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Nature of Series-Arc Faults and Parameters Affecting the Risk of Domestic Electrical Fires

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Abstract: The main cause of electrical fires, which is more severe in nature than non-electrical fires, is the series-arc fault. In this paper, the properties of series-arc faults are studied and the parameters affecting the risk of domestic electrical fires are analysed. In particular, a series-arc fault generator, made to align with the international standards, is used to study the characteristics of series-arc faults in a domestic electrical installation. The waveforms of common domestic equipment, in the absence of a fault and in the presence of a fault, are examined in detail. It is seen that arc current waveform can be identified as having a vertical edge appearing after the zero-crossing point. Further, the impact of series-arc faults on igniting a fire in domestic electrical installations are analysed using thermal imaging. Finally, ability of the most commonly used insulation materials which may aid the initiation of electrical fires due to the series-arc faults has thermally categorized. The study has shown that even a 2A arc current that is sustained for 2s can auto-ignite PVC, the most common insulation material in domestic installations.

Keywords: Series-Arc, Electrical Fire, Low Current, Arc Fault, Prevention, Temperature Behaviour

1. Introduction

Throughout the journey of electricity in the world history, there is no doubt that electricity has made the world a much better place to live in. However, considering the whole journey, a number of hazardous occurrences can also be found. One such occurrence is electrical shock for living beings and another hazardous situation is the initiation of electric fires. Although there are plenty of protection devices to reduce the occurrence of an electric shock, protection devices, to prevent electrical fires because of electrical faults, are few. The root cause for many of such fires is arc faults generated in electrical installation. Further, due to the lack of proper maintenance and wrong practice, the risk for electrical fires due to arc faults in the domestic environment is significant.

Electrical fires are more uncontrollable in nature than non-electrical fires. According to the world fire statistics, around 20% - 40% of residential fires have an electrical fault as their origin [1, 2]. Arc faults are the main cause for such fires [3, 4]. They are of two types, namely, series-arc faults and parallel / shunt arc faults, as shown in Figure 1 [5].

In Figure 1, a plug top where occurrence of both a parallel-arc fault and a series-arc fault can be seen. Parallel arc fault occurs between live conductor and earth conductor, or live conductor and neutral conductor. However,

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the series-arc fault occurs within a current carrying conductor, disconnected due to a damaged or a loose connection [6].

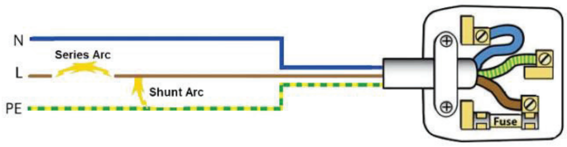

Figure 1 – Arc Faults in a Three-Core Cable

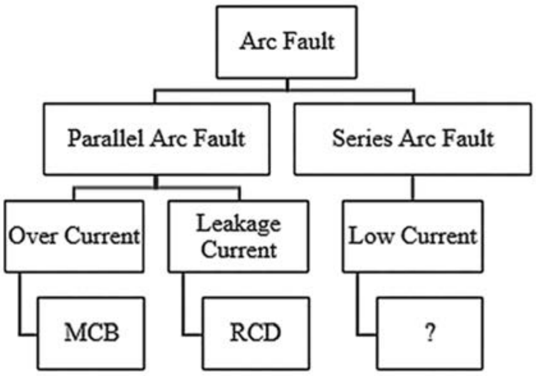

Figure 2 – Classification of Arc Faults

Parallel-arc faults can either occur due to over currents or due to heavy earth leakages, both of which can be detected by conventional protection devices such as MCB and RCD. as shown in Figure 2. However, in the case of series-arc faults, there will not be any significant overcurrent or any leakage current [7]. If the series-arc current lies below the rating of the MCB, which is usually the case, the MCB will not detect any overcurrent [7]. It is also not a leakage current, so that the RCD will not detect it either [2, 8]. Therefore, series-arc faults cannot be detected by the conventional protection devices. Thus, it is likely that the sustaining series-arc faults, which are low current faults, and would be the main cause for electrical fires in domestic installations [9]. These faults can occur inside an appliance, at entry to the socket outlet, in the inside of the connection of a socket outlet or inside conduit pipes carrying the wires [6].

When a series-arc fault occurs, radio frequency emission, infrared radiation, acoustic signals (audible sound) and deformation of current and voltage signals can be seen as the main physical features [2,10]. Out of the above parameters, the deformation of current and voltage signals produces significant results. These deformations may badly influence the electrical appliances. Because of the power quality reduction, it may affect the proper operation of some sensitive equipment as well. Much research is done to observe the behavior of series-arc faults ([11] [12] [13] [14]). However, distinguishing the series-arc fault and its identification is also challenging because some domestic appliances show some features which, even in their normal operation, are somewhat similar to series-arc fault features.

An arc, as an isolated incidence, is unable to ignite a fire without the support of the surrounding environment. Therefore, to ignite a fire due to an arc, the characteristics of the arc fault and the parameters of the environment that the arc is present in, are also important. Several research results show that the arc temperature may vary from several hundred degree Celsius to several thousand degree Celsius [6, 8]. So, when considering the fire risk due to series-arc faults, the temperature behaviour of the arc fault plays a major role. When the arc temperature rises above the auto-ignition temperature of materials, the risk of fire rapidly increases.

This paper focuses on both the nature of the series-arc fault and the parameters that affect an electrical fire in the domestic environment.

2. Series-Arc Fault Generator

The series-arc fault generator shown in Figure 3 has been developed as a simple and safe method of generating series-arc faults needed to study the characteristics and the behaviour according to the IEC 62606 standard [15]. A carbon electrode and a copper electrode, with one electrode pointed and the other flat, are used for creating a sustaining arc fault and to avoid melting and welding of electrodes. One electrode is fixed to a movable arm in order to control the distance between the electrodes, while the other electrode is fixed. The movable arm is moved with the help of a screw while a compressing spring smoothens the movements during arc formation and extinction. Wood and PVC, used as insulation materials, help to keep the insulation resistance always greater than 6MΩ, helps to ensure the operator safety. Figure 4 shows step by step (from bottom to top) ignition of series-arc fault, sustaining it and extinguishing.

Normal domestic electrical supply 230V, 50Hz is used as the power source. At the initial stage, the electrodes are touching together and the current is allowed to pass through it. Then, one electrode starts to move away slowly, using a screw, to create the series-arc fault. As the contacts separate, the series-arc fault is initiated. With further seperation of electrodes, the series-arc starts to grow longer by rapidly ionizing the surrounding air. A 5A current in the arc fault is capable of completing the path between the electrodes and keep the current sustained even beyond a 15 mm electrode seperation distance.

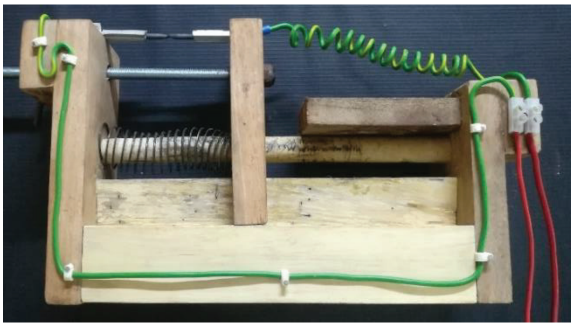

Figure 3 - Series-Arc Fault Generator

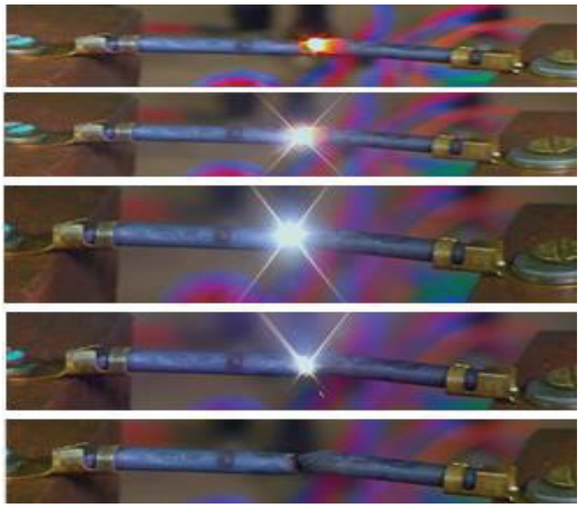

Figure 4 - Ignition, Sustaining and Extinguishing of Series-Arc Fault

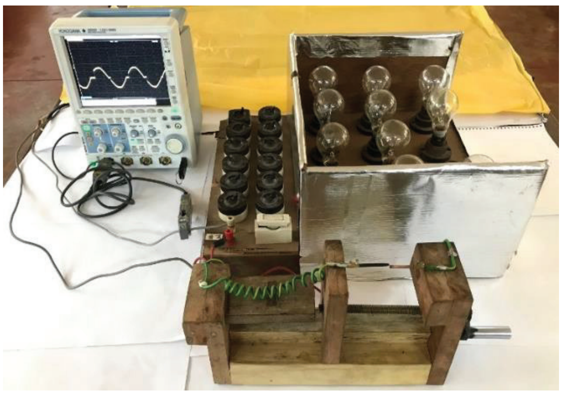

Figure 5 - Laboratory Setup used for Data Collection

2.1 Data Collection

Figure 5 shows the laboratory set up and Figure 6 shows the graphical representation of the arrangement used to collect the real-world data from various loads. The series-arc fault generator is connected in series with the 230V, 50Hz AC power supply and the load.

Using a digital oscilloscope, the arc current and the non-arc current, and the voltage waveforms were saved as data files.

Throughout the data collection period, the environmental conditions (temperature, pressure, distance between the two electrodes) were kept as constant as possible. In order to keep the distance between the two electrodes constant, the following methodology is followed. Initially the electrodes are touched and current supply is given. Then, the moving electrode is seperated by rotating the screw by 'one cycle', where the distance between the electrodes is 1 mm.

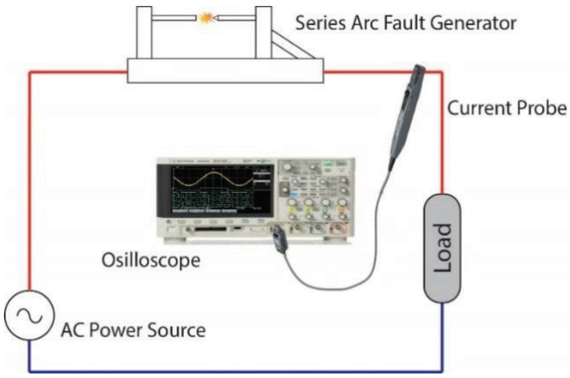

Figure 6 – Circuit Diagram of the Laboratory Setup Used for Data Collection

2.2 Voltage Waveform and Current Waveform Behaviour of Series-Arc Fault

Figure 7 shows the series-arc fault current waveforms and voltage waveforms of a set of incandescent bulbs obtained using the laboratory setup. The deformations occurring in the waveforms in the presence of a series-arc fault can be seen. These characteristics compare very well with those of Nasser [16].

When observing the current waveform, it can be seen that, almost in every half cycle, a vertical edge appears within the first quarter cycle period in sinusoidal wave, after a zero-crossing point [17]. This vertical edge occurs at the instance when the air breaks down between the two electrodes. Until that breakdown occurs, the magnitude of the current remains zero after the zero-crossing point. The reason is, until the voltage reaches the breakdown point, the circuit cannot get completed through the air gap between the two conductors. After that vertical edge, the current waveform will follow its normal sinusoidal path until it reaches the next zero-crossing point.

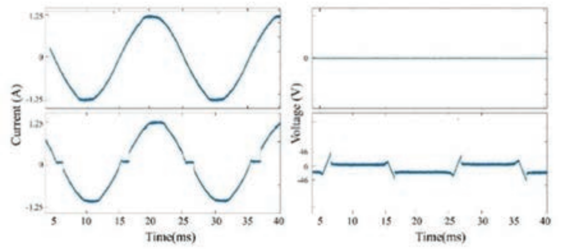

Figure 7 - Current and Voltage Waveforms of an Incandescent Bulb Load in the Absence and Presence of Series-Arc Fault

Considering the voltage waveform, just after the zero-crossing point, the voltage starts to align with the normal sinusoidal waveform between two electrodes, because it is moreover like an open circuit. After the voltage passes the air breakdown point, the two electrodes are connected through an ionized air path. Therefore, the voltage between the two electrodes reduce to near zero value. It does not come to zero because the ionized path through the air offers some amount of resistance. Both these current and voltage behaviours repeat every half cycle. There is another important feature to be noticed. That is, the nature of the vertical edge and other characteristics of the waveforms, tend to change every half cycle. In other words, it is very hard to find two identical cycles during the arc fault period.

When the current through the series-arc and the time of existence increased, the series-arc fault will start to stabilize between the two electodes. The vertical edge of the current waveform starts to vanish and it is hard to identify with the naked eye when the arc gets stable. The reason for this behavior is that the high current arc is creating a very thick plasma beam between the two conductors and it contains a very high amount of ionized air molicules. Also, when the arc sustaining time is increasing, the plasma beam becomes more stable and reaches thermal equilibrium. Therefore, insulation properties of the air are no longer effective to isolate the two conductors. The stable plasma beam will act as a conductive path.

Also, the deformation in the voltage waveform tries to attenuate with the distance from the arc origin, and it does not make a considerable change to the complete circuit. Therefore, further analysis has been focused on the behaviour of the current waveform.

3. Arc and Non-Arc Current Waveforms Analysis

3.1 Electrode Material Verification of Arc Fault Generator

When using carbon and copper as electrodes, the generation and sustaining of the arc fault is easy, because electrodes are not trying to melt and stick together. However, in the real world, most of the low voltage conductors are made out of either copper or aluminium. So, a test was carried out to find out, whether the series-arc current waveform characteristics strongly depend on the material of electrodes. One set of series-arc current waveforms is given in Figure 8 that has been collected from the laboratory arrangement. The test results justify that, there is no significant characteristic difference.

- C : Carbon Electrode
- Cu : Copper Electrode
- Al : Aluminium Electrode

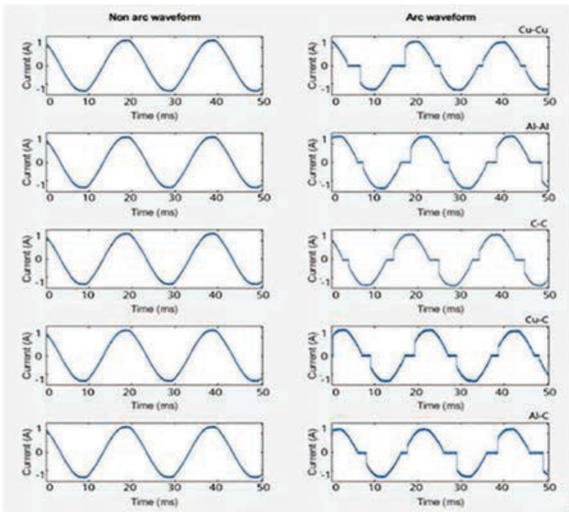

Figure 8 - Arc and Non-Arc Current Waveforms Obtained Using Different Electrodes

3.2 Analysis of Current Waveforms of Domestic Equipment

The study has shown that the domestic equipment current waveforms change from equipment to equipment as shown in Figure 9. The reason for this is that the domestic equipments are not ideal resistive, inductive or capacitive loads. They contain RCL circuits and even non-linear electronic components. Thus, the behavior of the arc current waveform changes depend on their oscillation characteristics [10, 18, 19].

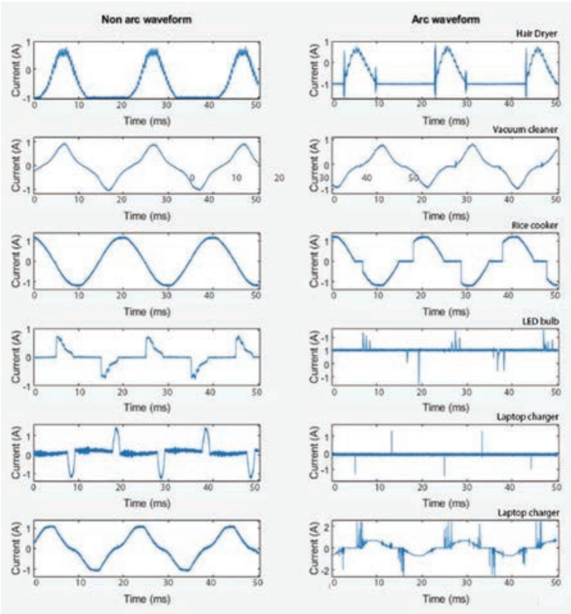

Figure 9 - Arc and Non-Arc Current Waveforms of Domestic Equipment

4. Temperature Variation and Fire Risk Analysis

It is clear that, when a series-arc fault is created, a plasma beam appears by connecting two electrodes through the air. That plasma beam contains a high amount of ionized air molecules and a considerable resistance through it. When a current is carried through the plasma, the I^2R (I = Current (A), R = Resistance (Ω)) loss creates heat that is used to ionize more air molecules. The rest of the heat dissipates to the surrounding environment. When an arc gets saturated, most of the heat created inside the beam is emitted to the surrounding environment, because further ionization of the air molecules is minimum.

The Series-arc fault, on its own, does not contain any igniting materials. So, it is obvious that an arc fault alone cannot ignite a fire. The reason for a subsequent fire is due to the arc causing ignition of the surrounding materials [20]. Therefore, three main parameters can be identified that directly affect to ignite a fire in residential installations:

- Amplitude of current that flows through the series-arc fault
- Series-arc fault sustaining time period
- Ignition and auto ignition temperature of the surrounding materials

4.1 Temperature Data Collection of Series-arc Fault

The thermal properties of the series arc fault were investigated using a thermal imaging camera. The electrode arrangement and the corresponding thermal image is as shown in Figure 10. Throughout the data collection, the distance with the thermal imaging camera and the series-arc fault is kept constant. Also, other environmental factors like room temperature and wind flow were also kept constant as much as possible. Because the properties of the series-arc fault are varying with time, to get a single temperature reading, the average of three readings was taken as the final temperature value.

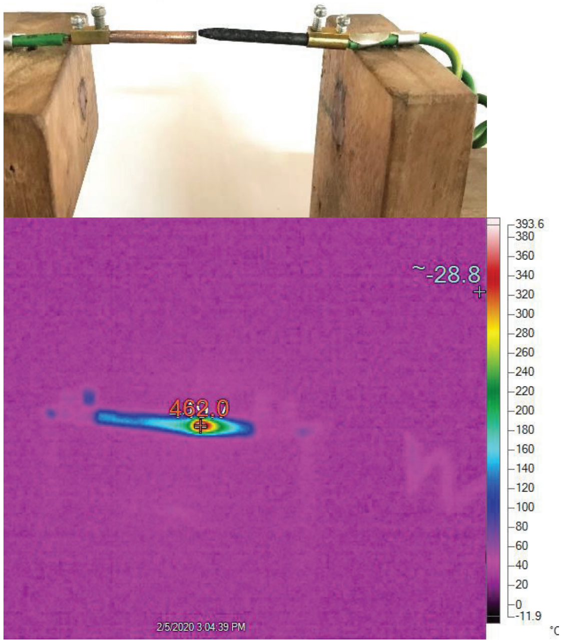

Figure 10 - Thermal Image of Series-Arc Fault with 1.5 A Current Using a Carbon Electrode and a Copper Electrode with 2 s Period

Moreover, after getting any temperature reading, a duration of five minutes was allowed to cool down the electrodes back to the room temperature. This was necessary to ensure the independence of temperature readings from each other.

Figure 10 and Figure 11 show the thermal data collection of a series-arc fault. When analysing the thermal image, it can be clearly observed that, at the point of arc fault generation (plasma), the peak temperature point occurred. From the middle point of the plasma to the outer environment, the temperature gradient rapidly decreased. Even though two seconds seem a short time period, a copper electrode is capable of conducting heat to a considerable distance and increase the temperature beyond 150 degrees of Celsius. Carbon electrode is not that capable of heat transfer because it is not a good thermal conductive material. As a result of the poor thermal conductivity of the carbon (graphite) electrodes, tip becomes red hot just after the arc fault. Further, with time, due to the high temperature of the arc fault, the carbon electrode starts to decay, resulting in a slight increase of the distance between the electrodes. Hence, the readings are taken as soon as possible after the arc initiation.

In Figure 11, the image shows the placement of thermal image camera and the series-arc fault generator for thermal image data collection.

Figure 11 - Physical Arrangement for Thermal Imaging

4.2 Variation of Arc Fault Temperature with Arc Current Magnitude

An experiment was conducted to study the relationship between the series-arc current magnitude with the temperature of the arc fault. An incandescent bulb load, together with a few resistors, was used as the load. Thermal images were taken directly on the arc fault to get the temperature of the arc. The arc current was increased from 0.25 A until 4.5 A in 0.25 A steps. Thermal images were taken after 2 s of the arc initiation.

Figure 12 shows the average and highest temperatures obtained from the experiment. Observing the results from the experiment, it is clear that series-arc fault temperature increases with the current through the arc fault by following a near linear relationship. The melting point of the copper is around 1100 degree Celsius. According to the increasing trend of the temperature in Figure 12, series-arc faults with a current greater than 5A are capable of melting down copper conductors.

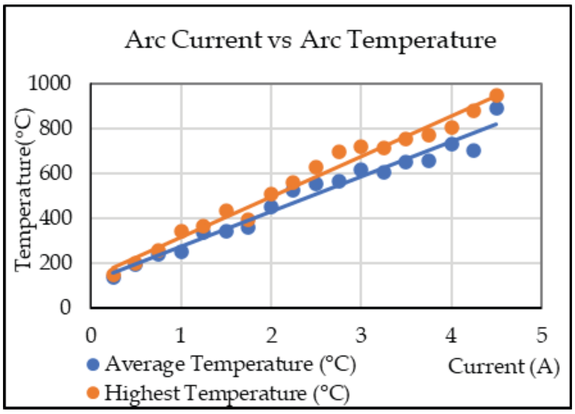

Figure 12 – Variation of Arc Temperature with Arc Current

4.3 Variation of Arc Fault Temperature with Arc Sustaining Time Period

An experiment was conducted to find out the relationship between the arc sustaining period and arc temperature. Arc sustaining time was increased by 1 s a step for a 1 A current and the temperature reading taken using the thermal camera. The series-arc fault current was kept constant all the time. Results in Figure 13 show that there is a non-linear relationship between the arc temperature and sustaining time period. The reason for this is that with time, series-arc fault becomes saturated between the electrodes. It means that the plasma beam created by the arc fault reaches thermal equilibrium. When the heat created by the I^2R loss is more or less equal to the heat dissipated to the surrounding materials, there will no longer be a temperature increment in the plasma. Furthermore, the saturation temperature also will change with the arc current.

4.4 Auto Ignition Temperature of Insulation Materials

The auto-ignition temperature of some common materials, normally insulating, which may be found in the home environment close to electrical circuits, is shown in Table 1 together with the auto ignition temperature. The auto ignition temperature is the temperature at which that material starts to ignite by itself without contacting with fire from the outside environment. It is seen that the autoignition temperature of common materials in the home is in the range of 200 to 450^{0}C, rarely exceeding

500^0C. Table 1 gives the auto ignition temperatures of some materials that commonly contact with current carrying conductors [21].

Table 1 - Auto Ignition Temperatures of Insulation Materials

Substance	Auto Ignition Temperature
PVC	450^{o}C
Paper	230^{o}C
Wood	250^{o}C
Polyethylene	330^{o}C
Rubber	260^{o}C
Leather	200^{o}C
Cotton	250^{o}C

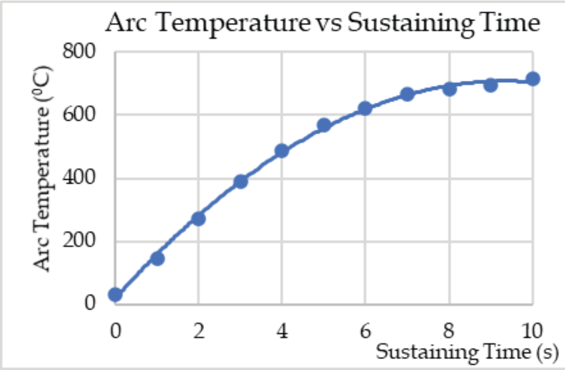

Figure 13 -Variation of Arc Temperature with Arc Sustaining Time Period

So, considering all the three parameters that can be used to analyse the risk of fire due to series-arc fault, it is clear that a 2 A arc that is sustaining for 2 s is more than enough to ignite a fire in the domestic environment. Also, a 1 A current series-arc fault sustaining for more than 4 s can also create a very high fire risk. That is, a 2 A arc sustaining for 2 s and 1 A arc sustaining for 4 s can increase the temperature of nearby insulation materials (wood, PVC) to their auto ignition temperatures. Therefore, even without touching the nearby insulation materials, series-arcs can ignite them within seconds. Furthermore, in most of the occasions, the insulation materials such as PVC and wood are installed touching the conductor. Since the flash points of PVC and wood are much lower than their auto ignition temperatures, the fire risk in such occasions is even greater.

5. Conclusions

Series-arc faults play a major role in creating domestic electrical fires. The most common protection devices such as MCB and RCD are not capable of detecting series-arc faults. To address this issue, this paper presented the studies of the characteristics of series-arc faults. The study showed that the most effective method to detect series-arc faults is to study the characteristics of the current waveform. However, the properties of the current waveform of a series-arc fault are unpredictable as they vary with time and from equipment to equipment. However, the main deformation in the current waveform can be identified as a vertical edge appearing after the zero-crossing point. Moreover, there are mainly three parameters affecting the risk of domestic electrical fires, which are presented in this paper using thermal imaging of series-arc faults. The results of the analysis show that 1) there is a near linear relationship between the arc current and arc temperature, 2) there is a non-linear relationship between the arc sustaining time period and the arc temperature, and 3) even a 2 A arc current that sustains for 2s can auto-ignite PVC, the most common insulation material in domestic installations. Although, in most of the domestic electrical installation protection systems, the detection of the series-arc faults is not addressed, to date, there is an immense risk of creating electrical fires by series-arc faults. Therefore, addressing this issue is a crucial task, in order to reduce the electrical fires in domestic installations.

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