

B1 INSULATED CABLES

Preferential Subject 3: OPERATION OF MIXED AC/DC SYSTEMS AND HVDC NETWORKS

Experiment design to study ignition and fire behaviour of components in LVAC and LVDC enclosures and plastic pillars

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SUMMARY

Electrical fires and arc flash events are considered to be one of the main hazards to the public in the low voltage network. Furthermore, the intensity of these events are anticipated to be higher as the AC network develops into a hybrid of AC and DC networks, because of the higher intensity of DC fault currents.

Electricity customers in New Zealand are commonly connected to underground LV reticulation network via a service fuse inside an LV enclosure, typically situated at the boundary of the road and the property. These are also known as an LV pillar in New Zealand, and as a Public Electricity Network Distribution Assembly (PENDA) internationally. Every year, a small percentage (estimated at < 0.1 % of the number pillars on the network) of this asset type may catch fire following an internal component failure, a so called “pillar fire”.

Pillar fires can be a significant hazard to people, property, and reputation due to the high number of assets in this fleet and their proximity to residential and busy urban areas. Understanding how overheating of connections can lead to such a fire are foundational to control this risk.

The contribution of this paper is reporting on the design of an experimental setup to understand how hot connections at a fuse progresses to pillar fires and arc flash events. These experiments are intended to form the basis for standardised tests for plastic pillars (PENDA’s) both LVAC currently in use, and the response of this process if these same plastic pillars would be used in networks operated at LVDC.

KEYWORDS

Low Voltage, Plastic, Pillar, Enclosure, Fuse, Insulated Cable, Micro-Arcing, Fire, Experiments and Testing

1 Introduction

Low-voltage pillars are a prominent feature in LV distribution networks in New Zealand and Australia. These are enclosed structures designed to safely house the electrical fuse(s) connecting customer's electrical installation to the network. These are typically located at the boundary between the property and the road, see Figures 1, 2 and 3 below.

Customers are generally connected to an underground low-voltage reticulation network via a service fuse. The fuse can be housed inside the residence or within enclosures located at the boundary between the road and the property, as per figure 4. Most LV cable and fuse failures (as shown in Figure 1, middle and right) in pillars are a nuisance to the customer, without causing damage to either the enclosure or third-party property.

However, a small percentage (estimated at $< 0.1\%$) of this asset type catches fire following an internal component failure, a so called "pillar fire", see figure 2 for several examples [1]. Such pillar fires can be a significant hazard to people, property and reputation. Furthermore, as a widespread feature in the public space, the combined risks to public safety, distribution infrastructure, and nearby property can be significant.

As a comparison, the prevalence of electrical fires in residences are a notable cause of harm in the community, with 24,200 reported cases in the USA in 2020. Recent NFPA statistics indicate that electrical fires resulted in 430 civilian deaths, 1,070 injuries, and US\$1.3 billion in property damage annually from 2015-2019 [2]. 85,000 cases were reported in China in 2019 [3], [4]. The Fire Services Department of Hong Kong reported a 43% increase in residential fire incidences between 2008 and 2010 [5] Fire Services Department 2008, 2010]. These statistics highlight the impact electric fires have on the community at global scale extending beyond this New Zealand research case.



Figure 1 – Example of a plastic pillar on fire at different stage, from start to end (left) and two other pillars on fire and the remains after fire (Reproduced from [6])



Figure 2 – Example of fuses mounted inside a pillar (left), a fuse base with fuse holder pulled out (middle), a burnt-up fuse base and fuse, with electrical wire with insulation burnt off (right) (Reproduced from –[6])



Figure 3 – Examples of plastic pillars commonly installed on the LV underground network in New Zealand (Reproduced from [1])

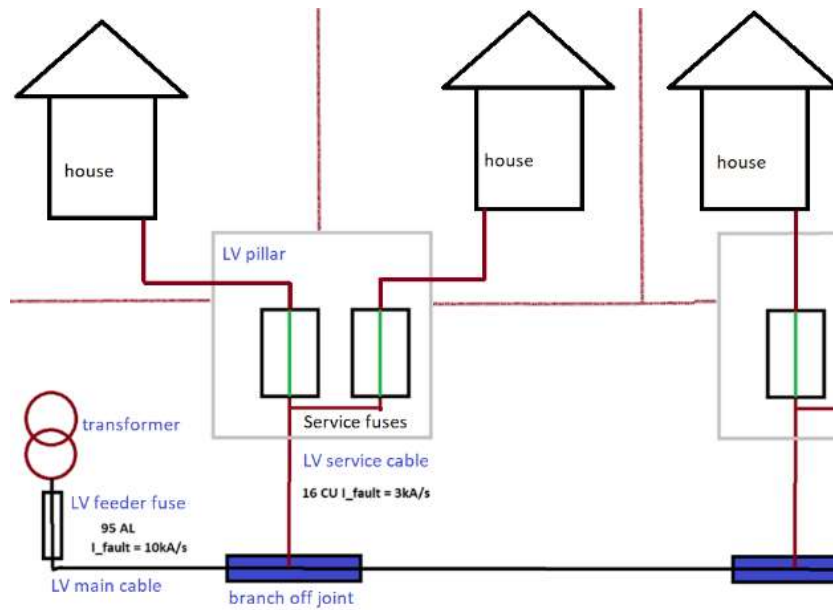


Figure 4 – Typical underground LV reticulation network in New Zealand (Reproduced from [1])

2 Background

Loose connections and arcing are the primary contributing factors to electrical fires in residences in the USA according to [5], see Table 1 below. Loose connections that have turned into hot connections can be detected by the changes in voltage across the connection due to the dynamic arc behaviour. Such dynamic behaviour has also been detected at customer connections. These are well suited for online detection [1], [Albany, 2024], and we believe are well suited to investigate the process of failure to fire.

Individual components in LV pillars, such as fuse holders and their bases, are required not to ignite (e.g. ‘turn to powder’ as seen in Figure 6 below) [7]. These requirements typically do not apply to the LV mains cable, nor the housing [8]. However, hot connections on fuses are suspected to be the main ignition sources [6].

Measurement data of voltages and currents can support analysing and identifying common ignition

patterns and failure characteristics in this type of LV pillars. The symptoms under investigation are the characteristics of the associated voltage- and current waveforms, the internal and external temperature and gas development within the low-voltage pillars. The experiment designs reported in this paper are intended to be used to both 1) develop both perform abnormal heat tests on LV assemblies and 2) enables diagnostic methods to be developed or improved for detecting issues that could lead to pillar fires.

Several of the cases of pillar fires presented in [1] will be discussed in this paper, including inspection photos of deteriorated connections between cable and fuse holder. The observations of hot connections as listed in [5] are very similar to the physical symptoms we have observed in damaged fuses in pillars [1], [6]

The experiments and tests we propose are intended to emulate real-world conditions, to provide insight into the ignition characteristics and fire behaviour of LV enclosures as a unit. that will show the process of failure to fire and the role of corrosion and loose connections, see figure 5 below. In particular, we believe LV pillars should be considered as a unified piece of equipment, and therefore testing should be performed on the LV pillar as a complete unit rather than the abnormal heat tests performed on individual components, such as the fuse [7]. This paper describes the tests that we believe are necessary to ensure reduction of fire.

Table 1 Physical Mechanisms causing electrical fires in residences in the USA [5]

Mechanism	Importance
poor connections	most ↓ least
arcing across a carbonized path	
arcing in air	
excessive thermal insulation	
overload	
ejection of hot particles	
dielectric breakdown in solid or liquid insulators	
miscellaneous phenomena	

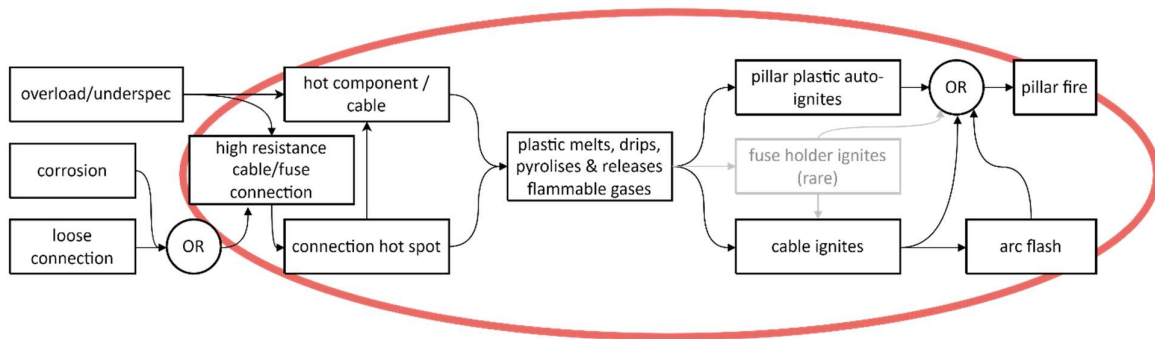


Figure 5 – The working hypothesis of progression from defective component to pillar fire (Reproduced from [1])

3 Symptoms of overheated fuses and wires from inspections

symptoms of overheating due to a 'hot connection' in residential fires include, among others, A) melted and deformed plastic, B) signs of pyrolysis (incomplete combustion) such as blackening, soot and brittle of the cable insulation & fuse holder, and C) signs of high temperature corrosion. These processes of hot and glowing connections have been experimentally studied by [9], [10], [11], [12], [13], [5] and [14].

For instance, the flame behaviour of polyethylene (PE) of pillar housing (being LDPE), and PE insulation of wire respectively are presented in [15], [16], and [17]. PVC pyrolysis described by [18],

[19] and [3]. The flame behaviour of the pillar housing material was confirmed to match flame behaviour of PE [16].

Inspection photos of fuses in pillars installed and in operation in the network show the damage that hot connections can cause to the fuse holder, the connected cables and the pillar housing [1]. The observations from inspections and fault reports match the observations from decomposition and fire behaviour of PVC and PE discussed before.

In previous investigations the fuse holders show signs of extensive damage, such as turning to soot, suggesting that these do not catch on fire. The photo in Figure 6 show an example of the effect of a hot connection (presumably) on the fuse holder and the PVC insulated wire, and the PE housing also showing signs of heat damage.



Figure 6 – Signs of pyrolysis (incomplete combustion) such as blackening, soot and brittle of the cable insulation. Also note the damage to the fuse holder and the connector nut and screw. [1]

4 Proposed Experimental Setup

4.1 Requirements on The Proposed Experiment: Environment and Outputs

The proposed experimental set up is intended to help investigate the process from loose connection to fire, following on from previous experiments on flammability of pillar housing materials [16]. The tests are intended to show whether the fire starts at the ignition of the (PVC) insulation of the cable, the PE housing, or the fuse holder, or a combination of these.

The experiments performed by [3], [11], [17], and [20] included gathering ignition characteristics while collecting data about voltage, current, temperature and gas development. These experiments served as examples and a basis of the experiments we propose. From our experiment(s) we hope to understand boundary conditions of deterioration between fire and high resistance without fire, as well as record typical voltage fluctuations associated with deteriorated fuse connections. Since the DC distribution network is fully in development across the world, we intend to repeat the experiments in AC as well as DC.

The parameters of interest are: time to ignition, ignited materials, conductor size, current level, movement of the connection, tightness of the connection, vicinity of hot connection to flammable materials, type of fuse holder, conductor and connector materials, and AC or DC current. The contact force between connector and conductor also influences the formation of a glowing contact.

4.2 Arc Voltage and Current Characteristics

The arc voltage is the voltage across the arc terminals, and it is proportional to the arc length. The length of the arc affects its stability, as arcs with lower voltages and currents require a smaller separation gap [10]. If the arc voltage is relatively high compared to the source voltage, which usually occurs during

an LV fault, the shape of the arc current will be deformed, distorted and unstable. Additionally, the behaviour of an LV fault can be intermittent where short periods of arcing alternating with periods of shorter or longer durations with no arcing [21]. Thus, the arc duration periods are indicators of the characteristics, behaviour and of severity of the arcing defect.

4.3 Conductor cross-section and arc current level

The time to ignition of PVC insulation depends on the current passing through an arc, as well as the cable conductor cross-section. Once a self-sustaining glowing contact has formed, within a short period, that glowing contact can ignite with air and start a fire. The associated changes in voltage and current during the overheating, ignition and burnout phases are shown in Figure 11. The parameters of voltage and current are significant factors in arcing and subsequent igniting of materials is apparent [11], [22].

The typical size cables in NZ into a pillar are 16mm² to 32mm² Cu, typically fused at 63A for residences. Experiments on PVC insulated copper wires with conductor sizes of 2.5mm², 4mm² and 6mm² wire cross-section, with an (overload) current up to 32.5 A for largest cross-section were performed by [22]. The results from this study aligned with a finding from [11] where the current was the most significant factor that determined the number of make/break operations needed for a glowing contact or charred insulation. A larger current lead to a higher likelihood that the wire will create a glowing contact or result in charred insulation. The heat distribution in a hot connection and copper wire was described and modelled by [3]. See the thesis for more details [23].

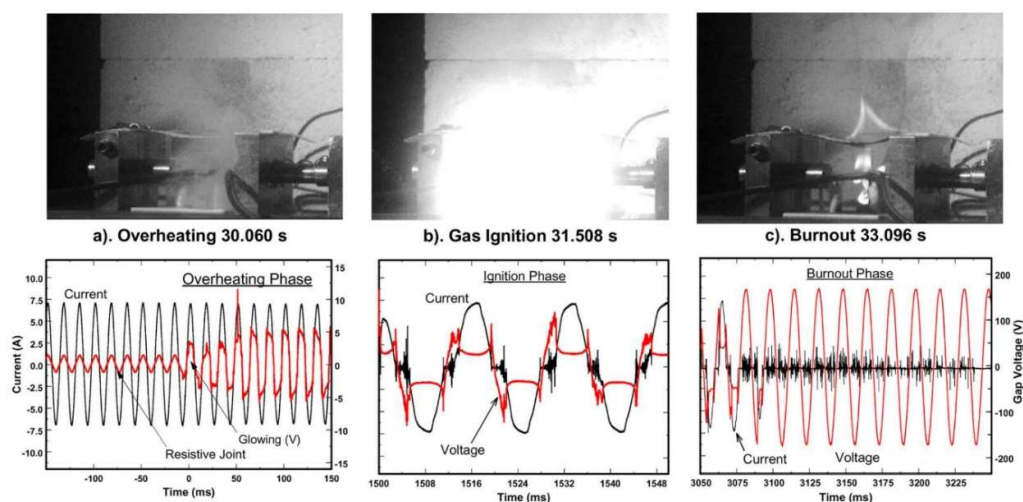


Figure 7 –Three stages of fire development from glowing contact to fire (Reproduced from [11])

4.4 Time to ignition and ignited materials

Voltage measurements on a deteriorating connection before a pillar fire indicates that such poor connections can be in place for weeks before a final break-down and fire occurs [1]. The fuse holder is not ruled out as a source of ignition, since the time until ignition may be longer than assumed in the standards, as these are tested for fire resistance by, for instance, the direct method [24] or indirect method [25] as shown in Figure 8. With these methods the sample is heated by flame or with a glow wire element, which are removed within a pre-set time, reflecting a temporary heat source. After these are removed, the sample either must not have ignited, or the flame is to extinguish within a preset time to pass the test.

Furthermore, the glow wire experiments on the PE housing material showed that the PE housing typically does not ignite when subjected to the short duration of glow wire test as per [25] and [16]. Therefore, the experiment includes longer duration tests to study the time to ignition of the components.

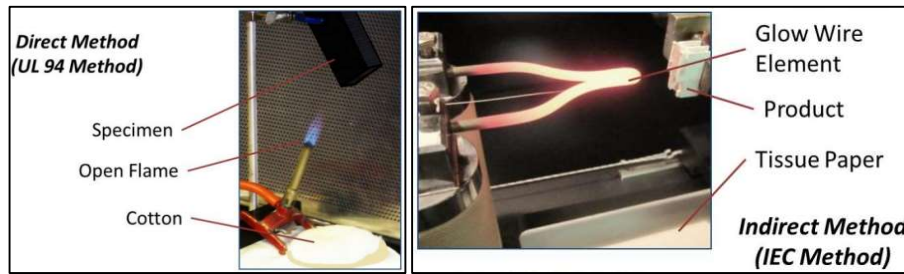


Figure 8 – Direct Method [24] (left) and Indirect Method – the glow-wire tests [25] (right) tests the specimen for ignition time by the heat from a temporary overheating component, (Reproduced from [16])

4.5 Breaking Current Arc Generator

Vibration from motor vehicles and impacts on the pillar housing may cause the connection to loosen. Vibration from traffic can be emulated by a shaker such as the example in Figure 13. Accurate and reliable arc generation depends on the selection of the correct mechanical movement between electrodes.

Three types of arc generators mechanically moving electrodes are commonly employed: 1) Vertical [26], 2) Horizontal [27], and 3) Vibration [28].

Various shaking set ups are anticipated to be tried during the experiments.

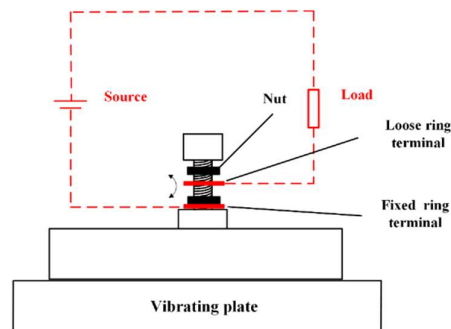


Figure 9 - Shaker Table-Based Arc Generator [29]

4.6 Gases Developed from Decomposing Polymeric Materials

The gases developed as the plastics decompose are both part of the ignition process, as well as an indicator of the processes that are occurring. Monitoring the mix of gases will help us understand the decomposition process, and thus the process of arcing to fire. Furthermore, the internal atmosphere within the LV pillars in New Zealand undergo large swings in temperature and humidity, often fully saturated, condensing air [1].

Being able to control the gas environment and measure the pressure allows for a more accurate simulation of real-life arc conditions, which aids in studying the ignition process by measuring the gas composition during the experiments. An arc chamber will allow us to control the environment and its change, to match the real-world internal atmospheric conditions of LV pillars.

The arc chamber employed by [26] was designed to replicate the arc chamber of a compact industrial circuit breaker. It enabled precise manipulation of several parameters such as contact materials, polarity contact opening speed, opening time, contact force, arc position, pressure, and wall material. An important feature of this arc chamber was the control of its internal gas via ventilation holes allowed for gas to exhaust on one end of the chamber. The chamber was also accompanied by a piezoelectric pressure transducer that measures the (change in) chamber pressure during the test.

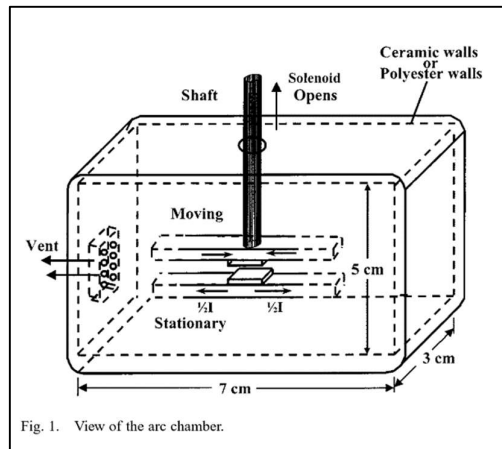


Figure 10 – Arc Chamber Experimental Setup [26, p. 1]

4.7 Conceptual Experiment Set-up with Design and Inspection Methodology

Figure 15 depicts the conceptual experimental setup. We intend to perform these experiments under both AC and DC power sources to understand the impact of the voltage. The DC voltage will be an equivalent value to compare to 230V AC. We plan to perform the tests on various commonly used fuse holder types and brands, fitted with the typical 63A fuse. Both connections of (e.g. bottom and top) of the fuse holders will be tested separately as the hot connection.

The main challenge in the experimental setup is creating corrosion and/or loose connections that can be consistently reproducible, with practical examples to protect equipment in [30]. [Utt, 2010] outlines practical inspection and autopsy methods to study the characteristics and behaviour of the electrical fires.

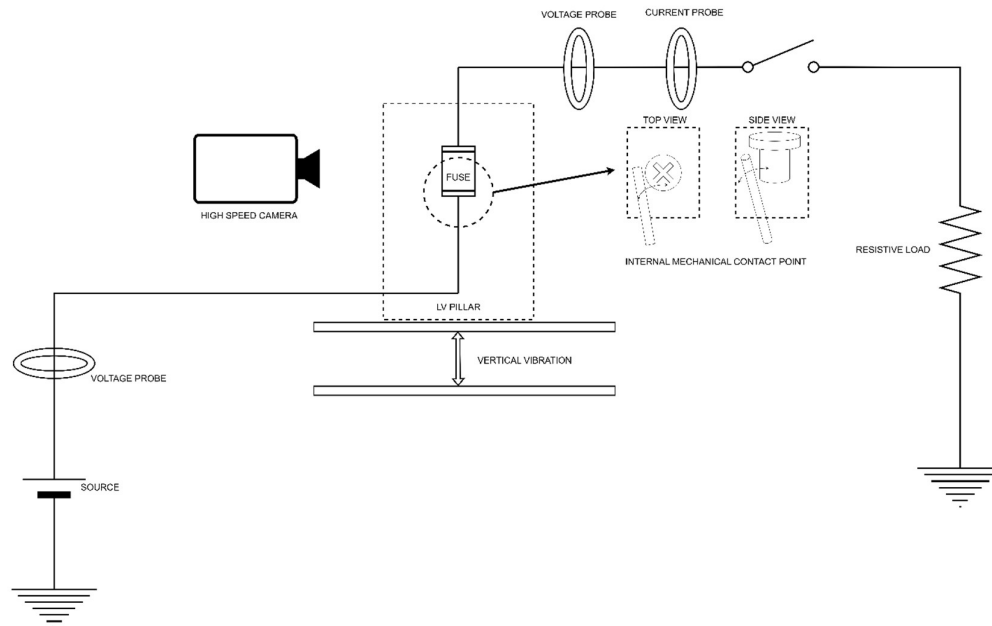


Figure 11 - Conceptual Setup of Experiments, See Text for Description

Table 2 - Equipment and components to be employed in the experiment set-up

Usage or Comment	Equipment Type
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230V +/- 6% at 50Hz [AS/NZS 3112] and [IEC 60038].	AC power source
325V DC Equivalent Voltage	DC power source
Voltage and current probes	Measurement devices
The shaker arc generating unit is positioned on the sample holder of the shaker head	Arc Generation (see example in [29], Figure 13)
Measures temperature, humidity and air pressure	Environmental sensors (see example in [31])
Record the heating and ignition processes.	Monitoring Instruments: High-speed cameras, gas detectors, infrared cameras and thermal sensors
Various lengths of cable are employed as an inductive load and a waveguide for high-frequency signal propagation and time delay.	Inductive Load
Simulate customer load conditions and control arc current	Resistive Load
Captures instantaneous voltage, current, and power. are employed to capture instantaneous, maximum, and minimum values	Digital Multi-channel Oscilloscope

4.8 Expected Outcomes

The anticipated results of this research are empirical results to both alternating current (AC) and direct current (DC) scenarios, progressing our understanding of the processes that lead to defects and pillar fires through improved understanding of plastic decomposition in pillars, low voltage arcing and the duration until ignition in electrical fires. These results should enable us to improve the design of the pillars to prevent fires, as well as collect data on fault currents and voltages to enable detection of incipient faults, and thus enable proactive repairs.

5 Conclusions and Future Work

LV pillars should be considered as a complete piece of equipment and therefore be type tested as an entire unit, including the combination of fuses, fuse holders, cable type (PVC/wire size), configuration etc. This paper describes the tests that we believe are necessary to ensure reduction of fire.

We claim that the suite of tests and design of plastic LV pillars as a whole are inappropriate for the environment and the system in which it operates, and therefore should be amended for LVAC.

Since LVDC arc and fault currents are a more severe load due to the lack of arc extinguishing during zero-crossings, a rigorous re-design and test regime is needed to produce equipment suitable for the future hybrid ACDC network to prevent an increase in fires as has been observed in solar panel and battery installations.

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