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Electrical Arching and Thermal Circuit Breakers: A Review

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Abstract: *The essence of electrical protective devices is to mitigate damage, to maintain system stability, and to maintain electrical consuming devices at the rated operating limits. The hazards involve in the consumption of electrical energy for homes and any other place must be well understood; because this would signal warning for proper safety. Age long protective device known to almost 99% users' of electricity is circuit breaker. But this device has its limitations. A review is therefore presented to examine the duties and limitation of residential electrical circuit breakers based on available information.*

Keywords: *Arcing, circuit breakers, temperature, electricity, fire.*

1. INTRODUCTION

There are two most common temperature protecting device in electrical protection systems, and these are, fuses and circuit breakers. Whenever the excess current flows through the fuse, the temperature of the conducting element increases and at some point, it melts. Any protective device is supposed to possess an inverse time characteristics, meaning that the higher the overload, the shorter the time it takes to clear the fault. A circuit breaker has a sensing element which may be solenoid and or bimetallic or both [1].

The purpose of any protective device is to promptly clear fault from power network. The objectives of protection system may include prevention of damage to equipment, lives and properties, minimization of the effect of faults on the utility system, and prevention of interrupted power supply. Fuses, being the oldest protective device, but it can also be seen as the simplest of all the various protection devices. They are usually connected in series with the live conductor by the melting fusible conductor that will respond to the current flow through them on inverse time basis [2]. The fuse elements are made of copper, aluminium, zinc or combination of any of this with their different melting point.

The heat produced by the flow of electric current through a cable, determines the operation of the fuse. The electric current is expected to increase when there is overloading, short-circuiting, and therefore, heat would be generated enormously, and invariably, the temperature of the fuse wire increases. At a point when the heat generated equal or more than the melting point of the fuse wire or elements, the fuse operates to protect the circuit [3]. The melting point for various fuse elements is presented in Table 1.

Table 1: Melting point of various elements [3]

Metal	**Melting Point of in Degree Centigrade**
Aluminium	671.5
Antimony	428.5
Copper	1092.5
Lead	329
Silver	999
Tin	239.5
Zinc	419.20

Figure 1: Rewireable cutout

Figure 1 is a rewireable cutout. The cutout is a protective device against overcurrent. The wire is expected to melt when overcurrent flows through it.

2. A CIRCUIT BREAKER

A circuit breaker is nothing but a protective device just like a fuse. The only difference is in their mode of operation and the construction. A circuit breaker is an electric power protective device that could make and break a circuit either manually or automatically under normal or abnormal condition. Abnormal condition could be when there is overcurrent, and or short-circuit while normal condition could be when the breakers trips for no-fault condition.

In [4], it was explained that circuit breaker is now more popular than fuse because of its easy breaking and making of circuit in-case of faults. In generation, transmission, and distribution of electric power, circuit breakers do not operate alone but must be well coordinated with relays and instruments transformers. The fault tripping time of this protection system is gotten from the relay through the trip circuit. Circuit breakers can be classified based on voltage range, location, and insulation medium. Low voltage circuit breakers are used for protection in residential buildings. This device is of voltage range between 1000 V and below. It is an air circuit current sensor. Example of low voltage circuit is miniature circuit breaker (MCB), and molded case circuit breaker (MCCB). They could operate on magnetic field or temperature. When the voltage is above 1000 V, a medium circuit breaker should be employed. Examples of medium circuit breakers include air circuit breakers, vacuum circuit breakers, and SF6 (Sulphur Hexa Fluoride) circuit breaker. Whether low, medium, high, extra high, and or ultra-high circuit, they operate on the same principle, the only difference being in their solenoid function.

Conventional circuit breakers and fuses have been investigated to see that many of it do not usually trip off in the presence of faults [5]. It is fact to note that if electrical wire or cord is damaged, there is possibility for continuous arcing to occur with an effect that would not cause a root mean square sensing device to open the circuit. This may be because of the lower root mean square value of the fault current compared to the overload time current curves for which the breaker is to respond. In the presence of any ignitable object, this arcing could continue until fire is initiated. Arc fault circuit breakers (AFCB) were developed to solve the problem of low sensitivity conventional circuit breakers it has on arcing. Arc fault circuit interrupter can detect parallel fault and ground current fault but series arcing fault becomes very difficult unless the fault progresses to parallel fault. All these conditions have placed limitations on the efficiency of many protective devices [6].

Domestic miniature circuit breakers are expected to provide protection against overload and overcurrent. An overloading is a case when a conductor is transporting more than rated current to load if the load is in excess of the capacity of the conductor. Also, an overcurrent situation occurs when there is short circuiting. Therefore, residential miniature circuit breakers are designed to protect equipment and lives from the menace of short circuiting and overloading. Overloading causes the temperature of the conductor increases to increase the insulation deformity and when insulation breaks due to excessive heating, fire is just the result. But the most unfortunate thing is that circuit breakers do not trip when extension sockets (cord) is overloaded or short circuited [7]. For arcing fault caused by cord insulation failure, residential miniature circuit breakers may not respond because of the insensitivity and the thermal trip function of the device.

Also, [8] defines arc-fault circuit breaker (AFCB) as a device intended to provide protections from the effects of arc faults by recognizing characteristics unique to arcing and by functioning to de-energize the circuit when an arc fault occurs. The continuous luminous discharge of electricity across an insulation medium supported by partial volatilization of the electrodes is referred to as an arc. Arc is simply a semiconductor with anode and cathode separated by air space or capacitor with metal plates separated by dielectric. Arc may not likely be able to ignite or sustain spark unless there is a conductive surface like organic or insulation materials and loosely touching conductors. The I^2R heating forms carbonized path on the surface which is a good ingredient for arc and could cause electrical fire.

Since conventional circuit breakers cannot sense arc fault; then arc fault circuit breakers are needed to give full protection for the entire network against any type of fault. If the AFCB is used to replace the circuit breakers in the distribution panel, the wiring would be protected beyond the panel; the protection may even extend to all electrical appliances connected to the circuit. Another way to connect the AFCB is to connect it to the outlet of the circuit. Connecting the circuit to the outlet branch of the circuit, protection is guaranteed to downstream branch circuit, cords, and against any unwanted effects of arcing [9].

During the late period of 1970's, electrical fires were understudied to be the major problem of submarines. But, with the coalitions of Johns Hopkins University Applied Physics and Navy, two major devices were designed to tackle the incessant submarine problems. Arc fault detector and continuous thermal monitoring systems were developed. These systems were not only suitable for military submarine advantage but for all electrical purpose in case of faults that could degenerate to fire. Ordinary circuit breaker may not open when arc fault occurs even if the arc is of several thousand amps since normal loads draw current of higher order. Arc is not short-circuit, but a resistive load yielding heat [10]. Circuit breakers specifically protect against overheating due to an overcurrent condition; circuit breakers may not be able to protect against arc faults.

Analysis carried out by [9] showed that circuit breaker age have noticeable effects on the magnetic trip level of the device, and for a 15 A breakers, a normal distribution average value of 212 A current is possible with 99% of the breakers having their magnetic trip current below or at 300 A. Also, for 20 A breakers, an average value of 202 A with 99% magnetic trip current of below or at 349 A current is possible. The study of [9] further stated that conventional circuit breaker can be an effective means of lowering the risk of parallel arcing fault in home run if the impedance of the home run wiring is less than a critical value as shown in Equation 1. Figure 2 consist of transducers that detect arcing.

$$\rho_L L < \frac{V_{rms}}{2}\left(\frac{0.8}{I_{mag}} - \frac{1}{I_{pssc}}\right) \quad \ldots\ldots\ldots 1$$

where ρ_L is the resistivity per unit foot of the sample cable,
L is the length of the home run in feet,
V_{rms} is the supply voltage
I_{mag} is the magnetic trip current of the circuit breaker
I_{pssc} is the short circuit current at the panel-board

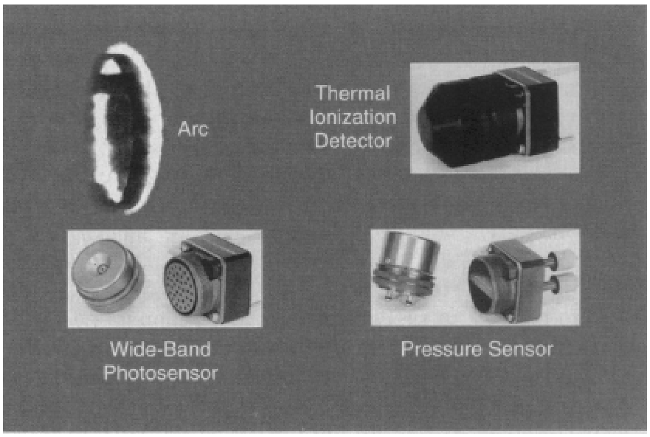

Figure 2: An arc detector components [10]

3. Causes of Electrical Fires

Electrical fire hazard is in increasing order as more and more electrical devices are being produced due to technology advancement. Possibility for electrical wiring ignition is very high. There are many factors responsible for this undesirable event. It was stated by [11] that some of the possible causes of residential electrical fires such as internal and external damage of electrical appliances, insulation failure, poor connection, and electrical loading. There is no little cause of electrical fire since fire is fire. When any of these occur, it usually leads to loss of lives and properties in the absence of fire arresters. This necessitates why more attention should be paid to investigation of the various possible causes wiring faults and how it can be averted. Loose connection, over-current, external heating, broken wire, over-voltage, insulation damage have contributed a lot to the cause of electrical fire globally. Series arcing in polyvinyl chloride (PVC) was investigated by [6]; glowing contact and series arcing were noted to be the two main source of overheating which always lead to fire outbreak. The difference between glowing contact and series arcing is that series arcing requires the need of insulation to bridge the gap in the loose or broken conductor, while glowing contact can be formed with or without insulation present.

In the review of the research on the identification of electrical fire trace evidence conducted by [12], short circuit can be classified as short circuit before fire and short circuit during fire. The short circuit before fire is one caused by the wire due to its own fault. The short circuit during fire is one as a result of electrical wire insulation fault under the influence of external flame or high temperature. Overloading of the wire will increase the temperature of the wire and this can also cause electrical fire. Poor contact may lead to high resistance at the contact point causing a temperature increase at the point; poor contact may also cause electric arc and damage to the wire insulation. Any of these effects, can result in electrical fire. Electricity leakage caused by bad contact such as socket and switch connector can result in high contact resistance; this will make overcurrent protection device difficult to activate, and when electric arc appears at the fault point, electrical fire may erupt. This electrical leakage can be traced to electrical wires, metal materials and electrical equipment

Under some certain conditions, a polyvinyl chloride (PVC) cable insulation decomposed when subjected to glowing via the conductor, leading to combustible gases that can ignite any fuel within its vicinity. The PVC insulation which decomposes when overheated was concluded to as consequence of glowing connection and arcing over surface by [6]. The methods that can be adopted to mitigate these effects of low current series arcs and glowing contacts on electrical fires include development of modern protective devices and improved insulation materials.

A laboratory experiment was conducted by [13] on glowing contact areas in loose copper connections. The conclusion of [13] is stated as follows:

1. When loose connection of current-carrying copper conductors occurs, and if this conductor is exposed to mechanical vibrations, the contact of this contact point may corrode to form Cu_2O.
2. This copper oxide layer is a semiconductor whose temperature could increase to about 150-200^{0}C.
3. Instability of current distribution of the oxide layer occurs when the current exceed a value of about 6 Arms.
4. 1235^{0}C is the maximum temperature of the oxide to which the melting of the conductor occurs.
5. The rate of increase of the corrosion results to increase in power dissipation to values which can cause fire hazard in the electrical installation.

The misuse of electrical equipments and installations causes roughly 25% of fires in building as reported by Norwegian statistics. The root cause of this fire is attributed to series or contact faults; series or contact is poor contact or broken wires where the current is limited by the load impedance [13].

Another cause of residential electrical fire is lightning strikes. Lightning fire (this is another form of electrical fire) do not occur as a result of direct ignition by the electrical currents of a lightning strike but from damage to the electrical system of the building. Indirect lightning strike is when lightning strikes the ground close to building, overvoltage and overcurrent induces on any conducting materials in the building by some process. Lightning strike could be caused by electrical arc-fault current. The overvoltage that induces the conductor generally results in insulation failure of the conductor [14]. This fact necessitates importance of lightning protection system of all exposed any conducting material that is used in making buildings. Figure 3 is a graph showing fire death per population size for thirteen countries.

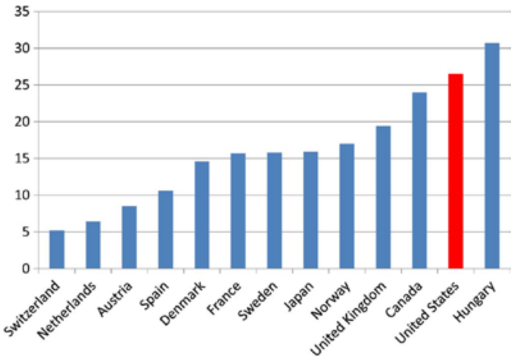

Figure 3: Fire Death per million population by country (1979 – 1992) [14]

The multiple photovoltaic (PV) systems residential rooftop fire caught the attention of National Electrical Code (NEC) and it suggested arc-fault circuit interrupters (AFCI) for mitigating device damage via these incessant occurrences. Series and parallel arc-fault are required to fully protect PV systems against fire hazard. Normally, PV arrays usually have zero impedance of module interconnect; but due to degradation in solder joints, PV wiring, and the likes (all these causes series arc fault), the impedance of the module increases from zero to some certain degree [15]. The more the fault exist in the module, the higher the arc which can ultimately cause electrical fire. A good protection system is therefore vital for solar systems in homes and any applicable areas.

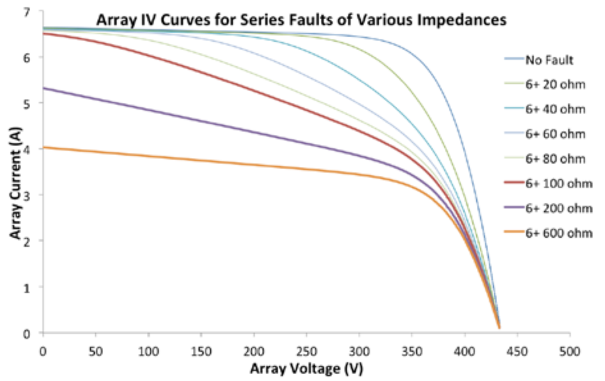

Figure 4: Effect of series arc fault on different impedance on arrays of Current-Voltage curve [15]

The two types of short circuit are the phase-to-phase short circuit and phase-to-ground short circuit. When short circuiting occurs, the metal conductor melt due to very high temperature. The insulation is expected to oxidized and burn itself. This short circuit current is very high, and therefore, the circuit breaker can break or cut off the power supply and thereby, fire can simply be avoided. In case of arc fault, the current is small, and the circuit breaker may not see it as fault. The short circuit (in this case, arc fault) current is supported by the impedance and the arc continues for a longtime. Temperature increase caused by arc can be up to 3000^{0}C ~ 4000^{0}C; this temperature is high enough to melt or burn any surrounding material easily [16].

Insulation carbonization is a serious arc formation problem. If wet path (wet path is when moisture and pollutant effects present in the insulation) is created in the insulation, leakage current would flow through it, which may gradually forms carbonize path. Once the initial current forms a carbonized layer, continuous current increases until the arc starts burning. The burning arc would invariably melt the conductor, and fire result is the end product. Another cause of arc fault is air ionization caused by external factors. The electric field of air is approximately 3MV/m [16]. During spark or arc, enormous heat is produced which is capable of causing ionization. The third cause of arc is short circuit. When two conductors are not tightly connected, large impedance exists which would make a very small current to flow that cannot be sensed by some protective device as fault. But as the arc persists, the temperature increases and the heat produced may be strong enough to burn any fuel material within its vicinity.

Figure 5 (a) is a series type arc circuit. The arc may occur when two conductors are in close contact by another conductor. The figure 5 (b) gives a series arc circuit. The arc occurs when a loose contact exists in same line of conductor. The little separating distance can result in ionization of air. As long as the load on the cable remains, the series arc will continue in series at lower levels of current than the load current. The persisted arcing with little current flow can lead to serious fire hazard. Figure 5 (c) shows a typical line-to-ground arc fault. The formation of this arc occurs when a ground path exists. This is what happens when a live conductor falls on the ground (especially high tension cable). The ground acts as the neutral point, leading to short-circuiting and fire being the final consequence [17]. A series arc occurs when a single conductor is involved. For a loose connection, corroded and cut conductor, a series arc will occur when there is load on the conductor. This load will determine the amount of arc fault current in the conductor. Consequently, a conventional circuit breaker cannot mitigate this type of fault even when it is almost raising the entire building down in fire. Chemical reaction of insulating material, and environmental factors such as rodent damage to insulation, metallic object cutting through the line of cords can also cause parallel arc fault. In parallel arc fault, there is a returning path for the current flow, and therefore, the fault may be term short-circuit arcing. But due to the short time span of the fault current (in kA) and inconsistencies in the flow of the current, a typical conventional circuit breaker may not trip to isolate the faulty part from the healthy part of the system [6].

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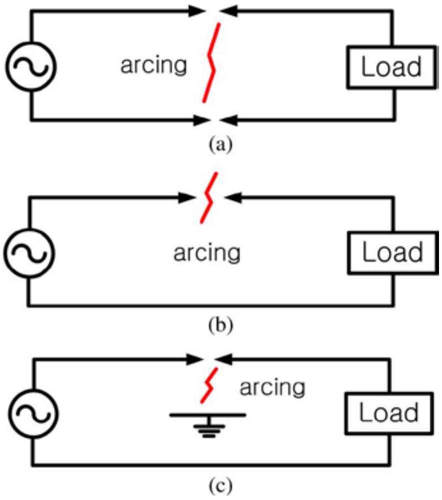

Figure 5: Types of arc fault circuits (a) line-to-line (parallel arc) (b) series arc (c) line-to-ground arc

4. Electrical Arcing

The definition presented by [17] is that arc is a continuous luminous discharge of electricity across an insulating medium and is typically accompanied by partial volatilization of electrodes. When electrons escape a gap producing a strong current with flash of visible light is called electrical arc. The total amount of current capable of sustaining an arc is called arc current while the voltage that exist in the gap during arc is referred to as arc voltage. One common event that happens when arc occurs is carbonization of electrical conductor insulation. Arc as a phenomenon is an unintentional occurrence without proper control, and invariably, exposing any combustible materials to fire hazard. An electric arc is a continuous luminous discharge of electric current having characterizing thermalized plasma and supported by thermionic emission from the cathode. Plasma in this sense means partial ionization of electrical neutral gas. When the plasma is hot, it is said to be thermalized plasma.

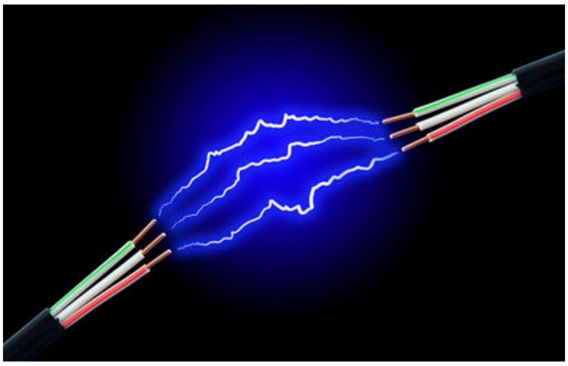
Figure 6: An arc as a visible plasma (www.scienceclarified.com)

An electrical arc is sustained and maintained between two metal conductors or electrodes with a sufficient voltage difference. [18] stated that in AC network, an arc will occur at two (2) multiply the power frequency. When a light arrester is installed with a gap in the conductor, there is possibility of arc explosion which may be capable of destroying the building on which it is installed. Therefore, it is imperative to carry out electrical wiring installation with great care and diligent. Arc is a physical phenomenon in which electrical energy is converted into heat energy.

Temperature and pressure of the surrounding of the conductor and insulation increases when arc energy is released due series and parallel arc fault. And this causes a thermal and mechanical stress to any equipments or material which could lead to serious fire hazard if persist [19]. The two gapped conductors must be operating at different potentials before arcing can occur. Arc is a situation in which there is a load on partially connected conductors. Several incidents that accompanies arcing include harmful light and sound, heating of any material in close contact, etc..

The damage that results from arcing is determined by its energy. [20] described a method for calculating the maximum arc energy in an electric circuit. This method can be used to access the arcing fault level that can cause damage. The product of the arc instantaneous current and voltage gives the arc power. The arc energy can be expressed as the integral of the arc power depending on duration of arc time.

$$E_{arc} = \int_0^T p_{arc} dt \quad \ldots\ldots\ldots\ldots 2$$

where p_{arc} is the three-phase arc power, E_{arc} is the arc energy, and T is the duration of time the arc exists.

Figure 7: AFCI with 30 mA Earth Leakage Protection [4]

[21] investigated arc in 240 Vrms and 120 Vrms series arcing faults in residential wires. Arc in 240 Vrms system tends to be higher than its counterpart 120 Vrms for the same diameter of cable and gap resistance. So, a higher arcing current gives a high temperature arc which can lead to increasing thermionic electron emission to an increase probability of breakdown after a current-zero crossing. This occurrence at current-zero crossing causes a voltage across the gap to rise with a likely ignition threat when the thermionic emission increases. Figure 8 is measure arc power for a series wire at 115 Vrms and 230 Vrms which validates the frequent occurrence of arcing in 230 Vrms often than its counterpart 120 Vrms.

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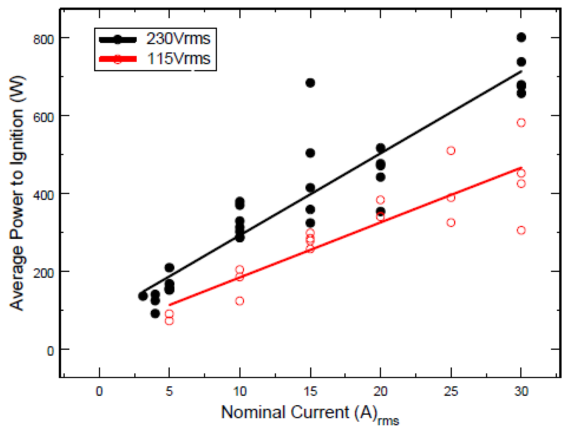

Figure 8: A measured arc power for a series wire at 115 Vrms and 230 Vrms [21].

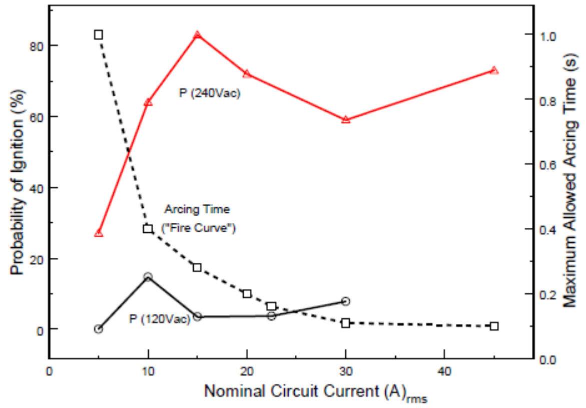

Figure 9: Underwriter Laboratory (UL1699) Fire Curve and Probability curves for ignition at 120 Vrms, and 240 Vrms with respect to the maximum allowed arcing current of the curve [21].

The report of three arc fault detectors products were reported by [7]. The product 1 is arc fault detector built to sense 100 mA fault current below and above rated 15 A overcurrent devices. For this device to operate normally, a delay is used instantaneously at the start of fault until the time if interruption of the fault and interruption occurs only if the fault continues. Product 2 is arc-fault detector that requires approximately 3 A above and below 20 A rated overcurrent device. The installation of this device is done in conjunction with the overcurrent device. Lastly, the product 3 is a arc-fault detector designed by [7]. The device has a direct arc detecting feature which will operate only when current is above the rated overcurrent device typically 20 A. This helps to avoid unnecessary tripping due to normal operational arc at load currents. The performance of these products is for different test is given in Table 2.

Table 2: Test results of products 1, 2 and 3. P is Pass, and F is Fail [7]

S/N	TEST	Product		
		1	2	3
1	Point contact arc (290 A)	P	P	P
2	Damped-motion contact arc (300/100 A)	F	P	P
3	Carbonized-path arc fault	F	F	P
4	Partial carbonized path arc fault	F	F	P
5	Wet-track arc fault	F	F	
6	Arc simulator number 1	P	F	
7	Arc simulator number 2	F	F	P
8	Series make/break contact arc: loose terminal	F	F	
9	Series make/break contact arc: broken wire	F	F	
10	Overheating conductor: Glowing contact	F	F	
11	Operation inhibit	F	F	
12	Unwanted tripping	F		F

5. Conclusion

Conventional circuit breakers can only protect overheating faults due to overloading and direct short circuiting. Arc fault that causes almost 50% of all electrical fire cannot be mitigated with the use of circuit breakers. Consequently, arc fault circuit interrupters with the use of today's technological sensors cannot be over-emphasized. To truly reduce the causes and effects of electrical fire, more and critical research will play a vital role. Taking the advantage of various sensors and semiconducting devices would be a great way out of the menace of electrical fire. In further publication, mathematical models of electric arc will be presented before carrying out analysis of an arc fault circuit breakers for residential applications

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