

Application of RCD and AFDD in low-voltage electrical installations for protection against fire

Abstract. The paper presents the principles of application of residual current devices (RCDs) in protection against fire. The permissible rated residual operating current of RCDs is discussed. Limitations in the operation of RCDs in this type of protection are indicated. A new type of a protective device against fire – arc fault detection device (AFDD) – is described.

Streszczenie. Artykuł przedstawia zasady stosowania wyłączników różnicowoprądowych w ochronie przed pożarem. Przeanalizowano wymagania odnośnie do największego dopuszczalnego prądu różnicowego zadziałania tych wyłączników. Zwrócono uwagę na przypadki, w których wyłączniki różnicowoprądowe mogą nie działać, mimo zagrożenia pożarowego. Omówiono również nowy typ zabezpieczeń w ochronie przed pożarem – urządzenia do detekcji zwarć łukowych.

(Stosowanie zabezpieczeń RCD i AFDD w instalacjach elektrycznych niskiego napięcia do ochrony przed pożarem).

Keywords: residual current devices, arc fault detection devices, fire protection.

Słowa kluczowe: wyłączniki różnicowoprądowe, urządzenia do detekcji zwarć łukowych, ochrona przed pożarem.

Introduction

One of the sources of fire in buildings is a leakage current flowing through the resistive elements, e.g. conductive dust or a carbonized insulation of conductors. Such a current flow may warm up these elements to the temperature causing fire [1-3]. Due to leakage currents, a fire of wooden poles of an overhead line may arise [4]. In some cases, an explosion of explosive conductive materials may occur. When organic materials like wood or straw are heated by the current for a relatively long time, their gradual transition to the pyrophoric phase has to be taken into account. Because of the heating, the fire resistance of these materials significantly decreases – the minimum ignition temperature changes from 250 °C to even 120 °C [3, 5]. Fire may also be ignited by arc short-circuits or by a series arcing due to mechanical damage of a cable or a plug (e.g. cable crushing by a heavy object) [6, 7].

As protection against fire in low-voltage electrical installations, residual currents devices (RCDs) are used [8]. These devices disconnect supply in case of detection of earth current, which may initiate fire [3]. Such devices are also proposed to be a protective one in conjunction with fire alarm sensors [9]. However, some types of arc faults may not be detected by RCDs, especially series arcing, because no residual current flows in case of such a fault. For protection against such an accident, arc fault detection devices (AFDDs) are recommended to be used. In some countries, their application is obligatory [10, 11].

The further part of the paper presents the principles of RCDs and AFDDs application in low-voltage electrical installation, in order to prevent fire.

Residual current devices in fire protection

Leakage current flowing through the resistive elements may produce an amount of heat sufficient to initiate fire. This amount of heat is expressed by the following dependence:

$$(1) \quad P_{th} = U_o \cdot I_{\Delta}$$

where: P_{th} – thermal power produced by leakage current, U_o – line-to-earth nominal voltage, I_{Δ} – leakage current.

Risk of fire can be reduced by the application of RCDs, provided that their rated residual current has value limiting the thermal power (1) to the permissible level. In a low-voltage power network of nominal voltage equal to

230/400 V, the highest thermal power produced in a circuit with an RCD is as in Tabl. 1.

Table 1. The highest thermal power produced by leakage current in a circuit of nominal line-to-earth voltage 230 V, for selected values of the rated residual current of RCDs

Rated residual current of RCDs mA	Thermal power W
30	7
100	23
300	69
500	115

The question is: which value included in Tabl. 1 is the permissible one (to avoid fire)? For many years permissible value of the rated residual current of RCDs in Poland was adopted as equal to 500 mA. This value is indicated in standard PN-IEC 60364-4-482:1999 [12]. However, newer parts of the standard of PN-HD 60364 series modify the above-mentioned requirement (≤ 500 mA) – they consider the application of RCDs, among others, for locations with risks of fire due to the nature of processed or stored materials, as presented below.

According to PN-HD 60364-4-42:2011 [13] (Clause 422.3.9), in TN and TT systems final circuits as well as current-using equipment shall be protected against insulation faults by RCDs of a rated residual operating current $I_{\Delta n} \leq 300$ mA. Where resistive faults may cause a fire (it may occur in overhead heating with heating film elements), RCDs of $I_{\Delta n} \leq 30$ mA shall be applied. In IT systems, insulation monitoring devices (RCMs) shall be used. Alternatively, RCDs with a rated residual operating current as specified above may be provided.

According to PN-HD 60364-5-53:2016 [8] (Clauses 532.2 and 532.3), for protection against the risk of fire, RCDs with a rated residual operating current $I_{\Delta n} \leq 300$ mA are required to be used. These devices shall be installed at the origin of the circuit to be protected. In IT systems, RCMs may be used as an alternative to RCDs, but only in locations which are supervised by instructed (BA4) or skilled (BA5) persons. The RCMs have to be installed at the origin of final circuits. Their rated residual operating current shall not exceed 300 mA.

Provision referring to the application of RCDs in installations with the risk of thermal effect is also included in standard PN-HD 60364-7-753:2014-12 [14] (heating cables and embedded heating systems). In this standard, the

Clause 753.415.1 informs that circuits supplying heating units shall have additional protection by the use of RCDs of $I_{\Delta n} \leq 30$ mA. Delayed type RCDs are not permitted. The above-mentioned provision [14] refers to additional protection (protection against electric shock), not protection against fire. However, heating systems, especially embedded systems, may give an increased risk of fire, and the use of RCDs of $I_{\Delta n} \leq 30$ mA is suitable for such a protection as well.

An analysis of the considerations regarding the use of RCDs for protection against fire leads to the conclusion that RCDs suitable for this kind of protection should have a rated residual operating current not exceeding 300 mA (in special cases $I_{\Delta n} \leq 30$ mA). This statement is valid for installations of nominal voltage 230/400 V. In other installations the permissible value of the rated residual operating current of RCDs is different. The condition is the equivalent value of the thermal power coming from leakage current. For example, in an installation of nominal voltage 400/690 V (line-to-earth nominal voltage is 400 V), maximal permissible value of the rated residual current is 100 mA ($69 \text{ W} / 400 \text{ V} = 172 \text{ mA} \Rightarrow I_{\Delta n} \leq 100 \text{ mA}$), not 300 mA. For an installation of nominal voltage 127/230 V maximal permissible value of $I_{\Delta n}$ can theoretically be higher than 300 mA. Fig. 1 presents the rated residual current of RCDs as a function line-to-earth voltage and assumed thermal power which should not be exceeded.

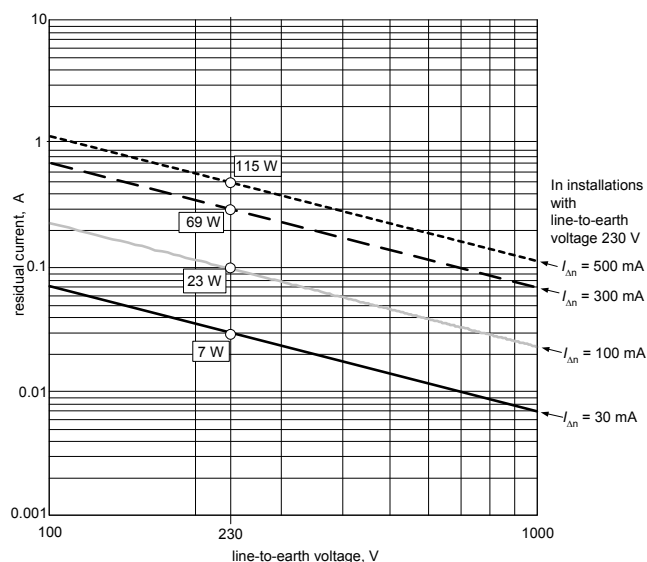


Fig. 1. Rated residual current $I_{\Delta n}$ of RCDs as a function of line-to-earth voltage and assumed thermal power which should not be exceeded [3]

When considering protection against fire with the use of RCDs, it has to be mentioned that in some cases RCDs may be “blinded”. RCDs may not react if a leakage/earth fault current is strongly distorted, in spite of the fact that the value of this current is very high [15-20]. Moreover, in three-phase systems, leakage currents flowing from each line conductor may symmetrize themselves (Fig. 2), and resultant current – residual current from the point of view of the installed RCD – is close to zero. In fact, insulation of conductors may be in bad condition, very high risk of fire exists, but the RCD does not react. Thus, one should remember that there are some cases in which RCDs in protection against fire are not adequate.

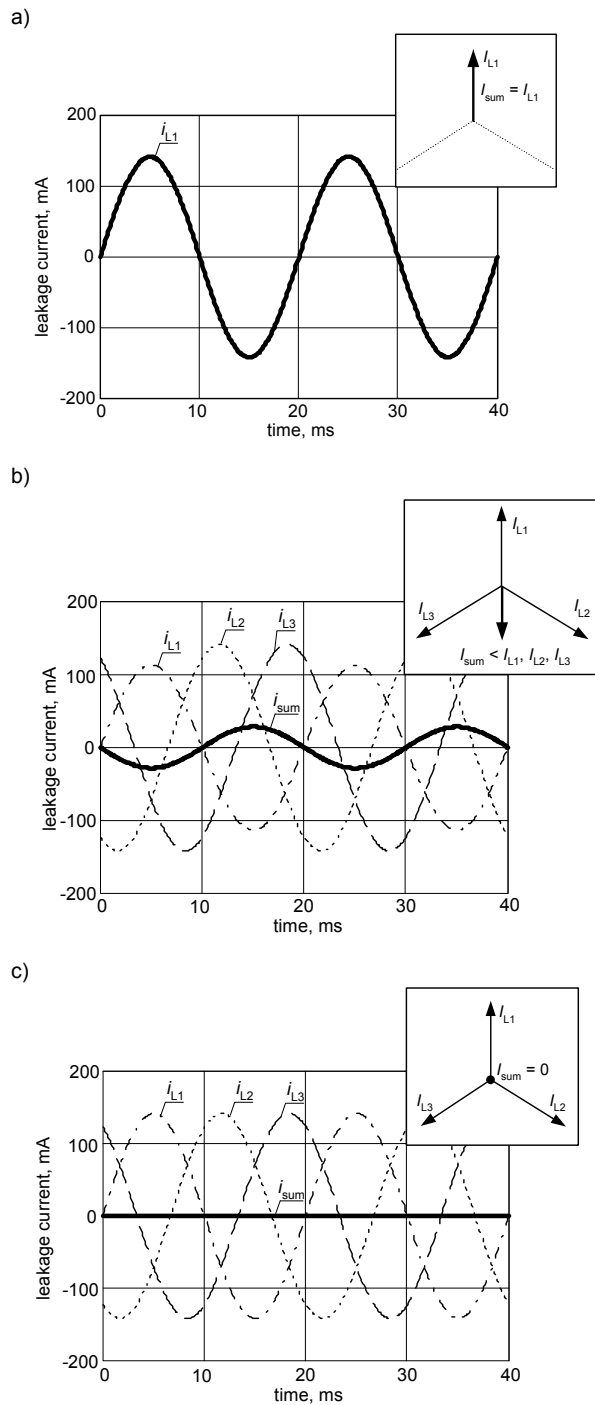


Fig. 2. Resultant current I_{sum} composed of leakage currents I_{L1} , I_{L2} , I_{L3} flowing from: a) phase L1: $I_{\text{sum}} = I_{L1} = 100$ mA, b) phases L1, L2, L3: $I_{L1} = 80$ mA, L2: $I_{L2} = 100$ mA, L3: $I_{L3} = 100$ mA; $I_{\text{sum}} = 20$ mA, c) phases L1, L2, L3: $I_{L1} = I_{L2} = I_{L3} = 100$ mA; $I_{\text{sum}} = 0$ mA

Arc Fault Detection Devices

Fire hazard also arises due to arcing in electrical installations. Earth faults with arcing can be detected by RCDs or circuit-breakers, but there are cases in which these protection devices are ineffective. For detection of faults with arcing, arc fault detection devices are recommended to be used. This is a new type of protection devices that is just beginning to appear in domestic electrical installations [21-24]. These devices have been used in the USA for many years [10] and have recently been required to be used in Germany [11].

If a resistive fault with the electric arc occurs between the phase (line) conductor and the neutral conductor

(Fig. 3a), the circuit-breaker (MCB) may operate if the value of the fault current is high enough to activate an overcurrent release of the MCB. In the case of a short-circuit between the phase conductor and the protective conductor, the residual current device (RCD) and/or the circuit-breaker (MCB) may operate – Fig. 3b. It is not possible to activate the tripping mechanism of the RCD in the case of series arcing (Fig. 3c), because there is no residual current. Series arcing is characterized by a relatively low value of current (this current is also a load current of the current-using equipment) – therefore the MCB may operate in a limited range (only for a sufficient current value). Detection of series arcing – even low-current arcing – is possible by AFDDs.

Requirements for AFDDs operation are included in standard PN-EN 62606:2014-05 [25]. This standard recognizes three types of arc faults in terms of the use of AFDDs:

- parallel arc fault – arc fault where the current is flowing between active (live) conductors in parallel with the load of the circuit,
- earth arc fault – arc fault where the current is flowing from active (live) conductor to earth,
- series arc fault – arc fault where the current is flowing through the load of the final circuit protected by an AFDD.

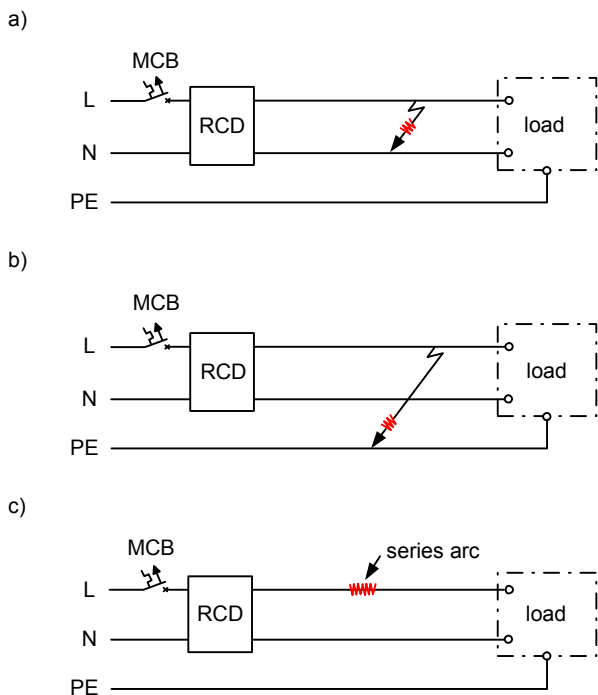


Fig.3. Arc fault: a) parallel, between L-N, b) earth, between L-PE, c) series, due to damage of line conductor; MCB – circuit-breaker, RCD – residual current device

Tripping characteristic of AFDDs depends on the value of the arc current. When test arc current is up to 63 A (low arc currents), the maximum break time t_b as a function of the value of the arc current I_{arc} is specified (Fig. 4). For example, if the arc current is equal to 2.5 A, the time is $t_b = 1$ s. For the arc current equal to 63 A, the maximum break time is $t_b = 0.12$ s. In case of high arc current (above 63 A), the standard [25] specifies the maximum number of half cycles N at the rated frequency as a function of prospective arc current I_{p-arc} (Fig. 5).

Arc fault detection devices should be constructed in such a way that they do not react on the arc that occurs

during normal operation of electric equipment. This arc may appear during switching on lighting devices or electronic devices as well as appears in case of the normal operation of motors, e.g. electric drills. The correct distinction of the arc coming from fault and the arc appearing during normal operation of the equipment is not an easy task and requires the use of an advanced system of detection and identification of arc parameters. The decisive criterion for the operation of the AFDD cannot only be the rms value of the load current or the current amplitude because in case of series arc fault these values are very small, they can be significantly smaller than the load current in the circuit without fault, but the fire hazard exists.

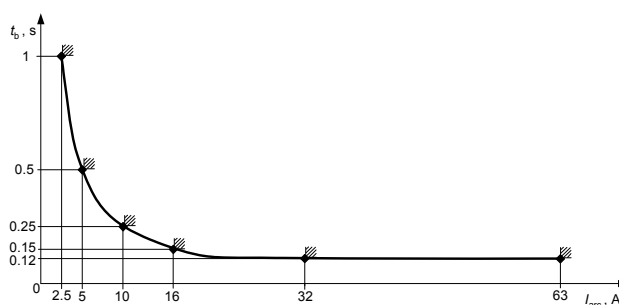


Fig.4. Required tripping characteristic of AFDDs for low arc current (up to 63 A) [25]; t_b – maximum break time, I_{arc} – test arc current (rms values)

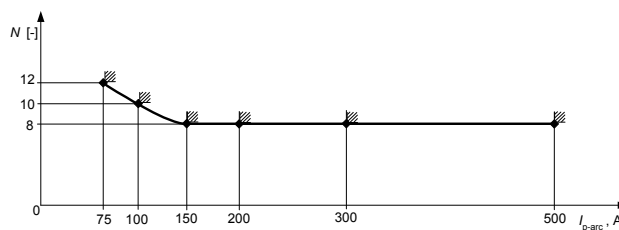


Fig.5. Required tripping characteristic of AFDDs for high arc current (above 63 A) [25]; N – the number of half cycles at the rated frequency, I_{p-arc} – prospective arc current (rms values)

A system for detection and identification of arc fault adopted in AFDDs analyzes especially an RSSI (*received signal strength indicator*), which is utilized in telecommunications and reflects the power present in a received radio signal. Comparison of this indicator coming from arc fault and coming from load current of electric equipment (mainly high-frequency components of the analyzed currents) enables to distinguish a fault from a normal state. Fig. 6 presents a comparison of the RSSI signal of an arc with the RSSI signal coming from a vacuum cleaner load current, an electric drill load current, and a home control signal [26].

According to the standard [25], AFDDs should not react during the following tests reflecting the operation of electric equipment in 230 V circuits:

- starting and operation of a vacuum cleaner with a rated current within the range (5÷7) A,
- turning on an electronic switching mode power supply, having a load current at least 2.5 A; this power supply should have a minimum total harmonic distortion (THD) of 100% and individual minimum current harmonics of 75% at the 3rd, 50% at the 5th, and 25% at the 7th,
- starting and operation of a capacitor-start motor (air compressor type), with a rated power of 2.2 kW,
- turning on an electronic lamp dimmer (thyristor type) 600 W with filtering coil controlling a 600 W tungsten

load; the dimmer should be turned on with the dimmer preset at full on, conduction angles of 0°, 60°, 90°, 120°, and at the minimum setting that causes the lamps to ignite,

- turning on and operation two 40 W fluorescent lamps plus an additional 5 A resistive load,
- turning on and operation of 12 V halogen lamps powered with an electronic transformer with a total power of at least 300 W plus an additional 5 A resistive load,
- turning on and operation an electric hand tool such as a drill with at least 600 W power.

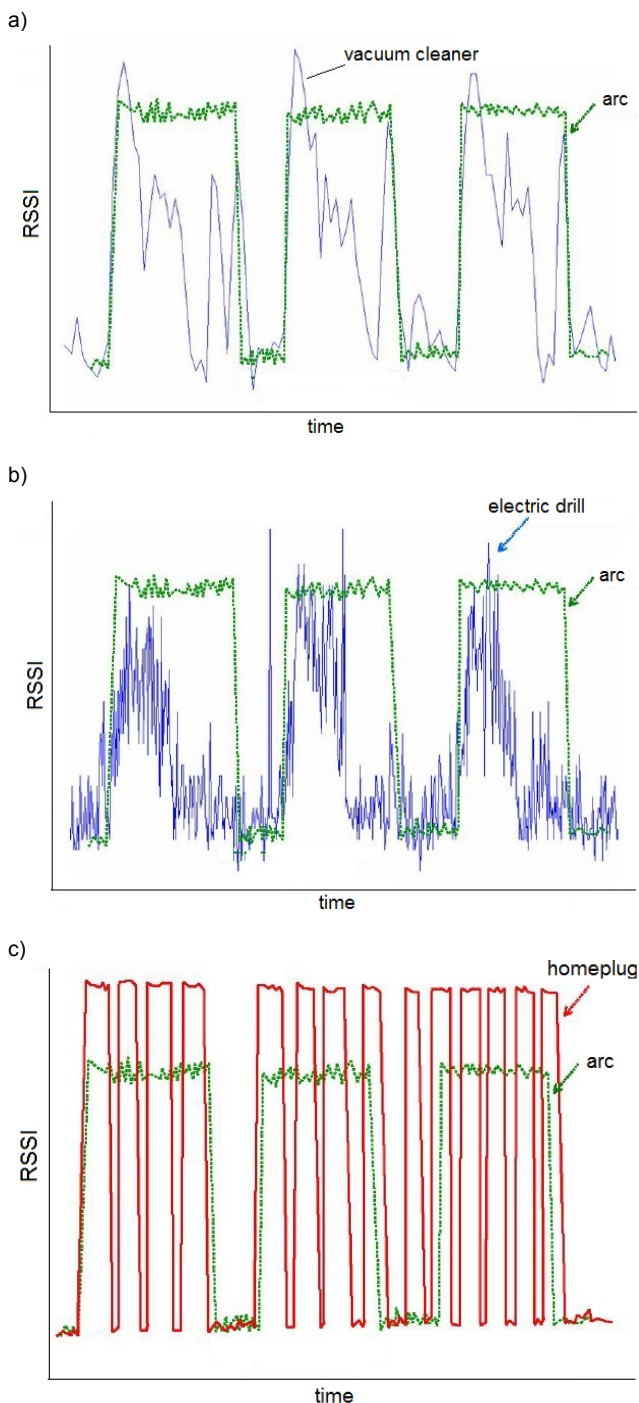


Fig.6. Comparison of RSSI signal from arc with RSSI signal from: a) vacuum cleaner load current, b) electric drill load current, c) home control signal [26]

Five Start-Stop operations are required to be performed. The loads are energized during the tests at least 5 s.

An AFDD can be constructed as a separate protective device or can be integrated with an RCD and an MCB. The standard [25] describes preferred and standard values, from which the following are the most important, in terms of the selection of AFDDs:

Rated voltage U_n

Preferred values: 230 V and 120 V (USA).

Rated current I_n

Preferred values: 6 – 8 – 10 – 13 – 16 – 20 – 25 – 32 – 40 – 50 – 63 A.

Rated frequency f

Preferred values: 50 Hz and 60 Hz; if another value of the rated frequency is used, it shall be marked on the device. Relevant tests shall be carried out at this frequency.

Minimum value of the rated making and breaking capacity I_m , Minimum value of the rated making and breaking capacity on one pole I_{m1}

The minimum value of both parameters (I_m and I_{m1}) is $10I_n$ or 500 A, whichever is the greater. A similar requirement is referred to RCDs without integrated circuit-breakers [3, 27]. Thus, AFDDs shall be back-up protected.

Rated conditional short-circuit current I_{nc}

Rated conditional short-circuit current for one pole I_{nc1}

Standard values of these currents (values of AC component of a prospective current, which an AFDD, protected by a suitable short-circuit protective device in series, can withstand under the specified conditions) are: 3 kA, 4,5 kA, 6 kA, 10 kA, 20 kA and 25 kA.

Recommendations regarding the application of AFDDs in low-voltage installations are included in standard PN-HD 60364-4-42:2011/A1:2015-01 [28]. According to this standard (Clause 421.7), protection with the use of these devices is preferred in final circuits supplying current-using equipment in the following places:

- in premises/rooms with sleeping accommodations,
- in barns, wood-working shops, stores of combustible materials (increased risk of fire due to the nature of processed or stored materials),
- in wooden buildings and other buildings made of combustible constructional materials,
- in fire propagating structures, e.g. very high buildings;
- in locations containing endangering or irreplaceable goods.

AFDDs are required in low-voltage installations in the USA for many years. They are called AFCIs (*arc fault circuit interrupter*). According to National Electrical Code [10], AFCIs have to protect circuits (120 V, 15 A and 20 A) supplying outlets installed in dwelling unit family rooms, dining rooms, living rooms, parlors, libraries, dens, bedrooms, sunrooms, recreation rooms, closets, hallways, or similar rooms or areas.

In the USA, these devices are also obligatory in PV installations of a rated voltage 80 V and above if the installations are integrated with a building [29]. Such AFDDs shall be suitable for application in DC circuits.

The requirement for the use of AFDDs was introduced in Germany in the 2016 year [11]. They are required in low-voltage circuits of a rated current up to 16 A, for supplying electric devices installed especially in: bedrooms, daycare facilities for children, homes for older or disabled people, in locations with increased risks of fire (combustible building materials), and in locations with irreplaceable goods – locations similar to those mentioned in standard PN-HD 60364-4-42:2011/A1:2015-01 [28].

Conclusions

Application of RCDs of a rated residual current not exceeding 300 mA in low-voltage installations may increase the fire safety of buildings. However, it should be mentioned that in some cases RCDs may not detect a significant value of current, in spite of the real fire hazard. It may occur when a leakage current is strongly distorted or when in a three-phase circuit the insulation of conductors is deteriorated on the same level in each phase (almost identical value of leakage current flows from each phase). For protection against fire caused by an arc fault, mainly AFDDs should be used. They are able to detect even series arc fault, which is characterized by a relatively low value of current, and no residual current appears, what excludes the possibility of detection of such a fault by RCDs.

Author: dr hab. inż. Stanisław Czapp, prof. PG, Gdańsk University of Technology, Faculty of Electrical and Control Engineering, ul. G. Narutowicza 11/12, 80-233 Gdańsk, Poland, E-mail: stanislaw.czapp@pg.edu.pl

REFERENCES

- [1] Chung-Seog Ch., Kil-Mok S., Hyung-Rae K., Dong-Woo K., A study on the carbonization characteristics of insulating materials between RCD terminals deteriorated by NaCl solutions, *Proceedings of the 7th International Conference on Properties and Applications of Dielectric Materials*, (2003), Vol. 1, 427-430
- [2] Chybowski R., Wpływ degradacji izolacji roboczej przewodów instalacyjnych na działanie wyłącznika różnicowoprądowego, *XV Konferencja Naukowo-Techniczna „Bezpieczeństwo Elektryczne ELSAF 2005” i V Szkoła Ochrony Przeciwporażeniowej*, Wrocław, (2005), 80-85
- [3] Czapp S., Musiał E., Wyłączniki ochronne różnicowoprądowe – część 2, *Monografie INPE*, zeszyt 59, (2017), COSiW SEP, Warszawa, Zakład Wydawniczy INPE w Belchatowie, ISBN 978-83-945411-4-9
- [4] Sokolowski P. J., Dwivedi A., Pathak S., Buratto F., Yu X., Investigating the impedance of a wooden power pole after a pole fire, *2008 Australasian Universities Power Engineering Conference*, (2008), 1-6
- [5] Krasucki F., Zagrożenia elektryczne w górnictwie. Wyd. Śląsk, Katowice (1984)
- [6] Arc fault detection devices AFDD, Application manual, OEZ Minia, (2017)
- [7] Electrically ignited fires in Low Voltage Installations, EATON, (2016)
- [8] PN-HD 60364-5-53:2016-02 Low-voltage electrical installations – Part 5-53: Selection and erection of electrical equipment – Switchgear and controlgear
- [9] Konieczny J., Zacirka R., Wykorzystanie wyłączników różnicowoprądowych jako elementów wykonawczych dla czujników przeciwpożarowych, *XIX Konferencja Naukowo-Techniczna „Bezpieczeństwo Elektryczne ELSAF 2013” i IX Szkoła Ochrony Przeciwporażeniowej*, Szklarska Poręba, (2013), 123-128
- [10] National Electrical Code (NEC), (2008)
- [11] DIN VDE 0100-420:2016-02 Errichten von Niederspannungsanlagen Teil 4-42: Schutzmaßnahmen – Schutz gegen thermische Auswirkungen
- [12] PN-IEC 60364-4-482:1999 Electrical installations of buildings – Part 4: Protection for safety – Chapter 48: Choice of protective measures as a function of external influences – Section 482 – Protection against fire
- [13] PN-HD 60364-4-42:2011 Low-voltage electrical installations – Part 4-42: Protection for safety – Protection against thermal effects
- [14] PN-HD 60364-7-753:2014-12 Low-voltage electrical installations – Part 7-753: Requirements for special installations or locations – Heating cables and embedded heating systems
- [15] Czapp S., The effect of earth fault current harmonics on tripping of residual current devices, *International School on Nonsinusoidal Currents and Compensation, IX Conference-Seminar (ISNCC) Łagów*, (2008), 1-6
- [16] Czapp S., The impact of d.c. earth fault current shape on tripping of residual current devices, *Elektronika ir Elektrotechnika*, 84 (2008), No. 4, 9-12
- [17] Czapp S., The effect of PWM frequency on the effectiveness of protection against electric shock using residual current devices, *Przegląd Elektrotechniczny*, 87 (2011), No. 1, 24-27
- [18] Czapp S., Guzinski J., Electric shock hazard in circuits with variable-speed drives, *Bull. Pol. Ac.: Tech.*, 66 (2018), No. 3, 361-372
- [19] Czapp S., Borowski K., Verification of safety in low-voltage power systems without nuisance tripping of residual current devices, *Electric Power Systems Research*, 172 (2019), 260-268
- [20] Czapp S., Method of earth fault loop impedance measurement without nuisance tripping of RCDs in 3-phase low-voltage circuits, *Metrol. Meas. Syst.*, 26 (2019), No. 2, 217-227
- [21] Asfani D. A., Negara I M. Y., Daniar F., Rifki W., Haq M. W. A., Wahyudi M., Analysis of low voltage arcing characteristic on direct short circuit through arcing thermal synchronization sensing and short circuit current, *2017 International Seminar on Intelligent Technology and Its Applications (ISITIA)*, (2017), 165-168
- [22] Gregory G. D., Scott G. W., The arc-fault circuit interrupter: an emerging product, *IEEE Transactions on Industry Applications*, 34 (1998), Iss. 5, 928-933
- [23] Martel J.-M., Anheuser M., Berger F., Time-current tripping characteristics at series arcing for Arc Fault Detection Devices, *The 27th International Conference on Electrical Contacts (ICEC)*, (2014), 1-6
- [24] Martel J.-M., Anheuser M., Berger F., A study of arcing fault in the low-voltage electrical installation, *Proceedings of the 56th IEEE Holm Conference on Electrical Contacts*, (2010), 1-11
- [25] PN-EN 62606:2014-05 General requirements for arc fault detection devices
- [26] Restrepo C. E., Arc fault detection and discrimination methods. *53rd IEEE Holm Conference on Electrical Contacts*, (2007), 115-122
- [27] PN-EN 61008-1:2013-05 Residual current operated circuit-breakers without integral overcurrent protection for household and similar uses (RCCBs) – Part 1: General rules
- [28] PN-HD 60364-4-42:2011/A1:2015-01 Low-voltage electrical installations – Part 4-42: Protection for safety – Protection against thermal effects
- [29] Johnson J., Oberhauser Ch., Montoya M., Fresquez A., Gonzalez S., Patel A., Crosstalk nuisance trip testing of photovoltaic DC Arc-Fault Detectors, *38th IEEE Photovoltaic Specialists Conference*, (2012), 1383-1387