EKSPLOATACJA I NIEZAWODNOŚĆ
MAINTENANCE AND RELIABILITY

Eksploatacja i Niezawodnosc – Maintenance and Reliability
Volume 24 (2022), Issue 2
journal homepage: http://www.ein.org.pl

Article citation info:
Czapp S, Tariq H, Szultka S, Szultka A, Zaitseva E, Levashenko V. Electrical safety in low-voltage DC microgrids with B-type residual current devices. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2022; 24 (2): 346–358, http://doi.org/10.17531/ein.2022.2.16.

Electrical safety in low-voltage DC microgrids with B-type residual current devices

Indexed by: Web of Science Group

Stanislaw Czapp[a,*], Hanan Tariq[a], Seweryn Szultka[a], Agata Szultka[b], Elena Zaitseva[c], Vitaly Levashenko[c]

[a] Gdańsk University of Technology, Faculty of Electrical and Control Engineering, ul. Narutowicza 11/12, 80-233 Gdańsk, Poland
[b] Energa-Operator SA, ul. Marynarki Polskiej 130, 80-557 Gdańsk, Poland
[c] University of Žilina, Faculty of Management Science and Informatics, Univerzitná 8215/1, 010 26 Žilina, Slovakia

Highlights

- Analyzing possible use of protective residual current devices in modern power systems.
- Determining the protective ability of RCDs for protection in DC microgrids.
- Indicating weak points of these protections applied in DC power systems.
- Electrical safety enhancement by redundant RCDs.

Abstract

Residual current devices (RCDs) are most popular devices used in low-voltage installations for protection against electric shock and fire. In cases of high risk of electric shock the application of RCDs is mandatory. Currently, the spread of local direct current (DC) microgrids is widely considered. This creates new challenges for protective systems, in particular those based on RCDs. The main purpose of the research is to test the operation of B-type RCDs by simulating the conditions that may occur in DC microgrids as well as assessment of the effectiveness of electrical safety with the use of such RCDs. The research has revealed that theoretically identical RCDs in terms of technical data can have different tripping properties, including no reaction to residual direct current, which poses a risk of electric shock. This signalizes the necessity of extension of the normative tests performed by manufacturers. The scope of these additional RCDs tests is indicated, from the point of view of the persons' safety in DC microgrids.

Keywords

DC microgrids, low-voltage systems, protection against electric shock, reliability, residual current devices.

1. Introduction

In the classical approach, electrical installations and devices in domestic or public utility buildings are supplied from 50 Hz sinusoidal alternating current (AC) power distribution networks. For this reason, electrical installations inside buildings, both in distribution and final circuits, are AC installations (usually 230/400 V). However, in recent years, there is a growing trend to apply a direct current (DC) microgrid as a local distribution network inside buildings [27, 31], especially commercial buildings [30, 41]. It may also be a network interconnecting buildings as presented in [4]. The DC microgrid enables easy integration of renewable power sources such as photovoltaic (PV) systems, wind power plants [7], fuel cells [32], as well as their connection to battery storage units [26]. Such a grid may conveniently cooperate with electric vehicles (EV) to be an intelligent charging system [18], also for wireless charging [47], ensure bidirectional power flow [37] or even be utilized for cooperation with special vehicles [34]. Electric vehicles connected to the grid may operate as energy storage units for balancing the load curve in the power system in Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) technologies [45]. Fig. 1 presents a general structure of the system utilizing a DC bus for energy distribution in the building.

Experiences from the utilization of an in-building DC microgrid supplied by local renewable energy sources indicate [44] that these microgrids are flexible in operation and economically attractive. The system utilizes a DC 380 V bus to distribute energy and to supply selected loads. The economic advantages of DC installation are also named in papers [29, 42]. The installation presented in [29] utilizes the following DC voltages: 12, 48, 65, 120, 190, and 380 V.

One of the most important issues which has to be considered when both designing and using DC microgrids is the safety of persons and equipment. There are many papers related to the control, reliability and safety of equipment. In the studied literature, various strategies of control of DC microgrids are discussed, including finite control set model [1], grid interface current directly controlled by a battery DC-DC converter [2], the control of the energy sources in the DC microgrid by the application of result adaptive proportional integral control [12], or application of mixed-integer nonlinear programming [14]. Other way of the control [15] uses effective autonomous decen-

(*) Corresponding author.
E-mail addresses: S. Czapp (ORCID: 0000-0002-1341-8276): stanislaw.czapp@pg.edu.pl, H. Tariq (ORCID: 0000-0001-5547-1094): hanan.tariq@pg.edu.pl, S. Szultka (ORCID: 0000-0003-4642-774X): seweryn.szultka@pg.edu.pl, A. Szultka (ORCID: 0000-0002-1234-7824): agata.szultka@energa-operator.pl, E. Zaitseva (ORCID: 0000-0002-9087-0311): elena.zaitseva@fri.uniza.sk, V. Levashenko (ORCID 0000-0003-1932-3603): vitaly.levashenko@fri.uniza.sk

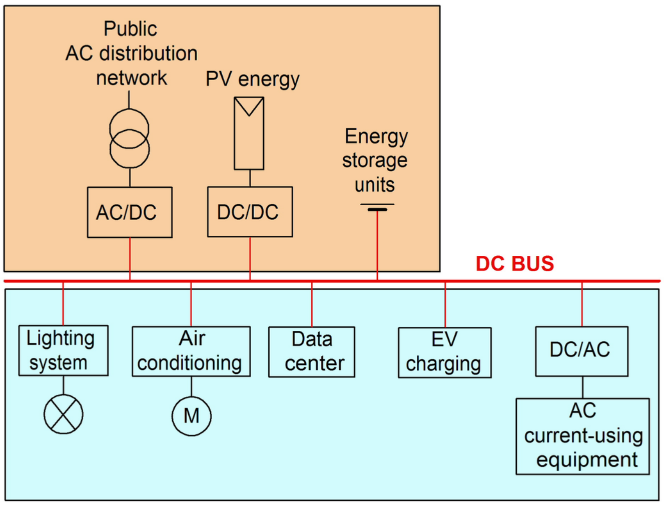

Fig. 1. General structure of the system utilizing a DC bus for energy distribution inside the building

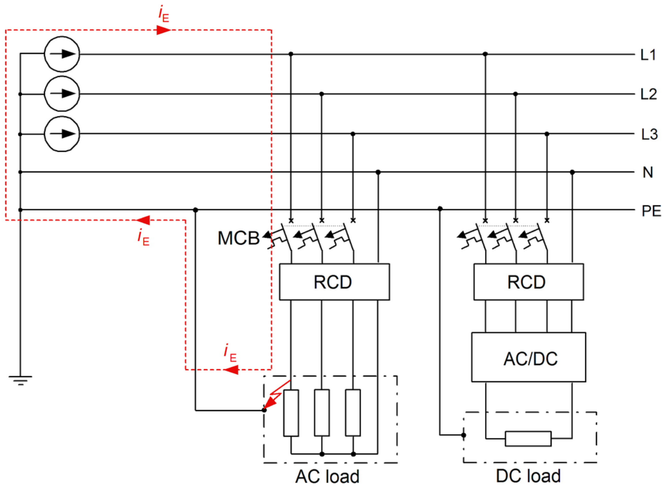

Fig. 2. The structure of low-voltage AC 230/400 V installation, and the flow of earth fault current i_E in the case of insulation-to-earth fault in AC load. MCB – overcurrent protection device (miniature circuit breaker), RCD – residual current device

tralized stabilizing control of DC microgrids, whereas in the paper [24], a strategy for controlling the charge and discharge of a battery bank in parallel with a DC microgrid fed by alternative energy sources is presented. On the other hand, reliability of supply in DC microgrids in considered in the paper [40]. With regard to protection systems in such grids, only equipment functional aspects, as presented mainly in [25, 46], are considered. Thus, a wide literature study shows that the problem how to maintain persons' safety, especially protection against electric shock, has not been deeply considered yet. The purpose of the authors of this article is to analyze the persons' safety aspect, which will fill the current gap in the field of DC microgrids.

From the persons' safety point of view, every electrical installation, regardless of whether AC or DC, has to fulfill the requirements of the standard [21]. This standard specifies the fundamental rule according to which the hazardous-live-parts are not allowed to be accessible, and the conductive parts are not allowed to be hazardous live:

- either in normal conditions, i.e., when there is no fault in the electrical safety system, or
- in single-fault conditions (usually related with insulation damage).

To achieve a sufficient level of safety in single-fault conditions, the following measures of protection can be used [16]:

- automatic disconnection of supply (following the insulation fault),
- double or reinforced insulation,
- electrical separation,
- non-conducting location,
- Safety-Extra Low-Voltage (SELV) or Protective-Extra Low-Voltage (PELV).

Out of the aforementioned measures, the automatic disconnection of supply is most commonly used. According to the standard [16], to prevent fatal electric shock when an insulation-to-earth fault occurs (Fig. 2), the protective device should disconnect the supply within the specified time. In final circuits of typical TN low-voltage AC 230/400 V installations, the maximum permissible time is equal to 0.4 s, while in installations with a similar voltage but of DC type, this time is 1 s.

An overcurrent protection device or a residual current device (RCD) may be used as a device responsible for disconnection of supply [9, 16]. The RCD is very often used for this purpose, and what is more, in some types of installations, e.g., electric vehicle charging installations [19], its use is obligatory. Selecting a given RCD, as well as assessing the reliability of its operation should be conducted very carefully. To make sure that the selected RCD is an effective protection device, its selection must be closely coordinated with the waveform shape of the earth fault current which may occur in the protected circuit. With reference to high-frequency residual current it is considered in [8, 11], whereas effects of harmonics are extensively studied and proved in papers [10, 39] but supraharmonics in the paper [13]. International standards [20, 22] recognize the following types of RCDs in terms of their ability to detect the waveform shape:

- AC – for residual sinusoidal alternating currents of network frequency (usually 50/60 Hz) only;
- A – as for AC-type, and for: residual pulsating direct current of specified current delay angles; residual pulsating direct current superimposed by a smooth direct component of 6 mA;
- F – as for A-type, and for: composite residual currents in circuits supplied between phase and neutral or phase and earthed middle conductor; residual pulsating direct currents superimposed on smooth direct current (smooth DC up to 10 mA);
- B – for residual sinusoidal alternating currents up to 1 kHz; for residual alternating currents superimposed by a smooth direct current of 0.4 times the rated residual current; for residual pulsating direct currents superimposed by a smooth direct current of 0.4 times the rated residual current or 10 mA, whichever has a higher value; for residual direct currents obtained from rectifying circuits as: two-pulse bridge connection line-to-line for 2-, 3- and 4-pole RCDs, three-pulse star connection or six-pulse bridge connection for 3- and 4-pole RCDs; for residual smooth direct currents.

Fig. 3 presents the structures of selected RCDs. The detection of the earth fault (residual) current i_Δ is based on the use of an iron core current transformer (CT). This current transformer is responsible for the transformation of current i_Δ to the secondary side of the CT, as well as for the production of the induced secondary voltage e_s and the current i_s. The secondary current i_s interacts with the relay (RE) and initiates its tripping if the value of current i_Δ exceeds the predetermined level dangerous for a human.

As can be seen, the detection of the earth fault current is performed with the use of an iron core current transformer, therefore it is very important to match the RCD to the expected waveform shape of the current. The most difficult for detection is a direct current with negligible pulsation (such as that from bridge diode rectifier or electrochemical DC power source, e.g., battery energy storage unit), because the magnetic induction in the iron core does not vary as sufficiently as in the case of sinusoidal current. In that case, it is not possible to induce appropriate voltage e_s at secondary side of the current transformer. In DC microgrids, the earth fault current with negligible pulsation has to be taken into account, and this current can only be detected by a B-type RCD. A special system requiring an auxiliary voltage is used

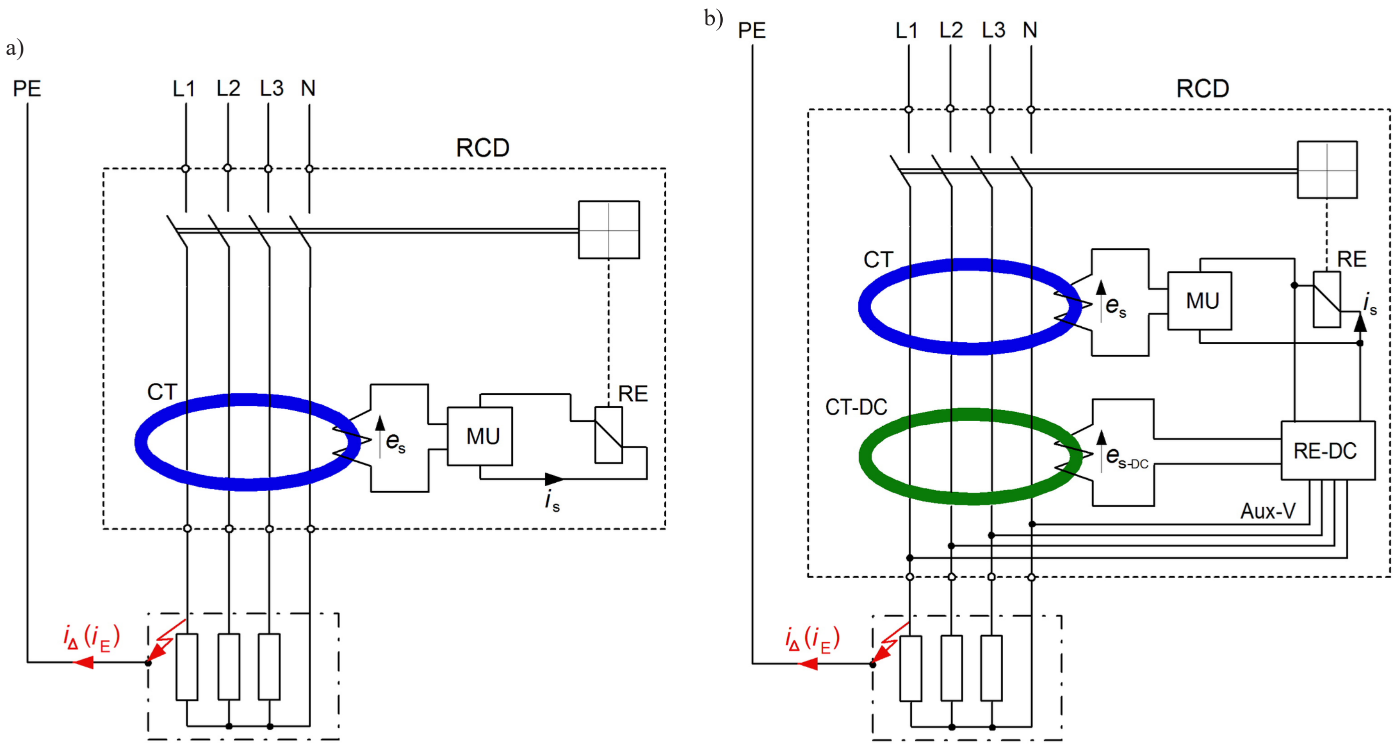

Fig. 3. The structures of selected residual current devices (RCDs): a) A-type, b) B-type; CT – current transformer for detection of AC residual currents and pulsating DC residual currents, CT-DC – current transformer for smooth DC current detection, MU – matching electronic unit for detection of pulsating DC residual currents or introducing the delay in tripping, RE – relay, RE-DC – special relay for smooth DC current detection, Aux-V – auxiliary voltage delivered to the relay RE-DC for smooth DC current detection, iΔ (iE) – residual (earth fault) current, is – secondary current flowing through the relay RE, es, es-DC – voltages induced at secondary side of the respective current transformers

in B-type RCDs to detect smooth direct current. In RCDs of many manufacturers, this system is composed of an additional current transformer (CT-DC) and a DC relay (RE-DC) – Fig. 3b. The analysis of the RCD data sheets presented by manufacturers ETI [3], ABB [35], and Doepke [36] shows that the auxiliary AC voltage of not less than 50 V is required to ensure proper operation of the RE-DC relay. This voltage should be connected to at least two poles.

Due to the fact that B-type RCDs, according to the manufacturers' data, require an auxiliary voltage to detect direct current, the following tests of their operational properties have been carried out in terms of their use in DC microgrids:

1) auxiliary voltage AC 230 V is used – it reflects the power supply to the DC network through a rectifier, and the RCD is installed at AC side of the rectifier; such a condition is assumed as a reference (normative),
2) auxiliary voltage DC 230 V is used – it reflects the potential use of RCDs in microgrid circuits in which only DC voltage is available,
3) auxiliary voltage is not used – it reflects a disturbance in the auxiliary voltage system.

For each of the three abovementioned variants and each RCD tested, the following aspects were checked:

- the tripping threshold of the RCDs with slowly rising residual current,
- the response of the RCDs to the suddenly applied direct current of a predetermined value.

Extensive studies of the literature and international standards provisions show that the problem of RCDs tripping in DC microgrids has not been analyzed so far. RCDs have not been tested in such aspects, hence the results of the research provide a new insight into the use of RCDs in more and more popular DC microgrids. Recognition of the properties of RCDs in such grids is very important from the point of view of persons' safety. The main purpose of the research is to test the operation of B-type RCDs by simulating the conditions that may occur in DC microgrids, and assessment of the effectiveness of persons' safety when such RCDs are applied. This test allows to identify weak points of these devices in terms of the effectiveness of protection against electric shock and fire. The results presented in this article can be the basis for extending the requirements of product standards relating to RCDs testing, before they are introduced to the market. This may improve the safety level in low-voltage systems.

The paper is organized as follows. Section 2 presents the results of detailed RCD testing for both slowly raising and suddenly applied DC residual current. These results are commented with reference to the suitability of RCDs for DC microgrids. Section 3 includes overall assessment of the tested B-type RCDs if used in such microgrids, along with the proposed modification of provisions of standards related to RCDs. This section also discusses increasing the level of safety through RCDs redundancy. Section 4 provides general conclusions and final assessment of B-type RCDs.

2. Laboratory testing of RCDs

2.1. Description of the laboratory setup and the scope of the test

The verification of the real ability of B-type RCDs for detecting smooth DC currents has been performed using the laboratory setup presented in Fig. 4. This setup is composed of:

- generator Gen-DC for producing smooth DC current I_{DC},
- rheostat R to adjust the value of the test current I_{DC},
- an ammeter for checking the value of the current which causes the tripping of the tested RCD,
- system Aux-V for an auxiliary voltage (AC 230 V or DC 230 V) delivered to selected poles of the RCD,
- the RCD under test.

Four B-type, 4-pole RCDs of a rated residual operating current $I_{\Delta n}$ = 30 mA have been tested. For testing purposes, these RCDs were

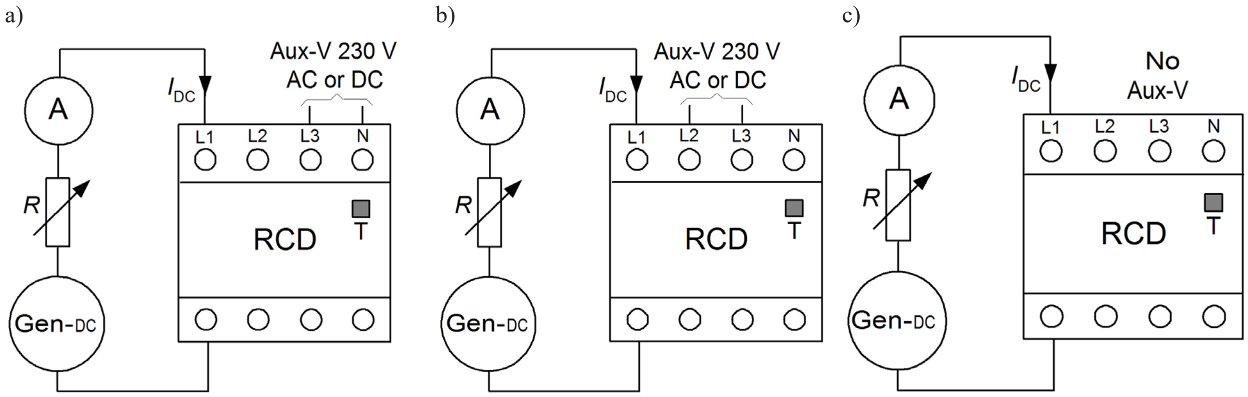

Fig. 4. Variants of RCD connection to the test circuit: a) auxiliary voltage delivered to L-N terminals, b) auxiliary voltage delivered to L-L terminals (L1-L2 or L1-L3 or L2-L3), c) no auxiliary voltage; Gen-DC – DC voltage generator, R – rheostat, A – ammeter, I_{DC} – smooth DC test current generated by Gen-DC, Aux-V – auxiliary voltage (AC 230 V or DC 230 V), T – TEST button for periodic rough operational verification of RCD

marked as RCD-B1, RCD-B2, RCD-B3 and RCD-B4. Each RCD was from a different manufacturer.

The test current I_{DC} was forced through one RCD pole, which reflected the flow of the earth fault (residual) current in a real circuit. As the auxiliary voltage should be applied to at least two poles of the B-type RCD, in the case presented in Fig. 4a this voltage was connected to poles L-N (in a real circuit the phase conductor L and the neutral conductor N are connected to these poles) whereas in the case presented in Fig. 4b – to two phase poles L-L (in a real circuit two phase conductors are connected to these poles). In the third case (Fig. 4c), no auxiliary voltage was delivered to the RCD.

According to the information presented in the previous section, diverse variants of RCD tripping have been verified. To show the scope of RCD testing in a clear and readable manner, individual tests are listed and commented in Table 1.

2.2. RCDs testing under slowly rising residual current

Before a detailed verification of RCDs, each RCD was tested by pressing the TEST button. This initial test was intended to verify that the RCD is mechanically sound and will provide correct results in further more detailed tests. After connecting the voltage to the two poles of the TEST button circuit (first AC 230 V, and then DC 230 V), each RCD operated correctly after pressing the TEST button. These positive results allowed for further research.

The testing under slowly rising residual current aimed to verify the tripping threshold of the RCD. The residual current was gradually increased (from almost zero) to achieve the tripping of the tested RCD. The value of the current at the tripping point was read from the ammeter. According to the standard [22], the proper tripping range for a smooth DC current is $(0.5–2.0)I_{\Delta n}$, i.e., for the tested RCDs it is within 15–60 mA. Fig. 5 presents the results of this test. The RCD-B1 (Fig. 5a) reacted properly each time, provided that the auxiliary voltage was connected. The tripping values were around 30 mA, that is, close to $I_{\Delta n}$. For this RCD, it was irrelevant whether the auxiliary voltage was AC or DC and whether it was connected to the L-N or L-L poles. In the case of no auxiliary voltage, the RCD-B1 did not react even to the highest value of the forced current, i.e., $20I_{\Delta n}=600$ mA (this case is marked “No tripping” in Fig. 5a).

The RCD-B2 showed similar properties (Fig. 5b). Its tripping current was about 25 mA for each variant of connecting the auxiliary voltage, and the lack of operation was noted in the absence of this voltage. The RCD-B3 showed worse properties (Fig. 5c). It operated well with the auxiliary AC voltage, however, when connecting the auxiliary DC to the L-L poles, there was no reaction to the residual current. The same effect was obtained in the absence of auxiliary voltage. The worst results were recorded with RCD-B4 (Fig. 5d). It did not respond to the residual current with auxiliary DC voltage connected, as well as without any auxiliary voltage. Such an RCD will

Table 1. Individual tests carried out during 30 mA B-type RCD testing

Test current I_{DC}	Auxiliary voltage					Comments
	AC 230 V		DC 230 V		No	
	poles L-N	poles L-L	poles L-N	poles L-L		
slowly rising	tested	tested	tested	tested	tested	Determination of the tripping threshold. The slowly rising current reflects gradual deterioration of the insulation-to-earth in the circuit.
suddenly applied with values: $0.5I_{\Delta n}$ = 15 mA $0.67I_{\Delta n}$ = 20 mA $I_{\Delta n}$ = 30 mA $2I_{\Delta n}$ = 60 mA $3I_{\Delta n}$ = 90 mA $5I_{\Delta n}$ = 150 mA $10I_{\Delta n}$ = 300 mA	tested	tested	tested	tested	tested	Checking the RCD’s response to a suddenly applied earth fault current. This sudden increase of the current reflects an earth fault in the circuit, or a human contact with the enclosure/conductor under voltage. This is a check of the RCD tripping at the most likely fault in electrical installation.
TEST buton pressing	tested with AC 230 V voltage delivered to the TEST circuit		tested with DC 230 V voltage delivered to the TEST circuit		not tested *	Verification of the correction of connections and general RCD’s ability for operation. The RCD should trip.

** If there is no voltage, the RCD does not respond to pressing the TEST button (as a rule).*

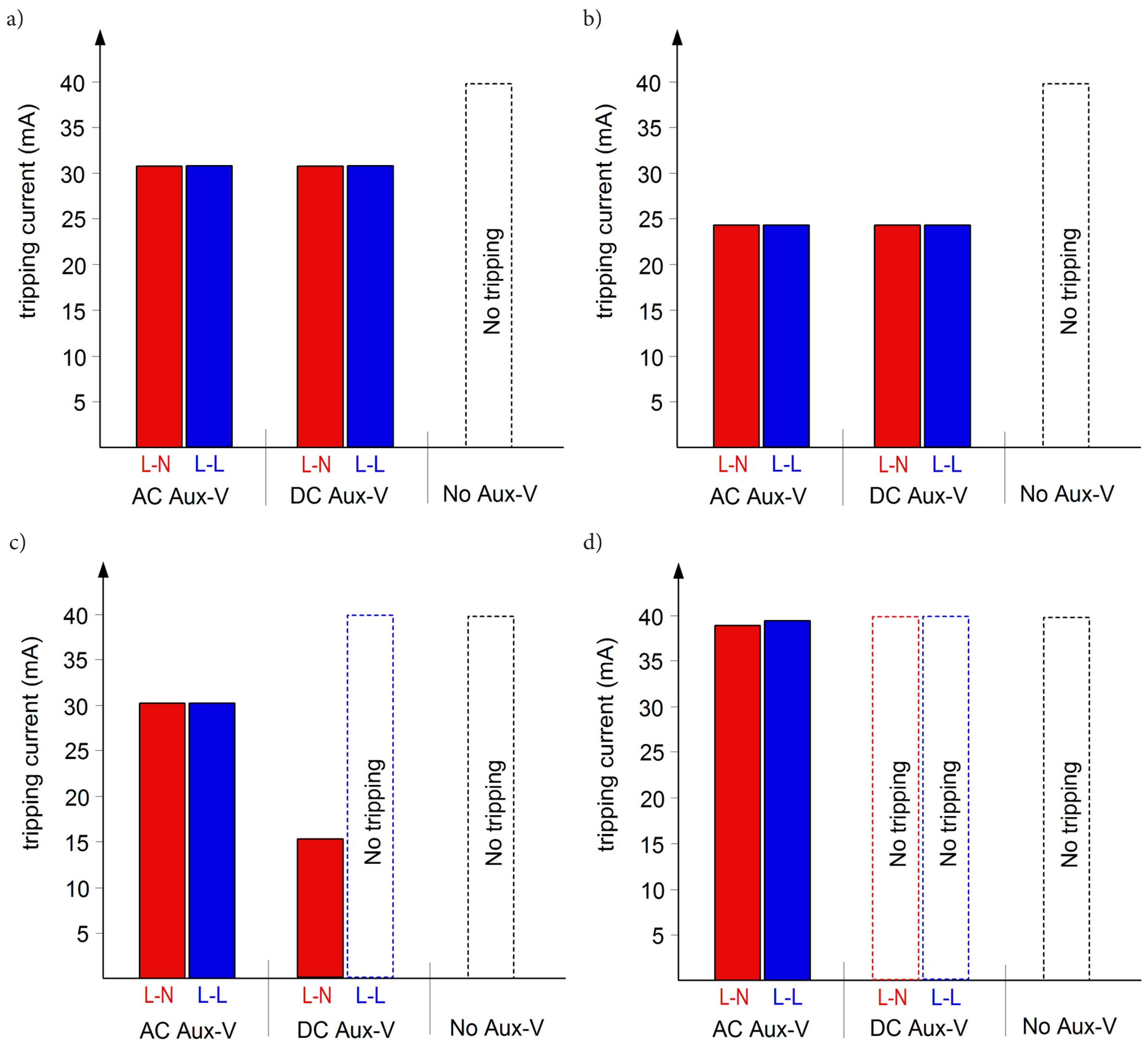

Fig. 5. Tripping current of 30 mA B-type RCDs during slowly rising smooth DC residual current. The RCDs are from: a) manufacturer 1 (marked RCD-B1), b) manufacturer 2 (marked RCD-B2), c) manufacturer 3 (marked RCD-B3), d) manufacturer 4 (marked RCD-B4); AC Aux-V – auxiliary voltage AC 230 V, DC Aux-V – auxiliary voltage DC 230 V, No Aux-V – no auxiliary voltage, L-N – auxiliary voltage connected to poles: phase L and neutral N, L-L – auxiliary voltage connected to two phase poles

not operate well in a typical DC microgrid when only DC voltage is available at input terminals of the RCD.

2.3. RCDs testing under suddenly applied residual current

Testing of RCDs under suddenly applied residual current reflects their real behaviour when an earth fault current starts to flow, or a person touches an enclosure with persisting dangerous voltage. At the moment of touching this enclosure, the body current suddenly starts to flow. During this test, a residual current with one of the predetermined values: 15, 20, 30, 60, 90, 150 and 300 mA was forced, and the "Tripping" or "No tripping" state of the RCD was recorded (Fig. 6 – Fig. 9).

Fig. 6 depicts the results of this test related to RCD-B1. Its behaviour is similar to that observed for slowly raised residual current. When the auxiliary voltage was delivered (AC or DC, regardless of poles), the tripping of the RCD-B1 occurred for the current of 30 mA or higher. These are positive results. The "No tripping" was noted for the cases without auxiliary voltage.

Slightly worse results were recorded for RCD-B2 (Fig. 7) and RCD-B3 (Fig. 8) when they were tested with the auxiliary voltage applied. For the auxiliary AC voltage, the RCD-B2 reacted to residual currents of 30 mA or higher (regardless of poles L-N or L-L). However, in the case of DC voltage, the tripping occurred at 30 mA and higher for L-N pole connection, while for L-L pole connection, it only occurred for residual currents of 90 mA and higher. For RCD-B3, its response was similar in the presence of the auxiliary AC voltage but slightly different for DC voltage. In this latter case, RCD-B3 tripped even at 15 mA and also at higher residual currents for L-N pole connection, while for L-L pole connection, RCD-B3 tripped only at 90 mA and higher. A very interesting behaviour of RCD-B2 and RCD-B3 was observed when no auxiliary voltage was delivered. Both of these RCDs reacted: RCD-B2 for currents 90, 150 and 300 mA, whereas RCD-B3 for currents 150 and 300 mA. It should be noted that with a slowly rising residual current, the aforementioned RCDs did not react to even as much as 600 mA.

The observed response of these RCDs to a suddenly applied residual current i_Δ in the absence of an auxiliary voltage is due to the fact that such a current/waveform has a high rise rate, higher than the sinusoidal current (Fig. 10), and this high rise rate may induce sufficient voltage e_s (being the function of the current rise rate di_Δ/dt) in the secondary winding of CT (Fig. 3b):

$$e_s = f(di_\Delta/dt) \quad (1)$$

Thus, the operation of the B-type RCD may be based on CT response (as auxiliary voltage is not necessary for its operation) and not on CT-DC response (Fig. 3b). A similar behaviour was observed for the last tested RCD, i.e., RCD-B4 (Fig. 9). Despite the worst char-

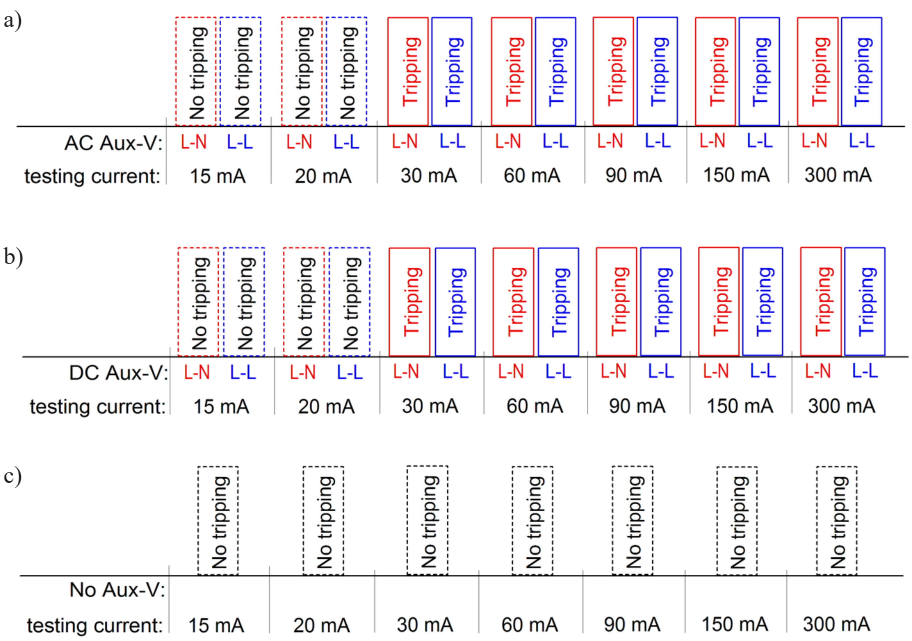

Fig. 6. Response of the 30 mA RCD-B1 to the suddenly applied DC residual current of: 15, 20, 30, 60, 90, 150 and 300 mA: a) AC 230 V auxiliary voltage used, b) DC 230 V auxiliary voltage used, c) no auxiliary voltage used; L-N – auxiliary voltage connected to poles: phase L and neutral N, L-L – auxiliary voltage connected to two phase poles

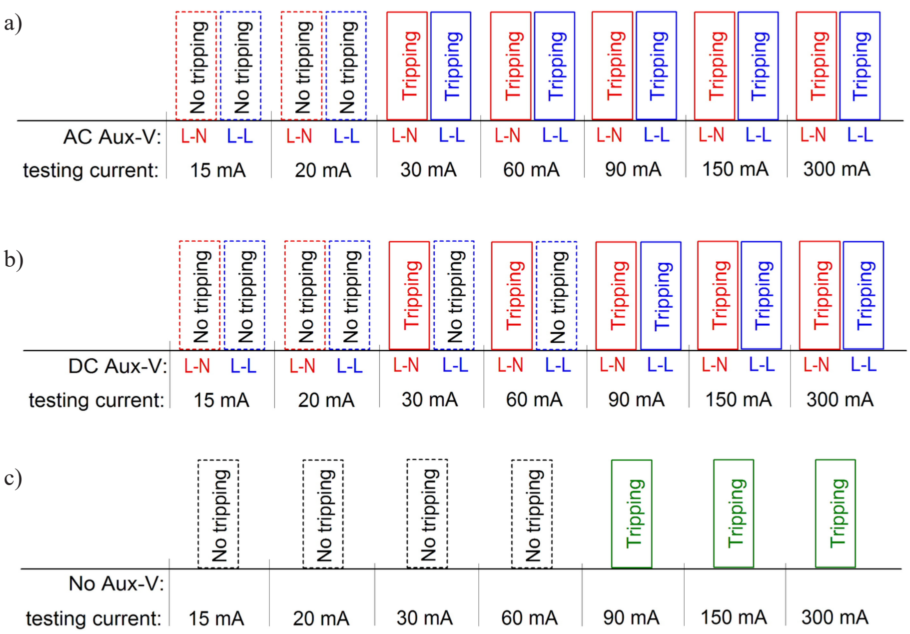

Fig. 7. Response of the 30 mA RCD-B2 to the suddenly applied DC residual current of: 15, 20, 30, 60, 90, 150 and 300 mA: a) AC 230 V auxiliary voltage is used, b) DC 230 V auxiliary voltage used, c) no auxiliary voltage used; L-N – auxiliary voltage connected to poles: phase L and neutral N, L-L – auxiliary voltage connected to two phase poles

acteristics for a slowly rising residual current (Fig. 5d) and suddenly applied current with the presence of auxiliary voltage (Fig. 9ab), this RCD reacted to suddenly applied current of 150 mA and 300 mA without auxiliary voltage. So as one can see, the most probable fault, i.e., high-value-current earth fault or touching an enclosure, produces a sufficiently rapid increase of the residual current, and hence, gives relatively favourable conditions for tripping of RCDs.

2.4. Oscillograms of current waveforms during RCD tripping

The oscillograms of the suddenly applied waveforms enable to observe the real disconnection time of the RCD, as well as to investigate properties of the two detection systems (associated with CT or CT-DC in Fig. 3b). The oscillograms have been recorded for various values of the suddenly applied residual current, but this paper presents only the selected case (for DC 300 mA) as an example.

Fig. 11 presents the results obtained for RCD-B1. As can be seen, the disconnection time (22 ms) does not depend on the type of the auxiliary voltage (Fig. 11a vs. Fig. 11b). This RCD was the only one which did not trip at 300 mA with no auxiliary voltage.

In the case of RCD-B2 (Fig. 12), the disconnection time for both types of auxiliary voltage both AC and DC was the same (20 ms). However, this RCD behaved differently in cases with no auxiliary voltage. It not only reacted to the residual current, but also the disconnection time was clearly shorter (12 ms) than when the auxiliary voltage was connected. Since there was no auxiliary voltage, only the first detection system (associated with CT in Fig. 3b) might operate, and it occurred. This was possible because, as aforementioned, the suddenly applied residual current of 300 mA has a high rise rate and is able to produce sufficient secondary voltage e_s.

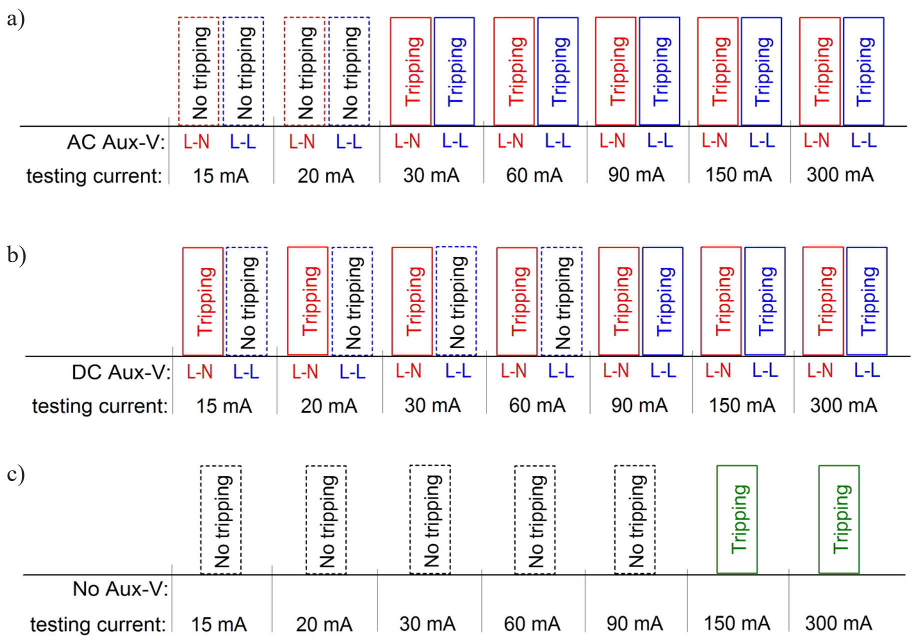

Fig. 8. Response of the 30 mA RCD-B3 to the suddenly applied DC residual current of: 15, 20, 30, 60, 90, 150 and 300 mA: a) AC 230 V auxiliary voltage used, b) DC 230 V auxiliary voltage used, c) no auxiliary voltage used; L-N – auxiliary voltage connected to poles: phase L and neutral N, L-L – auxiliary voltage connected to two phase poles

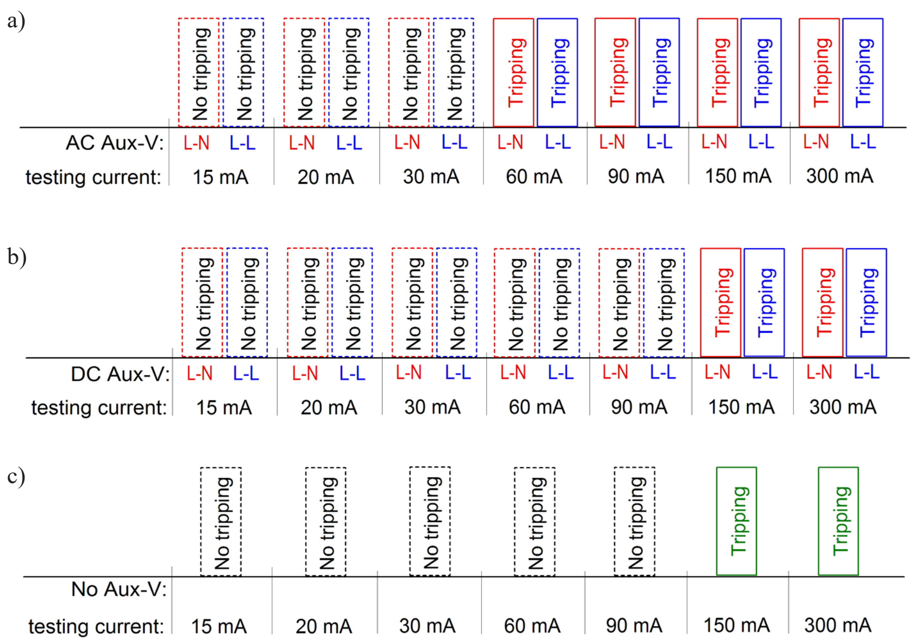

Fig. 9. Response of the 30 mA RCD-B4 to the suddenly applied DC residual current of: 15, 20, 30, 60, 90, 150 and 300 mA: a) AC 230 V auxiliary voltage used, b) DC 230 V auxiliary voltage used, c) no auxiliary voltage used; L-N – auxiliary voltage connected to poles: phase L and neutral N, L-L – auxiliary voltage connected to two phase poles

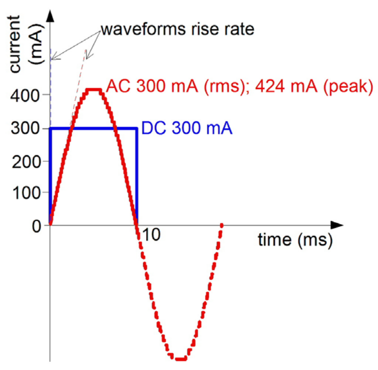

Fig. 10. Comparing the rise rates of the sinusoidal 50 Hz AC (300 mA rms) and DC (300 mA) waveforms

In the case of RCD-B3 (Fig. 13), the disconnection time for a residual current of 300 mA was always the same (for AC and DC auxiliary voltages, or when no auxiliary voltage was applied). It was equal to 24 ms.

Another behaviour was observed for RCD-B4 (Fig. 14). Here, the longest disconnection time at 300 mA occurred for the AC auxiliary voltage (30 ms – Fig. 14a), while in other two cases (Fig. 14b and Fig. 14c), only 10 ms was recorded. This is quite an unexpected positive feature of this RCD. With a high probability, the CT system, and not CT-DC, responded in these two cases.

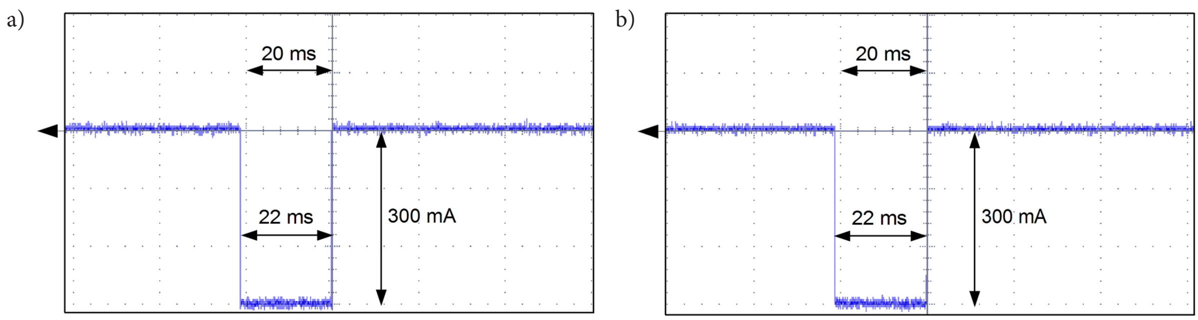

Fig. 11. Residual current oscillograms during the operation of 30 mA RCD-B1 under the suddenly applied DC residual current of 300 mA: a) AC 230 V auxiliary voltage used (poles L-N), b) DC 230 V auxiliary voltage used (poles L-N); no tripping when no auxiliary voltage used

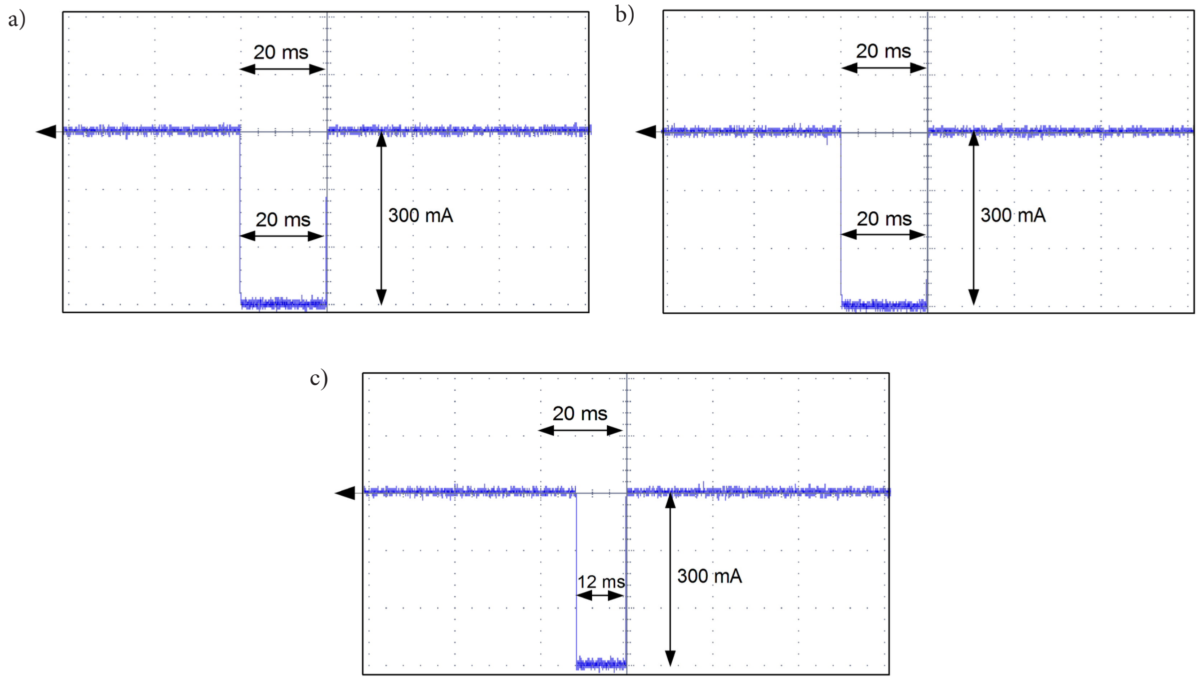

Fig. 12. Residual current oscillograms during the operation of 30 mA RCD-B2 under the suddenly applied DC residual current of 300 mA: a) AC 230 V auxiliary voltage used (poles L-N), b) DC 230 V auxiliary voltage used (poles L-N), c) no auxiliary voltage used

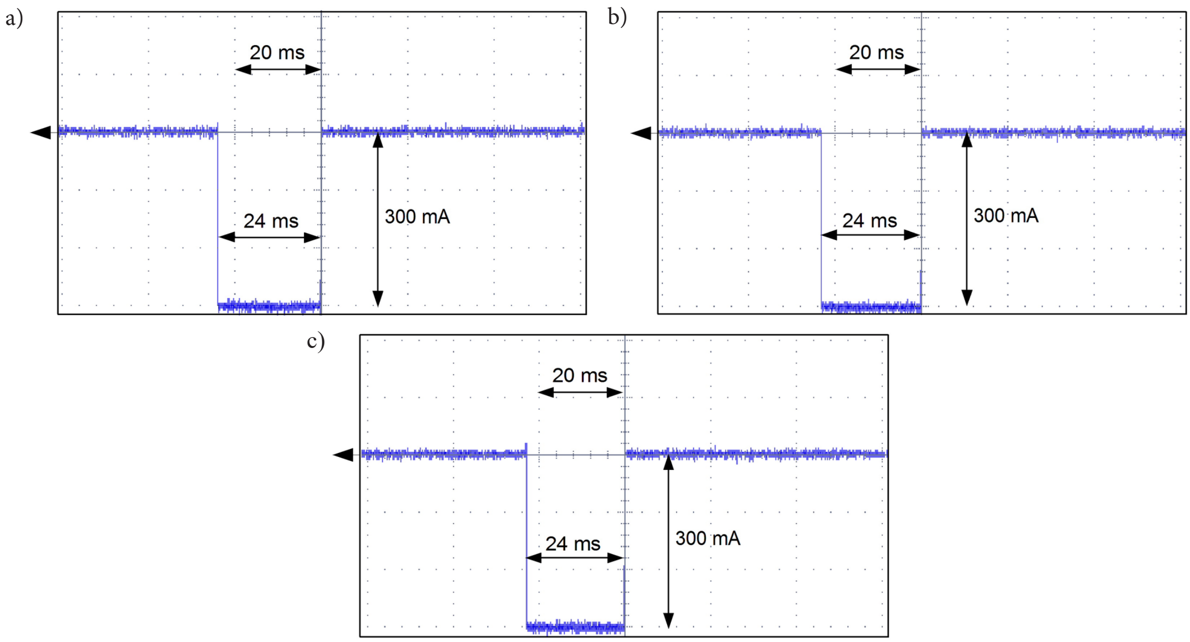

Fig. 13. Residual current oscillograms during the operation of 30 mA RCD-B3 under the suddenly applied DC residual current of 300 mA: a) AC 230 V auxiliary voltage used (poles L-N), b) DC 230 V auxiliary voltage used (poles L-N), c) no auxiliary voltage used

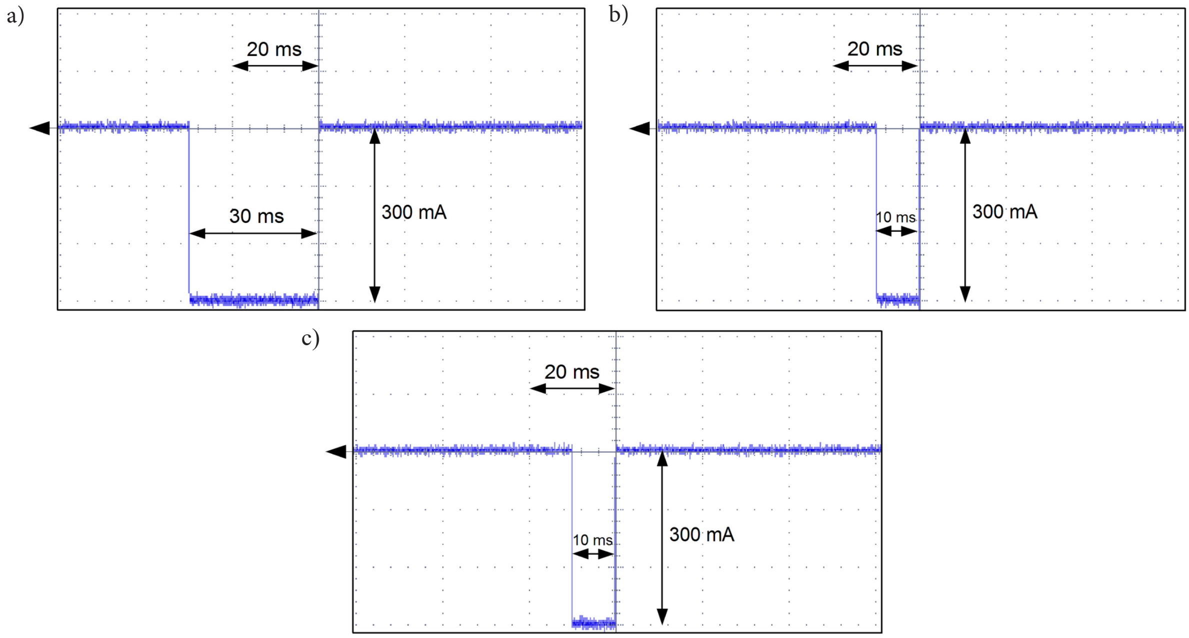

Fig. 14. Residual current oscillograms during the operation of 30 mA RCD-B4 under the suddenly applied DC residual current of 300 mA: a) AC 230 V auxiliary voltage used (poles L-N), b) DC 230 V auxiliary voltage used (poles L-N), c) no auxiliary voltage used

3. Assessment of electrical safety in DC microgrids with RCDs

3.1. Assessment of the safety based on tested B-type RCDs

The above-presented results of the tests have shown that protection against electric shock and fire in DC microgrids with B-type RCDs may not be achieved. The main safety problem is that in some conditions of supply occurring in DC systems, RCDs may not operate despite the current flowing to the earth and existing risk of electric shock or fire. Table 2 shows the results of the overall assessment of the tested B-type RCDs. In the case of the suddenly applied residual current, results for the value of this current equal to $2.0I_{\Delta n} = 60$ mA are presented only. This is the upper tripping limit for which B-type RCDs have to react under a DC residual current. If the RCD does not react at this value, the device can be classified as faulty. Results from Table 2 enable for easy comparison of the behaviour of the RCDs as well.

The analysis of the results contained in Table 2 allows for the conclusion that only one of the tested devices (RCD-B1) tripped in each auxiliary voltage variant (AC, DC, L-N, L-L). For RCD-B2 and RCD-B3, no tripping for auxiliary DC voltage (between L-L poles) was noted. The RCD-B4 is the worst protection device – it did not trip for any auxiliary DC voltage variant. As one can see, these are theoretically identical protection devices from the point of view of the nominal data but they behave differently. The lack of RCDs operation in some auxiliary DC voltage variants results from the provisions of the standards according to which RCDs are manufactured [20, 22]. These standards do not yet take into account all operating conditions possible in DC systems. In order to be sure that the B-type RCD will operate properly in DC systems, the provisions of the standards is recommended to be extended. These provisions should include the requirement that the B-type RCD operates properly also with the auxiliary DC voltage connected between any poles. Alternatively, it is suggested to introduce a different RCD type (e.g., "B-type extended") to the standards, which will be suitable for both AC and DC auxiliary voltage. Thus, manufacturers of RCDs will be obliged to make modifications to the devices design to meet the extended requirements of the standards.

Modification of the provisions of the standards is a long-term process (several years). Therefore, in some cases, the redundancy of RCDs is considered, based on the currently manufactured protections. In the next section, the impact of RCD redundancy on the effectiveness of protection in low-voltage systems is analyzed.

Table 2. General comparison of the behaviour of the tested B-type RCDs

No. of the RCD	Auxiliary voltage					Auxiliary voltage				
	AC 230 V		DC 230 V		No	AC 230 V		DC 230 V		No
	poles L-N	poles L-L	poles L-N	poles L-L		poles L-N	poles L-L	poles L-N	poles L-L	
	slowly rising test current I_{DC} (tripping/no tripping within the normative range 15–60 mA)					suddenly applied test current I_{DC} (tripping/no tripping at 60 mA)				
RCD-B1	(+)	(+)	(+)	(+)	(-)*	(+)	(+)	(+)	(+)	(-)*
RCD-B2	(+)	(+)	(+)	(+)	(-)*	(+)	(+)	(+)	(-)	(-)*
RCD-B3	(+)	(+)	(+)	(-)	(-)*	(+)	(+)	(+)	(-)	(-)*
RCD-B4	(+)	(+)	(-)	(-)	(-)*	(+)	(+)	(-)	(-)	(-)*

(+) tripping; positive assessment
(-) no tripping; negative assessment
(-) no tripping but no auxiliary voltage (power supply) is an abnormal state and, on this basis, the RCD is not assessed negatively*

3.2. Assessment of the safety enhancement in systems with redundant RCDs

According to the guide [23], the use of each product or system is associated with various hazards (they are a potential source of harm) and it is impossible to achieve full safety in all circumstances. However, an increased level of effectiveness of protection against electric shock and fire in low-voltage systems can be achieved by using more reliable protection elements (e.g., high-quality fuses, overcurrent protection devices or RCDs) or by redundancy of these elements. Unfortunately, the use of more reliable safety measures increases costs. Therefore, when using a given solution, the degree of increase in the level of safety should be analyzed.

There are various methods of analyzing of technical systems from the point of view of the reliability of their operation. In paper [5], the reliability function of aging multistate system with dependent components is determined, in case its components have piecewise Weibull functions. Reliability of components in smart grids, to which may also belong DC microgrids, is presented in [6]. With reference to non-coherent multi-state systems, the reliability analysis is discussed in publication [38]. In the case of installations with RCDs, considered in this paper, the reliability analysis methods for systems with possible cascading failures can be used [33]. However, the most suitable approach is the redundant approach [43] and it is used in further investigation.

In many low-voltage electrical installations, RCDs installed in final circuits are connected in series with the upstream main RCD (Fig. 15). Such a main RCD may be required as protection against fire – for example, according to [17], the whole installation in agricultural and horticultural premises has to be protected by an RCD having a rated residual operating current not exceeding 300 mA. In that situation, redundant connections are created [43] which may increase the level of protection against electric shock and fire in final circuits, because two RCDs connected in series (e.g., Main RCD and RCD-1 in Fig. 15a) constitute a parallel reliability structure (Fig. 15b). This protection is effective as long as at least one RCD is able to detect residual current and operate.

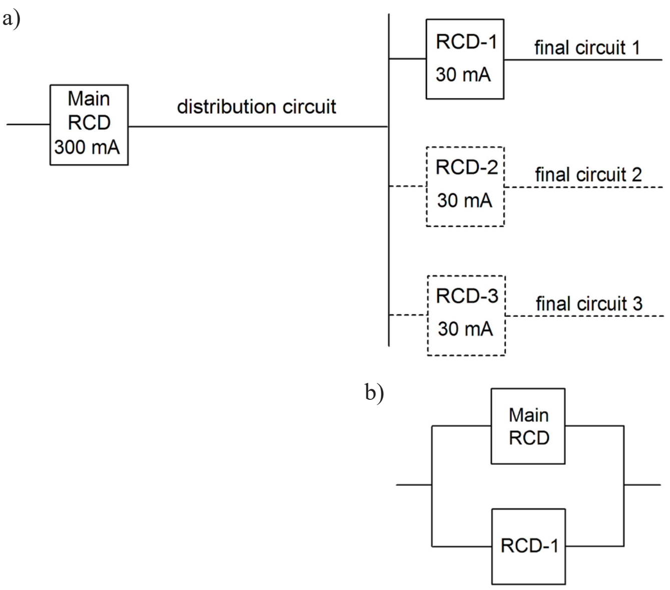

Fig. 15. The structure of electrical installation with RCDs connected in series (a), and the reliability model of "Main RCD – RCD-1" connection (b)

In such a parallel structure, the probability that the system consisting of many elements is not able to operate can be expressed by the relationship:

$$F(T_{up} \le T_{ex}) = F(T_1 \le T_{ex}, T_2 \le T_{ex}, \ldots, T_n \le T_{ex}) \quad (2)$$

where:

- T_{ex} – the expected up time of the protection system,
- T_{up} – the real up time, being the time interval for which the system is in an up state,
- T_1, T_2, T_n, – up times of individual system components: 1-st, 2-nd, *n*-th.

In the protection system composed of RCDs, its failure function is the product of the failure functions of individual system components (RCDs):

$$Q_{up}(t) = Q_{1RCD}(t) \cdot Q_{2RCD}(t) \cdot \ldots \cdot Q_{nRCD}(t) \quad (3)$$

in which consecutive components can be written as:

$$Q_{1RCD}(t) = 1 - P_{1RCD}(t) \quad (4)$$

$$Q_{2RCD}(t) = 1 - P_{2RCD}(t) \quad (5)$$

$$Q_{nRCD}(t) = 1 - P_{nRCD}(t) \quad (6)$$

where: $P_{1RCD}(t)$, $P_{2RCD}(t)$, $P_{nRCD}(t)$ are the reliability functions of the consecutive components (RCDs).

The up time of the entire system with effective protection against electric shock and fire is equal to the up time of the best element:

$$T_{up} = \max(T_{1RCD}, T_{2RCD}, \ldots, T_{nRCD}) \quad (7)$$

For RCDs, the exponential reliability function $P(t)$ can be assumed [28]:

$$P(t) = e^{-\lambda t} \quad (8)$$

The probability density function of failures can be expressed as:

$$f(t) = -P'(t) = -\left(e^{-\lambda t}\right)' = \lambda e^{-\lambda t} \quad (9)$$

and the failure rate is equal to:

$$\lambda(t) = \frac{-P'(t)}{P(t)} = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda \quad (10)$$

This failure rate takes a constant value, which means that it does not depend on the operating time of the system.

The up time of one RCD is:

$$T_{1RCD} = \int_0^\infty P(t)\,dt = \int_0^\infty e^{-\lambda t}\,dt = \frac{1}{-\lambda} e^{-\lambda t}\Big|_0^\infty = 0 + \frac{1}{\lambda} = \frac{1}{\lambda} \quad (11)$$

Thus, the up time of the safety system consisting of two residual current devices connected in series is:

$$T_{up} = \int_0^\infty P_{up}(t)\,dt = \int_0^\infty \left[1 - Q_{up}(t)\right]dt = \int_0^\infty \left[1 - \left(Q_{RCD}(t) \cdot Q_{RCD}(t)\right)\right]dt =$$
$$= \int_0^\infty \left[1 - Q_{RCD}^2(t)\right]dt = \int_0^\infty \left[1 - \left(1 - Q_{RCD}(t)\right)^2\right]dt =$$
$$= \int_0^\infty \left[1 - \left(1 - 2P_{RCD}(t) + P_{RCD}^2(t)\right)\right]dt = \int_0^\infty \left[2P_{RCD}(t) - P_{RCD}^2(t)\right]dt =$$
$$= \int_0^\infty \left(2e^{-\lambda t} - e^{-2\lambda t}\right)dt = \left(\frac{2}{-\lambda}e^{-\lambda t} + \frac{1}{2\lambda}e^{-2\lambda t}\right)\Bigg|_0^\infty =$$
$$= \frac{2}{\lambda} - \frac{1}{2\lambda} = \frac{4-1}{2\lambda} = \frac{3}{2} \cdot \frac{1}{\lambda} = 1.5 \cdot \frac{1}{\lambda} \tag{12}$$

The above calculation shows that doubling the number of RCDs gives only a 50% increase in the level of safety of the protective system. Due to the fact that B-type RCDs are relatively expensive (about 10 times more expensive than commonly used A-type RCDs), such a low increase in the protection level (less than 2 times) can be considered not entirely satisfactory. Therefore, it is extremely important that in the near future RCDs are adapted to the expected waveform shape of the earth fault (residual) current and especially to the auxiliary voltage available in DC systems, so that only one RCD is enough to achieve safety. As already mentioned, this requires modification of the relevant standards.

4. Conclusions

The above presented results indicate that theoretically identical RCDs in terms of rated data may clearly differ in the response to DC residual currents. When considering the usefulness of the tested RCDs in DC microgrids, RCD-B1 (Fig. 5a and Fig. 6ab) and RCD-B2 (Fig. 5b and Fig. 7ab) operate correctly regardless of whether the auxiliary voltage is AC or DC and whether it is connected to poles L-N or L-L. The use of RCD-B3 is limited in systems where only the DC auxiliary voltage is accessible. The problem with its operation in the presence of DC auxiliary voltage is especially noticeable in the case of a slowly rising residual current (Fig. 5c). When the DC voltage is connected to poles L-N, the tripping occurs, but when it is connected to poles L-L, it unfortunately does not. The worst device is RCD-B4 (for L-L connection), both for the case of slowly increasing residual current (no operation for DC auxiliary voltage – Fig. 5d), and for the suddenly applied current (Fig. 9ab). Regarding the ability to detect a DC residual current in the event of auxiliary voltage failure (this response is only possible for a suddenly applied current – Fig. 6c, Fig. 7c, Fig. 8c, Fig. 9c), the best behaviour was recorded for RCD-B2 (Fig. 7c).

The analysis and tests results described in the article are the first in this field and provide a new insight into the real properties of such RCDs. It is commonly assumed that expensive B-type RCDs are capable of detecting all types of residual current. However, as the above-discussed research shows, for this to be the case, strict conditions with regard to the auxiliary supply of these RCDs must be met. Therefore, to be sure that the currently manufactured RCDs will operate properly in a circuit with only DC auxiliary voltage available, additional verification of their operation should be performed, because the scope of normative tests applied by manufacturers are not sufficient to predict the RCD operation in these new conditions, e.g., in DC microgrids. Taking into account the results of the tests contained in this article, it is strongly recommended to modify the provisions of the relevant standards in the scope of the correct operation of B-type RCDs. These provisions should include the requirement that the B-type RCD operates correctly also with the auxiliary DC voltage. As an alternative, it is proposed to introduce a new variant of the B-type RCD to the standards, which will be suitable for both AC and DC auxiliary voltage. This is of key importance for effective protection against electric shock and fire, because, as can be seen from the above-presented analyses, even possible duplication of RCDs does not provide twice the level of protection.

Acknowledgement

The project is co-financed by the Polish National Agency for Academic Exchange and partially supported by the Slovak Research and Development Agency under the grant "Application of MSS Reliability Analysis for Electrical Low-Voltage Systems" (AMRA, reg. no. SK-PL-21-0003).

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