ENERGY TRANSFERS WITHIN ARCING FAULTS IN ELECTRICAL EQUIPMENT

Dr. David Sweeting, Professor A.D.Stokes

Sweeting Consulting, A1 Pindari Ave St. Ives 2075 Australia, david@sweeting.com.au
University of Sydney, PO Box 389 Newport 2106 Australia, stokes@ee.usyd.edu.au

Abstract: **An arcing fault often develops from an insulation failure within electrical equipment. Arcing faults are substantially unconstrained free-burning arcs within electrical equipment.**
In order to assess the hazards of arcing faults to personnel in the immediate vicinity of the fault it is necessary to understand their nature and be able to quantify the hazards.
This involves an understanding of the energy dissipation and the energy transfers in the near vicinity of these uncontrolled arcs.
This paper sets out to describe the physics of arcing faults and uses this to describe the energy transfers within an arcing fault.
This is the basis for describing the potential energy transfers to personnel in the vicinity of an arcing fault.

Keywords: **arcing fault, energy transfer, line radiation, emission, absorption, electrode jets, restricted column, diffuse column, electrode-material column, air column, plasma cloud.**

1. Introduction

When insulation fails in electrical power equipment, an arcing fault often develops within the electrical equipment. Whilst an arcing fault includes the equipment on which the fault arc is burning, the degraded insulation which allows re-ignitions and the fault arc itself, the terms arcing-fault and fault-arc will be used interchangeably in this paper. Arcing faults are substantially unconstrained free burning arcs but in some circumstances a limited amount of constraint is provided by the equipment in the vicinity of or containing the arcing fault.

This paper sets out to describe the physics of arcing faults in order to use this description to describe the energy transfers within fault arcs and in particular three-phase free burning arcs on parallel electrodes. This description is required to form the basis for assessing the arcing fault hazard to personnel, who work on or in the vicinity of high power electrical equipment.

This paper continues the work described in “Electric Arc Burn hazards” [1].

2. Research Background

The vast majority of the literature on arcs deals with arcs that have been constrained or stabilised either to study them or to make them useful.

Arcing faults are not constrained, they occur. They are not wanted and are extremely turbulent. The present task is to deal with what actually occurs in practice rather than what can be easily studied.

The bulk of the arc literature is based on single-phase opposing electrodes, where the current comes from one side and flows across to the other side. Useful devices such as circuit breakers and fuses have this characteristic.

Hazardous arcing faults in electrical equipment are virtually always on parallel electrodes.

The literature on parallel-electrode arcs has concentrated on measuring the velocity of arcs travelling along single-phase rail guns.
The available literature therefore needs interpretation for the present topic.

3. High Power Electrical Equipment

This paper only deals with electrical equipment connected to an electrical supply system, which can provide fault currents sufficient to cause significant injuries to personnel in the vicinity of an arcing fault. Such electrical installations consist of:

- Live Conductors (busbars/cables), which become electrodes for an arc,
- Neutral conductors, which become electrodes for an arc,
- Earth/ground conductors, which become electrodes for an arc
- Insulation between the live conductors and earth conductors

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- Enclosures
- Electrical Protection Systems

The words (phase/neutral/earth/ground) describe the electrical potential of a conductor. The words (conductor/busbar/cable) describe how the conductor carries current. The word electrode describes the conductor from which current flows into an arc. Phase, conductor and electrode therefore describe different properties of the same thing and may be used interchangeably within this paper.

3.1 Arcing Fault Electrode Configuration

For faults in high power electrical equipment, the arc burns from up to three parallel live conductors. It is these three live-conductors that contain the fuses or circuit breaker contacts of the protection that is designed to clear the fault. The three live-electrodes are likely to have near to the minimum practical separation for the voltage level of the equipment.

When the neutral conductor follows a separate route to the live conductors, it is likely to not be involved in the fault due to the lack of a mechanism to get fault current into the neutral.

When the neutral runs parallel to the live conductors it can form a fourth parallel electrode.

It is harder to generalise the path of the earth/ground currents in the vicinity of the arc root.

Due to the magnetic influence on the arc behaviour, the earth/ground current is most likely to enter the earth/ground plane of switchgear enclosures in the plane of the three parallel live conductors. That is either beyond the end of the three live electrodes or outside the two outer electrodes in the same plane. What is important is the initial direction of current flow from the arc root. This determines the direction of travel of the arc root. There are the following possibilities.

(a) Earth/ground currents return parallel to the three parallel live conductors in the enclosure walls either side of the three parallel live conductors. This produces arcing in up to five parallel electrodes. This outcome is driven by inductance effects.

(b) Due to the arrangement of the earth/ground conductors in the enclosure, the earth/ground current flows in a distinct direction. This outcome is normally driven by resistance effects.

3.2 Fault Location and Movement

Arcing faults are initiated at a particular location because of some unwanted event. Either the insulation fails or a conductor is accidentally placed across a potential difference. They rarely however remain at the initiation site.
The current enters the conductor at right angles to the surface and then flows back towards the source. This produces a magnetic driving force, which drives the arc root away from the source of supply.

As a result the arc will run away from the source of supply until it reaches something, which prevents it going further. This can be an end to the un-insulated conductor or a barrier.

Sometimes the arc voltage is sufficient to cause a breakdown of the insulation closer to the source of supply. This will cause a new arc to form at the breakdown point and the arc further down the conductor to extinguish. (Arcs will not burn in parallel for any length of time.)

The new arc will then run away from the source of supply.

Relatively stable arcing locations will therefore be found at the end of busbars, at gaps such as open contacts or before the conductors disappear inside insulation.

Highly mobile arcing locations often occur at the earth/ground electrode due to the influence of the self magnetic field of the current. They also occur on live busbars where there is nothing to provide stabilisation.

Highly mobile arcs behave differently to relatively stable arcs.

4. The Components of an Arcing Fault

An arcing fault within electrical equipment will be fed from up to three active (live) phases.

Depending on the source characteristics, the current from the active phases will return either on the other active phases or via a neutral or earth/ground system.

In general, the arcing fault will burn on,

> Up to three parallel active (live) conductors,
> With up to three mobile arc roots on the neutral and/or earth/ground, conductors.

The arc roots on the neutral earth/ground conductors are likely to be outside the active conductors on the same plane as the active conductors due to the self-magnetic field influences on the arc columns.

Each live conductor, which becomes an electrode for an arc, is only likely to have one arc root and one cathode/anode jet coming off it most of the time.

There is only one arc root per conductor because arcs will not burn in parallel for more than a brief moment due to the negative voltage/current characteristic of atmospheric pressure arcs. Due to this characteristic, the smaller current arc or the longer arc will rapidly commutate into the other parallel arc and self extinguish. When an arc root is highly mobile more than one arc root can occur.

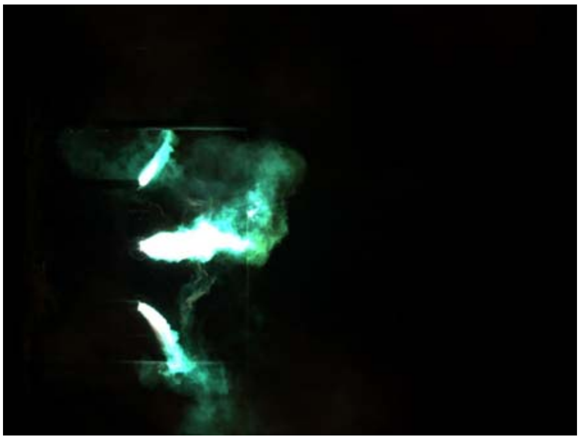

Fig. 1 One frame of a 5,000 frames per second movie of a 15,000Amp arcing fault on three live plus one surrounding earth electrodes.

Figure 1 shows an arcing fault on five-parallel conductors with the earth conductor surrounding the live conductors in the conductor plane. This shows that up to three extra arc roots can form on the earth/ground plane depending on the supply characteristics.

The arc roots on the live conductors move rapidly to relatively stable locations.

The arc roots on the earth/ground conductor are highly mobile and unstable. Even with a solidly connected surrounding ground/earth, the number of ground/earth arc roots oscillates between 0 and 3.

An arcing fault therefore consists of the following components:

- Cathodes, where electrons are emitted from the conductor and flow into the plasma,
- Anodes, where the electrons from the plasma re-enter a conductor (the cathodes and anodes are either highly mobile or relatively stable),
- Electrode material arc columns (these start at each stable electrode with a constricted arc column containing an axial plasma jet and tend to remain relatively straight.),
- Mainly air arc columns (these start at highly mobile electrodes and also connect between the constricted electrode-material jet columns),
- Some sections of constricted arc column in the plasma cloud can sometimes occur,
- Air which has not yet been contaminated by the electrode material,
- The plasma cloud generated by the arcs.

4.1 Cathodes and Anodes

At the cathode, electrons leave the crystalline structure of the conductor and enter the plasma of the arc core. At the anode, the electrons re-enter the conductor.

Both the cathode and anode spots have a cross sectional area, which is smaller than the neighbouring constricted arc column. As a result near to the cathode and anode spot the arc has a conical or hourglass shape.

The self magnetic field of the current in the column near to the electrode spot interacts with the current itself to draw air radially into the column, dissociate it, ionise it and drive the resultant plasma axially away from the cathode spot. This is what produces the electrode jets.

The same mechanism also increases the pressure inside the arc core above the surrounding air pressure.

Both the cathode and anode have a voltage drop of approximately 10 Volts over a distance of around a micrometer. Almost all of the energy from the 10 Volt electrode drop finishes up in the electrode material. For relatively stable arc roots on copper, aluminium and steel, this means it melts the metal and the pressure from under the electrode spot blows the molten droplets in all directions. With carbon electrodes (this includes carbonised insulation) the carbon does not go through a molten stage and it ablates from under the cathode spot. Carbon and steel electrodes can be heated to incandescence whereupon they become refractory electrodes that emit free electrons and are easy to restrike from.

Every time the current from a conductor changes sign, the cathode must change into an anode or the anode must change into a cathode. The creation of cathodes is the most difficult transition and requires sufficient voltage for it to occur.

The cathode consists of a positive ion space charge sitting of the order of a micrometer off the conductor surface. Every time a cathode is created this space charge must be created. This requires a minimum voltage of around 400Volts.

As a result the very small depth (in comparison to their cross section) of both the cathode and anode space-charges, the current always enters the conductor perpendicular to the conductor surface at the location of the arc root (sometimes called an electrode spot).

4.2 Constricted Electrode-Jet Arc Columns

The small cross section of the electrode spots results in conical or hourglass shaped arc columns in the regions of the electrodes.

The self magnetic field of the current in the column interacts with the current itself (positive ions and free electrons) to drive the plasma axially away from the electrode spot. [2] (The axial current density produces a circumferential magnetic field, which together with the radially outwards component of the current density produces an axial force on the ions and electrons.) This produces the electrode jets. It also draws cool air radially into the arc column to replace the plasma being driven out axially. The energy required to heat, dissociate and ionise the radial air inflow, cools the surface of the arc column and produces a sharp temperature gradient on the boundary of the arc core in the radial inflow region.

The strong radial air inflow and the sharp radial temperature gradient will insulate the side of an electrode jet. Thus electrical connection between two electrode jets will be difficult until after the strong radial inflow has abated and the columns have become more diffuse. This will correspond to where the arc column starts to become cylindrical.

The high velocity axial flow in the electrode jets is also such that two jets hydraulically repel each other.

This would indicate that there is a minimum arc length between two electrodes. This would be the sum of the length of two constricted arc jets up until when the boundary of the arc-jets become diffuse enough to allow the current to cross over to the other electrode jet.

In the arc column from the electrode spot up until where the current and plasma jet starts to go in different directions, the diameter of the arc is increasing, which means the current density is decreasing.

The decreasing current density is likely to be associated with decreasing electric field gradient, lower electron temperature and lower plasma temperature. Roberts 1972 [3] reported the core temperature of a free burning arc dropping from around 30,000° at the cathode to around 15,000° five centimetres away.

This is consistent with the three orders of magnitude reduction in luminosity of the arc column from next to the electrode spot until the diffuse mainly air column connecting the three electrode jets reported by Stokes and Sweeting in 2004. It is also consistent with the photographs in this paper where radiation from the arc core next to relatively stable arc roots saturates the camera and the diffuse columns and plasma cloud are often black.

The mobility of the arc root has a strong influence on the luminosity of the constricted column. On highly mobile and new arc roots, where the arc has dwelled for less time than needed to melt the electrode material, the arc jet consists mainly of air and is not strongly dominated by the electrode material. As well as the lack of molten electrode material, the highly mobile arc has a magnetically driven cross flow.

On the other hand with relatively stable arc roots, where the arc dwells long enough to produce a spray of electrode droplets, the constricted arc column and the plasma jet contains entrained electrode material that after a while oozes out of and envelops the arc column. The resulting electrode material sheath then absorbs most of the electrode line emission.

The following photograph shows a single phase arc where the bottom arc root has migrated off the molten electrode material and is now burning in oxygen/nitrogen whilst the top arc root is burning in copper vapour. Notice the influence on colour and luminosity from identical current.

Highly mobile and new arc roots appear like the one on the lower electrode. Not only does the colour change, the luminosity drops off dramatically.

Fig. 2. A frame from a 15kA single phase arc where the lower arc root drifted off the molten copper and produced an air dominated arc jet.

This photograph was recorded using extra neutral density filters to minimise camera saturation at the arc root. As a result the diffuse core is very weak and the plasma cloud is black.

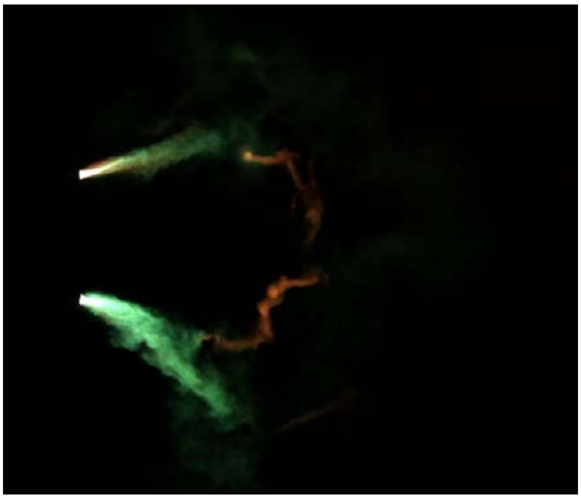

Fig. 3 A single-phase arcing fault showing the electrode vapour oozing out of the constricted column within centimetres of the electrode and an air dominated column connecting the copper dominated arc jets.

The electrode jet arc column up until where there is a divergence between the plasma jet and the current carrying core is therefore likely to be characterised by:

- A conical or hourglass variation in cross sectional area of the conducting core,
- The cross sectional area at any specific distance from the electrode proportional to current (a nearly constant current density with time or current),
- Radial inflow of air and axial outflow of plasma,
- A steep radial temperature profile at the electrode (due to radial cooling in-flow) becoming less steep as the jet is further from the electrode,
- A constant total voltage drop (as a function of both time and current) (the voltage drop given by one half of the minimum voltage between electrodes).

As you move away from the electrode,
- A drop in the electric field gradient (due to a drop in current density),
- A drop in plasma temperature (due to drop in electric field gradient and current density),
- A drop in luminosity of the arc by three orders of magnitude (measured),
- A drop in the intensity of emitted line radiation (lower field gradient/ electron temperature),
- A narrowing of the width of line radiation (lower atom/ion temperature),
- A broadening of the dark absorption band in the line radiation (due to a drop in the temperature gradient and therefore greater adsorption of line radiation),
- A drop in the intensity of the continuum radiation (due to a drop in the plasma temperature).

4.3 Arc Column Details

Whilst the electric field within an arc column acts on both the ions and the electrons, the vast majority of the energy is transferred to the lighter electrons. The electrons transfer their energy to the atoms and ions by collision.

In the arc core, the electron collisions with atoms and ions excite electrons attached to the atoms and ions and drive them to a higher energy state. When these electrons fall back to their normal energy level they emit light of a fixed frequency, which is determined by the difference between the two energy levels. This is the line radiation emitted by the arc. Line radiation dominates energy transfer within the core of atmospheric pressure arcs.

The temperature (thermal velocity) of the atoms/ions causes Doppler shifting of the line radiation. When added to Stark broadening, due to micro fields around each atom, the emitted line radiation is broadened.

Line radiation in the centre of an arc does not get very far however before it is adsorbed by another atom/ion. Near the edge of the arc, lines emitted with significant frequency shifting can escape from the arc because there are insufficient identical atoms/ions outside them to adsorb the radiation of that frequency. Thus the two edges of broadened lines with a dark adsorption band in the middle are often observed when studying the light emitted from electric arc columns.

In air, the oxygen and nitrogen molecules also adsorb all radiation in the vacuum ultraviolet. This is adsorbed by splitting the molecule and is not re-emitted when the molecule re-associates.

Arcs in air have their strongest line energy emitters in the vacuum ultraviolet. All of this energy is trapped when the radiation enters atmospheric air, which contains molecules. It therefore gets adsorbed at the molecular boundary of the hot plasma.

In the constricted arc columns with radial inflow of cooling air, all the vacuum ultraviolet radiation from the air flows out to the molecular boundary and some is then sucked back into the arc core by the radial inflow of gas.

If the constricted arc column is attached to a relatively stable arc root electrode material is entrained in the constricted column. Close to the electrode, lines from the electrode material are not absorbed by the surrounding air. This region therefore emits far stronger radiation than anywhere else along the arc column.

A short distance from the arc root, electrode material begins to ooze out of the arc column and this material then absorbs line radiation emitted by electrode material inside the arc core. The electrode material line radiation therefore drops off dramatically after electrode material begins to ooze out of the arc column. This can be seen in figure 3.

If the constricted arc column is attached to a highly mobile arc root or in the first few 100 microseconds after a new arc establishes, significant electrode material is not entrained in the arc jet. There is then no electrode material line emission and the main oxygen/nitrogen lines are absorbed at the molecular boundary. The observed radiation from the constricted arc column is then significantly (factors) lower.

In the oxygen/nitrogen arc column without electrode material, the vacuum ultraviolet radiation will radiate out to the molecular boundary (boundary of the plasma cloud) where it will be adsorbed and taken away with the plasma cloud.

For an object inside the molecular boundary, the oxygen and nitrogen vacuum-ultraviolet lines will reach the surface of the object.

The line radiation from oxygen and nitrogen atoms, which is not broadened, will be adsorbed by atoms and molecules within the plasma cloud. Only the broadened edges of the lines can escape from the arc/plasma-cloud to be observed. A sharp temperature profile helps the broadened line edges to escape because there is less gas of the same temperature to pass through in order to escape the arc. As the temperature gradient falls however, it is anticipated that the intensity of radiation that escapes will also fall because of greater adsorption.

Line radiation from the electrode material, copper and/or aluminium, dominates the radiation which escapes from the arc core so that it can be measured and/or cause burns to people. This is because there are few atoms outside the core to adsorb any radiation that escapes. For an electrode material arc burning inside the plasma cloud however, there is a source of electrode material vapour, which can adsorb the electrode-material radiation-lines.

Our photographs indicate that the intensity of line radiation from the arc column falls with distance from the electrode spot both due to lower emissions from lower temperatures and greater adsorption due to declining wall temperature gradients. When the column is inside the sheath and/or the cloud, the electrode-material lines are also adsorbed.

Continuum radiation that is a function of the plasma cloud temperature is likely to be the main radiation that escapes from the plasma cloud. The cloud beyond the arcing region is only however between 3000ºK and 5000ºK.

4.4 The Oxygen/Nitrogen or Diffuse Column

The arc column that connects the constricted arc jet columns to each other is mainly an oxygen/nitrogen column with little electrode material. It looks like a diffuse column because so much of the radiation is adsorbed. The lack of electrode material can be seen in the colour of the connecting column.

The arc current is flowing in a plasma core that is immersed inside the plasma cloud.

The luminosity of the diffuse arc columns is around three orders of magnitude smaller than that of the electrode-jet columns near to the electrodes.

This is likely to be due to both less emission due to a lower plasma temperature plus adsorption of the line-radiation by the surrounding plasma cloud. The plasma cloud contains electrode vapour, which allows it to adsorb line radiation emitted from any electrode material.

On three electrode systems, only one arc jet per electrode has been observed. This means the diffuse column has three ends, which must join somewhere in the middle. Whilst it is clear that the arc jet columns carry the same current as their electrode, the diffuse column current depends on where the join is.

Whilst the arc jet columns appear to have a reasonably constant length, the diffuse columns are blown out by the magnetic fields and continually restrike along shorter paths.

Arc voltage measurements with parallel electrodes indicate that the average length of the diffuse core is proportional to the instantaneous current. Arc voltages on parallel electrodes tend to be sinusoidal, whilst arc voltages on opposing electrodes tend to be constant with current. The difference is that arcs on parallel electrodes change their length with the current.

4.5 Changes in arc length

As the current increases after a current zero, the increased self magnetic force due to the current interacting with its own magnetic field blows the arc out to a larger radius and therefore a larger voltage drop along the arc column.

Then an arc column appears across a shorter path and the longer arc path decays. The shorter arc paths are usually air dominated with little electrode material radiation. They often start and remain a straight line between the arc jets as they travel in the jxB direction. This indicates that they are probably in an existing plasma flow.

The shorter path is between two arc columns and does not involve creating a new cathode drop. The gap is only stressed by the arc column voltage drop along the longer arc path.

To achieve breakdown with this level of voltage stress the gas between the arc jets needs to be already ionised by a mechanism other than electron avalanche.

We believe that the air on the breakdown path has been heated and ionised by line radiation from the existing arc columns. It is unlikely to be in thermal equilibrium so it is difficult to assign it a temperature.

It is however almost certainly inside the molecular boundary, where all molecules have been split by the strong vacuum ultraviolet oxygen and nitrogen lines. Since recombination of the atoms produces heat, this is a strong heating process.

The oxygen/nitrogen lines produced by recombination of electrons and oxygen/nitrogen ions in the arc columns will produce ions and electrons inside the molecular boundary and in doing so provide a mechanism for electrical heating of the same space without requiring electron avalanche ionisation of the plasma.

Inside the molecular boundary, we therefore expect a current density determined by the voltage distribution along the arc columns and electrodes plus the conductivity created by the oxygen/nitrogen recombination lines.

This current distribution will be driven by the jxB forces created by the magnetic field of the current in the electrodes and main arc columns. This will drive the plasma inside the molecular boundary and create a flow similar to what we observe in the movement of the new breakdown columns.

The arc shortening breakdowns therefore become an initiation of an electron avalanche mechanism inside bulk plasma travelling away from the electrodes and already carrying a much smaller current.

In some frames of our high speed videos more than one path breaking down into a constricted column can be seen. Also in some frames the breakdown is firstly to a bright highly constricted path decaying into a much less bright diffuse column within 100 to 200 microseconds.

This mechanism indicates that the molecular boundary is at least hundreds of millimetres away from the arc columns.

4.6 The Plasma Cloud

Once there is no current in the plasma, the temperature falls rapidly to around 5,000°K and then more slowly to around 3000ºK. We anticipate that radiation, some of which is further adsorbed in the surrounding plasma is still the dominant mechanism.

Whilst turbulent mixing can be seen in the photographs, the glowing cloud maintains an identifiable structure as it moves away from the electrodes.
This limits the ability of turbulent mixing to play a significant role.

Within the plasma cloud line radiation is expected to play a less significant role and normal black body radiation due to the thermal motion of the particles is expected to dominate.

5. Energy Flows

5.1 Energy Dissipation

The voltage and current in the arc produces four distinct energy sources.

The energy from 10 Volt anode and cathode voltage drops is mainly dissipated in the electrode material.

The energy from the approximately 10 Volts/cm of arc column voltage drop is initially transferred to electron velocity within the arc core.

The voltage distribution along the electrodes and arc columns also produces a much lower current distribution in the plasma surrounding the arc and the lower energy from this is transferred initially to the electrons in the plasma surrounding the arc columns.

The interaction of the self magnetic field of the current in the electrodes and arc column produces electromagnetic forces on the arc column and diffuse plasma inside the molecular boundary.

5.2 Electrode Drop Energy

On highly mobile or new arc roots, the energy dissipated in the electrode does not have time to melt sufficient electrode material to cause an electrode spray or feed significant electrode material into the constricted column next to the electrode.

In part the mechanisms causing high mobility also causes cross flow on the arc column and the column therefore burns in the cross flow material rather than material close to or from the electrode.

On relatively stable arc roots on copper, aluminium and iron, the energy dissipated in the electrode produces a pool of molten material under the arc root.

This energy produces a spray of electrode material. On copper electrodes this consists of small droplets of 1080°C copper, which settle on nearby surfaces. On aluminium electrodes this produces droplets of aluminium, which burn to insulating aluminium oxide.

Our recent experiments show that this also produces a flow of electrode material into the constricted arc column next to the electrode. After a few centimetres, this electrode material oozes out of the column and then absorbs line radiation from the electrode material.

5.3 Arc Column Energy

The energy dissipated by the approximately 10V/cm voltage drop along the arc column is initially transferred mainly to electron velocity.

Electron collision with the atoms and ions of oxygen, nitrogen and the electrode material excite electrons in the atoms and ions.

Decay of the excited electrons to their natural energy level produces line radiation, which is then broadened by Doppler and Stark broadening. [4]

This line radiation is emitted in all directions until it is absorbed by another atom or ion of the same element with the same thermal and electric field properties. Another way of describing this is the absorbing atom/ion has to have the same broadening mechanisms as the emitting atom/ion or the radiation will pass by.

Within the arc core there are plenty of absorbing atom/ions and the energy is transferred to the boundary by repetitive emission and absorption.

Next to the anode/cathode, the air inflow driven by the electrode jets produces a steep temperature profile in air, which allows the outer wings of each broadened line to escape leaving a dark space in the centre of the line. The centre of each line is absorbed by the cooler air surrounding the arc column.

With little electrode gas in the inflow to the constricted arc column, the lines from the electrode material are able to escape all the way to the camera.

The electrode material lines are also strong in this region because the arc column is constricted by the anode/cathode and the current density and plasma temperature is higher.

Within a few centimetres of the anode/cathode on relatively stable arc roots we have observed electrode vapour oozing out of the electrode jet, which then absorbs some of the electrode material lines and significantly weakens them.

As a result the bulk of the radiated energy reaching the camera comes from the first few centimetres of constricted arc column next to relatively stable arc roots.

With highly mobile and new arc roots the anode/cathode heating of the electrode material is unable to feed electrode material into the constricted column so only oxygen/nitrogen lines are emitted by the constricted arc core.

The centre of the oxygen/nitrogen lines will also be absorbed near the arc core and some of these will also cause electrons to be split off atoms and dragged away in the electric field. This will create the diffuse current, which is the third form of energy dissipation.

The rest of the strong oxygen/nitrogen lines will pass through the inner layer of air until they reach oxygen/nitrogen molecules. Since the strong lines of oxygen and nitrogen are emitted in the vacuum ultra-violet they will be absorbed by the surrounding oxygen/nitrogen molecules, which will be split into atoms.

Recombination of the oxygen/nitrogen atoms into molecules will then transform the energy into heat or thermal velocity of the molecules.

In this way the strong oxygen/nitrogen lines heat the air at a distance from the arc column and together with the lines from ion/electron recombination in the

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arc column core create a plasma cloud around the arc column core.

As a result of the above processes only the wings of oxygen/nitrogen lines in the visible spectrum reach the camera. These are much weaker than the electrode material lines, which reach the camera because the strong electrode material lines are in the visible spectrum and pass through air.

When plasma cloud containing significant electrode vapour comes between the arc column core and the camera, the intensity of electrode material radiation recorded by the camera also falls significantly due to absorption.

5.4 Diffuse Plasma Energy

The diffuse air plasma created by the absorption of the oxygen/nitrogen lines including those resulting from electron ion recombination in the arc column core is also subject to an electric field created by the electrodes and the arc column.

The current flowing in this diffuse plasma will also heat the plasma.

There are therefore two sources of heat for the air plasma within the molecular boundary.

Both of these energy supplies will stop after the molecular boundary and then the plasma will cool by the normal thermal radiation process, which follows a T^4 formula. This leads to an initial rapid cooling followed by a slower tail.

5.5 Electromagnetic Energy

The current through the electrodes and the arc column produces a magnetic field. This interacts with current density in the arc column and the diffuse plasma to produce electromagnetic forces on the electrons and ions.

These electromagnetic forces drive the electrode jets. They drive the arc column to expand in the form of an arc.

They also drive the diffuse plasma to move like a bulk flow in the same direction. This is evident in breakdowns which flow away as straight arc-columns instead of arc-shaped columns.

5.6 Other Energy transfers

As well as line radiation energy can be transferred by thermal conduction, turbulent mixing and continuum radiation due to the temperature of the gas/plasma.

Except on the steep sides of the constricted arc column, temperature gradients in the plasma cloud are not enough for significant conductive energy transfers.

When the camera is set to record radiation from the plasma cloud it maintains an identifiable pattern which means that the level of turbulence is also not large. In fact in the breakdown region it almost appears laminar.

Whilst we have yet to use a spectrometer on this arc, nearly all arc spectrographs show the lines as very much stronger than the continuum. We therefore think that the continuum will only dominate when line absorption and diffuse current heating have ceased.

6. Conclusion

Arcing faults in electrical equipment are normally supplied by three parallel active conductors.

An arcing fault will normally develop three relatively stable arc roots on the three parallel active electrodes.

On the ground/earth electrodes in the vicinity of the arcing fault highly mobile arc roots tend to form. These can vary over time between none and up to three separate arc roots.

The three relatively stable arc roots on the parallel active conductors will produce strong arc jets containing significant electrode material.

Sprays of molten (copper) or burning (aluminium) metal droplets are emitted from under the relatively stable arc roots.

The first few centimetres of the arc jets from relatively stable arc roots produce the vast majority of the radiation emitted from the arcing fault that reaches a camera or observer outside of the plasma cloud.

The electric field along the arc columns accelerates the free electrons in the arc column and these free electrons collide with the atoms and ions of oxygen, nitrogen and the electrode material.

These collisions raise the energy levels of the electrons in the three sets of atoms/ions causing some emission of free electrons.

The electrons falling back to their normal energy states emit line radiation which is Doppler and Stark broadened.

Due to absorption only the wings of the broadened lines in the visible spectrum reach an observer or camera.

The vast majority of the emitted lines are absorbed within the plasma cloud.

The electrode material lines are absorbed by electrode vapour that oozes out of the arc column and is left in the plasma cloud.

The strong oxygen and nitrogen lines are in the vacuum ultraviolet and are absorbed by oxygen and nitrogen molecules which are dissociated and heat the plasma on recombination. This leaves a molecular boundary around the arc column.

Inside the molecular boundary the lines from recombination of electrons and oxygen/nitrogen ions in the arc column cause ionisation and diffuse current flow in the surrounding plasma cloud.

When the arc column lengthens due to electromagnetic forces the increased arc column voltage drop causes arc columns to develop in the diffuse plasma cloud inside the molecular boundary. These new columns shorten the arc length.

These processes vary the arc length with current every cycle causing the arc voltage to follow something like a sine wave form.
Inside the molecular boundary the current in the diffuse plasma reacts with the magnetic field of the current in the electrodes and arc column to cause a magnetically driven flow of plasma.

As a result an unexpectedly uniform plasma cloud is driven away from the parallel electrodes.

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