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Examination of Electric Arc Behavior in Open Air

School of Electrical Engineering

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AALTO UNIVERSITY SCHOOL OF ELECTRICAL ENGINEERING		ABSTRACT OF THE MASTER'S THESIS

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Arcing faults which endanger the personnel and equipment near to its vicinity must be controlled so that we have high power quality, more security as well as more reliability in power systems. Therefore careful study of electric arc behavior in air is needed, more specifically how different parameters which affect reignition, behave near current zero.

A lot of research has been done, finding this behavior near current zero, in order to have better understanding of when interruption is possible, but generally those were concentrated on looking, this behavior, after arc interruption.

In this thesis, a different approach has been used to find the arc behavior near current zero. Basically indirect parameters of arc model has been found out, 15 μs before current zero, which tells the conductivity decay at that instant and Mayr Arc Model has been used to find out these parameters. Dependence of breakdown voltage of air, on temperature has also been investigated and different electrode materials have been used in order to see the electrode material dependence on breakdown voltage at a specific temperature of gap space.

Keywords: Arcing faults, Arc parameters, Breakdown voltage, Temperature, Interruption, Reignition, Current zero

List of Abbreviations

E	Electric field
B	Magnetic field
atm	Atmospheric
CB	Circuit Breaker
TRV	Transient recovery voltage
RRRV	Rate of rise of recovery voltage
S	Unit of conductivity-Siemens
dg/dt	Conductivity slope
kK	1000 Kelvins
AC	Alternating Current
DC	Direct Current
dv/dx	Voltage Gradient
U_{arc}	Arc Voltage
H	Unit of Inductance-Henry
EPA	Post Arc Energy
UV	Ultra Violet Radiations
hpa	Unit of Pressure-Hectopascal
J	Current density

Preface

This Master thesis has been done, at Aalto University, School of Electrical Engineering, at Department of Electrical Engineering as a part of SGEM project.

I would like to thank my supervisor Prof. Matti Lehtonen, who gave me this wonderful subject which I find more and more interesting, deeper I went in it. I must acknowledge that I am very thankful to him for believing on my potential during all my studies at Aalto University. His way of leadership and supervision has definitely encouraged me and made me more passionate about electrical engineering field.

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Espoo, August 2012.

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Chapter 1

1 INTRODUCTION

1.1 Background

Most of the faults in power systems are temporary faults out of which arcing faults are most common. An electric arc which is nothing but an electric discharge happened when electric-field between two conductors exceeds the breakdown strength of the air or other medium in the space between electrodes, is considered a source of harmonics [19]. When a high power arc exists, the temperature near it is so high such that it is issue of danger for the personnel as well as for the equipment staying near to it. When CB opens, in order to isolate a fault no matter whether it is arcing fault or short circuit fault, an arc exist between CB electrodes. Immediately after the interruption, arc reignition can occur, thus causing failure of interruption. Therefore discontinuity of power supply is prolonged in this way. Therefore correct knowledge of microscopic processes that can initiate and extinguish an arc is of great importance for reliability and quality of power in power systems. An understanding of the interruption and re-ignition of an arc discharge has obvious significance for the design and development of a wide variety of industrial devices.

1.2 Objective of the Research

The objective of this master thesis was to look closely on the behavior of electric arc in open air, such that to have better understanding that when interruption of AC electric arc can occur and what are the major factors that hinders the recovery of air space between the electrodes after the interruption. Electric arc conductivity decay near current zero is an important parameter in deciding arc interruption and reignition, as AC current interruption is generally achieved at current zero. Therefore arc conductivity decay near current zero was our first area to investigate; as more arc conductivity mean less probability of interruption. The second area of investigation of this master thesis research was to find out how the temperature effects the breakdown voltage of air space in the gap, such that we have better understanding of the breakdown voltage dependence of air on temperature.

1.3 Outline of the Thesis

This research work consists of six chapters as follows:

Chapter 2, gives an overview of the arc, its properties and related factors needed to understand the further discussion in following chapters. It gives the detail knowledge of phases of arcs.

Chapter 3, explains what are the factors that affect the recovery of breakdown strength after the interruption.

Chapter 4, describes the recovery dependence of gap space on temperature. It describes the arc parameters.

Chapter 5, describes the experimental methods used, their results together with the discussion as well as the comparison of the results that we obtained from the experiments, with research work of others.

Chapter 6, describes conclusion of this research work and future work, after which appendix showing MATLAB codes as well as measured readings, has been attached.

Chapter 2

2 OVERVIEW OF ELECTRIC ARC AND RELATED FACTORS

2.1 Different types of electrode

2.1.1 Refractory electrodes

A refractory electrodes, are also called hot electrodes has ability to sustain a strong thermionic emission which is emission of electrons when material is heated, without strong melting or vaporization (e.g. Tungsten). Hot cathode discharge is discharge in which thermionic emission is the main.

2.1.2 Non-Refractory electrodes

Non-refractory electrodes, are also called cold cathodes and there is very little thermionic emission in cold electrode when heated. When they are heated to a temperature to cause thermionic ionization, they start to evaporate (e.g. Copper, Silver). Cold cathode discharge is a discharge which is aided by secondary ionization.

Thermionic emission in cold cathode is not zero but is finite. This is shown in Figure 1 below.

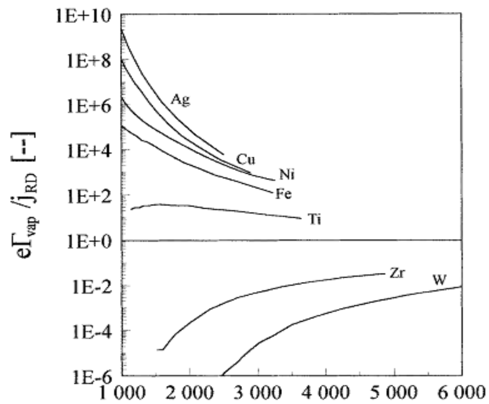

Fig 1: Ratio of flux of vaporized atoms to flux of thermionic electrons [1]

From Fig. 1 we can notice that as the temperature increases, ratio of vaporized atom to thermionic electrons of cold electrode decreases, while it increases for hot electrodes.

Non refractory electrodes show a very rapid (in micro seconds) dielectric recovery at current zero, but only to a level of a few hundred volts [p. 23-24, 8]. The recovery of electric strength is due to the relatively cold surface of the electrode, cooling a very thin layer of plasma adjacent to it from, temperature of many thousands of degree [8], where the plasma is a good conductor, to a few thousands degree only where it forms an insulating layer. Arc chute circuit breaker that uses metal arc splitter plates operates wholly on this concept.

2.2 Arc phenomenon in circuit breaker

In High Voltage circuit breakers the current interruption takes place near current zero as due to following reasons:

1. The voltage across arc and arc current are in phase, hence, arc is pure resistive. Near current zero, voltage is also minimum hence the arc energy is minimal and hence current conduction decreases.

2. Ions/electrons available for conduction in the medium are also minimum at that instant, as during current zero, temperature in the gap has also decreased due to losses, greater than energy input.

When a high current fault occurs and circuit breaker is tripped in order to interrupt it, breaker contacts move apart and the contact area decreases rapidly until finally the contacts are physically separated. When the contact area decreases to a very small spot, the contact resistance increases considerably while the flowing current becomes highly concentrated which consists of a core of extremely hot gas with a temperature of 5,000 to 20,000 K [p.16, 2]. Radial temperature distribution of an 80A arc is shown in different gases, in Fig. 2.

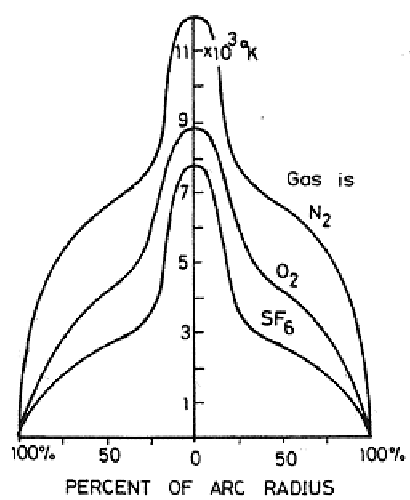

Figure 2: Temperature distribution of 80 A arcs [3]

This column of gas is fully ionized (plasma) and has a large electrical conductivity. When the current approaches zero, the arc diameter will decrease with the cross section approximately proportional to the current.

In the vicinity of zero passage of current, the gas is cooled down to around 2,000 K and if this temperature is less than ionization temperature of the medium between the gap, ionization will ceases. [2, p.16]

However ideally speaking an “ideal” AC circuit breaker would be able to open its contacts precisely at current zero crossing and there is no arcing. But in real situation, two reasons explaining the existences of electrical arc are following:

1. It is practically impossible to separate the contacts exactly at the natural zero current point due to the uncertainty in the measurement-order.
2. The reason why we are not able to have high insulation at current zero, is due to we have limited mechanical energy which opens the contact. This limited energy causes the existence of the arc. For instance, if the contacts start to open exactly at zero crossing, they require finite time (in few milliseconds) to fully open and during this time (start of opening and fully opening) an arc exists between the contacts. So instead opening of contacts exactly at current zero which can rather cause an arc to exists for next 10 ms, the best way is CB opens before current zero and as current approaches zero, gap conductance decreases and there is more probability for the arc to extinguish at first zero crossing.
3.

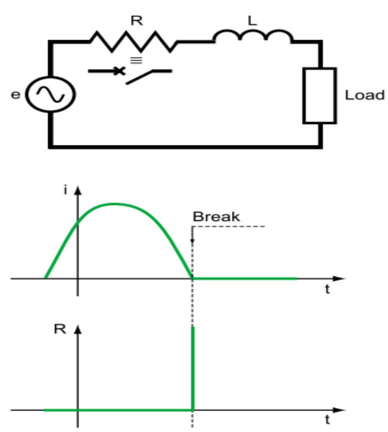

Figure 3: Demonstration of Ideal circuit breaker [p.6, 4]

The electrical arcing breaking process in CB takes place in three phases [p.7, 4] :

1. arc propagation phase,
2. the arc extinction phase,
3. the post arcing phase

1. Arc propagation phase

As generally the CB contacts, separate before current zero, however feeding of energy causes current continue to flow and hence this causes an arc to exist which is made up of a plasma column composed of ions and electrons (see Fig. 4). This column remains conductive as long as its temperature is maintained at a sufficiently high level. The arc is thereby “sustained” by the energy that it dissipates by the Joule effect. There is voltage drop near the electrodes called cathodic and anodic voltage and voltage drop in arc column. The sum of all these voltage drops is called the arcing voltage. Its value, which depends on the nature of the arc, is influenced by the intensity of the current and by the heat exchange with the medium (walls, materials, etc.).

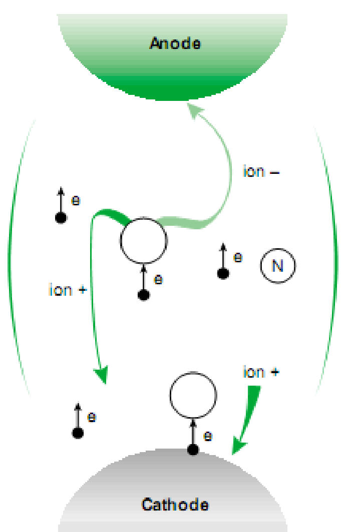

Figure 4: Electrical arcing in gaseous medium [p. 6, 4]

2. Arc extinction phase

The extinction process is accomplished in the following manner: near zero current, resistance to the arc increases according to a curve which mainly depends on the de-ionization time constant in the inter-contact medium (means how fast the deionization of the space takes place as the current approaches zero) (see fig. 5).

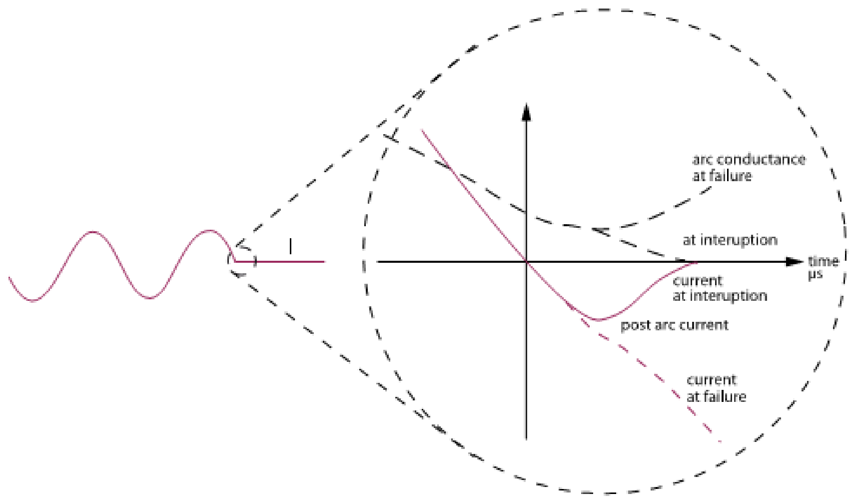

Figure 5: Change in arc resistance [p. 18, 2]

At zero current, this resistance has a value which is not infinite and therefore space has conductance (space is ionized, however no net movement of particles) but as the voltage across the gap start to appear electrons and ions are accelerated to the opposite polarities and hence this causes a post-arcing current across the terminals.

3. Post-arcing phase

This post arcing current can cause thermal reignition if its rate of rise is high enough after current zero (which is case for refractory electrodes) so that the voltage (which start to appear across the gap) and this post arc current, provide that much power which is greater than the power loss due to recombination as well as due to diffusion. However if after a while this post arc current ceases due to recombination or due to diffusion there is another period after which the rate of rise of voltage causes electric breakdown of the gap.

2.3 Regions in the arc

Arc is composed of three principle regions: the cathode region, the anode region and the arc column, no matter what the total arc length is. Through all these regions current is carried by electrons and ions. In a steady arc, a balance is made between power input and losses. Arc become unstable when there is disturbance in this balance [p. 186, 5].

2.3.1 Arc column

The arc column is a region in which ionized gas gives almost exact equalities of positive and negative charge densities, and are comparable to that of neutral gas molecules so that very low axial electric field exist in that region [5]. Heat produced by the I^2R losses in the arc column maintains the ionization and flows axially towards the electrodes and radially outwards from the arc. The ionization in the arc column is maintained by the energy dissipated in the arc. A steady arc adjusts its temperature and diameter such that power loss from arc is minimum. The extreme temperature and high conductivities are confined to the core of the arc column. Both these quantities decreases sharply at some radius beyond which there is no current conduction to speak of.

2.3.2 Cathode region

Cathode region is a region adjacent to the cathode. In the arc the current is carried partly by positive ions drifting slowly to the cathode from the plasma of arc column. In the space between the surface of the cathode spot (a very small point like object where from electrons leaves from surface of the cathode) and the cloud of positive ions there is a high electric field. This region is called cathode region. Therefore a significant cathode voltage drops builds up over the cathode region. The width of the region depends on the arc current, the medium in which it is burning and the cathode material.

2.3.3 Anode region

As like cathode region, anode region is a region adjacent to the anode, where due to cloud of electrons there exists an electric field, hence the voltage drop. For long arc gaps (gap distance more than fraction of inch), all the voltage appear across arc column (shown in Figure 9) however voltage gradient dv/dr near the anode and cathode is higher than in the column. The voltage distribution for long arc gap is shown in Figure 6 below:

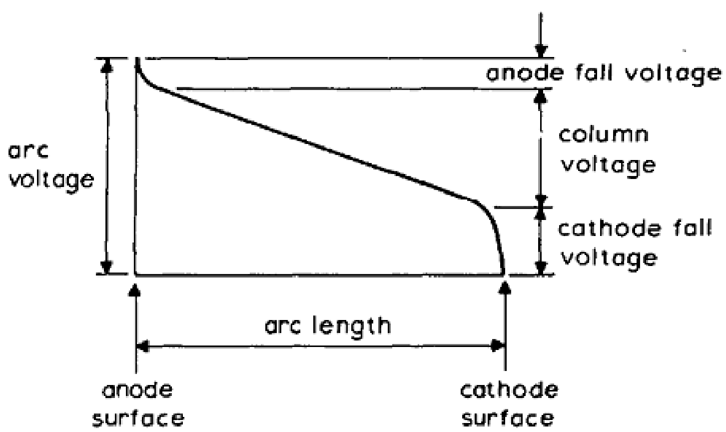

Figure 6: Axial voltage distribution of an long arc [p. 1132,6]

As we know that near anode and cathode there is quite high voltage gradient. This voltage gradient causes the charge particles to accelerate with a high speed, therefore due to this high acceleration the jet is quite straight and due to low voltage gradient in arc column the charge travelling path is not that straight but rather diffuse. The energy of the unit length of the arc jet is larger than that of the arc column. [p. 793, 7]

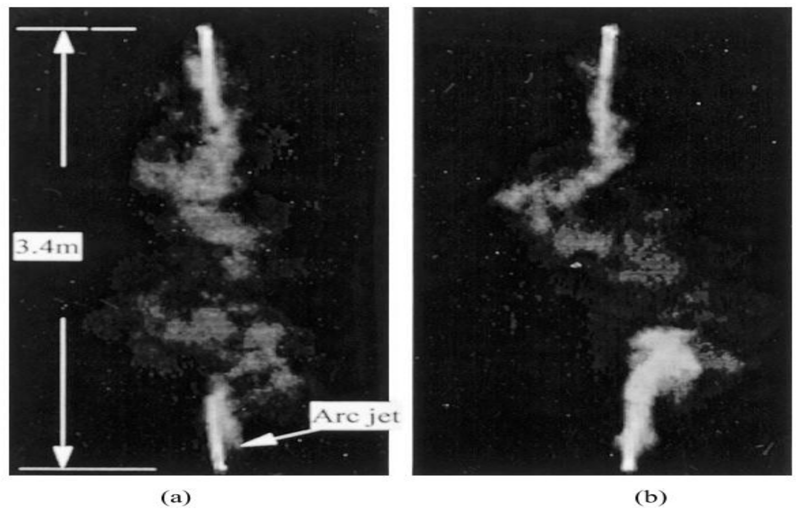

Figure 7: Long arc with electrode separation distance of 3.4m [p. 792, 7]

The Figure 7 shows that, the arc jet (which is caused by pressure gradient) is quite straight near at both anode and cathode however the arc column just follows diffuse path or meanders.

It has been found out [36] that the cathode or anode voltage drop is affected by the electrode material however this anodic or cathodic voltage drop of the SF_6, Argon and Air arcs, is independent of the current in the range of 10 to 20 000 A.

It should also be noted that the recovery and reignition of the electrode regions and arc column proceed simultaneously and interactively, the physical processes within these separate regions and within the transition zones between the regions being different.

The small temperature difference between electrode and plasma causes relatively weak cooling of the post-arc channel at the cathode [22]. This means that larger the temperature difference between electrode and plasma, larger will be the cooling of post-arc channel at cathode.

2.4 Ionization and Recombination

2.4.1 Thermal ionization

Thermal ionization occurs when a mass of gas is heated to such content that is sufficient for the random thermal velocities of the particles to cause ionization. The degree of ionization depends on pressure, the temperature and the ionization potential of the gas.

2.4.2 Ionization by collision

Ionization by collision is the ionization occurring in a gas by electrons that are directly accelerated by high electric gradients in the arc.

2.4.3 Recombination

When positively and negatively charged particles exist in a gas, there is a rate of recombination means pairs of oppositely charged particles recombine to form neutral particles. The recombination occurs more rapidly at low temperatures, where particles have lower velocities, than at high temperature because for recombination to occur the particles must remain close enough to one another for a sufficient time for recombination to occur [p.29, 8].

In circuit breaker arcs, two major ionization processes are of interest. During the conduction period, ionization is almost wholly thermal ionization means temperature of the gas is that much high that causes the detachment of electrons from the neutral particles. During very near current zero period, ionization by field emission can occur [p. 26, 8].

2.5 Breakdown regimes after arc current interruption

2.5.1 Thermal regime

The thermal regime occurs if rate of decrease of the current to be interrupted (di/dt, before current zero) and the initial rate of rise of the transient recovery voltage (dv/dt, immediately after current zero), provide enough power so that reignition occurs.

At current zero, electrical conductivity of the space in the gap is not zero, because, ions and electrons takes some time to disappear as a process of recombination or other power losses effect. With the rising recovery voltage, these ions and electrons accelerates to opposite electrodes hence it gives rise to what is called a "post-arc current, with amplitude up to a few Amperes. Whether or not interruption is going to be successful is determined by a race between the cooling effect of the space between gap and the energy input in the arc path by the transient recovery voltage and post arc current. When the scales of the energy balance tip in favor of the energy input the circuit breaker will fail thermally [p. 17, 2].

The thermal interruption regime for SF6 circuit breakers corresponds to the period of time starting some µs before current zero, until extinguishing of the post arc current, a few µs after current zero. [p. 17, 2]

2.5.2 Dielectric or spark breakdown regime

When the circuit breaker has successfully passed the thermal regime (means a few microseconds after post arc current), the transient recovery voltage (TRV) between the contacts rises rapidly (this transient rise depend on the circuit parameters across both ends) and will reach a high value. For example, in a single unit 245 KV circuit breaker, the contact gap may be stressed by 400 KV or more, 70 to 200 µs after the current zero [p. 18, 2].

In the dielectric regime the space between the gap, is no longer electrically conducting, but it still has a much higher temperature than the ambient. This reduces the voltage withstand capacity of the contact gap. The stress on the circuit breaker depends on the rate of rise and the amplitude of the TRV.

The withstand capability of the contact gap must always be higher than the transient recovery voltage otherwise a dielectric re-ignition will occur (dielectric failure). This requires an extremely high dielectric withstand capability of the gas, which is still rather hot and therefore has low density.

It has long been known that interrupted arcs between non-refractory electrodes (e.g., Cu, Ag) can be reignited only by the reapplication of a voltage in excess of the minimum spark breakdown value and that most of this appears across the cathode region of the discharge.

Refractory electrode regions however can have significant electrical conductance for appreciable times after interruption, so that, for example, continuity of current flow may be maintained through an AC current zero without the appearance of high-voltage transients. [23]

For the successful interruption two physical requirements (regimes) are involved:

- **Thermal regime:** The hot arc channel has to be cooled down to a temperature low enough that it ceases to be electrically conducting.
- **Dielectric regime:** After the arc extinction, the insulating medium between the contacts must withstand the rapidly increasing recovery voltage. This recovery voltage has a transient component (transient recovery voltage, TRV) caused by the system when current is interrupted.

If either of these two requirements is not met, the current will continue to flow for another half cycle, until the next current zero is reached.

Different techniques are used to extinguish the arc including:

- Division into partial arcs: As we know more the contact area of the electrode used more it has effect in cooling the arc next to it.
- Connecting capacitors in parallel with contacts: By doing this we decrease RRRV and hence energy input to the arc is less.
- Lengthening of the arc: By this we increase resistance to the arc current and area of cross section of arc decreases.
- Intensive cooling: By this we increase rate of recombination of ions and electrons, as by cooling the K.E of ions and electrons decreases which results in high rate of recombination.

2.6 Arc sectional area

Experiments show that the sectional area and the density of ions in the arc stream increases with current [p.422, 9].In ac arcs, **arc section** is not that which corresponds to the current flowing at the moment, but depends on the current which has been flowing previously. If the current previously has been larger, then the section will be larger than that corresponding to the momentary current [p.425, 9]. The reason for this, is that the ions of heavy weight will not have time to disappear instantaneously.

2.7 Interruption in DC and AC current

For direct current interruption, if there is direct current arc then resistance of the arc must be increased rapidly enough to force the current down to zero in a reasonably short time but not so rapidly that high over voltages are generated in the inductance of the circuit.[p.20, 8]

For ac arcs, there are two current zero every cycle, hence due to its nature, the current is decreasing naturally and resistance start to increase as current approaches zero due to natural deionization but more deionization can be achieved artificially which help the interruption.

If the arc current is very low, and arc becomes unstable (this instability is due to increase in losses of the arc than the input energy), as current approaches to zero, then due to this instability current can suddenly go to zero before its natural current zero. This is called current chopping. More little chopping of current near current zero, less over voltages are generated in the inductance of the circuit and hence across the gap which can be seen in Fig.8.

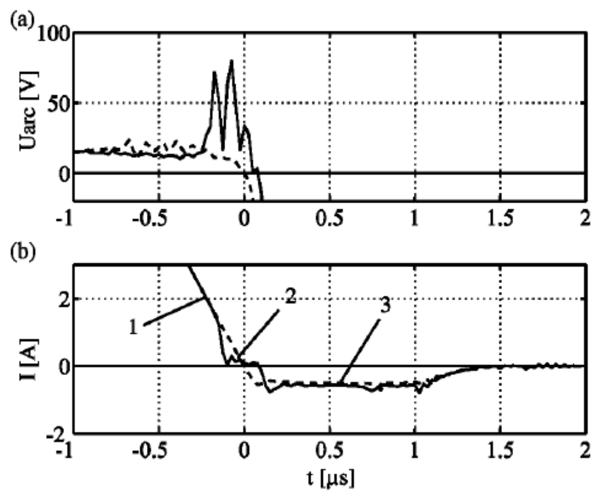

Fig.8. (a) Arc voltage and (b) post-arc current after a smooth current decline (dashed lines) and after a current chop (solid line). In both measurements, a peak-arc current of 39 kA and an arcing time of 3.4ms were used. [p.1590, 10]

2.8 Magnetic phenomena in arcs

The axial current flow in an arc sets up a circumferential field as shown in Figure 12.

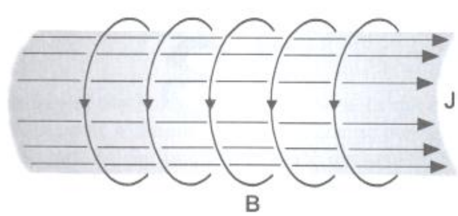

Figure 9: Self circumferential field set by arc current [p.326, 11]

This circumferential field interacting with the axial current sets up a pressure acting radially inwards.

If the cross section of arc changes along the length of the arc, current density changes and therefore pressure at the axis changes, and an axial pressure gradient exists. This situation occurs at the electrodes of arcs, where current densities are commonly higher than in the arc column due to high dv/dr (as cathodic and region has high dv/dr, which casues the current to be rather straight that arc coloumn and J=I/A, is higher). A high pressure thus exists in front of the electrode and this high pressure can set up a jet of plasma moving away from the electrode at velocities up to 10^5 cm/s [p. 32, 8].

Consider an infinite cylindrical column of conducting fluid with an axial current density J and a resulting azimuthal magnetic induction B. The force acting on the plasma, forces the column to contract radially. This radial constriction of the plasma column is known as the pinch effect.

As the plasma is compressed radially, the plasma numbers density and the temperature increases. The plasma kinetic pressure counteracts to hinder the constriction of the plasma column, whereas the magnetic force acts to confine the plasma. When these counteracting forces are balanced, a steady state condition results in which the plasma is mainly confined within a certain radius R, which remains constant in time. This situation is commonly referred to as the equilibrium pinch. When the self-magnetic pressure exceeds the plasma kinetic pressure, the column radius changes with time, resulting in a situation known as the dynamic pinch. [p. 325, 11]

Chapter 3

3 ARC IN OPEN AIR

3.1 Arc recovery

3.1.1 Effect of uniform and non-uniform field

Previous work has shown that faster dielectric recovery is obtained in uniform than in non-uniform field conditions [13]. This has been shown to be partly due to two effects each causing a lower breakdown voltage in the non-uniform field situation. One of these is that the process of photo detachment is more efficient in non-uniform field configuration in providing the space charge field enhancement required to promote breakdown at lower E values. The other is associated with the fact that E is higher at the electrodes(due to more dv/dx (cathode or anode voltage drop); at the electrode regions) than at mid gap in the more non-uniform field case, so that electrons coming from cathode region will have higher energies than those corresponding to average electric field. This results in increased ionization efficiency at mid-gap and consequently lower breakdown voltage in the non-uniform field case which cause a longer recovery time to a given voltage level.

3.1.2 Erosion rate

The increase erosion rate of a material electrode at after crossing a certain current limit before which erosion is not that significant, causes the roughening of the electrode surface and a lower breakdown voltage as a result of increased field non-uniformity[13].

3.1.3 Electrode material

The dielectric recovery after the arc extinction is influenced by the material of the electrode as well as the shape of the electrodes. The experiments[12] shows that recovery is faster with Ag-CdO contacts than with any other material tested, with flat contacts than with those having high point at the contact center, with cone shaped rather than butt contacts.

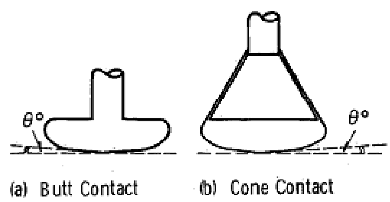

Figure 10: Geometry of cone and butt shaped contacts [12]

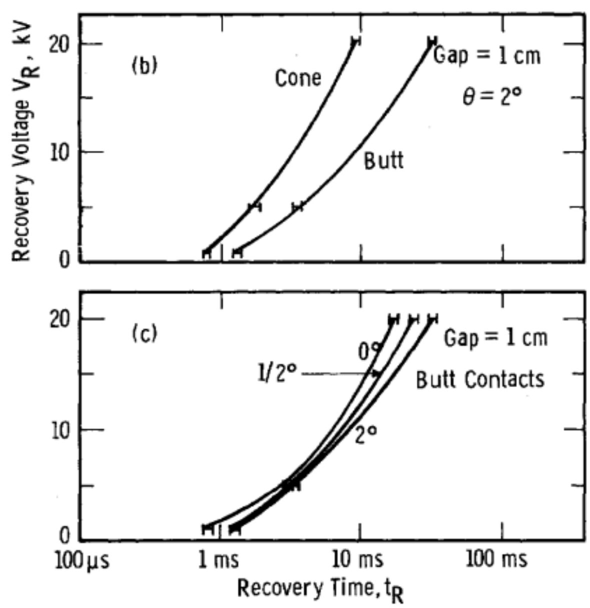

Figure 11: Recovery characteristics for 2.4 cm diameter Ag-CdO contacts in air at atm pressure following 1000A arc, where upper diagram shows the effect of contact shape on recovery and lower diagram shows the effect of contact surface angle on recovery [12]

We can see from the above figure that after 1000A arc interruption, the voltage across the gap builds slowly (time of arc extinction to the extent to which voltage has recovered is called recovery time). This is due to the fact that the conductance of the gap after current zero takes finite time to be zero. Hence conductivity time constant is an important parameter to describe the recovery of the gap space.

The following diagram is for cone shaped contacts with $\Theta = 2^{o}$ showing effect of different materials on recovery time.

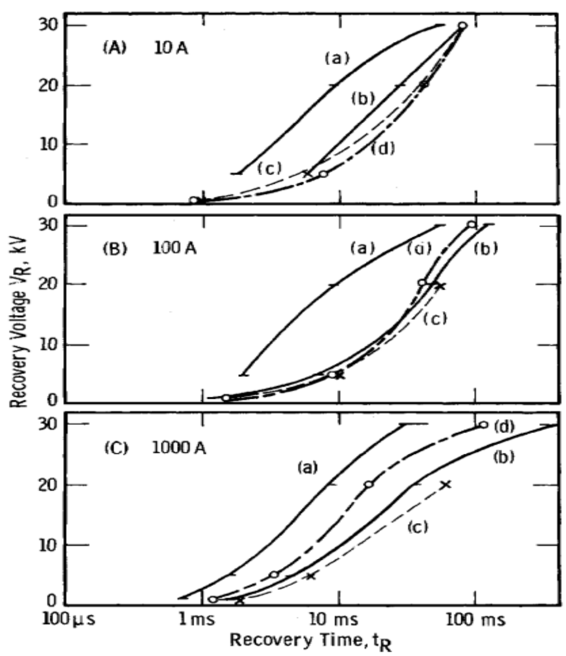

Figure 12: Recovery characteristics for 2.4 cm diameter contacts in air at atm pressure for different contact materials (a) Ag-CdO; (b) Ag-W; (c) Cu; (d) Ag [12]

3.1.4 Prior arcing

Fluctuations in recovery time to a given recovery voltage, depend on interval of applied voltage. Fluctuations with the smaller (2 mm) gap are primarily the result of electrode effects, whereas those with the larger (1 cm) gap are primarily related to effects in the gas [p.286, 12].

3.1.5 Electrode effects

With no prior discharges between the contacts, the gap required a large voltage, to breakdown the gap space. If applied at an interval again and again, the breakdown voltage gets lower than for first breakdown voltage.

The reason for this is when there is not prior arcing has occurred; the presence of an absorbed cathode layer has reduced the secondary ionization coefficient gamma of the gas and hence has increased the breakdown voltage [12]. Immediately after arcing, which tends to remove the oxide layer, a transient gamma increase can cause a reduction in breakdown voltage. Even when the oxide layer reforms after arcing, residual positive charges resting on the oxide layer or on dust particles deposited on the surface can cause an effective reduction in surface work function, with consequent gamma increase and breakdown voltage decrease.

3.1.6 Gas Effects

In addition to the electrode effects, however, gas effects can cause variations in breakdown voltage. It is known, for example, that electrical discharges in air result in the formation of various impurity products due to chemical activity in the cooling gas following the dissociation of 0_2 and N_2; in particular, NO_2, NO, N_20, and 0_3 are formed [12], and the latter two have very high electron attachment cross-sections at electron energies occurring at breakdown in air at atmospheric pressure. These products can cause a factor of 10 increase in the average electron-attachment coefficient, [15] resulting in an impulse breakdown voltage increase of up to 40%. It has been found that the increase in impurity concentration, and the resultant increase in breakdown voltage are greater following higher energy input to the gap, [16] means flowing higher arcing current.

The faster recovery observed with flat contacts compared with those having high contact surface angles is due to more uniform field configuration. [12]

Gas density reduction, due to preceding arcing, result in lower breakdown voltage. Increased secondary ionization coefficient gamma due to deposition of charge onto the contact surface result in lower breakdown voltage. [12]

3.1.7 Deion circuit breaker

It is evident that it is the slow rate of recombination of the ions in the arc space away from the electrodes which limits the applicability of the arc in air for interrupting high voltages. A fairly obvious suggestion would be to reduce as far as possible the arc space remote from a cathode and so far as possible causes all the arc to play in space close to a cathode, in other words to use a large number of short arcs in series. This is what is done in the Deion circuit breakers.

3.2 Circuit parameters and device to limit reignition

3.2.1 Circuit parameters

The arrangement of circuit parameters such as inductor and capacitor does effect the rate of rise of recover voltage and hence in turn affect the reignition phenomenon.

It has been concluded by [23], that the more the capacitance across the CB, the less the rate of rise of recovery voltage as shown in Fig. 13, and smaller the series inductance, smaller the rate of rise of recovery voltage as shown in Fig. 14.

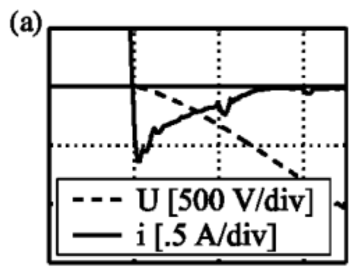

Figure 13: Measurement a.) with 10nF capacitor b.) with 1nF capacitor across CB [22]

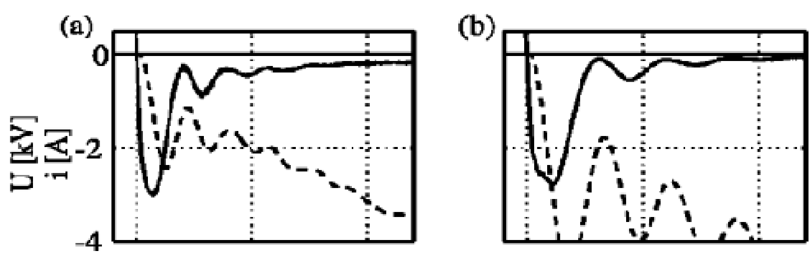

Figure 14: Measurement with series inductor a.) of 105 μH b.) of 225 μH [22]

3.2.2 Zinc Oxide device

Due to the high financial outlay costs involved, the power utilities have sought an alternative to reduce TRV peak. Zinc Oxide (ZnO) devices are being applied as an alternative to limit TRV peaks in circuit breakers and reclosers of 15 kV and 72.5 kV voltage class.

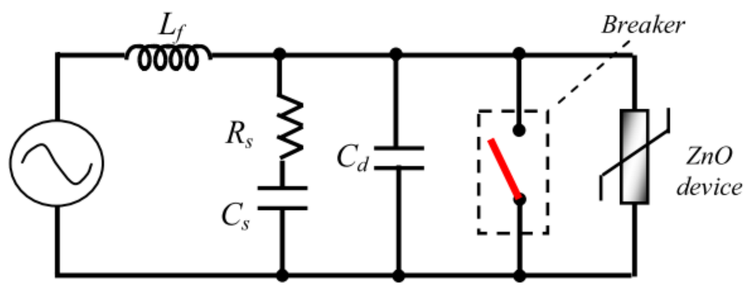

Figure 15: Schematic of circuit with ZnO device in parallel with the Breaker [24]

Taking into account Fig. 15, Capacitor C_s take care the magnitude and frequency of TRV. R_s adjust the attenuation level while C_d is related to the initial rate of rise of TRV.

3.3 Difference between Short Arcs and Long Arcs

3.3.1 Short arcs

Short arcs are the arcs which happen in a gap of distance fraction of an inch [p. 422, 9] preferably less than 10mm electrode gap. As we know the space next to cathode, deionized very quickly and have the capability to withstand few hundred of volts immediately after arc extinction. The space next to cathode layer deionizes rather slowly [p. 422, 9]. Hence after few hundred volts the recovery which is done by the space next to layer is rather slow. As deionization by the space next to cathode happens, the cathode layer becomes widened.

Hence a arc is short if it extinguish in a circuit which impresses less than a few hundred volts upon it, then use is made of recovered dielectric strength of cathode layer, and the arc is to be regarded as short. If however, the arc extinguish in a circuit which impresses more than a few hundred volts upon it, then use is made of recovered dielectric strength away from the cathode layer, and the arc is to be regarded as long.

Hence long arc is one in which during the extinction period the larger part of the recovered dielectric strength resides in the space away from the cathode layer.

3.3.2 Long arcs

From the electrical properties of an arc under steady conditions (volt-ampere characteristics) point of view, it has been found that for long gap arcs, arc voltage is directly proportion to the length of the arc.

$$U_{arc} = BL$$

Where B is voltage gradient of the arc column and L is length of the arc. This voltage gradient is almost independent of arc current so the long high current arc voltage is determined by arc length. From range of currents of 100 A to 20 kA, the average arc voltage gradients lie between 1.2 and 1.5 kV/m [p. 1141, 17]. It should be noted that the whole voltage drop come across arc column for long arcs.

After the initiation of the arc, with very high current flowing, there is no time taken by it to breakdown the gap again as due to high currents the temperature of the plasma is so high that it requires no breakdown voltage. Hence this seems like the situation as if there is pure resistor in the circuit however this resistor seems non ideal as one sees in the Fig.16, it more or less shows a hysteresis loop, in the arc voltage and current diagram. Moreover one can see that the arc voltage is high with the same current when current is increasing than with when current is decreasing. This is because the temperature of the arc becomes higher by the accumulated energy of the arc, which increases the conductivity of the arc. Therefore the arc resistance becomes smaller.

Arc voltage characteristics for **long arcs with high current** are shown in Fig. 16.

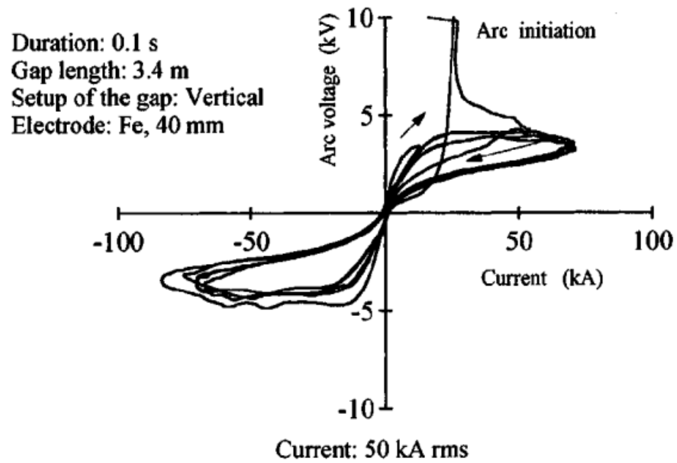

Figure 16: Arc voltage and current characteristics [p. 793, 7]

The long gap arc increases their length by the passage of the time. The elongation of the arc is determined by the magnetic forces produced by the supply current, the convection of the plasma and the surrounding air, the atmospheric effects. [17]

As due to its natural nonlinear behavior the arc is assumed as the source of harmonics which will distort the waveforms of the parameters in the component. Hence this parameter can be used as a good indicator which can distinguish the metallic faults with the arcing faults [19].

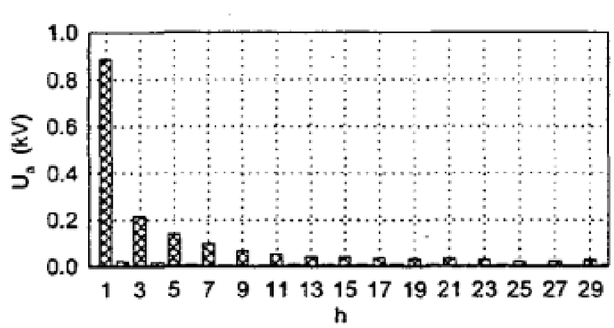

Figure 17: Arc voltage amplitude spectrum showing different harmonics[19]

Figure 17 shows the arc voltage amplitude. From the amplitude spectrum it can be observed that arc voltage total harmonic distortion is 41.1%.

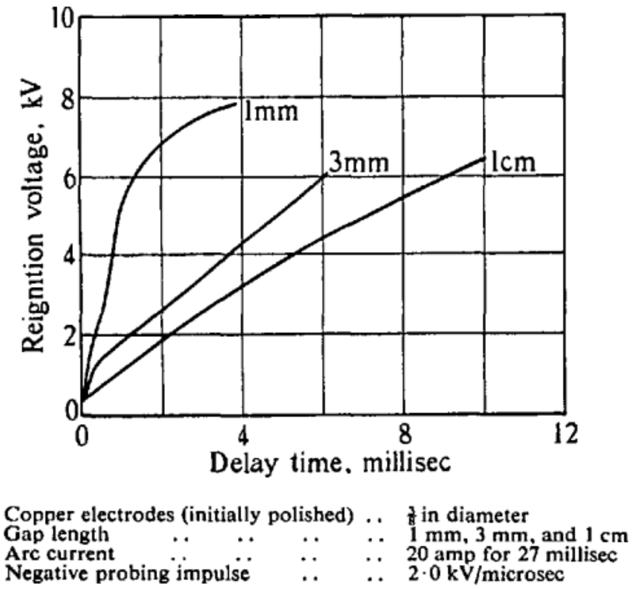

Figure 18: Reignition voltage/ time characteristics in air for various gap lengths [20]

From Fig. 18 we can notice that the small gap recover faster than that of the larger one. This is because of greater effect of electrode surface on cooling and deionizing the residual column **[20]**. So from this we can conclude that as both 1mm gap and 1cm gap, both have cathode layer which recover few hundreds of volts in equal time, the effect of electrode surface on cooling and deionizing the residual column is important (as for 1mm gap the electrode are near hence their contribution in cooling is greater). Hence shorter gaps recover faster than longer gaps [29].

The extinction of long ac arcs in the open is greatly influenced by the sectional area which the arc stream has at current zero. By confining arcs to slots and holes, the rate of deionization at current zero is greatly increased and therefore a large voltage/ cm of arc can be interrupted. [9]

Compton has shown that for the electric gradients which exist in the arc stream at atm pressure ionization by collision is entirely inadequate to supply the ions which are being lost. Also it has been found that ionization by collision is also negligible at the gradient which is impressed upon the arc space after arc extinction. Compton suggests that the high temperature in the arc stream is responsible for the ionization. [9]

In the following Fig.19, we can see few gases showing the density of ionization which is maintained entirely as a consequence of high temperature.

In Fig. 19 below is ionization dependence of different gases on temperature given by Saha's equation. We can see from these curves that appreciable ionization does not start until a specific ionization temperature of each gas. With further increase of temperature ionization increases very rapidly.

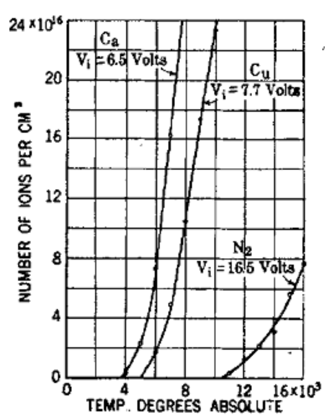

Figure 19: Thermal ionization of the gases [9]

3.4 Electric field of non-refractory cathode after current zero

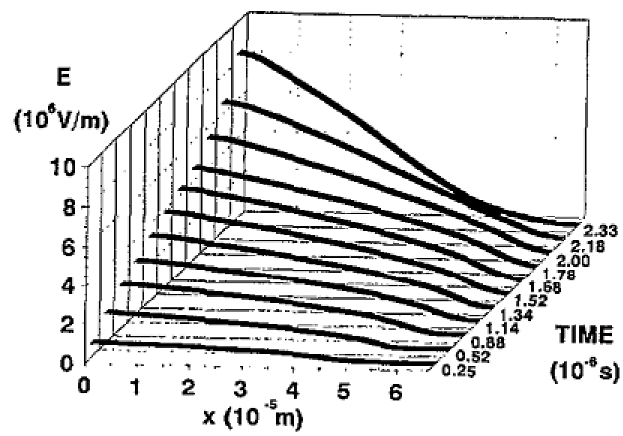

Fig. 20: Distribution of electric field along cathode layer [22]

We can see from Fig.20 that immediately after current zero the electric field in the cathode sheath grows very slowly.

3.5 Power losses from arc

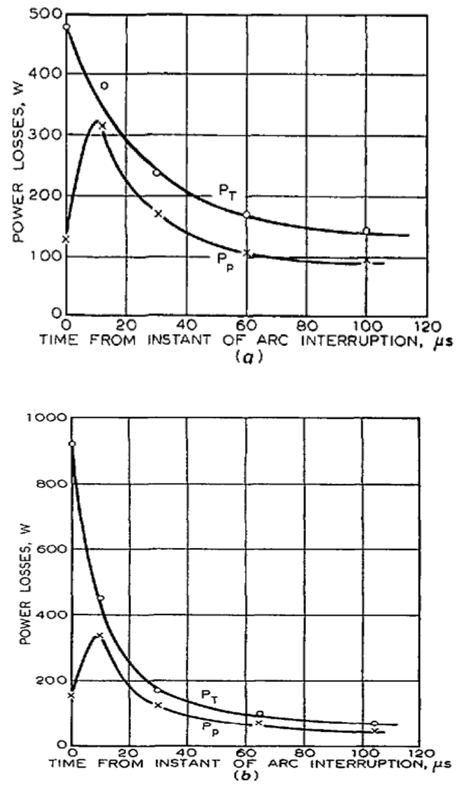

Fig. 21 : Variation of power loss after arc interruption. (a) Arc current: 10A (b) Arc current: 20A. P_T= Total arc loss; P_P= Positive coloumn loss. Carbon electrodes, 4mm diameter; gap separation 5mm

From Figure 21, we can see that higher the current interrupted higher the power losses near the interruption.

With refractory electrodes (carbon, tungsten, molybdenum) the hot electrode mass cools only slowly and a net negative space charge will be maintained by thermionic emission. Thus, for refractory arcs, reignition at the electrode is easily achieved at low voltages. For cold-cathode arcs (e.g. copper and mercury), the space charges are removed and the electrode regions can be reformed only by the application of at least the minimum sparking voltage, so that almost immediately after arc interruption (less than 1 μs) voltage recovery to about 300 volts occurs. Clearly, in the latter case, the process of thermal reignition in the gas will be masked, except for very short times after current zero, by the spark breakdown required in the electrode regions. [14]

3.6 Post arc energy

Post arc energy is an important parameter in deciding whether reignition will occur or not. If the post arc energy is less than power losses arc will extinguish and if post arc energy is greater than power losses arc will reignite.

In Fig. 22, a successful interruption is shown with its respective post arc current and post arc voltage. The calculated traces of post arc Power and post arc Energy are shown as well.

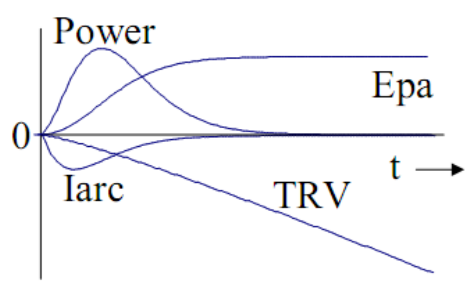

Figure 22: Post arc voltage and current and calculated quantities [26]

It has been shown [26], that effect of di/dt (rate of change of current before current zero) on post arc energy is more than that of dv/dt (rate of change of voltage after current zero); which can be seen in Fig. 23 and equation (1),but dv/dt cannot be neglected.

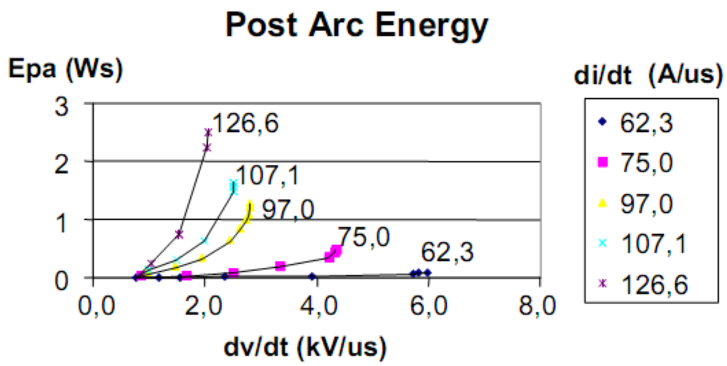

Figure 23: Variation dependence of post arc energy on di/dt and dv/dt [26]

$$\frac{\Delta Epa}{\Delta di\,/dt} = 7.9 \quad \text{and} \quad \frac{\Delta Epa}{\Delta dv\,/dt} = 3.7 \tag{1}$$

From this calculation we can see the relative influence of di/dt is about two times the relative influence of dv/dt. So this suggests that the reignition is more probable with high current slope before current zero than with low current slope before current zero. However as mentioned the effect of dv/dt cannot be neglected. A low current slope before current zero, but with a large dv/dt after current zero can also easily result in reignition.

Chapter 4

4 EFFECT OF TEMPERATURE AND ARC PARAMETERS

4.1 Effect of temperature

Figure 24, shows that the electric field intensity at the point of the cathode surface decreases with the swelling of electron emission, which can be explained by the reduction of net positive charge because of the increase in electrons.

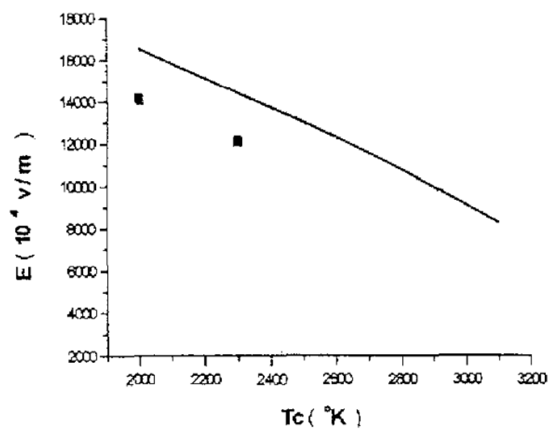

Figure 24: The relationship between the electric field intensity and the cathode temperature [25]

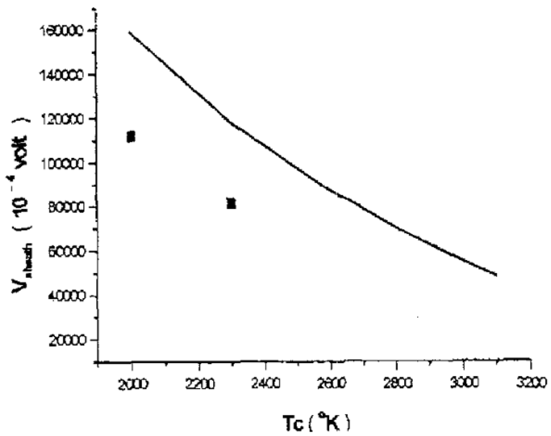

Figure 25: The relationship between potential and the cathode temperature [25]

Figure 25, shows potential drop of cathode sheath reduces with the increase in cathode temperature, which is caused by the decrease in electric field strength due to increase in electron emission due to temperature.

Figure 26, shows the length of the cathode sheath drops with the increase in cathode temperature.

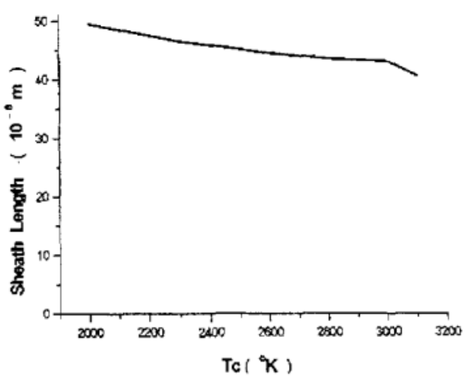

Figure 26: Relationship length of the cathode sheath and cathode temperature [25]

For an confined air, as the air temperature increases the kinetic energy of the molecule increases and this exerts pressure on wall of the confine material. Hence, pressure of the air increases as the temperature increases, keeping the volume of the container constant. For an unconfined air (which is not confined in any closed material), as the air temperature increases, the gas expands, hence volume of air increases, but pressure remains close to atmospheric pressure.

It should be noted that while happening of arc, it sends pressure waves to the surrounding [40].This pressure wave is very strong when breakdown happens and lightning is a good example of it. However due to open air configuration, for small energy arcs, the pressure remains close to atmospheric pressure.

Physical properties of the arc are greatly dependent on the temperature [29]. The dependence of various physical properties of air, on temperature is shown in Fig.27 below.

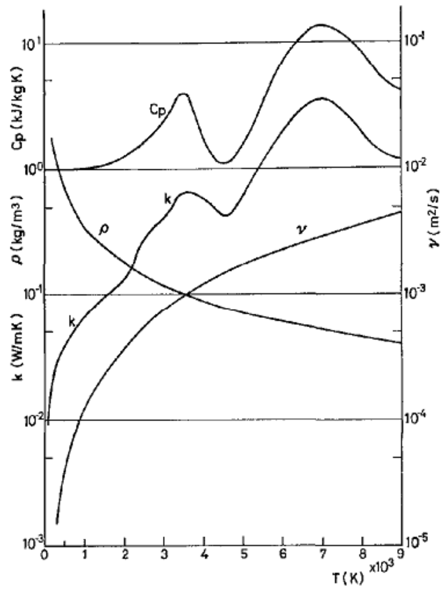

Fig. 27 : Physical properties of air as a function of temperature, all at atm pressure. K= Cofficient of thermal conduction, ρ mass density, C_P= specific heat per unit mass, ν =kinectic viscosity [29]

After arc extinction, breakdown voltage of air gaps, becomes a function of gas temperature of the gap [29][31], [32], [33] and recovery characteristics are governed almost entirely by the rate of decrease in the gas temperature, except for, in the very early stage of recovery. The voltage recovery characteristic of air gaps, i.e the temperature decay characteristic of arced gas, is dominated by the geometrical factors of the air gaps [30],[31],[33] and the physical properties of air[31],[32],[34][29].

The temperature of arced gas decays from several thousand kelvins at an early stage of recovery [31], [32] to 300K at full recovery, and the physical properties of air, change considerably with the gas temperature [29].

As was expected time constant of temperature decay is smaller for smaller gaps and larger for larger gaps [29] which strengthen the idea that electrode has important effect on cooling. It has also been found [29] greater the temperature of the arc, smaller the time constant, means arc of very high temperature tend to cool faster than arc with lower temperature. It can be seen in Fig. 28.

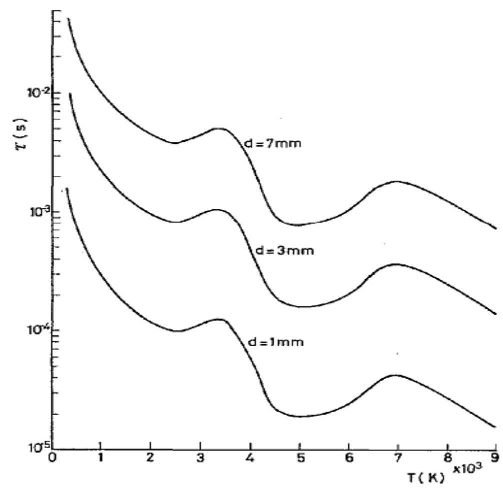

Figure 28: Time constants of the temperature decay process as a function of gas temperature [29]

The Fig. 29 shows the temperature decay of air gap, after extinction of 150 A arc across spherical electrodes with gap distance 1mm, 3mm and 7mm; derived by [29] with the help of Paschen's curve and voltage recovery characteristic of gap.

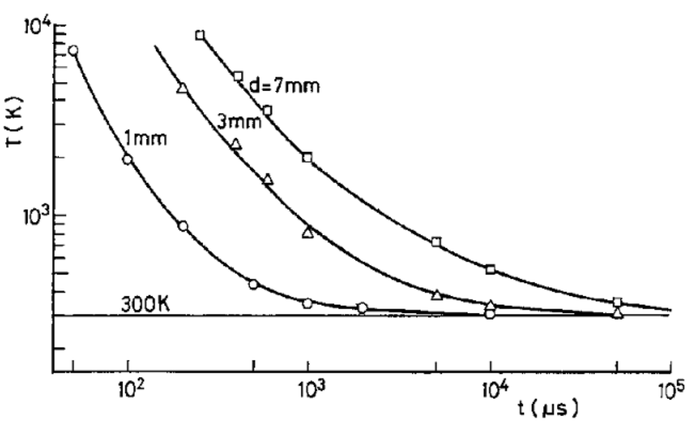

Fig. 29: Temperature decay of air after extinction of electric arc of 150A [29]

It should be noted that immediately after arc interruption, the space is fully ionised, and pashen law is not valid for ionised space [35], hence temperature decay chractertics were not found in early period after extinction of the arc.

4.2 Arc parameters

Two types of parameters can be readily used to gain insight in the processes around current zero that are very relevant in deciding arc interruption or reignition. [27]

These are called: (1) Direct parameters (2) Indirect parameters.

Direct parameters: These are the parameters that are directly available from arc current and arc voltage (for instance arc conductivity which is current/voltage). Use of these parameters gives insight into the margin of the breaker in interrupting the current, effectiveness of shunt capacitances etc.

The experiments done at KEMA laboratory [27] demonstrate that arc conductivity before current zero is an important factor in deciding interruption or reignition. It has been found [27] that if the arc conductivity 200 ns before current zero falls below 3 mS, then there will be interruption otherwise there will be reignition. Hence arc conductivity which is a direct parameter is an important parameter to consider while taking insight in to interruption process. It has also found out that [27] the conductivity limit value after which interruption is less probable, does not depend on the rating of circuit breaker shown in Fig 30.

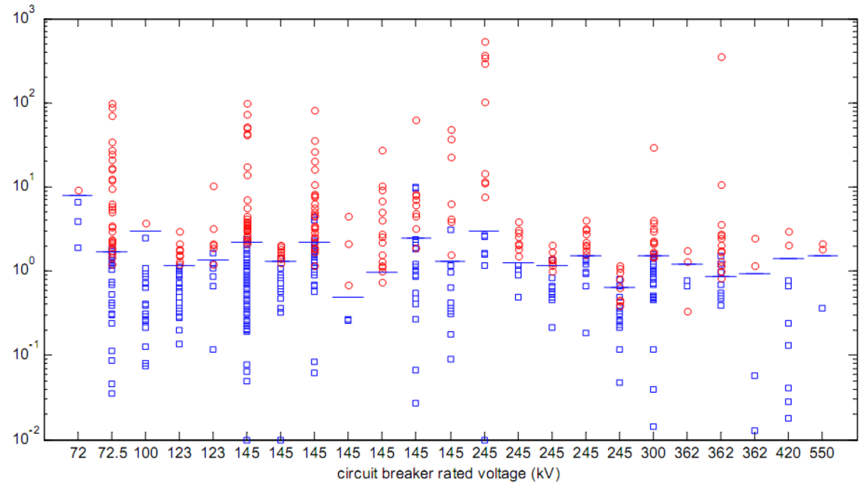

Fig. 30: Conuctivity value, 200 ns before current zero for circuit breakers of different ratings. Circles indicate observed failures, squares indicated observed interruptions. Horizontal lines indicates conductivity limiting value before 200 ns of current zero after which reignition happens [27]

Indirect parameters: Black-box models describe the wave traces of the arc current and voltage by a set of mathematical equations [28]. Indirect parameters are the parameters of a black box model of the arc. These parameters can be used in analyzing interruption behavior under conditions other than tested means which hasn't been experimented yet but having performed one basic experiment and after fitting the result in some arc's mathematical model, we will find the indirect parameters (for instance arc time constant, power losses etc.). These indirect parameters can be utilized to simulate the experiments which haven't been performed. Hence these parameters are useful tool for behavior forecasting of electric arc.

4.3 Heat losses from arc

The electrical power is dissipated in three regions of the arc: anode, cathode and plasma column. The area at cathode and anode has strong effect on the flow of heat energy to the terminal. Heat loss of arc is an important parameter in deciding how stable the arc is. Basically, heat losses are of three kind; Radiation loss, Convective loss and Conduction loss. Depending on the arc current, one out of these three losses is the dominating one. If the sum of all these losses from the arc exceeds the power input, arc becomes unstable and has more probability to extinct. When power losses are equal to input power, arc is just stable. When power input is more than power losses are becomes more stable. This stability increases with increase in the power input and decrease in the power losses. The explanation of these power losses is as follows:

4.3.1 Convection loss

As due to very high temperature of the arc which is basically caused by Ohmic losses, the density of air in between the gap becomes lower than the outward air. This causes a lift force to appear which makes the heated air of light weight to move upward. Therefore the outward air, moves downward and takes the position of lighter air and lighter air takes the position of heavier air. Therefore this release of heat to surrounding from the arc is called convection loss.

4.3.2 Radiation losses

All electric arcs emit radiation, the amount and character of which depends on the atomic mass and chemical composition of gaseous medium, the temperature and the pressure. As energy input to an arc increases, higher states of ionization occur and higher level of radiation result. By emitting radiation, the energy of arc gets lower.

Radiation from arc, is in the form of ultraviolet, visible and infrared light. Since the intensity of radiation is high, arcs pose hazards to operator and observers. UV radiation is particularly dangerous to the eyes but also can cause sunburn-like damage to exposed skin, while infrared radiation causes burning heat [37].

Radiation losses are dominant at high temperatures while the convection has a major role at low temperatures. [38]

It has also been found [39] that, the electrode material has effects on radiation extent. When Aluminum has been used as electrodes, the radiation was 65% higher than that of Copper electrodes. Increase in arc current gives almost linear rise in radiation. Increase in the electrode separation, gave a rise in radiation that was slower than linear.

At pressure close to 1 atm, radiation is not a significant factor in heat dissipation from the arc. At higher pressure, however the radiation may become a very important factor in energy dissipation. [41]

The arc radiation losses in atm air are 1%, but they become significant at pressure above 10 atm and for higher power arc. [42]

From all these research results, we can thus conclude that radiation losses become an important factor when:

1. energy input to the arc, hence arc temperature is very high
2. pressure of the medium between the electrode gap before arcing is much larger than atmospheric pressure.
3. electrode separation is large.

As during peak of the sinusoidal cycle of AC arc, the temperature is very high hence during this period radiation plays an important role in heat transfer.

4.3.3 Conduction losses

Conduction is movement of heat through a material. Conduction occurs when rapidly moving or vibrating atoms and molecules interact with the neighboring particles, thus transferring some of their kinetic energy to them. In gases, conduction is due to the collisions and diffusion of the molecules during their random motion. Photons in general, do not collide, one another and hence heat transported by radiation is not regarded as conductive.

Conduction has a dominant effect of heat transfer in solid. In gases the conduction is very little, the reason being the atoms in solid are more close to each other than gases, hence there are more collisions between atoms hence more transfer of heat, than in gases. However, the thermal conductivity of gases generally increases with increase in temperature.

4.4 Effect of thermal conductivity in cooling high temperature space

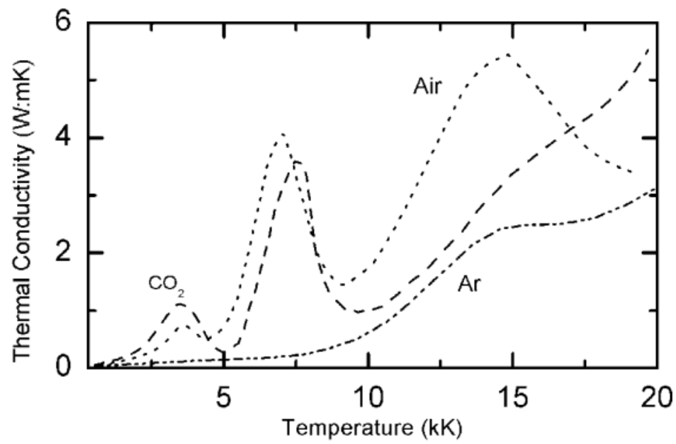

Fig 31: Thermal conductivity of Air, Argon and carbon dioxide [45]

The variation of the thermal conductivity, depends rather strongly on the nature of the gas as can be seen from Fig. 31, the high peaks at low temperature are related to the phenomenon of molecular dissociation. [45]

During the first instants of the extinction of electric arc, the variation of the axis temperature is mainly due to conduction and radiation losses because convection tends to cool down the external parts of the plasma but not the inner part.[45]

The lowest temperature at which peak thermal conductivity of nitrogen occurs is at 7000K, that means after arc extinction [21], the decay of temperature until 7000K is very fast but after that it is very slow. In SF6, there are several peaks of thermal conductivity at around 2500K, which leads to rather strong cooling until 2500K.

Chapter 5

5 EXPERIMENTAL RESULTS

5.1 Indirect parameters

It has been investigated [43] that the conductance of the arc at current zero is a good electrical parameter for determination of the ability of the circuit-breaker to interrupt the current. The reason for this, is that large power loss increases the chance for interruption. Large power loss is equal to small conductance. Because the resistance is the inverse of the conductance, the resistance at current zero is an equally good parameter.

The behavior of space in the electrode gap, after arc extinction was originally represented by Cassie and Mayr.

5.1.1 Cassie and Mayr Models

Cassie and Mayr, working independently, formulated two differential equations based on rather different concepts of the physical nature of the arc colomn.

Cassie assumed an arc column within which the temperature is fixed and uniform in space and time, having resistivity, power loss and energy content being constant. The cross sectional area varies with current and time.

Mayr assumed a cylindrical arc column of constant cross-sectional area within which the temperature varies with the arc's radial dimension and with time.

It has been observed that the Cassie model, with its steady state arc voltage, fits best the voltage and current waveforms for the arc during the period prior to current zero, whereas the Mayr model, describes best the characteristics of a low current arc. Mayr's equation becomes a better approximation only when the arc temperature falls to a level just above that at which electrical conductance due to thermal ionization practically disappears and the energy is transferred mainly by radial heat conduction.[46]

In this master thesis, for first experiment of measuring arc parameters, low current AC arc of 10A amplitude has been tested, in open air. The main purpose was to find how the conductivity falls near current zero period. As we were more concerned with conductivity decay near current zero and the arc was of low current, therefore Mayr model has been used as it is suitable to find conductivity decay for low current arcs. The Mayr model is as follows:

For low current electric arcs, the arc conductance is assumed to vary with a passage of time around current-zero, in accordance with

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\theta}\left(\frac{vi}{Q} - 1\right) \qquad (2)$$

where θ is arc time constant, Q is arc power loss.

At instant of current zero, the power input is zero and therefor, $vi = 0$, in equation (2) and we are left with equation (3) as follows:

$$\frac{dg}{dt} = -g\frac{1}{\theta} \qquad (3)$$

which is homogenous differential equation with solution as follows:

$$g = g_o e^{-1/\theta} \qquad (4)$$

Where g_o is some constant. The parameters θ and Q are called arc parameters. Arc time constant θ is defined as the ratio of energy stored per unit volume to the energy loss rate per unit volume [p 1.3, 41]. When the energy loss rate in the gap increases than energy stored in the gap, time of conductivity decay is less (means small time constant). This stored power in the gap basically is arc current multiplied with arc voltage.

5.2 Measuring electric conductivity decay near current zero

Electric arcs of frequency ranging from 50 Hz to 5kHz with constant current amplitude of 10 A has been performed. By increasing the frequency (from 50 Hz up to 5000Hz), keeping the amplitude constant, our main objective was, to make the slope of current near current zero more steep. It was done, in order to find out how different slope of current near current zero, effects the time constant means conductivity decay near current zero. The gap distance used was 0.11 mm as shown in Fig. 32. Figure 38 shows complete setup of the experiment performed.

Fig. 32: The electrodes with about 0.11mm gap used for the experiment (Photo: Tatu Nieminen)

Fig. 33: Complete setup of the experiment to find out indirect parameters of arc (Photo: Tatu Nieminen)

Arc time constant and power losses, 15 µs before current zero has been found. For each frequency sample (for instance 50 Hz and so on), about 150 zero crossing samples of arc current and arc voltage has been obtained from the experiments. Then after, the results were analyzed in MATLAB. The current and voltage waveform of the arc contained quite high frequency ripples. In order to make the waveform, smoothened, an MATLAB filter has been used (see IIR Filter in the appendix). Arc conductivity has been obtained by dividing arc current to the arc voltage and we obtained 150 samples of arc conductivity, from which an average of all the samples is taken. As our main purpose was to obtain, arc conductivity decay for specific time before current zero, hence a specific amount of sample points before current zero has been taken so that, we have, the average conductivity curve with a negative slope (means conductivity is decreasing).

5.2.1 Procedure to find out arc time constant and power losses for 50 Hz

For 50 Hz, arc voltage and arc current are shown in Fig. 34, with demonstration how the 2000 samples of arc voltage (Yellow color in Fig. 34) and 2000 of arc current (Black color in Fig. 34) has been taken before each current zero.

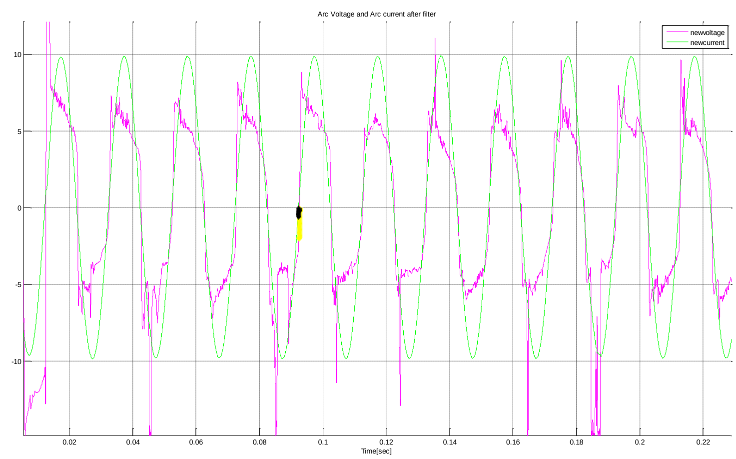

Fig. 34: Arc voltage and arc current for 50 Hz frequency

It should be noted that this is the demonstration for one case that how, 2000 samples before current zero (black color) and 2000 samples before voltage zero (Yellow color), are taken as arc current and arc voltage are negative, but we take all the 2000 samples before current zero, when arc voltage and arc current are both positive and both negative.

After this, input power which is arc voltage times arc current, for all 2000 samples before current zero (when arc voltage and arc current both positive and both negative), has been found out and it can be seen on following Fig. 35.

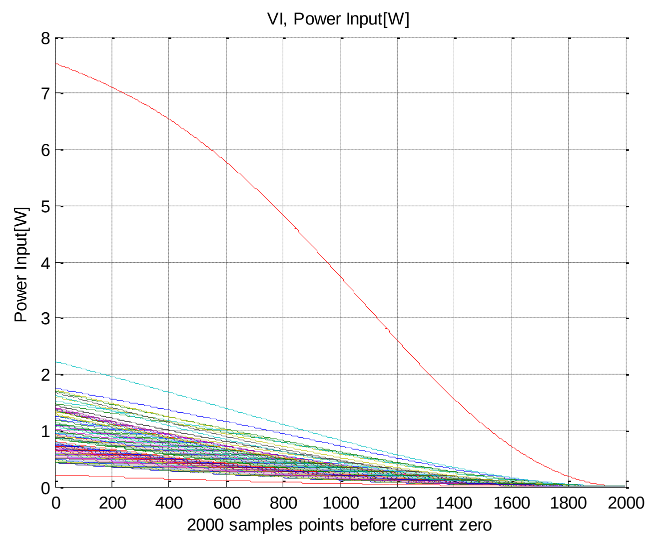

Fig. 35: Arc Input power for a number of cycles, 2000 samples before current zero

The curves, which were quite offset (for instance the very upper red curve in Fig.35), were removed in few cases such that we have very accurate result, when calculating the average value of all these input power curves shown in Fig. 36. The negative sign on horizontal axis of Fig. 36 shows, time before current zero.

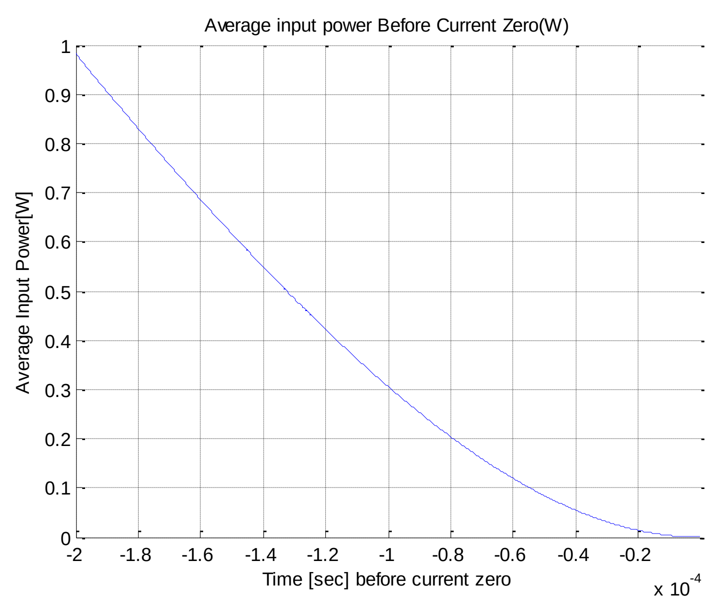

Fig. 36: Arc average input power for a number of cycles

After that Arc conductivity has been found, by dividing arc current to arc voltage, by taking each sample point of arc voltage and current, at specific time before current zero, for 2000 sample points, for a number of cycles. This is demonstrated in Fig. 37.

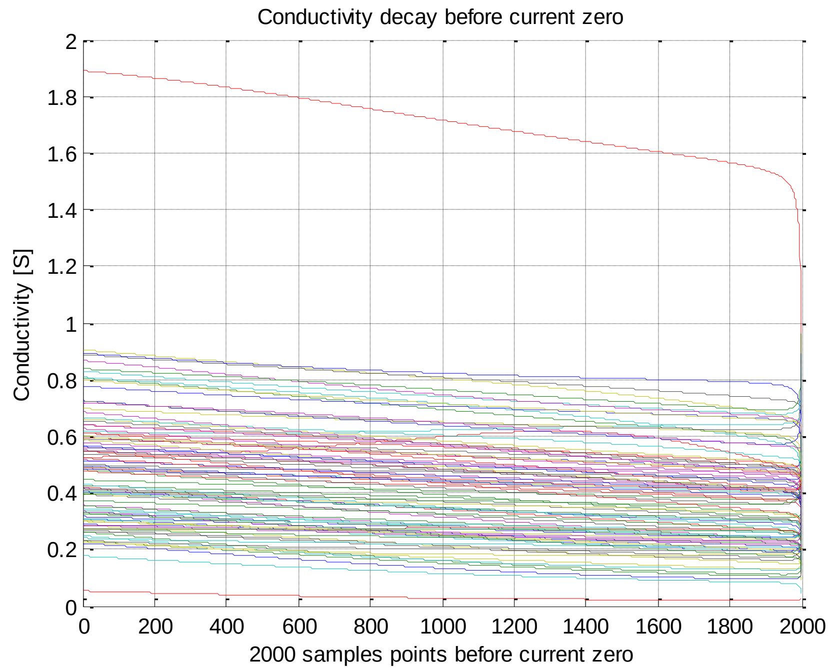

Fig. 37: Arc conductivity for a number of cycles before current and voltage zero

Similar procedure which has been adopted for calculating average input power, has been taken in calculating average conductivity. The Fig. 38 shows the average conductivity decay.

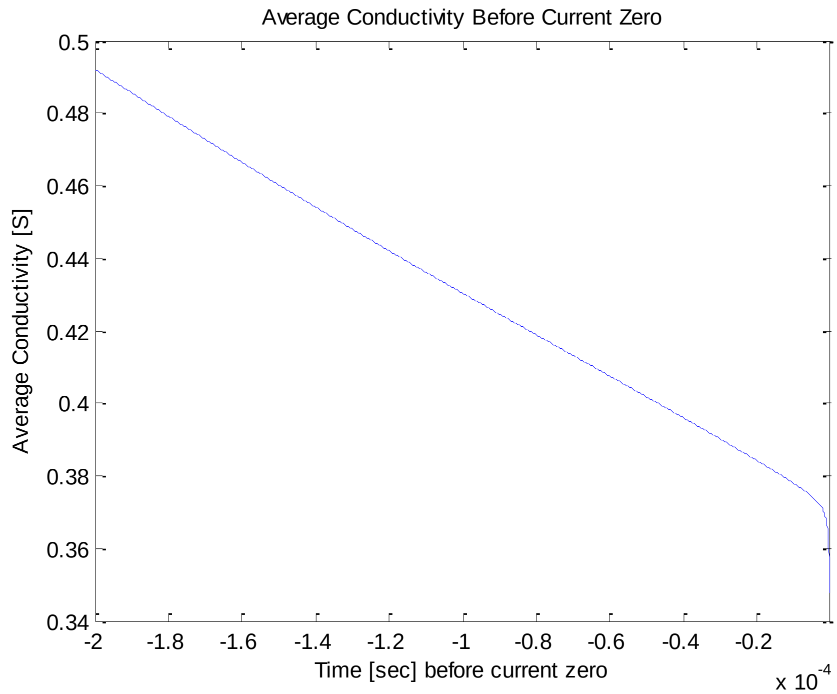

Fig. 38: Arc average conductivity for a number of cycles

In order to find arc time constant and power losses, the procedure followed by [44] was adopted which is explained as:

Taking in to account the Mayr's equation, firstly dg/dt curve, for a specific time before current zero has been found which is shown in Fig. 39.

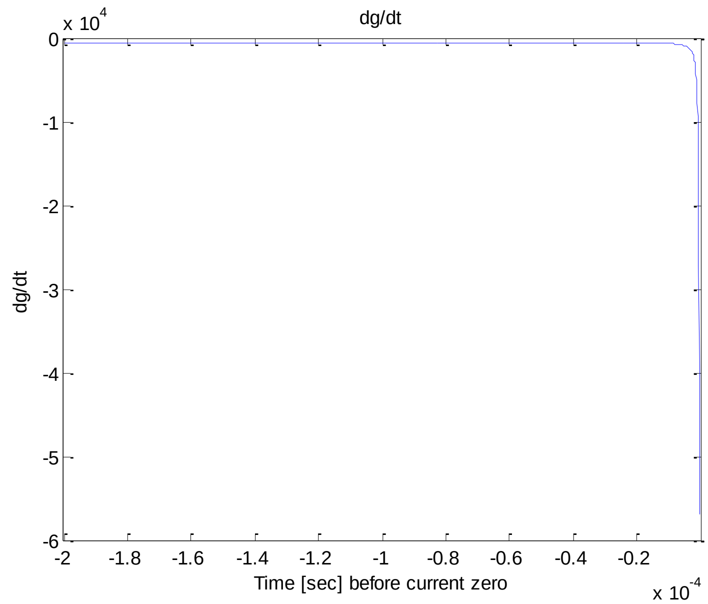

Fig. 39: dg/dt, 0,2ms before current zero

Then dg/dt/g curve versus time, before current zero has been drawn as shown in Fig. 40.

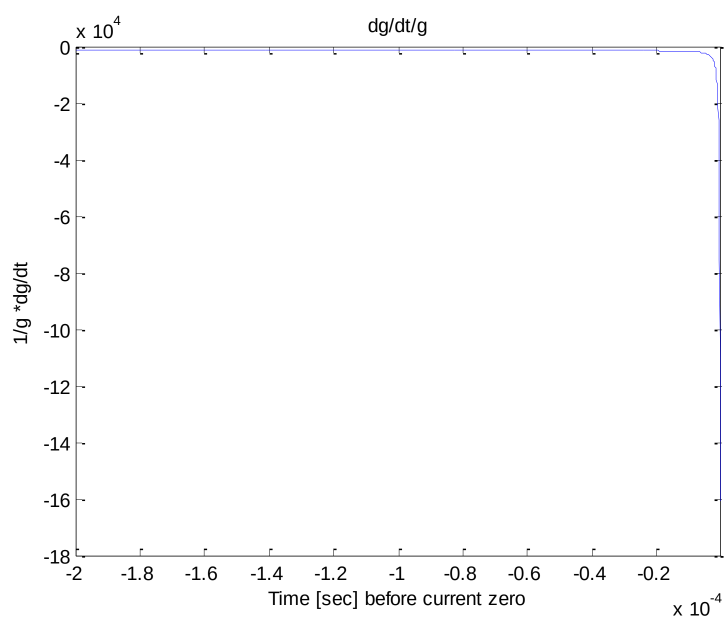

Fig. 40: dg/dt/g, 0,2ms before current zero

After this, dg/dt/g has been plotted with input power. Near to very current zero, (which we were scrutinizing the most, in order to find out the behavior of conductivity fall), a tangent at different points has been drawn. The point, where this tangent in dg/dt/g versus input power graph, meet with dg/dt/g=0, from that point a straight vertical line meeting the input power axis, has been drawn. The point where this straight vertical line meets the input power axis, is the power loss(W) at that specific time.

The point where tangent line meets dg/dt/g axis, with input power=0, has been divided by one, which is finally arc time constant (sec) at that specific time.

A more closer look of this procedure is shown in Figure 41.

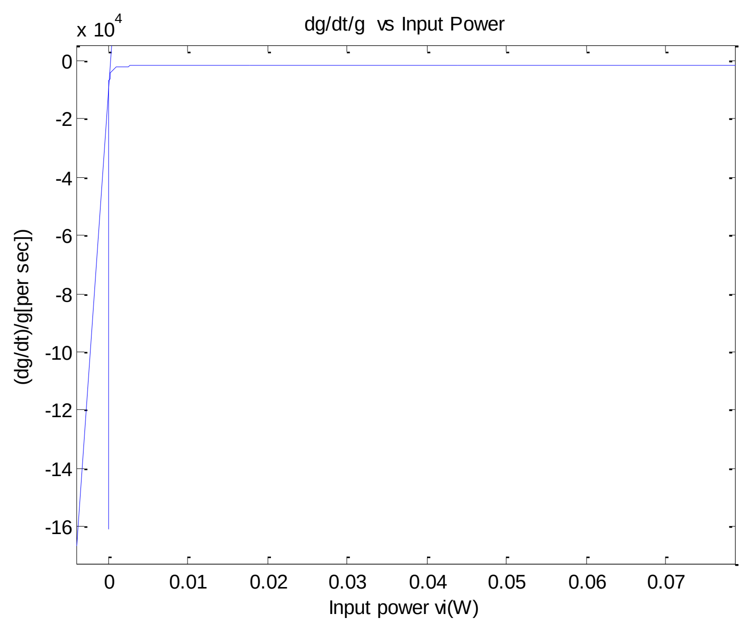

Fig. 41: Method showing, how arc time constant and power losses has been found

Arc time constant and arc power losses for 0,2 ms, before current zero, can be seen in Figure 42 and Fig. 43 respectively.

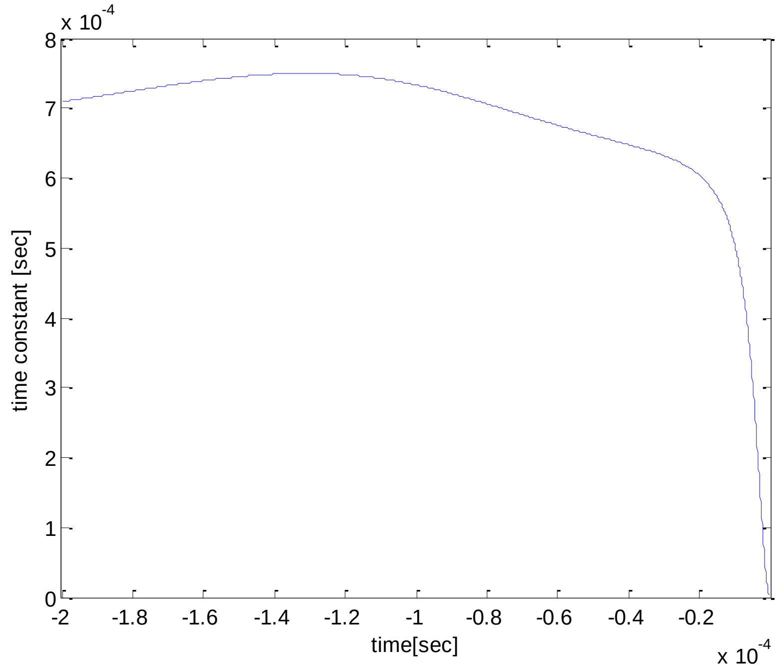

Fig. 42: Arc time constant, 0.2 ms before current zero

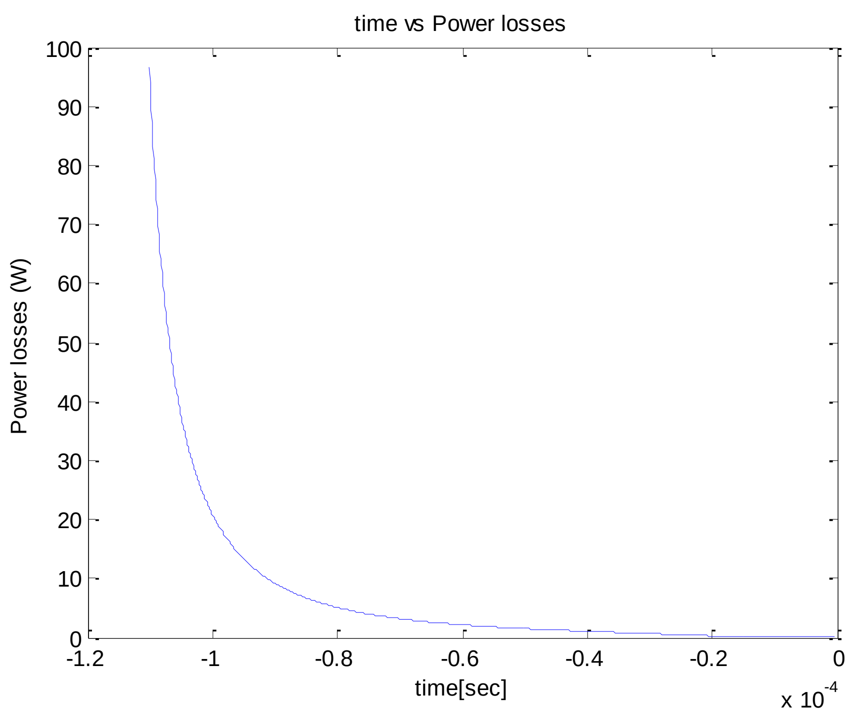

Fig. 43: Arc power losses

After finding, arc time constant and arc power losses at each specific time, these values has been put in the basic Mayr arc model and then arc conductivity has been found out in order to check our results. The following Fig. 44, shows the arc conductivity using Mayr model after filling arc parameters at each specific time.

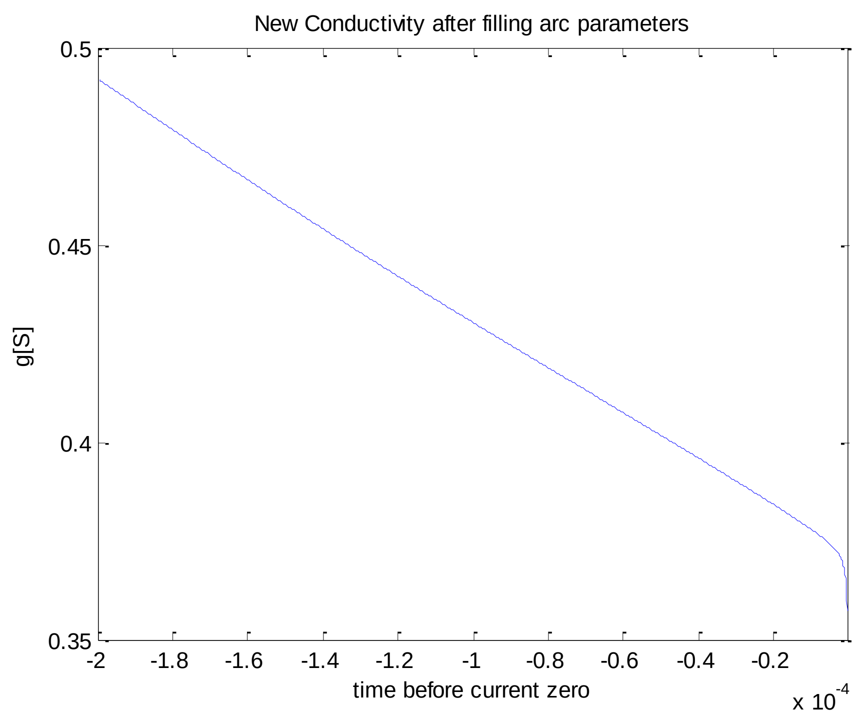

Fig. 44: Arc conductivity using Mayr arc model, after filling arc parameters

It should be noted that all these demonstration shown is for 50 Hz frequency cycles. Similar procedure has been followed for frequency up to 5kHz.

5.2.2 Results

The results obtained from this measurement can be seen in Figure 45 and Figure 46, below.

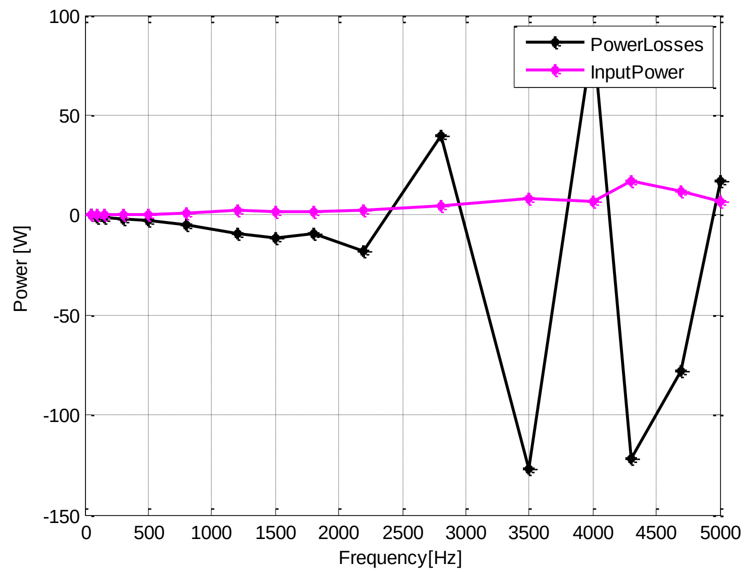

Fig. 45: Arc Input power and Power losses at different frequency

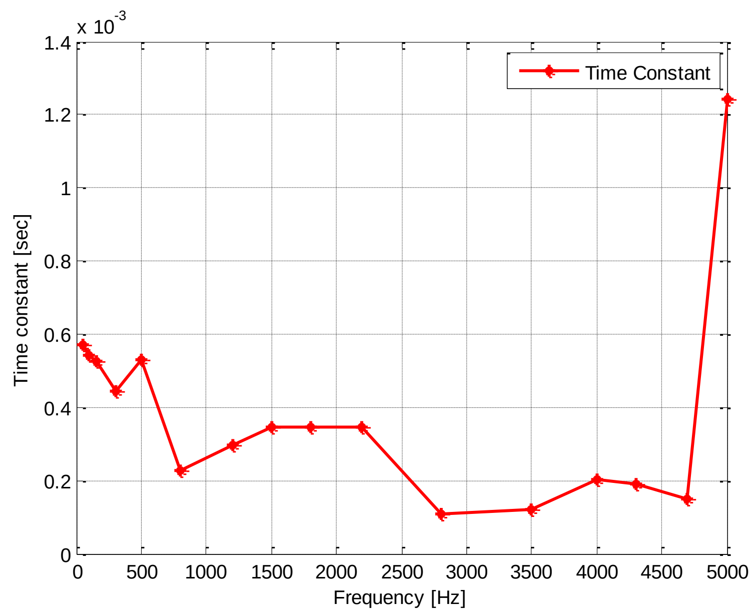

Fig. 46: Arc time constant 15µs before current zero at different frequencies

5.2.3 Discussion

With the increase in frequency, the arc power losses, using the procedure [44], has sometimes positive and sometimes negative value. The negative power loss at some specific frequency means, 15 µs before current zero, tangent on dg/dt/g curve on dg/dt/g versus power input graph graph meets the dg/dt/g=0, line at negative value of input power. From these results of measuring arc time constant and power loss, with the increase of frequency, no strong conclusion can be concluded.

5.2.4 Comparison of the results with other research work

In experiment done by [44], where circuit breaker contacts in Co_2 medium with pressure of 0,2 Mpa, gets apart on initiation of fault with arc current of 1,7 kA (peak value) with gap distance which increases from 0 to 15,4mm (Fig. 47) where arc interrupts, arc parameters has been found, 2µs before current zero. It should be noted that in [44], arc parameters has been found when the interruption was successful. This means arc conductivity value has been found from last waveforms current and voltage. Arc time constant and arc power losses, 2µs before current were 1,3 µs and 0,32 kW respectively.

According to [48], the arc time constant for air at 0,2 Mpa with arc current frequency of 45 kHz, were also found out to be range of few µs, but again this was the case when interruption was successful.

It should be noted that in our experiment, arc parameters has been found when there was no interruption which means that current and voltage waveforms were continuous. The input power in [44], was much higher than in our case as peak arc current in our case was 10A.

As there has been no interruption in our case, hence we expect arc time constant to be larger than few µs; which was the case, as arc time constant found out to be in range of ms (Fig. 46). Arc power losses were found out to be also small, because arc during the experiment did not interrupt. Because if it would have been interrupted then we would expect more power losses. According to [48], arc time constant of air are greater than that of Co_2.

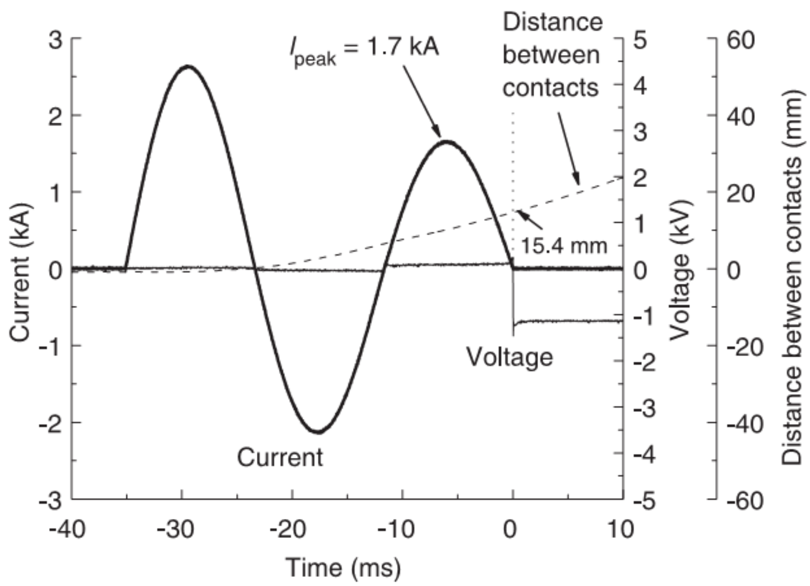

Fig. 47: Arc current, arc voltage and distance between the gap [44]

5.3 Effect of temperature on breakdown voltage

The second experiment has been performed in order to find out the effect of temperature on breakdown voltage in air for different five materials. The cross section of the material used as electrode was circular with electrode shape being rounded. Five materials used, in order to find out the differences of the effect of temperature on breakdown voltage of air, are as follows:

1. Stainless steel
2. Aluminum
3. Copper
4. Brass
5. Iron

The diameter of the rods used was 20mm. A furnace has been used to set a particular temperature, and rods were immersed in this furnace shown in Fig.48. This causes a uniform temperature between electrode gap. Complete setup of the experiment performed can be seen in Fig. 50. The breakdown voltage has been measured from ambient temperature until before, 100-200 degrees less than the melting temperature of the material rod used. The applied voltage used was sinusoidal with rise time of 1kV/s. The distance between the gap has been kept 5mm with an error in the precision of 0,2mm. As there is extension in the material with rise in temperature and as the structure of the material used is cylindrical with rounded edges, there has been extension of the material radially as well as axially. So when performed the test, each time when temperature has been increased, there has been material extension axially as well as radially. That means, when raised the temperature in the furnace, after the test in ambient air with the gap distance of 5mm, the gap distance has been less than 5mm due to axial extension. So each time, when temperature has been raised, the gap has been adjusted to 5mm, so that a good comparison of the result can be made at same gap distance. This adjustment has been done with the help of meter shown in Figure 49, such that when temperature in the furnace increased from one point to the next, before measuring the next temperature breakdown voltage value, the electrodes were brought together such that they touch and then by seeing the reading from the meter, 5mm gap has been set.

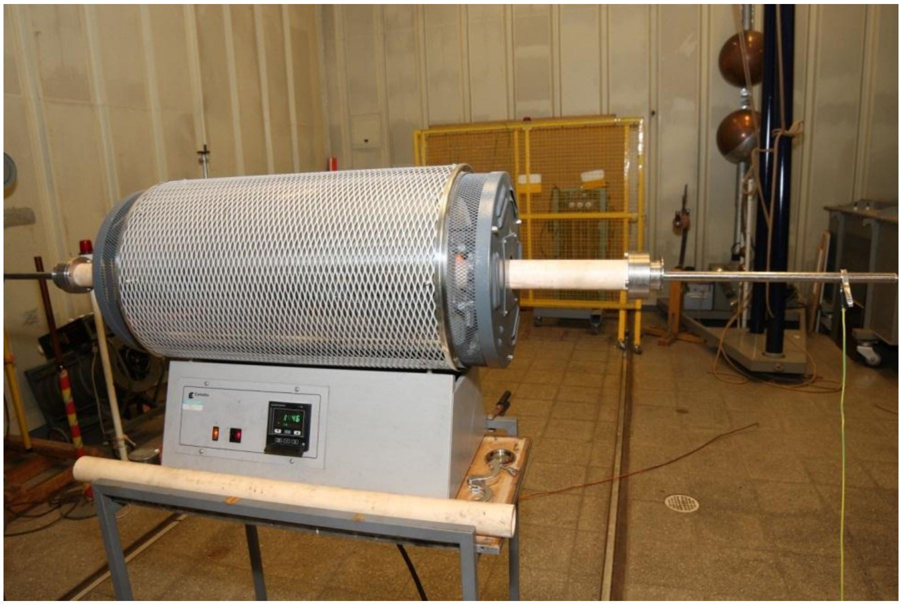

Fig. 48: Furnace used to raise the temperature of the space between gap to a set point (Photo: Tatu Nieminen)

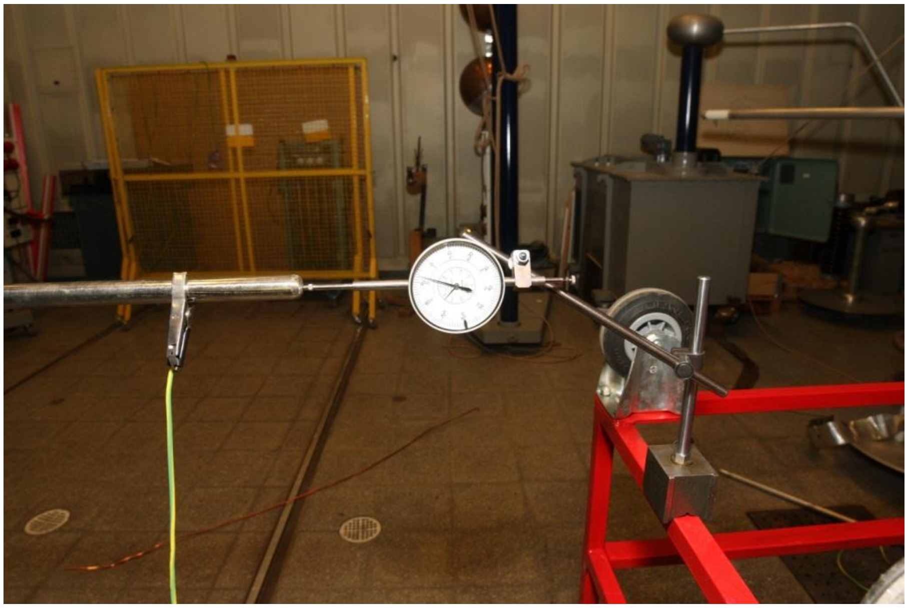

Fig. 49: Meter used to set 5mm gap, after expansion of the material (Photo: Tatu Nieminen)

Fig. 50: Complete setup of the experiment with a transformer (Photo: Tatu Nieminen)

5.4 Measurements

Test 1: Stainless steel

First, test has been performed with stainless steel. The ambient temperature was 21,9 ℃, with Relative humidity 15,4 %, Absolute humidity 2,97 g/m^3 and with pressure 1020,1 hpa on the day this experiment has performed. The melting point of stainless steel is 1510 ℃ [18], therefore temperature at which last breakdown voltage measurement has been done, was 1300 ℃.

Test 2: Aluminum

Second, test has been performed with Aluminum. The ambient temperature was 23,4 ºC, with Relative humidity 33 %, Absolute humidity 6,945 g/m^3 and with pressure 1017,27 hpa on the day this experiment has performed. The melting point of stainless steel is 660 ºC [18], therefore temperature at which last breakdown voltage measurement has been done was 400 ºC.

Test 3: Copper

Third, test has been performed with Copper. The ambient temperature was 22,5 ºC, with Relative humidity 42,4 %, Absolute humidity 8,476 g/m^3 and with pressure 1006,33 hpa on the day this experiment has performed. The melting point of stainless steel is 1084 ºC [18] therefore temperature at which last breakdown voltage measurement has been done was 850 ºC.

Test 4: Iron

Fourth, test has been performed with iron. The ambient temperature was 22,2 ºC, with Relative humidity 19,1 %, Absolute humidity 3,753 g/m^3 and with pressure 1006,24 hpa on the day this experiment has performed. The melting point of iron is 1536 ºC [18], therefore temperature at which last breakdown voltage measurement has been done was 1350 ºC.

Test 5: Brass

Fifth, test has been performed with Brass. The ambient temperature was 22,9 ºC, with Relative humidity 24 %, Absolute humidity 4,909 g/m^3 and with pressure 1003,46 hpa on the day this experiment has performed. The melting point of iron is 930 ºC [18], therefore temperature at which last breakdown voltage measurement has been done was 765 ºC.

The variation of breakdown voltage of air with temperature, using different electrode material can be seen in Fig. 51.

5.5 Test Results

From the results shown in Fig. 51, we can see that for all the materials the breakdown voltage decreases more or less in the same fashion when temperature of the electrode as well as between the electrode gap, increases (as the electrode were immersed in furnace, so when temperature in the furnace is raised, the electrode temperature also gets increased). It is also very interesting to know that for Iron and Stainless steel, the breakdown voltage stay constant for some temperature variation (for Iron breakdown voltage stay constant from 1000 ^{o}C to 1200 ^{o}C and for Stainless steel breakdown voltage stay constant from 1000 ^{o}C to 1150 ^{o}C and then it decreases again following the original trend.

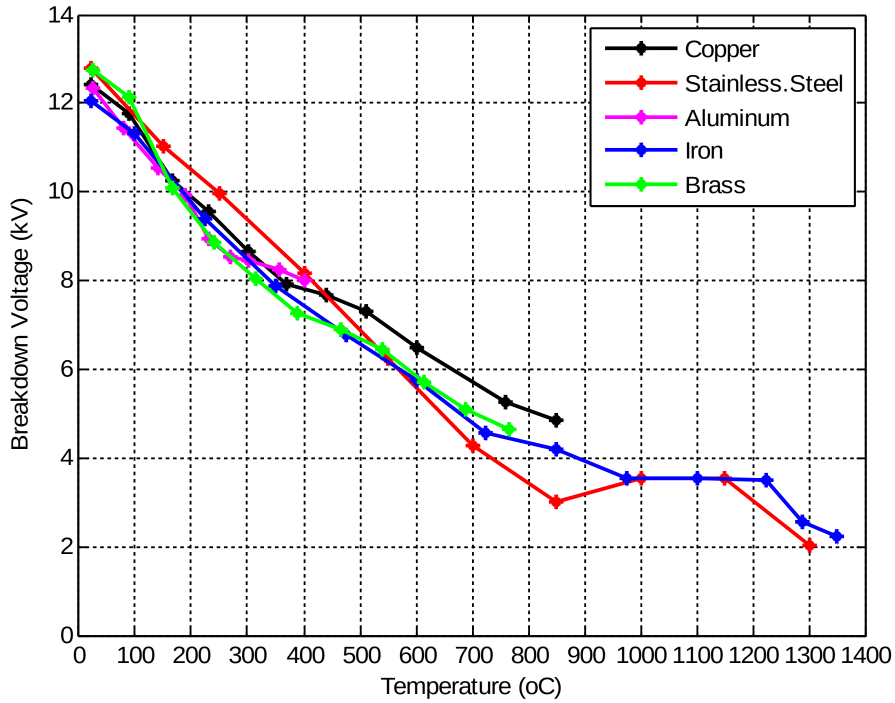

Fig. 51: Variation of breakdown voltage with temperature increase for different electrode materials

5.6 Comparison with other research work

In a research carried out to find out effect of temperature on breakdown voltage in air [47], it has been found that for millimetric gap, in an approximately uniform field, breakdown voltage is independent of the electrode material, where the electrode material used has been Copper, Elkonite (tungsten-copper) and Nimonic (nickel-chromium) and gap distance used were from 0,5mm, 1mm and 2 mm. In our experiments, the electric field was also nearly uniform due to rounded edge electrodes, and the difference of the value of breakdown voltage at specific temperature for different materials was found out to be not very large. It is also good to notice the fashion in which breakdown voltage in [47] decreases with increase in temperature, matches with our results.

Chapter 6

6 CONCLUSION AND FUTURE WORK

6.1 Conclusion

From this research work, it can be concluded that electric arc being complex phenomenon, depends on many factors, for instance the electrode gap space, electrode material, humidity etc. One of the important factor, that it highly depends on, is temperature. It can be concluded that the success of arc interruption depends on the temperature of the space between gap, as we can see from results of experiment 2, the breakdown voltage decreases with increases in temperature of the space between the gap. However it does not mean that increase in temperature give a linear decrease in breakdown voltage in open air as for a specific temperature rise, the breakdown voltage remains constant. There was not much difference in breakdown voltage for different electrode material used as electrode in air when temperature of the space as well as of the electrode has been increased. Our results match with [47], who says that in uniform E-field, the breakdown voltage is independent of the material of the electrode used.

Arc conductivity measurement, to get deeper understanding of interruption or failure of arc, is a good factor to look on. As concluded by [27], there must be some limiting value of arc conductivity, no matter what the voltage rating of the equipment, such that if the arc conductivity crosses that value, then reignition occurs. But from measured arc time constant and power losses values, we were not able to conclude that how increase in frequency hence increase in current slope effect the arc time constant. However as expected, for our case where there was no interuuption, arc time constant comes out to be in range of ms where in other researches

[44],[48], where there has been interruption, it came out to be in range of μs.

From the literature study used in this research, we can conclude that for short gap arcs the electrode material has dominating effect due to immediate recovery of cathode layer as well as quite low temperature of the electrodes than the arc column; however with gap greater than a inch, the gas in space between the electrode gap has dominating effect.

6.2 Future work

As for experiment 2, performed during this research work, a arc furnace has been used which increases the temperature of the electrode material as well as the air space in the gap. Therefore we found the breakdown voltage dependence on temperature. However it is good to know how only the heated air affects the breakdown voltage and how the heated electrode only effect the breakdown voltage in air for millimetric gaps. It will give us better understanding that, for short gap (in our case 5mm), which has the dominating effect on breakdown voltage, is it heated space in the gap or heated electrodes. This can be done for instance by heating the electrode, in furnace and then taking out of it in atmospheric air, and applying the voltage across the electrodes. The another test which will give the affect of heated space only on breakdown voltage, can be performed by, firstly heating the arc furnace and then immersing the cool electrodes in it.

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APPENDIX

1. Matlab commands for measuring arc time constant

1.1 Matlab commands for 50 Hz, to find out arc time constant and power losses

```
clear all;
close all;
clc

%Loading the sample points of measured arc current waveform
and naming it
%''Current''
current=ReadLeCroy('C2ballgapcurrent_50hz00000.trc');

%ZeroCSamples is a function built which gives number of
samples points for
%one complete sin cycle, we are dividing by 100 as we need
2000 samples
%before current zero
samples = ZeroCSamples(current)/100;

%IIR Filter is a filter made to remove, ripples of very
high frequency
%components from current and voltage waveforms of arc
newcurrent=IIRfilter(current.y,samples);
figure(1)
%plot(current.x,current.y) where current.x represents time
sample points
hold on;
grid on;
plot(current.x,newcurrent,'m')
title('Current(A)')

%EtsiNollat function find the zeros of newcurrent as
newcurrent is filtered
%waveform of current
currentZeros = EtsiNollat(newcurrent);
%Now we will find the indices where zeros of newcurrent
occurs
currentZeroind = find(currentZeros);
%Now we will take all 2000 indicices before current zero
currentIndLow = currentZeroind-samples;
currentIndHigh = currentZeroind-floor(samples/1000);

%Same procedure goes for voltage waveform
voltage=ReadLeCroy('C1ballgapcurrent_50hz00000.trc');
newvoltage=IIRfilter(voltage.y,samples);
voltageZeros = EtsiNollat(newvoltage);
voltageZeroind = find(voltageZeros);
voltageIndLow = voltageZeroind-samples;
```

```
voltageIndHigh = voltageZeroind-floor(samples/1000);


figure(2)

hold on;
grid on;
plot(voltage.x,newvoltage,'m')
%plot(voltage.x,current.y) where voltage.x represents time
sample points
%hold on;
grid on;
plot(current.x,newcurrent,'g')

hold on;
hold all;
grid on;

for k=60


plot(voltage.x(voltageIndLow(k):voltageIndHigh(k)),newvolta
ge(voltageIndLow(k):voltageIndHigh(k)),'y*')

plot(current.x(currentIndLow(k):currentIndHigh(k)),newcurre
nt(currentIndLow(k):currentIndHigh(k)),'k*')

end
legend('newvoltage','newcurrent')
title('Arc Voltage and Arc current after filter')
xlabel('Time[sec]')

hold off;



%The following will show how many times we have current
zero
koko = length(currentZeroind);
koko2 = currentIndHigh(1)-currentIndLow(1);
conductivity = zeros(koko,koko2+1);
figure(3);
hold all;
grid on;

%The following loop will give input power for a number of
cyles, 2000
%samples before current zero

for k=1:koko
power(k,:)=
(newcurrent(currentIndLow(k):currentIndHigh(k)).*newvoltage
(voltageIndLow(k):voltageIndHigh(k)));
plot(power(k,:));
```

```
title('VI, Power Input[W]')
xlabel('2000 samples points before current zero')
ylabel('Power Input[W]')
end
figure(4);
hold all;
grid on;

%Taking average of input power for a number of cycle at
specfic time
e= mean(power(1:koko,1:1999));
t=[-200e-6:0.1e-6:-0.0002e-003];
plot(t,e)
title('Average input power Before Current Zero(W)')
xlabel('Time [sec] before current zero')
ylabel('Average Input Power[W]')
figure(5);
hold all;
grid on;

%The following loop will give conductivity for a number of
cyles, 2000
%samples before current zero
for k=1:koko
    conductivity(k,:) =
(newcurrent(currentIndLow(k):currentIndHigh(k))./newvoltage
(voltageIndLow(k):voltageIndHigh(k)));
plot ((conductivity(k,:)));
title('Conductivity decay before current zero')
xlabel('2000 samples points before current zero')
ylabel('Conductivity [S]')
end
figure(6);
%Taking average conductivity for a number of cycle at
specfic time
g= mean(conductivity(1:koko,1:1999));grid on;
plot(g);
title('Average Conductivity Before Current Zero');
xlabel('2000 samples points before current zero')
ylabel('Conductivity [S]')
figure(7);grid on;
%Average condcutivity with time stamp
plot(t,g)
title('Average Conductivity Before Current Zero')
xlabel('Time [sec] before current zero')
ylabel('Average Conductivity [S]')

%The following loop will give the slope between two data
points of
%conductvity
for i=1:1998
     slope(:,i)=(g(i+1)-g(i))/(t(i+1)-t(i));
end
figure(8);grid on;
%Plotting slope with time
plot(t(1:1998),slope(1:1998));
```

```
title('dg/dt')
xlabel('Time [sec] before current zero')
ylabel('dg/dt')

figure(9);
grid on;
%dg/dt/g=slope_conductivity
slope_conductivity=(slope./g(1:1998));
plot(t(1:1998),slope_conductivity)
title('dg/dt/g')
xlabel('Time [sec] before current zero')
ylabel('1/g *dg/dt')



r=e(1:1998);
r1=fliplr(r);
slope_conductivity1=fliplr(slope_conductivity);
m=diff(slope_conductivity1)./diff(r1);

for i=1:(length(r1)-1)
y_intercept(i)=(slope_conductivity1(i)-m(i)*r1(i));
time_constant(i)=1/(y_intercept(i));
x_intercept(i)=((m(i)*r1(i))-slope_conductivity1(i))/m(i);
end
figure(10);
grid on;
plot(r,slope_conductivity)
hold on;
syms x
ezplot(m(17)*(x)+y_intercept(17))
hold off;
title('dg/dt/g  vs Input Power')
xlabel('Input power vi(W)');
ylabel('(dg/dt)/g[per sec])');
l=[-0.0004e-003:-0.1e-6:-200e-6];
figure(11);
grid on;
plot(l, -(time_constant))
xlabel('time[sec]')
ylabel('time constant [sec]')
k=fliplr(x_intercept);
%slope=dg/dt
j=fliplr(time_constant);
%tr is new conductivity(g) after filling arc parametrs in
basic Mayr
%equation
for i=1:1997
tr(i,:)= ((slope(i)).*(-j(i)))/((e(i)./k(i))-1);
end
figure(12);
grid on;
%Plotting, to check is, after filling the mesured arc
parametrs in Mayr
%equation, do we get the same counductivity curve
plot(t(1:1997),tr)
```

```
title('New Conductivity after filling arc parameters')
xlabel('time before current zero')
ylabel('g[S]')
figure(13);
grid on;
plot(t(900:1997),k(900:1997))
xlabel('time[sec]')
ylabel('Power losses (W)')
title('time vs Power losses')
```

1.2 Filter used to remove the high frequency ripple in measured waveforms

```
function odata = IIRfilter(idata,r)

rip = .05;  % passband ripple in dB
nfilt = 8;
[b,a] = cheby1(nfilt, rip, 1/r);
while all(b==0) || (abs(filtmag_db(b,a,1/r)+rip)>1e-6)
nfilt = nfilt - 1;
if nfilt == 0
break
end
    [b,a] = cheby1(nfilt, rip, 1/r);
end

if nfilt == 0
error(message('signal:decimate:InvalidRange'))
end
```

1.3 Filter used to find zero crossing of sine waveform

```
%This function finds the zero crossing of the sine waveform
function out = EtsiNollat(in)

flen = length(in);
maxin = max(abs(in));
out = (abs(in)/maxin)<1/750;
startind = 0;
for ind = 1:flen
if out(ind)
if startind == 0
startind = ind;
%starty = in(ind);
end
out(ind) = 0;
else
if startind
indl = ind + 10;
```

```
if indl > flen
indl = flen;
end
if sum(out(ind:indl)) == 0
endind = ind;
valiaika = endind-startind;
middle = floor(valiaika/2);
out(startind+middle) = 1;
%               disp(['välinkeskeltä ',
num2str(startind+middle)]);
%                disp(['väliaika ', num2str(valiaika)]);
startind = 0;
end
end
end
end
end
```

1.4 Measured value of arc parameters at different frequencies

```
clear all;
close all;
clc

% Power losses and Arc time constant at different value of
frequency,
% 15 us,before current zero
Frequency= [50 100 150 300 500 800 1200 1500 1800 2200 2800
3500 4000 4300 4700 5000 ];

PowerLosses= [0.1190000 -1.1470000 -0.8915000 -2.0400000 -
2.3840000  -4.5490000 -9.1950000 -11.3100000 -9.1400000 -
17.7700000 39.8400000 -127.1000000 89.1400000  -122.0000000
-78.0200000 16.9900000 ];

TimeConstant= [0.0005730 0.0005440 0.0005277 0.0004438
0.0005305 0.0002264 0.0002970 0.0003453 0.0003471 0.0003476
0.0001103 0.0001212 0.0002038 0.0001910 0.0001489 0.0012410
];
InputPower=[ 0.0080930 0.0230600 0.0437900 0.1116000
0.1989000 0.6387000 2.2930000 1.9090000 1.7600000 2.2140000
4.3340000 8.1860000 6.4540000 17.2400000 11.6000000
7.1070000   ];

figure (1)
%Time Constant


hand2=plot(Frequency,TimeConstant,'r-*');grid on;

set(hand2, 'LineWidth', 2);
legend('Time Constant')
```

```
xlabel('Frequency [Hz]')
ylabel('Time constant [sec]')


figure (2)
%Power Losses
hand1=plot(Frequency,PowerLosses,'k-*')
set(hand1, 'LineWidth', 2);

hold on;

%Input Power


grid on;
hand3=plot(Frequency,InputPower,'m-*');
set(hand3, 'LineWidth', 2);




hold off;

%axis([0 1400 0 14])
xlabel('Frequency[Hz]')
ylabel('Power [W]')
%set(gca,'XTick',0:100:1400)
legend('PowerLosses', 'InputPower')
```

2 Measured values from the experiment in order to find the effect of temperature on breakdown voltage

Test 1: Stainless steel

A.) Measurement at ambient temperature 21,9 ^{o}C

Breakdown voltage (kV) at ambient temperature 21,9 oC										
1	2	3	4	5	6	7	8	9	10	Average
12,9800	12,9700	12,7300	12,9700	12,4900	12,7100	12,9800	12,8200	12,7800	12,5300	12,7960

B.) Measurement at 150 ^{o}C

Breakdown voltage (kV) at ambient temperature 150 oC										
1	2	3	4	5	6	7	8	9	10	Average
11,0900	11,0100	10,9600	10,7500	11,2300	10,8600	11,2900	10,9800	11,2500	10,9000	11,0320

C.) Measurement at 250 ^{o}C

Breakdown voltage (kV) at ambient temperature 250 oC										
1	2	3	4	5	6	7	8	9	10	Average
10,4250	10,2260	10,1600	9,8514	10,0150	10,0480	10,0660	9,8248	9,3062	9,8102	9,9733

D.) Measurement at 400 ^{o}C

Breakdown voltage (kV) at ambient temperature 400 oC										
1	2	3	4	5	6	7	8	9	10	Average
8,4255	8,3216	8,2031	7,9244	7,5808	8,2210	7,9809	8,3356	8,5300	8,1820	8,1705

E.) Measurement at 550 ^{o}C

Breakdown voltage (kV) at ambient temperature 550 oC										
1	2	3	4	5	6	7	8	9	10	Average
6,4221	6,4458	6,3404	6,1976	6,3264	6,3341	6,1817	6,1653	6,0262	6,0628	6,2502

F.) Measurement at 700 ^{o}C

Breakdown voltage (kV) at ambient temperature 700 oC										
1	2	3	4	5	6	7	8	9	10	Average
4,4594	4,4383	4,3825	4,2313	4,2637	4,2527	4,2597	4,1950	4,0688	4,1150	4,2666

G.) Measurement at 850 ^{o}C

Breakdown voltage (kV) at ambient temperature 850 oC										
1	2	3	4	5	6	7	8	9	10	Average
4,0566	2,8919	3,0098	3,0445	2,9215	2,8248	2,8200	2,9138	2,8376	2,8376	3,0158

H.) Measurement at 1000 ^{o}C

Breakdown voltage (kV) at ambient temperature 1000 oC										
1	2	3	4	5	6	7	8	9	10	Average
3,7200	3,3400	3,4700	3,3400	3,4800	3,5400	3,6500	3,6500	3,7500	3,3400	3,5280

I.) Measurement at 1150 ^{o}C

Breakdown voltage (kV) at ambient temperature 1150 oC										
1	2	3	4	5	6	7	8	9	10	Average
3,7174	3,3444	3,4669	3,3422	3,4773	3,5398	3,6520	3,6468	3,7528	3,3395	3,5279

J.) Measurement at 1300 ^{o}C

Breakdown voltage (kV) at ambient temperature 1300 oC										
1	2	3	4	5	6	7	8	9	10	Average
2,1066	2,0449	2,0320	2,0700	2,0316	1,9906	2,0356	2,0310	2,0653	1,9821	2,0390

Test 2: Aluminum

A.) Measurement at 23,4 ^oC

Breakdown voltage (kV) at ambient temperature 23,4 oC										
1	2	3	4	5	6	7	8	9	10	Average
11,7470	12,6460	12,2060	12,2060	12,3830	12,3620	12,3770	12,4810	12,4750	12,5060	12,3389

B.) Measurement at 80 ^oC

Breakdown voltage (kV) at ambient temperature 80 oC										
1	2	3	4	5	6	7	8	9	10	Average
11,4890	11,5280	11,4970	11,5240	11,4920	11,4710	11,4650	11,4400	11,3880	11,3410	11,4635

C.) Measurement at 140 ^oC

Breakdown voltage (kV) at ambient temperature 140 oC										
1	2	3	4	5	6	7	8	9	10	Average
10,5590	10,5455	10,5310	10,5040	10,6180	10,5370	10,5680	10,5620	10,5360	10,5540	10,5515

D.) Measurement at 190 ^oC

Breakdown voltage (kV) at ambient temperature 190 oC										
1	2	3	4	5	6	7	8	9	10	Average
9,8898	10,0330	9,9458	9,9974	9,9495	9,9733	10,0100	9,8745	9,8604	9,8555	9,9389

E.) Measurement at 230 ^oC

Breakdown voltage (kV) at ambient temperature 230 oC										
1	2	3	4	5	6	7	8	9	10	Average
9,2064	9,0341	8,8556	8,9092	8,9200	8,8849	8,9056	8,8808	8,9067	8,9055	8,9409

F.) Measurement at 270 ^oC

Breakdown voltage (kV) at ambient temperature 270 oC										
1	2	3	4	5	6	7	8	9	10	Average
8,6426	8,5904	8,4988	8,5756	8,5529	8,5157	8,5566	8,4593	8,5115	8,5367	8,5440

G.) Measurement at 300 ^oC

Breakdown voltage (kV) at ambient temperature 300 oC										
1	2	3	4	5	6	7	8	9	10	Average
8,4717	8,4852	8,4359	8,5225	8,3752	8,3974	8,4542	8,4289	8,4335	8,4251	8,4430

H.) Measurement at 355 ^oC

Breakdown voltage (kV) at ambient temperature 355 oC										
1	2	3	4	5	6	7	8	9	10	Average
8,4159	8,2090	8,2743	8,0475	8,8146	8,0478	8,1386	8,1314	8,1575	8,1061	8,2343

I.) Measurement at 400 ^oC

Breakdown voltage (kV) at ambient temperature 400 oC										
1	2	3	4	5	6	7	8	9	10	Average
8,2188	8,0491	8,0011	7,9210	8,0162	7,8410	7,9097	7,9677	8,0783	7,8552	7,9858

Test 3: Copper

A.) Measurement at 22,5 °C

Breakdown voltage (kV) at ambient temperature 22,5 oC										
1	2	3	4	5	6	7	8	9	10	Average
12,2050	12,4990	12,2330	12,5980	12,2080	12,5190	12,3280	12,3830	12,8920	12,5280	12,4393

B.) Measurement at 90 °C

Breakdown voltage (kV) at ambient temperature 90 oC										
1	2	3	4	5	6	7	8	9	10	Average
12,2010	12,0880	11,7920	11,6900	11,7260	11,5650	11,6210	11,7610	11,5840	11,4950	11,7523

C.) Measurement at 165 °C

Breakdown voltage (kV) at ambient temperature 165 oC										
1	2	3	4	5	6	7	8	9	10	Average
11,1920	10,2230	10,1880	10,2170	10,1630	10,0300	10,1300	10,1640	10,0870	10,1450	10,2539

D.) Measurement at 230 °C

Breakdown voltage (kV) at ambient temperature 230 oC										
1	2	3	4	5	6	7	8	9	10	Average
9,6656	9,6851	9,7416	9,5526	9,5241	9,4710	9,4721	9,5239	9,4476	9,4365	9,5520

E.) Measurement at 300 °C

Breakdown voltage (kV) at ambient temperature 300 oC										
1	2	3	4	5	6	7	8	9	10	Average
8,9538	9,0229	8,9324	8,6962	8,5661	8,5928	8,5487	8,4834	8,3450	8,4333	8,6575

F.) Measurement at 370 °C

Breakdown voltage (kV) at ambient temperature 370 oC										
1	2	3	4	5	6	7	8	9	10	Average
8,1158	7,8989	7,8323	7,9466	7,8195	7,8639	7,9722	8,1076	7,8169	7,8388	7,9213

G.) Measurement at 440 °C

Breakdown voltage (kV) at ambient temperature 440 oC										
1	2	3	4	5	6	7	8	9	10	Average
8,5582	7,7886	7,5159	7,6240	7,6307	7,6623	7,5228	7,4967	7,5631	7,4446	7,6807

H.) Measurement at 510 °C

Breakdown voltage (kV) at ambient temperature 510 oC										
1	2	3	4	5	6	7	8	9	10	Average
7,8012	7,2769	7,3407	7,2220	7,1571	7,1386	7,3636	7,1044	7,3552	7,1450	7,2905

I.) Measurement at 600 °C

Breakdown voltage (kV) at ambient temperature 600 oC										
1	2	3	4	5	6	7	8	9	10	Average
7,1140	6,7023	6,3744	6,5014	6,3817	6,3542	6,3169	6,4786	6,3264	6,2146	6,4765

J.) Measurement at 680 °C

Breakdown voltage (kV) at ambient temperature 680 oC										
1	2	3	4	5	6	7	8	9	10	Average
6,0242	5,9318	5,8455	5,8520	5,8246	5,8081	5,7306	5,8121	5,7450	5,7380	5,8312

K.) Measurement at 760 °C

Breakdown voltage (kV) at ambient temperature 760 oC										
1	2	3	4	5	6	7	8	9	10	Average
5,2474	5,3196	5,3461	5,3014	5,2956	5,2720	5,2542	5,1670	5,2255	5,2314	5,2660

L.) Measurement at 850 °C

Breakdown voltage (kV) at ambient temperature 850 oC										
1	2	3	4	5	6	7	8	9	10	Average
4,9182	4,9092	4,8620	4,8921	4,8352	4,8440	4,8338	4,8401	4,7960	4,7783	4,8509

Test 4: Iron

A.) Measurement at ambient temperature 22,2 °C

Breakdown voltage (kV) at ambient temperature 22,2 oC										
1	2	3	4	5	6	7	8	9	10	Average
11,0400	12,0180	12,1670	12,1650	12,2130	12,2130	12,1710	12,2490	12,2520	12,1830	12,0671

B.) Measurement at 100 °C

Breakdown voltage (kV) at ambient temperature 100 oC										
1	2	3	4	5	6	7	8	9	10	Average
11,2690	11,2820	11,3220	11,2970	11,3140	11,3310	11,3190	11,3340	11,2870	11,3120	11,3067

C.) Measurement at 225 °C

Breakdown voltage (kV) at ambient temperature 225 oC										
1	2	3	4	5	6	7	8	9	10	Average
9,4895	9,3832	9,4681	9,4462	9,4046	9,3820	9,4042	9,3368	9,2975	9,3067	9,3919

D.) Measurement at 350 °C

Breakdown voltage (kV) at ambient temperature 350 oC										
1	2	3	4	5	6	7	8	9	10	Average
7,0082	8,0728	7,9900	7,9542	7,9862	7,9992	8,0040	7,9138	7,9397	7,8455	7,8714

E.) Measurement at 475 °C

Breakdown voltage (kV) at ambient temperature 475 oC										
1	2	3	4	5	6	7	8	9	10	Average
6,9591	6,8533	6,8986	6,8088	6,7518	6,6872	6,7428	6,7418	6,6339	6,6946	6,7772

F.) Measurement at 600 °C

Breakdown voltage (kV) at ambient temperature 600 oC										
1	2	3	4	5	6	7	8	9	10	Average
5,9044	5,7837	5,8037	5,8002	5,7392	5,7007	5,6470	5,6461	5,6698	5,6356	5,7330

G.) Measurement at 725 °C

Breakdown voltage (kV) at ambient temperature 725 oC										
1	2	3	4	5	6	7	8	9	10	Average
4,6309	4,4579	4,6213	4,6586	4,6520	4,5850	4,5753	4,5390	4,5106	4,5300	4,5761

H.) Measurement at 850 °C

Breakdown voltage (kV) at ambient temperature 850 oC										
1	2	3	4	5	6	7	8	9	10	Average
4,2059	4,2346	4,2214	4,2291	4,2232	4,2037	4,1627	4,1314	4,1084	4,1595	4,1880

I.) Measurement at 975 °C

Breakdown voltage (kV) at ambient temperature 975 oC										
1	2	3	4	5	6	7	8	9	10	Average
3,6637	3,5377	3,5285	3,5217	3,5174	3,5566	3,5275	3,4702	3,5211	3,5524	3,5397

I.) Measurement at 1100 °C

Breakdown voltage (kV) at ambient temperature 1100 oC										
1	2	3	4	5	6	7	8	9	10	Average
3,5067	3,5686	3,5708	3,4994	3,5028	3,5475	3,5491	3,5201	3,5783	3,5045	3,5348

I.) Measurement at 1225 °C

Breakdown voltage (kV) at ambient temperature 1225 oC										
1	2	3	4	5	6	7	8	9	10	Average
3,5439	3,5853	3,5217	3,5146	3,5475	3,4630	3,5519	3,5336	3,4065	3,4910	3,5159

I.) Measurement at 1290 ^{o}C

Breakdown voltage (kV) at ambient temperature 1290 oC										
1	2	3	4	5	6	7	8	9	10	Average
2,5469	2,5860	2,5214	2,5225	2,5499	2,5844	2,5202	2,6348	2,5988	2,6669	2,5732

I.) Measurement at 1350 ^{o}C

Breakdown voltage (kV) at ambient temperature 1350 oC										
1	2	3	4	5	6	7	8	9	10	Average
2,2564	2,2063	2,1720	2,2654	2,2208	2,2293	2,2663	2,1410	2,1572	2,1928	2,2108

Test 5: Brass

A.) Measurement at ambient temperature 22,9 ^{o}C

Breakdown voltage (kV) at ambient temperature 22,9 oC										
1	2	3	4	5	6	7	8	9	10	Average
12,2660	13,1380	12,9210	12,7510	13,0350	12,7020	12,4390	12,6050	13,0210	12,5760	12,7454

B.) Measurement at 90 ^{o}C

Breakdown voltage (kV) at ambient temperature 90 oC										
1	2	3	4	5	6	7	8	9	10	Average
12,8020	12,1200	11,8290	12,0590	12,0860	11,6730	11,9870	11,9220	12,3760	12,4344	12,1288

C.) Measurement at 165 ^{o}C

Breakdown voltage (kV) at ambient temperature 165 oC										
1	2	3	4	5	6	7	8	9	10	Average
10,1400	9,8230	10,2900	10,2810	10,3550	9,9585	9,8318	10,2340	10,0860	9,8662	10,0866

D.) Measurement at 240 ^{o}C

Breakdown voltage (kV) at ambient temperature 240 oC										
1	2	3	4	5	6	7	8	9	10	Average
8,6423	8,8826	8,7292	8,9104	8,9562	8,9860	9,0248	8,8054	8,8848	8,7506	8,8572

E.) Measurement at 315 ^{o}C

Breakdown voltage (kV) at ambient temperature 315 oC										
1	2	3	4	5	6	7	8	9	10	Average
8,0414	7,9270	8,3375	8,1903	7,8550	7,9702	7,9654	8,0846	7,9946	7,9756	8,0342

F.) Measurement at 390 ^{o}C

Breakdown voltage (kV) at ambient temperature 390 oC										
1	2	3	4	5	6	7	8	9	10	Average
7,3601	7,2304	7,3221	7,2943	7,2433	7,2714	7,2412	7,2323	7,2406	7,2195	7,2655

G.) Measurement at 465 ^oC

Breakdown voltage (kV) at ambient temperature 465 oC										
1	2	3	4	5	6	7	8	9	10	Average
7,0131	7,0003	6,9506	6,9267	6,8440	6,8637	6,9429	6,8353	6,9371	6,8010	6,9115

H.) Measurement at 540 ^oC

Breakdown voltage (kV) at ambient temperature 540 oC										
1	2	3	4	5	6	7	8	9	10	Average
6,5387	6,4351	6,5134	6,4142	6,4138	6,4609	6,4970	6,4031	6,2987	6,4336	6,4409

I.) Measurement at 615 ^oC

Breakdown voltage (kV) at ambient temperature 615 oC										
1	2	3	4	5	6	7	8	9	10	Average
5,7983	5,7880	5,7069	5,7812	5,7590	5,7375	5,6905	5,6862	5,6287	5,6711	5,7247

I.) Measurement at 690 ^oC

Breakdown voltage (kV) at ambient temperature 690 oC										
1	2	3	4	5	6	7	8	9	10	Average
5,1462	5,1656	5,1540	5,1499	5,1029	5,0671	5,1187	5,0664	5,0172	5,0074	5,0995

I.) Measurement at 765 ^oC

Breakdown voltage (kV) at ambient temperature 765 oC										
1	2	3	4	5	6	7	8	9	10	Average
4,4459	4,6275	4,5943	4,6093	4,6466	4,6351	4,6977	4,6620	4,7248	4,6922	4,6335