Doctoral Thesis
Shibaura Institute of Technology

A Study on Joule Heating and Arc-fault Induced Electrical Fire in Commercial grade Copper and Brass in Low Voltage Electrical system

2022 September

Sittichai Wangwiwattana

Graduate School of Engineering and Science
Shibaura Institute of Technology

Thesis for the Degree of Doctor of Engineering

A Study on Joule heating and Arc-fault Induced Electrical Fire in Commercial grade Copper and Brass in Low Voltage Electrical system

September 2022

Division	Functional Control System
Student ID	NB19508
Name	Sittichai Wangwiwattana
Supervisor	Prof. Dr. Yoshikazu Koike
Co-Supervisor	Prof. Dr. Hideki Yokoi

PREFACE

Back when I was living in Thailand. My father always put home security and his family at an utmost important. Luckily in my country. Armed home invasion is far few and Crime rate in my area has never been high. However, the main problem in Thailand is its fire hazard. Electrical fire hazard is one of the most proliferate fire incident in Thailand. Even more so that we were not able to track down the exact cause of the fire. My father has always told me when I have to live alone in the house for a few weeks to always check the electrical appliance around the house and if possible, never use anything that can caught fire. Unto the day I was given a chance by SIT and my advisor Yoshikazu Koike, I have a chance to study an electrical fire that my family, especially my father has been in a constant worried of our house caught fire and burn down. With this study. I will be able to educate my father and ease up to mind of my family member. I would also be able to reduce the chance of electrical fire not just in my house, but for anyone who have read this research.

ABSTRACT

This research focuses on Electrical fire causes by an arc-fault phenomenon. Arc-Fault is not commonly known as a main life hazard in a low voltage environment. Nonetheless arc fault remain one of the mysteries where the mechanism behind it is unknown. This thesis has uncovered that arc-fault phenomenon largely depend on the type of conductor used in the construction and its affected area. In which copper is the main cause of all low voltage arc-fault in basic electrical appliance. Alloy of copper that was used as an electrical conductor is no exception due to copper oxide semiconducting property. This thesis has also devised means to detect such phenomenon with effectively simple yet robust system that can be mass produce in for many applications. There are still a number of drawback and the limitation of the system which will need to be refine in the further study.

Table of Content

Preface **3**

Abstract **3**

Table of Content **4**

Chapter 1: Introduction **6**

1.1 Overview of Fire Hazard 6

1.2 Background of Glowing Connection and Arc-Fault 11

1.3 Previous Work by Other Researchers 18

1.4 Problem Statement of low voltage arc-fault 21

1.5 Research Scope 22

1.6 Thesis Structure 22

1.7 References 23

Chapter 2: Environment Setup and Experiment **25**

2.1 Experiment Configuration 26

2.2 Experiment Samples and Current Sources 29

2.3 References 33

Chapter 3: The relation between series type arc-fault and Voltage waveform **34**

Chapter 4: The relation between series type arc-fault and Contact temperature **41**

4.1 Heating effect in brass – brass contact 42

4.2 Heating effect in brass – copper contact 45

4.3 Contact resistance relation to the temperature of the contact 50

4.4 References 53

Chapter 5: The relation between series type arc-fault and Contact vibration **54**

Chapter 6: Contact Surface Inspection **61**

6.1 Light microscopy of the sample 61

6.2 Electron microscopy of the sample 67

6.3 X-Ray diffraction analyzes 81

6.4 References 86

Chapter 7: Overview of the Arc-Fault and Joule Heating Mechanism **87**

7.1 Micro-contact and current constriction 87

7.2 The Series Arc-fault in the system 88

7.3 Summary of the mechanism 93

Chapter 8: Detection and Prevention **95**

8.1 Detection Background 95

8.2 Voltage Disparity between Two cathode Method 95

8.3 Saturated Current Transformer Method 106

8.4 Conclusion to the Detection Method 118

8.5 References 118

Chapter 9: Conclusion **119**

9.1 Conclusion to the finding 119

9.2 Electrical appliance those are likely to cause fire are listed below with description 121

9.3 Action from the user can potentially increase chance of fire hazard from arc-fault are listed below with descriptions 121

9.4 Future Possible Study 122

Publication Lists **123**

Acknowledgement **124**

Chapter 1: Introduction

1.1 Overview of Fire Hazard

Since the beginning of human ingenuity, fire hazard has been one of the great unmakers of many civilizations. Either by natural occurring fire hazard such as wildfire from ambient temperature or lightning induced fire or human made fire such as arsons or accidental fire. This type of hazard is multiplied in its severity depend on the population density of the area and the construction of the building and its surrounding environment. Technological advancement in the industry area has never before increased the risk of fire beyond what can nature can cause. Steam engine requires a constant stream of burnable material to produce superheated water vapor. Oil lantern uses at night and in area where natural light could not reach such as area deep in the mine. Not until industrial level of electricity generation, once electricity and its device has become something not as a novel technology but as something that can be owned by anyone, that is when flammable devices like oil lantern and combustible mean of generating power in small household is phased out. However, the fire hazard is still something that cannot be weed out. Even though the technology in the household and devices no longer use combustible material that can catch fire easily. Electricity is still an energy which can be transfer and convert into thermal energy. The conversion rate from electrical into thermal energy may not be as efficient as a direct method when compare to direct thermal energy transfer. Since the power source is essentially infinite energy, the only limiting factor for the energy conversion is the material that is used to convert the energy itself. For example, an old lightbulb can convert electrical energy into thermal energy with tungsten filament. The filament is able to efficiently convert electrical energy into large amount of thermal energy. The filament would also produce light as a byproduct. Normally the filament is the limiting factor of how much power can be dissipate into itself. If the filament has infinite durability and the current carrying capacity is also infinite. In theory, the filament would pull as much power as the energy source can provide. In practical however, the filament will burn off from high temperature and shut off the circuit before any damage can be done. This basic is the same for most type of electrical fire hazard. If the electrical power is able to move from point A to point B within a medium, the specific medium is unable to move the electrical power efficiently. The power would be lost and would radiate into heat. If the radiate thermal energy is high enough, it can cause fire incidence.

Since Japan adoption of the electrical system back in 1878, electrical fire hazard has been one of the most prominent hazards in Japan. Especially the construction material of the building in town and city are mostly made off wood and paper. The population density of big city such as Tokyo made any type of fire hazard as a greater problem. In 1923, Great Kanto Earthquake has destroyed majority of the Tokyo. The Earthquake by itself does not cause large amount of damage, the firestorm that followed after the Earthquake causes by broken gas pipeline, overturn cookery and electrical short circuit in a major part causes large amount of death both direct and indirectly. Since then, Japan has been trying to monitor and control any type of fire hazard. Preferably, stop the fire from spreading from the primary area.

Until now, fire incident in Tokyo is in the reducing trend as shown in Figure 1.1. The main reason is that he technological advancement on fire detection for preventative method or devices increase in user awareness of the fire hazard.

Figure 1.1: The number of fire incidence in Tokyo area has been steadily decreasing.

Currently a fire hazard from human made cause is divided into two main types. First type is a direct action from human such as arson, children playing with fire, untended barbecue spit or accidental such as, people throwing a used cigarettes into a flammable material or product mishandling. This type of fire hazard can be hard to predict due to our human nature. If everyone is properly educated, this type of risk can be reduced. The second type is a mechanical failure or electrical failure of a machine. This type of risk can include indirect action from human activity. This type of man-made fire hazard is the most destructive of all due to unpredictability. When a machine was designed and used within its designed function, we are expected the machine to function as intended. A regular maintenance is in order. However, due to the environment factor, the machine may degrade or breakdown before its lifetime has reached. A mishandling of the machine can also reduce the machine lifespan. In this case, the machine needs to be inspect and supervise at all time. If there is a sign of incoming breakdown, the machine should be stop and change the part that required to be change. However, in the actual use, we are unable to supervise all machines. A mechanical breakdown can cause physical damage such as a gear set loose from the sprocket which jam up the production line and may damage anything or anyone near the affected area. An electrical failure in a machine can either stop the machine completely, Make the machine run at the speed that was not designed for. It can also directly cause an electrical fire as explained earlier in the introduction. According to Tokyo Fire Department report in 2020, even though overall fire incident is steadily decreasing, reports of electrical fire is in the increase trend as shown in Figure 1.2

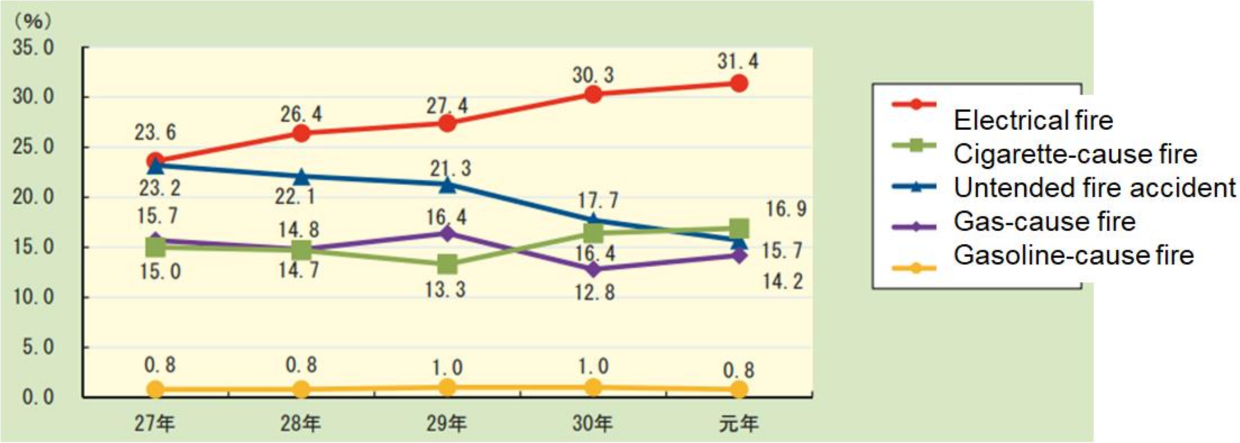
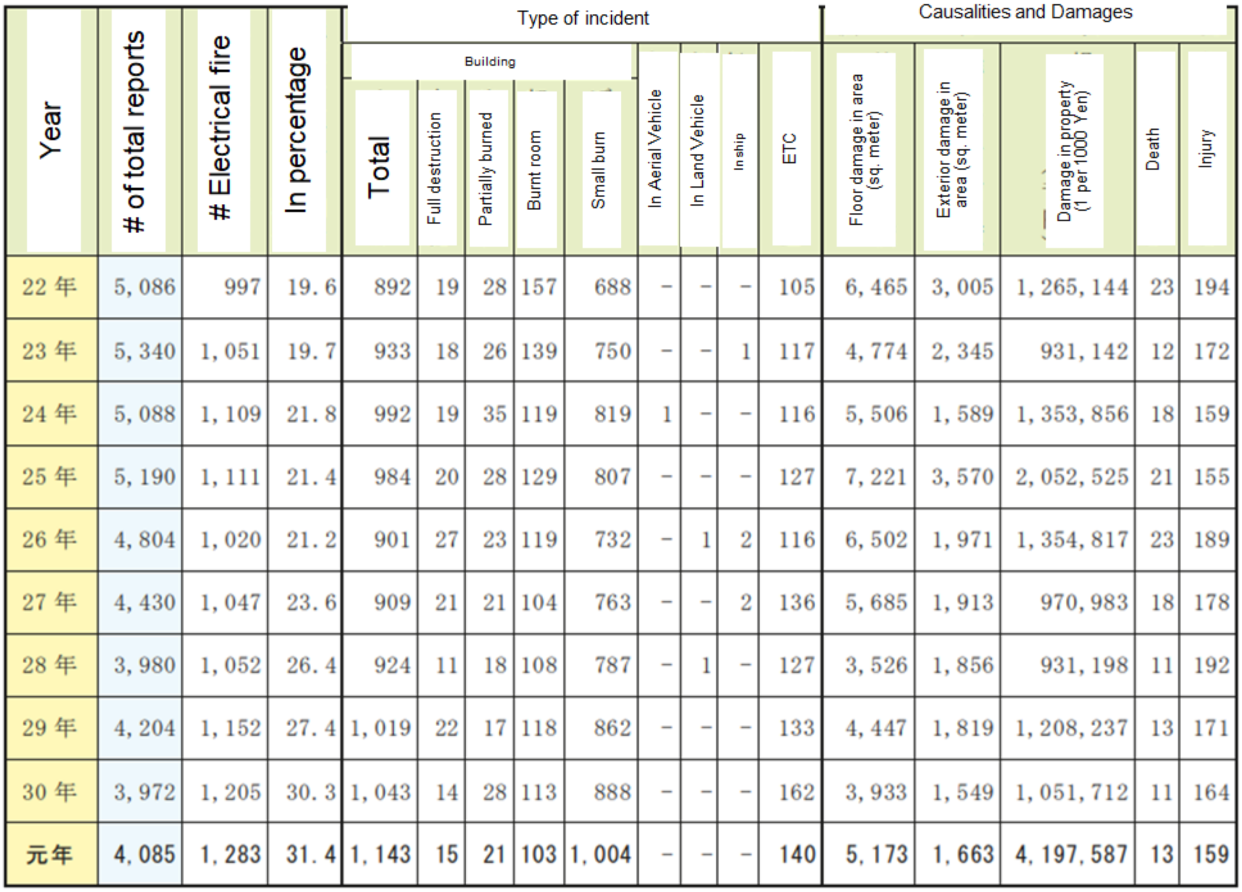


Figure 1.2: Electrical fire incidence is on the rise[1].



Year	# of total reports	# Electrical fire	In percentage	Type of incident									Causalities and Damages				
				Building													
				Total	Full destruction	Partially burned	Burnt room	Small burn	In Aerial Vehicle	In Land Vehicle	In ship	ETC	Floor damage in area (sq. meter)	Exterior damage in area (sq. meter)	Damage in property (1 per 1000 Yen)	Death	Injury
22 年	5, 086	997	19. 6	892	19	28	157	688	−	−	−	105	6, 465	3, 005	1, 265, 144	23	194
23 年	5, 340	1, 051	19. 7	933	18	26	139	750	−	−	1	117	4, 774	2, 345	931, 142	12	172
24 年	5, 088	1, 109	21. 8	992	19	35	119	819	1	−	−	116	5, 506	1, 589	1, 353, 856	18	159
25 年	5, 190	1, 111	21. 4	984	20	28	129	807	−	−	−	127	7, 221	3, 570	2, 052, 525	21	155
26 年	4, 804	1, 020	21. 2	901	27	23	119	732	−	1	2	116	6, 502	1, 971	1, 354, 817	23	189
27 年	4, 430	1, 047	23. 6	909	21	21	104	763	−	−	2	136	5, 685	1, 913	970, 983	18	178
28 年	3, 980	1, 052	26. 4	924	11	18	108	787	−	1	−	127	3, 526	1, 856	931, 198	11	192
29 年	4, 204	1, 152	27. 4	1, 019	22	17	118	862	−	−	−	133	4, 447	1, 819	1, 208, 237	13	171
30 年	3, 972	1, 205	30. 3	1, 043	14	28	113	888	−	−	−	162	3, 933	1, 549	1, 051, 712	11	164
元年	**4, 085**	**1, 283**	**31. 4**	**1, 143**	**15**	**21**	**103**	**1, 004**	−	−	−	**140**	**5, 173**	**1, 663**	**4, 197, 587**	**13**	**159**

TABLE 1.1: Up to 25% of all fire report are of electrical fire hazard[1].

From the report gathered by Tokyo Fire Department since 2012 until last year of 2021, 20% up to 25% of all fire incidence are caused by electrical fire. Even though the technology for fire prevention has been improved, the number of electrical fire incident has been steadily increasing. It is likely that electric device owned by one residence is increasing therefore the electrical fire incidence also increases due to the number of electric devices. The other hypothesis is that the electric device that was bought and manufactured before 2012 or after 2012 have already passed its operational lifetime. Therefore, electrical failure is likely to happen in such devices. In this case, the amount of electrical fire would only increase until all old device that already been used past its lifetime has been discarded or broken down to the point of inoperable.

	Short Circuit at the wiring	**Contact Overheating**	**Contact Shorting (Tracking)**	**Contact with Flammable Material**	**Overcurrent**	**Worn-down of insulation**	**Unsupervised Appliances**
Total Number	374	219	108	79	63	43	25

	Contact with heating element	**Firework causes**	**High energy electrical discharge**	**Broken electric wire**	**Misunderstood the function of the product**	**Had product switched ON without knowing**	**Product improperly built**	**Product is placed near wet place**
Total Number	15	25	24	22	21	20	12	9

	Spontaneous Combustion	**Product Mishandling**	**Flammable material dropped onto the product**	**Flammable material placed on the product**	**Heat from friction**	**Other causes**	**Unknown**
Total Number	8	7	5	5	4	21	37

発火源	合計	電線が短絡する	金属の接触部が過熱する	トラッキング	可燃物が接触する	過多の電流（含電圧）が流れる	地絡する	過熱する	絶縁劣化により発熱する	放置する・忘れる	火花が飛ぶ	スパークする	半断線により発熱する	考え違いにより使用を誤る	誤ってスイッチが入る（入れる）	放射を受けて発火する	火源が接触する	構造が不完全である	漏洩放電する	引火する	本来の用途以外の用に用いる	可燃物が落下する	可燃物を置く	摩擦により発熱する	その他	不明
合計	1,283	374	219	108	79	63	63	58	43	25	25	24	22	21	20	16	15	12	9	8	7	5	5	4	21	37

TABLE 1.2: Half of the electrical fire incident are not of human error[1] Green box are of human error; orange box is of non-human error. Table above is the translation of the bottom table.

The claim of the electric devices is having reached its operational lifetime and start breakdown which results in electrical fire. Tokyo Fire Department gathered the number of electrical fire incidents correlated with the causes as shown in Table 1.2. We can see that out of 1,283 electrical fire report in the last year. 374 of the incidents are caused by broken electrical cord and 219 of the incidents are caused by contact overheating. In total, almost 600 are caused by electrical failure and the minority of the report are product mishandling. Although broken electrical cord can be directed by mishandling of the product, the cause of the fire itself from such mishandling is either a power leakage from expose wire into ground. In short, this type of fire is a direct conversion of electrical energy into thermal energy. Contact overheating is also the same type of hazard. Therefore, in this research. We will be focusing on the contact overheating phenomenon.

1.2 Background of Glowing Connection and Arc-Fault

In this thesis, we will focus on low-current arc faults and glowing connection in commercial electrical appliances [3]. It is well known that a worn-out electrical socket or plug has the possibility of causing a fire due to poor contact conditions. The glowing condition occurs when electrical current flows between two contact points that are composed either of different or the same materials as shown in Figure 1.5

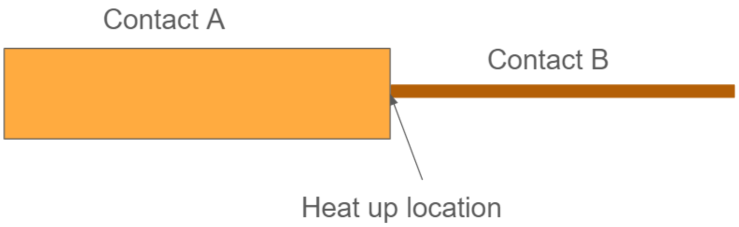


Figure 1.5: A simple picture with a condition that can cause overcurrent phenomenon. If Contact A is passing high amount of current where Contact B is not capable of handling such current, the first area that will heat up considerably is at the contact point where the resistance is the highest.

The contact point accumulates heat from the Joule heating effect, itself a result of contact resistance. Contact resistance is the actual resistance at the contact point or, if contact is small, the conducting spot between two points. In classical contact theory, as it relates to electrical fires, the amount of heat that is generated by contact resistance is proportional to the amount of current passing through the contact point as denoted by the formula.

$$P = VI \quad (1)$$

P as for power, V as for voltage and I as for current

It does not matter if the dissipated power is in the load itself or by the contact point. A small amount of power dissipated in a small area will heat up the contact area. Temperature rising may largely depend on the heat capacity of the material, the amount of heat that was transfer to the surrounding material or medium and the volume of the affected area. [4]

If the contact point has a high resistance, then more power will be dissipated at the contact area, eventually causing the material to glow “red hot.” The material around the glowing area is composed of molten oxides of the original construction material, such as iron oxides for the screw, nut fixtures and copper oxides for the wire terminals. High temperatures at the contact points can create a fire hazard if any flammable materials like electrical insulator housing are near them when they begin to glow and melt. Electrical insulator housing is usually made from wool and cloth. Cloth and wool material as an insulation material has been phased out in favor of modern rubber. However modern rubber is still susceptible to fire hazard when enough heat is applied onto the insulation. The heat from the glowing area can also conduct outward, thus heating the whole affected area and creating secondary glowing conditions near the initial one. The glowing connection phenomenon frequently happens in areas with a loose connection near the electrical terminal. The glowing connection is even more common when the construction material for the terminal is less conductive, such as the steel used for the screws. Terminals with steel screws can be found in older residential areas. Then, in the same areas, electrical fires are most likely to occur. Newer electrical terminals in modern buildings are made of electrical-grade brass or copper to reduce contact resistance, which likewise reduces the chance of initiating a glow. However, electrical contacts made from copper or an alloy of copper are responsible for glowing connections more in the comparison with any other type of connectors. The fire possibility in copper and copper alloy contact will be discussed further in this paper. The primary hazard associated with glowing connections is the subtlety of the phenomenon. A device or an appliance could have a glowing connection in the normal functioning operation. The only way to detect this phenomenon is to monitor the current that is delivered to the load. Additionally, an abnormal level of current draw should be detected. Such a monitoring routine is used only in places like factory where the surrounding environment contains material that could be a fire hazard (wheat dust, saw dust, etc.). Even if the critical temperature is reached, both the terminal and any electrical device connection situation will still work normally. The high temperature due to the glow can damage the insulation in the contact area. Consequently, a fire hazard occurs.

In addition to contact resistance, a glowing condition can also be caused by an arc fault. Arc faults can be divided into two main categories: series arc faults and parallel arc faults as shown in Figure 1.6

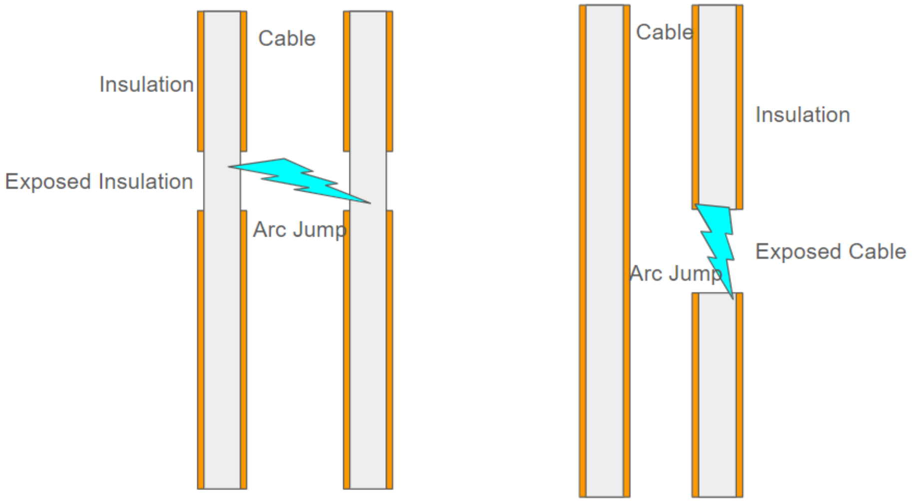


Figure 1.6: The left picture shows parallel type arc fault and the right picture show series type arc-fault. Parallel type arc-fault is more prominent on AC power line because the setup of the cable runs along the same cord.

In most circumstances, arc fault occurs on high-voltage switching boards where the voltage between ground and the live wire is high enough that the air between the two points of contact becomes ionized, resulting in an electrical discharge. This discharge can release an extreme amount of energy to the point where the heat at the arcing point can damage the insulation and the support structure. In a high voltage setting, such as that at a power station, the arc-fault discharge is capable of inflicting severe burns within a fraction of a second. The low-voltage arc-fault mechanism is similar to its high-voltage counterpart, however the discharge is not energetic enough to produce large arcs that can cause burns to objects in the surrounding environment. However, even though the low-voltage discharge is not intense enough to melt and break open the electrical contact, it can still be hazardous. The low-power electrical discharge can continuously accumulate heat at the affected area, resulting in the buildup of oxide layers. The oxides created by an arc fault can then induce glowing conditions, which eventually lead to an ignition when the temperature becomes higher than the flashpoint of the material surrounding the contact point. This includes the plastic housing and insulation that surrounds old electrical wires. The first type of arc fault is called short-circuit arcing, which is categorized as a type of parallel arc fault. This phenomenon occurs when the live electrical wire is exposed due to mechanical failure or to the degradation of the insulating and protective layers surrounding it. The live wire is then loosely connected to either a hot-to-neutral or a hot-to-ground cable. If two wires are tightly connected, then the connection can generate a substantial amount of heat proportional to the amount of current at the load center, which is enough to cause an extreme fire hazard. On the other hand, if two wires are loosely connected, then it is possible to obtain what is known as a “sputtering arc.” This type of parallel arcing is a low-current arcing between two wires that can generate enough heat to damage the insulation around the affected area. Once the majority of the insulation is damaged, it opens a path through which a high amount of current can flow. Modern electrical breakers can reliably detect this type of arcing, greatly reducing the fire hazard risk associated with this phenomenon. The second type of arc fault is called a series arc fault. It is a relatively new phenomenon and the least understood of the arc-fault types. Series arcing occurs when a broken wire arcs to itself in a co-linear pattern. The electrical spark caused from the broken contact of the wire is perceived as an arc. This kind of arcing is relatively low current compared to a parallel arc fault. However, the heat generated by low current is sufficient to damage or destroy the surrounding insulation and to ignite any flammable substances near the arcing area. In a controlled experiment for testing series arcing at sea level and at atmospheric pressure, breakdown voltage is expressed as follows according to the Paschen formula.

$$V = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1+\frac{1}{\gamma se}\right)\right]} \qquad (2)$$

A as Saturation ionization in the air at a particular electric field (112.501(kPa*cm)-1) *const for air*
B as related to the excitation and ionization energies (2737.50 V/(kPa*cm)) *const for air*
p =as 101325 kPa (Sea level atmospheric pressure)
d as Gap distance (in meter)
γse as Secondary electron emission coefficient at the cathode
V as Breakdown voltage

If we are to fill in this formula with the value, break down voltage is 100V. The breakdown distances would still be at average of 10 micrometers. Secondary electron emission from cathode and the electron reflection from anode barely increases as the distance for the arc-gap becomes shorter. According the theory, order of voltage for any arc-fault which can sustain the arc-fault is 100V. The distance relation to the voltage breakdown at its maximum range should not be farther than what can 144V can provided. Even more so that the electric power used in household is not a constant power but rather alternating current with peak and crest of the power. Therefore, the distance for the cable to sustain a continuous arc would vary in accordant with its current voltage level as shown in Figure 1.7. Even with such physics limitation, there is still reports of arc-fault in low voltage system. Even though parallel arc-fault is much more prominent in low voltage AC system, especially a broken electrical cord that the current jump between two different cable is very easy to detect with current apparatus such as Ground Fault Circuit Interrupter (GFCI) and simple fuse that short and burn out when too much current is drawn in a short amount of time. Hence the only problem in low voltage arc-fault is a series type.

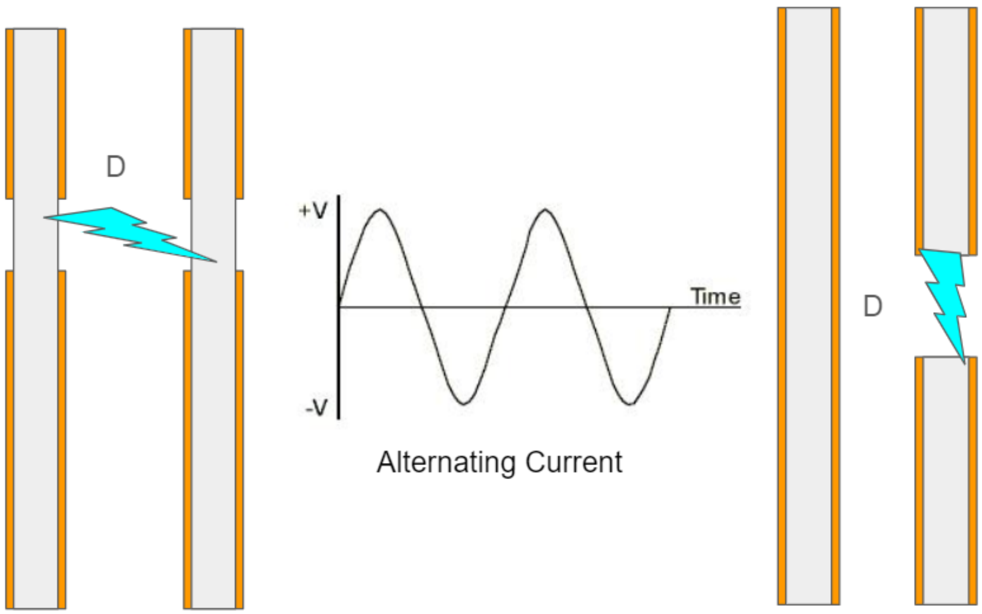


Figure 1.7: In theory. The *D* (Distance) would vary from 0 meter up to the maximum voltage of +*V* and -*V* can provided.

The problem of series type arc-fault that regular power breaker and fuse will not be able to detect. Because in the equivalent circuit of the system, an electrical arc in a series type or any glowing connection state is still an electrical conductor as shown in Figure 1.8. In this case there would be no electrical current leakage or abnormal power draw in which will not trigger any fuse or breaker. The only abnormality of this type of arc-fault is the heat generated at the affected area.

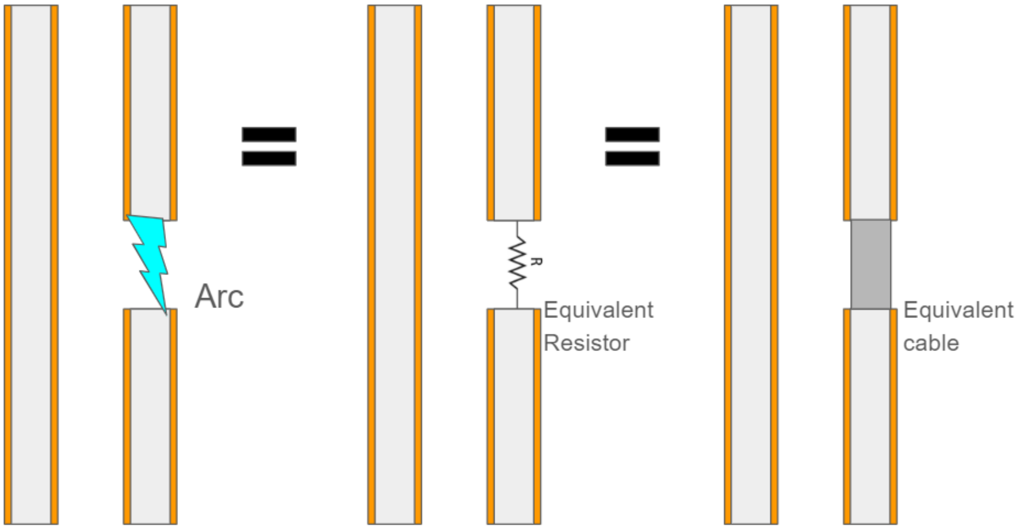


Figure 1.8: Arc-fault or glowing connection equivalent circuit is a resistor in the circuit which it will not trigger electric breaker or other preventative devices.

It is difficult to detect a fire hazard from a low AC voltage, like the 100 V power sources that are widely employed in Japanese consumer products. It is also hard to predict when and where it will happen. Electrical devices that change their current draw based on temperature can falsely identify a hazard as a glowing connection. Placing a temperature sensor near the electrical contact point is not a reliable solution since a glowing connection can happen at any points where there is a loose connection. This includes places within the machine or within the construction wall where a wire has broken. Series arc faults are also difficult to detect since a device has to be able to distinguish differences in the RF (Radio Frequency) component of the waveform between normal operation and operation after an arc fault has developed. There are many electrical devices that have an RF component that is similar to that of a series arc fault, which is what makes this differentiation a difficult task. The type of contact present at the arc fault’s location also has a major effect on the pattern of the RF waveform, therefore the detection system should be able to differentiate the waveform.

1.3 Previous Work by Other Researchers

Since electrical appliances first became common in households, researchers have conducted many studies on glowing conditions and series type arc faults. However, a replication of a series type arc-fault is difficult due to its physics limitation. Until now no researcher has been able to understand the actual mechanism and the condition of a low voltage arc-fault. Currently there are two main ways to replicate a series type arc-fault that is used in the study. One of trial for a low voltage arc-fault is used graphite bar that approaches to other type of metal. Some researchers use two graphite bars to produce a spark gap. This experiment is done by K. Zheng[4] as shown in Figure 1.9 and Figure 1.10.

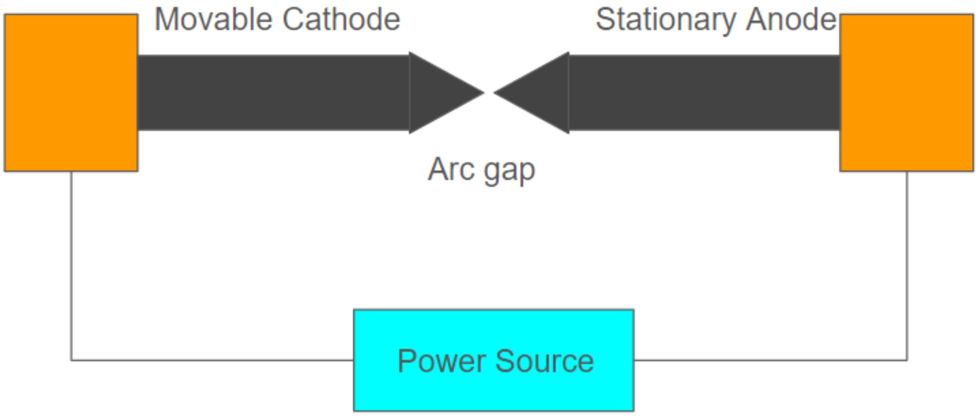


Figure 1.9: A visualized arc-gap method with graphite rod.

Figure 1.10: Arc gap generator by K. Zheng.

The main advantage of this method is that the arc-fault generate is very stable. Then, it is easy to study the current waveform caused by the arc-fault. Although arc-fault in low voltage was explained earlier, the distance between gap must be quite short. The voltage breakdown condition was unrealistic in an actual environment. Therefore, the experiment setup is only useful if we wanted to study just the arc-fault behavior after arc-fault initiation. The other method that was used more frequently by many researchers is an oxide gap generator. As we already discussed that a poor contact, the common glowing connection state and series type arc-fault, there is large amount of oxide near the contact area. Especially copper based contact produces oxide more. Therefore, in order to replicate the environment, the arc-fault requires the real sample. Researchers would use a contraption like a mechanical hand or movement. One of the example cathodes is shown in Figure 1.11 that is devised by J. Urbas [9] (figure 1.12)

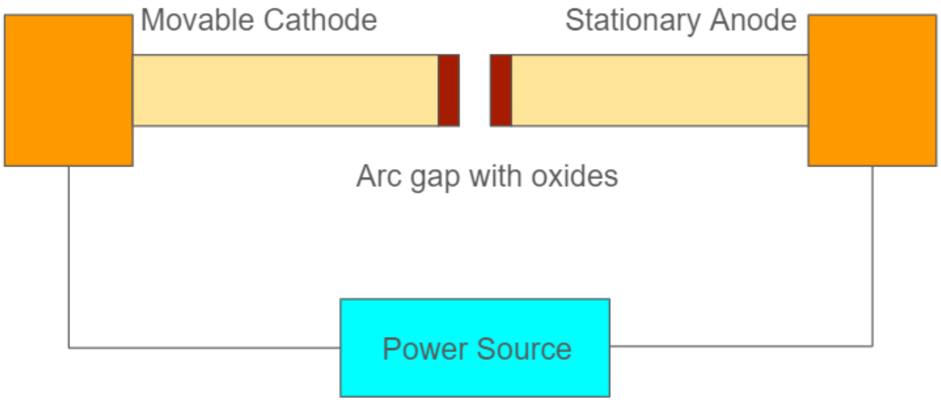


Figure 1.11: A visualized movable cathode method with the same material.

The contraption would then move the cathode and make contact with anode repeatedly until oxide has been formed. This is to simulate the uses by the end-user movement to the electrical plug or contact area. This method has the highest accuracy since actual arc-fault incident can be simulated differently from graphite method. The main drawback of this method is that the arc-fault generation can be extremely random. The random occurrence is almost same as the actual phenomenon. Hence this method requires long days or weeks in order to run the contraption continuously.

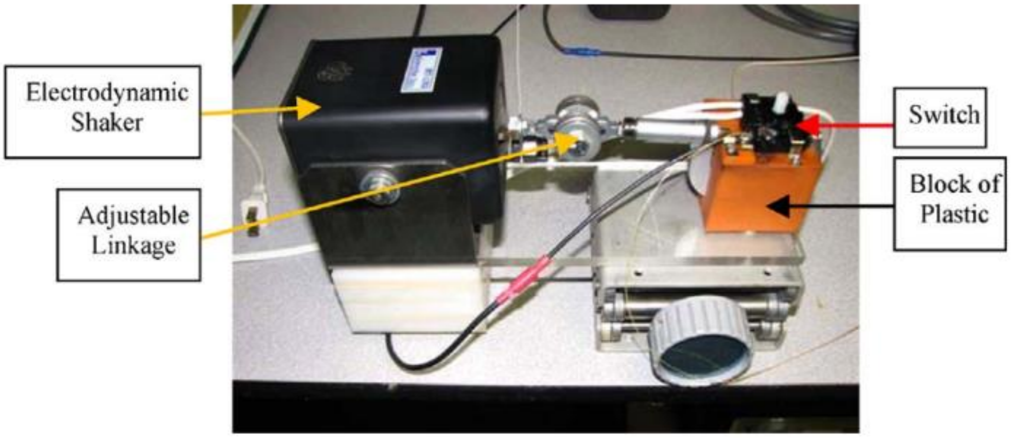


Figure 1.12: A “Contact shaker” created by Joe Urbas.

In series type arc-fault study, Meese and Beausoliel [5] in 1976 investigated glowing electrical contacts by passing an electrical current through the point of contact between two conducting materials. The contact point produced a substantial amount of heat enough to enable it to emit a glow. They also made some observations of the electrical discharge at the affected area. Hereafter, an electrical discharge from loosely connected parts will be referred as an arc fault. An arc fault usually occurs at points where contacts are loosely attached. Meese and Beausoliel also claimed that their results were applicable for 120 V because of normal voltage condition. Hagimoto [6,7] demonstrated that an arc fault cannot be sustained unless there is some external perturbation to the contact surface. Oxides of the contact material are formed by the high temperatures in the glowing portion of the contact spot. Shea [8] reported that the oxide bridge that is formed between the two contacts is the primary cause of the glowing condition. The contact material from which the oxides are formed is usually copper based. Stainless steel, which is used for the nuts and bolts for electrical contacts, and cast iron rarely create oxides. To sustain a glowing con-tact, there must be oxygen present in the environment to oxidize the copper material and to create an insulation bridge. Oxidized copper materials include copper(II) oxide, CuO, and copper(I) oxide. Cu2O. Cu2O behaves as a semiconductor. When glowing connections occur, CuO behaves as an insulator and increases the overall contact resistance. Since a high resistance at the contact surface produces Joule heating, the temperature there increases around the oxide bridge. Eventually, the temperature of Cu2O reaches a point where the contact material is able to oxidize. Thus more oxides are generated at the contact point. Subsequently, the overall contact resistance decreases as the temperature rises. Urbas [9] has shown that a current below 1 Arms can create glowing connections in commercial-grade household switches where the appliance is constantly perturbed by vibrations. He concluded that the push-in connection between the wire and the switch must be poor to create a glowing connection in the switch and suggested that the actual contact points in commercial-grade switches should be plated with silver. We can deduct from Urbas' setup the glowing connection in his work which is an electrical discharge from two conductors by making and breaking contact. Eventually, the discharge creates an electrical arc. This type of electrical arc can heat the point of contact to its glowing temperature. Glowing conditions for this type of contact do not follow classical electrical contact theory [10–12]. This theory is mostly concerned with a single type of conductive layer at a conduction spot with a continuous flow of electrons. In actuality, the electron flow is more likely to bounce off conductors in small contact spots. As a result, the actual electron flow produces Sharvin resistance, which then increases the overall contact resistance. Other researchers [13–15] were able to replicate a low voltage arc fault and devised a method to detect the phenomenon from the pattern of the waveform. They were able to recreate with a specific setup with various types of electrodes. However, the waveforms of the low volt-age arc fault from each type of the material are different [16]. Shea [17] deduced that the voltage waveform of copper-based material is the same where other types of contact, such as steel, are to be grouped differently. However, they were still not able to create an explanation why the two types have different behavior. Therefore, the actual mechanism behind such a phenomenon is still inconclusive.

1.4 Problem Statement of low voltage arc-fault

After all the literature review, we were able to draw in the conclusion that Both Series type arc-fault cause and its mechanism are not entirely understood. Most researchers were able to recognize the waveform, the pattern and the condition of the arc-fault generation**.** The problem statements can be summarized as followed.

1. The relation between series type arc-fault and glowing connection have yet to be established.
2. There seems to be a connection between arc-fault and the temperature of the contact due to the semiconducting properties of the oxide but so far, nothing is conclusive.

3. Although low voltage arc-fault is only possible in a certain conducting material claimed by J. Shea, the reason behind this phenomenon is inconclusive.
4. The means to recreate a low voltage arc-fault amongst researchers are still fragmented and different especially when each method deliver differences in the results.

1.5 Research Scope

The scope of this research aims to answer all the above question. Once all the questions and their mechanism have been fully explained. We will then devise the mean to detect such arc-fault in a correct way. The research scopes are listed as followed

1. Clear the relation of arc-fault and amount of electrical power supplied into the system.
2. Calculate heat dissipation on the contact area where arc-fault occurred.
3. Clear the mechanism of arc-fault in each type of contact metal between brass and copper.
4. Study the accumulation of oxides layer on each type of contact metal.
5. Investigate contact surface after arc-fault in the comparison to the initial surface.
6. Study the correlation between heat generation from electrical spark and oxides accumulation.
7. Find the way to detect or prevent the arc-fault.

1.6 Thesis Structure

This thesis will be divided into 5 main chapters. The first chapter is the introduction to background of electrical fire, classical contact theory, the arc-fault, glowing connection and previous work done by other researchers. First chapter will also include the research scope and its problem statement. Second chapter will explain the instrument. The sample used in the experiment and its setup. Each subsection in the chapter two will divide the experiment into each type of observation. Chapter three to Chapter six will be the result, discussion and the conclusion for each type of experiment that was setup Chapter seven will draw the conclusion to the mechanism of the arc-fault. In chapter eight will discuss and create the method to detect such phenomenon and the mean to prevent the incident. In chapter eight will also be divided into two main type of detection which will explain in details later. The ninth chapter is the final conclusion of the research.

1.7 References

1. Tokyo Fire Department: Cases of Fire Incidents. Available online: https://www.tfd.metro.tokyo.lg.jp/hp-cyousaka/kasaijittai/r02/data/R2_AllKasaiWeb.pdf (accessed on 12 January 2021). (In Japanese)
2. Tokyo Fire Department: Condition of Fire Incidents. Available online: https://www.tfd.metro.tokyo.lg.jp/saigai/toukei/r02/d1/gaiyo.pdf (accessed on 12 January 2021). (In Japanese)
3. Martel, J.M. Series Arc Faults in Low-Voltage AC Electrical Installations. Thesis, Technische Universitat Ilmenau, Ilmenau, Germany, 2018.
4. K. Zeng, L. Xing, Yaojia Zhang, L.Wang, Characteristics analysis of AC arc fault in time and frequency domain, 2017 Prognostics and System Health Management Conference (PHM-Harbin) Harbin, China, 2017
5. Meese, W.J.; Beausoliel, R.W. Exploratory Study of Glowing Electrical Connections; NBS BUILDING SCIENCE SERIES 103; Na-tional Bureau of Standards, U.S. Department of Commerce: Washington, DC, USA, 1977.
6. Hagimoto, Y.; Kinoshita, K.; Hagiwara, T. Phenomenon of glow at the electrical contacts of copper wires. Natl. Res. Inst. Police Sci. Rep. 1988, 41, 30–37.
7. Hagimoto, Y.; Kinoshita, K.; Hagiwara, T. Glowing Phenomenon at the Contact of Different Kind of Metals. Summary of Annual Meeting of Japan Society for Safety Engineering. Available online: http://www.tcforensic.com.au/docs/japan/japanall.pdf (accessed on 5 May 2022). (Translated by Author)
8. Shea, J.J. Glowing Contact Physics. In Proceedings of the 52nd IEEE Holm Conference on Electrical Contacts, Montreal, QC, Canada, 25–27 September 2006.
9. Urbas, J. Glowing Connection Experiments with Alternating Currents Below 1 Arms. IEEE Trans. Compon. Packag. Manuf. Technol. 2010, 33, 777–783.
10. Slade, P.G. Electrical Contacts: Principles and Applications, 2nd ed.; CRC Press, Taylor & Francis Group LLC: Boca Raton, FL, USA, 2014; pp. 79–83.

11. Caven, R.W.; Jalali, J. Predicting the contact resistance distribution of electrical contacts by modeling the contact interface. In Proceedings of the 37th IEEE HOLM Conference on Electrical Contacts, Chicago, IL, USA, 6–9 October 1991.
12. Timsit, R.S. Electrical conduction through small contact spots. In Proceedings of the 50th IEEE Holm Conference on Electrical Contacts and the 22nd International Conference on Electrical Contacts Electrical Contacts, Seattle, WA, USA, 23 September 2004.
13. Sritriai, E.; Kittiratsatcha, S.; Polmai, S. Low Voltage Series Arc Fault Detection Using Rogowski Coil. In Proceedings of the International Conference on Engineering, Applied Sciences, and Technology, Phuket, Thailand, 4–7 July 2018.
14. Li, S.; Yan, Y. Fault Arc Detection Based on Time and Frequency Domain Analysis and Radom Forest. In Proceedings of the International Conference on Computer Network, Electronic and Automation, Xi’an, China, 24–26 September 2021; pp. 248–252
15. Ming, Z.; Tian, Y.; Zhang, F. Design of arc fault detection system based on CAN bus. In Proceedings of the International Conference on Applied Superconductivity and Electromagnetic Devices, Chengdu, China, 25–27 September 2009; pp. 308–311.
16. Shea, J.J. Glowing connections in DC circuits. In Proceedings of the IEEE Holm Conference on Electrical Contacts, Denver, CO, USA, 10–13 September 2017; pp. 264–274
17. Shea, J.J.; Zhou, X. Material Effect on Glowing Contact Properties. IEEE Trans. Compon. Packag. Technol. 2009, 32, 974–740.

Chapter 2: Environment Setup and Experiment

A common misconception is that glowing connections and arc faults are similar. However, an arc fault is a continuous electrical discharge between two conducting points [1] that produces heat from an ionizing spark, whereas a glowing connection consists of purely resistive heating [2]. At a very high current, glowing connections can emit a bright light and be misidentified as an arc fault. As mentioned earlier, arc faults themselves can induce a glowing connection. In this research, we will focus on arc faults that can lead to a glowing connection or both phenomena at the same time.

Based on previous studies by many researchers, there are specific environment parameters and conditions for the contact point that must be met. If any of the conditions listed below is not present in the testing environment, then the arc fault will be much more difficult to produce. The voltage and current used in the experiment was set to common household levels, as suggested by Urbas [3] and Hagimoto [4]. The glow can occur at low power, but the energy released from it and the arcing is high enough to ignite the surrounding material. The conditions for the production of the oxide bridge are as follows.

1. The atmosphere must contain oxygen so that the copper-based material can be oxidized.
2. The conductor material should be of a type that has a high melting point and that behaves as an electrical insulator after it has been oxidized.
3. The two electrical conductors must have a poor contact spot [5] so as to increase contact resistance and Sharvin resistance, thus creating the Joule heating effect.
4. The electrical current passing through the contact spot should not be higher than the current capacity of the oxide or the contact spot, and it should not be lower than the threshold where electrical discharge becomes impossible for certain gap distances between the conductors.
5. To sustain an arc fault, an oxide bridge must be created from the conductor material.

2.1 Experiment Configuration

The experiment configuration is presented in Figure 2.1. The electrical socket and electrical plug blade are held tightly in place by a movable clamper. To produce the initial oxide bridge, an electrical current is passed through the conductor with a resistive load. By continuously making and breaking contact between the conductors, small arcing is produced and creates oxide patches at the contact area. Contact wear on the surface is accelerated by arcing [6] when the conductor makes contact. A small amount of mass is lost with each arcing instance, creating holes and an uneven contact surface. In an AC system, where the electrical current fluctuates between two peak values, if the conductors make contact at the zero-crossing point, then the discharge arc may not be present. To reliably monitor the lifetime of an electrical socket, the action of making and breaking contact must be performed at the peak voltage level of the AC system where discharge is the most energetic.

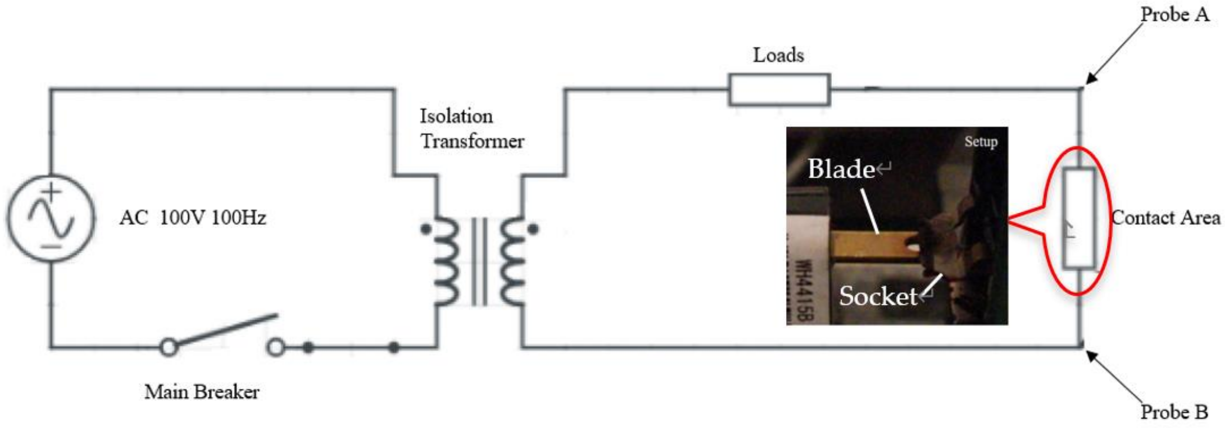


Figure 2.1: This figure shows the equivalent circuit of the experiment. The blade and the socket are clamp in place by two clamper and move in and out repeatedly to make and break the contact.

2.11 Oxide formation and corrosion simulation.

All 3 types of new sample are put into electric furnace at 400C, 600C and 800C to study the effect of heat in each range of temperature. The sample is to be use in the comparison between samples those are heated by arc-fault and conventional heating.

Figure 2.2: Furnaces used in the experiment to temper the copper metal.

MINI SH-OMT PID controlled 900W Electric Furnace.

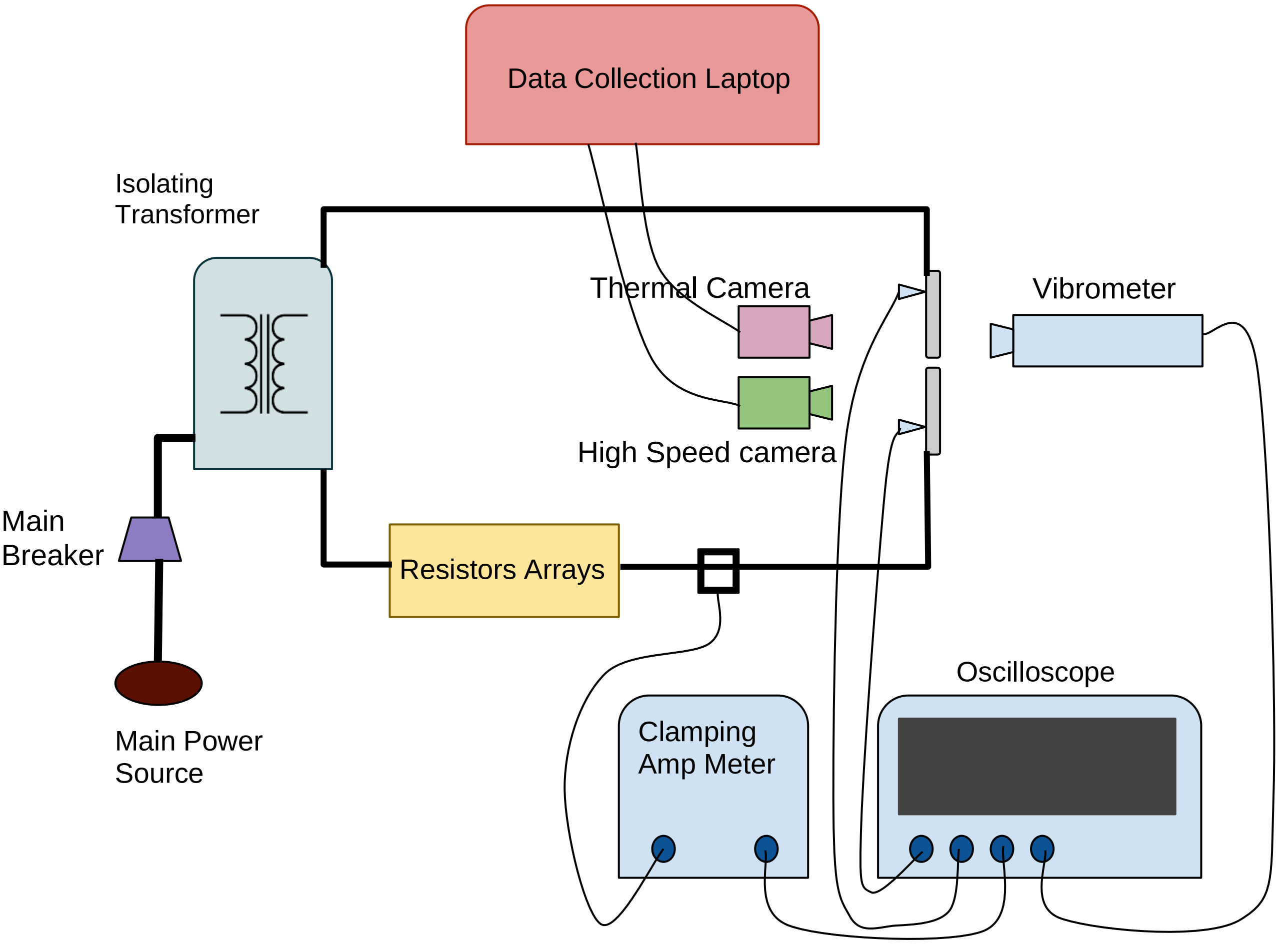


Figure 2.3: A drawing of the overall experiment setup.

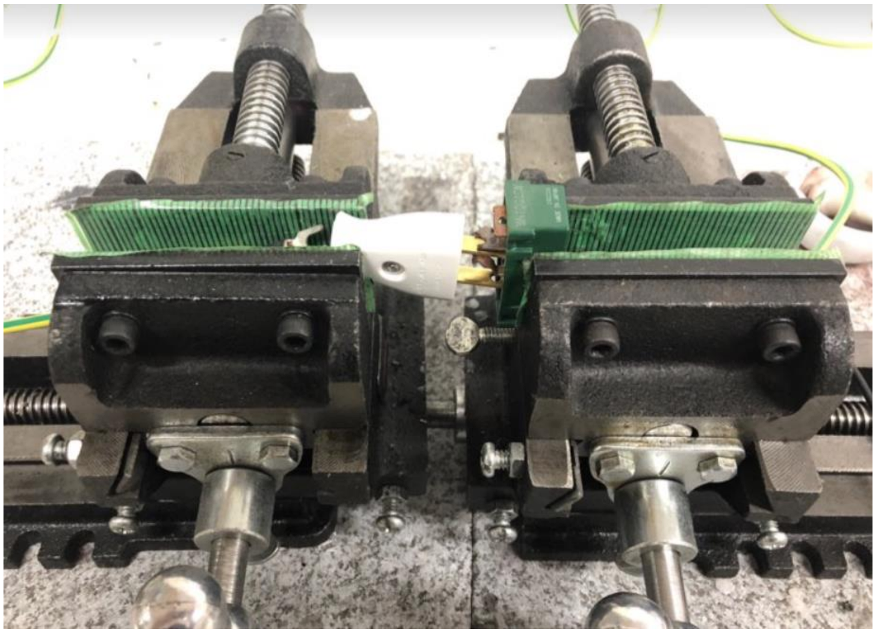


Figure 2.4: The Clamping setup. Noted the sample is held firmly in place.

These contain the list of the instruments used in the experiment for data measurement.

1. Tektronix A622 AC/DC Current Probe, Clamping Type
2. T3DS01204 Teledyne 4 Channel 500 MSa/s Oscilloscope
3. LV-1300 ONO SOKI Laser vibrometer
4. INFREC Thermal Camera
5. Casio EX-F1 High Speed Camera
6. FLUKE 8846A Precision Digital Multimeter
7. HIOKI 3801-50 Digital Multimeter

2.2 Experiment Samples and Current Source

The samples used for the electrical socket were made of Electrolytic Tough Pitch (ETP) Copper (C1100), which is a type of oxygen-free copper. This type of copper is commonly used as an electrical conductor due to its purity and low oxygen content.

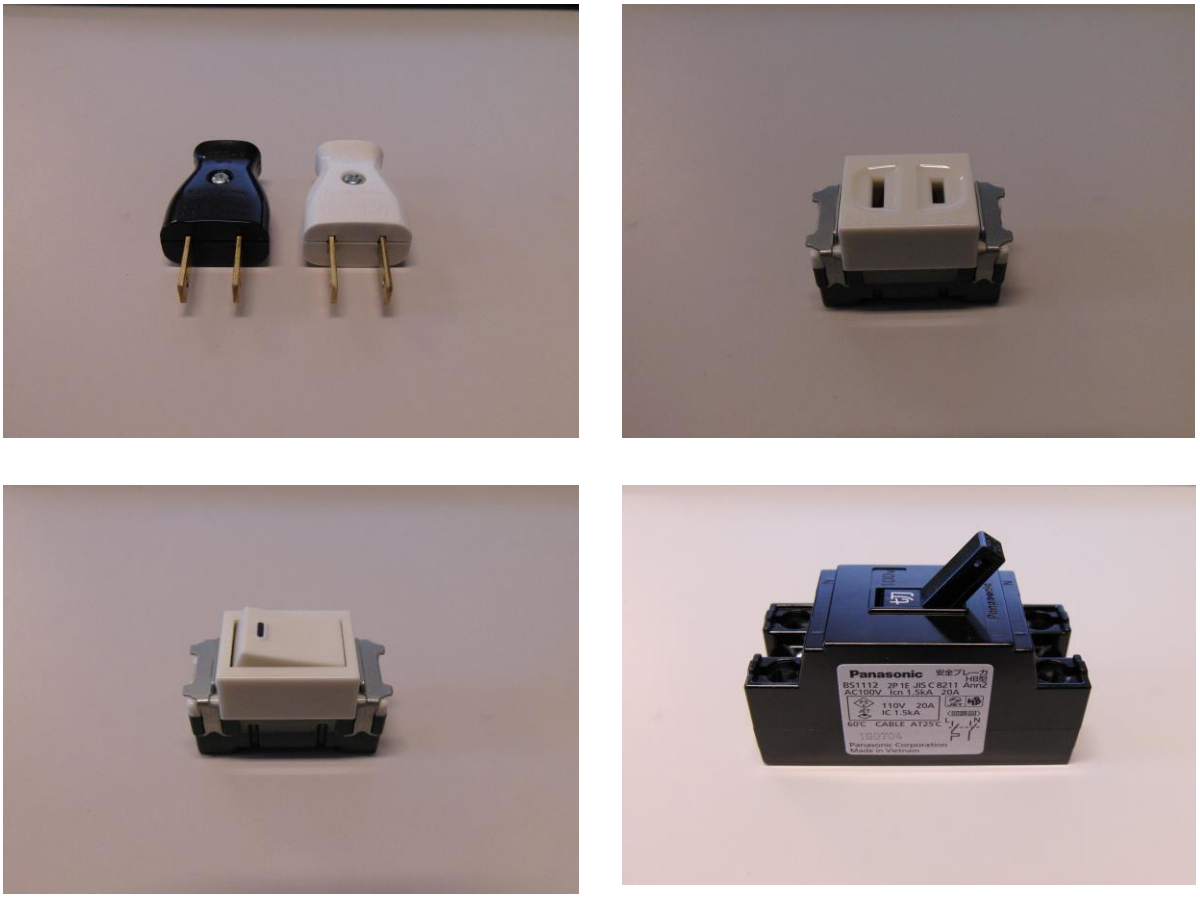


Figure 2.5: This figures show the sample and its interior copper used in the experiment.

Top right: Electric socket Rating 15A 125V Panasonic WN1001

Top left: Electric plug Rating 15A 125V Panasonic WH4415 / WH4415B

Bottom right: Electric Breaker Rating 20A 100V Panasonic BS1112

Bottom left: Electric light switch Rating 15A 300V Panasonic WN5001

It also exhibits high ductility and high impact strength, qualities that increase its lifetime as a contact surface. Another material used as a conductor in the experiment was an unknown alloy of electrical brass. It adhered to the Japanese Industrial Standards for electrical receptacles (JIS C 8303:2007) The experiment used an isolation transformer to protect the building fuse. However, due to the parasitic inductance of the transformer, the voltage and current were out of phase. The load used in the experiment was a set of wire-wound resistors with resistances of 12Ω, 25Ω, and 100Ω, respectively. All of the resistors exhibited insignificant parasitic inductance at 100 V and 50 Hz. The justification for choosing resistors with these values is that they are typical of what is commonly found in electrical appliances that are used in household environments. The current is measured using a clamper probe, and the voltage is measured between the two contact points. An oscilloscope is used to measure the voltage drop when an electrical discharge is present. To recreate the arc-fault. The electric socket and the plug blade is set between two clamper. The current is then pass into the system. The clamper then move in to make contact between two conductor. Then the clamper move out to the break the contact. This process is then repeated until patches of oxide is formed. Once the oxide patched has been form. The contact point is then relocated to the patch of oxide and make contact again. This is then repeated until Glowing condition and Arc-fault state is achieved. This process is repeated for all types of load used in the experiment.

Figure 2.6: Isolation transformer used in the main experiment.

Figure 2.7: The top wirewound resistor has value of 25Ω and the bottom one has value of 100Ω.

Figure 2.8: This wirewound resistor has value of 12Ω.

As with all the aforementioned experiment samples and the instrument uses in the observation. Our experiment will be divided into four main sections. Which are

1. The relation between series type arc-fault and Voltage waveform
2. The relation between series type arc-fault and Contact temperature
3. The relation between series type arc-fault and Contact Vibration
4. Contact Surface Inspection

Each step will be explained in the upcoming chapter. Each experiment will be divided into its own chapter. Each chapter will explain the overview of the experiment setup, The result and the discussion of the experiment. The Figure of the experiment will also be simplified to match what we wanted to observe and which are the instrument that will be used in each investigation.

2.3 References

1. Ettling, B.V. Glowing Connections. Fire Technol. 1982, 18, 344–349
2. Sletbak, I.; Kristensen, R.; Sundklakk, H.; Navik, G.; Runde, M. Glowing contact areas in loose copper wire connections. In Proceedings of the 37th IEEE HOLM Conference on Electrical Contacts, Chicago, IL, USA, 6–9 October 1991.
3. Urbas, J. Glowing Connection Experiments with Alternating Currents Below 1 Arms. IEEE Trans. Compon. Packag. Manuf. Technol. 2010, 33, 777–783.
4. Hagimoto, Y.; Kinoshita, K.; Hagiwara, T. Phenomenon of glow at the electrical contacts of copper wires. Natl. Res. Inst. Police Sci. Rep. 1988, 41, 30–37.
5. Iliuţă, C. Experimental research on electrical resistance of microcontacts. DOCT-US 2011, 3, 30.
6. Abbaoui, M.; Lefort, A.; Sallais, D.; Jemaa, N.B. Theoretical and experimental determination of erosion rate due to arcing in electrical contacts. In Proceedings of the 52nd IEEE Holm Conference on Electrical Contacts, Montreal, QC, Canada, 25–27 September 2006.

Chapter 3: The relation between Series type Arc-fault and Voltage waveform

.

In this Chapter, we wanted to see the relation between waveform and the arc-fault state as explained in the Chapter 1. Many others researchers have found out that arc-fault especially in copper-based connection has a distinct waveform. In order for our experiment to be correctly validated. Our waveform should match with the waveform reported by other researchers. Once we are able to match the same type of waveform. We will be able to deduce the mechanism and explain the behavior behind the waveform. Therefore, in this experiment we will need two set of voltmeter probes connected between two cathodes. This is to check whether if there is any voltage drop causes by arc-fault and joule heating. Current probe is also required in the experiment as shown in Figure 3.1.

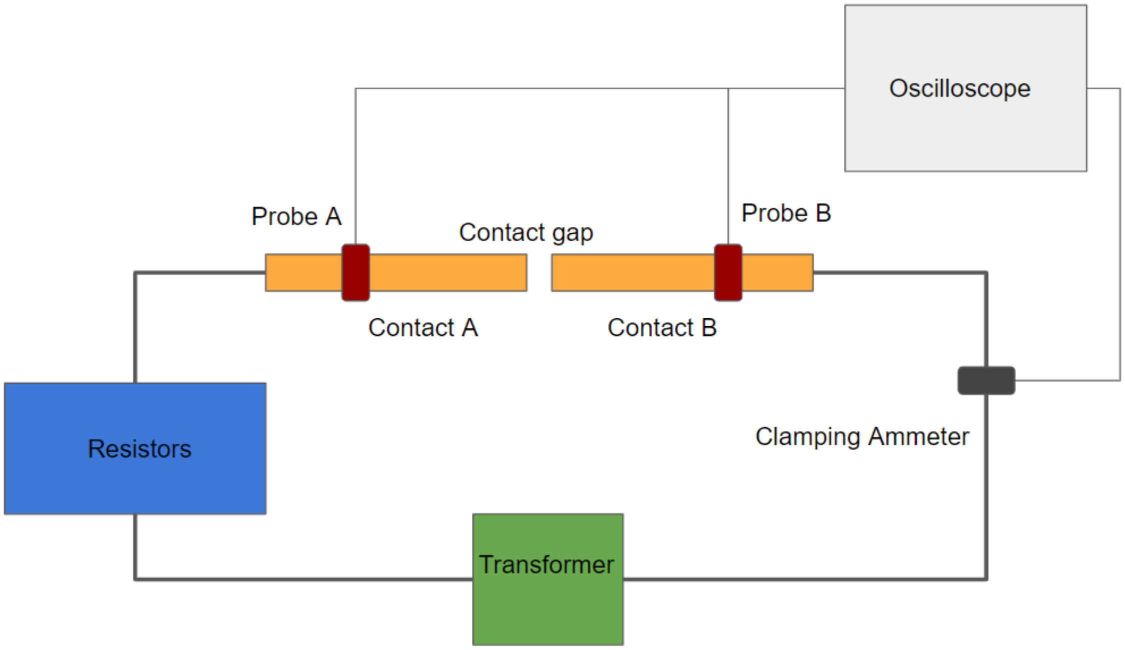


Figure 3.1: The simplified setup for the observation between waveform and arc-fault.

First, we will discuss the overview of the relation between arc-fault and the waveform we gathered from the experiment. In the voltage between two points of contact as shown in Figure 3.1. There should be no difference in waveform between two points of contact ideally. When we are trying to simulate the arc-gap, the arc-fault between two contacts should introduce as a contact resistance. Contact resistance in a classical contact theory behaves like a resistor. Therefore, there should be a small amount of voltage drop between two points as shown in Figure 3.2.

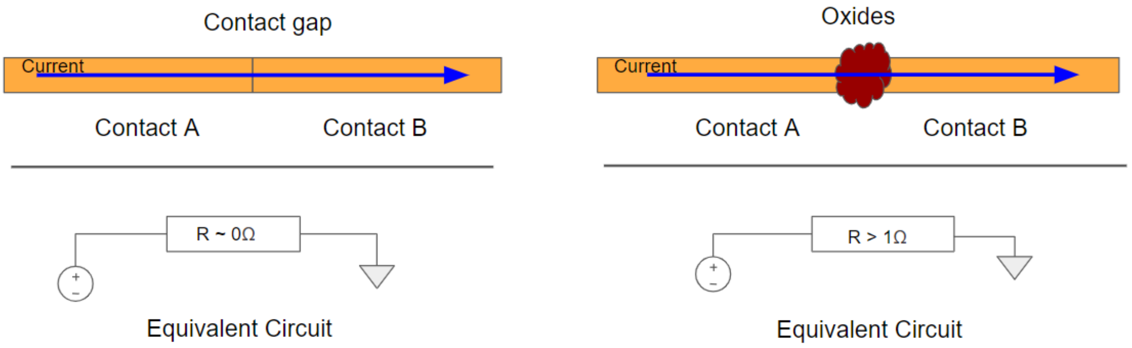


Figure 3.2: Oxide and other irregularity at the contact surface behave like a passive resistor which can create a voltage drop and dissipated power in the area.

As we did in the experiment, we made use of arrays of resistor from 100Ω, 25Ω and 12Ω. At effective voltage of 100V, the current is delivered through the prepared load at 1.00A, 4.00A and 8.33A respectively. When there is no arc-fault in the system, the voltage drops between two probes at contact A and contact B doesn't appear as expected. However, when there is an arc-fault in the system, the voltage drop does not drop in a passive manner where one of the contacts reduces in peak-to-peak voltage. The voltage fluctuates and drop sharply simultaneously when current has reached in zero-crossing point. At 1.00A setting, we are able to observe a sharp drop at the orange line as shown in the following Figures 3.4, 3.6 and 3.8. Hotline is cathode A and neutral line is cathode B in Figure 3.3.

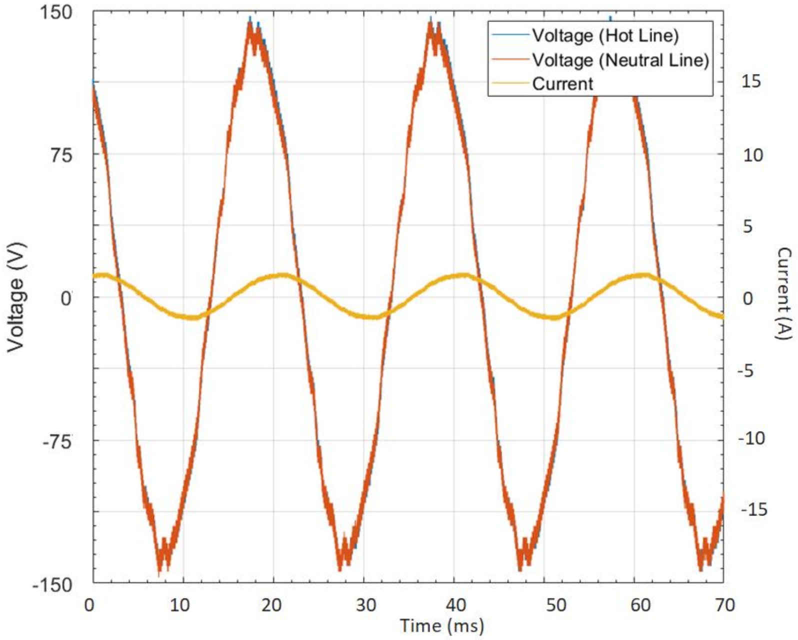


Figure 3.3: The waveform of 1.00A

setting without Arc-fault.

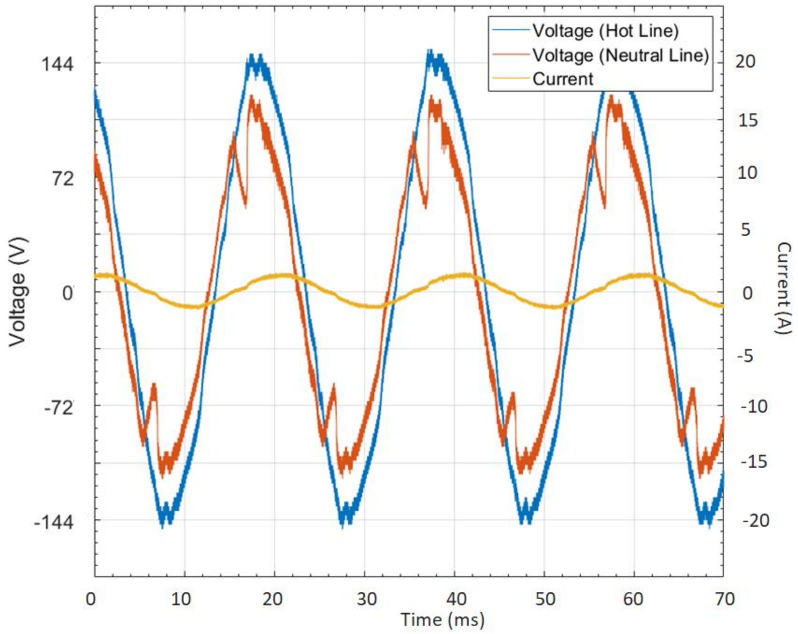


Figure 3.4: The waveform of 1.00A

setting with Arc-fault.

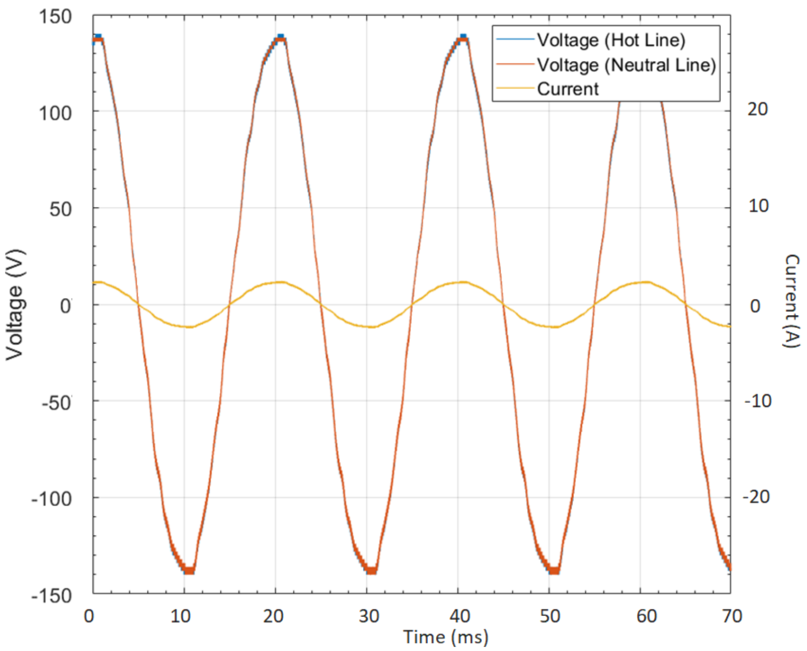


Figure 3.5: The waveform of 4.00A setting without Arc-fault.

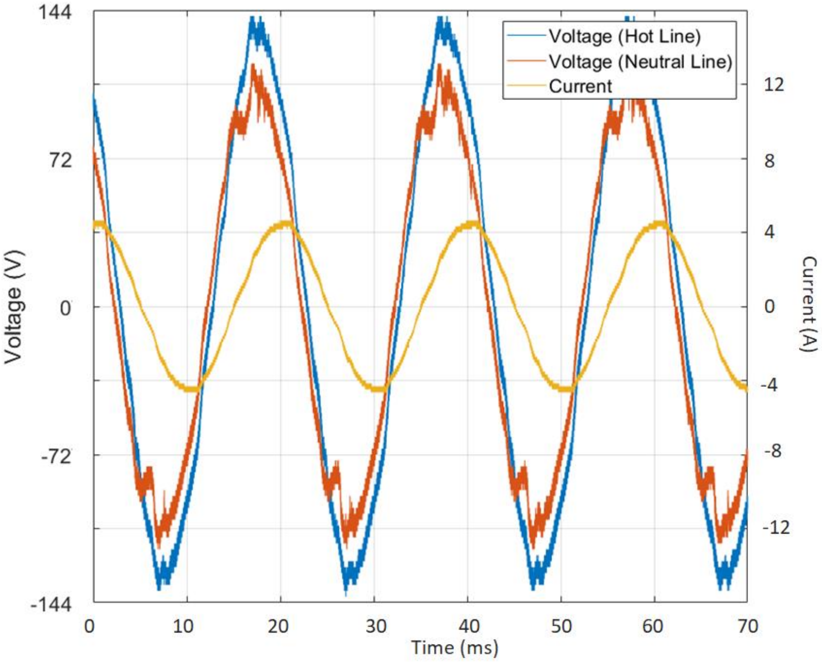


Figure 3.6: The waveform of 4.00A setting with Arc-fault.

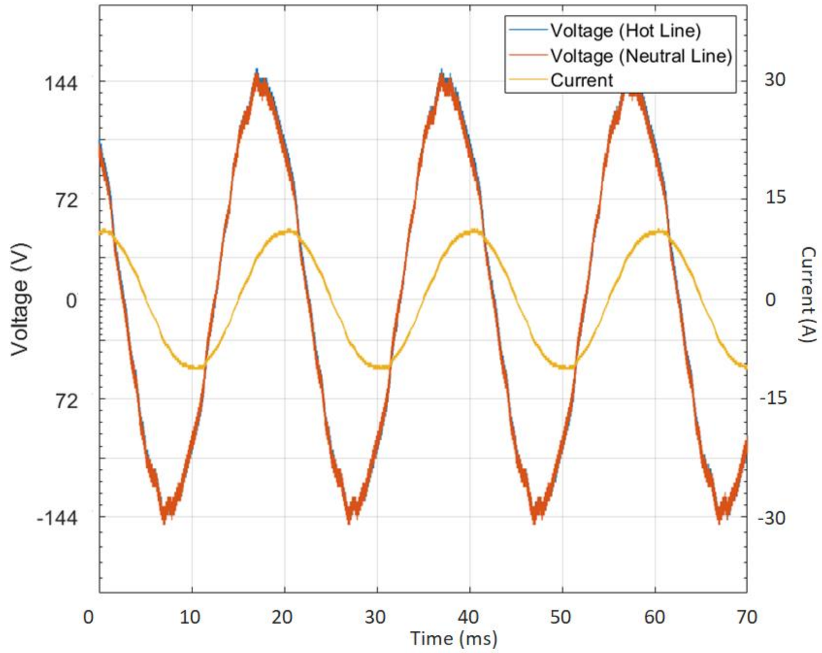


Figure 3.7: The waveform of 8.33A

setting without Arc-fault.

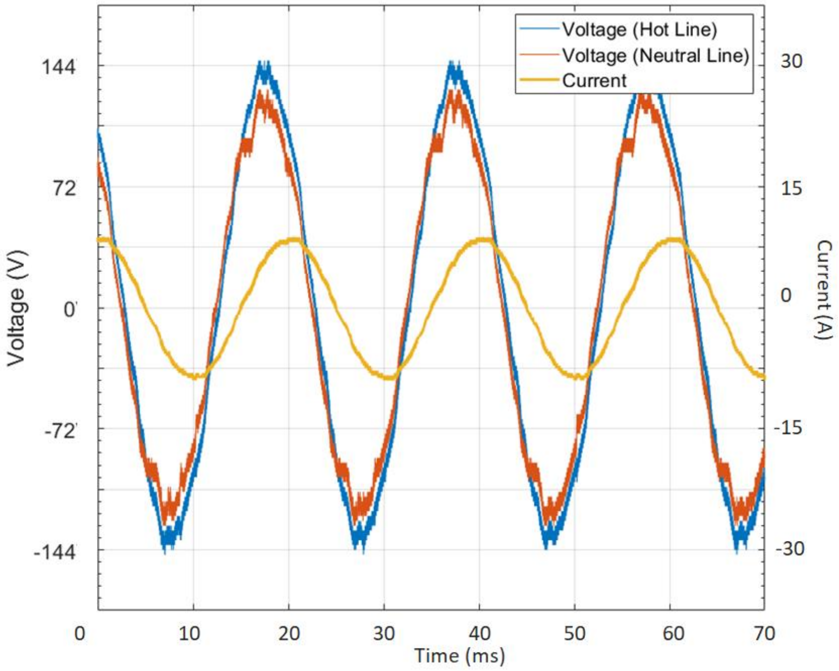


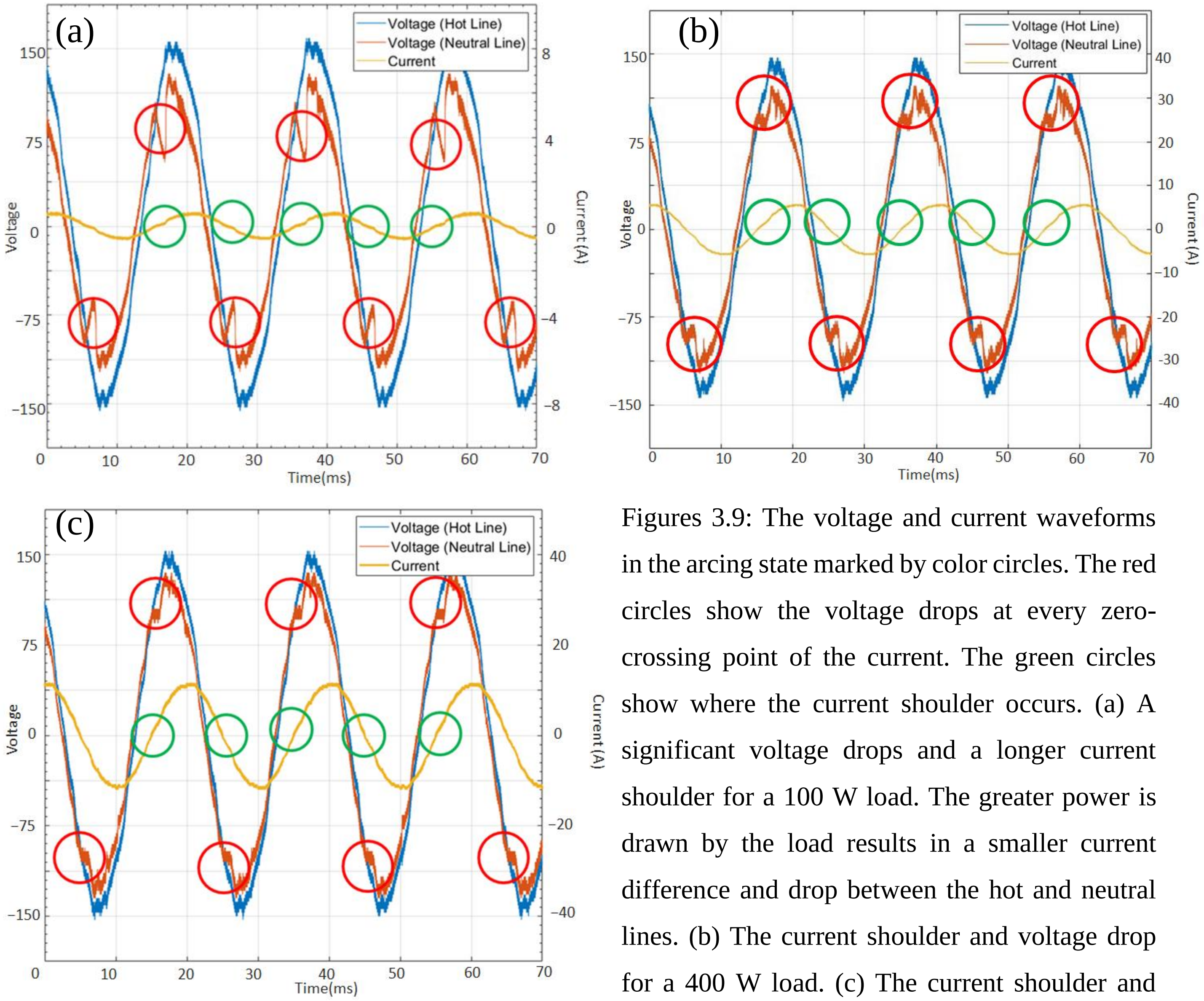
Figure 3.8: The waveform of 8.33A

setting with Arc-fault

The sharp drop in orange line at 1.00A and 4.00A shown in Figures 3.4 and 3.6 is also observed in 4.00A and 8.33A setting as shown in the chains of the following Figures 3.9.

According to the obtained result shown from Figures 3.3 to 3.8, it is suggested that ongoing arc-fault in the system is extinguished. Because the voltage drops momentarily at zero-crossing point of the current. Once the arc has been "snuff-out", the current waveform remained at zero creates a signature current shoulder as shown in Figures 3.9. This same waveform has also been obtained by Shea as referenced in Chapter 1.

The explanation behind current shoulder is as followed. When arc is presence in the system.



Figures 3.9: The voltage and current waveforms in the arcing state marked by color circles. The red circles show the voltage drops at every zero-crossing point of the current. The green circles show where the current shoulder occurs. (a) A significant voltage drops and a longer current shoulder for a 100 W load. The greater power is drawn by the load results in a smaller current difference and drop between the hot and neutral lines. (b) The current shoulder and voltage drop for a 400 W load. (c) The current shoulder and voltage drop for an 833 W load.

The “arcing state” was observed continuous arc-fault using high-speed camera (a CASIO EX-F1) of which maximum record speed is 1200 frames per second(fps) as shown in Figure 3.10. Arcing from all types of contact exhibited a pulsating discharge at twice the frequency of the AC system. In the DC system, the arc fault normally discharges from one end of the electrode to the other in a continuous manner. The explanation for the pulsating discharge in the AC system is that each period of the waveform contains two voltage peaks, that is, one positive peak and one negative. Once the breakdown voltage is reached, the air around the arc spot is ionized, and electrons move through the air with much lower resistance. The waveform of the current was measured using a current probe. The current waveform exhibits a small “shoulder” where the current level remains constant. The arc duration varies from 13 to 16.5 ms, and it is extinguished when the zero-crossing point is reached. The arc resumes once the voltage is high enough to overcome the oxide bridge.

It was found that voltage drop at certain point and the current shoulder appear at the irregularity of the waveform. It was also found that the irregularity of the waveform also produced a flashing / arcing state that “snuff” itself out and restart at the same interval.

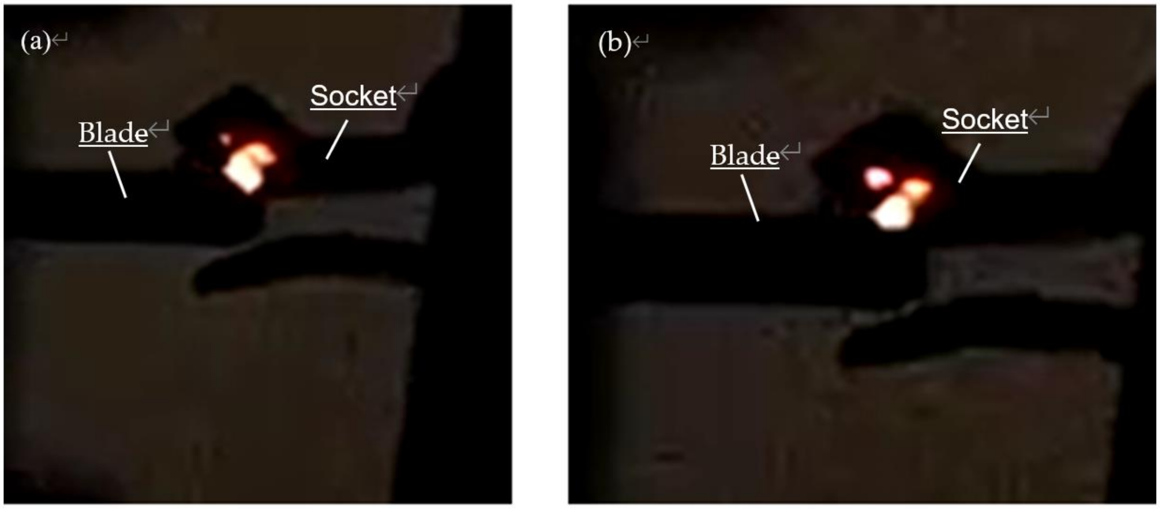
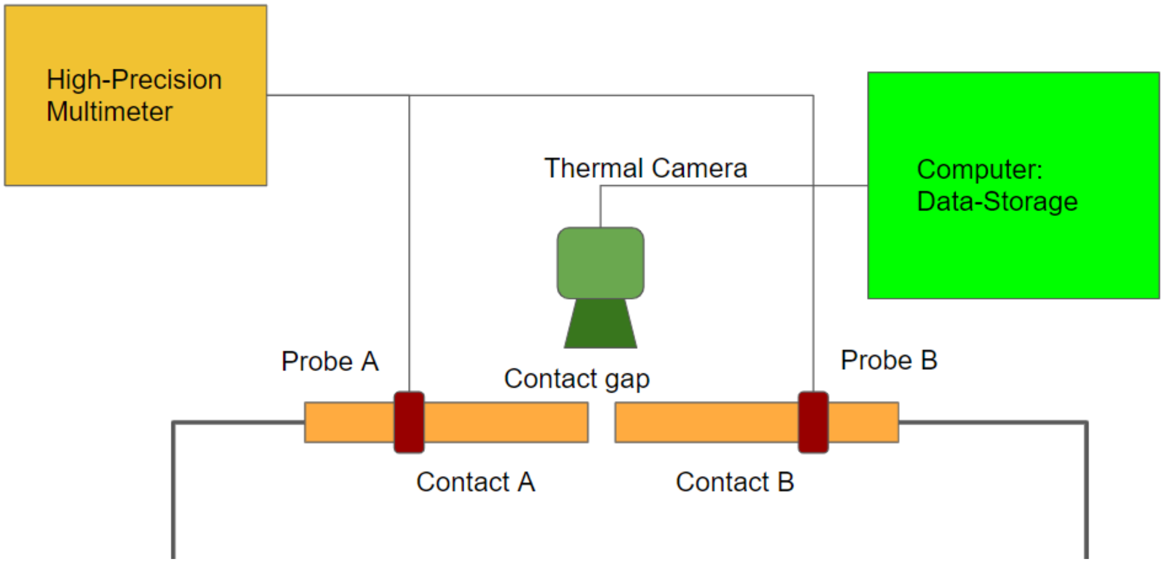


Figure 3.10: The arc at the contact point flash at a regular interval of 100Hz.

Chapter 4: The Relation between Series type Arc-fault and Contact temperature

There is one peculiar thing that was reported by researchers back in Chapter 1, that is the temperature of the arc-fault state is extremely high even if the current that pass through the point of contact is low. As low as 1.00A or less can generate substantial amount of heat. There has been report that sometime the affected area would not re-ignite after the circuit has been de-energized and cool down to a point. Hence, in this experiment we wanted to know if the contact temperature and the contact resistance do changes in various setting. Especially that it is well known that a certain oxide is a semiconductor. The simplified experiment setup is shown in Figure 4.1



.

Figure 4.1: The simplified setup for the observation between temperature and arc-fault.

Apart from the irregularity of the waveform, we are able to observe the other irregularities. For the other irregularities is that, various type of the contact starts to heat up due to both joule-heating effect and the arc-fault.

4.1 Heating effect in brass – brass contact

At 1.00A of current in brass - brass contact, we are able to observe that low current arc-fault enables to generate substantial amount of thermal energy on each arcing cycle as shown in Figure 4.2. Each arcing cycle must be energetic enough to create small patch of copper oxide at the contact point and boil away the oxide in each cycle which in this setting, the temperature is not hot enough. Due to the low current of the setting, the arc is not energetic enough to heat up area surrounding the arc-point beyond the affected area. In the other case where arc-fault does not occur on the bad contact connection, joule heating effect on the contact generates barely temperature change near the contact.

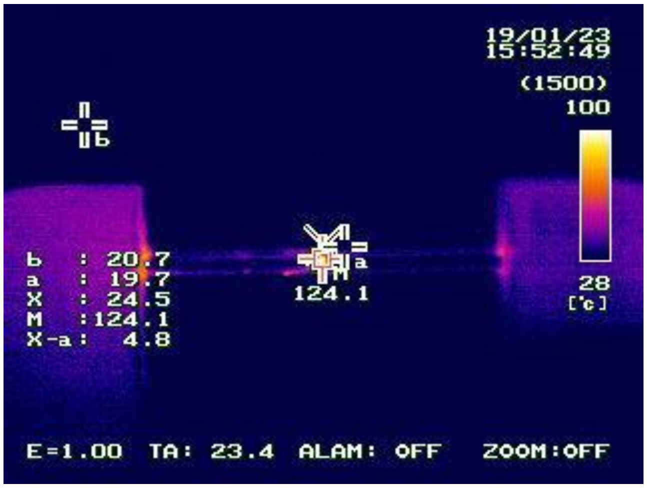


Figure 4.2: Heat generated from 1.00A Arc-fault.

At 4.00A of current in brass - brass contact, the arc-fault is energetic enough to create a small copper oxide bridge between two points of contact and to sustain its structural integrity in each cycle as shown in Figures 4.3 and 4.4. The thermal energy created from the spark is high enough to form copper oxides around the contact point. At this current setting, we also able to observe joule heating effect after the arc was intentionally extinguished as shown in Figure 4.5. The joule heating effect temperature near the contact point is still not hot enough to meltdown or light surrounding material on fire. The large joule heating effect will be discussed further down the chapter.

Figure 4.3: Heat generated from 4.00A Arc-fault.

Figure 4.4: Heat generated from 4.00A Arc-fault, 4 minutes later.

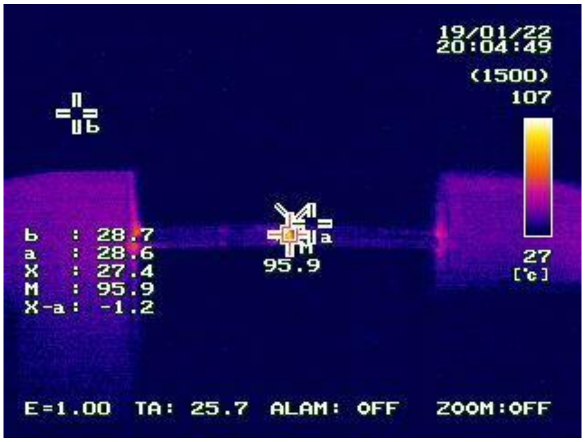


Figure 4.5: Heat generated from 4.00A Joule heating.

At 8.33A of current in brass - brass contact, it is expected to be the most energetic among all three current values. Since the system can provide the large amount of current, thermal energy created from the arc-fault is able to heat up surrounding material. Finally, at the contact point, it is able to set flammable material alight as shown in Figures 4.6 and 4.7. The contact heat rises up linearly and slowly. The temperature will continue to rise until heat dissipation reaches heat generation in equilibrium. The other behavior of 8.33A is the same as that of 4.00A although the temperature is much higher. At the actual contact point, the temperature could be higher than 124 °C as shown in Figure 4.8.

Figure 4.6: Heat generated from 8.33A Arc-fault.

Figure 4.7: Heat generated from 8.33A Arc-fault, one minute later.

Figure 4.8: Heat generated from 8.33A Joule heating.

4.2 Heating effect in brass – copper contact

At 1.00A of brass - copper contact, the thermal energy generation is substantially higher than brass to brass contact in both arc-fault state and regular joule heating state as shown in Figure 4.9 and 4.10. The oxide bridge forms up between two points of contact. Due to the low current, joule heating effect on the arcing case and non-arcing case is low.

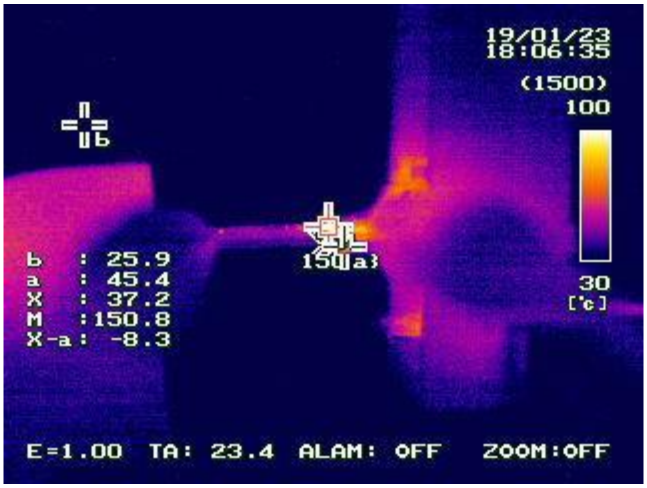


Figure 4.9: Heat generated from 1.00A Arc-fault.

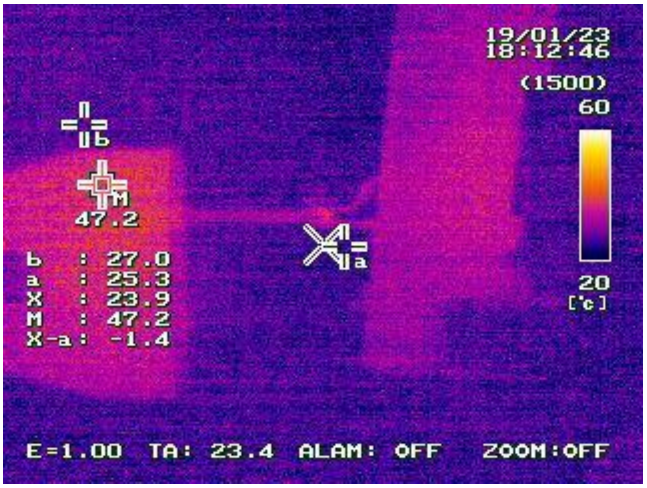


Figure 4.10: Heat generated from 1.00A Joule heating.

At 4.00A in brass - copper contact, it is expected that thermal energy from the arc is much higher than 1.00A contact, and is also much higher than brass to brass contact type. Temperature of the contact area rose up from room temperature to 500 °C within a minute of arc-fault as shown in Figure 4.11 and 4.12. The area around the contact conducted heat to nearby PVC housing and melt it down. Large oxide bridge is formed at exceptionally fast rate in the comparison to all brass - brass contact types and 1.00A case of brass - copper contact type. Heat accumulation of the joule heating effect of 4.00A is considerably faster than that of 1.00A as shown in Figure 4.9. It takes a few minutes to reach around 50 °C at 1.00A.   At 4.00A, 50 °C reaches at almost an instant.

Figure 4.11: Heat generated from 4.00A Arc-fault initial state.

Figure 4.12: Heat generated from 4.00A Arc-fault 1 minute and a half later.

Figure 4.13: Heat generated from 4.00A Joule heating initial state.

At 8.33A in brass to copper contact, the sample is unable to sustain prolonged arc-fault more than a few second. Therefore, we do not have a stable picture of 8.33A arc-fault state because the arcing state is so energetic that it broke off. It is suggested that the temperature may have reach to the point where copper oxide spontaneously turn back into copper from extreme temperature and melted off. In this experiment we only can observe the joule heating state at 8.33A of current. We made use of 4.00A arc-fault to create large oxide bridge of 1.5mm in diameter on the surface contact. Then, the oxide bridge is subject to 8.33A to study the joule heating effect at high current. As expected, that joule heating in higher current heats up the contact area substantially faster than that in lower current setting as shown in Figure 4.14 and 4.15.

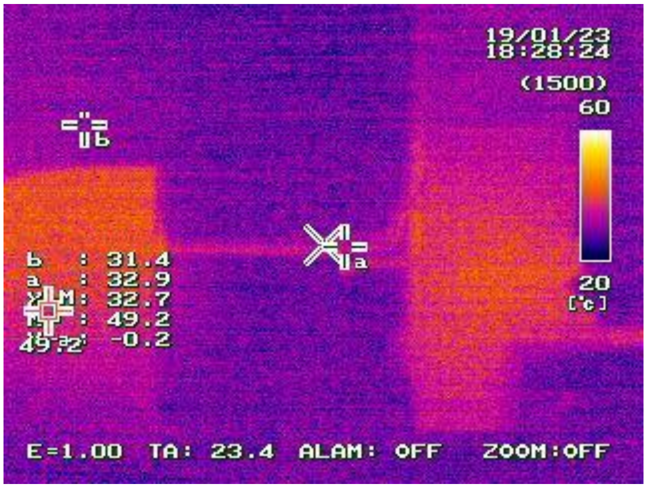


Figure 4.14: Heat generated from 8.33A Joule heating.

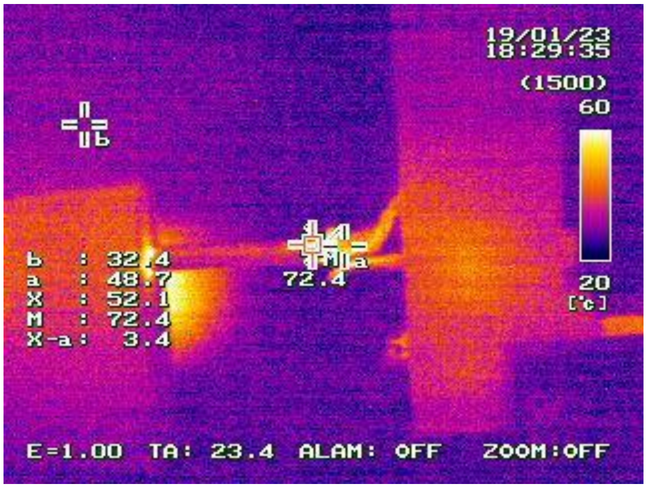


Figure 4.15: Heat generated from 8.33A Joule heating 1 minute later.

In this experiment result, we speculate that the heating effect only does not originate from the contact point for both brass to brass and brass to copper experiment. The heat generated from the base of the socket also heats up the electric wire. According to the thermal camera, it is unlikely that the heat in the contact area transfers the heat to the base of the equipment. As we can see in Figure 4.16, the blade body remains at room temperature while the base and the tip of the contact generates heat as shown in Figure 4.16. The other explanation is that brass does not passively emit infrared to the environment. Therefore, we see the metal in a deep black / cold state from the thermal camera. The area where arc-fault occurs emits infrared light actively so the thermal camera is able to observe the temperature near the spot. Whichever the case does matter, in this experiment we only wanted to know how much heat and energy is created in the arc-fault state.

Figure 4.16: Large amount of heat generated at the base of the blade could be the result of the heat transmission from the brass metal.

Both sides of the equipment generate substantial amount of heat and leak out of the PVC plastic hull. In this experiment, the base of the socket blade melted down after a prolonged arcing. The same result is obtained when we reproduce arc-fault with brass to copper contact heating. Base of the contact does not generate heat. Currently the mechanism behind this heating is unexplained although it is suggested to be caused by switching losses. Because two surface contacts between the electric wire and the socket blade carry parasitic heat capacitance which is shown in Figure 4.17.

Figure 4.17: Large amount of heat generated at the base of the blade.

4.3 Contact resistance relation to the temperature of the contact

By the result we obtained from both brass-to-brass case and brass-to-copper case, we speculate and find irregularity due to joule heating effect when there is no arc-fault on the system. Brass-to-brass case does generate more joule heating heat in the comparison to brass-to-copper. The difference between brass-to-brass and brass-to-copper is several Celsius degrees. It is suggested that the contact resistance in brass-to-brass case near the contact point could be much higher than brass-to-copper. Therefore, the heat is dissipated more even if the contact area is a better conductance. However, arc-fault initiates even though the arcing behavior between both types are similar. The contact with pure copper creates much more energetic arcing than that with brass-to-brass type. In our previous experiment, an oxide bridge is technically a resistor between two conductors. At a constant voltage level, resistance dictates how much current will be pass through itself. High resistance would not let high current pass through. If the resistor is capable of handling such current flow, it should not heat up. In the low resistance, the current would be able to move freely especially even if the resistor is unable to handle large amount of current. The resistor would heat and lit up in flame until the resistor is destroyed. Logically, we can apply the same consideration here. In brass-to-brass case, the oxide may have had more structural integrity and high resistance than one with brass-to-copper. Other peculiar thing that we were able to observe during the experiment is that the contact area would flare up and resume its arcing state when we leave the circuit for the joule heating effect to accumulate heat. This peculiar incident occurred especially in brass-to-copper case. This behavior has also been documented by an online study [1]. It is well known that copper oxide is partly semiconductor. Its conductivity is inversely proportion to the temperature.

The resistance of the contact area was measured between two contact points at various temperatures using a high precision multimeter. The current flow between the two contact points was set to 8.33 A. The reason for using a current of 8.33 A is that the generated arc fault is usually energetic enough to increase the temperature at the contact point beyond 600 °C. In order to sustain the arc-fault state in this high current setting where we were unable to sustain it naturally, we have to create an artificial oxide bridge. This is the same method we made to observe joule heating effect at 8.33A as explained in the previous subsection. At 600 °C, the heat is sufficient to generate large amount of copper oxide. At a lower current setting, such as 4.00A, the arc fault is not sporadic enough to raise the temperature of the contact area above 600 °C. The oxide bridge itself is not made of pure copper oxide but rather an amalgamation of fragment of copper and other impurities. The temperature data was taken from room temperature at 21 °C up to the highest temperature possible. Since joule heating state for both type of contact we done earlier. We are unable to increase the temperature normally with such a low current usage. In a normal use where joule heating effect that may cause fire. The contact is usually overload at a large amount of current. For us to simulate such heat accumulation. We resorted to artificially heat up the oxide bridge with external heater. The external heater used in the experiment is a set of candles. The overall idea of the setup is shown in Figure 4.28

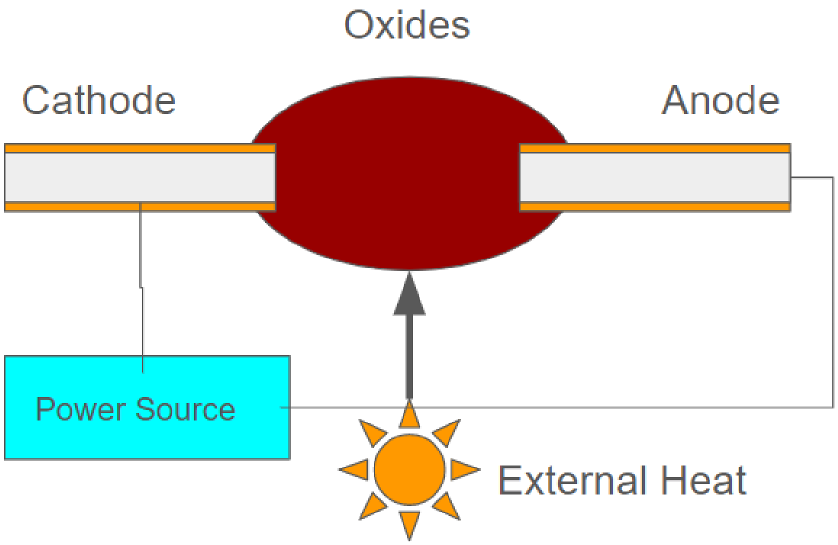


Figure 4.28: The oxide bridge is heated externally with a candle until the arc-fault state is able to start itself.

. Upon initiation of the arc-fault state at the temperature of around 130 °C, the temperature rapidly increased to around 230 °C then gradually rose to 700 °C. Two ohmmeter probes were inserted to measure the resistance between the two points of contact. The results show that when the temperature between the two points of contact was higher, the resistance was lower than it was at room temperature. This is shown in Table 4.1. The oxide bridge at the contact points acts as an electrical insulator. When the contact was perturbed while making and breaking the contact arc, the arc fault became self-sustaining. When the contact point reached a temperature at and above 520 °C, the resistance fluctuated between 1 kΩ and less than 100Ω. Therefore, in this experiment, the resistance value was measured for temperatures ranging from 21 °C to 520 °C. It was observed that at around 300 °C, the resistance value fell to the kilo Ω range, indicating that there were semiconductor properties at the contact point. [2-4] The semiconductor properties of copper oxide, which has a negative temperature coefficient, are well understood. The results we gathered indicate that current flow may be facilitated by the semiconductor properties of the contact surface.

TABLE 4.1: The relation between contact temperature and contact resistances.

Experiment No. (Cu-Cu discharge)	**Temperature Range in** °C	**Resistance Values in** Ω
Sample 1	21°C - 122°C - 238°C - 520°C	∞ - 124kΩ- 16kΩ - 530Ω
Sample 2	21°C - 131°C - 226°C - 520°C	∞ - 135kΩ- 26kΩ - 744Ω
Sample 3	21°C - 135°C - 231°C - 520°C	∞ - 150kΩ- 16kΩ - 631Ω
Sample 4	21°C - 146°C - 230°C - 520°C	∞ - 141kΩ- 19kΩ- 253Ω
Sample 5	21°C - 126°C - 217°C - 520°C	∞ - 133kΩ- 24kΩ- 342Ω
Sample 6	21°C - 119°C - 257°C - 520°C	∞ - 129kΩ- 29kΩ- 122Ω

With the result we gathered from this experiment we are able to conclude that the arcing state is causes directly by the semiconducting property of the copper oxide. Therefore, it does not matter if the contact point is made from Brass or other type of electrical brass. As long as there is any copper or alloy of copper near the contact point. Any spark or arc created by touching or breaking of contact would create certain amount of copper oxide which can create even more oxide in the process if the condition is suitable. In other type of contact where copper is not included in its material. It was also reported by Shea as referenced in chapter one that the arcing state and the heat distribution for Steel conductor is drastically different than the one with contact surface that made from copper or partially made of it.

4.4 Reference

1. “Glowing Connection on Screw Terminal” Posted by J Donia
   Available online: https://www.youtube.com/watch?v=mnYzGH7FS2k (accessed on 11 May 2022)
2. Anderson, J.S.; Greenwood, N.N. The Semiconducting Properties of Cuprous Oxide. Proc. R. Soc. Lond. Ser. A Math. Phys. Sci. 1952, 215, 353–370.
3. Ogwu, A.A.; Darmal, T.H.; Bouquerel, E. Electrical resistivity of copper oxide thin films prepared by reactive magnetron sputtering. J. Achiev. Mater. Manuf. Eng. 2007, 24, 172–177.
4. Rahnama, A.; Gharagozlou, M. Preparation and properties of semiconductor CuO nanoparticles via a simple precipitation method at different reaction temperatures. Opt. Quant. Electron. 2012, 44, 313–322.

Chapter 5: The Relation between Series type Arc-fault and Contact Vibration

As we have explained in Chapter 1, An electrical spark will only occur when there is enough electrical charge in an area to cause an air breakdown. In a low voltage setting such as 100V. The distance gap between two contact point must be extremely close distance. It is highly probable that the contact may have been perturb by external force that it creates a constant make and break contact. Such movement would create a distinct and continuous arc. Therefore, in this experiment we use laser vibrometer to check whether if the contact point has been perturbed by any force. High speed camera is used to observe of the perturb motion match with the arcing interval. The simplified experiment setup is shown in Figure 5.1.

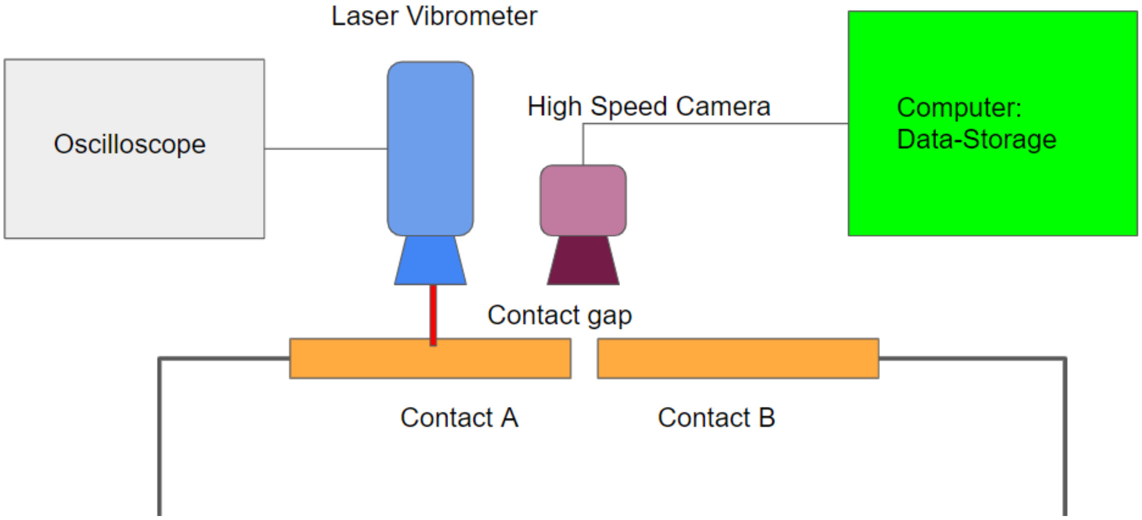


Figure 5.1: The simplified setup for the observation between vibration and arc-fault.

When an arc-fault occurs, sound is emitted from the contact point of the plug. As shown in the chain of Figure 5.2 to Figure 5.7. We are able to observed the vibration velocity between one with arc-fault and one without arc-fault. When the contact point is subjected to 1.00A of current as shown in Figure 5.2 and 5.3. We are able to observed the Figure 5.2, the one with arc-fault is that the waveform of the velocity plot exhibit a noticeable pattern where at the peak point of the waveform has a small velocity spike where the one without arc-fault in Figure 5.3 does not show to has such peak. We can also observe in the Figure 5.2 that near zero-crossing point of the current where the arc is extinguish as explained in previous subsection. The vibration velocity is also at zero. Once the current shoulder phase has pass through and the voltage has resumed its normal state as shown in Chapter 3. The vibration velocity spike up at the same time where voltage has reached its highest peak.

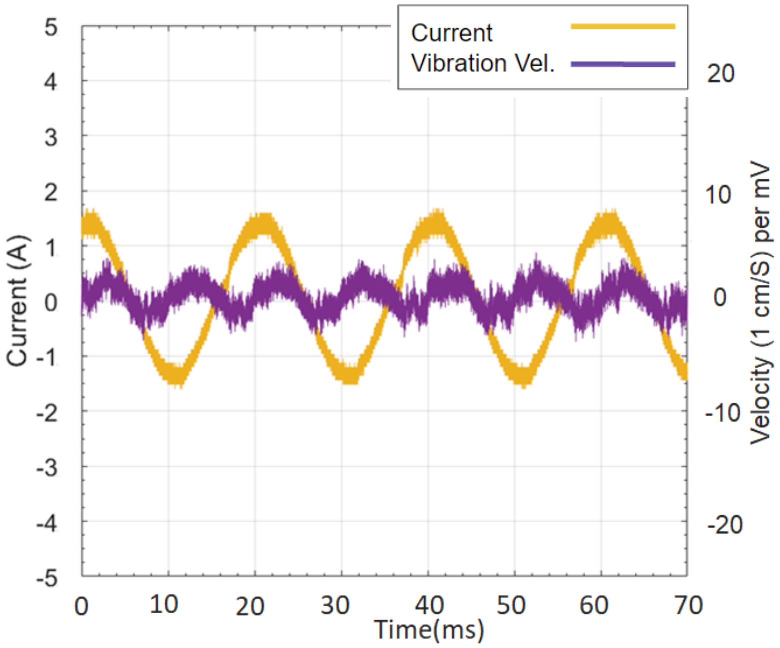


Figure 5.2: Vibration waveform of 1.00A current draw with arc-fault.

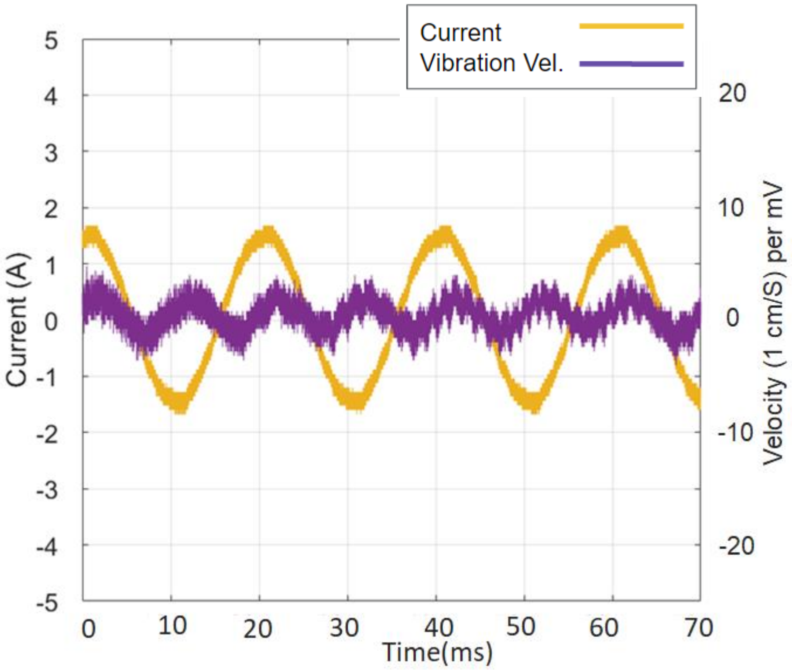


Figure 5.3: Vibration waveform of 1.00A current draw without arc-fault.

When we increase the current draw from 1.00A to 4.00A. The behavior of the vibration is still the same but the strength of the vibration is magnified by many folds as shown in Figure 5.4 and 5.5. Especially with higher vibration strength. The peak where vibration is at its strongest strength, its location in the period is much more prominent when compare to the 1.00A case. The peak vibration is at its strongest when arc re-ignited itself. Even though at highest current may create more vibration strength, it is suggested that the vibration strength may not depend on the amount of current that is passing through the bridge alone. When we compared vibration strength between 4.00A case and 8.33A case. 8.33A case as shown in the Figure 5.6 has relatively lower vibration strength even if the power draw is twice the level.

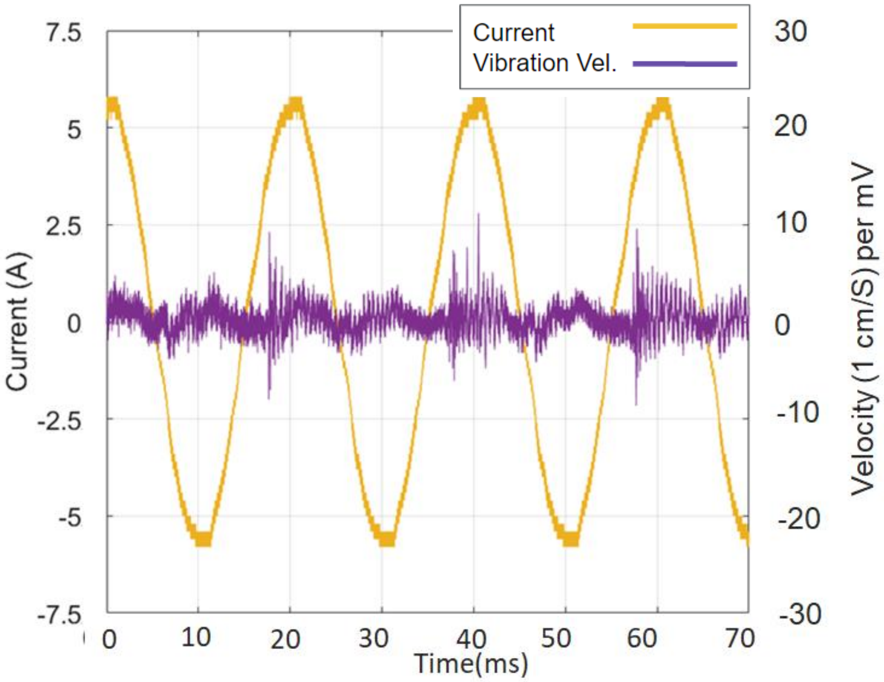


Figure 5.4: Vibration waveform of 4.00A current draw with arc-fault.

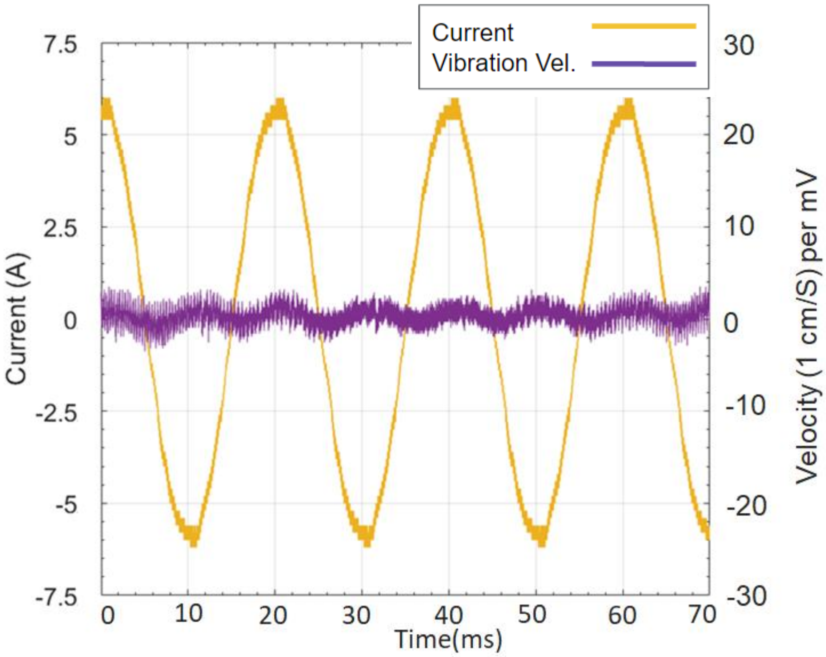


Figure 5.5: Vibration waveform of 4.00A current draw without arc-fault.

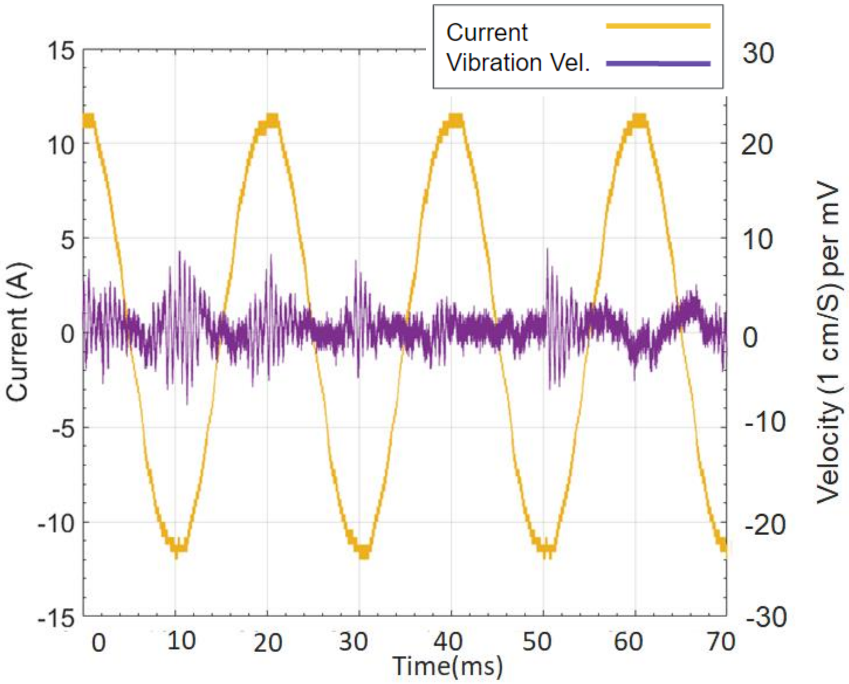


Figure 5.6: Vibration waveform of 8.33A current draw with arc-fault.

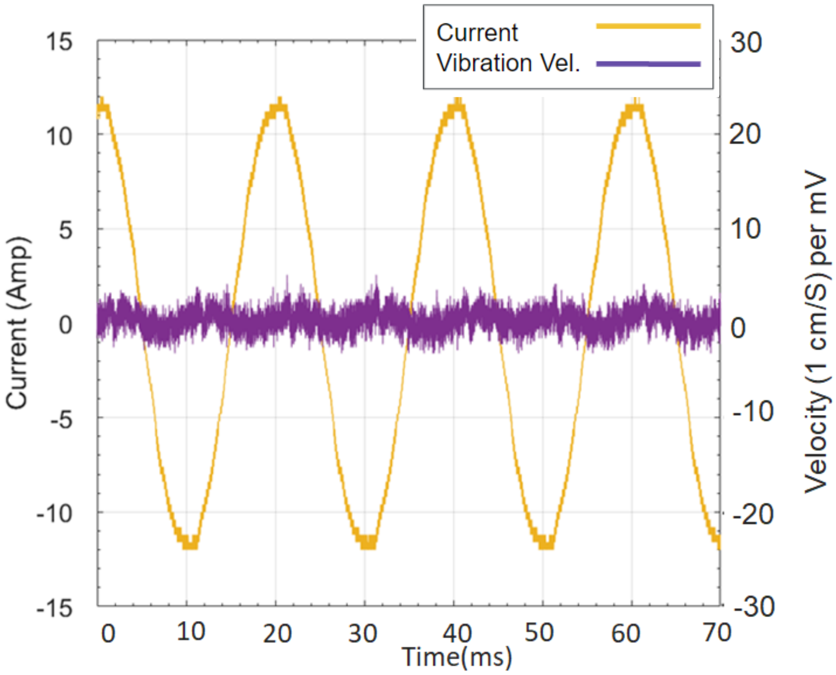


Figure 5.7: Vibration waveform of 8.33A current draw without arc-fault.

The vibration at the contact point is always observed even one with arc-fault and one without arc fault. and it is unlikely causes by electromagnetic force**.** According to these results, the vibration strength is directly proportional to the amount of current that is being passed through the contact spot. However, the variations in the vibration velocity every period are due to the contact surface area. The vibration strengthens when the arcing condition is present at the connection. Figure 5.9 shows an FFT analysis of the vibration velocity waveform in Figure 5.8**.** It also shows that the contact area will vibrate at twice the frequency of the AC. As we have explained earlier that the strongest vibration would occur every time the current reached the zero-crossing point. Vibrations that are caused by poor contact may not be present in the direct current setup due to its continuous discharge. This phenomenon is poorly understood due to the difficulties presented by the microscopic scale of the contact area in it. We were unable to make measurements of the thickness, width, and girth of the contact point. The amount of current that flows through that small contact area will need to be simulated by computer analysis in future research. Given what we know, there are two possible explanations for the vibration phenomenon. The first explanation attributes it to thermal expansion, and the second explanation attributes it to the electromagnetic field change within the small contact area. We will explain the thermal expansion explanation first. The strength of the vibration in the arc fault depends on multiple factors. The first factor is the amount of heat that is generated and dissipated in the contact area. It is directly proportional to the amount of current that passes through the contact spot and the resistance of the contact area. The second factor is the thickness of the oxide at the location where the current is flowing. As mentioned earlier, the arc fault extinguishes itself or is dimmed at every zero-crossing point and near the points where the current shoulder and voltage drop are observed. It is assumed that the temperature at the affected area initially decreases but then increases again when the arc fault is reinitiated. If the heat affects a large enough area, it may cause thermal expansion when the arc state flashes up. Consequently, the arc state will increase the size of the affected area and push away both contacts. When the arc extinguishes itself at the zero-crossing point, the affected area shrinks in size due to the reduction in temperature. This back-and-forth expansion may also initiate a secondary making or breaking of the contact spark, and it can also reinitiate the arc-fault state if the temperature falls too low near the new contact area. This means that in every arc-fault state, even if the setup is running with the same amount of current, the vibration strength would not be equal in every experiment due to the changes in the contact area. To replicate the vibration strength, the size of the copper oxide bridge at the contact area must always be the same. The other explanation is the electromagnetic field change. A sudden field change is experienced when the arc extinguishes and reignites and is similar to rapidly switching the circuit on and off. This produces an electromagnetic force that can attract the two contacts together.

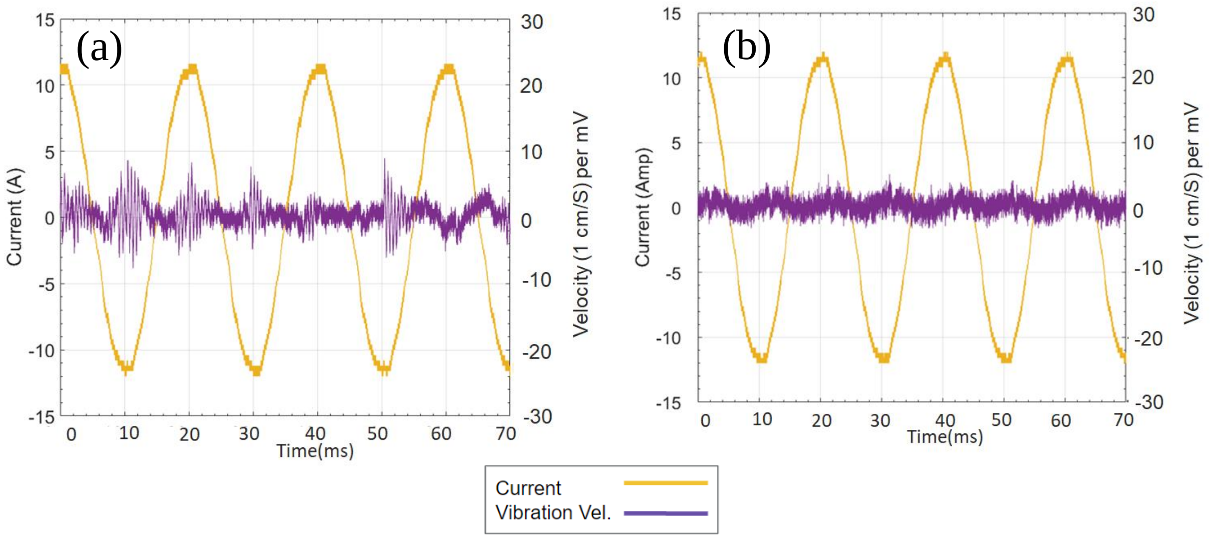


Figure 5.8. The voltage waveform and the vibration velocity waveform. (a) When there is poor contact in an arc-fault state, it is observed that the point of contact generates vibration pulses at

twice the frequency of the AC power supply. (b) When contact between the two electrodes is poor with no electrical discharge between the contact points, the vibration is still present, albeit at a significantly lower strength than that in the electrical discharge state.

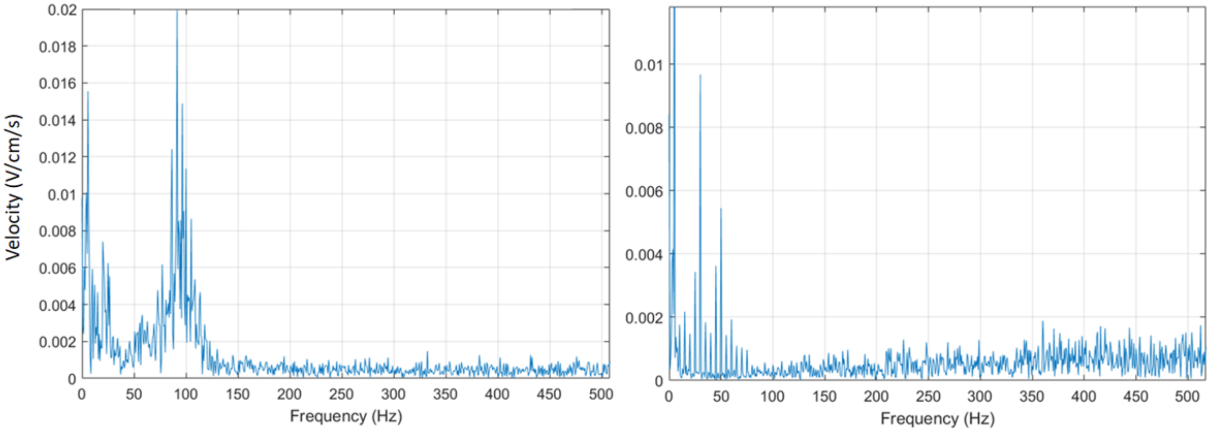


Figure 5.9. FFT results for the vibration velocity waveform. (a) FFT result for an arc fault present at 8.33 A. (b) FFT result for the normal state when both contacts are held firmly together. Notice that only the 50 Hz component is left, which may be caused by nearby vibrations from the power supply when there is no arc-fault state.

Chapter 6: Contact Surface Inspection

Once the contact has been used in the experiment and damaged by either electrical discharge or the heating effect. Light microscopy is used to crudely observe the surface of the contact and see the extent of the damage. Electron microscope was also used to closely inspect the contact surface. Electron microscope can have much higher image resolution than light microscope. However, electron microscope cannot identify the residue on the surface. Each residue has many colors depend on the type of oxides generate by the experiment. A sample that made from alloy of multiple metal will required Xray Diffraction analyzer to identify the residue of the material. The process and the order of the observation is shown in Figure 6.1.

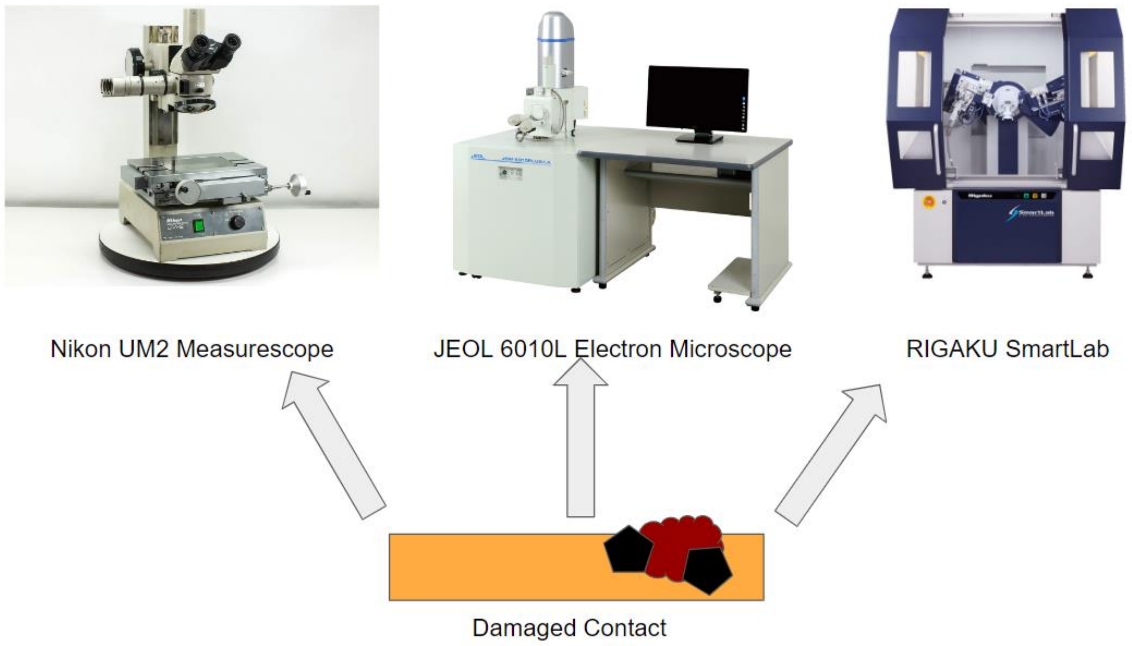


Figure 6.1: Measuring instruments uses in the analysis.

6.1 Light microscopy of the sample

The copper and brass contacts that were used in the experiment were examined using electron scanning microscopy (SEM, 6010LV, JEOL Ltd.) and light microscopy (Measurescope UM2, Nikon Co. Ltd.) to investigate the damage from the initial arcing contact. All of the copper samples used in the SEM were treated with a high concentration of hydrochloric acid to remove any copper oxides from the surface. The acid was able to remove both types of oxides, cuprous oxide (Cu_2O) and cupric oxide (CuO), from the surface and to expose the damaged copper beneath. Hydrochloric acid does not react with pure copper. On the other hand, the brass contact surface was not treated with acid since brass can react with hydrochloric acid and form a zinc chloride solution that can damage and alter the brass surface. The damage from a small initial arc is sufficient to reduce the effective contact area of the conductor. The brass sample exhibits less contact deterioration from the initial arc, although, the damage is still largely visible and features a large patch of black residue. It is thought that a single small arc can inflict enough damage to reduce the overall current carrying capacity of the contact area. However, in actual practice, it is not possible to determine the area of the contact surface that carries the current due to its microscopic scale. Any small movement by a human operator, either accidentally or from purposefully readjusting the setup, can drastically change the point of contact, thus altering the results. When the contact surface is subjected to repeat arcing, the average contact area may wear down leading to a reduction in the current carrying capacity and causing an over-current state.

Oxide formations were not observed on the surrounding copper material. The copper was leeched by the oxide at the contact surface and subjected to the electrical discharge. By taking the space of the affected area and effectively digging out the copper, the affected surface was replaced with its oxide counterpart. This type of erosion [1] is predominant when the electrical arc is energetic enough to remove a portion of the contact surface from the base material. Brass contact surfaces are much more resistant to electrical discharge wear, as is shown in Figures 6.2 and 6.3. The result has the same pattern as what was observed by Noboru [2] and Song [3].

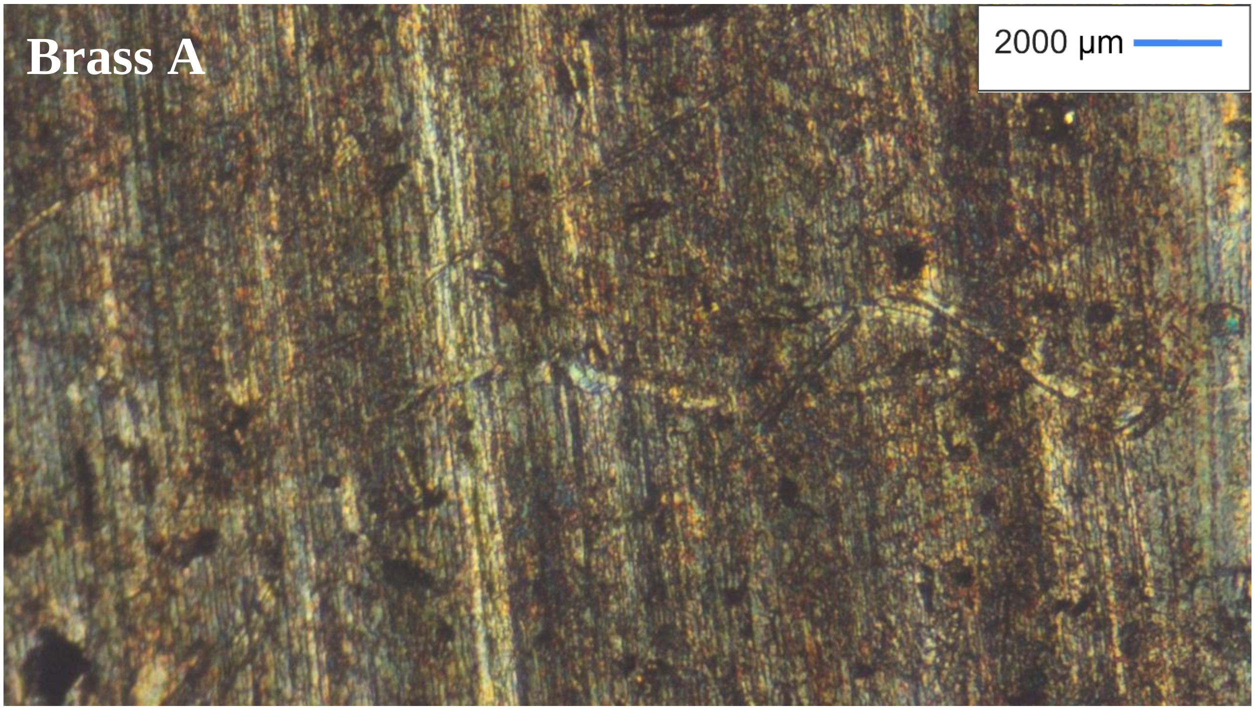


Figure 6.2: New brass surface at 5x zoom.

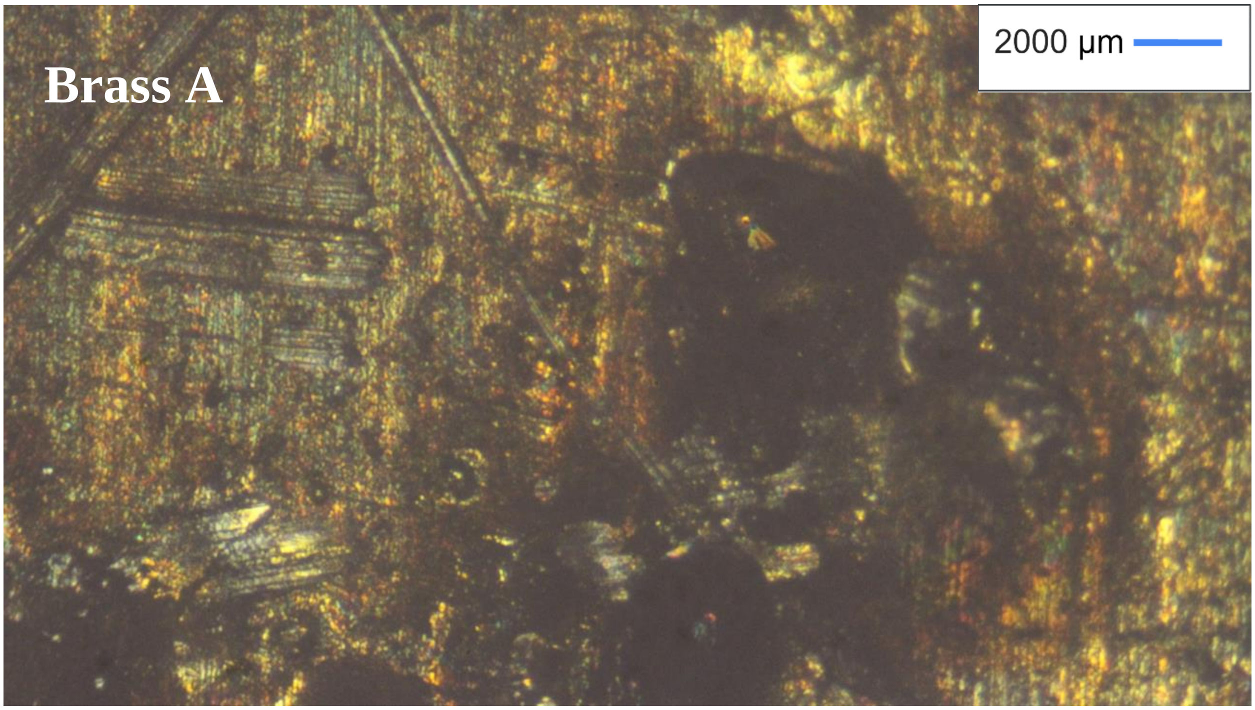


Figure 6.3: Damaged brass surface at 5x zoom.

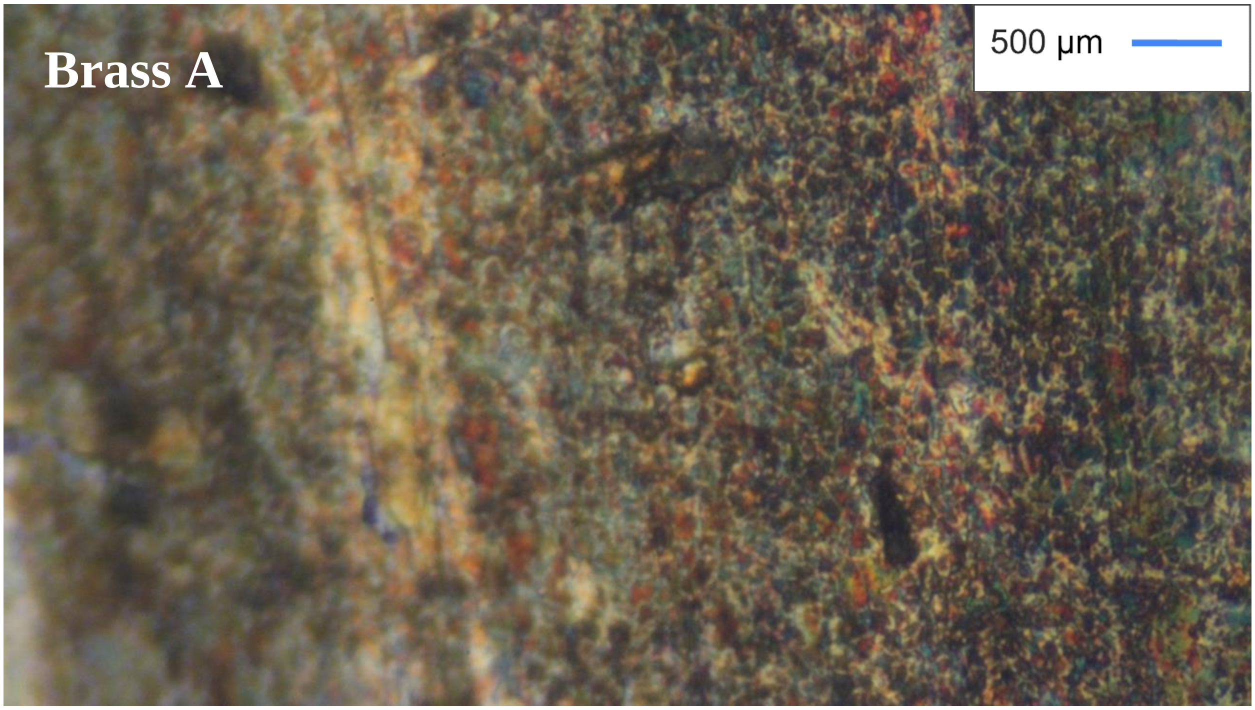


Figure 6.4: New brass surface at 20x zoom.

When brass surface is repeatedly subjected to electrical discharge. If the discharge is energetic enough to melt down a portion of the surface. We are able to observe a blob of black material which is not present when the surface is new as shown in Figure 6.4 under light microscope. The damaged one is shown in Figure 6.5. Black material in question is highly probable that the residue may have been an amalgamation of copper oxides of both types. The black blob has black body and distinctively red hue in reflection color. When the same sample is zoomed in further, we are able to observe streaks of copper color material embedded with the oxides as shown in Figure 6.6 and 6.7.

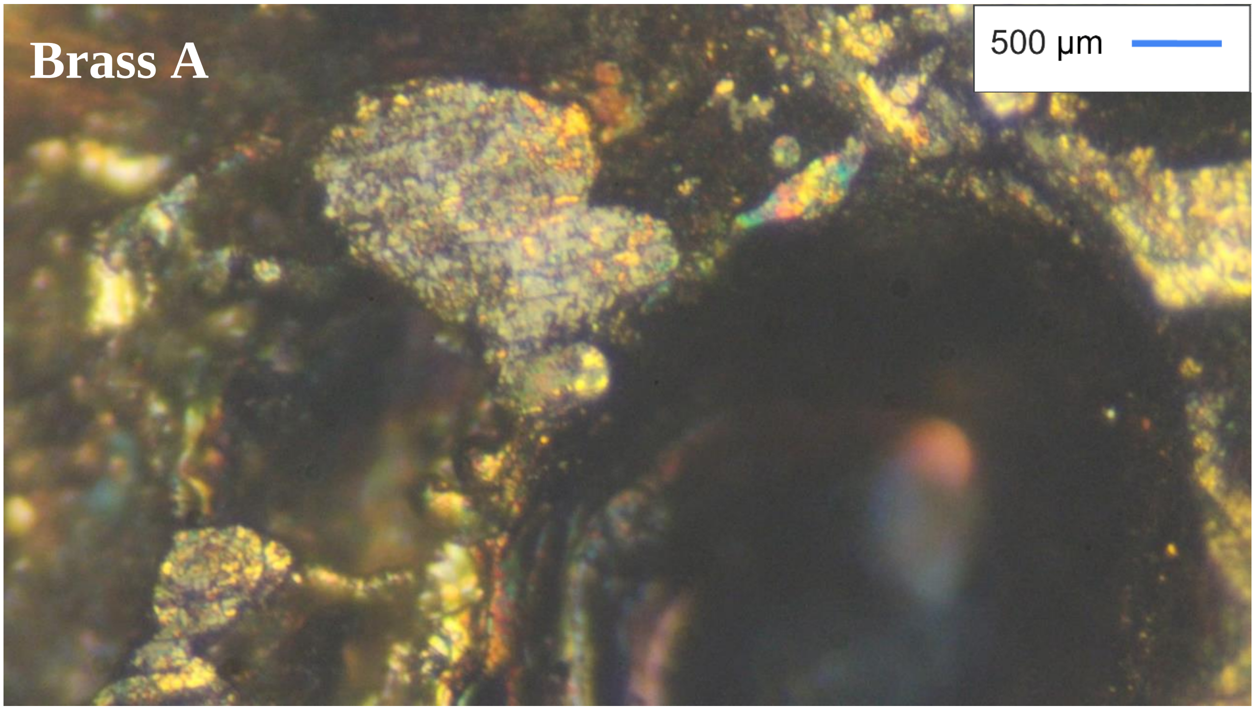


Figure 6.5: Damaged brass surface at 20x zoom, Visible CuO formation.

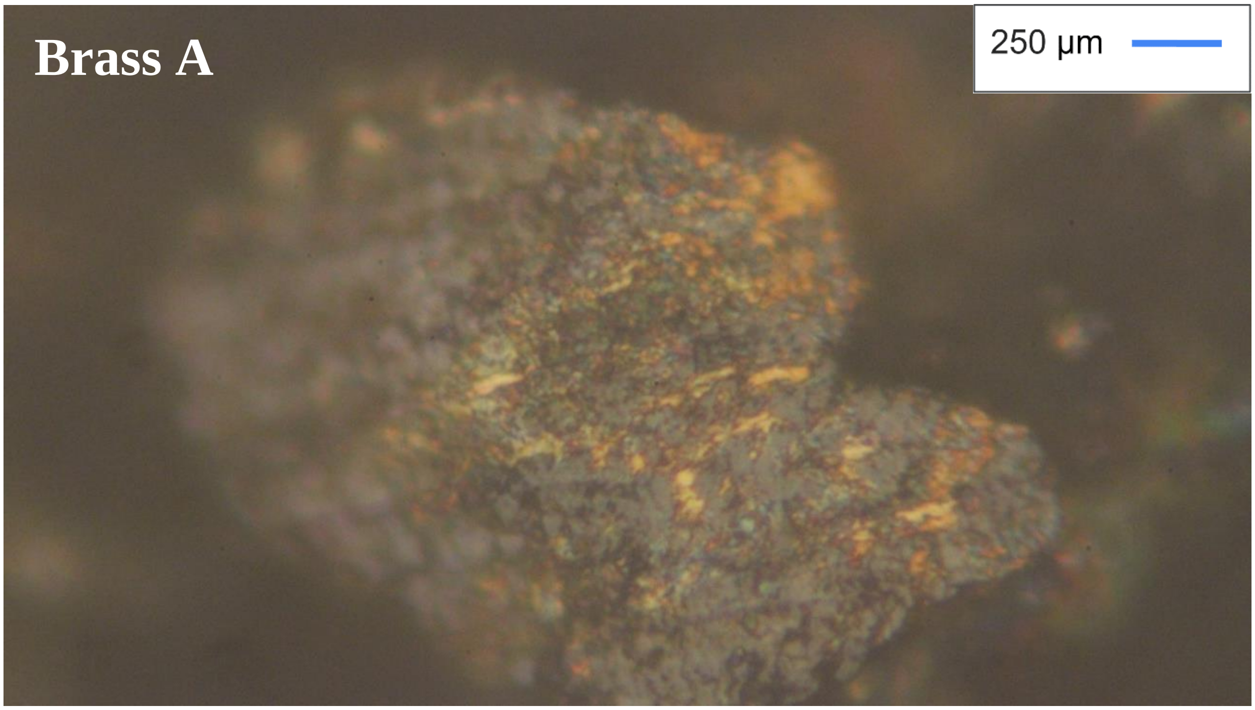


Figure 6.6: Damaged brass surface at 40x zoom, Visible copper separation.

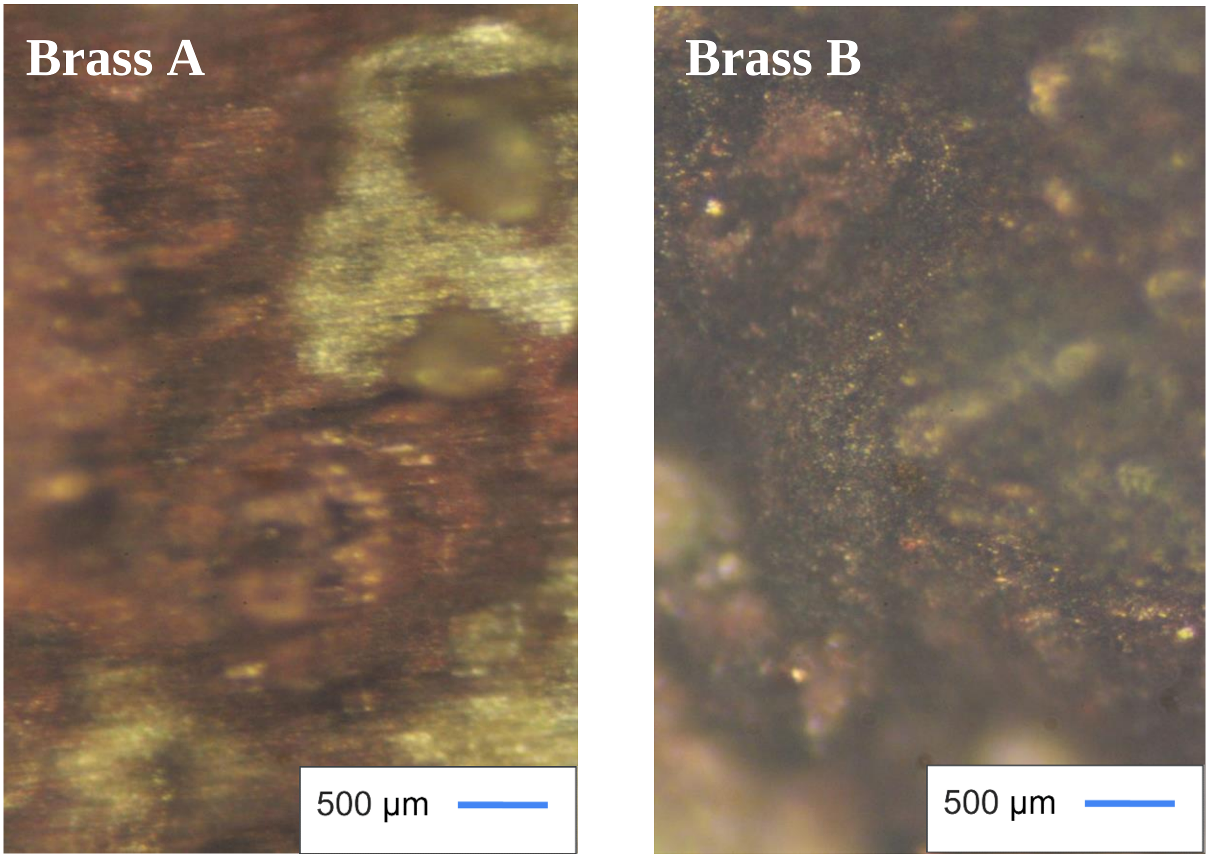


Figure 6.7: Brass A surface with visible copper, Brass B surface with visible copper.

The separation of copper from the alloy is nothing out of special. Brass is an alloy of copper and zinc where zinc has much lower melting point than copper. It is suggested that when the contact point is subjected to large amount of heat energy by either joule heating effect or electrical discharge. The colloid zinc portion of the alloy is melted down and separate out into either zinc oxide or mixed with the molten copper oxide. Since the zinc has lower melting point than copper. Zinc is then leech out of the contact and expose the surface of the copper. As we can observed in Figure 6.7. The patches of copper at the contact point are not a uniform flat surface made from copper, but rather a surface filled with peak and crevices of various type of matters.

6.2 Electron microscopy of the samples

A: Copper Samples

The following chain of Figure are the picture taken from electron microscopy. According to the result we got from light microscopy. We were able to observe patches of copper oxides created from contact heating. Due to the reflection and imperfection in the lens and the focus of the microscope. We are unable to adjust the focus of the microscope to fit with all height of the surface. Especially when some area of the surface has been damaged and created large number of bulges. Electron microscope enabled us to observe the extent of the damage on the contact surface. As explained earlier in the section. Copper sample that was damaged from contact heating has been wash off with high concentration of Hydrochloric acid to remove copper oxide from the surface and show the extent of the damage done by the heats. As shown in Figure 6.8 and 6.9, in Figure 6.8 is the undamaged and unused/new copper contact surface. The copper sample is basically a copper socket taken out of the plastic housing directly. Once an electrical spark of 4.00A is produced on the surface by make-break contact action as shown in Figure 6.9. We are able to observe that the surface has been effectively “dug-out”. The previous material that filled in the dug-out spot used to be a blob of copper oxides. Since the oxide has been remove by the Hydrochloric acid, we can see the hole. The other bulges on the surface is copper that may have been molten and re-attached itself. Once we zoom in further at 600X and 1000X Magnification as shown in figure 6.10 and 6.11. At 600X Magnification we are able to observe what we called “micro-pore” on the contact surface. These micropore effectively reduce the contact surface that used to carry current and its material elasticity. The loss in the elasticity will reduce the grip strength of the contact which will further reduce effective conducting surface when the surface is moved to unsuitable spot. These micro-pores can be seen up to 1000X Magnification level as shown in Figure 6.11. The formation of the pore is suggested to be heat induced due to circular shape of the pore. These pores may have been filled with copper oxides before it is wash off. This oxide may grow as the hole size increase. The oxidation continues if the temperature rose up to the point where oxygen in the air is allowed to oxidize with copper.

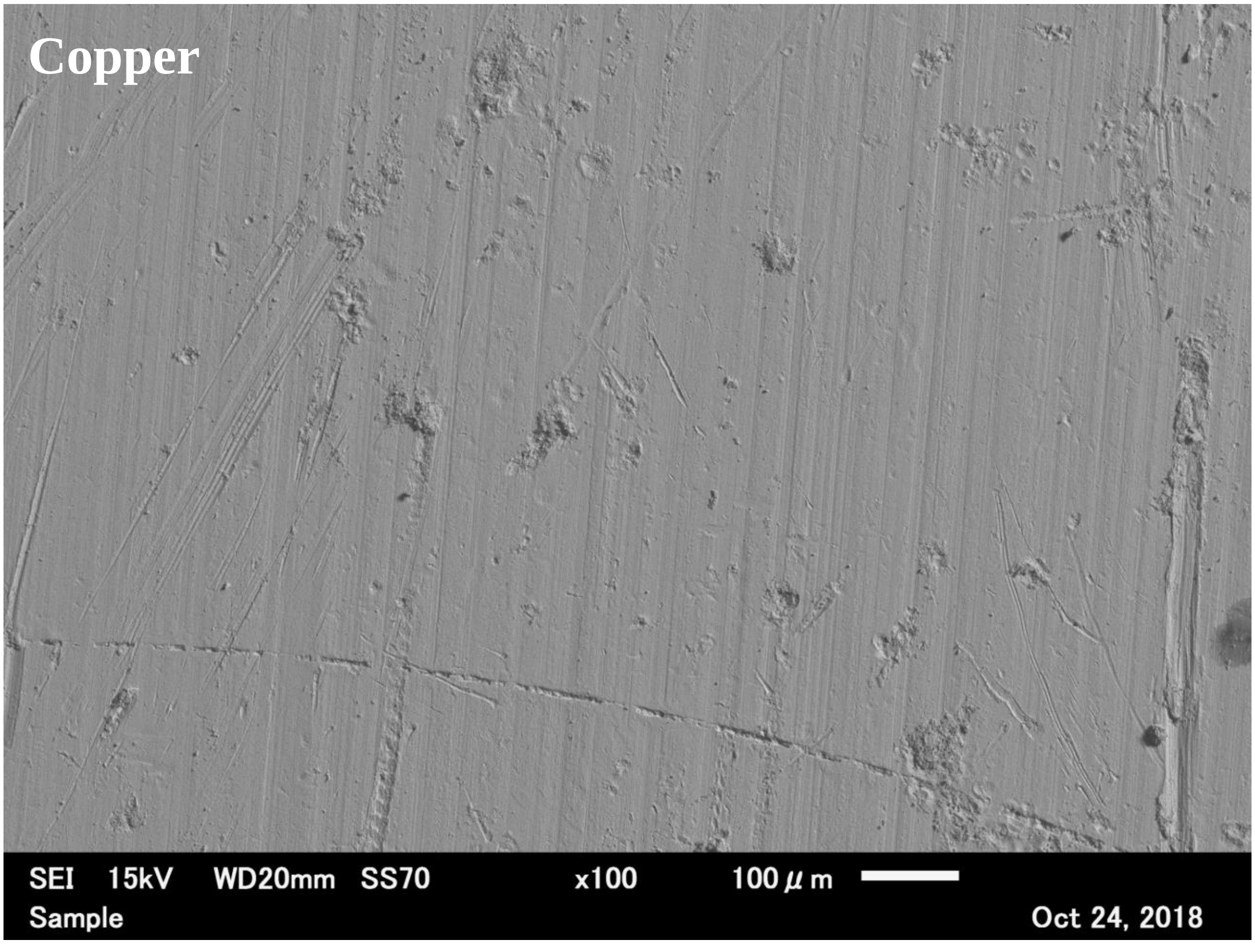


Figure 6.8: New copper surface under electron microscopy. Noted that the copper has not been treated with chemical before this picture is taken. The surface shown here is factory new.

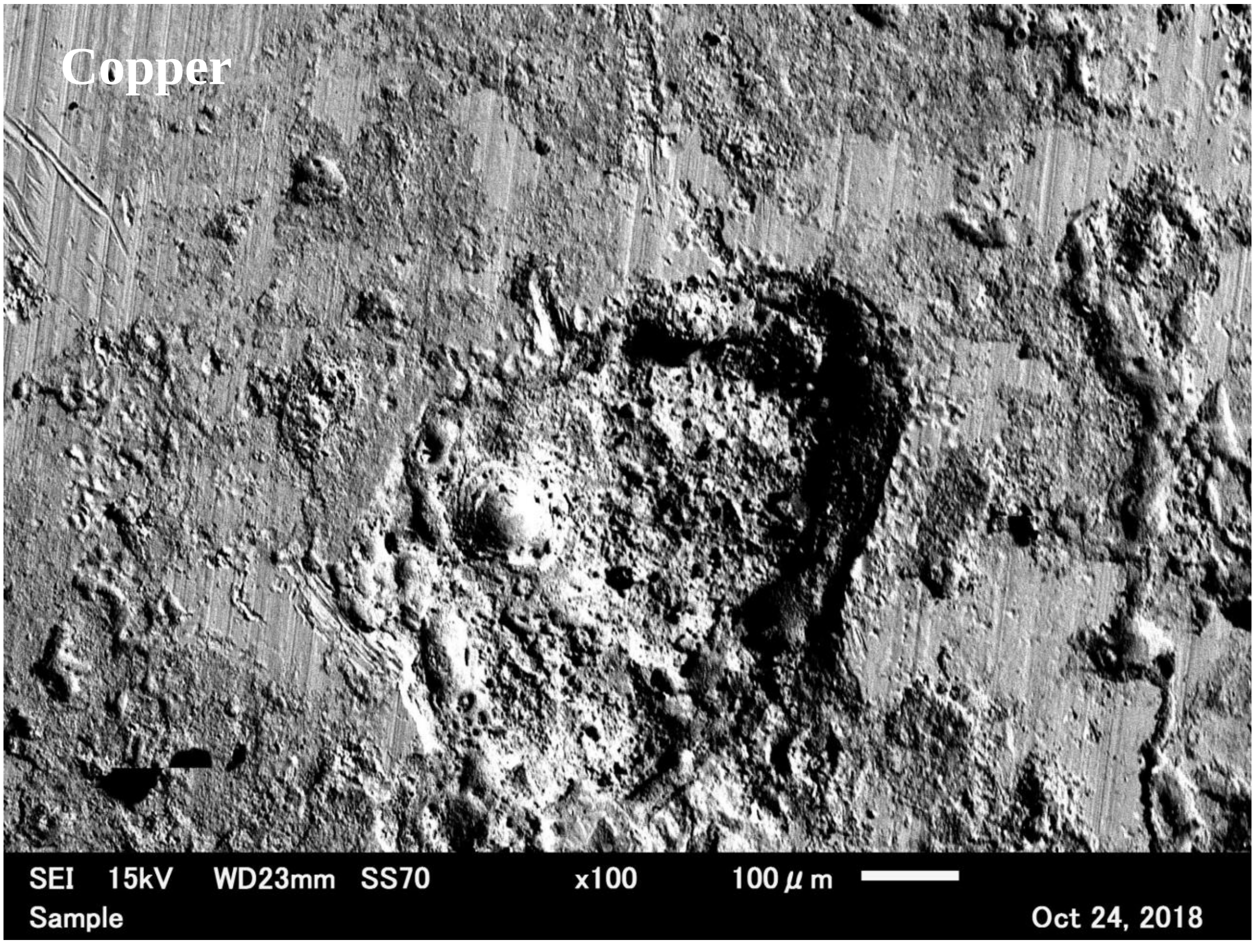


Figure 6.9: The same area of the copper surface after the copper was subjected to contact electrical Arcing. Noted that the contact area has been effectively dug out.

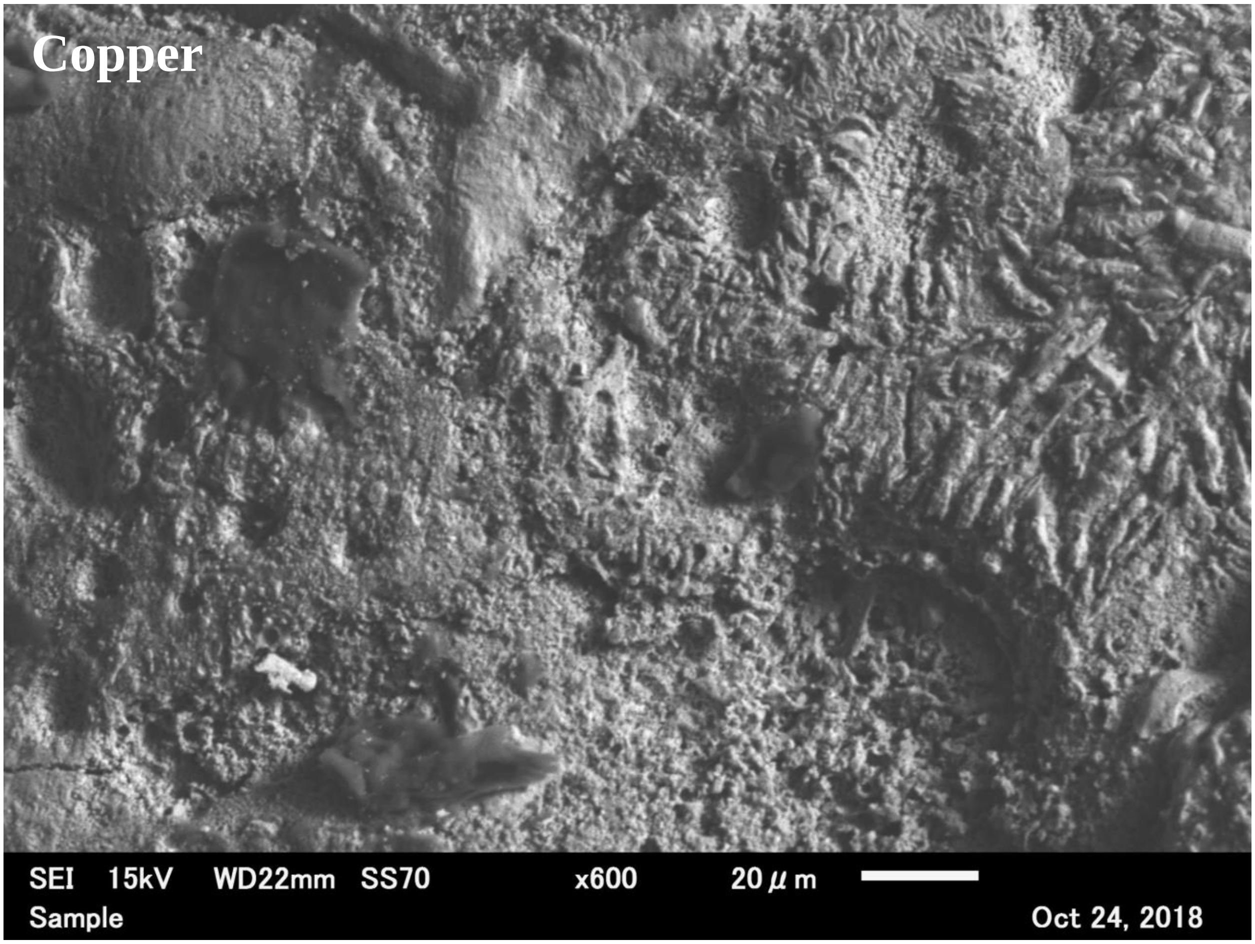


Figure 6.10: The same area of the copper with higher zoom. We are able to observed that copper surface has been melted and formed into patches of copper oxides.

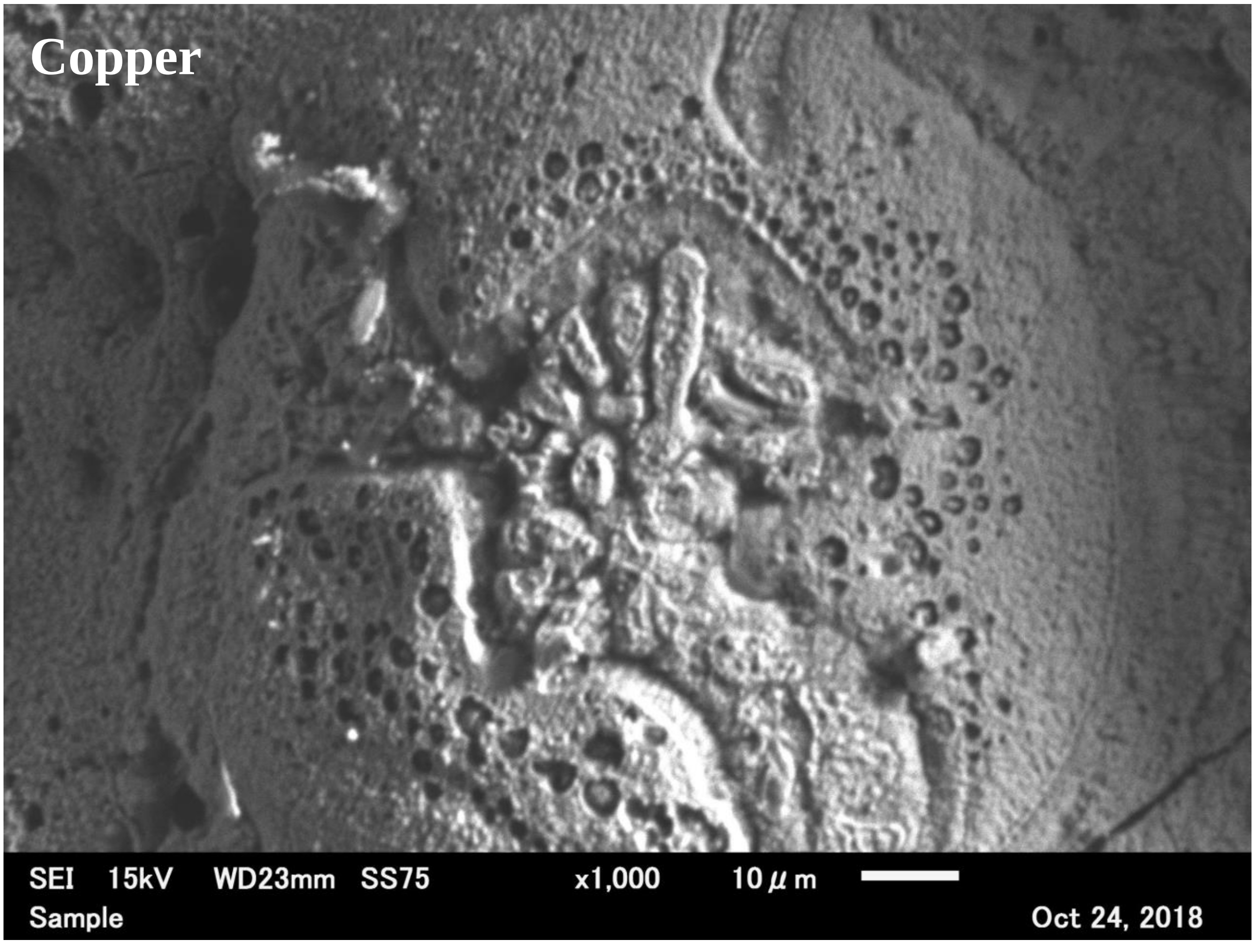


Figure 6.11: The same copper sample with 1000x Zoom level. We are able to observed that in a microscopic level that the surface develops micropores which can reduce overall effective contact area.

B: Brass Samples

In this chain of Figure will show the surface inspection Brass contact surface before and after it is subjected to 4.00A of electrical discharge. There will be two set of brass surface, for set A and set B. As explained earlier in the subsection. These brass sample is not treated with Hydrochloric acid like copper sample due to Zinc being reactive with the acid which can damage the overall contact surface. In Figure 6.12 shows the new brass A contact surface at 1000X. The magnification on this picture is at 1000X not at 100X so that we wanted to see that even the smallest area of the brass surface is relatively flat surface with less to no irregularities. Once a single electrical discharge of 4.00A is conducted on the contact surface as shown in Figure 6.13. We are able to see bulges of material formed on the surface and the surface around the contact area is no longer flat. Once we zoom in at 600X as shown in Figure 6.14. We are able to see that even if the area around the oxide bulge was not in a direct contact but the surface is deteriorate. It is suggested that the copper around that affected area has been “leeched out” by the formation of the oxide and some part of the zinc at the surface may have been molten off. When we zoomed in at 1000X as shown in Figure 6.15. Brass A does show the same pattern with the copper surface earlier. Micro-pores has been form and cracks can be seen. These pore and cracks reduce its structural integrity but still much more resilient than what pure copper contact offer. Brass sample B as shown in the Figures chain from 6.16 to 6.19 has the exact same result to Brass sample A. Which confirmed that even though brass is resilient to contact wear than pure copper. The same wear and its deterioration pattern are still the same.

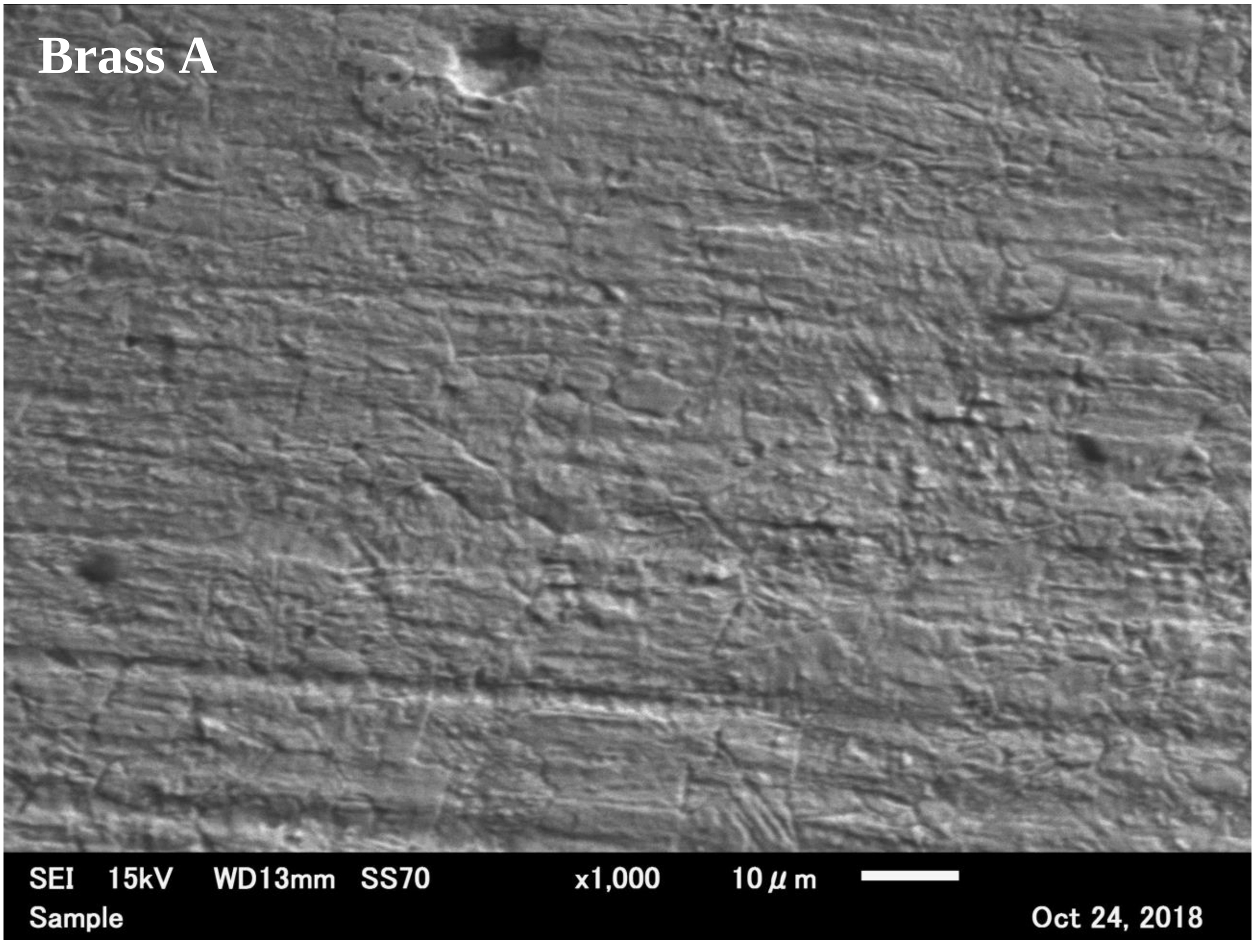


Figure 6.12: New brass surface under electron microscopy. Noted that the copper has not been treated with chemical before this picture is taken. The surface shown here is factory new. This is sample A.

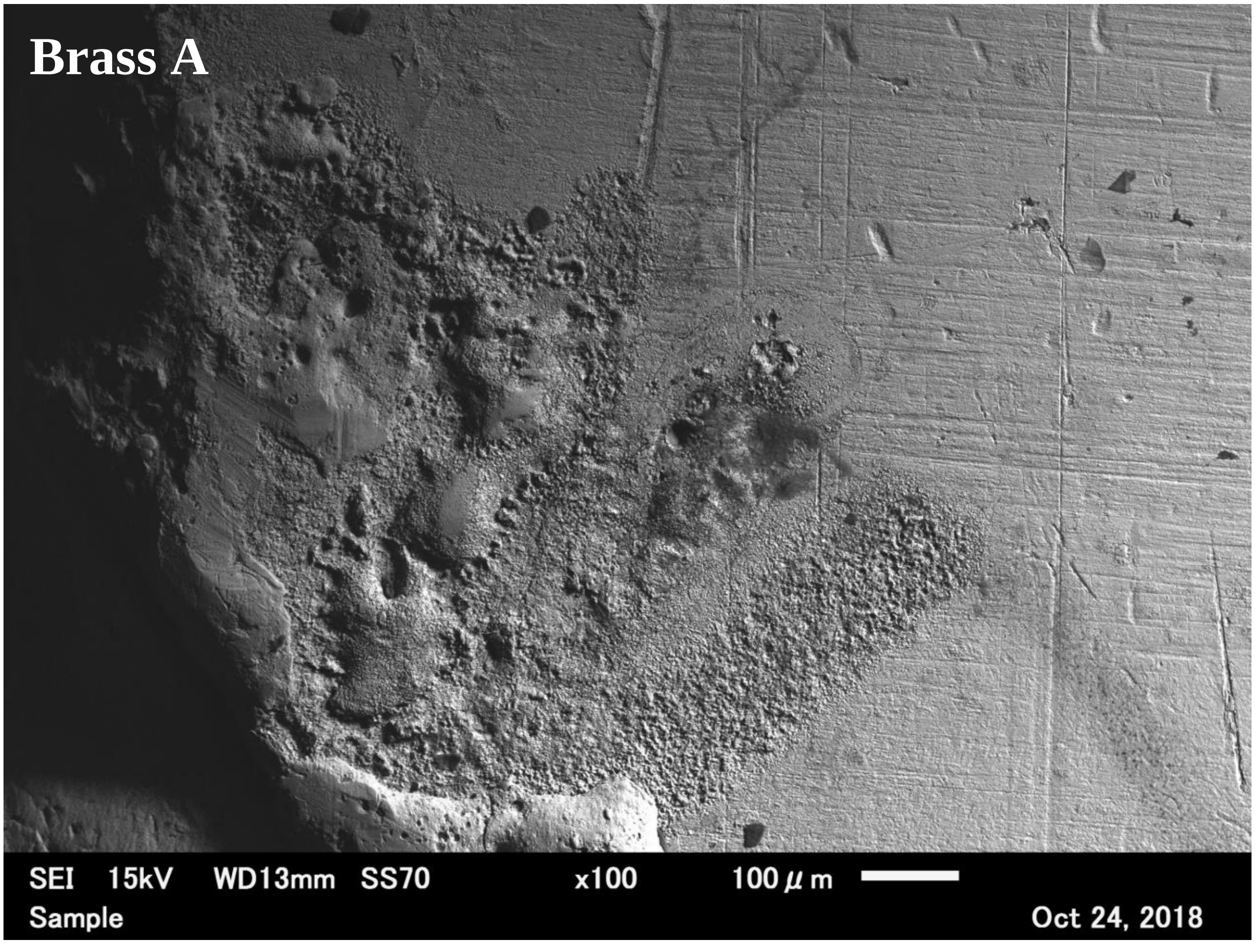


Figure 6.13: Brass sample A surface. We can observe and compare that the brass surface is more resilient at preventing electrical discharge to damage its surface.

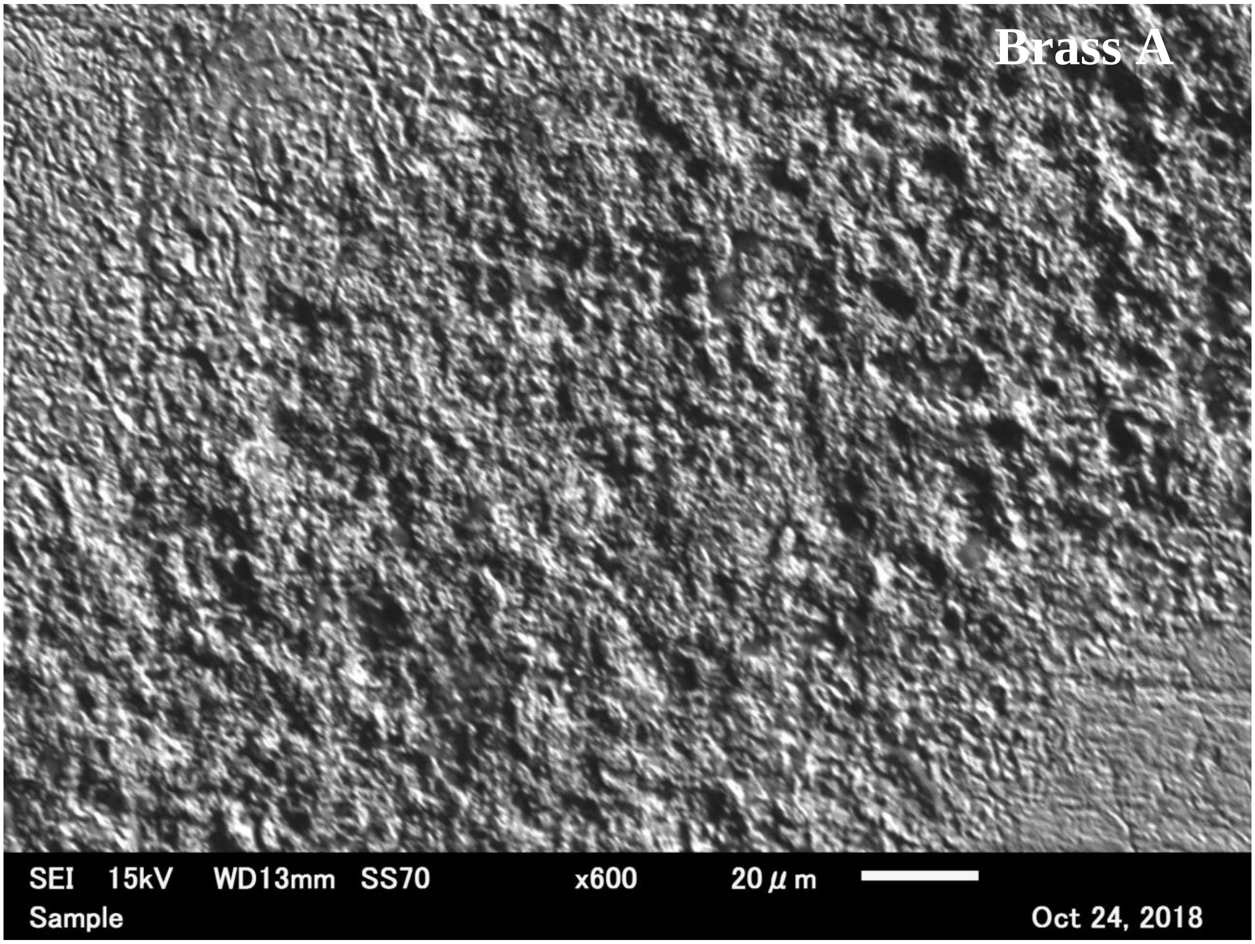


Figure 6.14: We can still observe that Brass sample A also exhibit small pores after it was used for one time.

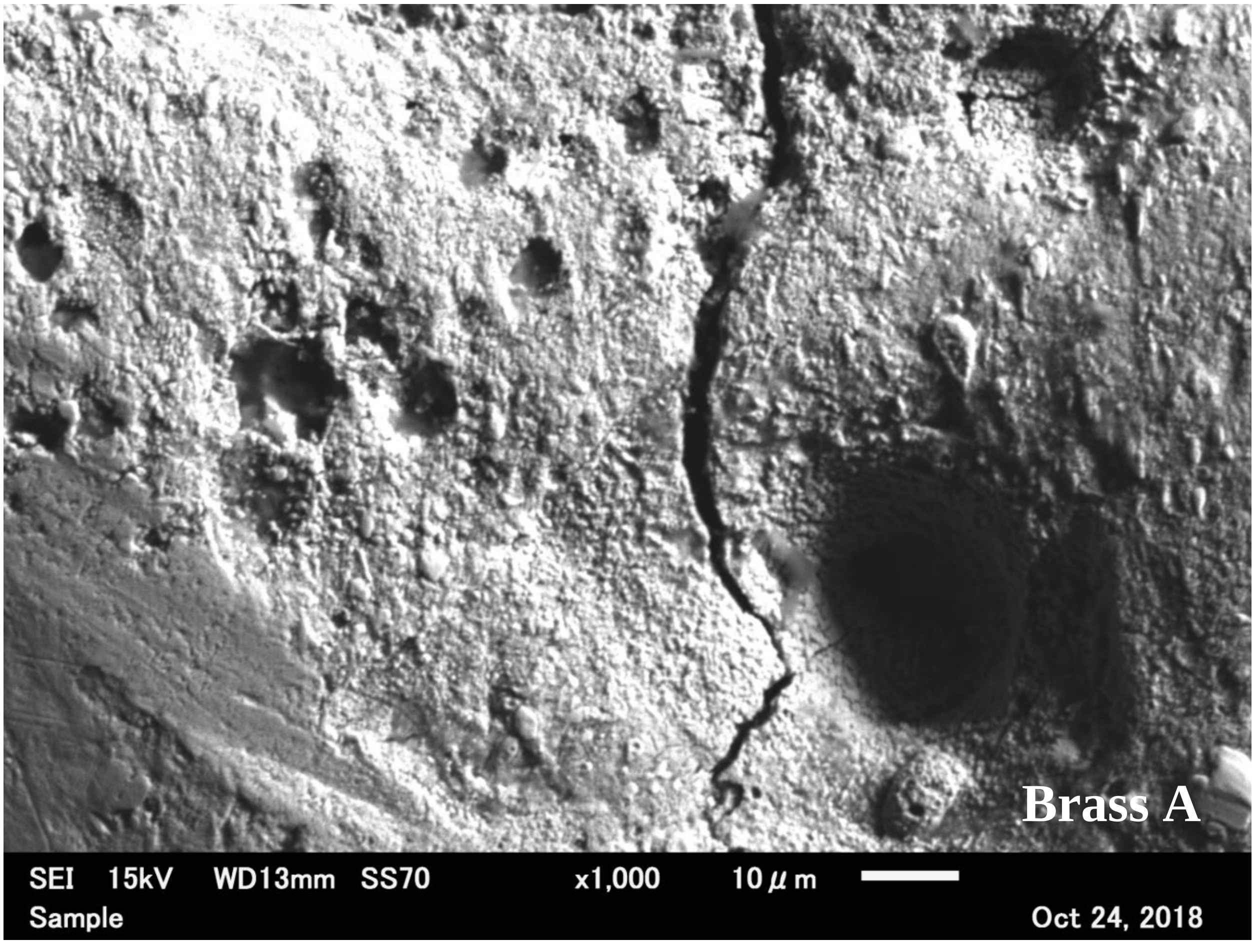


Figure 6.15: We can observe that in a microscopic scale for Brass A. Cracks is formed and micropore is still largely play important role for the contact degradation

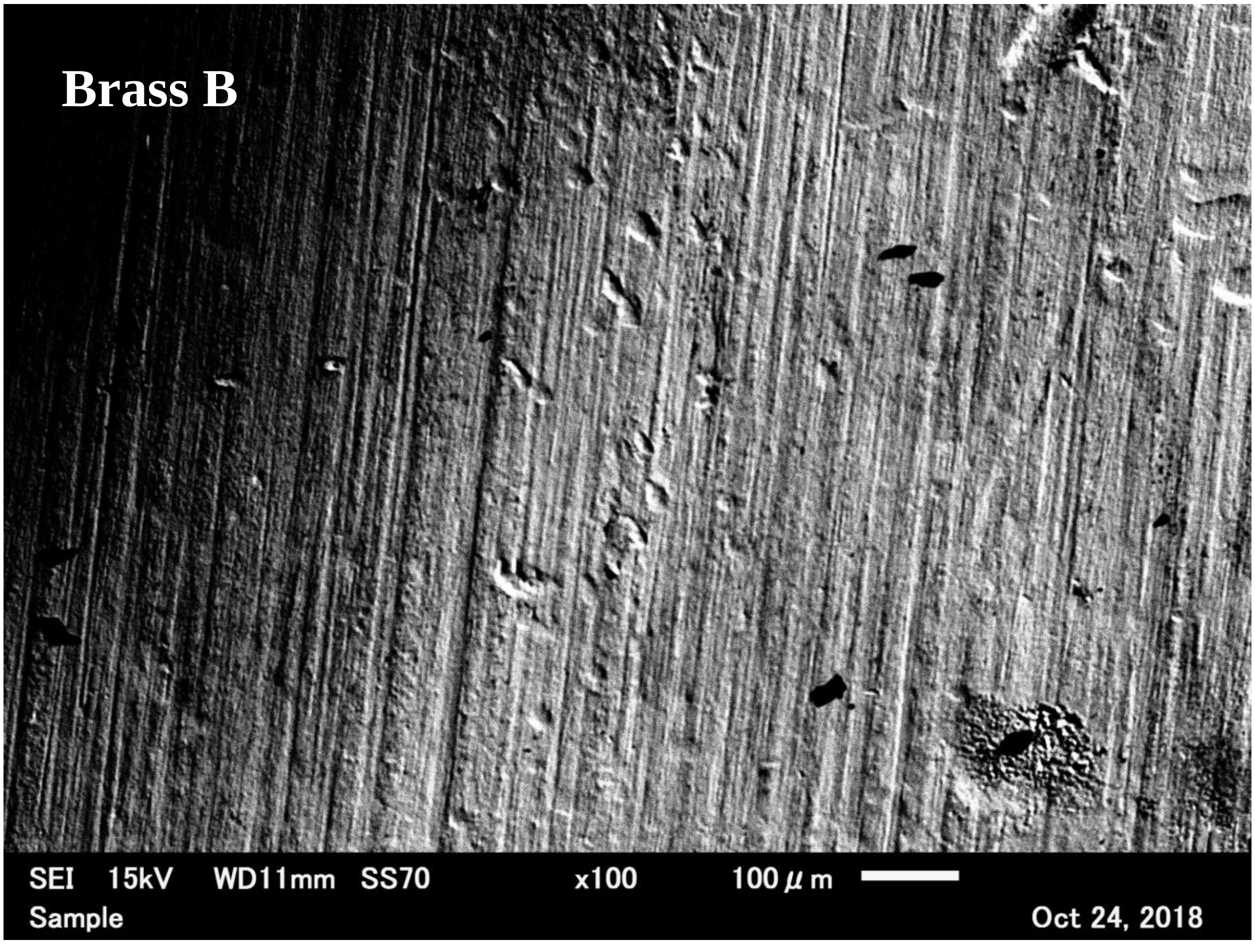


Figure 6.16: New brass surface under electron microscopy. Noted that the copper has not been treated with chemical before this picture is taken. The surface shown here is factory new. This is sample B.

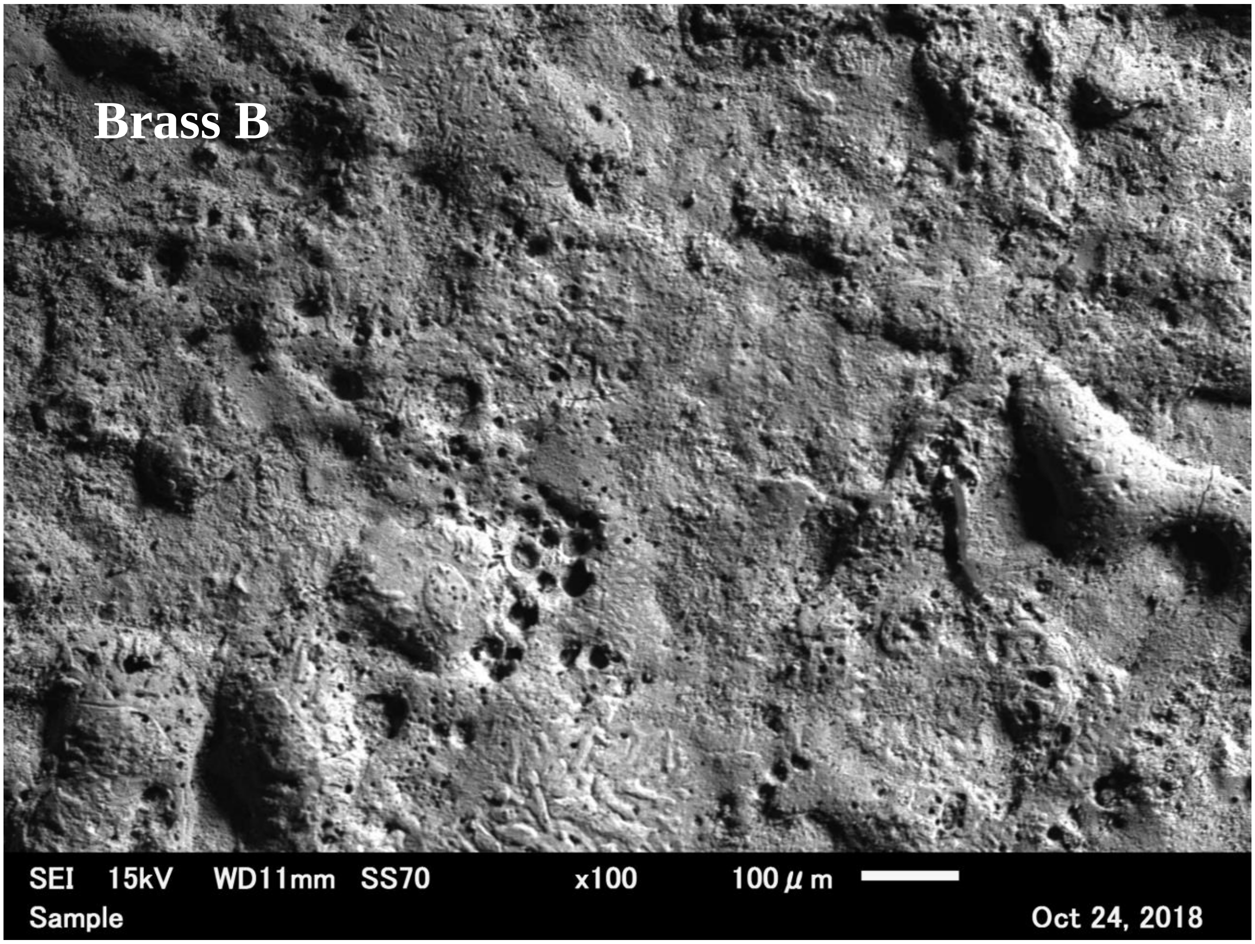


Figure 6.17: Brass sample B surface. As the same with Brass B, less material was lost due to the initial arcing

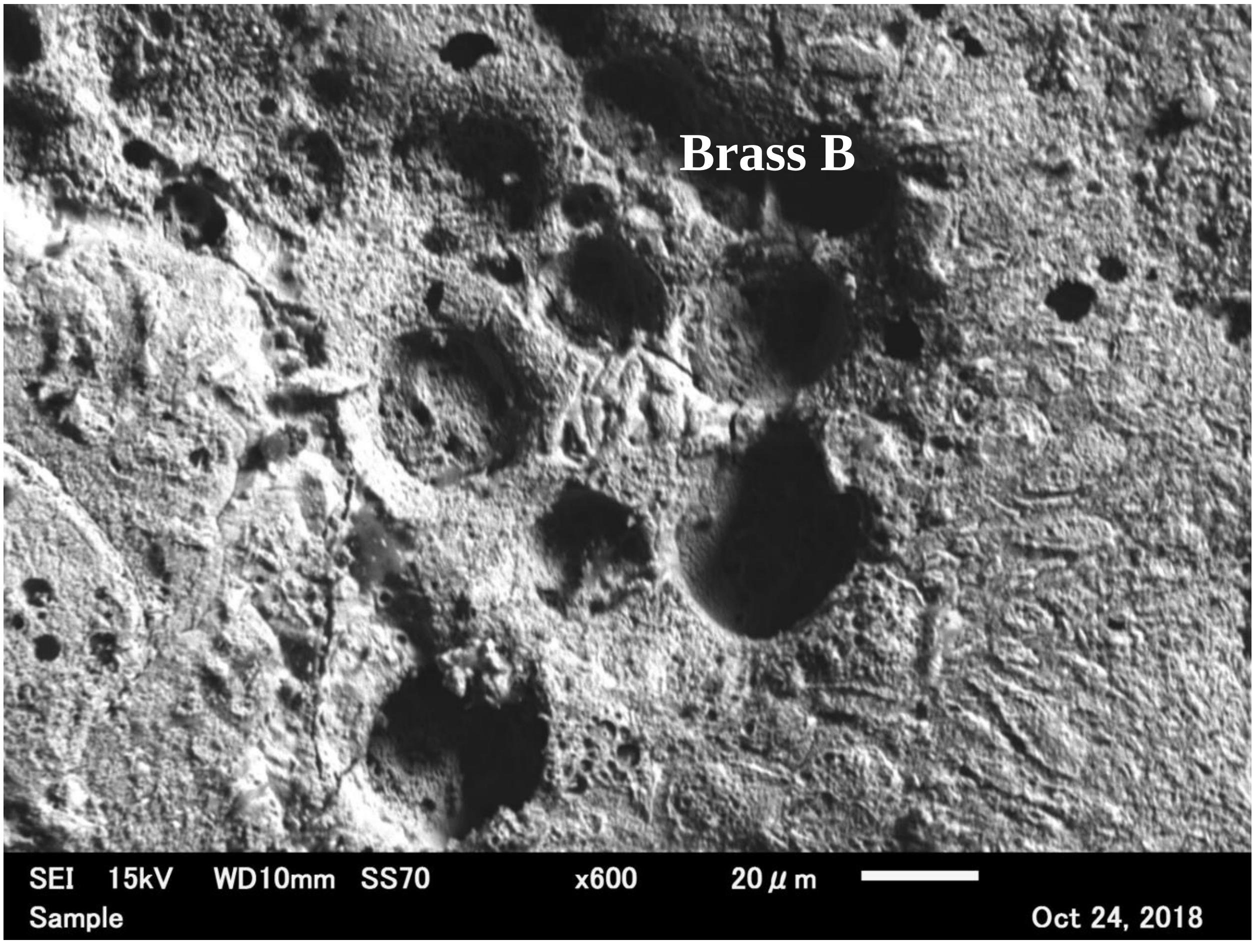


Figure 6.18: However, the damage is still prominent and many pores has been formed.

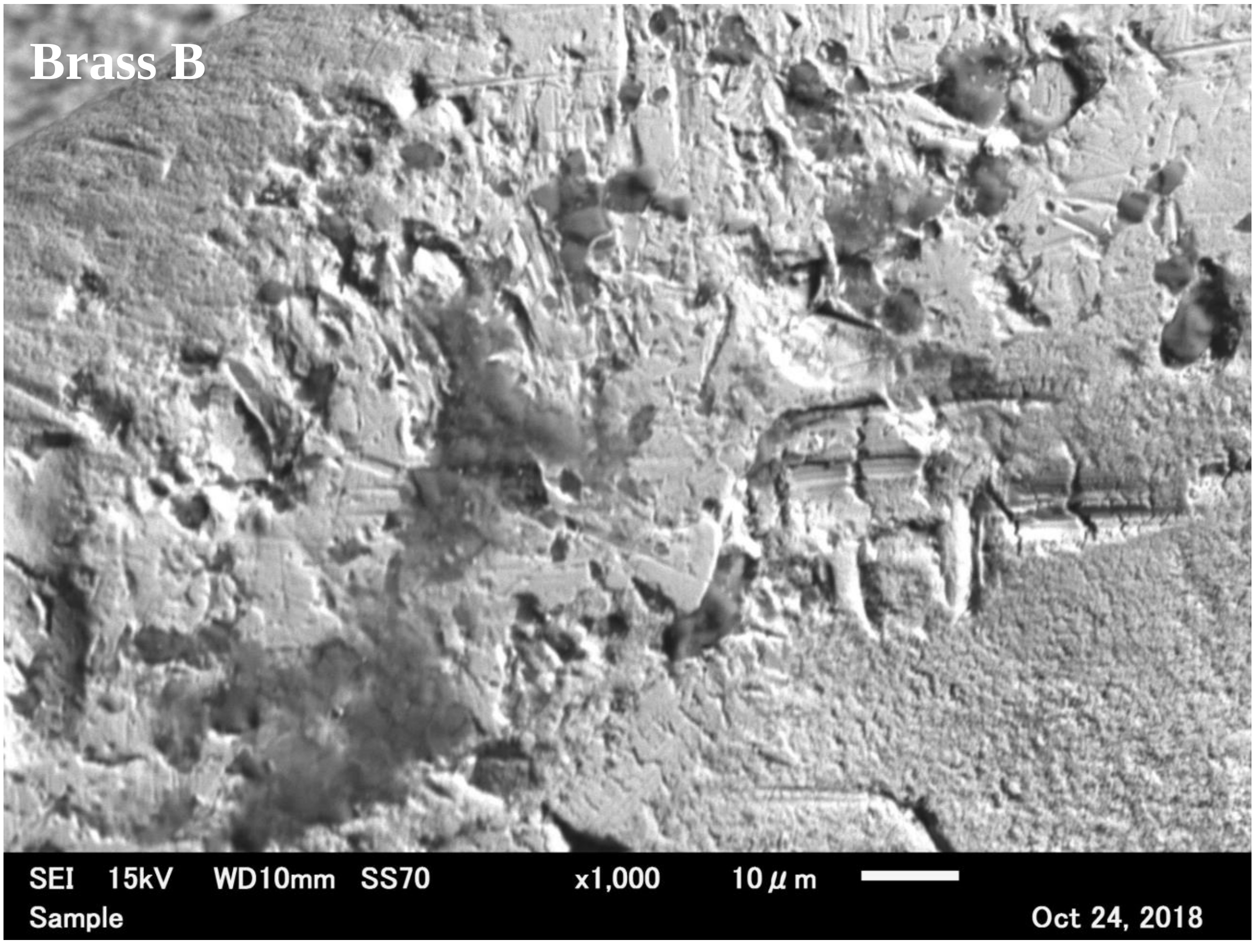


Figure 6.19: At the highest Zoom. We are able to seem the same type of crack on the Sample B. Which can conclude that Brass may not be as resilient for this type of application.

6.3 X-Ray diffraction analyzes

According to the result we got from the electron microscopy. Copper contact surface is self-explanatory that copper is damaged from any type of electrical spark and create copper oxides. However, in brass samples, we are uncertain if the material on the brass surface is actually copper oxide or other oxides such as zinc oxide. Visual observation with light microscope does show us that the “bulges” and patches of oxide is in black color. The only few things that can create black color in the environment are either copper oxide or carbon that has been leech out from the air. It is unlikely that carbon dioxide in the air is capable to oxidize in the heating environment and attach itself to the surface. Therefore, we took our sample to X-ray diffraction analyzer to investigate the material on the brass contact blade. The result is shown from Figure 6.20 to 6.23. The result shows that brass contact surface before it is wash with acid has substantial amount of copper oxides. Apart from the oxides, our brass samples bear copper from the contact heating. Brass - Brass contact type bear substantially small amount of copper on the surface when compared to Brass - Copper surface contact. Brass - Brass contact also bear small amount of Zincite (ZnO) on the surface with copper. This confirmed that copper and zinc within the brass contact separate out by extreme heat from the arc-fault. Brass - copper contact may have leach copper from the copper contact part and form small conducting bridge between two contacts as. The bridge is also heated up by both arc-fault spark and joule heating effect which create copper oxide on the surface of the bridge. The interior of the bridge does not expose to oxygen in the atmosphere therefore oxide do not form under the outer layer of copper oxide. It is suggested that the interior or the core of the oxide bridge may have been made from pure copper due to the high temperature that burn off the oxygen from the molecule.

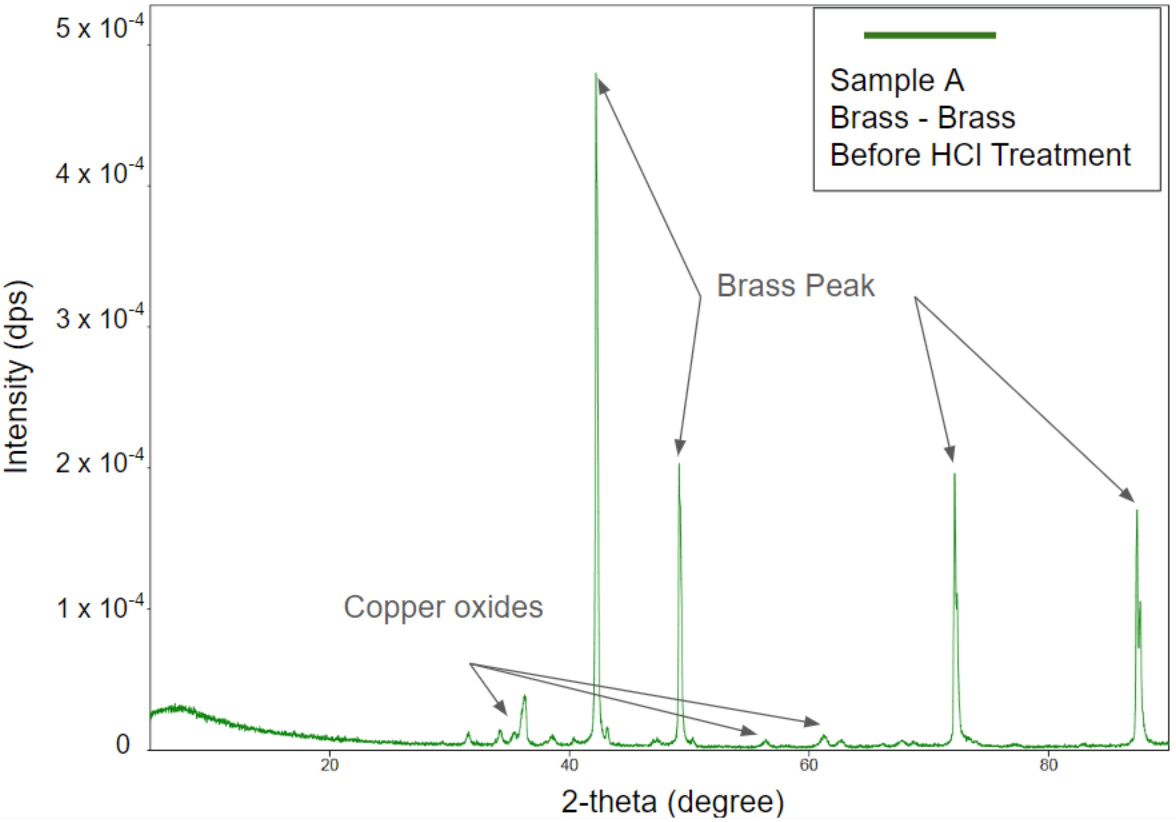


Figure 6.20: X-ray diffraction result of Brass A before washed off with HCl which was subjected to 4.00A of initial contact arc.

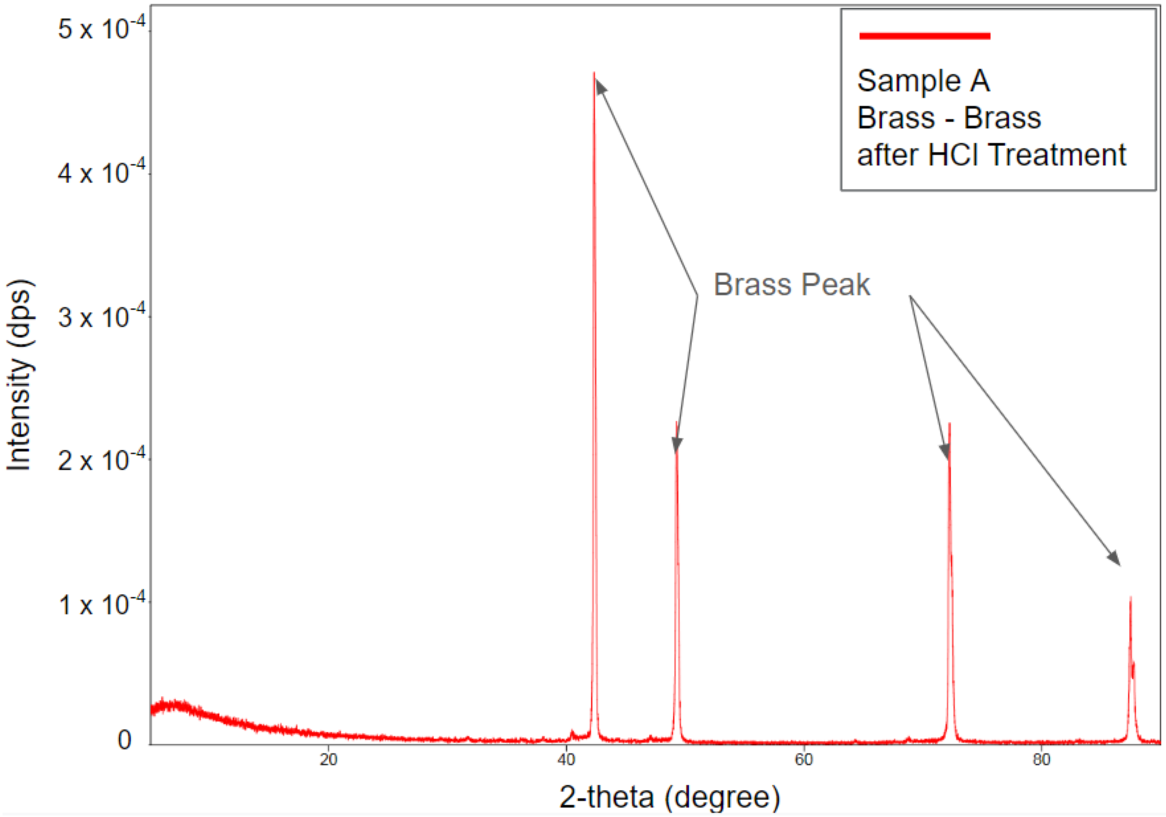


Figure 6.21: X-ray diffraction result of Brass A after washed off with HCl which was subjected to 4.00A of initial contact arc.

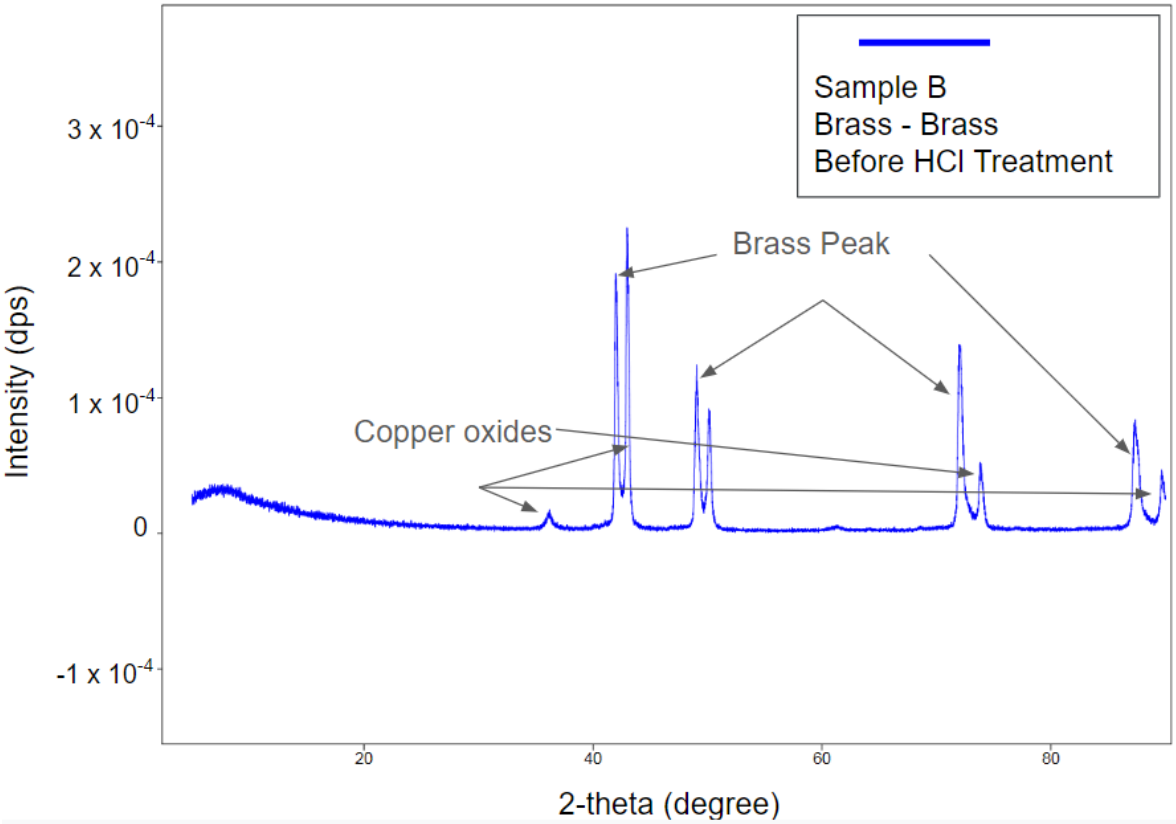


Figure 6.22: X-ray diffraction result of Brass B before washed off with HCl

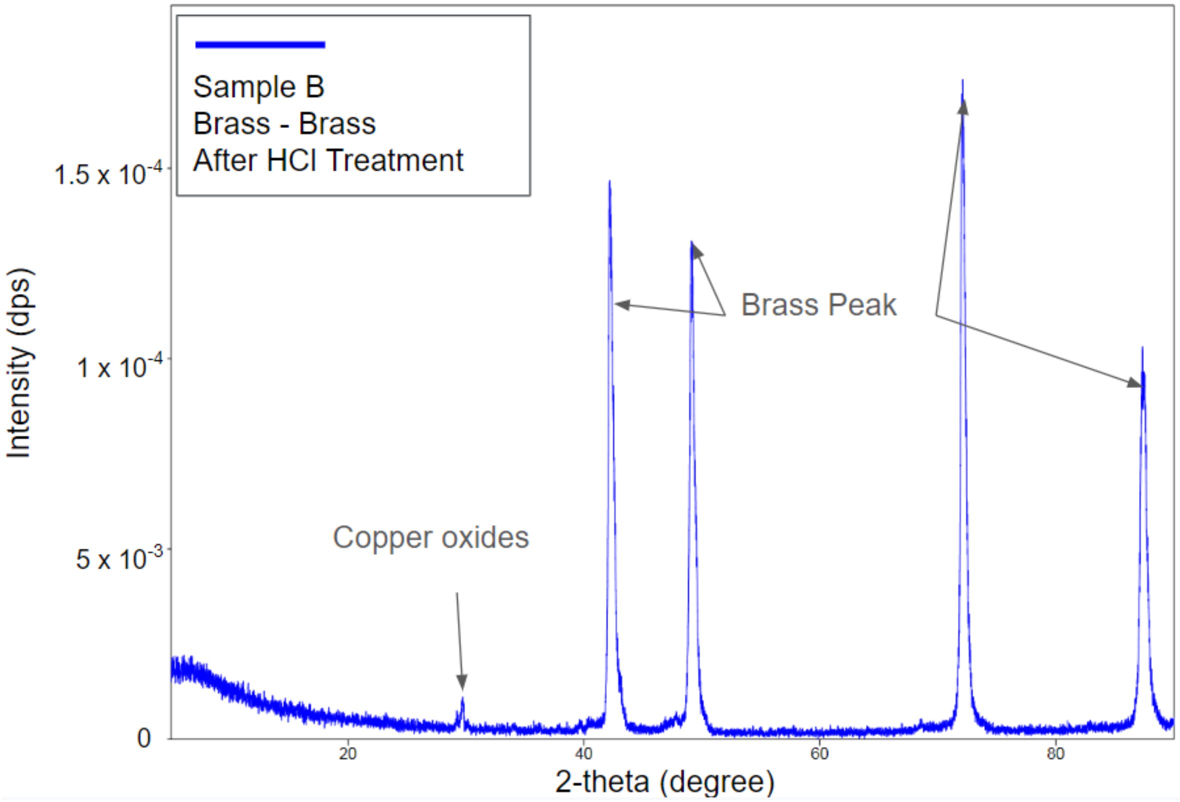


Figure 6.23: X-ray diffraction result of Brass B after washed off with HCl

We are able to conclude according to X-Ray Diffraction result that black residue on the damaged brass contact surface by electrical discharge leave considerable amount of copper oxide. Even though Brass does have higher resistant to contact wear for both mechanical induced wear and temperature induce wear. Brass is still an alloy of copper which when heated to a certain point. The copper is leeched out of the surface and formed copper oxide. This same oxide can initiate an arc-fault the same way as pure copper contact. As with this conclusion, Brass type contact surface does not significantly reduce the fire hazard that can cause by this same phenomenon.

6.4 References

1. Mcbride, J.W. The volumetric erosion of electrical contacts. IEEE Trans. Compon. Packag. Technol. 2000, 23, 211–221.
2. Wakatsuki, N.; Watanabe, T. Electric Characteristics and Contact Area Features of Melting when Making and Breaking Contacts. In Proceedings of the IEEE 61st Holm Conference, San Diego, CA, USA, 11–14 October 2015.
3. Song, J.; Koch, C. Wear Patterns and Lifetime of Electric Contacts. In Proceedings of the 54th IEEE Holm Conference on Electrical Contacts, Orlando, FL, USA, 27–29 October 2008.

Chapter 7: Overview of the Arc-Fault and Joule Heating Mechanism

The results we gather from Chapter 3 to Chapter 6 that we discussed earlier. We are able to come up with the mechanism behind this type of arc-fault in low voltage system. According to the observation and experiment in previous chapters. The factors that can causes high temperature in contact heating, both joule heating and arc-fault is divided into two types. The first is the interaction of micro-contact and current constriction in micro-contact. Micro-contact related can precipitate into severe joule heating effect. The second factor is copper oxide formation on the contact surface. The inherent property of the oxide would create an arc-fault which can dissipate large amount of heat energy once the condition is correct.

7.1 Micro-contact and current constriction

In household electrical appliance. Switches, Socket, Plug and etc. Contact surface are usually a type of component that is operated by human. Major factor in designing contact surface in this type of merchandise are divided into two types. First, the metal contact must be strong enough to maintain its structural integrity and its elasticity when subject to high stress and temperature. Second, the contact surface must be inert or non-reactive to the atmosphere. With these criteria. Brass, Copper, Nickel plated Copper are commonly used in plug and electric socket. While switch types contact are made from alloy of Silver-Nickel (99-1). Switch types contact merchandise for example, Electric breaker and light switch usually has limited lifetime written on the datasheet. Some other consumer grade electrical contact does not provide its contact lifetime. Once the metal contact is used, the surface of the contact is no longer flat in a microscopic level. In a right condition where two contact surface is connected by micro-contact.

Micro-contact resistance between two contacts is expressed in this equation $Rc = (\frac{\partial V}{\partial J})$ from V = 0, J is the current density in the area of micro-contact. The value of Rc is Ω/area. This imply that when contact metal is worn down enough. The joule heating effect would start on the point where two contact meet. If the micro-contact area is small and when large amount of current pass into it. The heating effect can reach to the point where copper oxide can form due to the large amount of heat in the affected area. The amount of heat that generate on this micro-contact is relative to amount of current, area of contact, temperature of the surrounding environment, thermal capacity of the contact material, thermal conductance of the material. Therefore, most studies dealing with the contact heating are hard to replicate even with the same setup and material. In order to replicate contact heating experiment. The area of micro-contact must be known by the experimenter.

The other factor that can deteriorates the micro-contact is the Lorentz force exerted on the contact surface. This magnetic repulsion force is known as Blow off force as expressed here

$$F = \frac{\mu I^2}{4\Pi} ln \frac{R}{a}$$

With low contact or faulty contact area. The contact would start to vibrate. The vibration direction depends on the direction of current and strength of the vibration is depended on amount of current and the contact surface area. As in the chapter four. We can observe that large amount of current exerts stronger vibration than lower current setup. In the studies, we used 50Hz Alternating current. In each cycle, current change in direction twice per period. This is why in the experiment we can observe that the vibration is at 100Hz. The problem with the vibration is that, if the contact area is not locked in firmly together. The vibration can cause the contact to break out from the connection at a short time and touch back again when the contact rebound. Break action induce reactive-load spark from the system and touching action induce inrush current spark. Each spark in micro-contact area can produce large amount of heat to form copper oxides. Once copper oxides is formed on the micro-contact area. Copper oxide would leach copper component from the contact which create porous contact surface and reduce overall contact surface area. Copper oxides is an excellent insulator, when in conjunction with micro-contact. Joule heating effect grow substantially until oxide bridge is formed. This will produce a runaway copper oxide breeding reaction at high temperature.

7.2 The Series Arc-fault in the system

Once the above condition has been fulfilled. The contact area is now ripe to start a low voltage arc-fault. As we known an arc-fault is a continuous electrical discharge over an air gap. Such discharge can generate large amount of thermal energy. Due to the actual break down voltage of the electrical arc in sea level atmospheric pressure. Such continuous arc cannot be replicate in a low voltage environment unless the exact condition must be suitable. Since we have discussed earlier that a copper oxide and any contact resistance is basically a resistor in the circuit. The same oxide that causes an arc-fault can be treated the same way. Hence the arc fault in this type of environment and its creation is shown in the chain of Figure 7.1 to 7.8. The step of the phenomenon will be explained with the Figures.

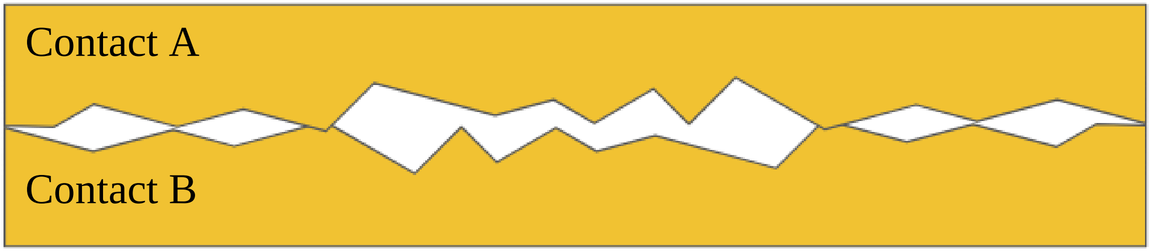


Figure 7.1: Non-Ideal contact state.

1. Contact surface is largely not an ideal contact surface. Both cathodes do not have a flat surface to conduct current. The area that two conductors touch each other can be at a very small area which can induce joule heating effect if the current overload at the conducting area. In this example we will consider that small contact area does not overload.

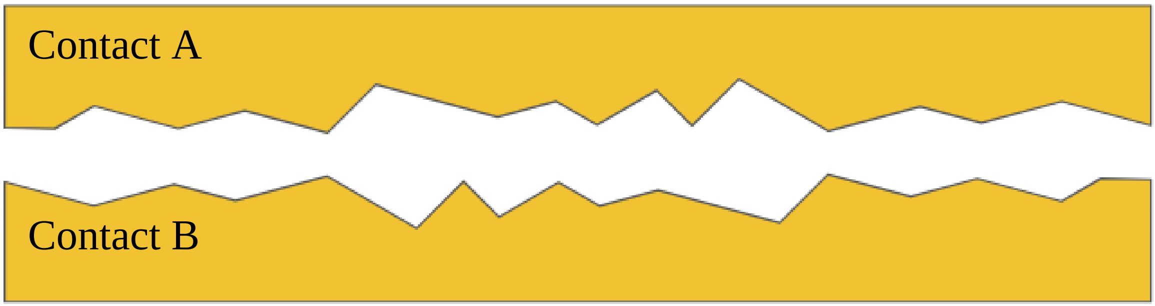


Figure 7.2: A contact is break open by external force.

2. Any perturbation on the contact. When both cathodes no longer in contact with each other. The circuit is considered cut open. Hence no power is delivered to the load

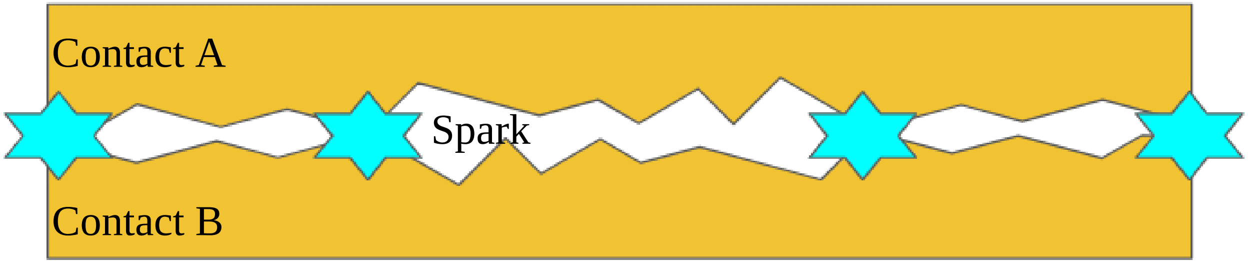


Figure 7.3: A contact spark is created by inrush current.

3. When both cathode touch with each other again. The current would rush back to the circuit load. The current rush would also create a contact spark at the contact points of the conductor. Normally there would be only one electrical discharge sport per contact. The first area that make contact would create a most energetic electrical discharge

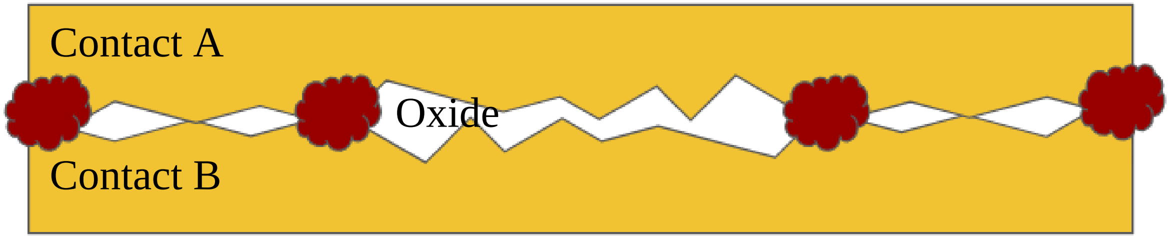


Figure 7.4: Oxides is formed around the contact points.

4. Oxides is then formed at the area where electrical spark occur. Since electrical spark generate large amount of heat to the point where the conductor’s material starts to oxidize with the air and create oxides in the area. The oxide can reduce current carrying capacity of the contact point, which causes Joule heating effect to heat up the affected area. The temperature can drastically increase in these locations if the conductor is already affected by overcurrent. In this example, we will assume that there is still no overcurrent.

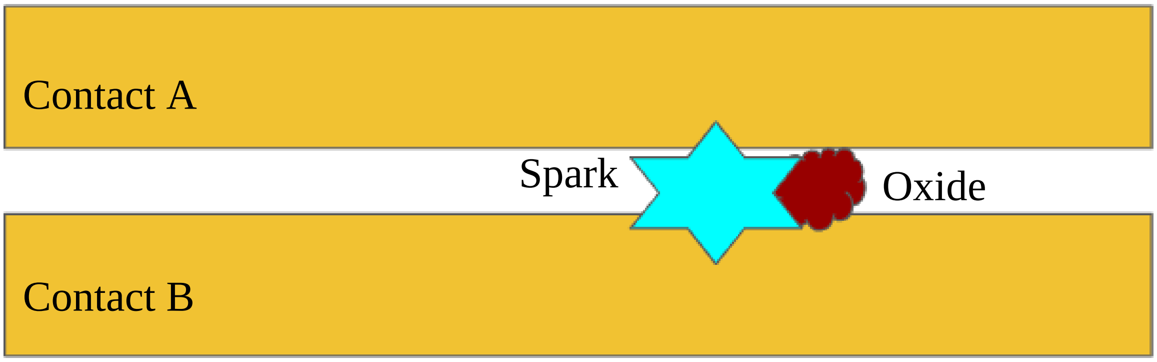


Figure 7.5: Closed proximity electrical discharge near the oxides.

5. If the contact has been perturbate again and the electrical spark is created near the patches of copper oxide. Such spark can transfer large amount of heat to the copper oxides.

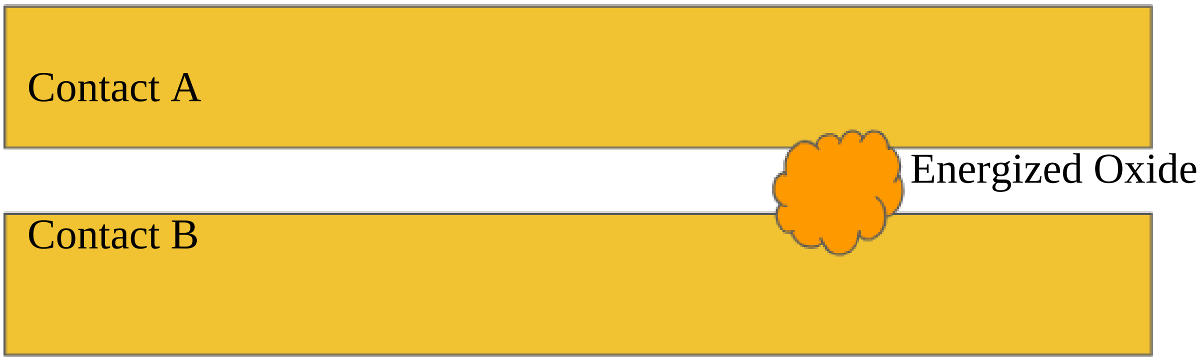


Figure 7.6: An energized oxide is a poor conductor.

6. Once the copper oxides has been heated up to the certain temperature as shown in Chapter 4. The copper oxide would energize and turn into a poor conductor. An energized copper oxides is able to conduct current but not in a large amount. Even a small amount of current level for a conductor standard can induced an overcurrent phenomenon and heat up the area around the contact point even more so than un-energized copper oxides.

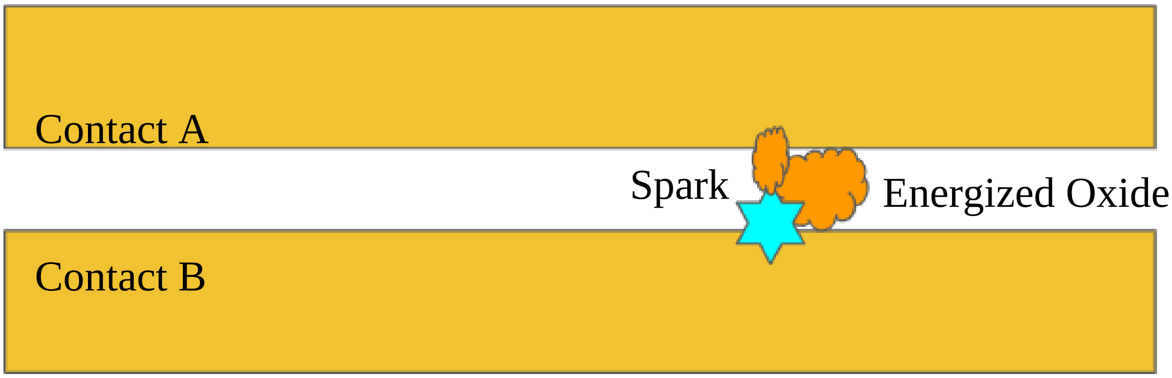


Figure 7.7: The induced vibration creates more electrical discharges.

7. Energized copper oxide patches create contact vibration as explained in Chapter 5. Such vibration would make-break contact at a very high frequency. The break action creates an electrical spark that generate even more heat at the affected area. The heat would start to leech copper from the surface and generate even more oxides.

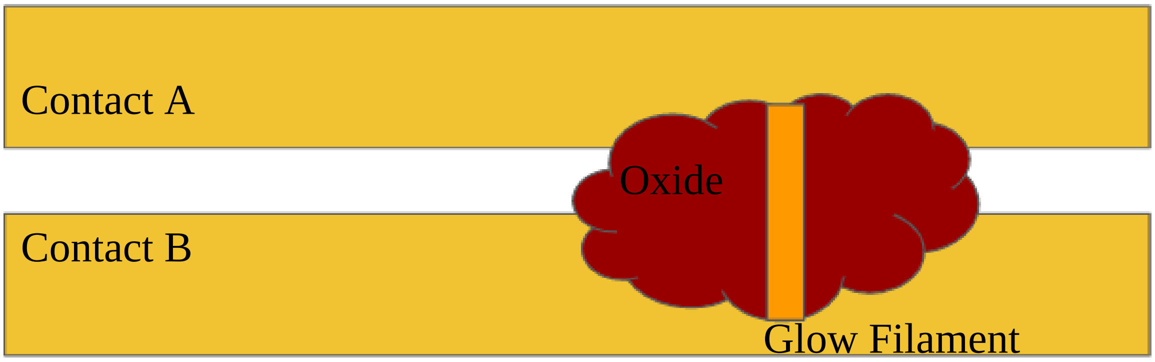


Figure 7.8: A glowing filament is formed and arc-fault state is subsided.

8. In the final phase of this phenomenon. The oxide bridge would grow in size to the point where both cathodes has now welded together by large oxide bridge. The bridge would also stop vibrating and the arcing state is also stopped. Since the oxides is still in the energized state. The current will still flow through the oxide. The highest temperature area is where the current would conduct itself through which created a signature "Glowing Filament" as observed by Shea which was explained such phenomenon in Chapter 1.

In conclusion, series type arc-fault in low voltage setting is not actually a classical arc-fault. But rather an advanced version of joule heating effect that created more heat due to the semiconducting properties of the copper oxide. Even though copper is considered to be a cheap and better conductor than regular steel or iron. This type of phenomenon can be difficult to predict when and where it will happen. Once the condition is suitable for this phenomenon can occur. The heat would generate at an extreme rate and cause an electrical fire at much faster rate than steel.

7.3 Summary of the mechanism

A fire hazard from a glowing connection can be accelerated by an Arc fault, as is explained in the steps below. The flowchart of the step is shown in Figure 7.9.

1. An initial electrical discharge produces small patches of insulating oxides.
2. A repeated discharge in the same location, such as what is caused when a plug is repeatedly removed from and reinserted into a socket during normal use, increases the area of the oxide patches.
3. Once the insulating patches, or the bulge, on the surface have increased to the point where the contact area is exhibiting overcurrent, the process will begin to produce heat through the Joule heating effect. At this stage, the process can be classified based on two main hazards. The first hazard occurs when there is no movement (insertion and reinsertion) of the plug. In this case, residual heat accumulates to the point where oxides can be created from the dissipation heat alone. The second hazard occurs when the contact surface moves so that it is no longer firmly connected, resulting in a vibration being created from the poor contact surface. This can induce a continuous electrical discharge that then greatly increases the temperature of the affected area, to the point where copper is able to oxidize with the atmosphere. Even if the contact area has already formed an oxide bridge, current can still pass through normally. This current flow, however, is not efficient. A small perturbation near the contact point by the operator or the environment can create a small initial spark that could then increase the temperature of the oxide patch near the affected area. If the spark is energetic enough, it can increase the temperature of the patch to the point where the oxide behaves as a semiconductor. A glowing connection or arc fault may then be initiated.
4. In a lower-current setting, a glowing connection can continue so long as there is current being provided and the resistance from the oxide bridge is not high enough to block the current flow. In a high-current setting, a glowing connection can be extremely energetic, so much so that it could melt off part of the oxide bridge. This could potentially split the bridge into two parts. In

this case, the current flow stops. On the other hand, in the case where the oxide bridge grows to such a size where it cannot easily melt and break the contact, it will continuously leech copper from both contact surfaces and grow further still. Eventually, a certain size is reached such that the arc fault stops completely and the glowing connection takes full effect.

5. Once the glowing contact area has been de-energized, the oxide bridge cools down to the point where the copper oxide behaves as an insulator. In this case, the contact surface does not pass any current. If the contact area has a small oxide bridge or a patch of conducting surface, then the contact area with the oxide bridge is able to pass current. The temperature of the small patch of conductive surface may increase due to overcurrent. If the temperature rises to the point where the majority of the oxide bridge changes its state back into a semiconducting phase, then the glowing connection will revert back to the state in step 3. The cycle will continue until the oxide bridge is broken or it is too large to pass current when the circuit is de-energized.

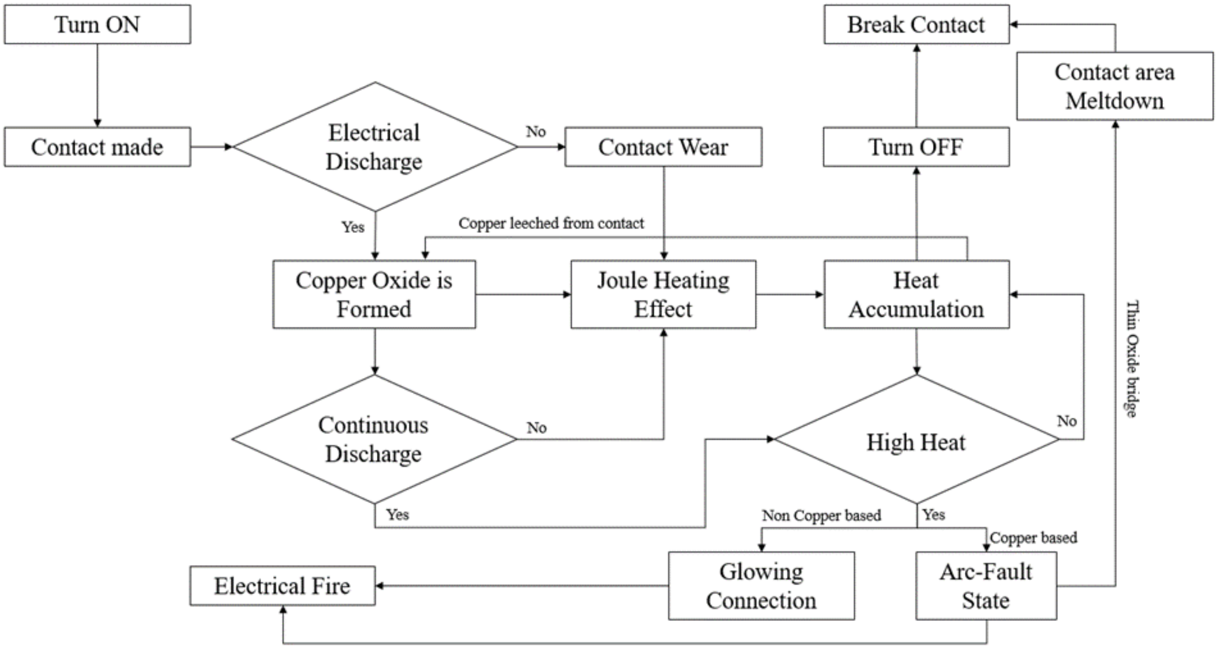


Figure 7.9: The process that leads to electrical fires from accumulated heat and arc-fault states.

Chapter 8: Detection and Prevention

As for our research we were able to see the exact pattern that is prominent in all series type Arc fault, no matter the type of devices as long as it is made from copper or contain the alloy of copper.

8.1 Detection Background

Many technologies have been developed to prevent the fire from occurring either by passive prevention such as improvement of electrical housing, electrical insulation properties of the cable and etc. Active prevention such as Ground Fault Circuit Interrupter (GFCI) and Arc-Fault Circuit Interrupter (AFCI). Currently AFCI outlet for household use can be very sensitive to voltage spike from electrical motor in the same network or electrical surge from the power plant itself which is a common occurrence in some countries such as Thailand. By applying AFCI outlet into important but relatively low power consumption electrical appliances such as refrigerators can induce accidental trips which can cause damage to perishables. Current AFCI outlet that is available in the commercial market made use of high frequency component detector as explained in the patent which can also be very accurate due to the specific high frequency component as explained in the previous chapter. However, the fabrication of such high accuracy detection method can increase the price point of the detection apparatus to the point where the socket could not be use everywhere and anywhere as user may desired. According to the previous finding. The series arc fault fire hazard risk is also not limited to appliance that consume large amount of power, but in fact it is the opposite. Therefore, in our research, we will try to devise a simple method to detect the Series Arc fault.

8.2 Voltage Disparity between Two cathode Method.

We found out that when there is a series type arc fault within the electrical cable. The voltage from neutral wire and the hot wire is not the same which is considered an abnormal phenomenon especially in such a passive load such as lightbulb and resistors array. We were able to see that when the lightbulb has arc fault state within the current carrying cable. The light flickers between normal light level and dim light level which implied that there is small amount of energy that was not delivered to the load. Therefore, the arc fault does not draw more power from the source but rather take away the power from the load to dissipate into large amount of heat. We made the experiment to test whether if such method can be use in the detection system and the circuit is as followed. In this study, we inserted Power Factor Correction block into the experiment to test whether power quality has any effect on the result which may alter the detection accuracy since the Isolating Transformer we used in the study has parasitic inductance which created a phase shift between voltage and current. More explanation will be explained further in the chapter.

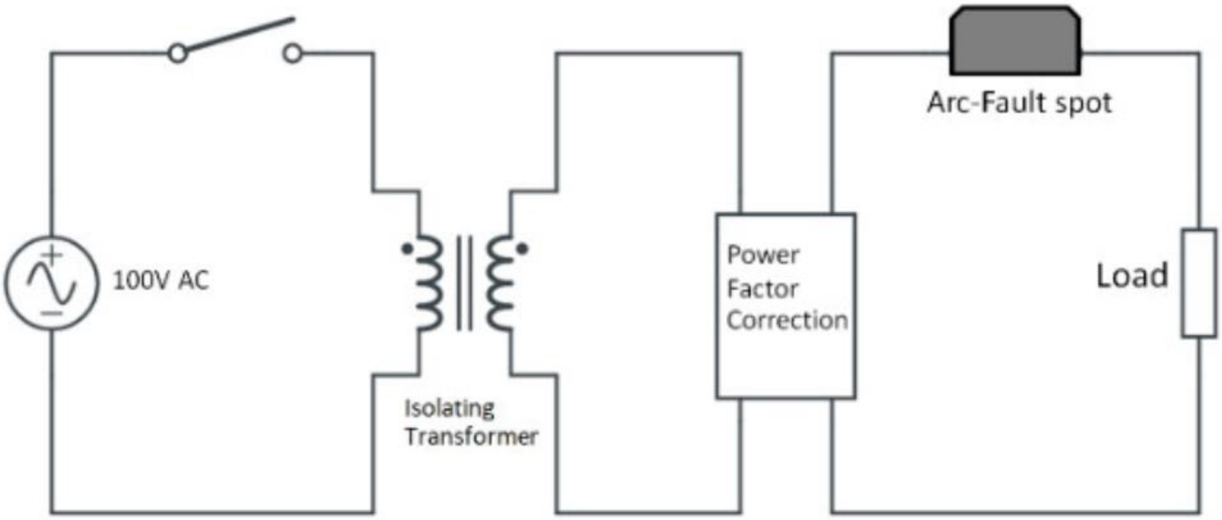


Figure 8.1: The equivalent circuit of the experiment.

The current source of the experiment is similar to the previous chapter. 100VAC at 50Hz as current source but instead of using regular isolating transformer as shown in Figure 8.1. The isolating transformer is a noise cut transformer to reduce current phase shift. Regular transformer create large amount of phase shift up to 90° phase shift between voltage and current, which is unsuitable for the study. The transformer is then output to power factor correction array which is then connected to the main load of the circuit. The array of capacitor as shown in Figure 8.2 and the transformer is shown in Figure 8.3.

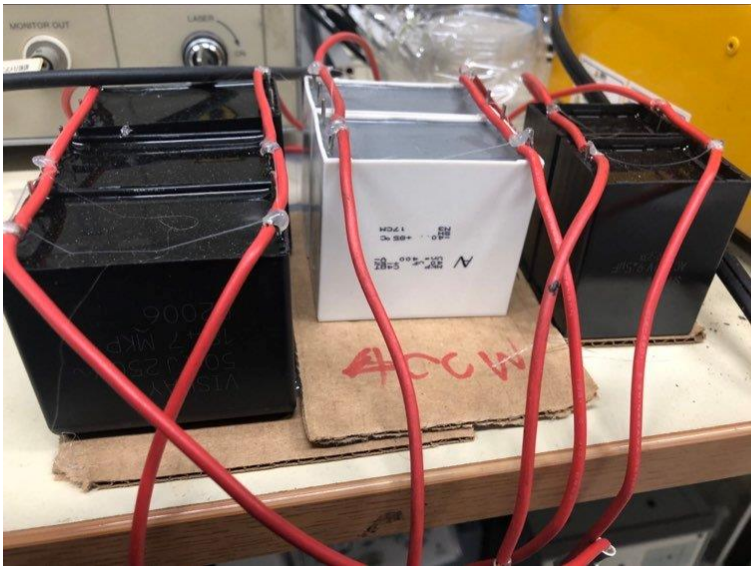


Figure 8.2: Array of capacitors used to power correct the phase shifted.

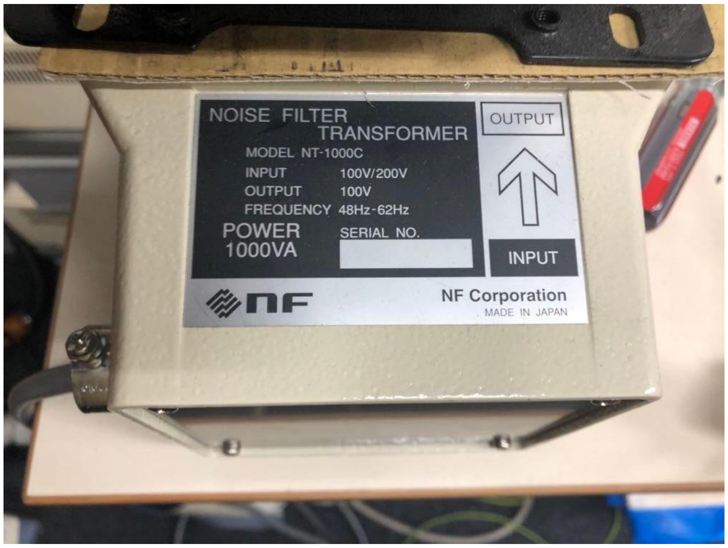


Figure 8.3: Noise Cut Transformer used in the experiment.

The array of capacitors is placed far from the circuit to reduce current harmonic distortion emanating from the transformer. The main load of the circuit used in the experiment is comprised of three set of wire-wound resistor value of 12Ω, 25Ω and 100Ω respectively. 12Ω resistors set is used to simulate for high wattage appliance such as electric heater while 100Ω resistor simulates low current appliance such as light bulb. According to our result and the mechanism behind this type of arc fault. We are able to replicate the state by applying mixture of Cupric and Cuprous oxide powder to the contact area. The contact area with dust is heated by creating the contact spark between two points. The residue heat from the electrical discharge is sufficient to melt down dust of oxide on the contact layer. Copper oxides powder is obtained by putting commercial grade copper-made electrical receptacle into temperature-controlled furnace. The receptacle is then baked at 600 °C which is the temperature where both type of copper oxide is formed but not hot enough for the oxides to degrade back into copper.

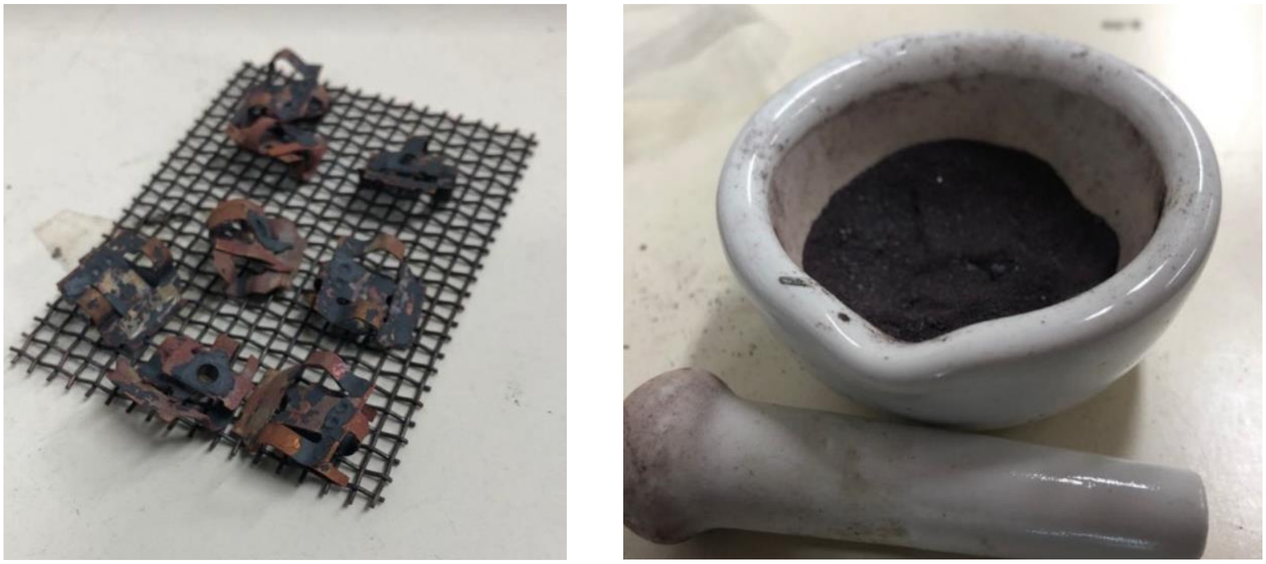


Figure 8.4: Baked copper type contact. The black residue and oxides is then combine and mash into powder with pestle.

The receptacle is removed from the furnace after 30 minutes. Shells of oxide layer is formed on the receptacle surface and easily knock off and grind down into powder form with simple mortar and pestle. This process ensured that copper oxide powder is formed from similar environment, temperature range and impurity like in arc-fault state. The following process is shown in Figure 8.5. The powder is applied on the contact surface in one of the conductors. The arc is then initiated by repeating make and break contact at the point where powder is applied. The heating process from the spark is enough to meltdown small amount of dust and adhere to the surface of the conductor.

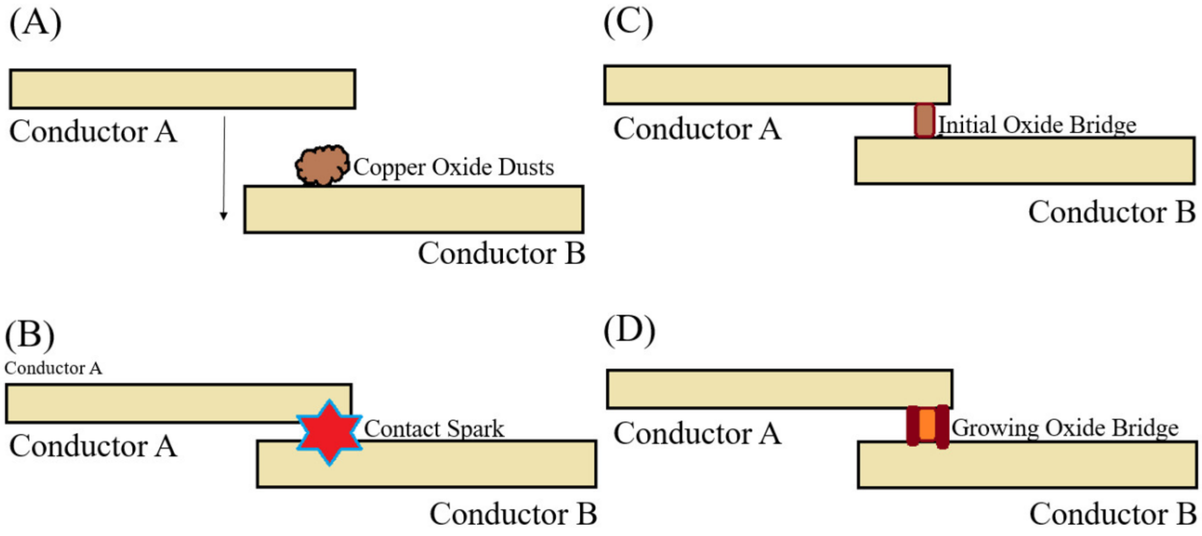


Figure 8.5: (A) Copper oxide is placed on one of the conductors. Electric Current is pass for both conductors. Both conductors made contact at where the copper oxide is at (B) which create a small oxide bridge due to the spark that melted down copper oxide. Then the bridge is exerted with extra current so that oxide is being leech from the conductor itself.

This process is then repeated until oxide bridge is formed at a desired size. Once the initial oxide bridge has been formed, six ampere of current is passed into the circuit which will produce a series Arc-fault. The initial oxide bridge will continually grow in size until the size of the bridge is around 2mm. At around the size of 2mm. The bridge will be sturdy enough to withstand current of 8.33Arms without meltdown which will break the contact while experimenting. The exact size was founded by repeated trial and error. A short experiment was run to confirm that there is power loss from the arc-fault. It is found that at 4.00A of current when the bridge is the size of 3mm. Around 44W was dissipated in area which drop the voltage from 100V to 94.45V in the use of 25Ω load practically. The calculated value is at 94.36V. Therefore. It is feasible to measure the voltage drop at load and if arc-fault phenomenon. The same result is obtained for 8.33Arms at 12Ω. All experiment is done 5 times each and average out. Power factor correction circuit was added to the experiment to investigate if voltage - current phase shift has apparent effect on power consumption and the arc fault itself. series arc fault generation procedure and its characteristic should be independent of phase shift. The experiment was carried out four times for each case. For example, 12Ω without arc fault and with arc fault state are carried out four times respectively. Voltage and current for each experiment are then noted to compare and average out the value. Then the same procedure is repeated for both 25Ω and 100Ω. The phase shift is created by combination of isolating transformer and array of wire-wound resistors. The adjusted power factor is 0.85 in all resistor value. This can conclude that load resistor may not contribute to the phase shift in the system. The inductive component of wire-wound resistors can change due to the temperature and current form. The capacitors value of 19µF, 80µF and 150µF were used in load of 100Ω, 25Ω and 12Ω respectively.

Voltage Disparity between Two cathode Method: The Result

The result we collected from the experiment is shown in TABLE 8.1 and TABLE 8.2. The value on the tables is accumulated from all the experiments for each load and average it out. We are able to observe that power quality from the electric source has minimal effect on the power that was able to be delivered to the load. As seen in 100Ω load which we can see that there is only 2 percent difference between two set. Where at even for low current setting.

TABLE 8.1: Amount of power delivered to the load in percent

Load	**Total power delivered to load in percent**			
	PF 0.85 & SD		**PF 1.0 & SD**	
100Ω	85%	1.22%	87%	1.41%
25Ω	87%	2.44%	89%	1.87%
12Ω	88%	1.22%	91%	0.70%

TABLE 8.2: Amount of power loss in Watt

Load	***Total Average Power loss to the Arc-fault discharge in Watt***	
	PF 0.85	***PF 1.0***
100Ω	*12.75 W*	*13 W*
25Ω	*42 W*	*44 W*
12Ω	*85 W*	*75 W*

The difference is at around 3 percent. We were able to draw the conclusion from the result that the amount of power that is discharged by the arc fault is purely dictated by the contact resistance at the affected spot. However, at a very low current as we can see from the TABLE 8.2, 12Ω load setting exhibit more power that losses into the discharge at 1.0 Power Factor. It is suggested that at very low current. In each experiment between 100Ω to 12Ω. Each contact area is disconnected from each other and contact to each other again. Which result in that the contact from the first experiment and its subsequent experiment may not be the same in its overall contact area and the resistivity. It is currently impossible to make sure that the contact between in each experiment is the same in area due to the lack of accurate measurement tool. However, when the experiment is done repeatedly, the pattern has been formed that at certain power of the discharge. The heated oxide would almost always be in the same size due to the current is only energetic enough to superheated the oxide bridge at that time. For low current however the current is usually not high enough to overcome the initial resistivity of the oxide and create arc-fault state. In order to restart the arc fault state when low current setting could not re-energize the circuit. An external heater, A candle is hover over the contact point and heat up until the temperature is rose high enough that the copper oxide bridge exhibit conducting properties. After the energized state has been achieved in low current state. The arc-fault is extremely sporadic. The arcing can be very bright for low current and sometime the arcing is very dim to the point that some arcing extinguishes by itself. This is caused by the oxide bridge is too large or too thick for current to pass through and heat up the oxide bridge sufficiently. Some of the current may change its path and create the Glowing filament. The filament is prominent on the surface of the oxide bridge which is different from regular glowing. The filament can sometime actively change the path of the current which make the discharging power can be lower than expected. Hence the result can be seen on the previous tables.

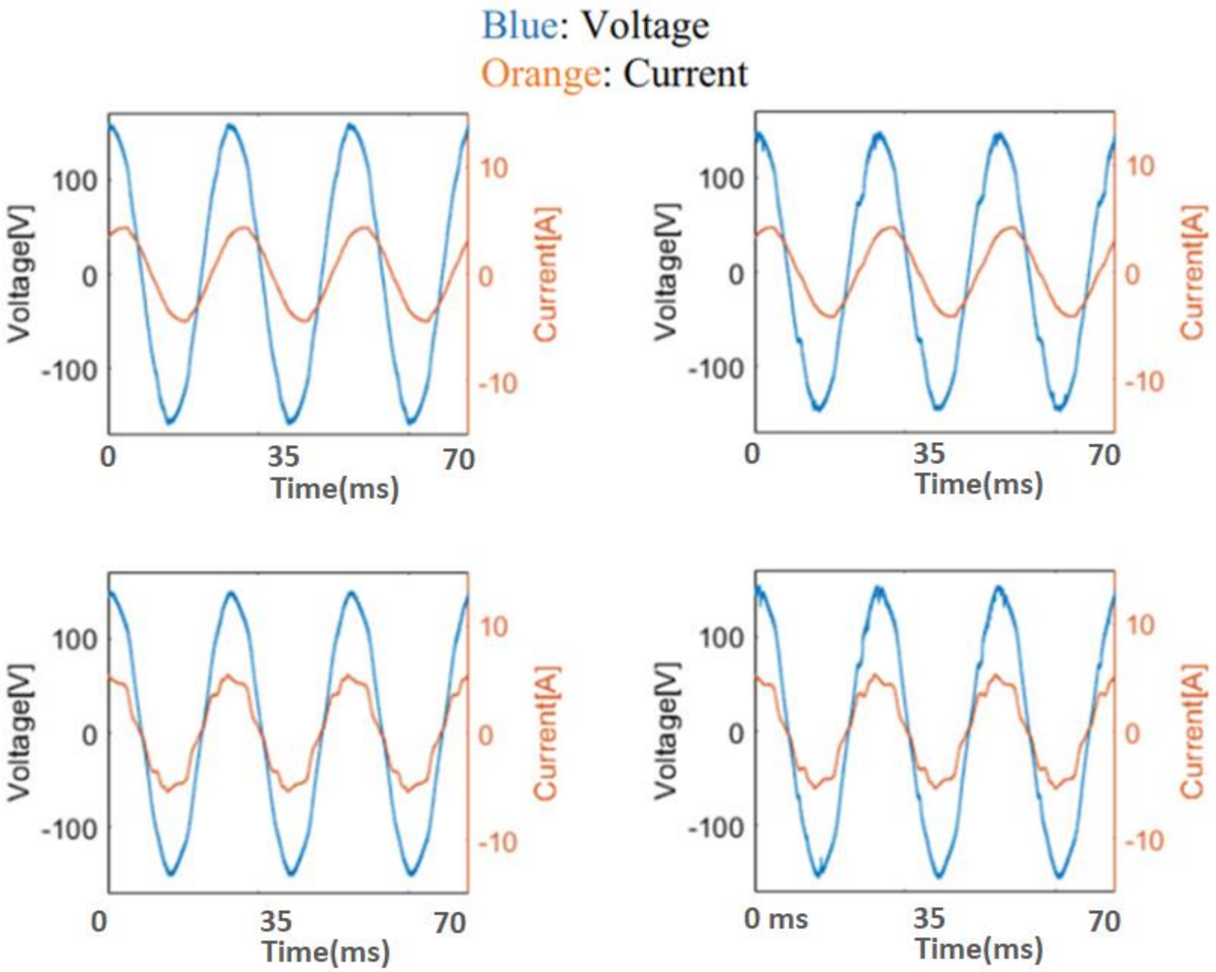


Figure 8.6: Top pictures has power factor of 0.85, Bottom pictures is the corrected power factor. Left two pictures show a normal state connection and right two pictures show an arc-fault state connection.

The waveform that was corrected by array of capacitor to counteract the inductance in the system distorted the waveform of the current slightly. Due to the Power factor corrector is essentially a passive correction and the capacitor that was used in the system was not optimized and made to be use for power correction. This creates the results that harmonic component introduced into the system. However, the harmonic distortion in the system barely has any effect on the result as shown in the previous tables. Therefore, the harmonic distortion or problem in the power source may not has major effect on the pattern of the arc-fault. However, we can see from the Figure 8.6. that there is still current shoulder near the zero-crossing point. As usual as from the earlier experiments that the voltage drops still happen near the zero-crossing point of the current. We were able to notice that at very low current setup (12Ω). It is more difficult to maintain constant state of arc-fault state. It is suggested that at near zero crossing point for 1.0 PF, both voltage and current is dipped to zero and no current and voltage can be pass through after. Where 0.85 PF that the voltage is not at zero when current value is at zero. Once the zero-crossing point has been passed at 0.85 PF. The voltage in that timing is high enough to push the current through the heated filament which can re-ignited the filament and maintain the arc-fault state. The current waveform harmonic that was caused by the capacitor. The waveform has been further plotted down and passed into Fast Fourier Transform and we have found out that. There is harmonic frequency at 2nd, 3rd and 6th. According to the regular problem with such passive Power factor correction. The harmonic component called Triplen harmonic is introduced in the system as shown in Figure 8.7 and 8.8. In a normal case, Triplen harmonic can be reduce by reducing the resonance of the system. The result of the fourier transform however the harmonic is not in the correct frequency. This is suggested that the harmonic component may have been shifted slightly by 25°. In the future, the simulation is needed to identify which component of the power factor correction unit is the cause of the resonance.

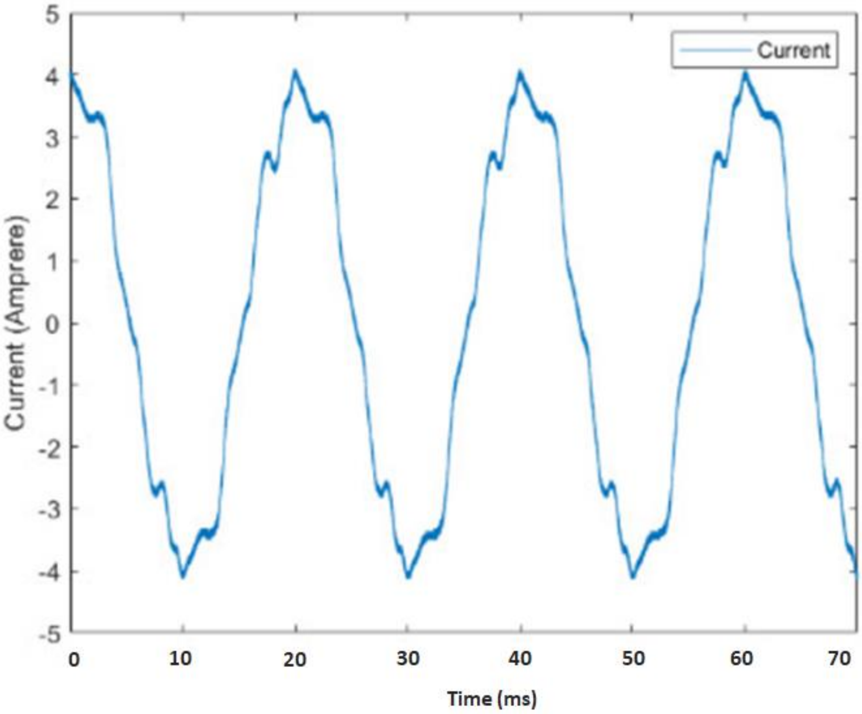


Figure 8.7: This is the current waveform from the experiment. Setup at 4.00A.

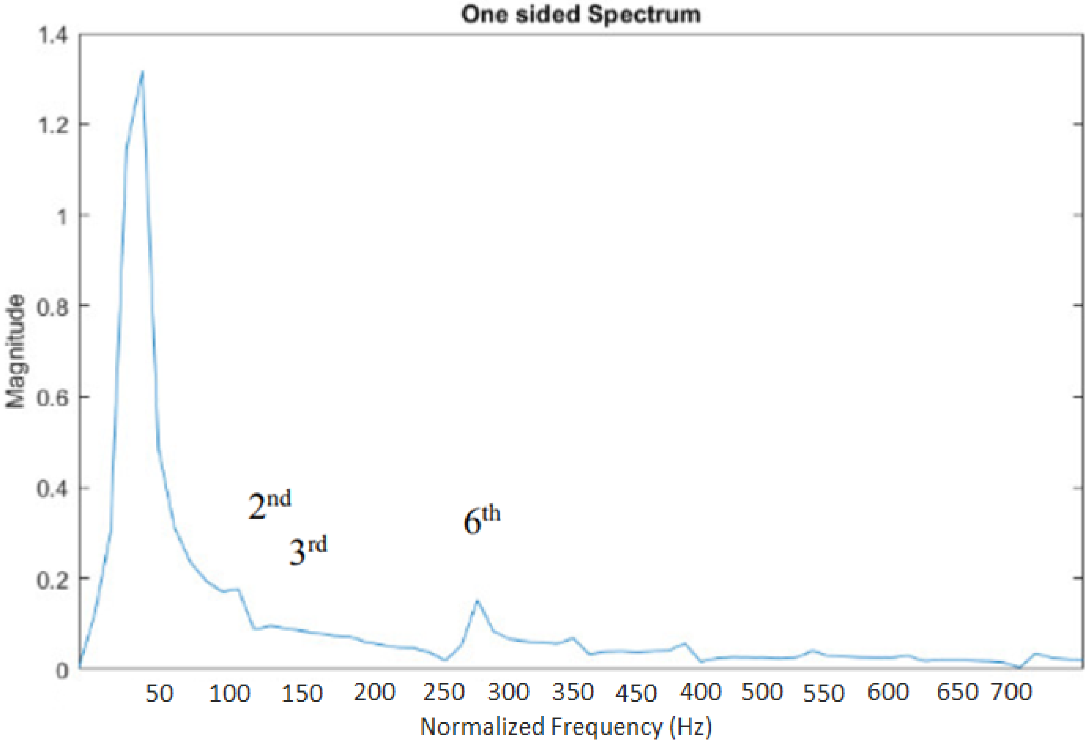


Figure 8.8: FFT result of the Fig 4. The harmonic frequency at 2nd, 3rd and 6th can be seen in the figure.

In conclusion with the result from the tables and the graphs. We were able to come up with the method to detect arc-fault as shown in the Figure 8.9. The devised detection system is basically a measurement of voltage and current. The probe is inserted and measure between Hot cable and Neutral cable. Voltage and current value disparity between two points can be further calculated into power. According to our result. The voltage near the contact point at the hotline, the peak voltage is reduced and current is also slightly reduced in peak which is then used to determine whether arc-fault is presence in the system. In order to differentiate from regular power usage and arc-fault usage. It is required to have a specific timer in the detection system. First the system will need to take the sample reference value. The reference voltage and current value must be the time when the device is functioning normally in the most ideal state as much as possible. Then this reference value is used to compare with the current Voltage and current value at the time. If the voltage and current peak point is reduced and lower than the reference value. The timer is then count down until the set threshold is reach. The timer is there to prevent false positive due to a small variation in power source. Power surge or power drop from electrical supplier may reduce overall power that was delivered to the device. As we can see that this type of detection drawback is that the margin of error of the detection system is extremely high. If the device itself is not of passive load such as of those with motor or the device that has power regulation to save power like air-conditioner. This system will not be applicable. This kind of detection is almost exclusively to passive power drawer device such as lightbulb. Old electric fan or an electric heater.

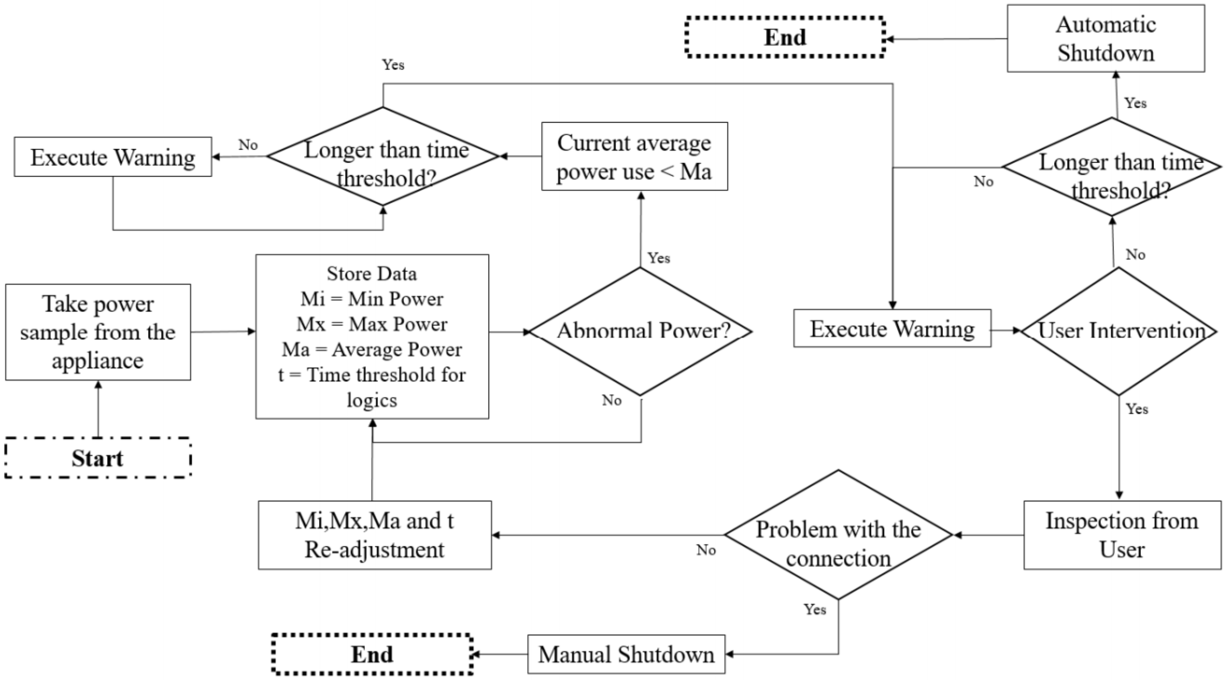


Figure 8.9: The represented flowchart is the system that can be used to detect both glowing connection and arc-fault. The devised system has to measure power used by the appliance as a reference point. Time threshold is needed to be hand adjust by the user. Time value is used to determine the cutoff point when there is no user interaction on report of the problem. If the current power usage is different from the reference data and time has passed beyond set threshold, the logic is then activated.

8.3 Saturated Current Transformer Method

In the processed of we designing the experiment for the previous detection. We found out that when current transformer used in the experiment was incorrectly setup. The voltage reading from the Current Transformer that we can received in the oscilloscope is not accurate to the actual current in the system. However, If we over-saturated the current transformer. It will produce very high peak voltage causes by the internal inductor released its stored energy as shown in Figure 8.10. Since we are dealing with AC power. At every specific interval. The polarity and electromagnetic direction are reversed. Before the polarity is reversed. The zero-crossing point is where the magnetic field is lowest in the cycle which is the place where inductor lose energy. Due to the property of inductor that if the current in the field is reduced. The magnetic field is collapse and the inductor release all its store energy at once which create the voltage spike. This phenomenon will only occur if the inductor core is over-saturated. Other researcher uses similar method with Rogowski coil [1].

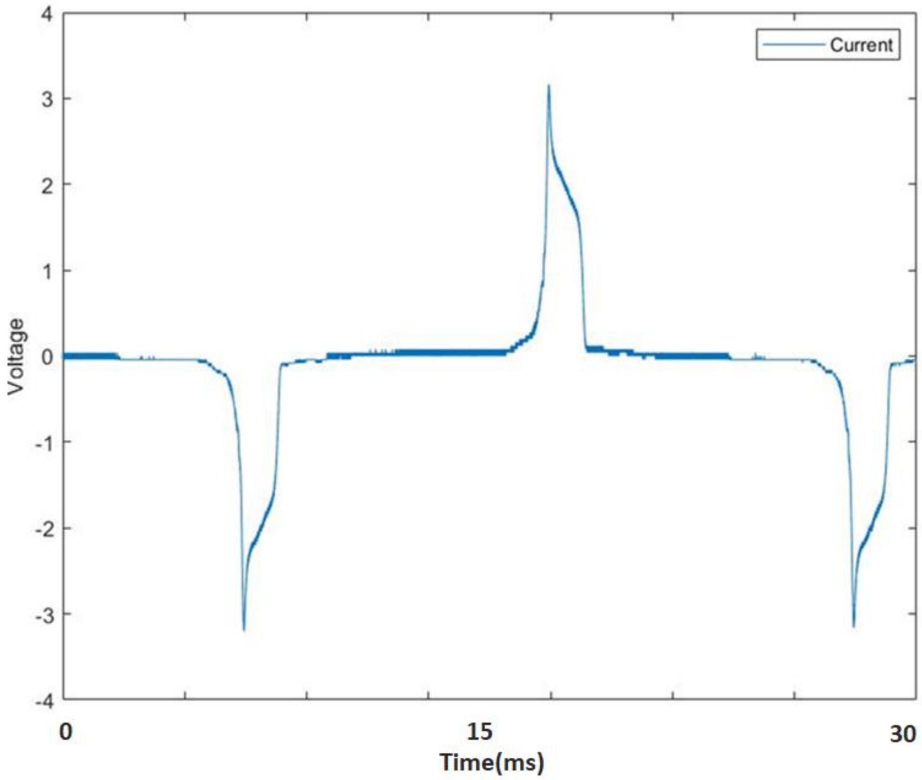


Figure 8.10: A typical outputted waveform from oversaturated current transformer.

Therefore, in the system that we are about to discuss is that. We exploit this specific property of the inductor in the Current Transformer. If the inductor in the transformer is over-saturated at a certain point. A small change in the magnetic field. Whether the changes are cause by a fluctuation in contact resistance or the power source. It should produce a substantial change to the magnetic field that energize the inductor. The result is that the voltage peak when the inductor releases its energy should change.

Figure 8.11: Current Transformer. MR Series by KEMET

The instrument and devices that was used in this experiment is MR series by KEMET, Zero-Phase Current Transformers. The transformer is rated for 50/60Hz and current rating of 10A. The datasheet provided that in order to avoid oversaturation of the capacitor. A burden capacitor value of 7Ω to 15Ω is required at the secondary coil. A microcontroller that was used in the figure is ATmega328P without high-speed analog digital conversion (ADC) although the speed of the microcontroller is sufficient to measure current waveform at 50Hz. We also aim to confirm our proposed system using low speed ADC.

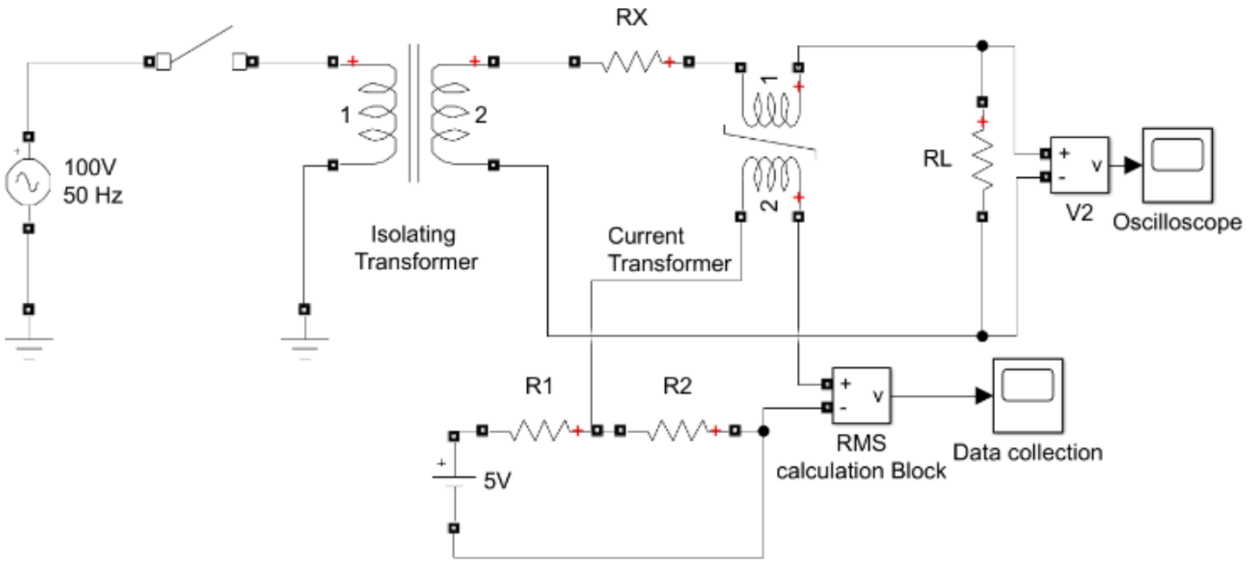


Figure 8.12: Circuit diagram of the experiment setup. Current probe connected to the secondary coil at the Isolating transformer is not shown in the Figure. The oscilloscope sampling speed is 250MHz. Data collection unit in the RMS block is 8MHz of sampling speed.

The experiment setup for the saturated current transformer is almost the same as the previous experiment. The load uses in the experiment are the same. Rating of 100Ω, 25Ω, 12Ω. The main differences from the previous one is that this experiment does not include Power Factor Correction block in the setup since power quality has minimal effect on how the arc-fault behaved as discussed in the previous study. Current Transformer is then added after the contact point. The current transformer does not have burden resistor built in. Therefore, in the circuit. We wanted our transformer to be ideally open circuit or extremely high resistance between two points. The voltage that is received from the secondary coil of the current transformer is then put into a voltage divider with 5-volt bias. This voltage divider is required since RMS calculation block is a basic micro-controller. The microcontroller Analog converter is not capable of reading negative voltage value therefore the voltage is biased to the level where it can be read by the microcontroller. RMS calculation block in the Figure is essentially not a True RMS calculation block due to the shape of the waveform that is received from the transformer is not in a sinewave. Hence, it is basically taking values from the transformer at fixed sample set and then average it out. The data is then collected into the computer. The process of recreating arc-fault in the system is the same as previous experiment. Oscilloscope is included in the experiment to provide reference point for each data set to make sure that the value received by the data collection unit is correct. The voltage divider value of R1 and R2 cannot be fixed. The changes in amount of power that is delivered to the load drastically change the normalized point. This experiment also included an actual passive electrical Appliance which are the Electric Heater and Electric Fan. Electric heater has the wattage rating for 400W and 800W. The electric Fan has watt rating from 30W, 45W and 60W.

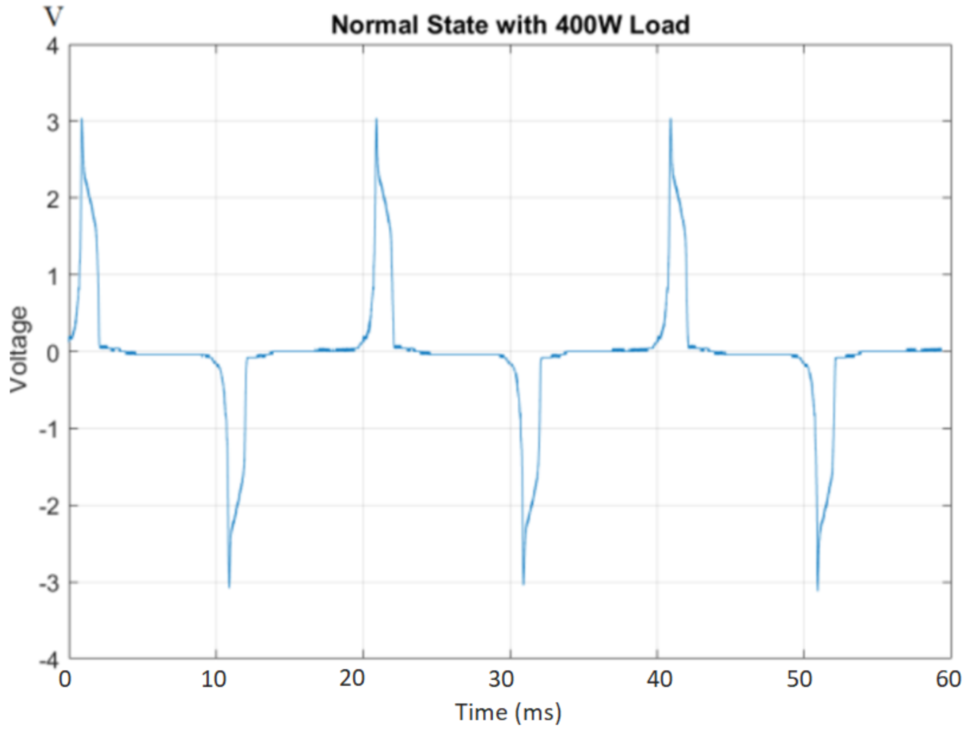


Figure 8.13: A figure of the saturated current transformer. There is no arc-fault in the system.

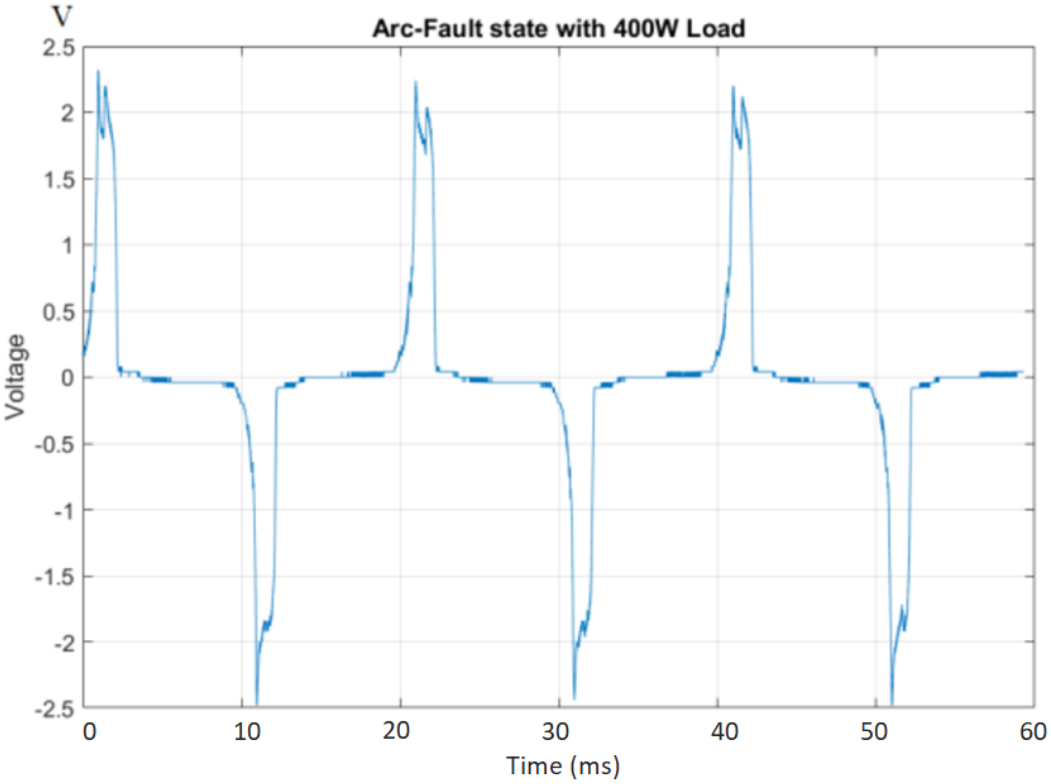


Figure 8.14: A figure of saturated current transformer with ongoing arc-fault in the system.

The experiment provided a satisfactory result. Which gone exactly as predicted. As shown in the Figure between Figure 8.13 and Figure 8.14. We can observe that when there is no arc-fault in the system. Over-saturated transformer releases its store magnetic energy and created spike at zero crossing point. The Figure 8.15 and Figure 8.16 shows the RMS value acquired from output waveform in the secondary terminal of the Current Transformer. The results are shown in the various type of load. According to Figure 8.15, the RMS value drops largely when arc-fault is presence in the system. The RMS voltage reduction in 400W wounded resistor is almost same as that in 400W heater. The arc-fault state has 25%~30% reduction in RMS value compared to non-arc-fault state. 800W heater setup has 20% reduction in RMS value. However, in very low wattage setup, all three fan’s RMS value in arc-fault state is much higher than non-arc-fault state. At 30W, 45W and 60W setting, the percentage increases by 230%, 160% and 130% respectively as shown in Figure 8.16. It is considered that in arc-fault state. The arcing between gap consumed more power and radiated as heat more than the electrical appliance itself. In arc-fault state.

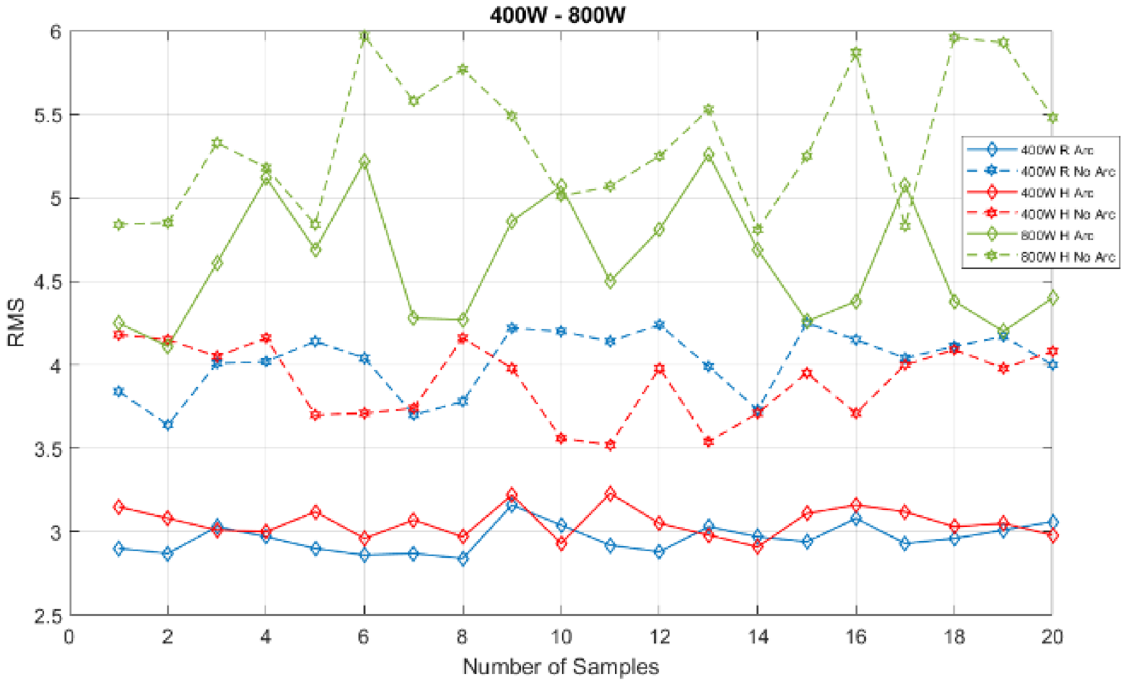


Figure 8.15: The comparison figure between no arc-fault state and arc-fault state in various type of load. This figure has range of 400W - 800W loads.

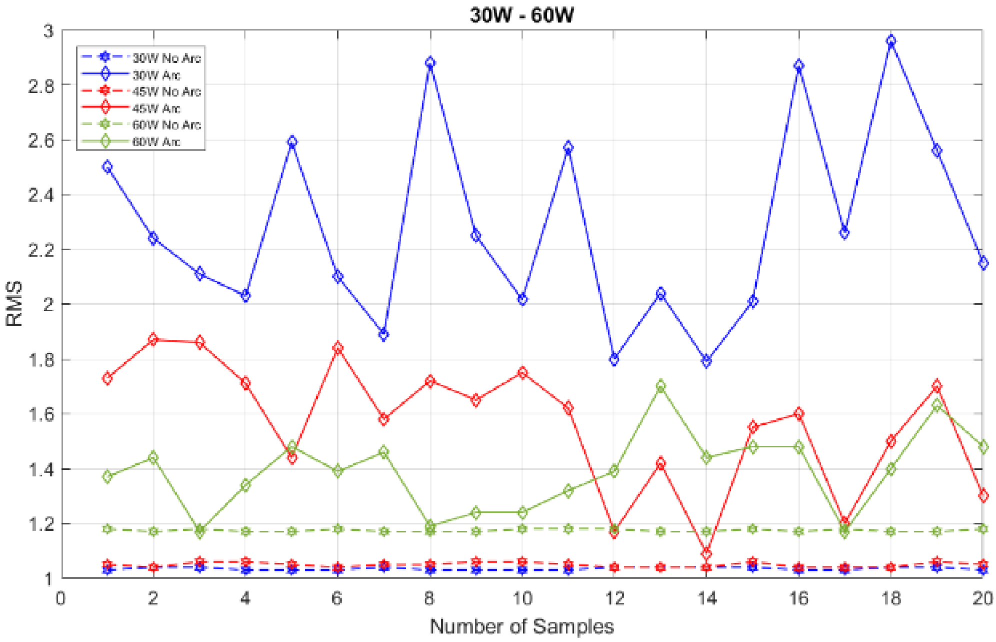


Figure 8.16: The comparison figure between no arc-fault state and arc-fault state in various type of load. This figure has range of 30W - 60W loads.

To confirm with the claim that in a very low power application. The purposed system may not be accurate to predict the arc fault. Another experiment was conducted with a lower rating CT of 7.5A max. As shown in Figure 8.17 and Figure 8.18 For a 300W Arc-Fault state and without Arc-Fault state. One with arc fault has lower peak to peak voltage than without arc-fault. When the experiment was conducted on 100W load. The Arc fault state has higher peak to peak voltage than without the arc. As we suggested that in a very low wattage application. The arc-fault can consume and radiate more power than the source that consume it. The scope of this research is not to detect a very low power arc-fault due to its high difficulty of sustaining the arc-fault and the state that can initiate arc-fault. However, the new current transformer used in the experiment has different core magnetization value which when the magnetic field from the electrical wire changes by the resistance change by the arc fault. There are less abrupt changes in the magnetic field in the core. Which does not produce low and high peak as seen in Figure 8.13 and Figure 8.14 It is implied that in order to maximize the accuracy of the system. The core of the CT should be sensitive to changes in magnetic field

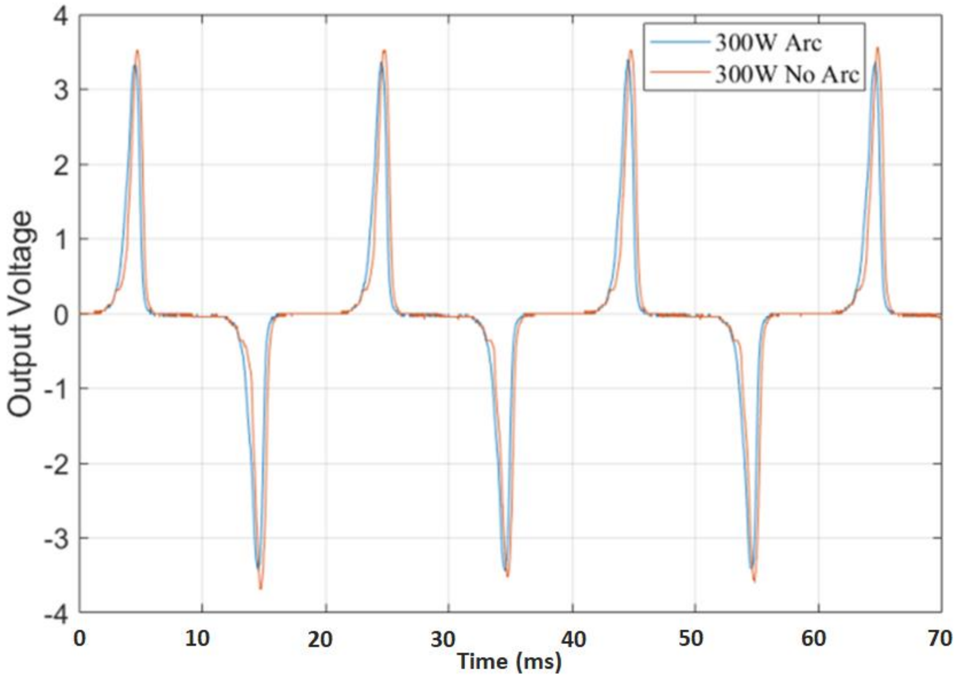


Figure 8.17: The experiment result with 7.50A CT and the load of 300W from wirewound resistors.

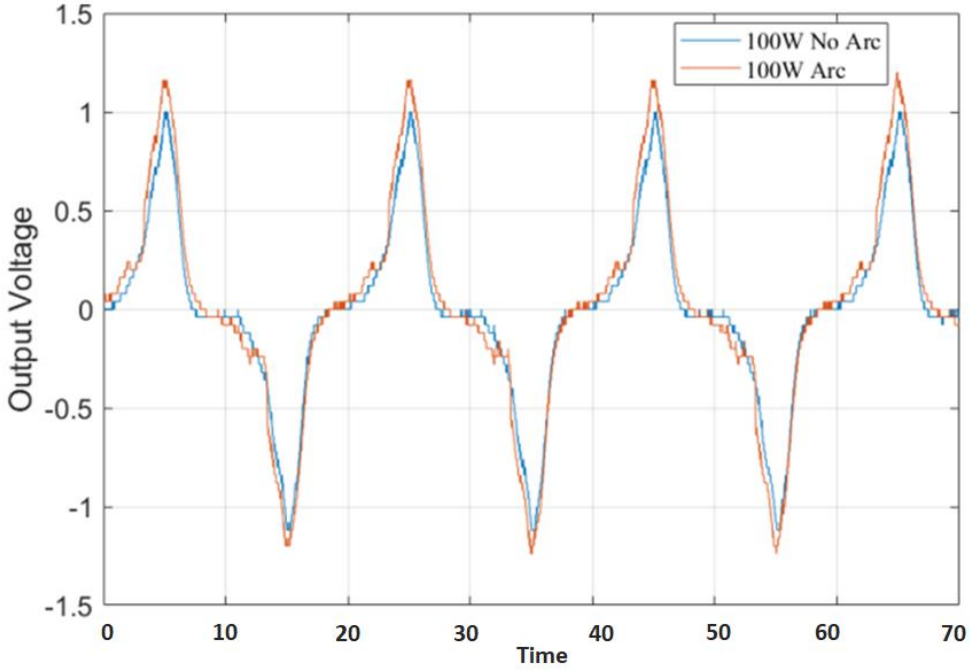


Figure 8.18: The experiment result with 7.50A CT and the load of 100W from wire wound resistors.

We are able to compare this novel method to the other method we purposed in our previous study where we used properly calibrated CT to measure the current changes when there is an arc-fault in the system. As shown in Figure 8.19, the Figure shows the normal state and arc-fault state at 400W resistor array. The value difference between two states is only from 3 to 5 percent. The difference depends on the load. Higher the load the difference between normal and arc-fault state is even lower where low load produces higher current difference, it still however produces marginally difference in value which can be an issue when designing a simple and robust detection system. Saturated CT Method has much higher detection sensitivity for low voltage and low current operation which is suited for the scope of the research

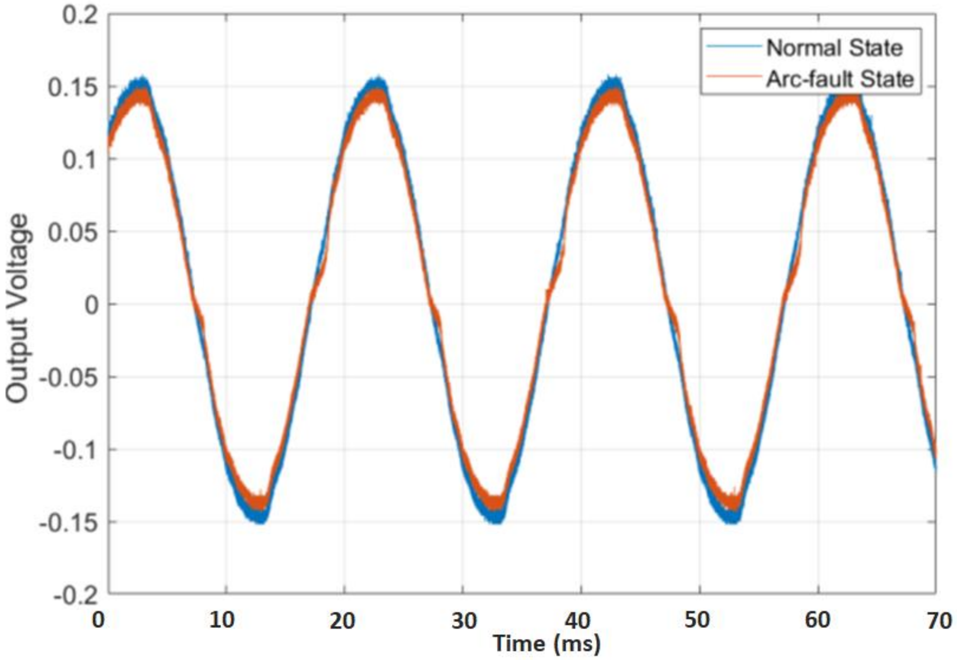


Figure 8.19: The output from current transformer when proper burden load is used. Noted that in arc-fault state. The overall peak of the waveform is slightly lower than normal state. A small waveform distortion near zero crossing point can be seen.

We made a simulation of the system with MATLAB to validate that a fluctuation of the resistance value near the contact point is the main cause of the reduced voltage peak on the secondary coil of the current transformer. The Simulation circuit is as shown in Figure 8.20

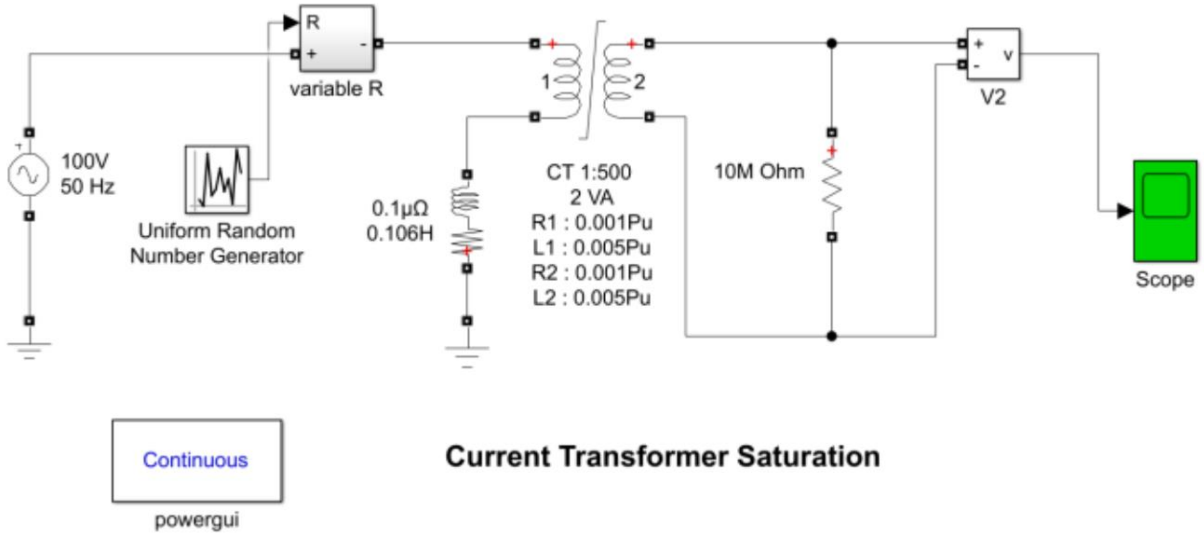


Figure 8.20: The block diagram in MATLAB simulation. Base design is available in the main MATLAB website. This is a modified power_ctsat [2] to fit the parameter needed in the simulation. The parameter is as followed in the Figure.

This MATLAB simulation was a modified from “power_ctsat” made by G. Sybille. Unspecified value in the Figure is as of following. Winding resistance and winding inductance for both coils are kept to as much as ideal as possible. Each coil has resistance value of 0.001pU and inductance of 0.005pU. Due to the complexity of modeling non-ideal core where size, shape, and core material have direct impact on the magnetization of the core. Datasheet of the CT used in the experiment does not provide sufficient data to model the core in the simulation. Hence a common value from similar type of CT was picked. In any non-ideal transformer simulation, there are two type of value that is needed to be specify. Tow values are magnetization resistance (Rm) and magnetization inductance (Lm). Magnetization resistance is a magnetic loss in the core by its material which is divided into two main parts. Magnetic loss resulted from hysteretic loss and eddy current Loss. Both type of losses is not required in specific value for the simulation. Magnetizing inductance is more complicated because the exact data of type of material for the core and the shape of the core are required. Additionally, wire is wound around the magnetizing core. Therefore, Lm is calculated by the formula as follows.

$$L = \frac{N^2 A\, u}{P}$$

The shape of the inductor used in the simulation is common toroid. The simulation objective is to achieve the same patter with known variables rather than to replicate the shape of the waveform from the oscilloscope exactly. Therefore, RL component on the primary coil is kept as ideal as possible. As a result, Rm value of 0.1μΩ, Lm is of 0.106H which is a common value for similar type of transformer. The simulation result is as shown in Figure 8.21 and Figure 8.22. As we can see in both Figure 8.21 and Figure 8.22, the result from the simulation is similar with the experiment result. As arc gap resistance (RX) is introduced into the primary coil, the peak drop down significantly even the resistance value is very low. The simulation in the Figure also included the fluctuation of resistance as explained earlier. The gap resistance changes rapidly depend on the current phase where at zero-crossing point exhibits highest resistance value. In the simulation, the resistance is randomized between 12Ω to 300Ω. The frequency of change in resistance in real experiment is difficult to predict due to the constant changes in current value which is not possible to predict. In the simulation, resistance changes at 10kHz setting matched with the result in the experiment. In the actual experiment as shown in Figure 8.13. The arc change in intensity depend on the current period of the source. Hence resistance value may have change rapidly in each cycle. In Figure 8.22 we can observe that the peak of the voltage has a fluctuation that could mean that the resistance changes may exceed 100Hz by several order of magnitude. 1kHz – 10kHz changes in resistance value seems to give the most accurate result.

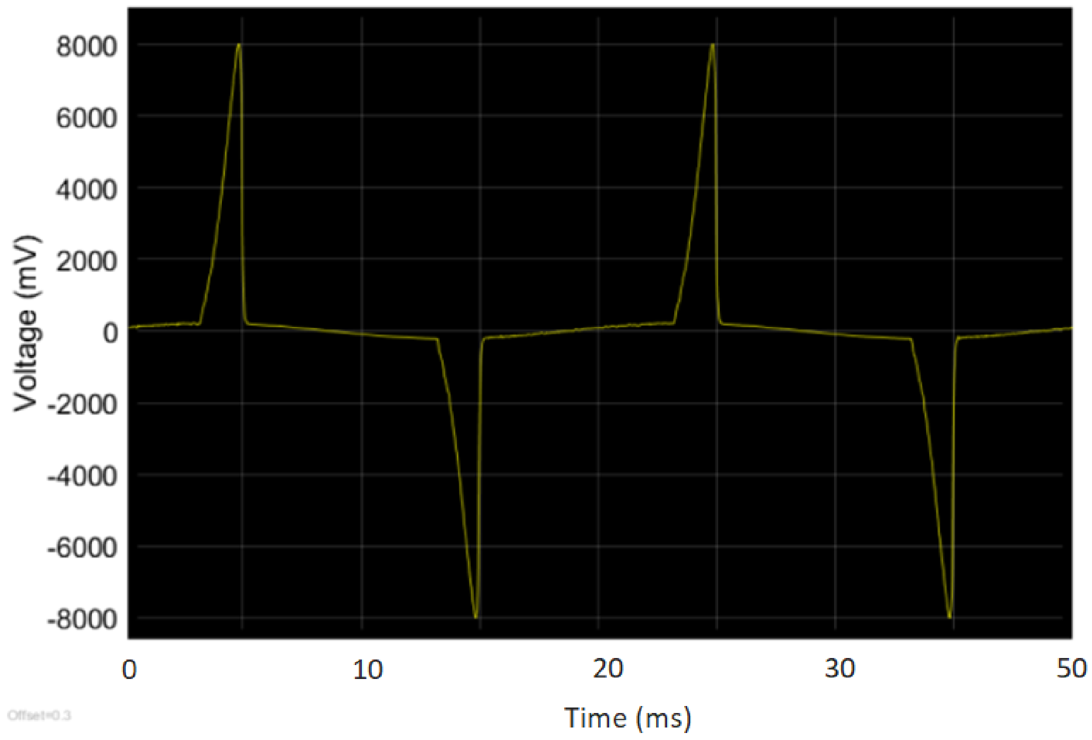


Figure 8.21: MATLAB simulated current transformer. Arc-fault is not presence in the system.

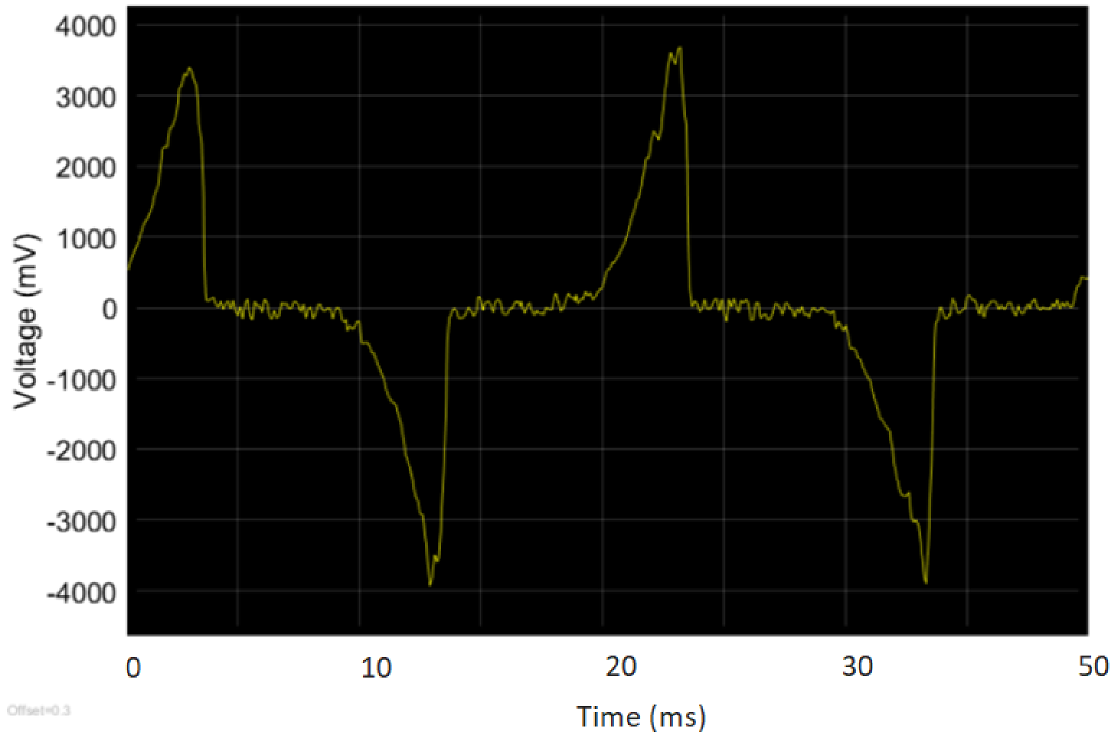


Figure 8.22: MATLAB Simulated current transformer. Arc-fault is presence in the system. It is noted that the figure has varying R value at the frequency of 10kHz

8.4 Conclusion to the Detection Method

It is prominent that the detection method with Over-saturated Current Transformer is a direct upgrade to the Voltage difference between two cathode method. The accuracy and detection rate in theory is exceptionally higher than the first method. However, for both detection method will still have the same drawback. The main draw back for the system is that for certain appliance that radically changes in power draw within it usage routine is unsuitable. Since both methods rely on the amount of power draw by the main load and the power dissipation at the arc-fault gap. Since most of the arc-fault related fire incident is largely causes by unattended electrical appliance or the device that is not being in constant supervision by the user. These methods are most suitable on passive device. Currently in this research work. The actual prototype detection device has not been realized and used in a real environment yet. Therefore, a future study on how to create such device that is capable of using in multiple power load draw is required.

8.5 References

1. E. Sritrai; S. Kittiratsatcha; S. Polmai,"Low Voltage Series Arc Fault Detection Using Rogowski Coil", 2018 International Conference on Engineering, Applied Sciences, and Technology, Phuket Thailand 4-7 July 2018
2. G. Sybille, “Current Transformer Saturation” Accessed on Oct. 11, 2021. [Online].https://www.mathworks.com/help/physmod/sps/ug/currenttransformer-saturation.html

Chapter 9: Conclusion

9.1 Conclusion to the finding

In conclusion from the previous chapters from 3 to 6. The mechanism of arc-fault that was reported and replicated by previous researches done by other researchers. In chapter 3 we were able to obtain the same result of the voltage and current waveform, which include the typical characteristic of a typical copper-based arc-fault. This deduced that our result has been validated and the obtained data is correct. According to the information we obtained from chapter 3 result is that the voltage drop and current shoulder that's appear in the waveform is directly linked together. Where at certain point in the time period. The arcing stopped at the same position where the voltage drop started and the current shoulder appeared. The result is also correlate with the visual observation obtained in chapter 4 and 5. In chapter 4, we were able to observe that the arc-fault in our study is not a continuous arc-fault, but rather a pulsating arc. The pulse time interval is also correlate to the result we obtained back in chapter 3. This confirmed that the pulse is causes by the current shoulder where the current was not able to make it through the conducting point which turn the circuit off, hence the voltage drops. However, in a higher power setting. The voltage drop is less prominent and the arc is much more continuous. It is suggested that in a high-power setting. The pattern of the pulsating arc is different. We found out that the temperature of the oxide bridge is directly related to the state of the arc-fault as we observed in chapter 4. Due to copper oxides bridge is partially a semiconductor. Where the resistance is reduced from insulator stage to conductor stage at a certain temperature. When the temperature is too low. The arc-fault cannot be started. If the oxide bridge has been heated up to the conducting point by any mean, the arc-fault state can start. Which generate large amount of heat and create even more oxide bridge. In a regular setup, electrical discharge would only occur if two contact point has been perturbed by external force. In chapter 5, we were able to observe that a poor contact also vibrates at twice frequency of the power source. Such vibration is suggested to causes by the change in electromagnetic field in a small area. The vibration amplifies in strength when arc is already presence in the system. The vibration can be large enough to initiate make-break contact at every cycle which create a continuous electrical discharge. Electrical discharge generates large amount of heat at the contact point which is capable of heating the oxide bridge near the contact area to the point where the oxides bridge turn into a conductor state. In chapter 6, we came to the conclusion that, initial electrical discharge creates large amount of heat. The heat is energetic enough to melt a portion of the copper contact surface. Brass contact surface were known to be more resilient to mechanical wear and corrosion. The result we obtained is that brass is still susceptible to the creation of copper oxide due to zinc component in the alloy can be leech out of the metal with the electrical discharge. Therefore, any copper-based contact surface will bear inherent risk for this type of electrical hazard.

We were able to draw the overall mechanism and concluded in chapter 7. In order to produce arc-fault in the system. Certain criteria must be met to produce sustainable fault. According to the result we got in this experiment that, a single spark or no-spark at all can lead to joule heating. An initial spark on the contact produces substantial amount of copper oxides on the surface. The surface is also compromised by the extreme heat from the spark which reduce effective contact area and increase joule heating effect from micro-contact. If the electrical spark is not presence in the initial contact but if the contact between two electrode is faulty. Contact resistance alone can generate heat, which depend on the amount of current that pass through the contact area. Micro-contact can also aggravate breaking and touching action when both contact is not firmly hold in place. This can lead to contacts vibration and create discharges that produce copper oxide in the process. This process further deteriorates contact life.

Type of electric household appliance that may affect by this heating mechanism can be anything that include copper bearing element as contact or current carrying cable. As the cord or fragile part of the wire is bend and break off. This can easily produce initial spark and greatly increase total resistance in the wire. If the appliance uses large amount of power, when the faulty wire is subject to large current at set amount of time. The wire can start breeding copper oxide which increase total resistance in the wire. Extra copper oxide created from the wire can heat up the point of contact even further until the temperature rise above flash point of the insulator and burn down. Textile wrap wire are mostly used in the old house cabling system and some high-power cable equipment are layered under metal wrap to increase strength.

Extension cord and plug can consider to be a fire hazard when it is used for a long time especially without constant supervision in which the cord or the plug can be damaged by environment factor or accident in the area. Extension plug that are sold in cheap price and in large number around the world is mostly made from either ETP copper or Electrical brass which lose its grip overtime due to the oxygen in the air that diffuse into the structure and made the metal lose its elasticity, When the grip is loosen to the point where contact is not firmly held together, Initial spark can cause when the wire is moved. Once initial spark is created, the contact grip is compromised and can cause heat to generate when the grip is subject to high current passage.

9.2 Electrical appliance those are likely to cause fire are listed below with descriptions.

a. Third-party installed electric plug: This kind of plug can cause heat to accumulate where the cable and plug blade is connect if the plug is subject to high current. A large of third-party electric plug that does not come with the electrical appliance lack of nickel coating which is mainly used to reduce the wear on the surface.
b. Housing Electric socket: This type of socket must be change to reduce the chance of electrical fire when the socket loses its gripping force.
c. Extension cord and plug: This is the most dangerous type of appliance, this type of fire hazard largely depend on how many appliances connected to the extension cord, how much power does the extension cord draw. Movement of the extension cord can fasten the process of electric socket loosening its grip force.
d. Handheld High power electrical appliance: This type of appliance cord and setup are move every time when it is used. Current conducting fragile part may partially break off and increase the total resistance in the wire and cause fire when used in a prolonged period. Especially the long electric cable cord which can bend and break inside. Which may lead to both type of arc-fault.

9.3 Action from the user can potentially increase chance of fire hazard from arc-fault are listed below with descriptions.

a. Bending of the cord: Cord bending to store it in a small space can compromise the wire or other fragile current carrying components.
b. Turning the electric appliance on before inserting into the electric socket: By turning the appliance electrical switch on can cause initial spark on both contact on the plug and in the socket.

c. Pulling the electric plug out before turning the appliance off. Breaking action can cause initial spark on both contact which compromise the contact surface.
d. Pulling the electric plug out in a forceful manner which may damage the contact on the both sides. The socket may lose its elasticity due to the overexpanding movement.

However, when all thing is considered. It is not possible or unfeasible to totally remove or avoid mishandling of the contact by the user. Copper based contact and as a main current carrying method will always be a risk. The best-case scenario is the contact point of all electrical appliance may need to be changed into non-copper base material or plated to the point where copper oxide cannot be generated from the initial arcing. The contact material that is unsuitable is not limited to copper. Mainly copper has a semiconducting property that is undesirable for such use. Other type of material that has the same properties as copper is also unsuitable as a contact material.

At this time, contact material replacement from copper into other type of metal may not be possible due to the economic advantage of copper-based materials. Many devices have been created to counteract and prevent this type of arc-fault. However, the device limitation is that this type of arc-fault's mechanism is largely unknown. The device operates on the probable characteristic of such phenomenon. Which in turn create detection unreliability. In chapter 7, we devise our own method of detection according to the mechanism we obtained from our study. The saturated current transformer method is the most promising candidate. The system is capable of detecting most type of copper-based arc fault. However, there are still limitation in this method that is needed to be study further.

9.4 Future Possible Study

As mention is Chapter 8 that there are two new ways to detect an arc-fault state. Saturated Current Transformer method is assumed to be superior than the voltage disparity between two cathode method. However, both type of detection has not been tested in an actual environment and an actual practical prototype has yet to be created. The experiment and the devices used in the study is still in a very preliminary where a lot of factor and variable has to be finetune for each and every experiment. In the future study, an actual prototype may need to be created and study the limitation and the drawback for each detection system

Publication Lists

Related Publication

Journal Paper

S. Wangwiwattana, K. Yoshikazu, “Joule Heating and Arc-Fault-Induced Electrical Fires for Commercial-Grade Copper and Brass in Low-Voltage Electrical Systems” Appl. Sci. 2022, 12(9), 4710; https://doi.org/10.3390/app12094710

Conference Paper

S. Wangwiwattana and K. Yoshikazu, "Detection Method for Fire Incident due to Arc-Fault in Home Appliances," 2022 IEEE International Conference on Consumer Electronics (ICCE), 2022, pp. 1-4, doi: 10.1109/ICCE53296.2022.9730397.

S. Wangwiwattana and K. Yoshikazu, "Arc-Fault Detection method with Saturated Current Transformer," 2022 2nd International Conference on Image Processing and Robotics (ICIPRob), 2022, pp. 1-5, doi: 10.1109/ICIPRob54042.2022.9798716.

Other Publication

Sittichai Wangwiwattana, Rardchawadee Silapunt, Yoshikazu Koike; "The Evaluation of Crowd Density Estimation with Wi-Fi Signal Band in Closed Space via Ray-Tracing Simulation "Advanced Engineering Forum (Volume 33).
https://doi.org/10.4028/www.scientific.net/AEF.33.33

Sittichai Wangwiwattana, Rardchawadee Silapunt, Yoshikazu Koike, "A Study of Crowd Density Estimation with Wi-Fi Signal band in Closed Space", 2018 15th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2018**,** pp. 708-711

長谷川裕祐，星野嘉彦，小船浩司，小池義和，WANGWIWATTANA SITTICHAI，"接触部過熱の出火機構の究明に関する研究"，第67回全国消防技術者会議（2019年11月）

ACKNOWLEDGEMENTS

I would like to express my gratitude to many individuals who supported me in this research work. Their contribution to this research work is crucial for the success. Without such individuals' assistances, this research may have been much more difficult to move forward in each stage. Especially I wanted to express my gratefulness to my supervisor, **Professor Yoshikazu Koike**, Department of Electronic Engineering, Shibaura Institute of Technology, Japan. For his valuable time, many advices and support in this work. Especially the part where my advisor would provide me every instrument and absolute freedom to progress in my research work without any pressure. I had a great time with the work I have done and contribution to the Laboratory

I am grateful to **Prof. Hideki Yokoi, Prof. Shin-ichiro Kanoh, Prof. Chinthaka Premachandra** and **Prof. Takaaki Ishii** from University of Yamanashi for their agreement in reviewing my dissertation and their valuable comments to improve it.

I would like to offer my gratitude to **Assist, Prof. Dr. Rardchawadee Silapunt** from the Department of Electronics and Telecommunication Engineering, King Mongkhut's University of Technology Thonburi for her valuable time and providing me many chances and offers for my pursuit into academic career.

I would like to offer a special Thanks to Tokyo Fire Department for their insights on the study topic. They have also provided me many samples that assist with the study.

Last but not least. I would like to express my deepest gratitude to my family. There had been many problems both from the outside and my own personal problem. They had help me through and provided me with many consulting sessions which kept my mentality in shape and being able to progress in my study without problem.

Special thanks to all other people and my other friends from outside Shibaura Institute of Technology who gave me many insights on the study. Their profession and knowledge had given me many ideas to progress in this research work. Finally, for any error or in adequacies that remain in the work is entirely my own responsibility.