Status of the use of arc fault detection devices in Norway

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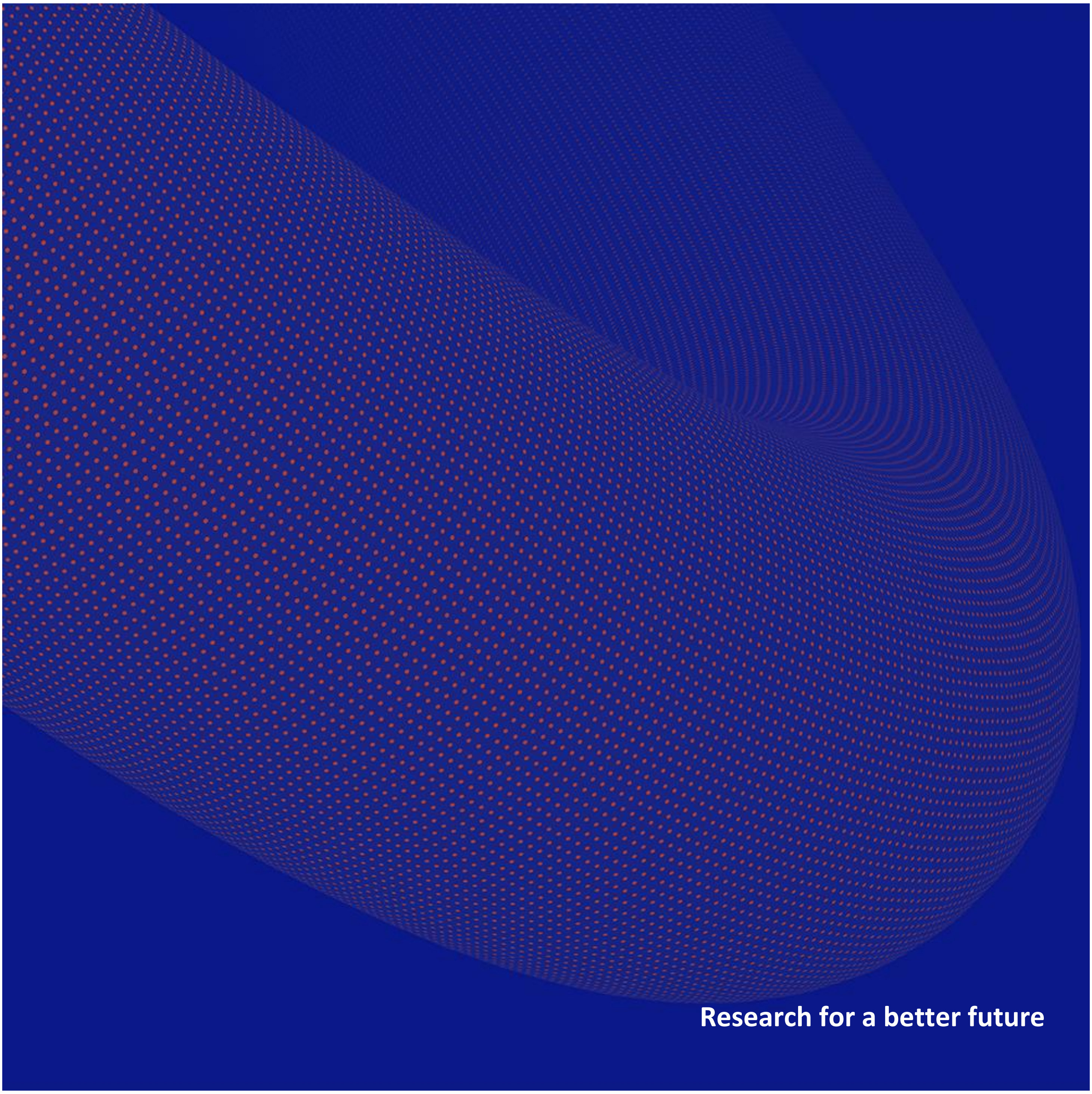

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Title:
Status of the use of arc fault detection devices in Norway

Summary:

This project aims to provide an independent assessment of the status of the use of arc fault detection devices (AFDD) in Norway, primarily based on published research in the field and information obtained from authorities, experts and manufacturers supplying AFDDs to the Norwegian market. The work is limited to components with specifications corresponding to the General requirements for arc fault detection devices (IEC 62606).

The specified issues and questions relating to the use of AFDD in Norway are elucidated in the report. For example, this may include whether there are special Norwegian conditions that make AFDDs a reliable fire prevention measure or whether the reliability of the AFDDs available on the market today is adequate. An overall technical description of the phenomenon of arc formation is presented, together with a review of the function and operation of AFDDs. The test requirements of the General requirements for arc fault detection devices are also assessed. Also discussed are the possible underlying reasons behind the high occurrence of series arcing as a cause of fires in the Norwegian fire statistics.

The work has led to the following recommendations:

- A review of the causal categories for fires caused by electrical faults is recommended in the Norwegian Directorate for Civil Protection's (DSB) fire statistics, and it should be assessed whether the causal category of 'series arc faults' should be changed to 'series faults'.
- It is recommended that the General requirements for arc fault detection devices (IEC 62606) be expanded to include new and more comprehensive test requirements, that better reflect conditions in actual electrical installations.
- It is recommended that an independent body conducts a test study, in which a large number of AFDDs are fitted to different types of electrical installations and monitored over time.
- It is recommended that documentation be obtained demonstrating that AFDDs constitute an effective fire prevention measure before any requirement concerning AFDDs in electrical installations is introduced.

This report is an English version of the original report (IFE/E-2021/004), translated from Norwegian by a third-party service provider.

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Contents

1 Introduction

The purpose of this work is to provide an independent assessment of the use of AFDDs in Norway, primarily based on published research in the field and information obtained from authorities, experts and manufacturers supplying AFDDs to the Norwegian market. The work is limited to components with specifications corresponding to the standard IEC 62606 - *General requirements for Arc Fault Detection Devices (AFDD)* [1], also referred to as the AFDD Standard. The work is also confined to the study of existing literature, and no new research or experimental trials have been performed in this project.

In simple terms, an AFDD can be described as an electronic component that disconnects the electrical circuit that is being protected in an electrical installation when dangerous arcing is detected. Such arcing, whether series or parallel arcing, is typically not detected by earth fault and surge protection devices. Dangerous arcing in electrical installations presents a fire risk, and fire statistics indicate that a significant number of building fires occur annually in Norway due to arc faults. A recommendation was introduced in Norway from 1 January 2019 through the standard *NEK 400:2018 Electrical low voltage installations* [2], to implement measures to protect against the effects of series faults in final circuits. Consequently, Norwegian authorities have yet to introduce requirements on the use of AFDDs.

This report addresses and highlights specific issues and questions relating to AFDD use in Norway. For example, this may include whether there are special Norwegian conditions that make AFDDs a reliable fire prevention measure or whether the reliability of the products available on the current market is adequate. The report will first present relevant information taken from available fire statistics, then provide an overall technical description of the phenomenon of arc formation, followed by a review of the functionality of AFDDs, their operation and testing requirements. Finally, a number of considerations related to AFDD use as a fire prevention measure are presented.

2 Fire statistics

Fire statistics are available for most countries. Not all such statistics are publicly available, and the level of detail and categories often vary from country to country. This chapter focuses on statistics for building fires caused by electrical faults, as these are most relevant for assessments related to the use of AFDDs.

2.1 Norway

The following fire statistics are available for Norway:

- Norwegian Directorate for Civil Protection (DSB) statistics, based on entries made in the reporting system **BRIS**
- Finance Norway fire insurance claim statistics (**BRASK**), based on insurance payouts
- Norwegian Fire Protection Association (Norsk Brannvernforening) statistics, based on National Criminal Investigation Service (Kripos) records (**Knitre** database)

2.1.1 BRIS reporting system

DSB has recorded fire statistics since 1986. BRIS is a Norwegian abbreviation for the words 'fire, rescue, reporting and statistics', and is a reporting system that was implemented in January 2016. Data entered in BRIS is used by both the Norwegian fire service and other organisations which are responsible for fire prevention. *Brannstatistikk.no* is an online service provided by DSB that provides an overview of all fire and rescue service call-outs in Norway since 2016. According to DSB, the purpose of *Brannstatistikk.no* is to publish data from BRIS and to place a greater emphasis on fire prevention. The service was launched for users logged in from the fire service and the 110 emergency service in June 2019. A beta version of the service was launched in November 2019.

A summary report of the fire statistics for 2018 is available on DSB's website [3]. Out of a total of 5,089 registered assignments in 2018 relating to building fires, 3,537 assignments (approximately 70%) were associated with residential fires. The source of fires for residential fire assignments is distributed as follows [3]:

- Not reported: 50.9%
- Unknown: 20.2%
- Electric ignition source: 13.1%
- Open fire: 8.6%
- Other source: 4.0%
- Self-ignition: 2.7%
- Natural phenomenon: 0.5%

Correspondingly, the cause of fire for these residential fire call-outs is distributed as follows [3]:

- Not reported: 50.9%
- Unknown: 22.1%
- Misuse: 11.3%
- Equipment/product fault: 5.1%
- Other: 4.0%
- Arson: 3.4%
- Faulty installation/facility: 2.9%

What is immediately apparent from these statistics is that the level of under-reporting is extremely high, thus the quality of the database is questionable, as it is impossible to assume that unknown and unreported causes are distributed in line with the fires determined as being attributable to a specific cause. Nevertheless, the number of fires caused by an electrical fault will be statistically significant and represent a significant percentage.

DSB's fire statistics divide fires caused by electrical faults into eight subcategories, and the distribution of these during the period 2009–2014 was as follows [4]:

- Other/unknown electrical fault: 51%
- Series arc faults: 35%
- Component failure: 7%
- Short circuit/parallel arc faults: 3%
- Creep currents: 2%
- Earth faults: 1%
- Power surges: 1%
- Line breaks: 0%

It may also be added that DSB's definitions of series arc faults, earth faults and creep currents are as follows [5][6]:

- **Series arc faults** are due to poor contact in an electrical connection. Contact failure results in a locally higher resistance and subsequent overheating and can lead to a persistent arc fault. This can cause insulation to burn or ignite, resulting in a fire.
- **Earth fault** means that one or more phase conductors have a random or undesirable connection to earth, such as to metal housings on equipment or metal screens in cables.
- **Creep current** is a current on an incorrect circuit. Poor cleaning (dust, oil spills, etc.) and lightning surges can create undesired current pathways to earth or between live conductors, resulting in overheating.

The category **Other/unknown electrical fault** includes both fires where the cause is unknown (unknown cause) other than being due to an electrical fault, and fires not covered by the defined subcategories (other cause).

2.1.2 BRASK – fire insurance claim statistics

Finance Norway is responsible for BRASK, and believes that the quality of the database is sufficiently good to provide a true overview of the trend in claims. The basis for the data in BRASK is fire insurance claims reported to non-life insurance companies. All of the major insurance companies in Norway have provided data for BRASK since 1985. Collectively, these cover more than 90% of the Norwegian insurance market. Claim data is updated two years back in time in order to provide a true overview of claims. Only claims that are sufficiently well coded and that have resulted in compensation are included in BRASK. The code was revised in 2009. The fields 'sector' and 'age of building' were introduced in connection with this. These fields were coded as 'Unknown' before 2009.

Around 15-20 times more fires in residential properties were recorded in BRASK compared with the number of residential fires in BRIS. This may be due to varying definitions of fire and because many small fires and imminent fires are only reported to the insurance companies and the fire service is not called out. A fire in BRASK reflects a policy on which a payout has been made. Fires leading to compensation amounts greater than NOK 200,000 are coordinated and registered as a single fire in cases involving several policies. BRASK also includes claims due to electrical phenomena, typically power surge claims involving items such as a freezer or other electrical equipment being destroyed, but where there is no fire with naked flames. There are many such claims; however, these make up only a small proportion of the total compensation paid in respect of electrical fires [5].

Tables 1 and 2 below provide several examples of registered claim cases taken from BRASK during the 10-year period between 2010 and 2020.

Table 1: Number of claim cases for private residences where permanently fitted electrical equipment is the source, broken down according to cause.

Cause	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	SUM
Estimated arson	2	0	3	18	14	9	5	2	5	6	15	79
Self-ignition	33	40	8	7	13	28	34	17	24	29	23	256
Human error	17	15	29	36	34	26	46	38	41	41	42	365
Technical failure	101	111	115	125	130	108	257	185	257	221	212	1,822
Lightning strikes	154	481	270	616	1,926	502	800	545	505	964	677	7,440
Claims due to electrical phenomena	480	674	705	1,025	1,439	1,005	1,316	1,109	1,421	1,419	1,357	11,950
Other or unknown	181	145	190	240	317	356	383	315	424	457	449	3,457
TOTAL	968	1,466	1,320	2,067	3,873	2,034	2,841	2,211	2,677	3,137	2,775	25,369

Table 2: Number of claim cases for private residences for all fire sources, broken down according to cause.

Cause	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	TOTAL
Estimated arson	181	195	118	198	160	173	148	174	169	192	174	1,882
Self-ignition	439	501	352	347	308	422	473	348	483	409	394	4,476
Human error	492	548	860	962	843	957	1,161	820	1,055	952	803	9,453
Technical failure	890	970	619	663	614	550	993	932	961	767	588	8,547
Lightning strikes	2,200	4,552	1,345	3,374	8,334	1,761	4,087	2,051	2,046	3,755	2,154	35,659
Claims due to electrical phenomena	2,803	3,945	2,985	4,177	6,233	2,981	3,766	2,653	3,200	3,386	2,881	39,010
Other or unknown	7,847	7,185	5,826	6,821	8,854	6,917	8,292	10,720	12,491	13,488	11,919	100,360
TOTAL	14,852	17,896	12,105	16,542	25,346	13,761	18,920	17,698	20,405	22,949	18,913	199,387

It is immediately apparent from these figures that there is considerable annual variation. For example, the number of claims in 2014 in Table 2 is very high compared with, for example, the number for 2015, and the reason for this may appear to be a larger number of claims due to lightning strikes.

2.1.3 Knitre – the empirical database for fire investigations

The Norwegian Fire Protection Association cooperates with the Fire and Chemistry Section under the Norwegian National Criminal Investigation Service (Kripos) in connection with the Knitre database. Knitre was launched on 13 November 2020 and collates empirical data relating to the causes of fire, generally based on fire investigation results. The database also collates literature and trials conducted both nationally and internationally, to identify causes and research and development more generally. The database aims to stimulate an increase in the number of fire investigations, build up experience data and share knowledge. The experiences from Knitre may also influence the preventive work. The Norwegian Fire Protection Association and the Fire and Chemistry Section under Kripos are responsible for structuring and quality-assuring the content of Knitre.

The goals behind the creation of the database are as follows:

- To help clarify the causes of fires.
- To help strengthen the community involvement of the police and other stakeholders concerning fire protection.
- To contribute to awareness and commitment concerning the results of fire investigations.
- To contribute to cooperation and knowledge-sharing between fire investigation environments both nationally and internationally.

The database is not generally accessible to the public, it is rather designed to assist the police, fire service, local electricity supervisory authorities and the insurance sector in identifying the causes of fire and preventing fires. Agreement-regulated access may be applied for by persons whose work involves investigating fires for commercial purposes and private individuals not conducting commercial activities, but who contribute to fire investigations.

Nelfo was granted access to the Knitre database in October 2021 and was given permission to reproduce the statistics presented in this report. As of 1 November 2021, a total of 447 cases had been registered in the database. Of these, 14 cases are registered under the causal category 'series arc faults', 9 cases are registered under the causal category 'short circuit/parallel arc faults', 17 cases are registered under the causal category 'contact failure' and 5 cases are registered under the causal category 'overheating', and when all of these cases are added together (45 in total), they represent around 10% of all cases registered in the database. Arc faults are cited in a relatively high number of the investigation cases registered under these four causal categories.

Some of the investigation cases related to arc faults have been studied in more detail in this project. The primary focus of a case registered in the database typically involves documenting the actual cause of the fire, which means that there is limited information on what gave rise to the incident (e.g. use of incorrect installation material, defective installation, or inadequate maintenance), or the consequences (extent of damage). Detailed photographs are provided in several cases of molten copper beads and surface oxidation of copper conductors, which are typical characteristics of series faults in electrical circuits with high current loads. This is covered in greater detail in Chapter 3.

2.2 International

Corresponding international fire statistics also exist, from which the percentage of fires registered as being caused by an electrical fault can be deduced. Table 3 summarises the percentage share of all registered fires caused by an electrical fault in selected countries and regions.

Table 3: Percentage of fires caused by an electrical fault in various countries for the period specified [7][8].

Country	Percentage	Period
EU	13–20%	2004
USA	5–18%	2009–2011
United Kingdom	18%	2010–2020
Germany	33%	2002–2013
China	27%	2005–2010
Norway	21%	2009–2013

It is immediately apparent from the figures in Table 3 that the percentage of fires caused by an electrical fault does not appear to differ significantly in Norway compared with the percentages recorded in other relevant industrialised countries.

3 Arcing in electrical installations

According to International Electrotechnical Vocabulary (IEC 60050), an arc is defined as follows:

- *"Luminous discharge of electricity across an insulating medium, usually accompanied by the partial volatilization of the electrodes".*

Correspondingly, the Great Norwegian Encyclopedia's (Store norske leksikon) definition of an arc is *'a luminous, curved current pathway running between two live metal or carbon pins in air'*. In this context, an arc occurs when there is a weak electrical connection between live parts (electrical conductors or a connection point), which results in a spark or lightning-like arc with a very high temperature in the air space surrounding the connection. The primary difference between a spark and an arc is that a spark is a transient phenomenon, while an arc is of a certain duration [9]. Arc formation in electrical installations is undesirable and potentially dangerous; however, certain types of consumer equipment generate (desired) arcs as part of their function, such as electric brush motors found in items such as vacuum cleaners and electric drills. See references [4], [10] and [11] for a summary of the physical aspects of the phenomenon of arcing.

Arcing in electrical installations may take various forms and a distinction is often made between series arcs and parallel arcs. Figure 1 illustrates the difference between these. A series arc occurs in series with the load (Figure 1a), while a parallel arc may occur between two conductors (L and N) in the installation in parallel with the load (Figure 1b) or between a conductor and the ground (Figure 1c).

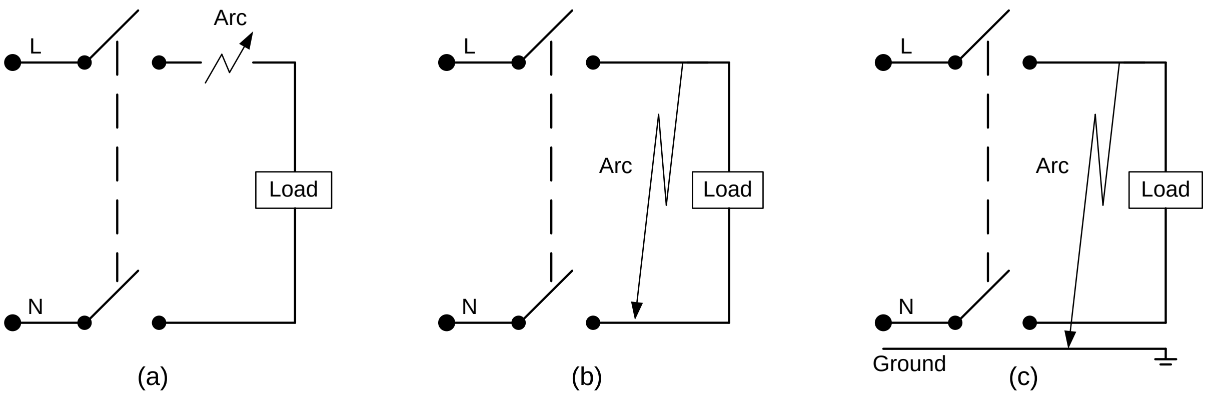

Figure 1: Various types of arcing that may occur in an electrical installation. (A) Series arcs, (b) Parallel arcs, (c) Earth fault arcs.

Arcing can have many origins, but the three main reasons why arcing occurs in an electrical installation are [12]:

1. **Short circuits**. These occur when low resistance and high current occur suddenly, often as a result of two live metallic conductors coming into contact with each other. The current in a short circuit arc is generally inversely proportional to the impedance of the conductors.

2. **Carbonisation of insulation**. Persistent arcing can occur in low voltage networks as a result of a 'carbonised track' forming in the insulation between two conductors. Moisture and contamination on the surface of the insulation can cause leakage currents, and over time this can create a charred track in the insulation resulting from a thermal decomposition process. Polyvinyl chloride (PVC) is a common insulation material used in wires and cables in electrical installations because it is a low-cost material with good mechanical properties. Unfortunately,

PVC is relatively prone to this type of charring compared to other polymers, such as cross-linked polyethylene (XLPE) [7].

3. **External ionisation of the air**. It is difficult for arcing to establish in air at normal atmospheric pressure with the application of 230 V AC because the dielectric strength of air is 3 MV/m under these conditions. The dielectric strength of air may be significantly reduced if a plasma of ionised gases forms in the air. Arcing or flames can result in such plasma formation, and if this ionised gas is transported to other parts of an installation, additional arcing (fire-induced arcing) may occur.

3.1 Sequence of events for series faults

The collective term series faults includes series arcs. According to DSB's fire statistics, series faults frequently cause fires in electrical installations, where series arcs are registered as the cause of around a third of fires caused by an electrical fault. The greatest risk of series faults is in weak or weakened electrical connections where the current load is high, i.e. where power-intensive equipment leads to a high load on the circuit. The challenge is that the current on the circuit is not significantly affected by a series fault, which means that conventional safety installations such as circuit breakers (overload protection) or earth fault protective devices are unable to detect the fault and disconnect the power supply to the circuit.

It is important to clarify the actual sequence of events in order to understand how a series fault can develop into a fire. Figure 2 shows a sketch illustrating the links between the various concepts included in the description of the phenomenon. A series fault is a weak electrical connection that may occur for various reasons. The fault leads to an electrical barrier affecting the current flow at the point where the fault occurs. The subsequent sequence of events is complex and dynamic with multiple stages occurring in different orders and simultaneously affecting each other. The formation of various arc types in the process is therefore largely dependent on electrical parameters, the original conditions, and earlier stages in the process, such as resistance heating and glowing. The outcome of a series fault may be the dissipation of electrical energy with subsequent heat generation and local overheating, which poses a high risk of combustible materials igniting subsequently leading to a fire. The various stages in this sequence of events are described in the following section.

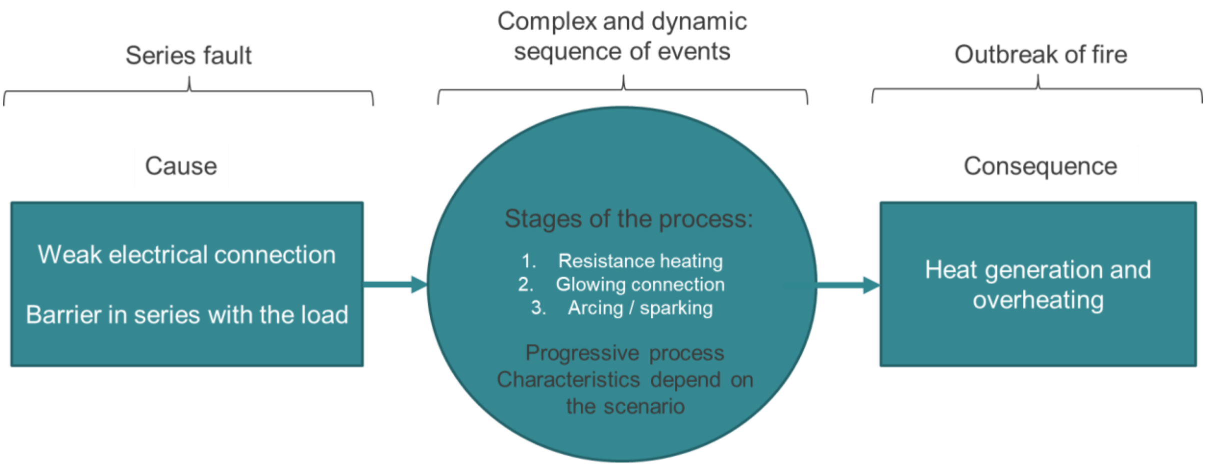

Figure 2: Sketch illustrating the sequence of events from the occurrence of a series fault (cause) to the outbreak of fire (consequence).

3.1.1 Resistance heating

Where there is a weak or weakened electrical connection, the electrical resistance will be higher, which may result in local heating under significant current loads. An increase in temperature can accelerate a process involving oxidation and metal deformation. An oxide coating, in the form of Cu_2O, can form and spread on the surface of the copper conductor, causing the current to pass through this coating. The Cu_2O coating has significantly higher electrical resistance than the metal, resulting in a process that is self-reinforcing or progressive, where the temperature continues to increase because the extent of the oxidation of the metal conductor increases. Such contact points can potentially result in heat generation of 30-40 W at a current of 15-20 A through the point [9]. There are also other causes of resistance heating in an electrical installation, including [9]:

- Too much insulation
- Severe overload
- Current leakage and earth faults
- Power surges/voltage spikes

3.1.2 Glowing connections

The heat generation can become so great in a weak electrical connection that the connection begins to glow. This is because a high power dissipation may occur over a relatively limited area (point). The relationship between temperature, resistance, current and voltage in a weak electrical connection on application of AC is summarised in reference [10]. Sletbak et al. studied Cu_2O formation and found that this oxide layer (filament) glowed at 1,200-1,300°C, which is a sufficiently high temperature to ignite most common combustible materials [13]. The reason why the current is restricted in a thin filament in the surface of the oxide layer relates to the fact that the oxide has a negative temperature coefficient. It was also established that the current could be concentrated in such a filament at currents as low as 0.15 A, and that the power dissipation depends on the current and the age of the filament. In the case of Sletbak, et al., a power dissipation of 17 W at 1 A was measured [13]. Other studies also observed that glowing connections can occur at relatively low currents of around 0.15-0.8 A [14].

3.1.3 Arcing associated with series faults

A loose live connection may in many situations be exposed to mechanical vibrations causing the electrodes to move relative to each other. The origins of mechanical vibrations may vary and may be periodic or transient in nature. Such vibrations may result in movement that causes the electrodes to become temporarily separated from each other, which can create small arcs between the conductors [13]. Four different ways in which series arcs may occur have been described [15]:

1. An arc is formed when live electrodes are separated from each other. The arc will extinguish if the distance becomes too great. Arcs may be created this way, even at lower voltages.
2. An arc may occur when the electrical voltage across two electrodes becomes higher than the breakdown voltage of the material separating the electrodes. A spark may then occur between the electrodes, which may develop into an arc if the current and voltage is sufficiently high.
3. When a carbonised track is formed between the electrodes, arcing may occur taking the path of this carbonised track.
4. A glowing connection between the electrodes can lead to arcing.

An example of a sequence of events observed for a series arc is as follows [16]: In the case of a newly formed arc, it has been observed that in the beginning (in the sparking phase) a discharge occurs generating white noise. Low and high-frequency noise eventually disappears as heat generation continues, and this discharge eventually transitions to a glow phase, with a glowing current path in the oxide layer that develops from the metal surface of one electrode to the metal surface of the other electrode. Current paths of several centimetres have been observed [13][16]. Both the length and the thickness of the oxide layer increase during the glowing phase. The space in the gap between the electrode is filled with copper oxide. The metallic copper simultaneously disappears from the electrodes. This process corrodes the electrodes some distance from the location of the fault, meaning that material is transported towards the contact area. The result is the accumulation of a thick oxide layer around the electrodes at the point of contact. Eventually, the current path along the oxide layer becomes so long that the ability to conduct current to a glowing filament in the oxide layer cannot be maintained. Two alternatives may then be observed for the subsequent sequence of events:

- It is no longer possible to maintain electricity flow at a 230 V voltage pressure, i.e. the fault site remains insulating until an impulse surge can restart the flow again.
- A situation occurs where the voltage across the fault site is around 500 mV. Low-level heat development could mean that this condition is long-term in nature, given that nothing happens to change the conditions at the point of contact (current load, mechanical stresses, fractures, corrosion). The end state is therefore either a complete break or a conductive state with near ohmic behaviour.

It is also argued that it is difficult for arcs to occur in 230 V electrical installations without the atmosphere having already been ionised from either existing/adjacent arcing or a fire (combustion gases). Fire-induced arcing is considered the most common situation with regard to forensic traces caused by arcing at the site of a fire [9].

3.2 Research in Norway and internationally

Three master's theses in the field of series fault protection have been completed at the Department of Electrical Power Engineering at NTNU – Norwegian University of Science and Technology in the period 2012-2016 under the supervision of Associate Professor Eilif Hugo Hansen. A relatively extensive account of the phenomenon of series faults has been provided in the thesis reports, and reading these reports is recommended for further technical insight:

- **Series fault protection in electrical installations**, 2012 [11]: The main objective of the master's thesis was to investigate whether solutions for detecting series faults exist in the market, the requirements made for such protection in other countries and the solutions that exist in the countries requiring series fault protection.
- **Series fault protective devices for protection against fire**, 2015 [10]: The master's thesis sought to explore the conditions associated with ignition for various types of series faults and to investigate the suitability of types of series fault protection to protect against fire. The thesis included attempts to find the triggers causing ignition. The tests indicated that it is possible to start a fire under certain conditions solely as a result of a glowing connection. AFDDs from various suppliers were also tested with the aim of exploring the potential and limitations of AFDDs.
- **Test of arc fault detection devices**, 2016 [4]: This master's thesis tested series fault protective devices in accordance with the standard IEC 62606, and any weaknesses in the AFDDs were assessed.

A study was performed by Energiforsyningens forskningsinstitutt A/S (EFI) in the early 1990s on behalf of Gjensidige Forsikringsselskap A/S. This work was recently made publicly available in the report 'Detector for contact/insulation faults'. [16]. The report examines the potential for detecting series faults in electrical installations.

A study from NTNU and SINTEF titled 'Glowing contact areas in loose copper wire connections' was published in 1991 [13]. This study supports the claim that fires caused by series faults are not necessarily due to series arcing, based on several experiments involving glowing connections. One of the formulations is worded as follows: *"It is very likely that the processes which were demonstrated in these model experiments will take place in loose contacts under real life conditions. It is strongly believed that they represent a more likely explanation than arcing for the large number of fires caused by series faults."*

A number of reports have been prepared by SINTEF NBL (Norwegian Fire Research Laboratory) with themes relevant to AFDDs. DSB has been the client for many of these reports.

- Analysis of DSB's fire statistics for building fires during the 10-year period 1994-2003 (*Analyse av DSBs brannstatistikk for bygningsbranner i tiårsperioden 1994-2003*), Report NBL A04122, 2004 [17].
- Development of fire damages in Norway compared with other Nordic countries – Reasons for differences (*Brannskadeutviklingen i Norge sammenlignet med andre nordiske land – Årsaker til forskjeller*), Report NBL A06116, 2006 [18].
- Fires caused by electrical installation materials (*Branner på grunn av elektrisk installasjonsmateriell*), Report NBL A06121, 2007 [9].
- Incidents involving fire in electrical installations (*Hendelser med brann i elektriske anlegg*), Report NBL A12137 [19].
- Overheating in electrical materials and equipment as a source of ignition in buildings (*Varmgang i elektrisk materiell og utstyr som tennkilde i bygninger*), Report NBL A06122, 2007 [20].
- Fires caused by electrical faults in installation materials and low temperature heat impact from lighting (*Brann på grunn av elektrisk feil i installasjonsmateriell og lavtemperatur varmepåvirkning fra belysning*), Report NBL A08120, 2008 [21].
- The development of fire damages in Norway - measures to reduce fire damages (*Brannskadeutviklingen i Norge - tiltak for å redusere brannskadene*), Report NBL A08111, 2008 [22].
- Electric cables and fire risk (*Elektriske kabler og brannrisiko*), Report NBL A12123, 2012 [23].

Notable international literature includes the work of V. Babrauskas, J. Shea and J. M. Martel:

- V. Babrauskas has published several books and a number of scientific journal articles containing topics related to the causes of fire in electrical distribution systems [15][24][25]. Babrauskas established Fire Science and Technology Inc. (FSTI) in 1993.
- J. Shea has published considerable research involving topics concerning the causal relationships of fires occurring in electrical installations [26]-[29]. Shea has been affiliated Schneider Electric Company and Eaton Corporation since 1993.
- J. M. Martel published a doctoral dissertation entitled 'Series arc faults in low-voltage AC electrical installations' in 2018. The dissertation addresses many years of research on the phenomenon of arc formation in electrical installations and methods for detecting arcs in the form of AFDDs [7]. Martel has been affiliated with Siemens AG for over 10 years.

4 Arc fault detection devices (AFDDs)

The main function of an AFDD is to protect against both series and parallel arcing by breaking the current in a circuit if an arc is detected that the AFDD identifies as dangerous. This section presents various key aspects relating to AFDDs.

4.1 History

Siemens published a white paper in 2012 documenting the history of AFDDs, which in the USA are referred to as *arc fault circuit interrupter*s (AFCI) [30]. Arc detection technology was developed in the early 1990s, and by 1993, the technology was being used in circuit breakers. The first commercial AFDD became available in 1997, and in the same year, the first proposal emerged introducing requirements for protection against arcing in the United States. The 1999 version of the National Electrical Code (NEC) stipulated that as of 1 January 2002, the installation of AFCIs in bedrooms in new buildings and in 'remodelling projects' would be required, meaning therefore that the requirement had no retroactive effect. The requirement was extended in 2008 to apply to circuits for living rooms, and was further extended in 2014 to cover kitchens. AFCIs are now required in 48 states in the USA under the NEC. Canada has adopted the same approach as the United States regarding the introduction of requirements for AFDDs. Section 210.12 of the 2017 edition of the NEC states that:

- *All 120-volt, single-phase, 15- and 20-ampere final circuits supplying outlets or devices installed in dwelling unit kitchens, family rooms, dining rooms, living rooms, parlors, libraries, dens, bedrooms, sunrooms, recreation rooms, closets, hallways, laundry areas, or similar rooms or areas shall be protected by AFCIs.*

The Siemens memorandum states that the justification for developing this technology was that a study conducted by the United States Fire Administration (USFA) in the 1980s identified that the death rates from fires in the USA were 2-4 times higher than they were in Europe, and that fires in electrical installations were a major contributor to this problem [31]. It is notable that in the USA and Canada, the power grid operates at 120 V AC (60 Hz), while in Europe it is 230 V AC (50 Hz). The current load in electrical installations will therefore typically be greater in the USA and Canada than in Europe.

Arc detection in the form of AFDDs adapted to the European power grid have been commercially available in Europe for over 10 years, but there has hitherto been limited requirements imposed by the authorities concerning the implementation of these. Requirements were introduced in Germany in December 2017 for AFDDs in buildings where fires would be critical such as museums, historic buildings, daycare centres and nursing homes, etc. [32]. In most other countries, including Norway, AFDDs are only recommended for certain installations where the consequences of a fire would be significant, which will be elaborated in section 4.5.

4.2 The Norwegian market

A Norwegian AFDD based on research conducted by EFI [15] and a patent developed by Trondheim-based company TransiNor was introduced in September 2001. The product was called ElDetector and was further developed and put into production by Bærum-based company IT & Prosess (ITP). Besides detecting arcing in electrical installations, the unit also had functions for directional earth fault indicator and voltage measurements [33]. The ElDetector is also mentioned in a SINTEF NBL report from 2008, where it is stated that Gjensidige Forsikring is developing this AFDD and that the product was tested in SINTEF's study [21]. The manufacturer of ElDetector was stated as PowerCraft.Net.

Siemens introduced an AFDD unit adapted to the Norwegian market in 2014, and now seven years later there are at least six different manufacturers offering AFDDs in Norway. These manufacturers include ABB, Eaton, Garo, Hager, Schneider Electric and Siemens. All AFDDs available in Norway will be designed in accordance with the requirements set out in the standard IEC 62606 – General requirements for Arc Fault Detection Devices. Independent certification bodies will typically carry out component certification by verifying that the component meets the requirements defined in this standard. An example of such a certification body is the *VDE Testing and Certification Institute* in Germany.

It is not known exactly how many AFDD units have been sold on the Norwegian market, but demand for such products appears to remain low in line with the fact that the use of AFDDs is only *recommended* by Norwegian authorities. An estimate based on feedback from manufacturers supplying AFDDs suggests that fewer than 1,000 AFDDs were installed in Norway in the seven-year period between 2014 and 2021. By comparison, several hundred thousand combination units (earth fault protection combined with overload protection) are sold annually in Norway.

4.3 Component function

The primary function of an AFDD is to protect against dangerous arcing in an electrical installation. An AFDD must be fitted at the start of the circuit it is intended to protect. The power supply to the circuit will be interrupted in the case of both series and parallel arcing if an arc is detected that the AFDD identifies as dangerous. The AFDD should ideally be able to simultaneously identify harmless arcing normally generated by consumer equipment and not disconnect the circuit in such cases. AFDD units often incorporate additional functionalities, meaning that the unit may provide protection against earth faults, overloads, short circuits (no impedance at fault site) and power surges. Such AFDD units are often referred to as AFDD combination units. A typical AFDD unit typically also has other noteworthy properties, including tripping if there is a permanently elevated voltage in the installation (>275 VAC) resulting from a fault in the low/high voltage network such as a phase loss or an N-conductor loss.

Conventional earth-fault protection, surge protection, circuit breakers and combination units cannot normally detect arcing in an electrical installation. Table 4 summarises the protection functions of these components compared with AFDDs and AFDD combination units.

Table 4: Comparison of protection functions for different components.

Component	Short circuit	Overload	Earth fault	Series arcing	Parallel arcing	Transient surge	Persistent elevated incorrect voltage
Earth fault protection[1]	×	×	√	×	×	×	×
Surge protection[2]	×	×	×	×	×	√	×
Circuit breaker[3]	√	√	×	×	×	×	×
Combination unit[4]	√	√	√	×	×	×	×
AFDD[5]	×	×	×	√	√	×	√
AFDD combination unit[4,5]	√	√	√	√	√	×	√

[1] Designed with specifications in accordance with the standard NEK IEC 61008-1:2010
[2] Designed with specifications in accordance with the standard NEK IEC 61643-11:2012
[3] Designed with specifications in accordance with the standard NEK IEC 60898-1:2019
[4] Designed with specifications in accordance with the standard NEK IEC 61009-1:2010
[5] Designed with specifications in accordance with the standard NEK IEC 62606:2013

Figure 3 shows the typical design of an AFDD combination unit. AFDD units are also available on the market that only provide arc protection and that only comprise a single module (18 mm wide). The most important specifications for an AFDD are generally described in data sheets for such products. The unit has a manual test button to test the trigger function of the device. AFDDs may also have built-in self-testing functions to test the analogue electronics and detection algorithms at a time interval of a few hours. There is also an LED indicator located on the front indicating the operating condition of the device and to provide the consumer with details of the cause of any disconnection. The warranty period for an AFDD typically varies from one to five years, while the expected service life is often specified in terms of the number of electrical operations (typically > 4,000) and mechanical operations (typically > 20,000). The price of an AFDD combination unit varies according to specification, but is usually around NOK 2,000 (including VAT) for a private customer. In comparison, a combination unit costs just under NOK 500 (including VAT).

Figure 3: Typical design of an AFDD combination unit with three modules (54 mm wide).

4.4 Detection principle

The current flow in a series fault will typically result in high and low-frequency noise signals that can be used for detection at central locations in an electrical installation such as a distribution cabinet. These noise signals are propagated both in the network (wired) and in the room (radiated radio noise) [16]. An AFDD fitted in a distribution cabinet will continuously monitor the intensity and duration of sequences of high-frequency noise on the current curves. A built-in microprocessor runs algorithms that analyse these signals and momentarily disconnects the circuit connected on detection of abnormal conditions such as the formation of dangerous arcing. Algorithms and detection principles often vary from manufacturer to manufacturer. It has been claimed that it is likely a requirement that detection must take place during the initial period following the contact fault (in the sparking phase) because most low and high-frequency noise occurs at the beginning. The discharge starts as an arc/spark discharge with noise frequencies (white noise) up to 300 MHz. The low and high-frequency noise eventually disappears while heat generation continues. When the fault transitions to the glowing phase, the noise frequency decreases to around 1 MHz [16].

Different electrical equipment may produce high and low-frequency noise signals under normal conditions, and therefore one of the main challenges for AFDD technology is distinguishing between loads producing noise signals similar to dangerous arcing and instances when dangerous arcing is actually occurring in the electrical installation. The following must be taken into account in order to distinguish noise from arcing in an electrical installation from other random electrical noise (e.g. desired arcing) [16]:

- The current of the noise signal

- The power surge on the contact connection
- The degree of asymmetry of the charge transport
- Electrical noise exceeding 10 MHz
- The degree of chaos in asymmetry and high-frequency noise

It may be added that the strength of the noise signals decreases with increasing current transmission in a series fault, such that it typically becomes harder to detect arc formation based on high-frequency noise signals at high current loads [4]. Noise frequency has also been observed to increase with increasing gap between the conductors [16].

The principles of the Siemens AFDD (5SM6) are described relatively extensively in the product's data sheet [34]. This AFDD protects against both parallel and series arcing. A sketch illustrating the design principle of the device is shown in Figure 4. The detection principle of an AFDD is generally to measure and analyse high-frequency noise signals and current curves on the conductor (L) connected to the unit. These signals are processed in an analogue circuit before being sent to a microcontroller for processing. A trigger signal is sent to the switch mechanism when the microprocessor recognises dangerous arcing, which disconnects both conductors on the circuit.

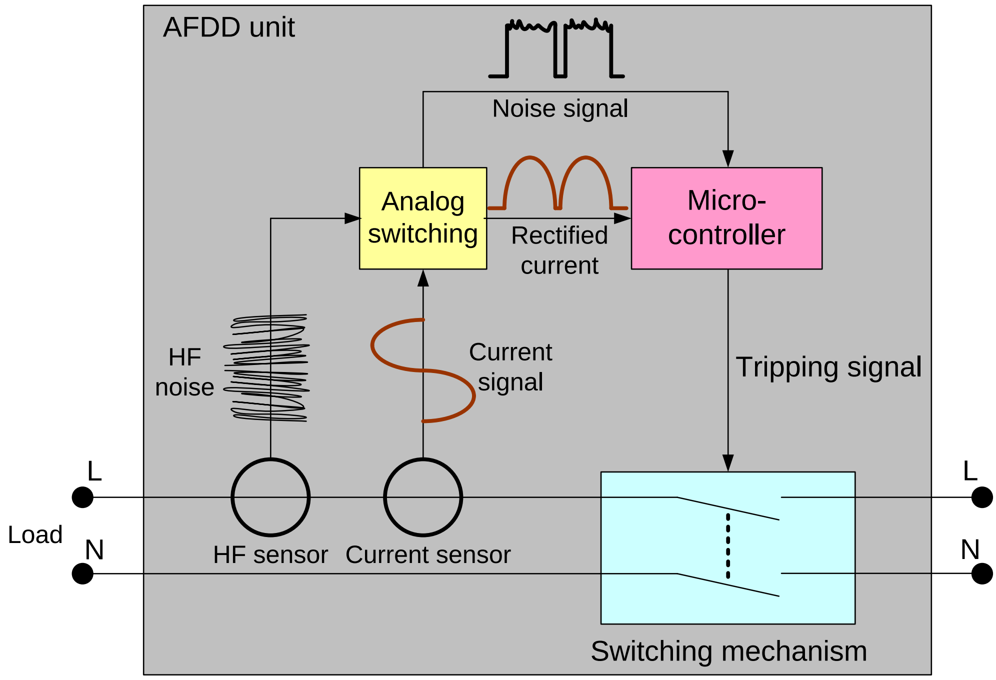

Figure 4: Outline sketch of the design of a Siemens 5SM6 AFDD [34].

A parameter RSSI (Received Signal Strength Indication) is defined for the actual arcing detection for a Siemens 5SM6 AFDD, which represents the effect of the arc at a given frequency and bandwidth. There are two conditions that must be met for an AFDD to interpret the noise signal as being associated with dangerous arcing. The RSSI must first attain a value greater than a predefined limit value. Both conditions are met if the time-derived RSSI value is also greater than a predefined limit value. As soon as the accumulated fault exceeds a predefined limit value, the microcontroller will issue a disconnection signal to the switching mechanism. Undesired disconnections are prevented by immediately resetting the accumulated fault to zero if the protective device detects 'atypical arcing' [34].

4.5 Standards

4.5.1 Electrical low voltage installations - NEK 400:2018

A recommendation was introduced from 1 January 2019 in NEK 400:2018, sub-standard 4-42 with the title *Protection against thermal effects* implementing measures to protect against series faults in final circuits [2]. This includes:

- Areas designated for sleeping
- Areas where there is a fire risk due to the properties of materials being processed or stored (BE2 areas)
- Areas with combustible construction materials (CA2 areas)
- Building structures that help to spread fire (CB2 areas)
- Areas of irreplaceable value

It is furthermore highlighted that the use of arc detection equipment (AFDD) in AC circuits in accordance with IEC 62606 would satisfy the recommendations above. When an AFDD is used, it must be placed at the beginning of the circuit it is to protect.

There is also an informative supplement to NEK 400:2018 (Annex 42A) addressing arc detection equipment. This includes a claim that AFDD use in AC circuits in accordance with IEC 62606 may help reduce the risk to individuals, domestic animals and property caused by extensive fires propagated by electrical installations and appliances. The following three units are specified in IEC 62606:

- AFDDs as a single unit comprising an AFD unit and opening devices and that are intended to be connected in series with a suitable overcurrent protective device
- AFDDs as a single unit comprising an AFD unit integrated into an overcurrent protective device
- AFDDs comprising an AFD unit and a specified overcurrent protective device to be installed on site.

NEK 400 is normally revised every four years, with the next edition planned for July 2022.

It is also notable that NEK 400:2002 introduced a requirement in Norway for earth fault circuit breakers on all final circuits to protect against fire. Requirements for earth fault protective devices have gradually been introduced in Norway with the requirement in 1991 for earth fault circuit breakers in all wet rooms and with the requirement in 1998 for earthing on all final circuits.

4.5.2 AFDD Standard – IEC 62606

A standard dedicated to AFDDs in the form of *IEC 62606 – General requirements for arc fault detection devices* was published in 2013 [1]. The standard is relatively comprehensive and the document contains around 150 pages. The standard defines a number of requirements AFDDs must satisfy. The AFDD units on the market are generally designed and constructed to satisfy these requirements. Besides general requirements and tests, such as switching capacity, dielectric and isolating capability, service life, heat resistance, electromagnetic compatibility and thermal, mechanical and electrical endurance, specific requirements for the component's function are set out in Chapter 8 of the standard, including response time for the detection of dangerous arcing. Limit values for an AFDD's break time in detecting dangerous arcing for various test currents are specified, and these specify that the protective device must break the power supply to the circuit within the limit values given in Tables 5 and 6 for test currents below and above 63 A [1].

Table 5: Limit values of break time for a given test arc current at 230 V AC up to 63 A.

Test arc current (RMS value)	2.5 A	5 A	10 A	16 A	32 A	63 A
Maximum break time	1 s	0.5 s	0.25 s	0.15 s	0.12 s	0.12 s

Table 6: Maximum number of arcing half-cycles within 0.5 s for 230 V AC above 63 A.

Test arc current (RMS value)	75 A	100 A	150 A	200 A	300 A	500 A
Number of arcing half-cycles	12	10	8	8	8	8

The AFDD Standard describes three specific methods of arc generation to be used in the testing. Arcs are either generated using an arc generator or by using specially designed cable samples. An arc generator is used for series arc tests and must have a transition comprising a copper electrode and a carbon electrode separated by a variable distance. One cable sample is also used for series arc tests and is a damaged multi-core cable with a carbonised track in the insulation, while the other cable sample is used for parallel arc testing and is a multi-core cable that is cut using a thin steel blade. In this case, the knife blade will create a short circuit between the conductors [1]. Note that the AFDD Standard contains no tests to simulate a weak connection. The most likely reason for this is that the duration of the tests would quickly increase and would also become unpredictable and difficult to reproduce.

A total of 20 different tests have been defined to ensure that AFDDs work satisfactorily. These are listed in Table 8 in the standard and are reproduced in the list below [1]. The tests include the verification of series and parallel arc detection, detection characteristics when masking/covering the arc noise (interfering loads are connected) and immunity to incorrect results, and all of these fall under item 7 of the list.

1. Indelibility of marking
2. Reliability of screws, current-carrying parts and connections
3. Reliability of terminals for external conductors
4. Protection against electric shock
5. Dielectric properties
6. Temperature-rise
7. Verification of the operating characteristic
8. Mechanical and electrical endurance
9. Behavior under short-circuit conditions
10. Resistance to mechanical shock and impact
11. Resistance to heat
12. Resistance to abnormal heat and to fire
13. Verification of the trip-free mechanism
14. Test of resistance to rusting
15. Verification of limiting values of the non-operating current under overcurrent conditions
16. Behavior in case of surges caused by impulse voltage
17. Verification of reliability
18. Verification of ageing of electronic components
19. Electromagnetic compatibility
20. Verification of protection due to overvoltage due to a broke neutral in a three phase system

5 Considerations

The topics presented in the previous sections will be discussed and contextualised in this section. The key issues to be discussed are:

- How many fires and imminent fires occur annually in Norway caused by arcing in electrical installations?
- How good are the test methods and requirements stipulated in the AFDD Standard, i.e. is an AFDD designed to satisfy the requirements of the AFDD Standard actually capable of detecting dangerous arcing in real-world situations where conditions are often different and unpredictable?
- How reliable are the current AFDDs commercially available when used with final circuits, both in terms of detecting dangerous arcing and avoiding accidental disconnection (nuisance tripping)?
- Would introducing requirements for AFDDs in electrical installations in Norway constitute a good fire prevention measure?

5.1 Causes of fire

There are a number of weaknesses in DSB's fire statistics. The database relating to the causes of fire is generally characterised by a high degree of under-reporting (causes of fire that are not reported) and incorrect reporting (cases that are reported but where the cause of fire is unknown). A circular from the Director General of Public Prosecutors to the Norwegian police service requires the police to investigate all fires to determine the cause. In practice, DSB's statistics show that a report on the cause of a fire is only received for around 70% of building fires to which the fire service responds. This is potentially a source of error if the remaining 30% is unequally distributed. The population density of Norway is also low. This means that some police stations have limited experience in conducting fire investigations. Some of these have only a few or fewer than one fire per year to investigate. This may be a contributory factor behind why the percentage of fires where the cause is 'Unknown' is as high as 25%. DSB has commented on the statistics emerging from the cases recorded in BRIS for the 2018 annual report by stating that the figures must be interpreted as the assessment of the fire and rescue services, and as such, compiled under hectic circumstances, and consequently may vary in each case from the cause of fire determined by the police [3]. A DSB report from 2010 addressing statistics for fire deaths during the period 1986-2009 [35] states that *'it has been problematic throughout the period that the fire causal code of "Unknown" has constituted a very high percentage of around 20%. Multidisciplinary investigation teams have been trialled in recent years in parts of the country comprising police representatives, the fire service and the local electricity supervisory services (Det Lokale Eltilsyn (DLE)) to attempt to improve this situation. It is hoped in the long run that this will increase competencies in fire investigations and therefore improve statistics on the causes of fires'*.

Some parts of the registration form were completed incorrectly prior to December 2009, and it was also possible to register more than one alternative for some of the entries in the form, resulting in so-called duplicates. This was corrected from December 2009 with the introduction of controlled electronic reporting. The introduction of the BRIS registration system and the creation of the Knitre database may constitute good measures in elevating the quality of the statistics on the causes of fires. In any case, an electronic platform has been implemented, potentially enabling improved control and quality checking of data registered in the system. It is however questionable whether the persons registering data in BRIS have the requisite time and skills to create a high quality database. A high degree of expertise is likely required in determining the cause of a fire when the source appears to be an electrical installation. It is unclear how many fire investigators possess such expertise in Norway.

Series arc faults are the most commonly registered cause of fires due to an electrical fault. This share is around 35% and has not changed significantly over the past two decades. This would therefore suggest that there is no particular trend in one direction or the other based on fire statistic registrations over a relatively long period of time. DSB's definition of a series arc essentially suggests that contact faults (series faults) are the same as series arc faults. It is questionable whether this is appropriate. There is no good scientific basis suggesting that all contact faults lead to arcing. As early as 1992, Sletbak commented that causes of fire registered as series arc faults are highly likely to be the same phenomenon as that registered as a glowing connection in other countries [13]. SINTEF NBL has in several reports highlighted that [21]:

- *'It is a paradox that around half of residential fires are caused by series arc faults according to DSB's fire statistics, while at the same time the term 'series arc fault' is not cited as a cause of fire in international fire literature. The alternative explanation in the literature, i.e. glowing connections, which the majority of actors in the electricity community appear to be unaware of in Norway, was documented by Norwegian researchers around 1990 (Sletbak)'.*

A Norwegian study from 2012 also highlights the following [11]:

- *'Series arc faults as a cause of fire are therefore highly likely to be the same phenomenon as that registered as glowing connections in other countries. Since both series arcing and glowing connections are common series faults, there are many indications to suggest that they are registered as the same fault. This suggests fire investigators interpret electrical faults differently, most likely because the cause of electrical fires remains to be fully understood. It is however highlighted that the differences between the phenomena can be difficult to distinguish following a fire'*
- *'The main problem with series faults in electrical installations is most likely to be glowing connections and not series arcing.'*

Similar claims were made in a SINTEF NBL report from 2008 [22]:

- *'Series arc faults cause around half of the fires in electrical installations in Norway according to DSB's statistics on the causes of fires. What other countries refer to as glowing connections is highly likely to be the same cause that DSB designates a series arc fault. Both causes are typical series faults and both are due to contact failure. Based on how such phenomena are defined, a persistent series arc fault is however a more intense ignition source than a glowing connection. The reported temperatures for glowing connections are 1,200-1,300°C, and persistent arcs can result in temperatures of several thousand degrees. This is far higher than what plastic materials are exposed to under standards for the approval of plastic materials used in electrical materials and equipment, such as the European standard IEC 60695 and the American standard UL94.'*

A study from 2015 states the following [10]:

- *'DSB's statistics on the causes of fire contain a weakness however. Chief Inspector Susanne Moen at the fire group for Oslo Police District wrote in an email dated 17 March 2015 that there are no uniform guidelines on what is required to conclude a particular cause of fire. This means that it is the discretionary assessment of the individual in question that determines whether a fire is registered as an 'electrical fault' for example, or whether the evidence is considered too weak and thus the fire is registered as 'Unknown' instead. In the period 2010-2013 (inclusive), the percentage of fires registered with a cause of "Unknown" was 19%'*
- *'There is also a lack of clear guidelines on registering the various electrical causes in cases where the conclusion of a cause of fire is permissible. This is also something that must be assessed by the individual in question. The fact that it is difficult to draw a specific conclusion if the evidence is not considered robust enough may help explain why as many as 48% of fires caused by electrical faults are registered as "Other".'*

- *'The result of a lack of guidelines for registering the cause of a fire that appears to have started with an electrical socket, for example, is that this is not necessarily registered with a more specific cause than that of "Unknown" or "Other electrical cause". Without a more thorough technical examination, it is difficult to adequately document that the evidence is robust for a series arc fault for example. The police can register this as "Unknown" or "Other electrical fault" in relation to DSB and provide a few words about the probable cause of the fire in the comments field. The consequence of this source of error is that fires caused by resistance heating and series arcing are likely to be greater than the DSB statistics would suggest. This assertion was confirmed in a telephone conversation with Moen on 16 March 2015, and is supported by Stensaas' review of the comments in the comments field of DSB's registration form' [9]."*

Several SINTEF NBL reports address the issue of whether overheating in electrical installation materials is due to glow or series arcing. Statements include [21]:

- *'When a fire occurs in a residential property and the fire investigation indicates overheating at a connection point in the centre of the fire, it is generally concluded that the cause of the fire is an electrical fault resulting from a series arc.'*
- *'In an analysis of DSB's fire statistics for the 10-year period 1995-2004, it was shown that 50% of the fires in electrical installation materials in general and 57% of the fires in sockets are registered as being due to series arcing.'*
- *'In comparison, similar statistics from the USA (NFPA), based on around 19,000 fires per year that started in installation materials in homes in the five-year period 1999-2003, show that only 6% of the fires were due to series arcing, while 47% of the fires were due to various forms of short circuit.'*
- *'The figures above clearly indicate that the actual cause of overheating in installation materials is poorly understood and that such errors are interpreted in different ways.'*
- *'Series arc faults are seldom cited as the source of fire in other countries (USA, Japan, UK, Canada). The overheating of electrical material is explained by the formation of copper oxide at the connection point. This leads to increased resistance and heat generation, which eventually begins to glow at temperatures in the range of 1,200-1,300 ℃.'*

This illustrates the importance of designing high-quality reporting forms to collect information for statistical purposes. One example of this is the fire statistics shown in Table 7, where the number of registered fires caused by an electrical fault and the incorrect use of electrical equipment is distributed by causal category for the period 1996-1998, taken from the DSB publication Elsikkerhet, no. 56. It can be seen that the category of overheating was introduced in 1997 and quickly grew to become the largest category in 1998 (together with earth faults). It can simultaneously be seen that the number of fires registered under the category of series arc faults almost halved between 1997 and 1998, and it may be speculated whether this was because many of the registrations that would have normally been made under this category were subsequently registered under the category of overheating. It may be appropriate to question whether arcing has been overestimated in fire statistics owing to the inadequate design of reporting forms. The category of series arc faults may have become a catch-all item for poor electrical connections (contact failure).

It is also notable in Table 7 that the earth faults category is larger than the category of series arc faults in 1998. In the period 2009-2014 however, only 1% of fires registered as being due to an electrical fault were registered under the causal category of earth faults (while around 35% were registered under the category of series arc faults). This may relate to the fact that requirements for earthing and earth fault circuit breakers have been gradually introduced in all final circuits.

Table 7: Number of registered fires caused by an electrical fault or incorrect use distributed according to causal category for the period 1996-1998.

Causal category	1996	1997	1998	TOTAL
Other misuse	24	29	67	120
Other known cause	155	164	239	558
Poor maintenance	33	56	73	162
Earth fault	83	365	490	938
Short circuit arc	46	80	67	193
Creep current	46	47	57	150
Material failure	151	244	332	727
Series arc faults	462	652	363	1477
Radiation	14	8	1	23
Thermostat failure	20	22	35	77
Covering	14	25	20	59
Stove fire	19	39	51	109
Overheating		195	462	657
Unknown cause	57	77	122	265
TOTAL	**1124**	**2003**	**2379**	**5506**

5.2 Testing requirements for AFDDs

In the AFDD Standard (IEC 62606), the minimum current for which dangerous arcing must be detected is 2.5 A with a limit value for the break time of one second for 230 V AC; see Table 5. The purpose of the tripping characteristic given in Table 5 is to limit the dissipated energy to 100 J where a constant arc voltage of 40 V is assumed [7]. The corresponding requirement is set at 5 A and one second for 120 V AC. There are therefore no requirements in Norway for AFDDs to trigger in response to dangerous arcing for current loads lower than 2.5 A. Experimental trials have suggested that even arc currents as low as 1.7 A and possibly even lower, may possibly ignite surrounding materials [29]. Another study found that it was possible to ignite the cable sample used in the experiment using arc currents lower than the minimum requirements in the standard. The AFDD did not break the current in the circuit, and the cable sample that burned was therefore continuously supplied with energy [10]. The same study proposed an assessment of whether the minimum arc current at which the standard requires arc detection could be reduced without this leading to an unacceptable increase in unintentional disconnections [10].

Questions have therefore been raised whether the current limit of 2.5 A is appropriate. The historical reason for setting the limit value at 2.5 A is unclear. This may be a compromise in order to achieve the desired component function (few unintentional disconnections) and an acceptable fire risk (low probability of ignition). It has been observed that voltage drops across a contact fault are typically of magnitude 10-30 V. It has been stated that if it is assumed that the risk of ignition is set for a power dissipation at the fault location of 30 W, this implies a current load of 1-3 A [16]. Tests have been performed on arcing in PVC cables where the probability of ignition at a 1 A current load was 11% when the arc current itself was 0.8 A. Correspondingly, the probability of ignition was greater than 50% at a 2 A current load and a 1.6 A arc current [7].

This suggests that there are also challenges in designing a good experimental set-up for the realistic testing of AFDDs. The AFDD Standard has attracted criticism because more comprehensive tests are not required for nuisance tripping and arc detection in a circuit with multiple loads connected, which may result in currents similar to arc currents [10]. A challenging element is the difficulty in developing a method for generating arcs with different characteristics while simultaneously maintaining an expectation that such standard tests will be reproducible. The ability to generate arcs with different characteristics in a reproducible manner is not necessarily adequate in revealing whether an AFDD is suitable for protecting an electrical installation. There is a potential risk of an AFDD only being designed to detect the well-defined and reproducible arcs used in the test procedure. It is important that the variance of the arc must be understood, accepted and implemented in the test method [7]. It is also pointed to that when the tests in the AFDD Standard are performed, carbon is already present at the fault location, either associated with the choice of material (carbon electrodes) or the thermal decomposition of material (PVC insulation). Carbon has thermionic properties, i.e. charged particles are emitted when it is heated, resulting in the ionisation of ambient air. It has therefore been claimed that the verification tests in the AFDD Standard are somewhat artificial, and there appears to be a discrepancy between the procedure defined in the standard and the actual series faults that can occur in an electrical installation [8].

Arc formation in electrical installations is a complex phenomenon and further research and testing appears to be required to further develop the AFDD Standard in the form of the introduction of new testing methods and the definition of more realistic test requirements. A comprehensive study from 2018 presents a number of suggestions for improvements to the AFDD Standard based on experimental trials. One of the purposes of the study was to verify whether the tests and criteria for AFDDs were reasonable and to reveal whether the methods used to generate arcs for conducting such tests were compatible with the arc characteristics occurring in real situations. Some of the recommendations from this study include [7]:

- *Start the verification of the series arc detection at 1 A.*
- *Use the energy limitation as a test criterion for series arc detection instead of a time-current characteristic.*
- *Use the same test criteria for series arc detection as for AFDD with 120 V, 230 V, and 400 V rated voltage.*
- *Use carbonized cables to generate series arcs and avoid using an arc generator with graphite and copper electrodes.*
- *Perform masking and nuisance trip tests with combinations of more than two appliances.*

In addition, a recommendation has been made based on a relatively new study which states that the AFDD Standard should also take capacitive loads into account, as it appears that AFDDs have problems detecting series arcs when there are capacitive loads on the circuit [36].

5.3 Special Norwegian circumstances

As previously mentioned, a relatively large percentage of residential fires registered caused by an electrical fault fall under the causal category of ‘series arc faults’ (around 35%). It has previously been speculated that there may be special Norwegian circumstances accounting for such a high percentage. Conditions referred to include the following [9]:

- The power grid is unique (IT/TN network).
- Large number of wooden buildings
- Electricity is used for heating, which may result in continuously large loads on final circuits
- Inadequate fire investigations
- Varying interpretations of electrical faults
- High frequency of faults in electrical systems

Norwegian households have traditionally used electrical heating appliances, which often results in high and long-term loads on final circuits. Series faults could therefore potentially lead to a large power dissipation and therefore constitute a greater fire hazard in Norway than in other countries [11]. Certain findings have been made when comparing Norwegian fire statistics with corresponding statistics for other Nordic countries, and can be summarised as follows [18]:

- No more people die in fires in Norway compared with other Nordic countries. The average number of deaths per 100,000 inhabitants in the years 1999-2003 was 1.3 for Norway, 1.4 for Sweden, 1.5 for Denmark and 1.7 for Finland.
- There is no greater frequency of fires in Norway compared with other Nordic countries. The average number of call outs for fires per 1,000 inhabitants in the years 2000-2004 was 2.7 for Norway, 2.9 for Sweden, 3.2 for Denmark and 2.5 for Finland.
- Electrical faults are less frequently registered as the cause of fatal fires in Sweden (3%) compared with Norway (9%), Finland (9%) and Denmark (12%).
- Norway has a relatively high percentage of residential fires registered as being due to an electrical fault (20%) compared with Sweden (8%) and Denmark (13%).

The fire risk in Norway does not appear to be particularly high - on the contrary; however, it appears that residential fires registered in Norway are more frequently caused by an electrical fault compared with other Nordic countries. As a possible explanation for this, the study states that electricity is less common as a source of heating in Sweden, and that a larger percentage of Sweden's population live in apartment blocks and tenements, where testing and inspection of electrical installations may be better [18]. It is nevertheless notable that the percentage of fires registered as being due to an electrical fault in Norway does not differ significantly from the percentage registered for the EU or the United Kingdom; see Table 3.

It is unclear why the causal category of 'series arc faults' constitutes a relatively high percentage of fires caused by an electrical fault in the Norwegian fire statistics. As mentioned in Section 5.1, this may relate to the design of the registration forms and the definition of a series arc fault chosen by DSB. No documentation has been identified in this project suggesting that dangerous arcing actually occurs more frequently in electrical installations in Norway compared with other Nordic countries. Nor has any research been identified revealing anything about the frequency of arcing in electrical installations.

5.4 Reliability of AFDDs

The AFDD Standard (IEC 62606) describes a number of requirements that AFDDs must satisfy. Some of the tests check that an AFDD can detect dangerous arcing (series, parallel and earth fault arcs), and examine whether the AFDDs can detect dangerous arcing in circuits where there are various interfering loads that may mask the characteristic arc noise. It is furthermore examined whether AFDDs can tolerate being exposed to sources generating noise signals and current curves resembling dangerous arcing without accidental disconnection occurring (nuisance tripping). Ideally, an AFDD should detect all dangerous arcing while simultaneously ensuring that harmless arcing does not lead to unintentional disconnections. Designing such AFDDs may be technologically challenging, considering the complex sequence of events for a series fault in an electrical installation; see Figure 2.

Some independent studies have been published in which the reliability of AFDD units has been systematically tested. A Norwegian study from 2015 conducted at NTNU tested AFDDs from different manufacturers for nuisance tripping by connecting different loads to the test circuit simultaneously [10]. This included conducting tests with multiple and different types of loads from those described in the AFDD Standard. The objective was to create a more real-world situation than represented by the tests of the AFDD Standard, and the results of the tests were considered capable of providing meaningful data on how AFDDs work in an actual residential installation. The results section illustrates the difficulties in performing good reproducible experiments when arcing is induced in poor contact connections. Many different sequences of events were observed for contact faults, in turn illustrating that series faults in an electrical installation have complex and dynamic characteristics. The experiments and test results were more predictable when an arc generator in the form of an experimental rig built by Siemens [7] corresponding to that defined in the AFDD Standard and cable samples with carbonised tracks in the installation (specially produced in a high voltage laboratory at Siemens in Germany) were used. Five AFDDs from two different manufacturers were used in the tests. Some of the most important considerations and findings from the study are summarised as follows [10]:

- *'Arcs produced using carbonised cable samples constitute the test method in the AFDD Standard most closely representing the arcs that may occur in a residential installation.'*
- *'The experiments using carbonised cable samples gave good results for all protective devices. The results of the tests are a clear indication that the AFDDs can protect against damaging arcs that may occur in an installation.'*
- *'The tests using an arc generator gave unsatisfactory results. The requirements of the AFDD Standard were not met.* For *the cases not satisfying the AFDD Standard, the AFDD did not detect arcs in almost all cases. The reason for this may be because the arcs are interpreted as harmless by the AFDD.'*
- '*The arc generator cannot create an arc identical to what may be expected to occur in a residential installation. This is because graphite electrodes behave differently from copper electrodes. The gases emitted when a graphite electrode is exposed to the heat of an arc will not be the same gases emitted from a copper electrode. A copper electrode will melt under the influence of an arc. The fact that graphite electrodes do not melt is advantageous when generating arcs. It is considerably easier to produce a stable arc because the distance between the electrodes does not increase as rapidly when a graphite electrode is involved*.'
- '*The AFDDs made no incorrect detections of arcs when tested with various kitchen appliances (hand mixer, stick blender, hair dryer, vacuum cleaner, iron and fan heater)*.'
- *'However, the protective devices also failed to trip when demanding loads were combined with arcs in the way that theyshould have.'*
- '*The tests intended to test the protective device for nuisance tripping are far from adequate to draw any conclusion on the ability of AFDDs in detecting arcs. Part of the reason for this is that too few different devices were tested. Devices of the same type but produced by different manufacturers should also be tested. The tests should comprise both old and new products. Too few tests per AFDD were performed for the results to be considered reliable.'*
- *'AFDDs appear to have considerable potential in protecting against a significant proportion of damaging series faults that may occur in residential installations because series faults ranging from arcs to glowing connections appear to be the most damaging.'*

An investigation in another Norwegian study from 2016 conducted at NTNU examined whether AFDDs function satisfactorily when subjected to tests not corresponding to those defined in the AFDD Standard [4]. Several experiments were performed in the study, using different load types with current curves and noise formation similar to that of circuits with dangerous arcing. Loads providing large starting currents similar to the current of a parallel arc were also considered. Five AFDDs from two different manufacturers were used in the tests. All of the AFDDs were subjected to three different tests (weak connection with oxide coating, glowing connection between steel and copper, vibrating weak connection) to detect dangerous arcing at a relatively high load current (15 A), in addition to a test for nuisance tripping in the form of unintentional disconnection. Some of the most important considerations and findings from the study are summarised as follows [4]:

- *'With other types of test set-up, it is possible to determine whether AFDDs are only suitable for detecting arcing included in the AFDD Standard, or whether the protective devices are suitable for all types of arcing occurring in residential installations.'*

- *'It is harder to determine a simple and reliable test set-up simulating a weak connection in a residential installation. It usually takes a long time before a series fault occurs in a weak connection, possibly because the tightening of the connection is weak, parts of the conductors are damaged, or there is a high current load in the current circuit.'*
- *'Series arcs occurred at the connection point in all of the experiments performed using a weak contact connection, and all of the AFDDs detected the series arc and disconnected the current from the circuit.'*
- *'The insulation melted around the connection point immediately prior to a series arcing at the connection point. It is assumed that the air contained ionised gases from the molten plastic insulation on the connection point when a series arc occurred, possibly contributing to the formation of powerful and sustained arcing.'*
- *'The AFDDs had a weakness in the detection method for parallel arcs. Some electrical appliances and tools generate large starting currents, so that the protective device assumes there is a parallel arc and will disconnect the current from the circuit*.'
- *'Most homeowners have electrical equipment with low-pass filters in their homes. This is particularly the case for fuse circuits leading to the living room and kitchen. In one experiment, a PC power supply was connected to the circuit, and in another experiment, a fluorescent light fitting with conventional ballast was connected to the circuit. The AFDD failed to detect series arcing in the circuit in these experiments.'*

A Swedish study from 2021, conducted at the KTH Royal Institute of Technology, focused on testing various AFDDs commercially available, to better understand component performance and identify whether these actually perform according to their intended function. Different methods were used to create series arcs (parallel electrodes, burnt plugs/sockets and loose connections in sockets) and the tests were performed using different loads in the test circuit. AFDDs from four different manufacturers (Eaton, Hager, Schneider Electric and Siemens) were tested for their detection of series arcing. The AFDDs were not tested for accidental disconnection. Some of the most important considerations and findings from the study are summarised as follows [36]:

- *The Eaton and Siemens AFDDs were highly capable of identifying these arcs and tripping, while the Hager and Schneider AFDDs did not so readily trip for this type of arc. This observation led to the hypothesis that the AFDDs have significantly different tripping algorithms, possibly analyzing different parameters to detect the arc fault*.
- *There seems a clear trend that the AFDDs perform much better when there are no capacitive loads in the system. The performance of AFDDs in general were poor when the system included capacitive loads. Since general systems in present day usually contain capacitive loads, the AFDDs not performing as expected is of concern.*
- *It can be concluded that AFDDs could be useful for high-risk applications as back up protection because they are able to detect some series arcs and successfully trip the system, but they are not entirely reliable as there are cases in which series arc fault go undetected.*

A British study from 2020 tested an AFDD using an arc generator with carbon electrodes and a cable sample with a carbonised track prepared according to the AFDD Standard. There are relatively few details about the experiment in the report published. The findings from the study can be summarised as follows [8]:

- *Using cleanly cut carbon electrodes at a load current of 7.5 Amps, the AFDD did not reliably trip.*
- *Having altered the geometry and temperature of the carbon electrodes as result of immediately previous arcing, subsequent arcing at loads at 7.5 Amps were detectible by the AFDD.*

- *It is possible that the shape of the electrodes influenced the density of carbon vapour in the arc column, and hence, singly or together with elevated temperature, altered the striking voltage and changed how pronounced the shouldering of the current waveform was.*
- *Using carbon rods as described at item 2 above, the experiment was repeated with load current of around 1 Amp (230 Watts). Arcing occurred but the AFDD did not trip.*
- Using cable samples with carbonised tracks, *an AFDD prevented arc-initiated ignitions but not in all cases.*.
- *It is evident that there exists a margin in which dangerous arc-faults might exist undetected*.

There appears to be relatively little documentation available on the subject of testing AFDDs under conditions not necessarily coinciding with those defined in the AFDD Standard (IEC 62606). The studies referred to above are not considered to be comprehensive enough to draw any conclusion on whether or not the reliability of an AFDD in a real electrical installation is good enough, or otherwise. A general comment on the studies is that it is somewhat concerning that it is apparently relatively easy to construct tests (conditions) in which AFDDs are either unable to detect series arcs or accidentally disconnect. Six of the manufacturers supplying AFDDs on the Norwegian market were asked whether they had performed field studies where a large number of AFDDs have been installed in electrical installations (in real buildings) and monitored over time. None of the manufacturers could document that such field studies have been performed in Norway. The AFDDs on the Norwegian market are certified, which means that an independent certification body has verified that the AFDDs satisfy the requirements in the AFDD Standard. Manufacturer AFDD certificates are available on request.

5.5 Troubleshooting following disconnection

The main function of an AFDD is to disconnect the circuit it is intended to protect on detection of dangerous arcing. Product data sheets often specify a procedure for consumers to follow when the AFDD has made a disconnection. Consumers can also take a reading from the AFDD when a disconnection occurs to find out further details of the cause. A number of flashes on an LED indicator generally indicates the cause of the fault. General advice and systematic instructions for further follow-up is often available in the product data sheet. Depending on the cause of disconnection, the manufacturer-specified troubleshooting process can quickly become complicated for consumers without a basic knowledge of electricity and electrical installations. The most appropriate solution following a disconnection will often be to call in a certified electrician to perform troubleshooting using the correct equipment and procedures.

Immediate reflections related to troubleshooting following a disconnection include:

- It is important that the number of unintentional disconnections an AFDD makes is very low, so that the consumer respects the fact that there may be a potential fault in the electrical installation and that there is a risk of fire as long as the fault remains unidentified and uncorrected.
- Hiring an electrician to perform troubleshooting following a disconnection is relatively expensive and many consumers may therefore opt not to do this and perform their own troubleshooting instead. It may therefore be appropriate to have clear guidelines or recommendations produced by the authorities or insurance companies regarding expectations and requirements made of consumers following the disconnection of a circuit. This may be especially relevant if requirements for AFDDs are introduced for final circuits in residential installations.
- As with earth faults, traditional troubleshooting methods may be used to identify the location of arcing in electrical installations. This includes electrical measurements, thermography, dividing the circuit, and visual inspections combined with observations of sound, light and odour formation. Electrical (radio) noise occurs in the event of a fault, and this is propagated

both in the wiring network and in the surroundings. Noise radiated to the surroundings decreases sharply with distance and this may therefore be relevant in locating detected arcing. For example, if the distance to the contact fault is less than 10 m, the noise level is highly likely to be greater than the background noise [16]. Special equipment is available on the Norwegian market to identify short circuits in live cables. Such equipment includes reflectometers (echometers) that can measure the distance to short circuits for voltages up to 600 V and cable lengths of up to 3,000 m [37]. It may for example be of interest to manufacturers of AFDDs to develop reliable instruments for locating arcing in electrical installations, or possibly further developing AFDDs to include built-in functions for locating arcs.

- Who would be responsible should a fire break out in an electrical installation after a circuit has been reconnected without thorough investigation and possible correction of the fault? What should be the criteria for a consumer to start using the circuit again if an approved electrician could not identify the reason why the AFDD disconnected the circuit? Clear guidelines produced by the authorities should also be available in this case.

5.6 Fire prevention measures

There has been a marked decline in the number of people killed in fires since DSB began recording fire fatalities in 1979. More than 80% of all fire fatalities involved house fires during this period. Elderly people requiring care, people with disabilities and persons dependent on intoxicants are vulnerable groups. For example, people over the age of 70 are 4-5 times more likely to die in a fire compared with the rest of the population. An average of 38 people died annually in fires during the most recent five-year period (2016-2020).

Of the 510 fatal fires during the period 2005-2014, electrical faults were registered as the cause of the fire in 11% of cases [38]. In comparison, the corresponding figure was 9% for 185 fatal fires reported during the period 2001-2003 [17]. This means that around 3-4 persons are assumed to die annually in fires caused by an electrical fault. Assuming around a third of fires caused by an electrical fault are caused by arcing, this may suggest that 1-2 persons die annually in fires caused by arcing. Moreover, around 5,000 building fires were registered in DSB's fire statistics for 2018. Approximately 20% of these fires are registered as having been caused by an electrical fault, and if in turn it is assumed that around a third of fires caused by an electrical fault are caused by arcing, this indicates a few hundred building fires are caused by arcing in Norway every year.

It has therefore been recommended since 2019 to use AFDDs in accordance with IEC 62606 to protect against the effects of series faults [2]. Nevertheless, fewer than a thousand AFDD units have been sold in Norway, suggesting that interest in using the product as a fire prevention measure is low. The reason for this is unclear, but factors may include high cost, limited knowledge of the product in the market, undocumented effect and other measures considered more reliable (effective). For example, a number of fire prevention measures not involving AFDDs have been implemented in recent years in the Norwegian agricultural sector to reduce the risk of fire. The Agricultural Fire Protection Committee (*Landbrukets brannvernkomite*) lists the following information on its website (https://www.lbk.no/brannstatistikk/):

- *In 2020, 141 fires were registered in farm buildings and 140 residential fires, causing damage in excess of NOK 100,000 on Norwegian farms. The total compensation for fires in residential buildings and farm buildings was NOK 254 and 198 million respectively.*

- *A total of 852 farm animals died in fires in 2020. This is significantly lower than the most recent 10-year average, which was 6,800 animals a year but the goal is that no animals should die in fires.*

- *The majority of imminent fires in farm buildings are due to electrical faults, particularly overheating in fuse boxes. Electrical fire prevention inspections using heat-seeking cameras is the most important measure in detecting such issues before a fire occurs. Fire hazard faults have been inspected and repaired on over 20,000 electrical systems.*

- *Preventing fires and being able to extinguish imminent fires are important. Following the demands of the insurance industry introduced in 2016, almost 7,000 farmers have now obtained certificates in hot work, involving firefighting exercises.*

- *Norway was the first country in the world to protect farm animals by using fire alarms. There is now also a requirement for direct notifications to be made to mobile phones.*

- *Temperature sensors are also being tested for installation in fuse boxes in agricultural settings. The aim is to provide notification to a mobile phone if abnormal temperatures are detected. This does not replace electrical controls; however, it enables farmers to monitor hazardous electrical faults between inspections and allows them to call an electrician out for repairs rather than the fire service.*

The above suggests that electrical inspections, notifications and training are fire prevention measures have led to documented good results in Norwegian agriculture. Another measure frequently referred to is automatic extinguishing systems. A report from 2017 presented the following correlation regarding the effect of such extinguishing systems as fire prevention measures [38]:

- *The percentage of fatal fires where an automatic extinguishing system was installed is negligible (0.9%). This is most likely because the vast majority of fatal fires occur in the home, with half of these fires occurring in detached houses where there are no requirements for fire extinguishing systems.*
- *Moreover, a quarter of fatal fires occur in apartment blocks where there are no requirements for fire extinguishing systems unless the block has three or more floors and was designed after 2010. The instances (fatal fires) in the database where extinguishing systems had been installed occurred in institutions where the fire had not developed sufficiently in any of the cases to trigger the system.*
- *The fact that the introduction of a requirement for automatic fire extinguishing systems in all homes may have a significant effect on the number of people killed in fires cannot be excluded. 83% fewer deaths were reported for fires in buildings in the USA where automatic fire extinguishing systems were installed during the period 2004-2013.*
- *A more targeted alternative to permanent automatic fire extinguishing systems may be to strengthen the scheme some municipalities have to deploy mobile automatic fire extinguishing systems for persons where there is an increased risk of fire.*

Stove guards are another fire prevention measure recently introduced. It has been a requirement since 2010 for new homes (including holiday homes) to be fitted with stove guards, which also applies to older homes if a new circuit is fitted for a stove. Schemes have also been created where particularly vulnerable people can have a stove guard fitted free of charge by assistive technology centres. DSB fire statistics suggest that around half of fire service call outs are caused by electric stoves. The fire service responded to 4,323 house fires in private homes in 2019, and 1,847 (44%) of these were registered as fires and imminent fires involving an electric stove. It is unclear how many of these registered cases actually led to a fire, but the fire statistics largely suggest that stoves pose a relatively high risk of fire compared to other consumer equipment in private homes, and stove guards therefore appear to be a targeted fire prevention measure. It is notable that the fire statistics for 2019 provide no information on how many of the stoves where there was a fire or imminent fire had a stove guard fitted, which may have facilitated in understanding how effective stove guards are as a fire prevention measure in Norway. Some Norwegian insurance companies offer premium discounts if an FG-approved stove guard has been fitted. The same applies to performing electrical inspections. Gjensidige states the following on its website (https://www.gjensidige.no/godtforberedt/content/el-kontroll-gir-en-tryggere-hverdag):

- *An electrical inspection is performed by a certified inspector, who checks both the fuse box and the rest of the electrical system hidden in conduits and connections. Sockets, appliances such as stoves and washing machines, smoke alarms and fire extinguishing appliances are also checked. Information is also provided on how to use electrical equipment safely.*
- *You will also receive a form following the inspection informing you of the things that are in order and what may need to be corrected. Once this has been done, you are entitled to a price reduction in the insurance, regardless of whether this is for a permanent home or a holiday home. The exact discount is calculated specifically for each individual case, but is generally between 10 and 20 percent.*

Norwegian insurance companies do not appear to have introduced a similar scheme for fitting AFDDs in accordance with IEC 62606. As previously mentioned, Gjensidige Forsikring was involved over a number of years in the 1990s and 2000s with the development of the Norwegian AFDD ElDetector, suggesting that the insurance industry was previously very interested in introducing AFDDs as a fire prevention measure. The present stance of insurance companies with respect to AFDDs is unclear.

6 Summary and recommendations

DSB's fire statistics contain a significant amount of valuable information and thus are particularly useful to society. Some of the data is easy to register correctly in the database, meaning that the basis for much of the statistics is sound. Regarding the registration of the correct cause of fire, it is evident that there are considerable challenges in creating a database that is good enough. The pie chart in Figure 5 presents the distribution of the eight different causal categories for residential fires caused by an electrical fault in the period 2009-2014 and illustrates this challenge well. Less than half of residential fires were historically registered under a causal category, highlighting the difficulty in determining the cause of fire in cases where electrical energy has been identified as the cause of ignition. Other factors that may play a role are a lack of resources and the expertise of the bodies responsible for fire investigations. The establishment of the BRIS and Knitre databases in 2016 and 2020 respectively may be a step in the right direction in improving the quality of fire causal statistics.

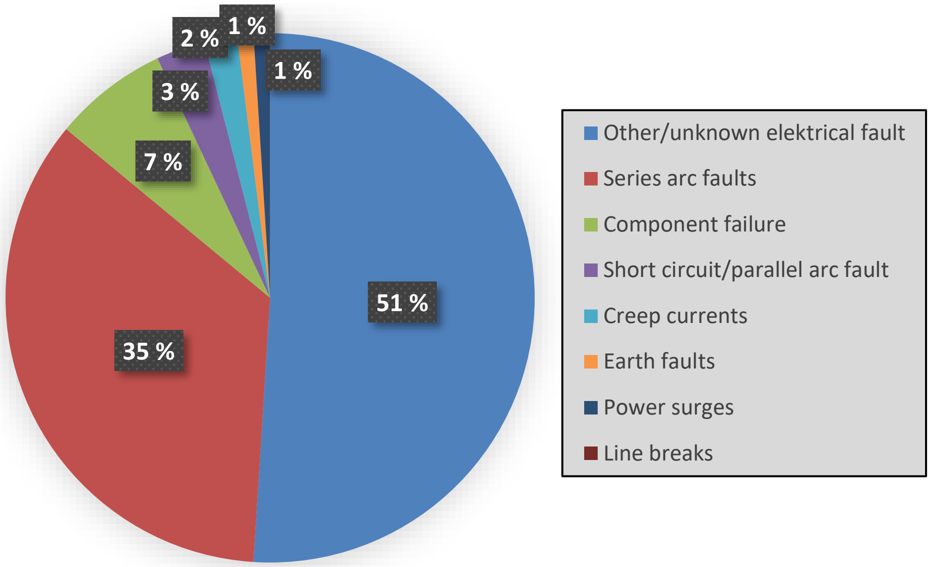

Figure 5: Distribution of the various causal categories for residential fires caused by an electrical fault in the period 2009-2014 [4].

Series arc faults are a major causal category, accounting for around 35% of all residential fires caused by an electrical fault. Since the early 1990s, several specialist disciplines in Norway have highlighted that causes of fire registered as series arc faults are highly likely to be the same phenomenon as that registered as glowing connections in other countries [13]. It is questionable whether DSB's definition of series arc faults is appropriate, and it should be assessed whether the causal category of 'series arc faults' should instead be referred to as 'series faults'. As with resistance heating and glowing connections, arcing may be viewed as part of the sequence of events for a series fault. There is no good scientific basis to suggest that all series faults lead to arcing, or that arcing always triggers the ignition of a fire. There is much to suggest that arcing may be a contributory factor. It has been pointed out that investigations of various fault scenarios have demonstrated the complexity of a series fault in an electrical installation [7]. One of the processes outlined is that the contact surfaces of a weak and sparking contact become oxidised. This leads to a glowing connection and overheating. As the oxidation process develops and the power dissipation increases, the temperature of the glowing filament at the point of contact will reach a critical value and evaporate. It is at this point that the glowing filament will break and an arc may form [7]. The mechanisms involved in the development of a series fault are complex and remain to be fully understood.

Arc formation in electrical installations is a complex phenomenon and further development of the AFDD Standard (IEC 62606) in the form of the introduction of new testing methods and defining more realistic test requirements is appropriate. Several recent scientific studies present a number of proposed improvements to the AFDD Standard based on experimental trials and observations. These proposed improvements include:

- Start the verification of the series arc detection at 1 A, i.e. a significant reduction compared with the current value of 2.5 A.
- Arc energy should be measured directly instead of measuring the break time and comparing the result with the trigger characteristic, i.e. limit values for the arc energy should be introduced instead of a time-current characteristic.
- The tripping characteristic for series arcing should be identical for different mains voltages.
- Carbonised cables should be used to generate series arcs and using an arc generator with graphite and copper electrodes should be avoided.
- Masking and nuisance trip tests should be performed using combinations of more than two appliances, including where there are also capacitive loads on the circuit

There is relatively little documentation addressing the testing of AFDDs under conditions different from those defined in the AFDD Standard. The few scientific studies available are generally not comprehensive enough to reveal whether the reliability of an AFDD in a real-world electrical installation (e.g. in a residential installation) is good enough or not. It is however somewhat concerning that it is apparently relatively easy to construct tests in which AFDDs are either unable to detect dangerous arcing in an electrical circuit or accidentally disconnect (in the case of harmless arcing). Extensive field testing of AFDDs appears to be required to obtain credible documentation of the reliability of AFDDs in order to clarify 1) how well suited AFDDs are to protect against series faults in electrical installations, 2) what percentage detection of dangerous arcing by an AFDD may be anticipated in a real-world electrical installation, and 3) how many accidental disconnections by an AFDD may be anticipated in an ordinary residential installation.

There is a lack of documentation demonstrating that AFDDs constitute an effective fire prevention measure, with no proven link between the use of AFDDs and a reduced fire risk. Fire prevention measures have been introduced in recent years that have proven to be reliable. Inspections of electrical installations have reduced the fire risk in agricultural situations. The introduction of requirements for such inspections, for example in connection with the transfer of residential property, could be considered either in preference to or in combination with the introduction of requirements for AFDDs in residential installations. Consideration should first be given to introducing any requirements for AFDDs gradually, following documentation that these constitute an effective fire prevention measure. A gradual introduction might mean that installations at increased risk (high power load, agricultural buildings, buildings worthy of protection, care/nursing homes and bedrooms, etc.) would be covered by such a requirement first.

Recommendations

The work has led to the following recommendations:

- A review of the causal categories for fires caused by electrical faults is recommended in the Norwegian Directorate for Civil Protection’s (DSB) fire statistics, and it should be assessed whether the causal category of ‘series arc faults’ should be changed to ‘series faults’.

- It is recommended that the General requirements for arc fault detection devices (IEC 62606) be expanded to include new and more comprehensive test requirements, that better reflect conditions in actual electrical installations.

- It is recommended that an independent body conducts a test study (research project) in which a large number of AFDDs are fitted to different types of electrical installations and monitored over time.

- It is recommended that documentation be obtained demonstrating that AFDDs constitute an effective fire prevention measure before any requirement concerning AFDDs in electrical installations is introduced.

7 References

[1] International Electrotechnical Commission (IEC), “General requirements for arc fault detection devices”, IEC 62606, 2013.
[2] Norsk Elektroteknisk Komite (NEK), "Elektriske lavspenningsinstallasjoner", NEK 400:2018, 2018.
[3] Brannstatistikk 2018, "Tall fra rapporteringsløsningen (BRIS) fra brann- og redningsvesenet til DSB", Direktoratet for samfunnssikkerhet og beredskap (DSB), 2019.
[4] M. Fagerås, "Testing av lysbuevern". Master’s thesis, NTNU, 2016.
[5] B. A. Mostue, "Brannskadeutviklingen i Norge - tiltak for å redusere brannskadene", SINTEF NBL as, Rapport NBL A08111, 2008.
[6] A. Steen-Hansen, J. P. Stensaas, S. Fjær, K. Storesund, "Elektriske kabler og brannrisiko", SINTEF NBL as, Rapport NBL A12123, 2012.
[7] J. M. Martel, "Series arc faults in low-voltage AC electrical installations”, PhD thesis, Technische Universität Ilmenau, 2018.
[8] K. Hoare, “Arc Fault Detection Devices (AFDDs) - Are they worth it?”, Hoare Lea Consulting Engineers, November 2020.
[9] J. P. Stensaas, "Branner på grunn av elektrisk installasjonsmateriell", SINTEF NBL as, Rapport NBL A06121, 2007.
[10] M. B. Nilsen. "Seriefeilvern som beskyttelse mot brann". Master’s thesis, NTNU, 2015.
[11] C. O. Larsson. "Seriefeilvern i elektriske installasjoner". Master’s thesis, NTNU, 2012.
[12] V. Babrauskas, "How do electrical wiring faults lead to structure ignitions", Proc. Fire Mater. Conf., pp. 39–51, 2002.
[13] J. Sletbak, R. Kristensen, H. Sundklakk, G. Nåvik and M. Runde, "Glowing contact areas in loose copper wire connections", IEEE Trans. Comp. Hybrids Manufact. Technol., vol. 15, no. 3, pp. 322–327, Jun. 1992.
[14] J. Urbas, “Glowing connections experiments with alternating currents below 1 Arms”, IEEE Holm Conference on Electric Contacts, 2008.
[15] V. Babrauskas, Ignition Handbook, Fire Science Publishers, Issaquah, WA, 2003.
[16] G. Nåvik, B. Aspmo, D. I. Ekrem, R. Kristensen, "Detektor for kontaktfeil/isolasjonsfeil", Energiforsyningens forskningsinstitutt A/S, Technical report no. TR 3811, 1991.
[17] B. A. Mostue, J. P. Stensaas, "Analyse av DSBs brannstatistikk for bygningsbranner i tiårsperioden 1994-2003", SINTEF NBL as, Rapport NBL A04122, 2004.
[18] B. A. Mostue, "Brannskadeutviklingen i Norge sammenlignet med andre nordiske land – Årsaker til forskjeller", SINTEF NBL as, Rapport NBL A06116, 2006.
[19] K. Storesund, A. S. Hansen, B. A. Mostue, C. Sesseng, "Hendelser med brann i elektriske anlegg", SINTEF NBL as, Rapport NBL A12137, 2012.
[20] J. P. Stensaas, "Varmgang i elektrisk materiell og utstyr som tennkilde i bygninger", SINTEF NBL as, Rapport NBL A06122, 2007.
[21] J. P. Stensaas og K. Nygård, "Brann på grunn av elektrisk feil i installasjonsmateriell og lavtemperatur varmepåvirkning fra belysning", SINTEF NBL as, Rapport NBL A08120, 2008.
[22] B. A. Mostue, “Brannskadeutviklingen i Norge – Tiltak for å redusere brannskadene”, SINTEF NBL as, Rapport A08111, 2008.
[23] A. S. Hansen, J. P. Stensaas, S. Fjær, K. Storesund, “Elektriske kabler og brannrisiko”, SINTEF NBL as, Rapport NBL A12123, 2012.
[24]V. Babrauskas, "Mechanisms and modes for ignition of low-voltage PVC wires, cables and cords", Fire and Materials, pp. 291–309, 2005.
[25] V. Babrauskas, "Mechanisms and modes for ignition of low-voltage, PVC-insulated electrotechnical products”, Fire and Materials, pp. 151–174, 2006.
[26] J. Shea, "Glowing contact physics", in Electrical contacts-2006, proceedings of the fifty-second IEEE Holm conference on, 2006, pp. 48–57.

[27] J. Shea, "Conditions for Series Arcing Phenomena in PVC Wiring", IEEE Transactions on Components and Packaging Technologies Volume 30, pp. 532–539 (2007)
[28] J. Shea and X. Zhou, "Material effect on glowing contact properties", in Electrical contacts-2007, the 53rd IEEE Holm conference on, 2007, pp. 90–97.
[29] J. Shea, "Identifying causes for certain types of electrically initiated fires in residential circuits", Fire and Materials, vol. 35, pp. 19–42, 2011.
[30] Siemens Industry Inc., “History of the AFCI”, white paper, 2012.
[31] J. Banks, R. L. Rardin, “Selected International Comparisons of Fire Loss”, Georgia Institute of Technology, 1980.
[32] DIN VDE 0100-420:2016-02 Errichten von Niederspannungsanlagen Teil 4-42: Schutzmaßnahmen – Schutz gegen thermische Auswirkungen
[33] Teknisk Ukeblad, "En gnistrende verdensnyhet", Produktnyheter, 15 August 2001. https://www.tu.no/artikler/en-gnistrende-verdensnyhet/273258
[34] Siemens AG, 5sm6 AFD unit. technical manual, siemens ag infrastructure and cities sector low and medium voltage division, 2012.
[35] Direktoratet for samfunnstryggleik og beredskap (DSB), “Kjenneteikn og utviklingstrekk ved dødsbrannar og omkomne i brann - Ein gjennomgang av DSBs statistikk over omkomne i brann 1986–2009, Rapport, 2010.
[36] G. Alqabbani, "Tests of series arching and arc fault detection devices in low voltage systems”, Masteroppgave, KTH Royal Institute of Technology, 2021.
[37] LiveWire Innovation, Arc Chaser™ LW-AC120
[38] C. Sesseng, K. Storesund, A. Steen-Hansen, "Analyse av dødsbranner i Norge i perioden 2005 – 2014", RISE Fire Research, RISE-rapport A17 20176:1, 2017.