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Residual current devices in installations with PV energy sources

Abstract. The paper presents the principles of residual current devices (RCDs) application in photovoltaic (PV) installations. Provisions of standards in this regard are commented on, in particular, attention is drawn to the lack of obligation to use of RCDs in PV installations. The issue of the shape of the earth fault current and the level of leakage currents in such installations are discussed. These factors influence the selection of RCDs in terms of their rated residual operating current as well as the type of tripping characteristic.

Streszczenie. W artykule przedstawiono zasady stosowania wyłączników różnicowoprądowych (RCDs) w instalacjach fotowoltaicznych (PV). Skomentowano zapisy norm w tym zakresie, w szczególności zwrócono uwagę na brak obowiązku stosowania takich zabezpieczeń w instalacjach PV. Omówiono problematykę kształtu prądu ziemnozwarciowego oraz poziom prądów upływowych charakteryzujący te instalacje – są to czynniki wpływające na dobór znamionowego prądu różnicowego oraz typu charakterystyki wyzwalania wyłączników różnicowoprądowych. (Wyłączniki różnicowoprądowe w instalacjach z fotowoltaicznymi źródłami energii).

Keywords: photovoltaic installations, protection against electric shock, residual current devices.

Słowa kluczowe: instalacje fotowoltaiczne, ochrona przed porażeniem elektrycznym, wyłączniki różnicowoprądowe.

Introduction

The principles of protection against electric shock in low-voltage installations are included in particular in standard PN-HD 60364-4-41:2017-09 [1]. When considering photovoltaic (PV) installations, the provisions of standards PN-HD 60364-7-712 [2-3] and IEC 60364-7-712:2017-04 [4] should also be taken into account. Standards [2-4] provide a guide for protective measures against electric shock to be used on the DC side and the AC side of installations containing PV energy sources. These standards also contain some guidelines on the use of residual current devices (RCDs). However, the guidelines are quite general and require more detailed comments. Based on the works related to high-frequency earth fault currents [5, 6] and especially waveforms with harmonics [7-10], as well as verification of RCDs [11], the proper operation of RCDs strongly depends on their correct matching to the expected shape of the earth fault current. This is one of the most important aspects that should be considered when selecting RCDs in PV installations.

Therefore, the provisions of standards relating to the protection against electric shock and selection of RCDs in PV installations are presented and commented on below. The problems of RCDs operation in such installations, when DC component in the earth fault current occurs, are also discussed.

Provisions of standards

A characteristic feature of PV installations is, among others, that they include both DC voltage and AC voltage circuits. The PN-HD 60364-7-712:2016-05 [3] standard defines permissible measures of protection against electric shock separately for the DC side and the AC side of the installation. Tabl. 1 specifies these measures of protection.

Comparison of the data in Tabl. 1 with the provisions of the standard PN-HD 60364-4-41:2017-09 [1] leads to the conclusion that in PV installations the use of the following protection measures is not allowed:

- for basic protection – obstacles, placing out of reach; (both on DC and AC sides),
- for protection in case of a fault – the automatic disconnection of supply on the DC side, electrical separation on the DC side, non-conducting location (both on DC and AC sides).

With reference to the RCDs' application, the standard [3] delivers only short provisions in the following clauses:

- 712.53 Protection, isolation, switching, control and

monitoring,

- 712.531 Devices for fault protection by automatic disconnection of supply,
- 712.532 Devices for protection against the risk of fire.

Therefore, RCDs may be used on the AC side of PV installations as part of the measure automatic disconnection of supply. They may also be used for protection against the risk of fire.

In the aforementioned clauses it is stated that if the RCD is used, its type shall be of B, unless:

- at least a simple separation between the AC side and the DC side is provided by the inverter, or
- at least a simple separation between the RCD and the inverter by a transformer is provided, or
- the construction of the inverter ensures that B-type RCD is not necessary; it should be stated by the inverter's manufacturer.

Table 1. Measures of protection against electric shock allowed in PV installations, according to PN-HD 60364-7-712:2016-05 [3]

Type of protection	DC side	AC side
	Protective measure	
basic protection	basic insulation of live parts	basic insulation of live parts
	barriers or enclosures	barriers or enclosures
protection in case of fault	---	automatic disconnection of supply
	double or reinforced insulation	double or reinforced insulation
	extra-low-voltage provided by SELV or PELV	extra-low-voltage provided by SELV or PELV
	---	electrical separation (only one item of current-using equipment)

Based on these provisions, it can be concluded that RCDs are not mandatory in PV installations. The point is that if the designer decided to use an RCD in a PV installation without simple separation (but there is no obligation to use RCDs), i.e., in practice in an installation without a transformer, then this RCD should be B-type. Such a type because there may be unidirectional residual currents of low pulsation and other residual current devices (except type B+, which has enhanced residual current detection capabilities in relation to B-type) will not respond

to such currents. Examples of simplified earth-fault current waveforms that can be expected in photovoltaic installations are shown in Fig. 1.

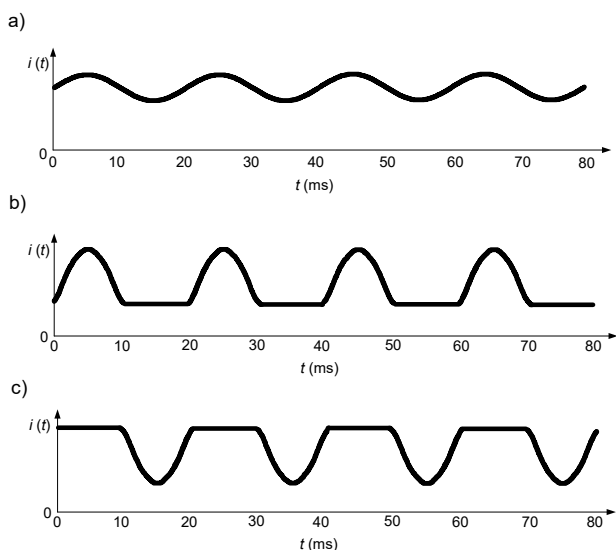


Fig.1. Simplified earth fault current waveforms $i(t)$ in case of the earth fault on the DC side in a PV installation; according to [12]. Waveforms containing: a) sinusoidal component and smooth DC, b) pulsating DC (half-wave) and smooth DC (both components of the same polarity), c) pulsating DC (half-wave) and smooth DC (components with opposite polarity)

Table 2. Types of RCDs due to the ability to detect a specific waveform shape of the residual current [13, 14] and their usefulness in PV installations

Symbol	Waveforms detected by RCD of the particular type	Comments referring to RCDs in PV installations
AC	<ul style="list-style-type: none"> sinusoidal alternating current (generally 50/60 Hz) 	it is not recommended for PV installations
A	<ul style="list-style-type: none"> sinusoidal alternating current (generally 50/60 Hz), pulsating direct current, pulsating direct current with superimposed smooth direct component up to 6 mA 	it is suitable for a limited extent – e.g. when simple separation is used between the AC and DC sides of a PV installation
F	<ul style="list-style-type: none"> as with type A, pulsating direct current with superimposed smooth direct component up to 10 mA, alternating current containing harmonics (single-phase supply) 	as with type A
B	<ul style="list-style-type: none"> sinusoidal alternating current up to 1000 Hz, sinusoidal alternating current with superimposed direct component up to 10 mA or $0.4I_{\Delta n}$, pulsating direct current with superimposed direct component up to 10 mA or $0.4I_{\Delta n}$, direct current obtained from a two-pulse rectifier supplied from two phases, direct current obtained from a three-pulse/six-pulse rectifier supplied from three phases, smooth direct current, current containing harmonics 	suitable for PV installations even without simple separation between the AC and DC sides
B+	<ul style="list-style-type: none"> as with type B, sinusoidal alternating current up to 20 000 Hz 	as with type B

Tabl. 2 shows the types of RCDs and normative shapes of the residual current under which these RCDs are tested. Comments referring to their usefulness in PV installations are included in Tabl. 2 as well.

In the provision of the standard [3], the requirement concerning RCDs does not refer to the obligation to use RCDs in PV installations. It relates to the type of the RCD if it is decided to install it (type B is required to be used, not, for example, type A or type AC).

RCDs, if installed, are usually utilized to ensure the automatic disconnection of supply in case of an insulation fault. In the event of an earth fault in the point indicated in Fig. 2, a circuit-breaker MCB1 or an optional RCD has to disconnect the supply. There are no requirements as to the rated residual operating current of the RCD in a PV installation between the inverter and the busbars of the AC distribution board.

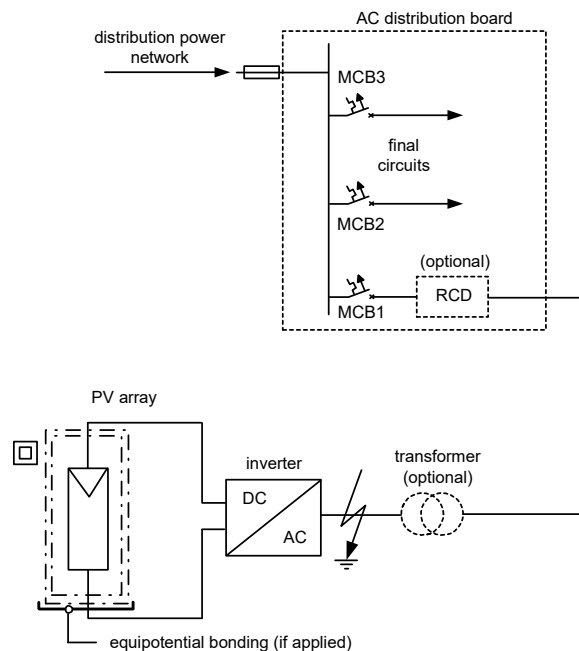


Fig.2. Sample installation with PV energy sources. RCD – residual current device, MCB – miniature circuit-breaker

In the TN system, the following condition of the effectiveness of protection against electric shock is to be fulfilled:

$$(1) \quad Z_s \leq \frac{U_o}{I_a}$$

where: Z_s – the earth fault loop impedance, U_o – the line-to-earth nominal voltage, I_a – the current giving disconnection of supply with the required time.

Moreover, the circuit with the inverter (Fig. 2) can be considered as a distribution circuit and the automatic disconnection of supply in a TN should occur within a time not exceeding 5 s (not 0.4 s as for final circuits). This circuit does not require additional protection in the case of direct contact, e.g., such as in typical socket-outlet circuits having a rated current $I_n \leq 16$ A. Therefore, there is also no need to install RCDs of $I_{\Delta n} \leq 30$ mA. Such RCDs may trip unnecessarily due to the high natural leakage currents in the PV system and interrupt the power supply. According to the data included in [15], the leakage currents of a set of PV modules with a rated power of several kilowatts can be within the range 9–45 mA. For this reason, inverters' manufacturers indicate in their manuals that the rated residual operating current of RCDs in PV installations should not be less than 100 mA or 300 mA. In the case of

high-power PV installations, with three-phase inverters, the recommended rated residual operating current may even be higher than 300 mA [16].

If the designer of the electrical installation recommends the application of RCDs for fire protection purposes, then, in accordance with the standards PN-HD 60364-4-42 [17] and PN-HD 60364-5-53 [18], they shall have a rated residual operating current no higher than 300 mA, and shall be installed at the origin of the protected circuit.

It should also be noted that in TN and TT systems, according to PN-HD 60364-4-41 [1] and PN-HD 60364-5-53 [18], the following devices that ensure disconnection of the power supply in the event of a single fault may be used:

- overcurrent protective devices (circuit-breakers, fuses),
- residual current devices.

Residual current monitors (RCMs), in principle, give only a signal and are not considered sufficient to provide single fault protection. The standard IEC 62020-1 [19], dedicated to RCM devices, states that the purpose of these devices is only to warn in the event of a residual current exceeding a certain level – they are not protective devices disconnecting the power supply. Monitoring devices (RCMs) embedded in PV inverters are therefore not sufficient for residual current protection if one is to be used in this installation for protection by automatic disconnection of supply. The embedded RCD can be considered a sufficient device and the inverter's manufacturer should inform about its presence.

Testing of RCDs

If a DC component appears in the residual current waveform, it influences the tripping threshold of RCDs. For this reason, the standard [3] contains a provision that in some cases it is necessary to use B-type RCDs (as given in section "Provisions of standards").

Laboratory tests of tripping of RCDs at the residual current containing DC component have been performed. The RCDs have been tested in the presence of the following waveforms:

- AC sinusoidal with superimposed smooth DC component,
- pulsating DC (half-wave) with superimposed smooth DC component.

It was investigated how the tripping threshold of the RCDs changes if a smooth DC component of various values appears in the residual current. The DC component was adjusted to the following values: 0, 6, 15, 30, 60, 90, 150 mA. After adjusting one of the aforementioned values of the DC component, the other component of the residual current (AC sinusoidal or pulsating DC/half-wave) was increased to the point of tripping of the tested RCD.

Fig. 3 shows the results of tests of three A-type RCDs with a rated residual operating current of $I_{\Delta n} = 30$ mA. In the cases presented in Fig. 3a, there is a noticeable influence of the DC component – the tripping threshold of RCDs increases, but each of the tested RCDs reacted. The best properties has the RCD2. The rms value of the sinusoidal component at which RCD2 tripped did not exceed 30 mA, even when the DC component was 90 mA. The test results presented in Fig. 3b show that the residual current waveform composed of a pulsating DC (half-wave) and a smooth DC component creates more difficult conditions for tripping of RCDs than in the case of a waveform with a sinusoidal component and a smooth DC component. The RCD3 tripped only when the smooth DC component did not exceed 60 mA, and its real tripping current at this value significantly exceeded $I_{\Delta n}$. The RCD1 reacted only when the DC component did not exceed 30 mA.

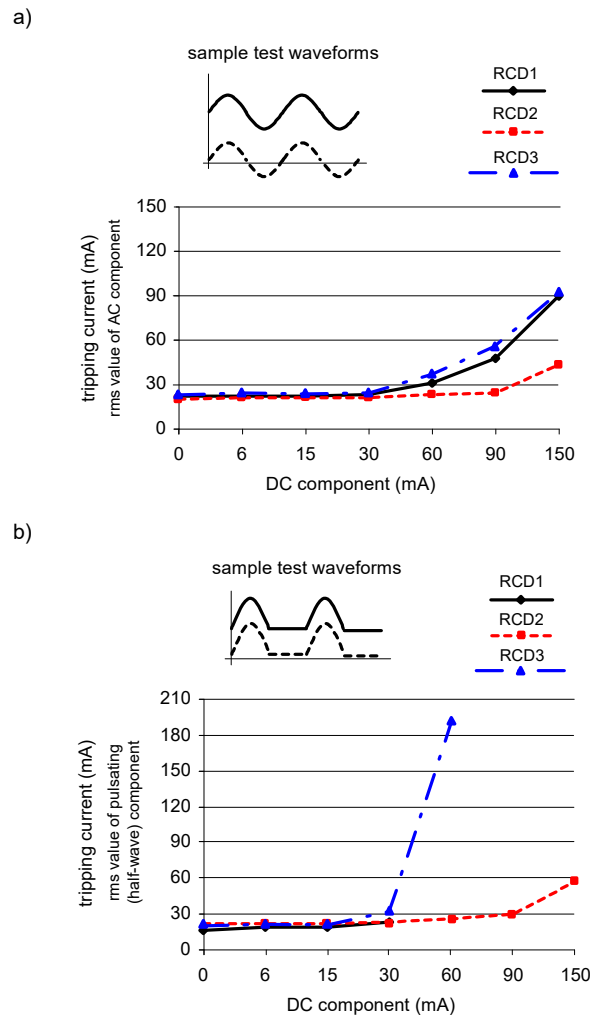


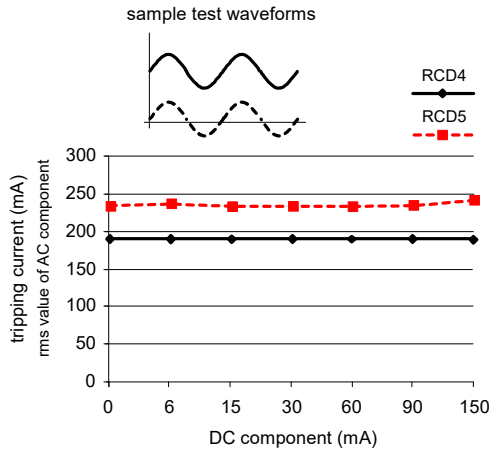
Fig.3. The tripping current of three A-type RCDs of $I_{\Delta n} = 30$ mA (RCD1, RCD2, RCD3) under the residual test current composed of: a) AC sinusoidal and smooth DC components, b) pulsating (half-wave) and smooth DC components. The smooth DC component has the following values: 0, 6, 15, 30, 60, 90, 150 mA

The results of similar tests of RCDs with a rated residual operating current of 300 mA show (Fig. 4) that the influence of the smooth DC component of the above-mentioned values is significantly lower on these RCDs (compared to the 30 mA RCDs). Their real tripping current did not exceed the value of $I_{\Delta n} = 300$ mA, even for a DC component equal to 150 mA.

This is due to the fact that for RCDs with $I_{\Delta n} = 300$ mA, the DC component 150 mA is only 50% of the rated value $I_{\Delta n}$. In the case of RCDs of $I_{\Delta n} = 30$ mA, it is as much as 500% ($150 \text{ mA}/30 \text{ mA} = 5$). So, for a given value of the DC component, an RCD with a relatively higher-rated residual operating current (e.g., 300 mA) will behave better than the one of $I_{\Delta n} = 30$ mA.

The indicated rising of the RCD tripping threshold is related to the influence of the DC component on the induced voltage in the secondary winding of the current transformer of the RCD. In order for RCD to operate, the secondary current i_{sec} of a sufficiently high value has to flow through the relay RE (Fig. 5). This current depends on the induced voltage e_{sec} , and that in turn depends on the value, the shape of the residual i_{Δ} (primary i_{pri}) current and the properties of the iron core of the current transformer CT.

a)



b)

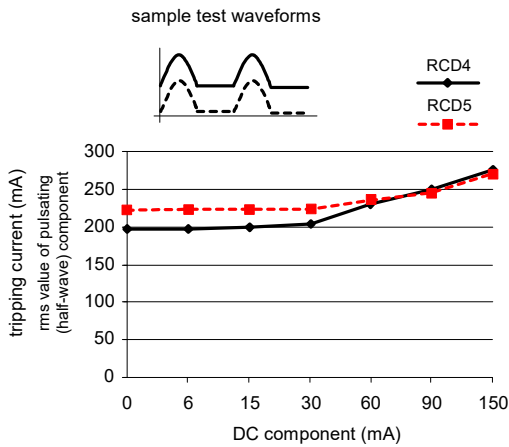


Fig.4. The tripping current of two A-type RCDs of $I_{\Delta n} = 300$ mA (RCD4, RCD5) under the residual test current composed of: a) AC sinusoidal and smooth DC components, b) pulsating (half-wave) and smooth DC components. The smooth DC component has the following values: 0, 6, 15, 30, 60, 90, 150 mA

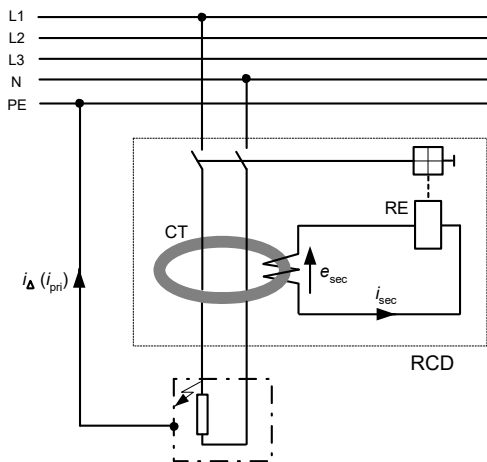


Fig.5. A simplified structure of the RCD. CT – current transformer, RE – relay, $i_{\Delta}(i_{pri})$ – residual (primary) current, i_{sec} – secondary current, e_{sec} – induced secondary voltage

Figs 6-8 show the primary current i_{pri} and induced voltage e_{sec} oscillograms when:

- there is no smooth DC component superimposed on the half-wave residual/primary waveform (Fig. 6),
- a constant component of 150 mA is superimposed on the half-wave residual/primary waveform (Fig. 7),

- a constant component of 300 mA is superimposed on the half-wave residual/primary waveform (Fig. 8).

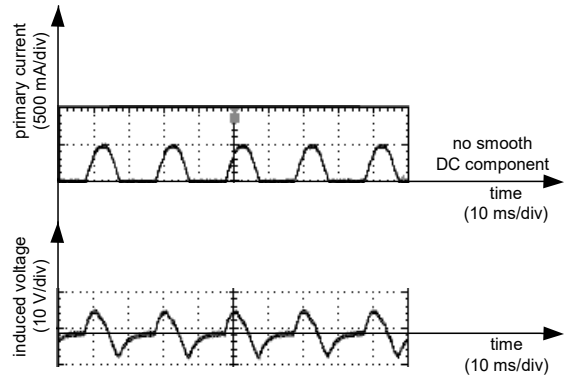


Fig.6. Oscillogram of the primary current (half-wave) of the RCD's current transformer and oscillogram of its induced secondary voltage. No smooth DC component superimposed on the half-wave. Current transformer from an RCD of A-type and $I_{\Delta n} = 300$ mA

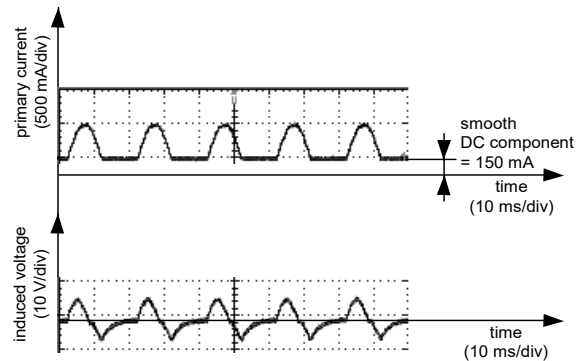


Fig.7. Oscillogram of the primary current (half-wave and superimposed smooth DC) of the RCD's current transformer and oscillogram of its induced secondary voltage. Smooth DC component of value 150 mA. Current transformer from an RCD of A-type and $I_{\Delta n} = 300$ mA

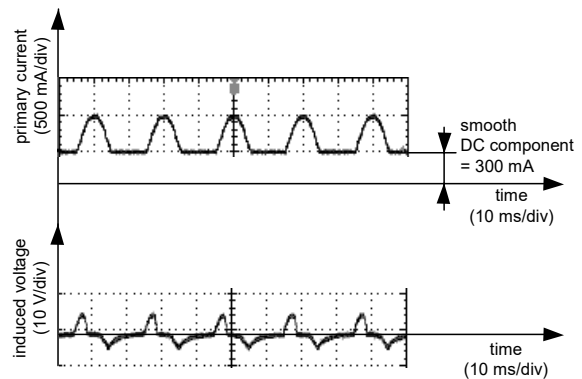


Fig.8. Oscillogram of the primary current (half-wave and superimposed smooth DC) of the RCD's current transformer and oscillogram of its induced secondary voltage. Smooth DC component of value 300 mA. Current transformer from an RCD of A-type and $I_{\Delta n} = 300$ mA

In the case of the last-mentioned composite waveform, a clear change in the shape of the induced voltage can be seen (Fig. 8). This voltage has the lowest value (compared to the waveforms shown in Fig. 6 and Fig. 7), which adversely affects the RCDs' tripping threshold.

Conclusions

Residual current devices in PV installations are not mandatory equipment. However, if it has been decided to use RCDs, attention should be paid to recommendations of the inverters' manufacturers regarding the value of the rated residual operating current of RCDs. This value must not be very low to prevent unnecessary disconnection of the PV system, due to leakage currents. The type and properties of the inverter should be analyzed, and the absence or presence of a transformer that galvanically separates the DC side from the AC side should be found, because it may have an influence on the type of the RCD to be used in the PV installation. As can be seen from the analysis presented in this paper, the selection of an RCD of an inappropriate type (e.g., A-type instead of B-type when the DC component has a high value) may result in the lack of effective protection against electric shock in the PV installation – the RCD may have an increased tripping threshold at a high DC component or it may not react at all.

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