IMPROVED METHODOLOGY FOR TESTING THE COMPLIANCE OF RESIDUAL CURRENT DETECTION OF NON-ISOLATED GRID-CONNECTED PHOTOVOLTAIC INVERTERS

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Abstract – **Ensuring user safety in transformerless photovoltaic (PV) inverters is crucial due to the high leakage current caused mainly by the PV modules' capacitance. Compliance with safety standards IEC 62109-2:2011 and IEC 63112:2021 demands leakage current tests utilizing a variable resistive-capacitive (RC) load. However, limited research has been conducted to assess the impact of test parameters on result conclusiveness. To address this gap, this paper investigates the influence of AC mains voltage phase angle on trip time results in the continuous leakage current test as per these standards. Our experiments, performed with five commercial transformerless PV inverters, reveal significant sensitivity of the results to this specific parameter. Supported by RMANOVA analysis, our findings substantiate this observation. Subsequently, we discuss potential strategies to enhance the accuracy of test outcomes and propose a well-defined methodology to ensure repeatability and reliability of results.**

Keywords – **Leakage Current, Photovoltaic Inverter, Residual Current, Safety Standards, Test Methodology.**

I. INTRODUCTION

Transformerless Photovoltaic (PV) Inverter topologies have been widely adopted to increase efficiency and reduce costs of PV systems. However, the lack of galvanic isolation between the PV generator, along with the presence of AC common-mode voltage at the DC input [1], can result in high levels of leakage current, which predominantly flows through the parasitic capacitance between DC terminals and the grounded aluminum frame of the PV modules [2], [3]. This leakage current increases fire hazard and impairs the detection of residual currents caused by electric shock [4]. PV protection standards have been developed to ensure adequate personnel and system safety such as IEEE Std. 1374 [5], NEC article 690 [6] and IEC 62548 [7]. In addition, safety standards specific for power converters for PV systems have been developed, such as IEC 62109-1 [8] and IEC 62109-2 [9]. In 2021, IEC 63112 [10] was published to update or replace many requirements and tests related to residual current defined in IEC 62109-2, which is expected to be reviewed. However, safety against fire and shock hazards still poses many challenges [11], so the development of new protection schemes is an important research issue [12]–[18].

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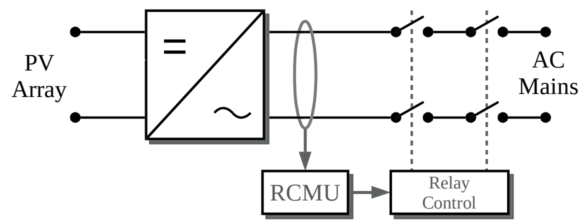

Fig. 1. Residual current detection scheme in non-isolated PV inverters according to IEC 62109-2.

The requirements and testing procedures outlined in IEC 62109-2 [9] and IEC 63112 [10] are crucial to safety of PV systems. These procedures define the necessary requirements and testing procedures against fire and electric shock on the DC side of PV inverters [5]. In Brazil, the PV installation standard ABNT NBR 16690 and the PV inverter INMETRO ordinance reference these IEC standards for protection requirements and testing against residual current. According to these standards, transformerless PV inverters must be equipped with a residual current device (RCD) or a residual current monitoring unit (RCMU), as illustrated in Figure 1 [19]. To ensure physical separation of all current-carrying conductors from the mains, relays must be used to provide single fault-tolerance disconnection.

RCDs are not applicable in most cases since PV arrays have large capacitance to ground which generate a residual current higher than 30 mA under normal conditions; therefore, RCMU is the usual solution. Before starting operation, a transformerless PV inverter must measure the array insulation resistance, and only connect if the measured resistance does comply with minimum requirements. When connected, RCMU must continuously measure the residual currents and open their electromechanical relays when trip conditions occur. Trip time for sudden changes in leakage current depends on its magnitude. The critical case is for steps of 90 mA, for which trip time must be less than 40 ms, i.e. disconnection must occur in less than 2.5 cycles of grid voltage at 60 Hz. According to IEC 62109-2 and IEC 63112, residual current tests of RCMU are performed by inducing current steps of different magnitudes. Tests are repeated five times for each DC pole and for each current step magnitude. The inverter must pass in all attempts to comply. However, there is no assurance that these five test attempts are executed at some critical instant, since the standard does not specify some test conditions. Thus, the results may be poorly repeatable and critical test conditions may not be detected.

Transformerless PV inverters are being adopted worldwide, even in places accessible by people. The DC side is usually protected only by insulation resistance metering and the RCMU, which are embedded in the inverter. Thus, if critical safety conditions are not detected in PV inverter compliance tests, there may be serious safety hazards for users. Moreover, high repeatability is required for certification purposes, because tests performed in different laboratories or even in different test attempts must not lead to different pass/fail results, especially when dealing with user safety requirements [20].

The main objective of this paper is to analyze how the mains voltage angle affects continuous leakage current trip time test procedures for transformerless PV inverters, following IEC 62109-2 and IEC 63112 standards. Additionally, we propose a methodology for improved result repeatability and reproducibility [21], [22]. Our tests utilized automatic equipment specially designed for the purpose, featuring a digitally controlled RC load for precise AC mains voltage measurement and solid-state switching.

The experimental tests were conducted on five commercial transformerless PV inverters, including three single-phase inverters (1.5 kW, 2 kW, and 5 kW) and two three-phase inverters (8 kW and 12 kW) from different brands and topologies. The hypothesis that the AC mains phase angle influences the results was statistically tested using RMANOVA analysis.

RMANOVA was chosen due to its effectiveness in evaluating multiple factors' impact (e.g., AC mains phase angle) on continuous leakage current trip time test results. It accommodates variability within and between different inverter models and test conditions.

Furthermore, the RMANOVA analysis revealed that not defining the AC mains phase angle introduces Type A uncertainties to the results. Type A uncertainties arise from data variability due to repeated observations. By precisely defining the AC mains phase angle during testing, we minimize these uncertainties, leading to more reliable and accurate results.

The study emphasizes the significance of using statistical methods like RMANOVA to assess various variables' impact on test results. Our methodology, incorporating testing at different AC mains phase angles using automatic equipment, reduces Type A uncertainties and enhances the validity of leakage current testing according to IEC 62109-2 and IEC 63112. This enhances confidence in the equipment passing the test, particularly when measured values are close to the compliance limit.

II. RCMU REQUIREMENTS AND TESTING

According to IEC 62109-2 [9] and IEC 63112 [10], non-isolated grid-connected PV systems shall comply with two main requirements: i) the PV inverter must measure the PV array insulation resistance to the ground before connecting to the grid, and it must not connect if insulation resistance is below a given lower limit; ii) when connected to the grid, the inverter must continuously measure the residual current to detect potential electric shock and avoid fire hazard. Protection against residual current can be achieved with a type-B 30 mA RCD for measuring DC and AC components, or an RCMU. When using an RCMU, the inverter must disconnect if there is excessive continuous leakage current or sudden changes in residual current. The requirements and tests of RCMUs are specified in the following subsections. The setup used for testing both requirements is shown in Figure 2, where laboratory power sources emulate the PV array and the AC grid.

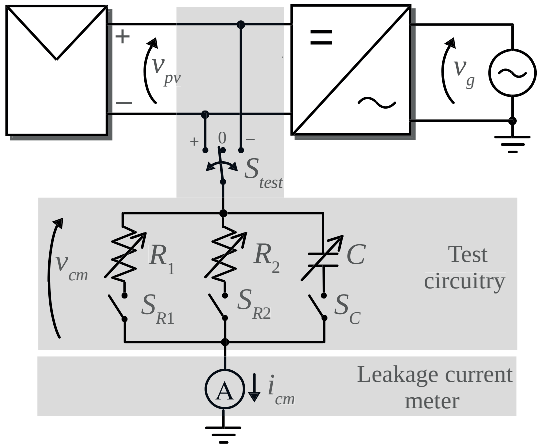

Fig. 2. Setup for testing RCMU protections in non-isolated PV inverters according to IEC 62109-2.

A. Continuous Leakage Current

Excessive continuous leakage current can cause fire hazard. Inverters with a power rating of up to 30 kVA must disconnect with a maximum of 300 mA rms of leakage current. In IEC 62109-2, inverters rated over 30 kVA must disconnect when measuring continuous leakage current up to 10 mA per kVA of rated power. The same limits are defined in IEC 63112, but with an overall limit of 5 A for inverters rated over 500 kVA. Disconnection shall occur within 300 ms, and the inverter must indicate a fault. It can reconnect to the grid if insulation resistance greater than the limit is measured.

The procedures for testing the protection of a transformerless PV inverters against excessive continuous leakage current are shown in Figure 3, divided in two tests:

a. Trip level tests (Figure 3a): an adjustable resistance is connected between one of the PV poles and ground. Starting with high resistance, the resistance is slowly reduced until the inverter leakage current exceeds the inverter maximum limit and it disconnects from the grid. The recorded trip level for the tested pole is the rms leakage current at which the inverter disconnects.

b. Trip time tests (Figure 3b): first, the resistance is adjusted to conduct a leakage current 10 mA below the trip level. Then, another resistance is connected in parallel, adjusted to conduct a leakage current of 20 mA. This step forces the leakage current to exceed the previously identified trip level. The interval between this step and the inverter disconnection is the recorded trip time.

The trip time tests are performed five times for each connected DC pole. This paper focuses on this test, demonstrating that the AC mains angle φ, when the 20 mA

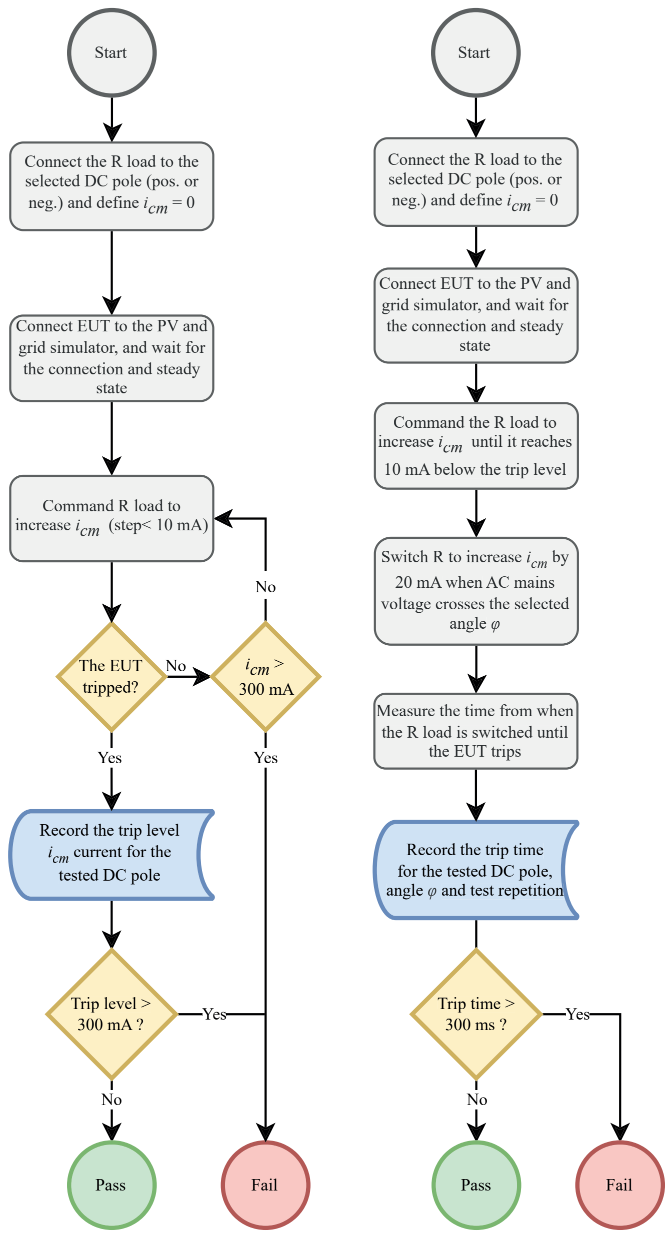

Fig. 3. Continuous leakage current test procedures: a) Trip level measurement; b) Trip time measurement.

resistance is connected, affects the trip time results. In the standard tests, the angle is not specified, making it arbitrary. In this study, we adopt a modified methodology and conduct tests at several pre-defined angles.

B. Sudden Change in Residual Current

In a non-isolated PV system, contact with residual currents above 30 mA can lead to electric shock. To prevent this occurrence, the inverter must rapidly disconnect from the grid upon detecting a sudden increase in residual current. In addition to the resistance, the test procedures for this requirement also involve the capacitive part of the load (Figure 2), which emulates the parasitic capacitances. To test this requirement, three resistive current steps are performed over a baseline capacitive current. The residual current steps used for testing and their corresponding maximum trip times are specified in Figure I. Note that detailed analyses of the residual current sudden change tests require further study, specifically focusing on those tests. These analyses will not be addressed in this paper.

TABLE I
Maximum Disconnection Time for the Residual Current Sudden Change Test for PV Inverters with RCMU

Residual current steps for testing	Max. disconnection time
30 mA	300 ms
60 mA	150 ms
90 mA (updated in IEC 63112)	40 ms

III. UNCERTAINTIES AND STATISTICAL ANALYSIS IN PV INVERTER LEAKAGE CURRENT TESTS

Standardized tests are defined to evaluate equipment behavior. Any test has uncertainties that are related to calibration, measurement equipment accuracy, testing methods and characteristics of the Equipment Under Test (EUT).

To obtain conclusive results, the uncertainty related to calibration, measurement equipment accuracy and method must be much lower than the uncertainty of the EUT. According to the Guide to the Expression of Uncertainty in Measurement [23], the uncertainties of a measurement can be classified as:

a. Type A: relative to the data collected from a series of independent observations and evaluated using statistical methods associated with analysis of variance (ANOVA). Examples of type A uncertainties are the mean value and standard deviation of the results of an experiment or measurement repeated several times.
b. Type B: components of measurement uncertainty determined by means other than a type A. Examples of type B uncertainty are equipment calibration reports, proficiency testing reports, datasheets or manufacturer's manuals.

Levels of confidence higher than 95% are normally acceptable for expanded uncertainty in metrological systems. This level of confidence results in an expanded uncertainty twice as much as the combined uncertainty. Thus, uncertainty of repeatability must be reduced to much lower values than the acceptable limit to enable conclusive test results. This is made possible by defining test conditions in as much detail as possible.

To measure the influence of the grid phase angle φ on the trip time tests, the following methodology was employed for 5 inverters. First, the trip level (in mA) for a specific DC pole of each inverter is determined. Then, the trip time tests are conducted for each pole of every inverter, connecting a 20 mA additional resistance when the AC mains voltage crosses a pre-defined angle. The defined crossing angles φ are 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. Each testing point (DC pole, AC angle) is repeated 5 times, resulting in 80 tests per inverter (2 poles × 8 angles × 5 repetitions). Table II summarizes the

TABLE II
Testing Parameters to Measure the Influence of φ

Parameter	Specification
AC phase angles φ	0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°
Tested Poles	Positive and Negative Poles
Trip time tests per EUT	8 angles × 2 poles × 5 repetitions = 80 tests
EUT	5 inverters detailed in Figure III

testing parameters.

After all data had been collected, it was submitted to a repeated measures analysis of variance (RMANOVA) to determine if the trip time difference between each test condition is due to effective influence of φ or due to normal inverter behavior. RMANOVA is the equivalent of one-way ANOVA, but for related, non-independent groups, and it is the extension of the dependent t-test. It is also referred to as a within-subjects ANOVA or ANOVA for correlated samples.

The RMANOVA tries to determine if the difference between the averages reflects a real difference between the test groups, or is due to the random noise inside each group. For the tests conducted in this paper, the variable parameter between the groups is the AC voltage phase angle φ at which the leakage current increases above the inverter trip level. The dependent variable is the trip time of the inverter leakage current protections.

The RMANOVA test uses two variables to test the hypothesis: the p-value and F-value. The F-value represents the ratio of variance between the groups (or conditions) to variance within the groups. A higher F-value indicates a more substantial difference between group means compared to the variability within each group, making it more likely to reject the null hypothesis. The p-value associated with the F-value represents the probability of observing an F-value as extreme as the one obtained, assuming the null hypothesis is true. In general, if the p-value is below a predetermined significance level (such as 0.05), researchers can reject the null hypothesis.

In RMANOVA, the null hypothesis (H_0) states that the mean differences between the 8 related groups are not significant, and thus, there is no impact of φ. The alternative hypothesis (H_A) is that the mean differences of at least two groups are statistically significant. This suggests that there is an effect of φ on trip time results, as φ serves as an independent variable among the related groups. This way, rejecting H_0 means that there is significant effect of φ on trip time results.

IV. EXPERIMENTAL SETUP AND METHODOLOGY

We have designed and implemented an equipment to test PV inverters against the requirements of Section II.The setup includes an electronically controlled RC variable load and a supervisory system, which are shown in Figure 4. A photo of the prototype is shown in Figure 5.

In [24] and [25], electronically controlled variable resistance schemes are proposed. In the latter, 8 binary weighted resistors are connected in series, resulting in 256 possible different combinations of resistances. In this study, the same binary logic is applied to implement the resistive and capacitive load, but using parallel resistance and capacitance binary combinations.

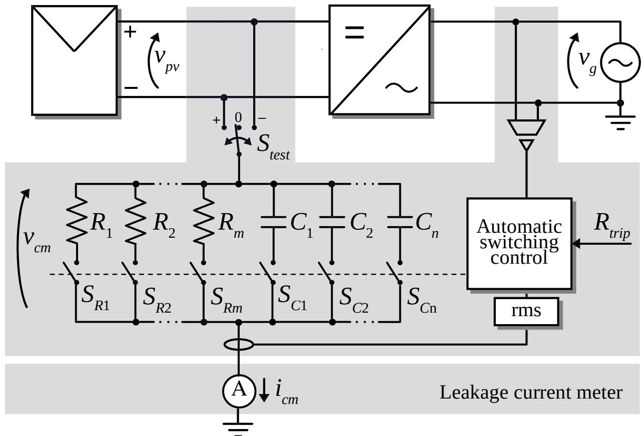

Fig. 4. Setup for automatic testing of residual current detection in non-isolated PV inverters.

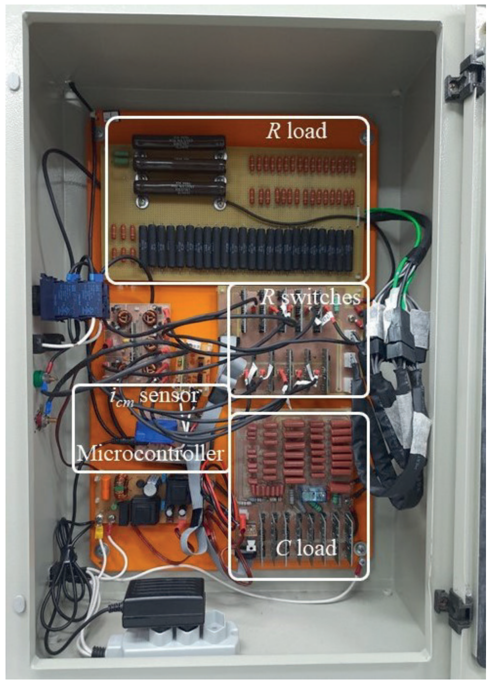

Fig. 5. Leakage current automatic testing system.

Figure 4 depicts the variable RC load scheme used in the study. The resistive part of the load consists of 10 resistors connected in parallel, where the first resistor resistance R_1 and the subsequent resistors have $R_2 = 2R_1$, $R_3 = 4R_1$, $R_4 = 8R_1$, and so on. Semiconductor switches control the conduction of each resistor. Similarly, the capacitive part of the load consists of 8 capacitors connected in parallel, with semiconductor switches controlling the current conduction of each capacitor. v_{cm} represents the voltage between one of the inverter pole terminals and the ground terminal, while i_{cm} denotes the leakage current. The resistive and capacitive loads may have 1024 and 256 different equivalent resistances and capacitances, respectively, which can be continuously adjusted by controlling the state of the semiconductor switches.

A microcontroller switches the RC load elements and is monitored and controlled externally by a supervisory system. A PLL filters and measures the AC voltage to acquire precise phase angle information φ. The leakage current is measured by a LMG670 power analyzer (ZES Zimmer GmbH), with a reading accuracy of $0.01\% + 0.02\%$ of the upper range value. Details about the setup are in [26].

Experimental results have been carried out on three single-phase inverter and two three-phase inverter. The procedures for measuring trip level and trip time results are demonstrated next, followed by a description of the trip-time results of the continuous leakage current test with different values of φ. Finally, the Discussion Section reports the statistical analysis (RMANOVA) of φ influence on the trip time results, with a significance level of 0.05 (5%), that is the maximum chance allowed rejecting H_0 while H_0 is true. This threshold is defined by the researchers and 0.05 is a standard value for statistical analysis.

A. Demonstration of Leakage Current Test Procedures

The procedures shown Figure 3 for measuring trip time and trip level for the 1.5 kW single-phase inverter (Inv1) are demonstrated here.

a. Trip level test (Figure 6(a)): the test began with a high resistance connected from the positive PV pole to ground. The resistance was continuously reduced, increasing the leakage current. When the inverter disconnected from the mains, the maximum leakage current was recorded as the trip level. In this demonstration, the obtained trip level was 127 mA, lower than the 300 mA limit, so the inverter passed the trip level test.

b. Trip time test (Figure 6(b)): this test was performed under the same conditions of the trip level test (voltage and connected pole), with the chosen AC mains angle to switch the 20 mA resistance set at $\varphi = 0°$. First, the resistance required to increase the leakage current by 20 mA was determined. Then, the total resistance was continuously reduced until the leakage current reached 10 mA below trip level. At the specific phase angle $\varphi = 0°$ (left dashed vertical line), the 20 mA resistance was connected, causing the leakage current to exceed the inverter trip level. The inverter disconnected when the leakage current reached zero (right dashed vertical line), resulting in a measured trip time of approximately 42 ms. This time was well below the limit of 300 ms defined in the standard, indicating that the inverter successfully passed this test.

V. EXPERIMENTAL RESULTS

Trip time results for the continuous leakage current test were obtained using five inverters, and their parameters are presented in Figure III. The selection of these inverters was based on factors such as representation of widely used brands in Brazil and availability in our laboratory.

The ambient conditions were controlled to keep temperature at $23° \pm 3°C$. The five inverters were allowed to achieve thermal steady-state, and all tests in the same inverter were conducted in a sequence, without interruption, beginning at $\varphi = 0°$ and ending at $\varphi = 315°$, in steps of 45°. For three

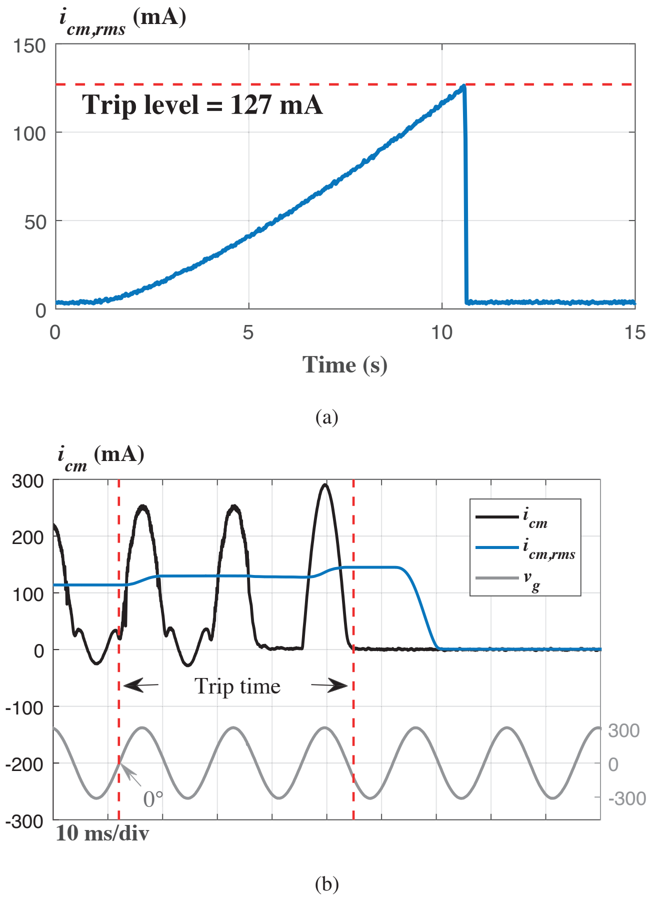

Fig. 6. Demonstration of the continuous leakage current trip time measurement for Inv1 (positive pole): a) trip level; b) trip time.

TABLE III
EUT Parameters

Parameter	Inverter label				
	Inv1	Inv2	Inv3	Inv4	Inv5
Quantity of phases	single	single	single	three	three
Nominal Power	1.5 kW	2 kW	5 kW	8 kW	12 kW

phase inverters, one of the phases was chosen as a reference for defining φ. The positive DC pole was tested first, and both DC and rms AC voltages were kept constant during all tests. Each measurement point was repeated 5 times. Figure 7 shows the mean and the 95% confidence interval of the trip time measurements based on five repetitions for each pole and inverter.

The results were analyzed according to the RMANOVA method, covered on section IIIFigure IV shows the F-statistics and p-value for all the tests conducted.

VI. DISCUSSION AND PROPOSED TEST AND METHODOLOGY

In this section, we first discuss the results obtained, and then we present an improved test methodology to reduce Type A uncertainties by applying the developed test setup.

Out of the 5 tested inverters, Inv1 (positive pole test), Inv2, Inv4 and Inv5 exhibited p-values lower than the chosen significance level ($p < 0.05$), indicating a statistically

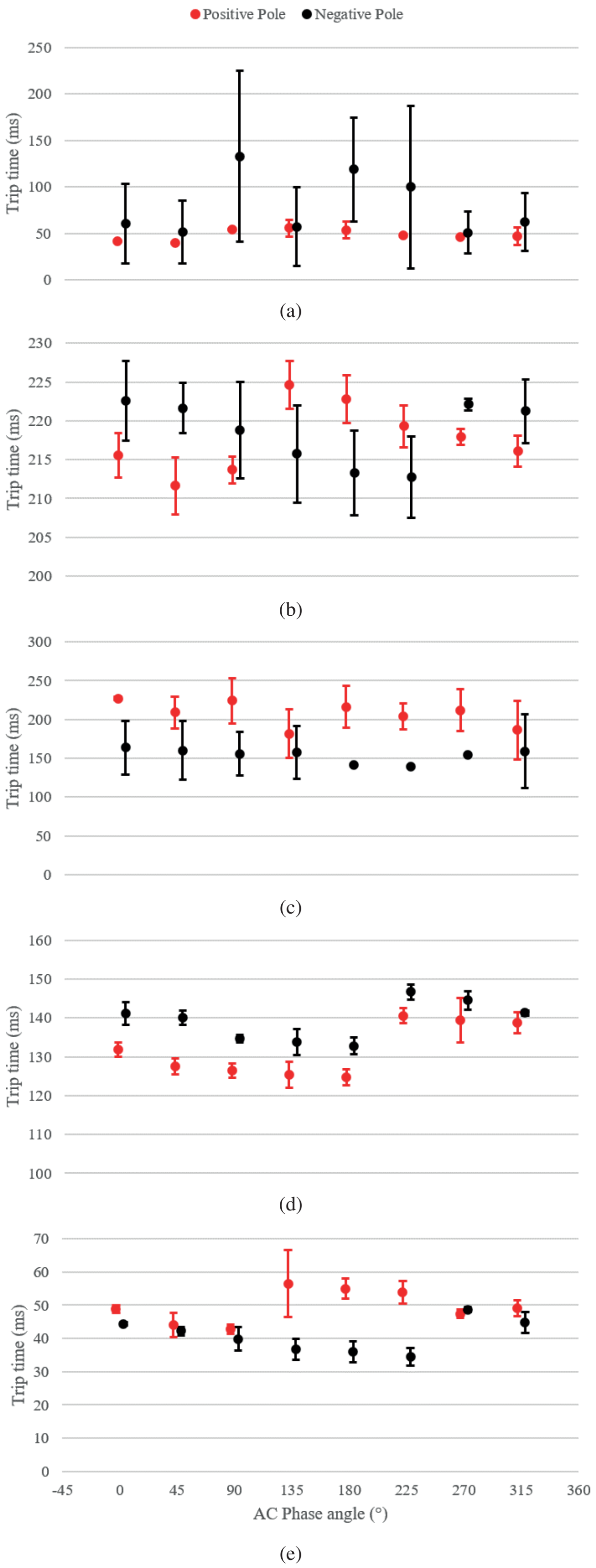

Fig. 7. Trip time results (mean and 95% confidence interval) at different AC phase angles φ when the switch is activated. Results for: a) Inv1; b) Inv2; c) Inv3; d) Inv4; e) Inv5.

significant effect of φ on the trip time of the inverters. For Inv3 and the negative pole test of Inv1, we cannot assert that

TABLE IV
F-statistics Results of the Measurement Conditions

Inverter	Tested PV pole	F-statistics results	p-value
Inv1	positive	$F(2.45, 9.79) = 7.99$	$p = 0.007$
Inv1	negative	$F(2.41, 9.64) = 2.49$	$p = 0.129$
Inv2	positive	$F(2.37, 9.47) = 22.25$	$p < 0.001$
Inv2	negative	$F(1.78, 7.13) = 5.26$	$p = 0.042$
Inv3	positive	$F(2.28, 9.1) = 3.04$	$p = 0.093$
Inv3	negative	$F(2.28, 9.13) = 0.62$	$p = 0.577$
Inv4	positive	$F(1.56, 6.25) = 42.02$	$p < 0.001$
Inv4	negative	$F(2.31, 9.24) = 38.40$	$p < 0.001$
Inv5	positive	$F(1.75, 7.02) = 10.28$	$p = 0.009$
Inv5	negative	$F(2.76, 11.03) = 29.34$	$p < 0.001$

the differences between the group means are solely due to φ, because the p-value was higher than the significance level.

It is important to note that the 95% confidence interval shown in the figures is not related to the significance level. While the significance level indicates the risk of rejecting the null hypotheses while it is true, the 95% confidence interval is based on the standard deviation, which indicates the spread of the measured values around the mean value and is an indicative of the stability and repeatability of the results.

The RMANOVA results of the tested inverters show that the worst-case φ condition (higher trip time) is not constant. For the single-phase 1.5 kW inverter (Inv1), the worst case was $\varphi = 135°$ for the positive PV pole and $\varphi = 90°$ for the negative pole. Furthermore, the negative pole test with $\varphi = 90°$ had the highest standard deviation. For the three-phase 12 kW inverter (Inv5), the worst-case angles were $\varphi = 135°$ and $\varphi = 270°$ for the positive and negative terminals, respectively. This indicates that the AC mains angle leading to a higher trip time cannot be predetermined without prior analysis.

Since the tested equipment are commercial inverters, and the firmware, control strategies, and inner power electronics topologies are protected by the manufacturer, it is not possible to determine the exact reasons for the trip time differences. Therefore, statistical analysis is essential to reach conclusive results.

Possible causes for the trip time differences are:

i) The zero voltage or zero current switching (ZVS or ZCS) of electromechanical relays, used to increase safety and lifespan, may delay the inverter's disconnection from the grid;

ii) Differences in leakage current of the positive and negative PV poles may be caused by the DC-DC boost converter topology. For an usual boost converter, the negative PV pole is connected to the negative pole of the DC bus, and the positive PV pole terminal has lower voltage to ground than the positive pole of the DC bus. Therefore, the voltage between negative PV pole and ground is higher than the voltage between positive PV pole and ground. Depending on the methods for measurement DC and AC content of the residual current, this may cause differences in trip level results.

Based on our results, we propose a methodology for performing the test in Section A.considering the values of φ experimented with in Section V.The test equipment must be able to switch the R load precisely at the specified φ

(0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°). Although this methodology multiplies the total quantity of testing points by 8, it is important to improve the confidence of the test results, especially when measured values are close to compliance limits.

Currently, the existing procedures mandate only 5 repetitions, disregarding φ. Considering a scenario where the inverter fails the test in 25% of the φ range ($0° - 360°$), the inverter's probability of passing the 5 repetitions is $0.75^5 = 23.7\%$. This introduces a substantial element of luck into the test results. By introducing the AC voltage angle φ as an additional parameter in the test procedure, we seek to minimize this element of uncertainty. This adjustment would allow a more accurate and repeatable assessment of the inverter's protection against continuous leakage current.

VII. CONCLUSIONS

This study specifically investigated the influence of the grid voltage phase angle on the continuous leakage current trip time results of PV inverters and proposed an improved testing methodology to reduce measurement uncertainties and increase confidence levels. The results of the RMANOVA analysis demonstrated that the grid voltage phase angle does have a statistically significant effect on the trip time results of four of the five inverters, and that the worst-case condition (higher trip time results) cannot be defined without prior analysis. The proposed methodology includes testing the inverters in eight different controlled AC mains phase angles, which helps to reduce Type A uncertainties and achieve higher confidence levels in the results.

The contributions of this study are significant for the PV inverter industry, testing laboratories, and standard committees, as they provide a better understanding of the grid voltage phase angle's impact on continuous leakage current test results and propose an improved methodology to increase the reliability of the test results. The findings of this study suggest that the influence of the grid voltage phase angle should be considered in future updates of IEC 62109-2, IEC 63112 and other safety standards. Overall, this study has important implications for ensuring the safe and reliable operation of PV inverters in the field.

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