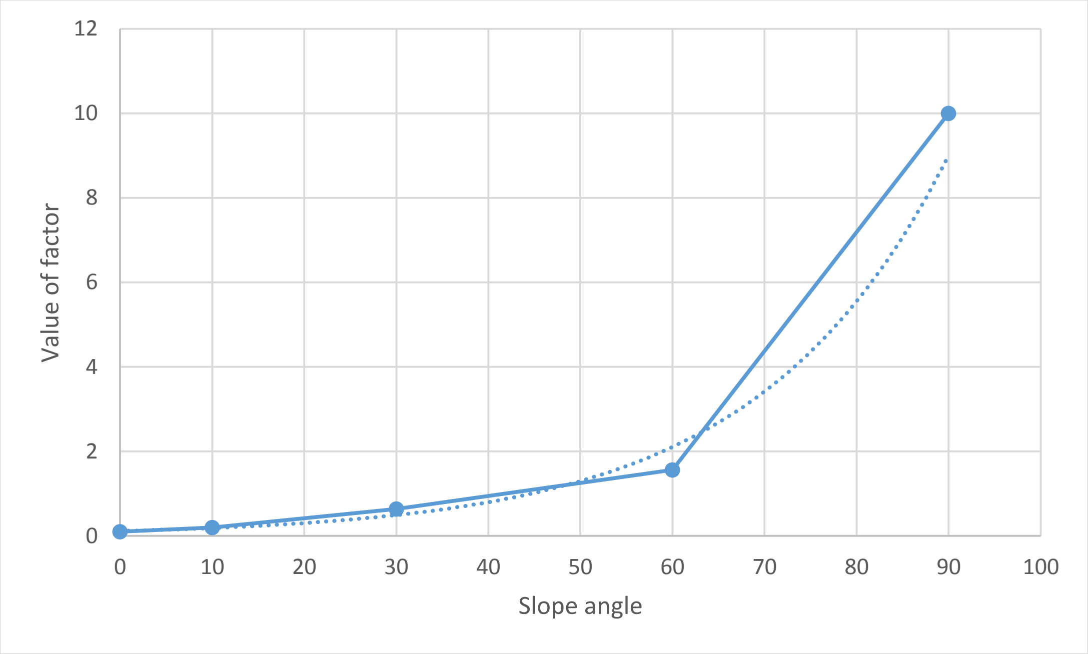


Figure 4.3. *Graph between factor values and the slope angle.*

As the value of the slope angle is increased, the value of the factor multiplying with the spring force (F_S) is starts rising, the dotted line is showing the trend-line, which according to equation (4.7) minimizes the value of the applied force (F). Therefore, more force is required to drive the contact across the fixed contact. The decrease of force (F) indicates the increase of the impact on the contacts. In figure 4.3, it can be seen that the minimum value of the impact force can be achieved when the slope angle is 0°.

In real, F_S value does not remain constant. It increases as the moving contact gains height against the chamfer, which will further increase the value of the multiplying factor (eq. 4.7) because of increase in the value of 'μ'.

The value of spring force is decided during the contact designing process. It is based on the value of contact resistance and short circuit current value. Therefore, it is more challenging to modify it compared to the chamfer modifying. A high value of the spring force helps in achieving a good thermal stability but it will also increase wearing.

- **Knee-Shaped design for Impact point shifting:** The provision of the knee-shaped design, explained in the previous section, will delayed the first-impact point shifting with switching operations, as explained in section 3.1.3. In the presence of a knee-shaped design (figure 4.1), the shifting of the first-impact point is stopped by the addition of extra material, therefore arcing during switching operations could not shift towards the main area.
- **Increase of wiping area:** In reference to section 3.1.5. The increase of the main area has potential to resolve the issue of small wiping area on the main area. It will provide more surface area (compared to the existing design) for wiping which will improve the cleaning process of the contacts surface, as shown by the red arrows in figure 4.4.

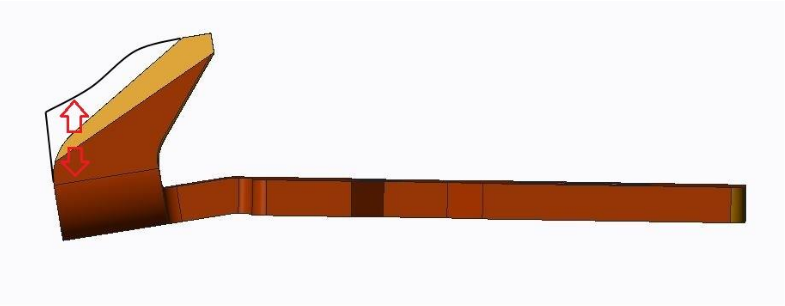


Figure 4.4. *The fixed contact of* OT630. *Red arrows show the main contact area used during wiping action.*

- **Degradation due to Initial and final point:** The provision of the knee shaped design along with chamfer has potential to resolve the problem mentioned in 3.1.2. This design modification will provide more overlapping area (figure 4.5, indicated by arrow head) between the contacts. The increase of the overlapping area will decrease current density, which eventually decreases the power loss. The increase of the overlapping area also minimizes the value of the blow-off force. The contact surface at microscopic scale has small peaks due to surface roughness, as explained earlier, these peaks will act as parallel paths for current flow. The increase of the overlapping area will also increase the number of parallel paths. These paths will divide the current value depending on their cross-sectional areas. Therefore, the contact blow force 'F_B' will decrease.

Figure 4.5 *The fixed contact of* OT630. *Red rectangle is showing moving contact. Black curve is showing modified geometry of the contact. Black arrow is showing the overlapped area during connection.*

4.1.2 Irregular current flow

This solution is addressing the challenge explained in section 3.1.4. In this solution, the surfaces of both moving and fixed contacts are modified. A semi spherical or ball-shaped area is provided on the moving contact, as shown in figure 4.6. Whereas, a rectangular pattern is provided on the main area of the fixed contact.

A rectangular-dotted pattern is provided on both sides of the fixed contact as shown in figure 4.6. The pattern is limited to the main area region; therefore, it will not add more friction because of surface roughness during contact closing operation.

Spring force is kept the same as in the existing design. The iron plate on the top of moving contact is modified therefore spring force on contacts remain same. Therefore, it is expected that the contact resistance value in relation with contact force will not be affected in this design modification.

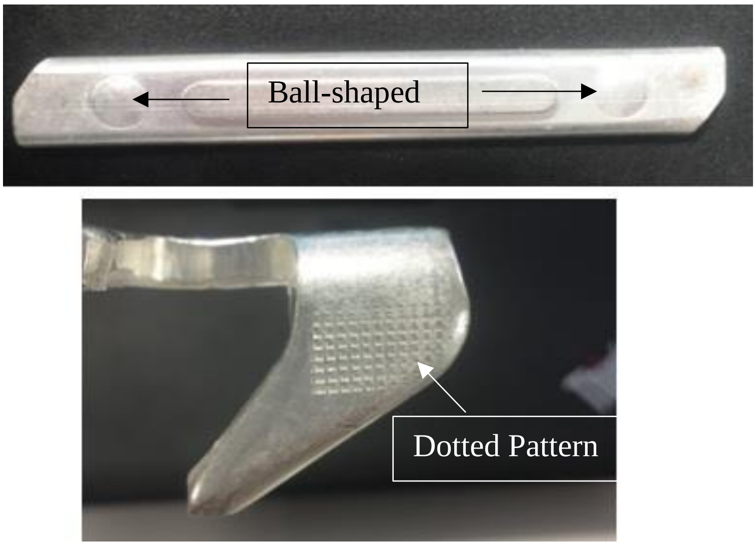


Figure 4.6. *Top: Moving contact with ball-shaped surface. Below: dotted-pattern-shaped fixed contact.*

The purpose of ball-shape is to clean the burnt lubricant on the main area of the fixed contact and conduct current from the same area, in this way contact resistance will become stable and low. The surface roughness because of the pattern on the fixed contact increases the contact area between the contacts.

Further, it will make the point of high pressure and current flow coincident, therefore stable and low value of contact resistance can be achieved for a long time. This design modification will also address the robustness challenge (figure 4.7) during switch operations between contacts by removing wearing difference between both sides of a contact. The irregular wearing mainly arises due to design tolerances in contacts design and mechanism. Which can be managed up to some percentage with ball-shape contact.

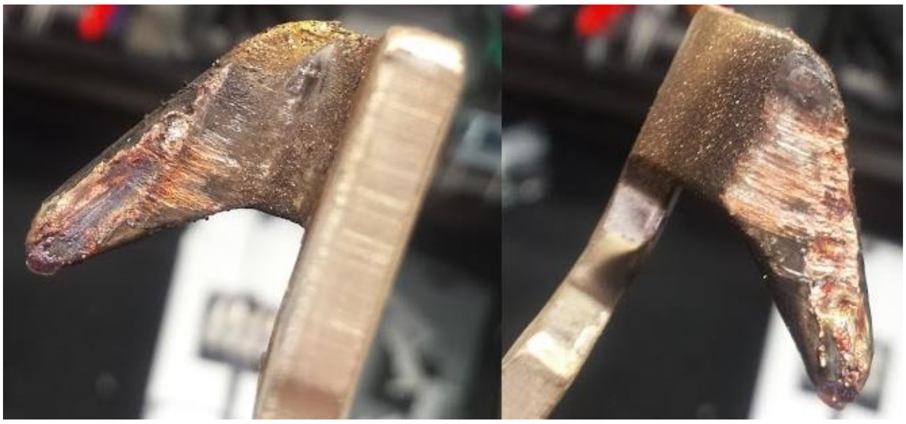


Figure 4.7 *Irregular contact wearing on the both sides (Top and bottom) of a same fixed contact.*

4.1.3 High contact closing force

The issue of high contact closing force, explained in 3.1.6, can be resolved by modifying the moving contact design in a way that the impact force on contacts can be minimized. In this solution, the mass of a moving contact is decreased hence decreasing impact force.

In this design modification, the concept of conservation of momentum is utilized in order to decrease the impact force on the contacts because of the contacts inertia.

The idea of how the design modification of the moving contact terminals will be done is shown in figure 4.8. For convenience one side of the fixed contact arm is shown. Same changes will be made on the other side as well. In figure 4.9, the first design from top is showing the existing solution, whereas the second design is showing the proposed solution.

In figure 4.9, the mass of the contact arm is divided in to two parts by the help of a rectangle because of their different mass values. The mass inside the rectangle is shown by m_1, whereas the mass outside the rectangle is shown by m_2. The distance from axis to the outer edge is shown by length *l*, and width is shown by *w*.

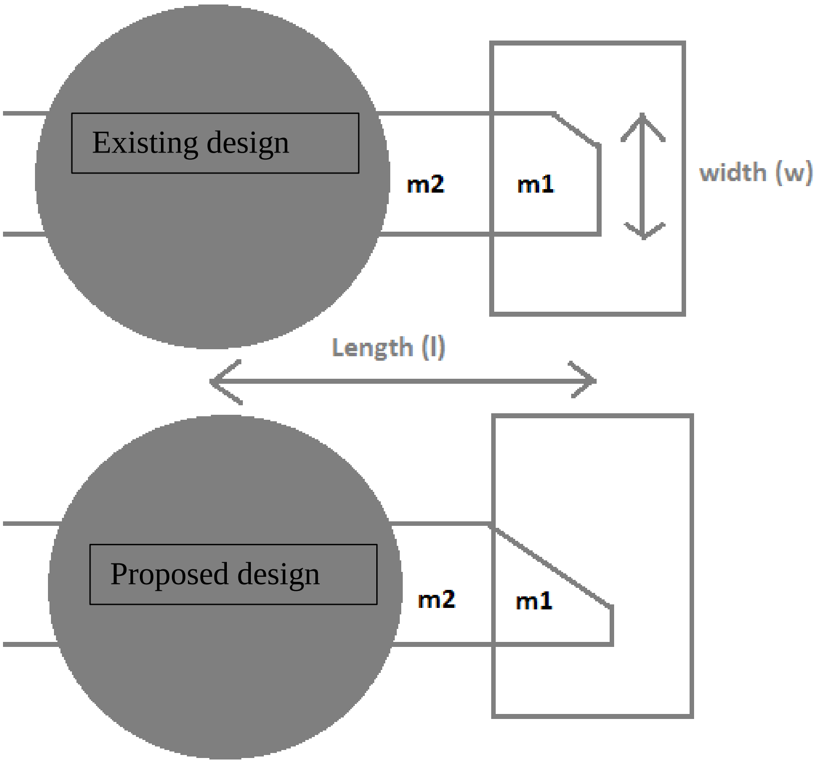


Figure 4.8 *The moving contact module of* OT630*. "*m_1*" shows area which make impact during contact closing. "*m_2*" shows main contact area.*

In linear dimensions, the forces due to masses m_1 and m_2 of the moving contact having acceleration 'a' are:

$$F_1 = m_1 \times a \tag{4.9}$$

$$F_2 = m_2 \times a \tag{4.10}$$

The linear momentum related to different mass values are:

$$p_1 = m_1 \times v \tag{4.11}$$

$$p_2 = m_2 \times v \tag{4.12}$$

In result of design changes shown in figure 4.8, the momentum related to ‘m_1’ will decrease, therefore the total liner momentum (p_{T}) of the moving contact arm will also decrease:

$$p_{\mathrm{T}} = p_1 + p_2 \tag{4.13}$$

In order to keep the value of total momentum same, as we know the moving contacts rotate during contact closing, therefore the relation between linear momentum and angular momentum L can be understood as: (figure 4.10)

$$L = r \times p_{\mathrm{T}} \tag{4.13}$$

$$L = I\Omega \tag{4.14}$$

So, the change of linear momentum will also changes the value of angular momentum. In order to keep the angular momentum unaffected, the moment of inertia (I) can be adjusted, as the relation of moment of inertia for a rectangle with length (l) and width (w) is:

$$I = \frac{1}{12} m(l^2 + w^2) \tag{4.15}$$

If the length of a moving contact arm is decreased, then the conservation of angular momentum can be done by increasing its width. Therefore, the value of angular momentum and moment of inertia, according to equations (4.14) and (4.15), will remain the same as it is in the existing design. In addition, there will be no need of making changes in the switch’ operating torque.

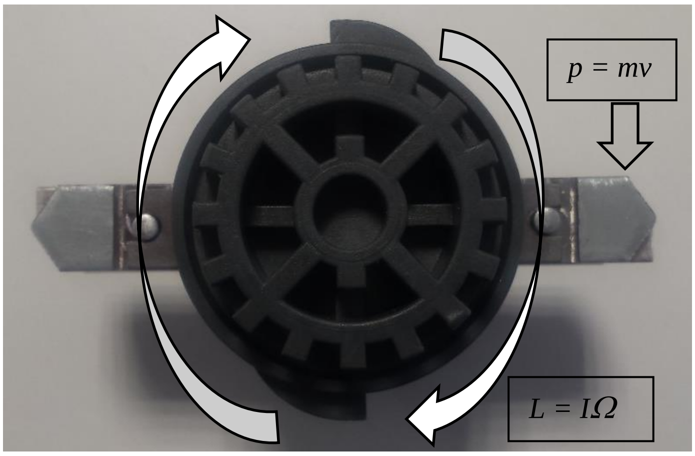


Figure 4.9 *The moving contact module of* OT630.

4.2 Surface Treatment.

In this sub-chapter potential solutions related to the both contact lubrication and contact plating are presented. The contact lubrication and plating are closely related with each other therefore their solutions are proposed together.

The solutions proposed in 4.2.1 and 4.2.2 are tested in this thesis, whereas solutions suggested in 4.2.3 will be tested in the future.

4.2.1 High thermally stable contact grease

In the selection of contact grease for the switches, it is necessary that it should remain thermally stable and consistent on the contact surface during a switch’s lifetime. Therefore, a lubricant sample with high temperature limit will be the preferred solution for the application. Long-term thermally stable grease can be manufactured by a combination of thermally highly stable base oil (i.e. PFPE) and thickener, along with suitable additives.

For the contact lubrication, potential solutions were found in collaboration with one of the grease manufacturer. The contact grease samples are provided for the testing by the supplier. They are listed in table 4.1.

Table 4.1: Temperature limit, drop point and composition of contact grease samples provided by the supplier.

Sr. no.	**Contact Grease Sample**	**Temperature limit**	**Drop point**	**Base oil / Thickener/Additive**
1	Lubricant B	$-50\ ℃ \leq T \leq 130\ ℃$	$\geq 220\ ℃$	Synthetic hydrocarbon oil / special calcium soap/ *NA*
2	Lubricant C	$-50\ ℃ \leq T \leq 150\ ℃$	$\geq 180\ ℃$	*NA*
3	Lubricant D	$-40\ ℃ \leq T \leq 150\ ℃$	$\geq 220\ ℃$	*NA*
4	Lubricant E	$-50℃ \leq T \leq 180℃$	*NA*	PFPE / PTFE /*NA*

4.2.2 Silver Iodide (AgI)

Silver iodide is suggested as a solid lubricant for the contacts. Silver-plated contacts are reacting with iodine to form a layer of silver iodide on the surfaces. It does not have any negative effects on the environment and it complies with the environmental requirements i.e. RoHS. Silver iodide also protects the contact surface from the Sulphur corrosion.

Plating process

Silver iodide plating is obtained by an electroplating process in which silver is used as an electrode for both the anode and cathode. Potassium iodide is used as an electrolyte. During the process, silver acts as a substrate and iodine reacts with the topmost layer of the silver electrode (about 1 µm) and forms a black layer of silver iodide. [12]

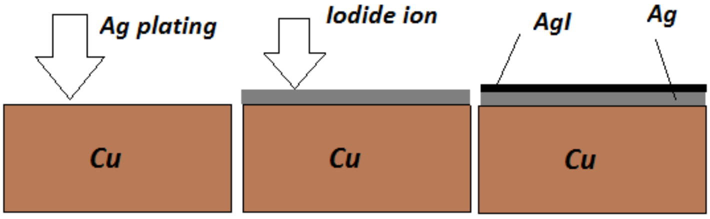


Figure 4.10 Process of contact plating silver iodide on the copper contacts (left to right). [12]

Contact resistance

In order to evaluate the contact resistance, surface friction and wearing rate of silver iodide [12], a pin-on-disc setup as a tribometer was used for testing (figure 4.11). The test was performed so that a cylindrical pin of pure silver was slid back and forth against the surface of AgI-treatment. The sample is prepared by electroplating 2 µm of silver iodide on a silver-plated copper disc. The applied load on the pin was 10 N. As a result of sliding the silver pin has made wear tracks of 10 mm long and 2 mm wide at a speed of 8 cm/s. A current of 10 A is supplied through the pin-on-disc assembly to measure the contact resistance.

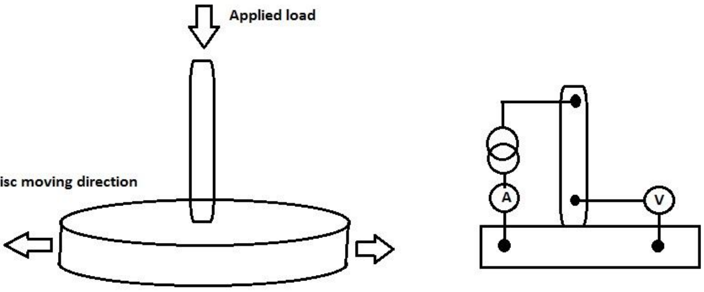


Figure 4.11 *(Left): Schematic diagram of tribometer: pin-on-disc setup. (Right) Contact resistance measuring setup. Contact resistance and surface friction is measured from this setup.*

The results obtained through the test show that silver iodide has a high initial value of contact resistance when compared to pure silver due to resistivity of AgI material. Which decreases with operations removing AgI and exposing pure silver. At about 500 operations, its value drops to a low value (100 µΩ) which is comparable to pure silver (~ 85 µΩ); it remained below 100 µΩ up to 10,000 operations until surface friction value starts increasing. Figure 4.12 shows the graphical results of this test.

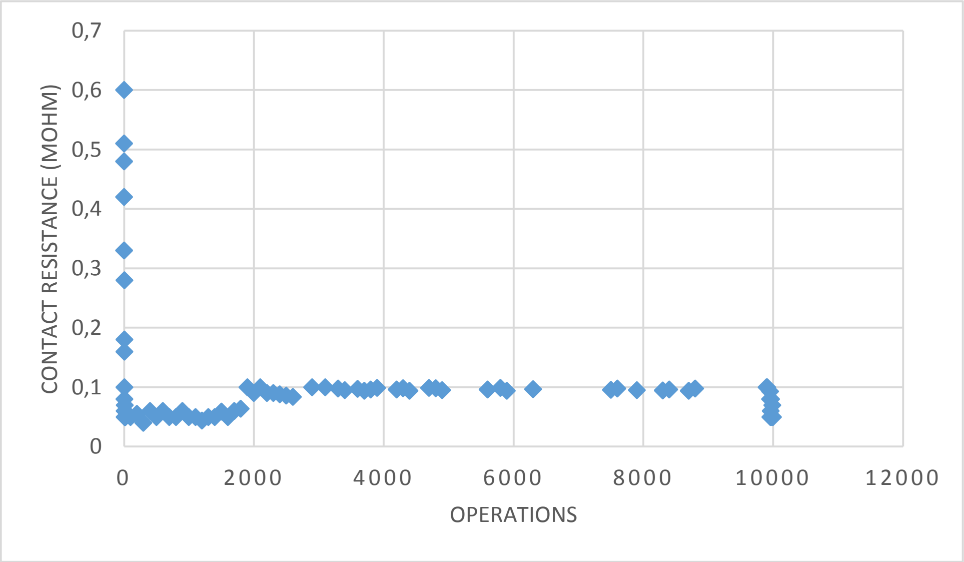


Figure 4.12 *Contact resistance of a silver pin sliding on an* AgI *plated contact disk. [12]*

According to figure 4.13, Ag-AgI plating combination on contacts has shown more favorable results as compared to AgI-AgI combination. The use of silver iodide with silver helps in controlling the effect of high resistance. However, Ag-AgI (lubricated) has shown the most favorable results.

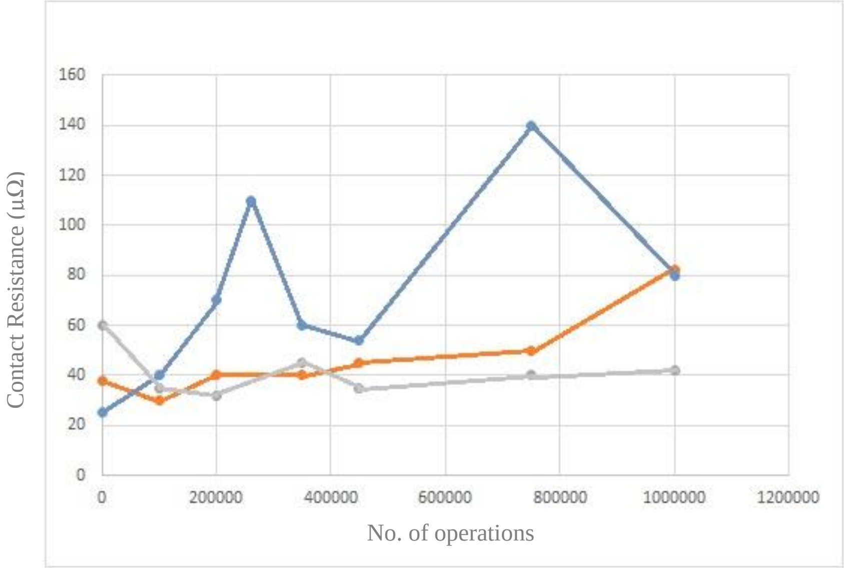


Figure 4.13. *Contact resistance of samples: Blue curve:* AgI-AgI, *Orange Curve:* Ag-AgI, *and Grey curve:* Ag-AgI *(Lubricated). [17]*

Coefficient of friction

The value of friction coefficient during pin-on-disc test obtained was stable during the lifetime test on the AgI plating, in which silver iodide lasted till 1,900,000 operations. The value

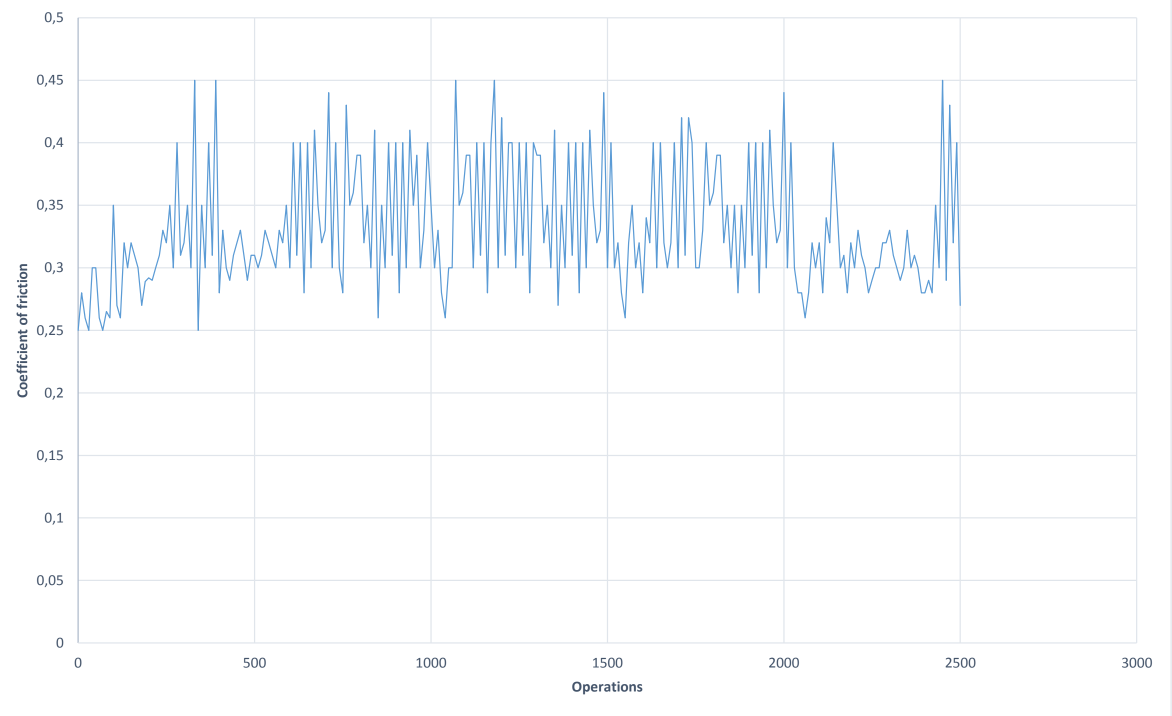


Figure 4.14 *Friction coefficient from the centre of the wear track measured during* 2,500 op. *[12]*

remains fairly stable (0.4) before silver is exposed, and the frictional coefficient exceeds above 1.2. The variation of the friction coefficient value with operations is shown in figure 4.14.

Thermal properties

Silver iodide can remain stable up to a temperature of about 555 ℃. At higher temperature, it disintegrates and converts into pure silver and iodine. Whereas, it starts decomposing in to silver and iodine after 200 ℃. On the basis of these results, it is recommended to keep the contact temperature below 150 ℃ in electrical contacts with silver iodide plating. [12]

4.3 Arc Interruption.

In this sub-chapter, the potential solutions related to arc interruption are explained. The solutions proposed in this section are not tested in this thesis. These solutions will be considered in future research work in collaboration ABB Corporate research center, Sweden.

4.3.1 Arcing chamber modification.

In this solution the idea about positioning of arcing chamber is proposed. The main purpose behind this approach is to quickly move an arc away from the contacts and extinguish it. As a result it will not damage the contacts' surfaces during the breaking operations.

This can be achieved by modifying the arcing chamber with provision of arc runners (metal used to guide arc). In addition, an exhaust hole is provided at the rear side of the arc chamber, which is used to exhaust hot gases and to utilize the hot gas flow in order to push the arc away from the contacts and towards the arcing chamber during circuit breaking. This concept is demonstrated in figure 4.16.

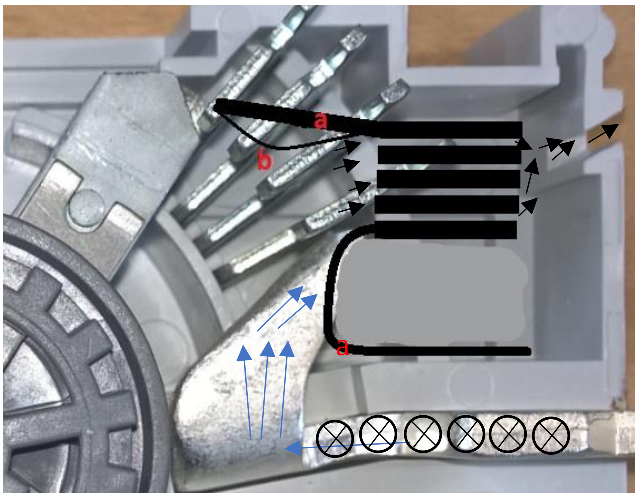


Figure 4.16 *Arcing chamber. Blue arrows represent current flow. Black circles arrows represent magnetic field direction. Black arrows representing gas flow direction. "a" and "b" shows arc runner.*

Arc runners are made of ferromagnetic material. They are used to pick an arc from the both contacts: fixed and moving. The flow of current during positive half of a cycle (figure 4.16: blue arrows) flowing through the fixed contact will generate magnetic field (figure 4.16: black crosses). The magnetic field on interaction with arc runner (provided in parallel) will induce an electromotive force (emf) in it. Therefore, during current breaking, it will be easy for the arc runner to pick an arc from the contact surface and guide it to the arcing chamber.

The arc runner shown in the figure 4.16 will be attached with the arcing plates and it will be extended from its middle as shown in figure 4.17.

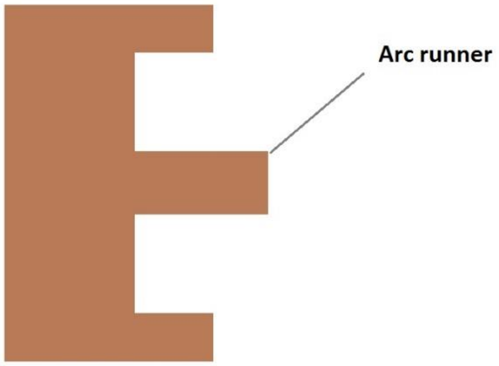


Figure 4.17 *Modified arcing plate with an arc runner*

The exhaust hole will be provided in a way that there is a proper separation of the switching chambers. One chamber per opening gap and there will be no mixing of gases between them, as shown in figure 4.18. In addition, exhausts are provided on the each side of a chamber. Whereas their opening size will differs, the exhaust at the rear side of an arcing chamber will be bigger than the other.

In the presence of an arc runner attached to the arcing plate, there will be no need of providing an arc runner on the fixed contact surface.

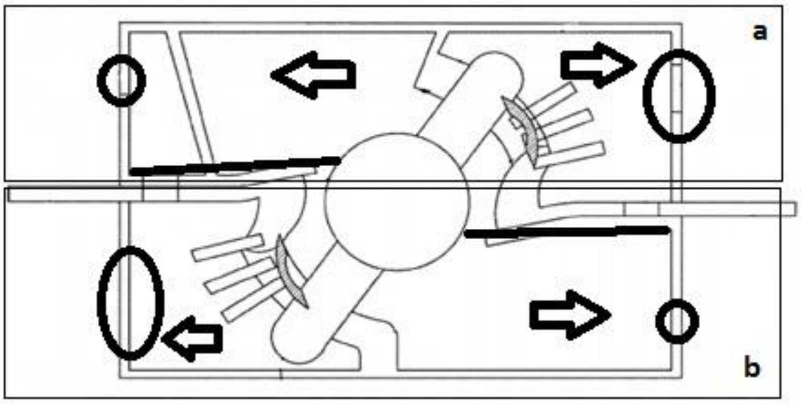


Figure 4.18 *The switch chamber is separated in two sections as "a" and "b" shown by rectangles. Big and small circles are showing the possible location of exhaust holes. Arrows indicate the flow direction of hot gases.*

4.3.2 Arcing plate material

Arcing plate material affects the arc energy value during arc interruption. The use of different plating materials for the arcing plates (existing: Zinc) help in decreasing the arc energy value by fast arc interruption. It is because of the composition of an electric arc plasma, which in the presence of different materials increases voltage drop in an electric arc. This decreases arc current flow and extinguish electric arc. According to ABB’s empirical knowledge, the use of nickel and brass as a plating material for the arcing plates has reduced the arc energy value. Similarly, the use of material for the arcing plates’ coatings has also decreased the arc energy value.

5 Testing

In this chapter the tests which have been performed in this thesis are explained. In addition, the timeline of all the tests proposed in this thesis study is also presented.

5.1 General

The design verification of a switch-disconnector is done by testing the product according to the standards i.e. IEC 60947-1 and IEC 60947-3. These standards explain the type of tests, procedures and conditions required for a product to validate its design. IEC 60947-1 explains the general rules about low-voltage switchgears and control-gears, whereas IEC 60947-3 includes the information specific to the switches.

The tests required for a switch-disconnector are divided into five sequences in table 5.1.

Table 5.1: Scheme of test sequences [13]

	Sequences	**Tests**
1	General performance characteristics	Temperature-rise Dielectric properties Making and breaking capacity Leakage current Temperature-rise verification. Strength of actuator mechanism.
2	Operational performance capability	Operational performance Dielectric verification Leakage current Temperature-rise verification.
3	Short-circuit performance capability	Short-time withstand current Short-circuit making capacity Dielectric verification Leakage current Temperature-rise verification.
4	Conditional short-circuit current	Fuse protected short-circuit withstand Fuse protected short-circuit making Dielectric verification Leakage current Temperature-rise verification.
5	Overload performance capability	Overload test Dielectric verification Leakage current Temperature-rise verification.

Based on the application of switches, these are further classified in to different utilization categories i.e. AC-22A, AC-22B, AC-23A, AC-23B etc. For this thesis AC-23A is used. AC-23 is used for applications where connected loads are highly inductive. [13] This provides the value of current and voltage as a multiple of nominal rated current, voltage and power factor or time constant used during making and breaking operations. The category A represent switches, which are used for a large number of operations (with and without current). Whereas, category B is added for the switches where less operations are required.

The value of nominal current decides the number of operations. In *Table 5.2,* number of operations based on current rating i.e. 630A and utilization category for AC OT630E03 switch is shown.

Table 5.2: *Number of operating cycles for the nominal current ratings for different utilization categories [13]*

Rated operational current	**Category A**		**Category B**	
	Without current	**With current**	**Without Current**	**With Current**
630 A	4000	1000	800	200

In laboratory testing, related to thermal stability, temperature-rise and operational performance tests are of main importance. In case of switch-disconnector, the temperature-rise limit at the cable lug is 80K. It is also a main decision making parameter in this thesis.

If the contacts get damaged during operational performance tests then, the temperature rise will be beyond the temperature-rise limits defined by the standards. In table 5.3, the value of current and voltages are being shown to operational performance and make-break tests.

Table 5.3: *Values of current and voltage for operational performance and make break test for* AC-23A /AC-23B *utilization category. [13]*

Test	**Utilization category**	**Making**			**Breaking**			**No. of cycles**
		I/I_e	U/U_e	$\cos\varphi$	I_c/I_e	U_c/U_e	$\cos\varphi$	
OP.	AC-23A / 23-B	1	1	0.65	1	1	0.65	*Table 5.2*

I : *making current*
I_c: *breaking current*
I_e: *operational current*
U : *applied voltage*
U_e: *rated operational voltage* U_r: *operational frequency*

5.2 Tests in the thesis

In order to gather data regarding parameters affecting the thermal stability of switches, the operational performance test sequence is performed in this thesis.

The parameters collected from temperature-rise and operational performance test are further used for analysis purposes. In temperature-rise test; temperature-rise, voltage drop, apparent power, power factor in each terminal are measured. Whereas, in operational performance test; applied voltage, applied current, number of operations, arc time, and arc energy are measured.

The sequence of activities performed to collect parameters is shown in table 5.4. This sequence is divided in 200 op, 500 op, and 1000 op, after each part contact resistance was measured and temperature rise verification was done. The sequence in data collection is important as values of temperature rise and contact resistance varies before and after operational performance test.

Table 5.4: *Sequence of test for parameters collection.*

Test sequence	Order
Temperature-rise	1
Contact resistance (100 A DC)	2
Operational performance test	3
Contact resistance (100 A DC)	4
Temperature-rise verification	5

For contact resistance, a source of 100A DC is used to measure the voltage drop across terminals from which resistance is calculated.

During temperature-rise test, thermocouples are used as temperature sensor to measure the temperature of different parts of switch. In the temperature rise verification test, the rated value of AC current is flowed through the switch until its components acquire a steady temperature. After a certain time period from the point where the temperature gets stabilized is measured. In addition, at the same instant the voltage drop across the contacts is measured. The temperature rise test is performed at a voltage level of 3-4 V because of short-circuit operation (figure 5.1). The measured values of voltage drop shows the presence of contact resistance.

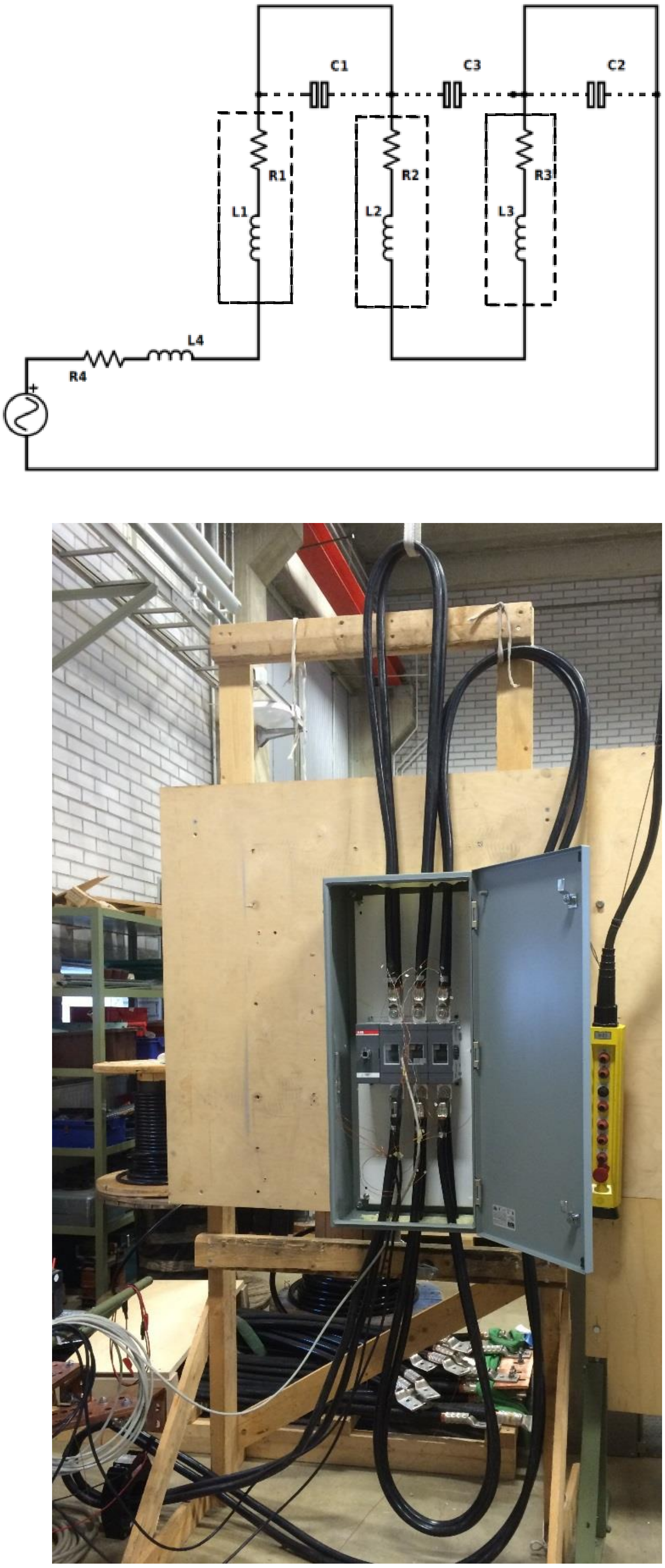


Figure 5.1. *Top: Circuit configuration during temperature-rise test of 3-phase switch is shown. Dashed lines show the switch parts between incoming and outcoming terminals. The contacts are connected in series.* R_4 and L_4 form the load of the test system. Parasitic capacitors of the cables showed by dotted-line. Down: Temperature-rise test setup.

In table 5.5, all the tests which are planned in this thesis along with their expected time of testing is shown. Tests that are performed in this study are: (1) Data verification test, (2) Arc energy test, (3), modified contact design test (4) silver iodide plating test, and (5) lubrication test. Among these, lubrication test is planned before the thesis study, whereas analysis of its test results are done in this thesis. During testing, the lubricant B is used.

Table 5.5: *Test planned in the thesis.*

	Test planned in this thesis	**In thesis**	**After thesis**	**Reference**
1	Data verification test	X	--	--
2	Arc energy test	X	--	--
3	Modified contact test	X	--	4.1.2
4	Silver iodide plating test	X	--	4.2.2
5	Modified contact & arc energy test	--	X	Test (2+3)
6	Low friction plating	--	X	4.2.3
7	Arcing plate with different plating material test	--	X	4.3.2

5.3 Planned tests

Following are the tests performed in this thesis.

5.3.1 Data verification test

This test is performed to validate the data of existing design of OT630E03 at 690V and 400V. Parameters are collected from temperature-rise and operational performance test. This test is a reference for the other tests those are performed in this thesis. In table 5.6 summary of test plan for this test is shown.

Table 5.6*: Test plan for data verification test (Operational performance test). [13]*

Switch	I_e	U_e	$\cos \varphi$	No. of cycles
OT630E03	630A	400V	0.65	1000
OT630E03	630A	690V	0.65	1000

5.3.2 Arc energy test

This test is performed with different number of arcing plates with various configurations to test the effect of number of arcing plates on arc energy value or to check the effectiveness of the arc chamber. The effectiveness will be evaluated whether decrease of arcing plates is increasing the arc energy values or not. With different number of arcing plates, the effect of thermal stresses on contact surfaces and corresponding temperature rise is also evaluated. Testing plan used in this test is similar to the data verification test.

The purpose of this test is to check the effects of an electric arc on the contacts. The effect of arc energy on temperature rise values is measured. For this purpose, different scenarios are generated from the best to worse, which are categorized on their ability to interrupt an electric arc. The switch in its existing design is supposed as the best case, to have four arcing plates per gap. Therefore, the order from the best to worse case is: standard sample, sample ‘a’, sample ‘b’, and sample ‘c’.

In the standard switch, four arcing plates per contact gap are used. In this test, the number of arcing plates are decreased. In sample ‘a’ (figure 5.2) only two arcing plates per gap are used. In sample ‘b’ and ‘c’, one arcing plate per gap are used and their places are shown in figure 5.3 and 5.4.

The number and position of the arcing plates have three configuration as shown below:

a. Middle two plates for each gap.

Figure 5.2 *Arcing plates in sample a.*

b. The only pale close to the fixed contact for each gap.

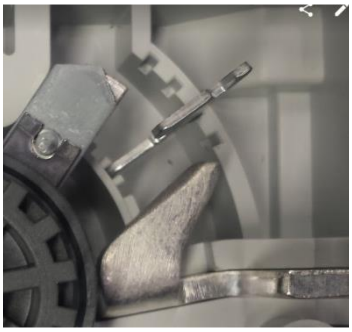


Figure 5.3 *Arcing plates in sample b.*

c. The only plate close to the moving contact (at the open state).

Figure 5.4 *Arcing plates in samples c.*

5.3.3 Modified contact test

This test is performed to test the hypothesis in the sub-chapter 4.1.2. The test plan for this test is the same as shown in table 5.6, except that it will be performed only at 690V. The test plan used in this test is similar to the data verification test.

This test determines to what extent the value of the contact resistance and temperature rise are stable. In addition, the effect of the new contact geometry on the lubricant burn-off is also evaluated.

Visual inspection of the tested samples is done to check the comparison of the contact wearing with the existing solution. The wearing of the contact because of both contact closing force and surface pressure is checked.

5.3.4 Lubrication test

Lubrication test is divided into two sub-tests: ambient temperature rise test and electrical endurance test. For either test, new samples are used for each new condition.

Ambient temperature rise test

The purpose of this test is to check the thermal and oxidative stability of the lubricant samples. In this test, the lubricant samples are applied on the electrical contacts (without switch casing) and placed inside an oven at three different temperature and time conditions. These three conditions are as follows:

- 200 ℃ for 3.5 hours.
- 150 ℃ for 7 days.
- 110 ℃ for 7 days.

Electrical Endurance test.

The purpose of this test is to check the thermal stability of the lubricant samples during current flow (under charged condition). In this test, the lubricant samples are applied on the electrical contacts (with switch casing) and operational performance tests are conducted in accordance with IEC 60947-3 standard.

In this test OT400E03 and OT1600E03 were used as testing samples. Each lubricant sample is tested on both switches on its current ratings. These switches differ on the basis of their thermal stability and robustness, the latter one is more thermally stable and robust. From this, the effect of thermal stability and robustness of the switch lubricant behaviour can also be evaluated.

In case of OT400E03, a switch sample with no contact grease is added, shown in figure C4, in order to get a reference value of the switch’s contact resistance for other samples. Similarly, no grease sample for OT1600E03 was prepared to test. For OT400E03, contact resistance is measured after every 500 operations and for OT1600 it is measured after every 200 operations.

The summary of test plan of operational performance tests is shown in table 5.7.

Table 5.7: *Summary of test plan for lubrication test.*

Switch	I_e	U_e	$\cos\varphi$	No. of cycles
OT400E03	400A	690V	0.65	3000
OT1600E03	1600A	690V	0.8	1000

5.3.5 Silver Iodide test

In this test, silver iodide plating on the electrical contacts are tested. Testing plan used in this test is similar to data verification test.

In the sample preparation, the fixed contact is plated with silver iodide and the moving contact is plated with pure silver. Silver iodide plating is done on the contact with silver plating of 5 µm, in which 1 µm is reacted with iodine and formed into silver iodide. Therefore, approximately 1 µm thickness of silver iodide plating can be supposed in this case.

The purpose of this test is to check the performance of silver iodide as a replacement of contact grease, and how much it affects the thermal stability of a switch. Therefore, in this switch sample no contact grease is applied on the contacts' surface.

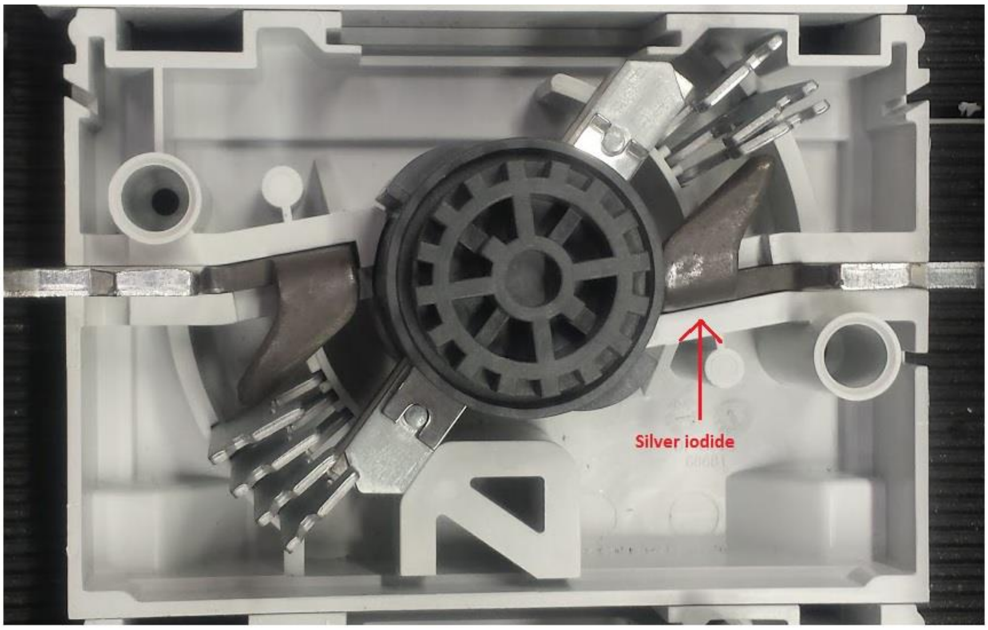


Figure 5.5 *Fixed contact plated with silver iodide.*

6 Results and Analysis

In this chapter the analysis and discussion of the test results obtained through the testing proposed in chapter 5 are presented. All the relevant measurements and data logged during the said tests are placed in appendices for reference.

6.1 Arc energy test

In this sub chapter, test results of the arc energy test for the current rating of 630A at 400V and 690V are presented. The parameters such as arc energy and temperature-rise are compared with the test results of data verification test (*Appendix A).*

The analysis of the test results at 690V and 400V are explained separately and a correlation between the arc energy and temperature-rise values are assessed. For analysis purposes, root mean square (RMS) values of arc energy were taken into account. The test results of arc energy and temperature-rise are shown in *Appendix B.*

6.1.1 Analysis of Test Results

Analysis of Arc Energy-Temperature Rise Correlation

At 690V, the trend of liner temperature rise up to 500 operations remained the same for all the samples. This trend is correlated with the arc energy (200 operations) except in case of sample c.

At 1000 operations, prominent increase in the value of temperature rise can be seen. The correlation of this increase with arc energy is more clear. In standard sample and sample a, temperature rise (1000 op) is correlated with the arc energy at 500 operations due to cumulative effect of contact wearing. In samples b and c, the temperature rise (1000 op) showed a correlation with arc energy at 1000 operations.

At 400V, the arc energy values are low when compared to the arc energy values at 690V. In this case, the arc energy and temperature rise values did not show clear correlation between them for all samples at any operations level.

Analysis of arcing plates effect on arc energy

The variation of the number of arcing plates has not much affected the value of arc energy. A decrease in the number of the arcing plates has not shown any trend of decreasing or increasing the arc energy value. This can be further understood by comparing the average value of the arc energy (1-1000 operations) for all samples at 690V and 400V separately. At 690V, the average value of the arc energy was approximately the same for all samples. Similarly, samples at 400V have showed approximately the same average values for arc energy. Therefore, the variation in the arc energy value is mainly due to the AC supply and not because of the arc plates.

Brief Discussion

Comparison of the temperature rise curves of samples: 690V up to 500 operations and 400V up to 1000 operations showed the same temperature rise trend. Therefore visual inspection of samples (400V) at 1000 operations can explain the linear temperature rise of the samples (690V) up to 500 operations. The visual inspection showed that the samples (400V) at 1000 operations still have silver on its most of area along burnt lubricant on it. Further contacts were less degraded while comparing it with samples (690V) at 1000 operations. Therefore temperature rise of 690V up to 500 operations is partially because of contact wearing and burnt lubricant, whereas it was remained low due to silver. The wearing of the contact decreases the removal of corrosive layers via sliding action.

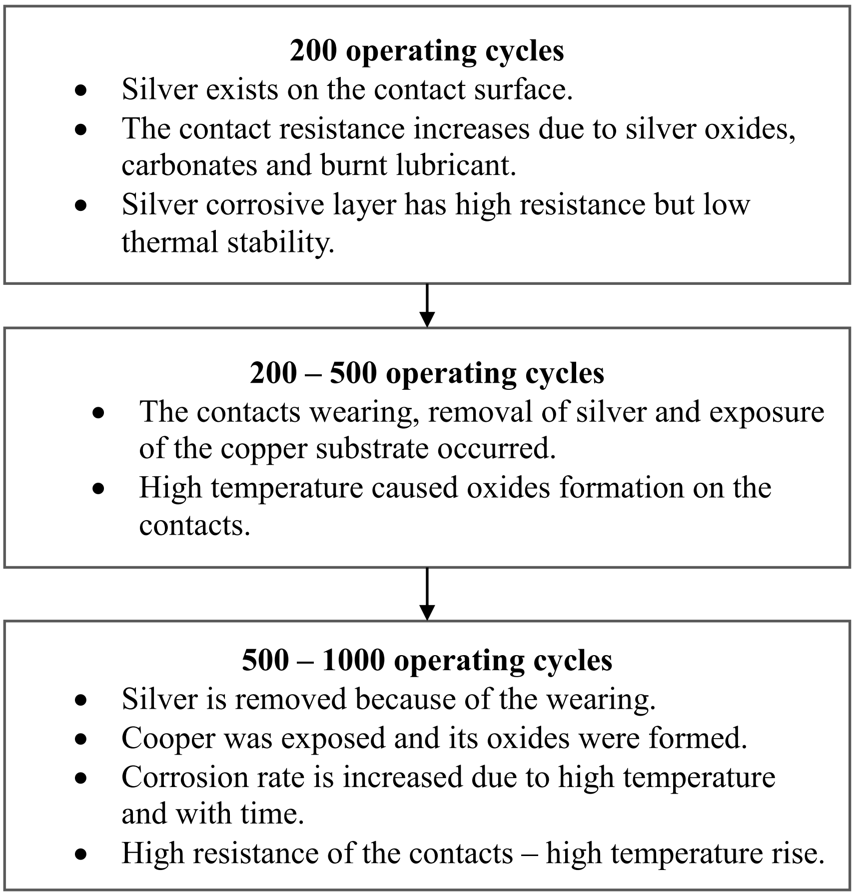
At 1000 operations, the difference of the temperature rise at 690V and 400V was further researched by visual inspection of samples. In the samples at 690V, silver was removed and copper was exposed completely. Red and black coloured layers of copper oxides have covered the surface. Those samples which showed high temperature rise had larger area covered by the corrosive layers. Whereas at 400V, silver was present and copper was not exposed. In addition, in cases where copper was exposed the coloured layers of its oxides did not present. Visual inspection has shown relation between the presence of corrosive layers of copper and high temperature rise. And formation of these layers depending on high arc energy values. Therefore, arc energy values and temperature rise are making correlation via development of copper’s corrosive layers. In addition, severe contact wearing in case of 690V has made the removal of corrosive layers via sliding action more difficult, which up to some percentage has affected the temperature rise.

The difference of contact wearing between samples at 690V and 400V is due to arcing during the contact making operations, which is more severe in case of 690V.

Recommendations

Based on test results, some improvements can be made as:

- Decrease of temperature rise around the contacts via arc chamber modifications, therefore in case of high arc energy development of corrosive layers can be minimized.
- Evaluation of the arcing behaviour therefore arc chamber can be modified to interrupt the electric arc and decrease the arc energy value.
- Contact design modification which can minimize wearing during contact making, or to modifying it which can save the main contact area from wearing. Therefore, the silver coating on it can last longer.



200 operating cycles

- Silver exists on the contact surface.
- The contact resistance increases due to silver oxides, carbonates and burnt lubricant.
- Silver corrosive layer has high resistance but low thermal stability.

200 – 500 operating cycles

- The contacts wearing, removal of silver and exposure of the copper substrate occurred.
- High temperature caused oxides formation on the contacts.

500 – 1000 operating cycles

- Silver is removed because of the wearing.
- Cooper was exposed and its oxides were formed.
- Corrosion rate is increased due to high temperature and with time.
- High resistance of the contacts – high temperature rise.

Figure 6.1: *Brief summary of the processes happened during the switch operations.*

6.2 Modified Contact Test

In this test, the contacts are modified and tested only at the rated voltage of 690V. The purpose of this design modification was to test the effect of the contact design modification on the long-term thermal stability of the switch. Test results of the temperature-rise of the modified contacts sample are compared with the standard sample's test results. Visual inspection of the contacts after the 1000 operations is done and, therefore the difference of the contact wearing between the two samples can be measured.

6.2.1 Test Results

The graph of the temperature rise for the each terminal of the modified contacts sample as a function of the switch operations is shown in *Appendix C*. These values are compared with the standard sample values which are shown in *Appendix A.*

a) At new condition, temperature rise values are approximately the same while ignoring the switch design tolerances. Whereas, in modified contacts the temperature rise decreases with switch operations (dips in temperature rise curves) as compared to the standard sample.

b) At 200 and 500 operations, the value of temperature rise is approximately the same.

c) At the 1000 operations, the modified contact sample has shown a high and irregular value of temperature rise until the first switch operation during temperature rise test was being made. The value of temperature is decreased for most of the terminals after the first operation, whereas the rest of switch operation did not affect it very much.

d) Visual inspection showed that in the modified contacts samples, the wearing of the fixed contact is lower compared to the standard sample. In figure 6.2, the difference of the contact main area wearing at 690V after 1000 electrical operations can be seen. The arrow heads

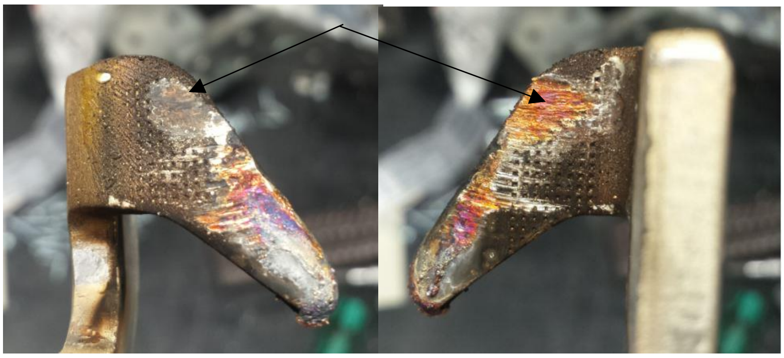


Figure 6.2 *Black arrows showing main area of contact of the modified contact sample after 1000 electrical operations.*

show the contact points between contacts. In the modified contacts, the wearing is very focused on a small portion of the main area of contact. Therefore, ball-shaped design has kept the current conduction and surface wearing at the same point.

Brief discussion

The ball-shaped contact surface on the moving contact focuses the current flow on the main contact area which has decreased the availability of the new contact points as compared to the existing design. In case of the area under the ball-shaped tip is covered with the insulating layers in addition to mass loss. Visual inspection of the samples after 1000 operations showed that at the most of contact points corrosive layers of copper are present, otherwise it is covered with burnt lubricant. The presence of copper's corrosive layers along with contact wearing causes a high temperature rise at 1000 operations. The irregularity in the temperature rise curve occurs when the ball-shaped surface wears off from these layers.

In this design modification, the issue of the switch robustness could not be completely eliminated. The surface roughness imparted through the dotted pattern on the fixed contact surface area has increased the temperature-rise values. It was due to filling of the space in the pattern with burnt lubricant hence decreasing the contact area. It also made the removal of corrosive layers from the contact's surface layers more difficult.

The design modification made in this prototype could not produce favourable results regarding the temperature rise. Therefore, it requires further modification.

Recommendations

- Further design modification which eliminate the dotted pattern on the fixed contact.
- Increase of the width of the main area of the fixed contact and to decrease the error due to switch robustness.

6.3 Contact Lubrication Test

In this test different lubricant samples were tested. The results of this test will be evaluated for the thermal stability of the lubricant samples at different temperature levels. The results include values for four new lubricant samples along with one existing sample.

6.3.1 Findings of Ambient temperature rise test

In this test, the lubricant samples were heated in an electric oven at different temperature and time conditions, explained in section 5.7. No current was passed through the switches during this test.

a) In table 6.1, the test results are shown, in which the lubricants are assigned with numbers from ‘1’ to ‘5’ depending on their performance from the best to worse. If a lubricant is assigned with a rating ‘1’, it shows that it sustained its original condition and provided lubrication on the contact surface. Whereas, if a lubricant is assigned with a rating ‘5’, it means that on heating it get carbonised and converted in to a hard polymer and losing its lubricating capability.

Table 6.1. Test results of ambient temperature rise test

Grease sample	**Temperature range**	220 °C	150 °C	110 °C
		3,5 h	7 d	7 d
Lubricant A (existing solution)	– 40 °C … 150 °C	3	2	1
Lubricant B	– 40 °C … 130 °C	4	3	1
Lubricant C	– 50 °C … 150 °C	2	4	1
Lubricant D	– 40 °C … 150 °C	5	5	5
Lubricant E	– 50 °C … 180 °C	1	1	1

Brief discussion

The result of visual inspection shows that heating of samples at 220 ℃ resulted in burning of samples (Refer appendix figure D1). In this case, only the lubricant E retained its original condition (shown in figure D2), whereas all the rest of the samples were carbonised and converted in to a dry polymer. The excellent performance of the lubricant E is attributed to its synthetic base oil (material ‘f’), which is more thermally stable than the hydrocarbons used in other samples.

At the temperature level of 150 ℃; which was at the maximum temperature limit for the Lubricant C, Lubricant D and Lubricant A; and higher than the maximum temperature limit of the Lubricant B, and below the maximum temperature limit of the Lubricant E after the test, only the Lubricant E was remained in its original condition, shown in figure D2, whereas all the rest of the samples were carbonised and converted in to dry polymer.

Visual inspection of samples heated up to 110 ℃ shows no traces of carbonization. All of the samples remained in their original condition except the Lubricant C, which converted to a dry hard layer (shown in figure D3).

In the ambient temperature-rise test, the Lubricant E has performed well in all the test conditions compared to other samples. It remained in its original condition during all the tests. This difference of its performance is because of its base oil, material ‘f’, whereas in the rest of samples it is based on hydrocarbon oil. Besides, there are other factors which affects its thermal and oxidative stability, but it requires a detailed explanation of its chemical composition which is beyond the scope of this thesis.

6.3.2 Electrical endurance test

In this test, the thermal stability of the lubricant samples during operational performance was tested. The test determines the effect of current flow, applied voltage, mechanical stress due to the switch opening and closing and arcing impacts on lubricant samples. In figure D4 and figure D5, the value of the contact resistance as function of the switch operations for the terminal ‘L2’, for OT1600 and OT400, are shown. L2 is selected for analysis because of E03 switch configuration, in which L2 bears more thermal stress compared to other terminals.

The Electrical endurance test main findings are:

a) In case of OT400, contact resistance with the Lubricant E sample shows comparatively stable behaviour (shown in figure D4). This behaviour is comparable to the values of the same switch with no-grease conditions which offers the lowest contact resistance values up to 1000 operations (shown in figure D4). The stable trend of the Lubricant E is attributed to the material ‘f’ used as a base oil, which is wear resistant and possess better thermal stability.

b) In OT1600, the Lubricant E has shown comparatively more stable values of the contact resistance amongst all other samples. At new conditions, its resistance is high due to the material ‘t’ thickener used as its base oil, which later becomes comparatively stable. In addition, due to the high contact force of OT1600, the trend of the contact resistance values is more stable than OT400.

Brief discussion

In case of synthetic hydrocarbon based lubricant, the value of contact resistance as a function of the switch operations is increased from its initial value up to a high value and then it has started to decrease. The peak value of the contact resistance is because of the layer of burnt lubricant on the contact's surfaces, which has increased the contact resistance value. As it get removed with further switch operations, the value of the contact resistance decreases.

In case of the material 'f' based lubricant, the presence of the material 't' as a thickener has provided a good wear resistance. In addition, in case of high temperature rise PFPE has evaporated without leaving behind any insulating films, therefore no high peak in the contact resistance curve is seen. The presence of the material 't' as a thickener in the lubricant has caused relatively a high value of contact resistance at the new condition.

The value of the contact resistance in the OT1600 is affected by a high contact force and operating torque when compared to OT400. Therefore, the value of the contact resistance of the lubricant samples are more stable. Nevertheless, the Lubricant A has still shown an unstable behaviour of the contact resistance value.

The condition of the lubricant samples after the electrical endurance test was checked by a visual inspection. All the lubricant samples, in the both OT400 and OT1600 switches, were carbonised. Even the Lubricant E could not retain its thermal stability.

6.3.3 Recommendations

- Further testing of more the material 'f' based samples (without solid lubricants) having high maximum thermal limit could provide better results.

6.4 Silver Iodide test

In this test, silver iodide is tested as a plating solution for the contacts, explained in the chapter 5. The test results are presented in *Appendix E*. No grease was used in this test.

6.4.1 Analysis of Contact resistance with Silver-Iodide plating

a) At 690 V, the results of the contact resistance for AgI-plated sample shows high values at new conditions, which then decreases and becomes stable at higher operations (figure E1). Whereas, in case of the standard (only silver) sample, contact resistance value at the new conditions is lower than AgI-plated samples.

However, the value resistance for the standard sample gradually increases at higher number of operations, which remained fairly stable and low in the AgI-plated sample. So, for larger number of operations AgI-plated contacts has offered a more favourable output.

b) In case of the standard switch sample at 400 V, the high value of the contact resistance is because of the burnt lubricant on the contact surface. The comparison of the AgI-plated switch sample with the standard sample at 400V has shown that the temperature rise values in the both samples are approximately equal at 1000 operations.

Brief discussion

The reason of the low and stable value of the contact resistance in the AgI-plated sample is because of the availability of silver on the contact surface. Whereas, in case of the standard switch sample at 690 V, copper is exposed and forms corrosive layers, therefore the contact resistance values are un-stable and high. In case of the standard switch sample at 400 V, the high value of the contact resistance is because of the burnt lubricant on the contact surface despite silver presence. The burnt lubricant has covered the contact surface and, therefore high resistance of the contact resistance was recorded.

6.4.2 Analysis of Temperature Rise for Silver-Iodide plating

a) The comparison of the AgI-plated sample at 690V with standard sample at 400V shows approximately equal temperature rise at 200, 500 and 1000 operations.

b) The comparison of the AgI-plated and standard sample at 690V has shown the effect of AgI plating on the temperature rise more clearly. Temperature rise value of the AgI-plated sample at the 1000 operations is low and stable, whereas its value in the standard samples become high and unstable with switch operations.

Brief discussion

The difference between the contact resistance values at the new condition of the AgI-plated contacts compared to the standard sample is high because of the resistivity of AgI plating. This is, according to results shown in figure 4.12. After the switch operations have removed of this layer and exposed of silver has caused a low and stable contact resistance. AgI plating acted as an additional plating layer on silver plating, therefore it has delayed the wearing of pure silver. As a further result the exposure of copper has delayed.

Upon visual inspection it was found that, in both cases as: AgI-plated at 690V and standard sample at 400V, silver was present in good condition on the contact surfaces. Both samples have silver on their contact surfaces and less contact wearing, therefore temperature rise is low. The high resistance of the standard sample is because of the exposure of copper, and therefore presence of insulating layers. Whereas in the AgI-plated sample the insulating layers are not present because of no exposure of the substrate copper and the presence of silver plating in a good condition.

The comparison of the temperature-rise values have shown the potential of the AgI plating in keeping the temperature rise low and stable by keeping the contacts' surface in a good condition.

6.4.3 Recommendations

- Use of lubricant with Ag and AgI contacts can be tested.
- AgI on both fixed and moving contacts can be tested.

7 Conclusion

“How long term thermal stability of low voltage electrical switches is affected by the contact design, surface treatment and arc interruption?”

Long term thermal stability of switches is degraded by highly resistive corrosive layers on the contacts’ surfaces. These layers, developed as a result of burnt lubricant, did not pose any challenges to the thermal stability. The corrosive layers of copper have emerged as one of the main challenge for the long-term thermal stability. These layers are developed by removal of silver from the copper surface and the presence of high temperature around the contacts. The depreciation of silver is mainly driven by the contacts making arcs. The energy released by contacts breaking arcs cause high temperature rise around the contact surfaces which causes accelerated development of corrosive layers.

So, the long-term stability of a switch can be ensured as long as the silver is present on the contact surfaces.

Some of the proposed solutions were verified in this thesis. Following are the key findings:

- Arcing plates did not show a significant effect on the arc energy. The arc energy is mainly dictated by the phase difference. The effect of the arc energy on temperature rise was more prominent when silver had worn out. At 400V and up to 1000 operations, the thermal stability of the switch is not challenged. The same effect has been observed for 690V for up to 500 operations.
- Contact design modification has decreased contact wearing. Whereas, the temperature rise values were high and irregular. This design modification did not give favorable results compared to the standard switch. The switch robustness issue could not be resolved with the modified design.
- Contact lubricant did not pose a challenge for the thermal stability of switches. The thermal stability of lubricants showed key dependency on its chemical composition. The material ‘f’ based lubricant has proven a better replacement for hydrocarbon based lubricants.
- Silver iodide plating has provided significant improvement in switch thermal stability. Silver iodide has proven a potential replacement for lubricants in the sliding

contacts. A significant decrease in contacts wearing has been found using silver iodide.

7.1 Recommendations

The following recommendations are decided for the switches based on test results can be given.

1. Replacement of the Lubricant A with thermally stable lubricant E may be recommended.
2. Modification of the contacts design to decrease wearing during switch closing and to increase switch robustness is needed.
3. Arc chamber design improvement to decreases the temperature around the contacts should be done.
4. Silver iodide has shown remarkable performance however further testing on multiple samples must be conducted to validate its performance.

7.2 Future research

Future research in following areas are recommended.

1. Contact Material: The selection of the contact material which offers the same temperature rise curve as copper but with low temperature rise value at the new condition.
2. Arc Interruption: Development of the arcing chamber which decreases the arc energy values for rated voltages of 690V and higher.
3. Contact Plating: Application of contact technologies such as Ag/GO, which offer no grease, less wear, better thermal properties, and longer life than Ag.

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