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Assessment of Personal Safety Concerns of Plug and Play Photovoltaic Inverters using a Black Box Approach and Laboratory Measurements

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ABSTRACT

The increasing use of plug and play photovoltaic systems has raised concerns about their safety, especially with nonprofessional installations, which existing standards only partially address. This study proposes a black box testing approach to assess the personal safety of plug and play inverters. A total of 25 microinverters are assessed using three tests: (1) analyzing the residual voltage at the mains plug after disconnection, (2) the feed-in current increase under low grid voltage conditions, and (3) the maximum touch temperature during operation. Residual voltage testing reveals that 56% of the inverters comply with the limit of the latest official German plug and play system standard draft and behave similarly to other tested electrical devices. Further investigation is required to determine if exceeding this limit presents a direct safety risk. However, adding a relay was identified as an effective measure to ensure compliance. Under low voltage conditions, current increases up to 26.3% were measured, potentially stressing nondedicated circuits. In the temperature test, a positive correlation between the inverters power density and the touch temperature was found. The findings of this analysis provide insights for future standardization efforts and offer guidance to manufacturers in improving the safety of these PV systems.

1 | Introduction

The number of plug and play photovoltaic (PV) systems, also known as balcony PV or plug-in PV, has increased significantly among end consumers over the last 2 years. These systems typically use microinverters with a maximum output power depending on the national regulation (e.g. 600 or 800 VA). In Germany, currently, the largest market for plug and play PV systems, 435,000 systems were registered in 2024 according to the trade association of the German solar energy industry (BSW), nearly doubling the registration numbers of 2023 [1, 2]. In June 2025, more than one million systems, with a power of more than 1 GWp, were registered in the market master data register, indicating a high market growth [3]. Due to the ease of installation, many plug and play systems are not declared to the regulatory bodies. A German study in 2022 found that approximately 80% of the systems are not reported [4]. The same study showed that more than 70% were sold with the standard mains connector in Germany (Typ F).

One of the main driver for plug and play systems are the low systems prices, plus the low or nonexisting installation costs, and the rising household electricity prices in the recent years in combination with a high self-sufficiency ratio [5]. For example, a plug and play PV system (800VA) for 700 € has levelized cost of energy of around 0.14 €/kWh (500 kWh/a year over 10 years; without discontinuation) and is therefore more than two-times cheaper than the average household electricity price in 2024 in Germany (0,39 €/

kWh [6]). These systems not only open up a new PV market segment but also expand the national PV capacity to include small balcony areas. A potential study for plug and play PV systems in Switzerland calculated a technical potential of 894–1040 GWh, while only including balcony installation [7]. This would add up to 1 TWh to the Swiss facade PV potential of 17 TWh [8].

Plug and play PV systems are also applied outside of Europe. In 2017, the South Korean capital Seoul declared that it would distribute PV modules to one million households by 2022 [9]. The power of the system is between 260 and 300 W and the purchase of such systems was subsidized by the Seoul Metropolitan Government. The current status of plug-and-play systems in Seoul is unknown to the authors. In May 2025, the US state of Utah adopted bill HB340, which permits 1200 W of backfeed through a standard 120 V AC mains socket [10]. In addition, it exempts plug and play systems from the approvals that larger PV systems must obtain. The plug and play system must meet the standards of the most recent version of the National Electrical Code and must be certified by Underwriters Laboratories or an equivalent nationally recognized testing laboratory.

In terms of personal safety, the installation of plug and play PV systems by end users is more critical than professionally installed PV systems, as most of the microinverters used for plug and play systems were designed to be connected to the grid via a fixed connection. Further safety aspects, such as the residual voltage at the mains plug after grid disconnection, possible overload situations of distribution circuits, and interference with RCD functionality, are currently discussion points [11]. The risk potential of overloading a cable section (also known as breaker masking) due to a plug and play system varies on national level due to the different cable cross-sections and fuze ratings for the distribution circuits and the installation date of the electrical installation. Other important safety aspects, relevant both across the EU and globally, are directly related to the PV inverter. Current inverter safety standards (e.g. IEC 62 109–1 [12]) address some of the safety concerns briefly. Due to the variety of PV inverter configurations, general standards are unlikely to soon cover all the mentioned aspects comprehensively.

Throughout Europe, there are additional inconsistent regulations concerning the connection of the grid via a standard mains plug. According to Point 551.7.2 of HD 60 364-5-55, connecting a generation unit to a final circuit via a plug connection is generally prohibited. However, certain countries have adopted national exceptions to this rule, including Switzerland, the Netherlands, and the UK. The document from the Swiss Federal Inspectorate for Heavy Current Installations regarding plug-and-play PV systems originates from there [13]. In Germany, the grid connection of these systems is only allowed through a dedicated special feed-in socket [14]. Conversely, in Austria, there is a lack of specific regulations, placing the responsibility on the distributor to ensure adherence to prevailing standards, which may include performing a risk analysis and assessment if required [15]. Even though the installation of plug and play systems is not permitted in a country, people will still install those systems, due the economic or ecologic reasons. With a standard for such systems, defined requirements would be available, providing a clear safety indication for consumers and other stakeholders (e.g. landlords, insurers, and so on.)

In 2023, the first draft of a German product standard (E DIN VDE V 0126–95 [16]) for plug and play PV system was published by the VDE. This draft is currently in its second revision and outlines requirements for all components of a plug and play PV system, such as module mounting frame, inverter, PV modules, DC connectors, and grid connection. The mounting frame, PV modules, and DC connector requirements align with those of conventional PV systems. For the connection to the grid through a standard mains plug, new requirements are defined that would legalize this type of connection, as current standards [14] do not allow it yet. For this new requirement, limited information and experience is available on the behavior of plug and play PV inverters regarding their residual voltage behavior. Previous publications on microinverters that are used in plug and play systems focused on efficiency measurements and yield estimations [17, 18]. A study conducted by the photovoltaic institute (PI) Berlin [19] in 2017 analyzed the interference with RCD functionality of three microinverters and assessed overload situations of cable sections for plug and play systems of 600 VA through laboratory measurements. In 2025, the methodology from PI Berlin for assessing overload situations of cable sections was analyzed for 800 VA plug and play systems by the HTW Berlin [20]. The PI study from 2017 [19] further discussed protection against electric shock in the context of residual voltage at the mains plug after unplugging, although without laboratory measurements. A recent US study analyzed barriers for plug and play PV systems in the USA and also discussed three safety aspects (touch safe plugs, breaker masking, and bidirectional residual circuit devices) [21]. Both studies, which address touch safety of plug and play systems with standard mains plugs, argue that the anti-islanding function and/or the relay of the interface protection mitigate residual voltage risks or ensure a safe behavior. This line of reasoning is misleading because the anti-islanding function and the relay for grid and system protection are primarily designed to safeguard the system and grid (including protecting grid technicians in the event of unforeseen islanding), rather than serving the purpose of personal safety. While these functions provide a galvanic separation between the inverter's power electronics and the mains plug, it is important to note that the residual voltage level may remain noncompliant due to the presence of nonswitchable capacitors, as noted in the draft of the German plug and play standard.

The mentioned publications show the lack of data on the behavior of microinverters used for plug and play systems concerning the grid connection through standard household hold plugs (e.g. Typ F in most of the EU and T13 in Switzerland). This could lead to overregulation's and additional bureaucratic procedures in testing and installation, thus causing higher costs for consumers.

The behavior of plug and play with respect to the mentioned safety aspects (residual voltage at the mains plug after disconnection, possible overload of a cable section and touch temperatures) are examined under the Swiss project 'Plug & Play Photovoltaic Systems' [22]. The project also examines the PV potential of plug and play systems in Switzerland [7] and analyzes the extension of the national plug and play system limit from 600 [13] to 800 VA. In addition, the results of the tests and learnings of the project will be used as input for a national Swiss plug and play system guideline.

In this article, the main objective is to analyze a set of microinverters used in plug and play systems in context of safety concerns and assess their safety risks, if present. The safety concerns are assessed through laboratory measurements under real conditions. A black box testing approach for the measurements is proposed and employed, using only parts and connectors that are accessible during normal operation, eliminating the need for disassembly. Finally, the safety risks of the measured microinverters are discussed for the conditions analyzed in context of the current gap in standardization.

In the subsequent pages, 'microinverters used in plug and play systems' and 'plug and play inverters' are used as synonyms, even though there might be a terminological change in the future (i.e. microinverters can be used for plug and play systems, thus they are plug and play inverters, but considering future clear safety regulations, not every microinverter might be a plug and play inverter).

2 | Experimental Section

2.1 | Devices under Test

To assess the safety concerns of plug and play inverters 25 different microinverters from 11 manufacturers are analyzed. The inverters and their main parameters are shown in Table 1 representing typical inverters on the current market. The nominal AC power values range from 300 to 2000 VA. Not all inverters of the test set are in the power range of national plug and play systems limits (600 VA for Switzerland, 800 VA for most of EU countries [23]—e.g. Germany, Austria), but their output can be limited via software to the corresponding limits. In addition to 23 single-phase inverters, there are also two three-phase inverters in the available device selection, presenting a scenario in which the plug and play limit is extended to three-phase systems (600 or 800 VA per phase). Based on national limits for plug and play PV systems (A: <=600 VA, B: <=800 and >600 VA, and C: >800 VA), 16 devices under test can be assigned to category A, 5 to category B, and 4 to category C, neglecting that two or more inverters can be used for a plug and play PV system. Due to space reasons in the plots, the long inverter naming will be shortened (e.g. NEO-800M-X to NEO-800). All inverters, except the Enphase microinverters, were operated with the components provided in the scope of delivery. The Enphase inverters are first initialized with an IQ gateway and then used without gateway and Q-Relay. This is not the usage configuration intended by the manufacturer, but it is realizable and observed in practice, which makes it relevant from a safety perspective.

2.2 | Safety Tests

Based on currently discussed safety risks of plug and play PV inverters and a review of potentially applicable standards, three tests are defined for the laboratory measurements. The test conditions are defined according to the proposed black box testing approach, where only parts and connectors are utilized that are accessible during normal operation. Further, no additional communication gateways or monitoring equipment is used and no firmware updates are carried out. This reflects a typical consumer situation, where users often do not regularly update their devices due to lack of awareness, technical knowledge, or simply out of negligence. The following enumeration gives an overview of the tests, their origin and conducted adjustments to existing tests:

- Residual voltage after disconnecting

  Plug and play inverters incorporate power electronic circuits similar to other household appliances that include built-in capacitors, which may retain residual voltage after disconnection from the grid. Furthermore, as part of their function as generation systems, these inverters are required to cease power injection and open the safety relay upon grid disconnection or in the event of grid failures.

  The residual voltage test is derived from the draft of the German product standard for plug and play PV systems (E DIN VDE V 0126-95:2024-6 [16]), where it is applied if a standard mains plug is used for the grid connections. As the applicable chapter is currently under discussion, modifications may be implemented prior to the final publication. The test is adapted according to the black box approach, as the standard requires voltage measurements directly at the capacitors. The residual voltage limit (the maximum touch voltage must be below 34 V in 1 second) is kept unchanged, which originates from IEC 60335-1 [24]. The product standard draft also mandates that the residual voltage test is conducted at nominal power, 50% of the nominal power, and at the lowest feasible rated power. Due to the number of inverters under test, the residual voltage test in this article is only conducted at nominal power, as it is assumed that this condition represents the worst-case condition.

- Limitation of feed-in current at low grid voltage

  To prevent overloading of nondedicated distribution circuits, plug and play inverters should limit the feed-in current to nominal feed-in current at any voltage level. This test is also derived from the current draft of the product standard for plug and play PV systems (E DIN VDE V 0126-95:2024-6 [16]). The test is to be carried out according to DIN VDE V 0124–100 [25] with an additional voltage step at 0.85 V_n (n for nominal), where the feed-in current in this test must not exceed 3.5 A with a tolerance of 2%. DIN VDE V 0124–100 requires that the working point for every voltage is kept for 10 min after stabilization. Due to the number of inverters, the step time is reduced in this campaign and additional voltages are added to the voltage profile (see Chapter 2.2.2) for further insights in the inverter behavior at low voltage levels.

- Maximum touch temperature

  Plug and play inverters use convection cooling to dissipate thermal losses. This cooling concept has the disadvantage that it is dependent on external factors such as the ambient temperature or the mounting situation. Therefore, the surface of the inverter can reach temperatures that pose a safety risk to people in the event of contact. In this test, the maximum touch temperatures at two conditions (see Chapter 3.2) are measured and compared with the limits for touch temperature defined in IEC 62 109–1 [12].

TABLE 1 | List of inverters under test, their main parameters (MPPT range, DC input parameters, continuous current, power rating, and peak values for current and power) and important additional comments.

Manufacturer	**Inverter**	**Min. MPPT voltage (V)**	**Max. MPPT voltage (V)**	**Max. input voltage (V)**	**Max. input current (A)**	**Numbeer of inputs (–)**	**Max. continuous AC power (VA)**	**Max. peak AC power (VA)**	**Max. continuous AC current (A)**	**Comments**
					1-Phase inverter					
Aeconversion	INV500-90	40	80	90	11	1	480	—	—	—
Aeconversion	INV315-50	24	40	50	9.5	1	300	—	—	—
Altenergy Power System	DS3-S	28	45	60	18	2	600	—	—	—
Altenergy Power System	EZ1-M	28	45	60	20	2	799	—	—	Output power reduced by the seller to 600 VA via software
Deye Inverter Technology	SUN-M80G3-EU-Q0	25	55	60	13	2	800	—	3.7	—
Deye Inverter Technology	SUN600G3-EU-230	25	55	60	13	2	600	—		With external relay SUN-MI-RELAY-01
Dongguan Kaideng Energy Technology	WVC-300	25	45	60	13.7	1	300	310	—	—
Dongguan Kaideng Energy Technology	WVC-600	22	60	60	12	2	580	600	—	—
Enphase Energy	IQ7A	38	43	58	10.2	1	349	—	—	No Q-Relay used
Enphase Energy	IQ8MC	25	45	60	14	1	325	—		No Q-Relay used
Envertech	EVT360	22	48	60	12	1	360	—	1.64	—
Envertech	EVT560	24	45	54	12	2	560	—	2.72	—
Estar Energy	HERF-500	16	48	60	14.5	1	490	—	—	—
Estar Energy	HERF-1000	16	48	60	14.5	2	980	—		
Growatt New Energy	NEO-800M-X	28	60	60	18	2	800	—	—	Name plate stats NEO 1000M-X, therefore output power must be reduced to 800 VA

(Continues)

TABLE 1 | (Continued)

Manufacturer	Inverter	Min. MPPT voltage (V)	Max. MPPT voltage (V)	Max. input voltage (V)	Max. input current (A)	Numbeer of inputs (–)	Max. continuous AC power (VA)	Max. peak AC power (VA)	Max. continuous AC current (A)	Comments
Hoymiles Power Electronics	HM-300	16	60	60	11.5	1	300	—	—	—
Hoymiles Power Electronics	HM-600	16	60	60	11.5	2	600	—	—	—
Hoymiles Power Electronics	HM-800	16	60	60	12.5	2	800	—	—	—
Hoymiles Power Electronics	HMS-1800-4T	16	60	65	15	4	1800	—	—	—
New Energy Technology	GMI500	24	40	50	20	1	490	—	—	—
New Energy Technology	GMI700	24	40	50	28	1	650	—	—	—
New Energy Technology	SG600MD	24	40	50	12	2	590	600	—	—
Northern Electric Power Technology	BDM-600	22	55	60	18	2	580	600	2.52	—
					3-Phase inverter					
Altenergy Power System	YC1000-EU	16	55	60	14.8	4	900	1130	1.64	—
Hoymiles Power Electronics	HMT-2000-4T	16	60	65	16	4	2000	—	2.9	—

The aim of the tests and the assessment is not to declare devices as unsafe in the scope of the measurements, it rather aims to identify situations for plug and play systems where clear requirements are necessary. A declaration would first (1) require exiting limits, which are, for example, due to the draft status of E DIN VDE V 0126–95 subject to possible change and not yet in force. Second (2), the application of microinverters as plug and play inverters adds further design requirements to the development process which were not required in the past. Thus, microinverters intended for rooftop installation—designed in compliance with existing safety and performance standards—may require additional specifications when deployed in plug and play systems. Capacitors as an example, which were originally implemented to meet requirements like electromagnetic compatibility, might now affect the residual voltage characteristics and require pre- or postmanufacturing adaptations for the system.

All tests are conducted at the Laboratory for Photovoltaic Systems (PV Lab) of the Bern University of Applied Sciences in Burgdorf (BFH), where a dedicated test bench has been developed especially for the test 'Residual voltage after disconnecting'. The test setup and conditions of the three tests are explained in the following subchapters. A detailed description of the measurement steps is provided in the supporting information material of this article.

2.2.1 | Residual Voltage after Disconnecting

The scheme of the measurement setup for the residual voltage test is shown in Figure 1 for the test of one inverter. The plug and play inverter under test (DUT) are connected to the PV module simulator(s) (Modul Sim) on the DC side and to the plug side of the socket connection on the AC side. The power analyzer is connected to the setup as illustrated (detailed device names and settings are presented in Table 2). To ensure the same grid conditions for each measurement and prevent interferences from other grid connected devices, the setup uses a grid simulator. Figure 2a shows the physical measurement setup, without the grid simulator due to space reasons. Figure 2b illustrates the function of the automated mechanical disconnection through the linear motor. Due to the parallel connection of three Swiss T13 sockets on the grid side and three measurement cards on the power analyzer, it is possible to measure three inverters simultaneously. Measurements of three-phase inverters are also possible with this setup, given that a T15 socket (three-phase) has the same space requirements as a T13 socket (one-phase).

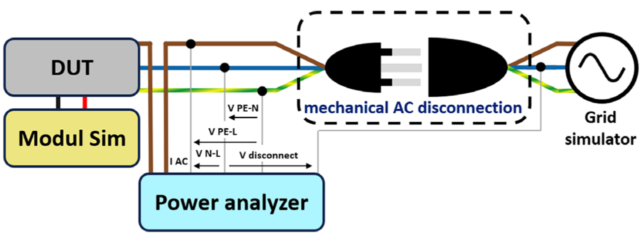

FIGURE 1 | Measurement scheme of the residual voltage test for one inverter. (DUT = device under test, i.e. microinveters).

TABLE 2 | Simulator and measurement devices for the residual voltage test and their settings.

Device	Product name	Settings
	Simulators and actuators	
PV module simulators	Delta Elektronika SM330-AR-22 Delta Elektronika SM100-AR-75	–
Grid simulator	Regatron TC.ACS.50.528.4WR.HC.LC	1 phase or 3 phase grid with 230 V_{RMS} (Phase-Neutral)
Mechanical mains disconnector	ETEL linear motor	Velocity: 50 mm/s Acceleration: 50 mm/s^2
	Measurement devices	
Power analyzer	Dewetron DEWE3-PA8-RM with 3x TRION3-1810M-Power-4 measurement cards	Sampling rate: 50 kHz

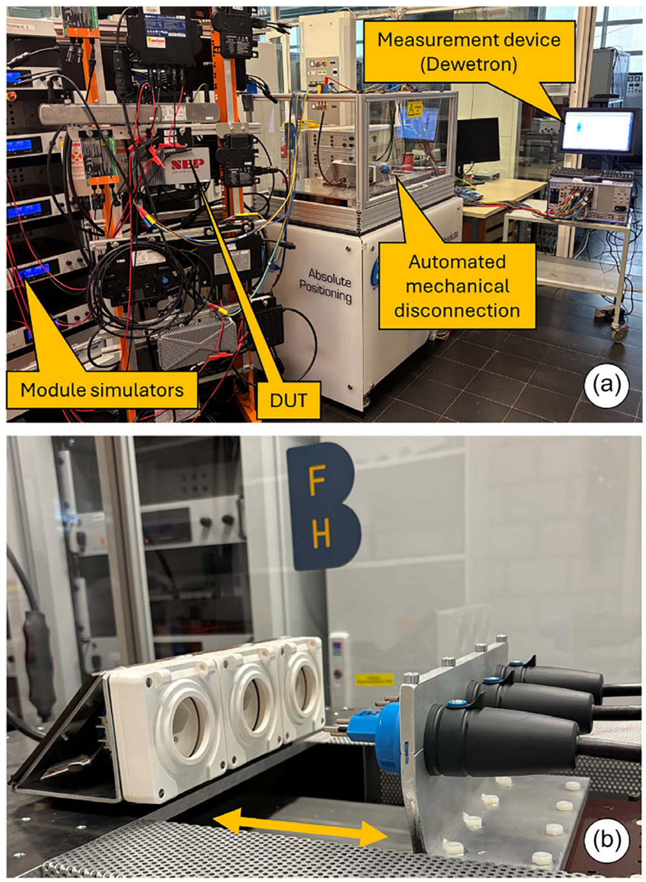

FIGURE 2 | (a) Test setup for the residual voltage test and (b) detail of the automated mechanical mains disconnection.

The inverters or their enclosure are deliberately not connected to the protective earth of the installation, even though this would be possible, due to the increased safety risks associated with this configuration.

Due to the number of inverters, the residual voltage test is only conducted at nominal power and repeated 30–50 times, depending on the start time of the inverter, to ensure measurements at different phase angles. The required DC power is not determined iteratively and the *I–V* curve parameters are set with the following conditions: The MPP power for each DC input is the nominal AC power increased by 10% (accounting for losses) and divided by the number of DC inputs. The *I–V* curve parameters are calculated according to the conditions stated in Figure 3, where the ratio V_{MPP}/V_{OC} is adjusted from the EN 50 530 [26] to current module parameters.

The residual voltage test is conducted with the following procedure: First, the AC connection to the grid is closed with the linear motor and the corresponding *I–V* curves are activated on the module simulator(s). When the inverter reaches the nominal power, the AC connection is opened through the linear motor and the measurement is triggered by the power analyzer. A trigger pre- and post-time of 1 s is used. The process is repeated automatically with the same unplug conditions in context of velocity and acceleration.

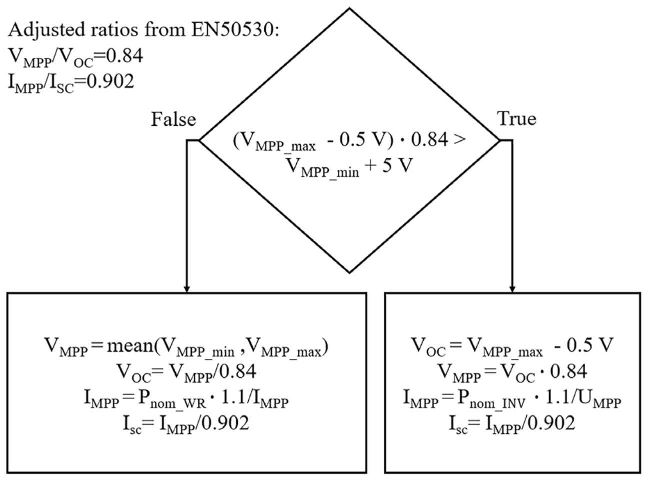

FIGURE 3 | Calculation of the *I–V* curve parameters for every plug and play inverter.

In addition to plug and play inverters, other electrical household devices are analyzed with the same test procedure for a comparison of the residual voltage behavior.

To minimize the influence of the measuring device on the measurement, the input impedance should be as high as possible. Although the voltage channels of the used power analyzer (Dewetron) have a input impedance of 5 MΩ || 2 pF [27], the input resistance in the residual voltage test is reduced to 3.3 MΩ due to the measurement of the three possible touch voltage combinations (e.g. L-N||N-PE + L-PE). For the residual voltage test of three phase inverters, the number of combinations of touch voltages is 10 and the input resistance per voltage channel is therefore reduced to 2 MΩ.

Compared to a setup with a (solid-state-) relay, the chosen setup represents realistic conditions and the measurement is not influenced by switch bouncing or parasitic capacitive effects. The disadvantage of the chosen setup is that no defined phase angle can be set for the grid disconnection.

The measurement files are processed in Python after the measurements. As the measurement is triggered at the middle socket connection (see Figure 2), it is possible that the disconnection occurred earlier or later at the other two sockets. For this reason, an individual disconnect time is calculated for each socket. The disconnection for this article is defined, where the voltage V_{PEN} exceeds 1.35 times the mean values of the first 0.5 s in the pretime window. In the second step, the timestep is determined, where the maximum touch voltage falls below 34 V, and the time for the voltage decline is calculated. In the last step, the voltage at the point of disconnection is determined for the analysis. Figure 4 shows the current and voltage curves of a plug and play inverter after disconnection from the mains.

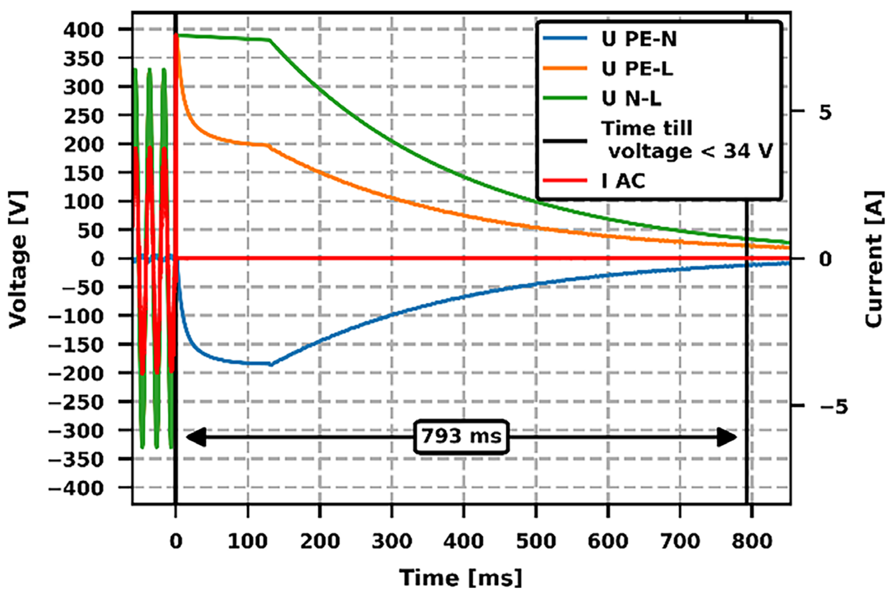

FIGURE 4 | Current and voltage after disconnection from the mains of a plug and play inverter (600 W).

The current drops to 0 A after disconnection because the plug is not under load (e.g. body resistor), and the voltages show the typical voltage curve of a capacitor discharge. At $t = 130$ ms, the change in voltage gradient indicates switching activity. The maximum touch voltage falls below the voltage limit of 34 V after 793 ms and thus complies with the 1 s limit of E DIN VDE V 0126-95:2024–6.

2.2.2 | Limitation of Feed-in Current at Low Grid Voltage

The measurement scheme for the test 'Limitation of feed-in current at low grid voltage' is shown in Figure 5. In this test, the same setup and devices as in the residual voltage test, except for the mechanical AC disconnection, are used. To ensure the same voltage at the grid connection point for every inverter, the voltage is controlled through a sense cable. In this test, only one inverter per measurement run is used.

The applied voltage profile for the test is illustrated in Figure 6a, with a ramp time of 5 s and a step duration of 30 s. This profile differs from the requirements of DIN VDE V 0124–100, thus, a second and compliant profile (see Figure 6b) is used to validate the inverters behavior (e.g. stabilization time). Three inverters, chosen from the available set, are used for the validation. This profile has a ramp time of 1 min and a step duration of 15 min.

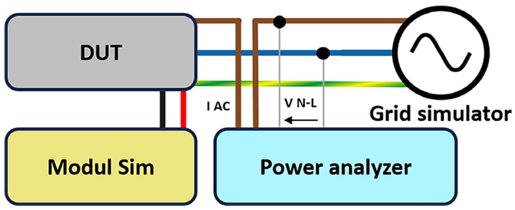

FIGURE 5 | Measurement scheme of the test "Limitation of feed-in current at low grid voltage" for inverter.

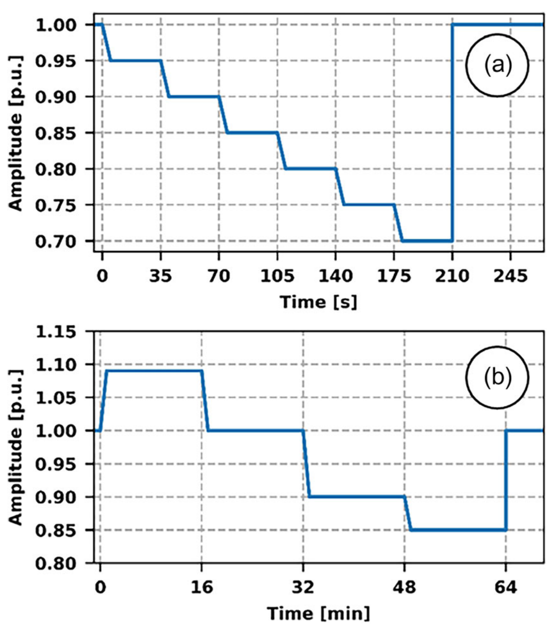

FIGURE 6 | (a) Voltage profile for testing the limitation of feed-in current at low grid voltage and (b) profile according to DIN VDE V 0124–100 [25] and E DIN VDE V 0126-95:2024-6 [16].

For the analysis, it is determined if the inverter increases the feed-in current (measured as 20 ms true RMS value) during the test compared to the starting current and at which voltage does the inverter shut down. In addition, it is analyzed to determine if there are differences in the inverter behavior between the two voltage profiles of Figure 6.

2.2.3 | Maximum Touch Temperature

The measurement scheme for the maximum touch temperature test is shown in Figure 7 for one inverter. For time reasons, three inverters are tested in parallel. The inverters are supplied on the DC side by the module simulators (Modul Sim) and are connected to the laboratory grid–no grid simulator is used. At every inverter, the temperature is measured in the middle of both sides of the inverter (see Figure 8). The used measurement devices and simulators are presented in Table 3 with their main settings.

IEC 62 109–1 [12] requires that the maximum temperature must not exceed the defined limits in the most severe rated operating conditions. In this test, the limits for 'Enclosure parts accessible to user by casual contact' of Table 3 in IEC 62 109–1 are used. The limit for metal parts is 70°C and for plastic and rubber parts is 95°C. All plug and play inverters under test have metal enclosures; expect the two Enphase inverters, which have polymer enclosures.

Since microinverters use convectional cooling, the convectional heat flux formula can be rewritten to show the dependencies of the surface temperature of the inverter. The formula given in (Equation 1) assumes a constant heat transfer coefficient α, where the surface temperature $T_{\text{Inv\_Surface}}$ is the sum of the necessary temperature difference ΔT to dissipate the inverter losses, which are a function of the input power P_{In} and the corresponding efficiency $\eta(P)$, and the ambient temperature T_{Amb}.

$$T_{\text{Inv\_Surface}} = \frac{\dot{Q}_{\text{Conv}}}{A \cdot \alpha} + T_{\text{Amb}} = \Delta T(P_{\text{In}}, \eta(P)) + T_{\text{Amb}} \quad (1)$$

The most severe operating conditions are thus present at high ambient temperatures, small cooling surfaces, high input powers,

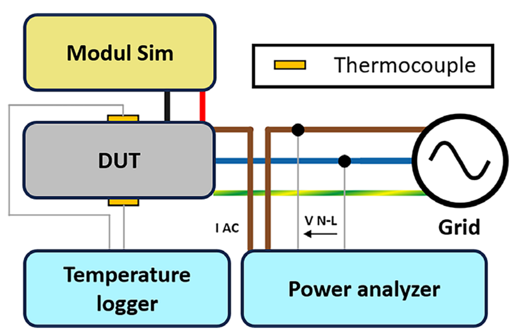

FIGURE 7 | Measurement scheme of the maximum touch temperature test.

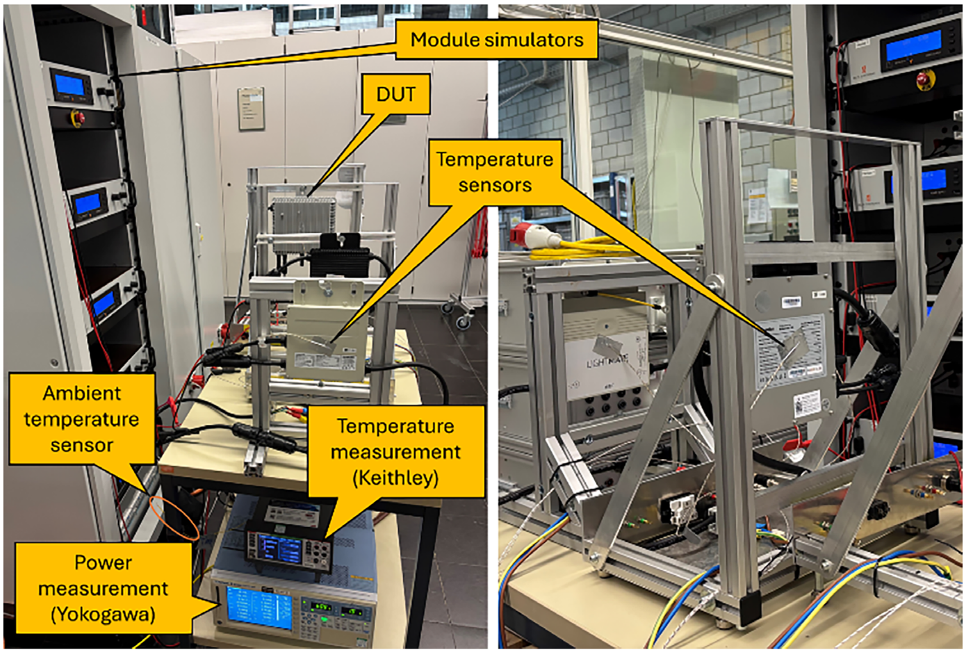

FIGURE 8 | Test setup for the maximum touch temperature test.

TABLE 3 | Simulators and measurement devices for the maximum touch temperature test and their settings.

Device	Product name	Settings
	Simulators	
PV module simulators	Delta Elektronika SM330-AR-22 Delta Elektronika SM100-AR-75	Irradiance ramp according to Figure 9
	Measurement devices	
Temperature measurement	Keithley DAQ6510 with 7700 measurement card	Thermocouples: -Inverter temperature: Typ T -Ambient temperature: Typ K Data acquisition every 10 s
Power analyzer	Yokogawa WT3000	Data acquisition every 10 s

low efficiencies, and limited convection (i.e. low heat transfer coefficient). For the test, it is assumed that the microinverters have mounting conditions with sufficient convection. In this setup, the input power—defined as a function of irradiance—is the only variable actively adjusted. The effects of ambient temperature can be considered retrospectively by calculation as given by (Equation 1). Figure 9 presents the irradiance profile used for the test, which serves as the basis for adjusting the *I–V* curves defined in Chapter 2.2.1. The profile has a ramp time of 2 min and a step time of 3.5 h to reach steady-state conditions. An irradiance of 1000 W/m^2, corresponding to standard test conditions, represents the operating point at nominal power, while 1500 W m^2 is used to simulate increased input power levels

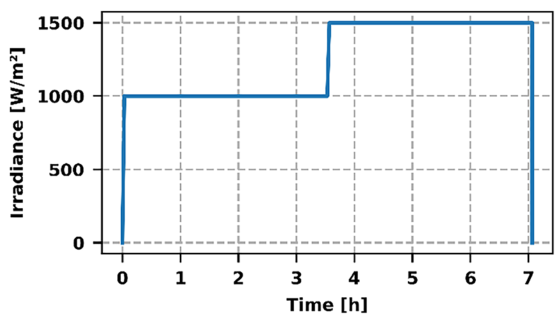

FIGURE 9 | Irradiance profile for the maximum touch temperature test.

available to the inverter (i.e. overpaneling). It can be ruled out that the maximum voltage range will be exceeded due to the increased irradiance, as the PV simulators slightly reduce the open-circuit voltage at an irradiance of over 1000 W/m^2—in contrast to the physical behavior of PV cells at a constant temperature.

The measurement files are analyzed for the maximum touch temperature and the corresponding timestamp of each inverter, thus indicating if a higher input power has an influence on the temperature behavior. Based on the determined maximum touch temperature and the ambient temperature at that timestamp, it is determined at which ambient temperature the maximum allowed touch temperature is exceeded.

3 | Results and Discussion

The results of the laboratory measurements are presented in the following subchapters. Two inverters from the same manufacturer were not restarting after the residual voltage test (WVC-300) and the maximum touch temperature test

(WVC-600). The inverters showed error states via the LED indicator but were not reachable via the monitoring App. Therefore, not all three tests could be conducted on these two inverters.

3.1 | Residual Voltage after Disconnecting

The results of the residual voltage test are presented in Figure 10 for the 25 microinverters under test at nominal power and for five electrical consumer devices under different load conditions. The duration of the overall voltage discharge ranges from hundred milliseconds to more than 12 s. No measurement showed that an inverter would maintain a constant 230 V_{RMS} AC output voltage after unplugging. Out of the test set, 14 inverters (56%) comply with the residual voltage limit of E DIN VDE V 0126-95:2024–6, while the other 11 inverters exceed the limit with at least one measurement. Two inverters (DS3-S and EZ1-M) have one measurement out of the limit, which represents a probability of exceedance of 2.5% and 2.3%. Another seven inverters have discharge times under and over the 1 s limit, with 39.5%–95.7% of the values over the limit. All measurements of the three phase inverters (YC1000-EU and HMT-2000) exceed the limit, although the discharge times differ by a factor of more than four. Categorizing the inverters based on their power (A: <=600 VA, B: <=800 VA and >600 VA, and C: >800 VA) (the inverter EZ1-M is classified in category B even though it is reduced to 600 VA) shows that 44% of the category A inverters ($n = 16$), 20% of the category B inverters ($n = 5$), and 75% of the category C inverters ($n = 4$) exceed the limit. Adding a categorization based on inverter manufacturers to the analysis has only little effect on the results, as (A) 40%, (B) 20%, and (C) 67% of at least one inverter from a manufacturer in the category has discharge times over 1 s.

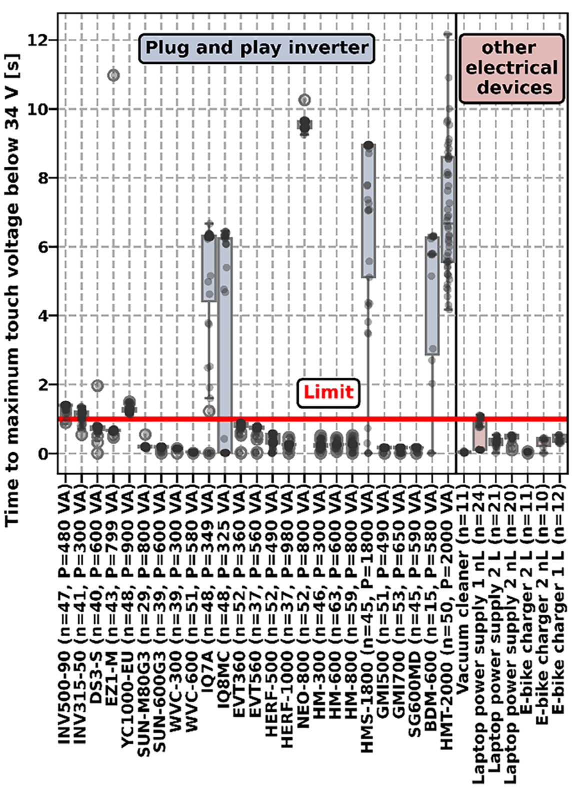

FIGURE 10 | Results of the residual voltage test (time until the maximum touch voltage is below 34 V) for the plug and play inverters and other typical electrical devices. (nL = no load; L = load). The red "Limit" line is the residual voltage limit of E DIN VDE V 0126-95:2024–6.

Due to the different basic population of the categories, the relative values need to be used with caution, as a change in a smaller population causes a higher relative value change than in a bigger population. Based on the analyzed inverter set, no correlation between the inverter power and number of limit-exceeding inverters can be determined.

The results of the residual voltage tests for the five electrical household devices show that one device exceeds the limit with at least one measurement. Further, similar time ranges for the compliant plug and play inverters and the corresponding electrical devices can be observed.

As a result of the variation in discharge times for certain inverters, Figure 11 illustrates the relationship between the time it takes for the maximum touch voltage to fall below 34 V and the voltage at the moment of disconnection. Due to the high spread in discharge times, the values are normalized. While certain inverters (EVT360, BDM-600, IQ7A) exhibit a clear dependency of the discharge time on the disconnect voltage (i.e., phase angle), for the majority of the tested inverters a consistent correlation cannot be determined from the figure. Two factors are influencing the graphical analysis. First (1), inverters with very constant discharge times (e.g. HM-800, WVC-300, and YC1000-EU) could have a dedicated discharge circuit, for example, nondisconnectable capacitors, which is not tuned on all devices to the 1 s limit. This, as a disadvantage of the black box approach, cannot be clearly determined without information from the manufacturer or by analysis of the internal circuit. Second (2), it was found that the defined condition for the disconnection point is not generally suitable to closely get the correct voltage at every disconnection. This is a minor problem for the calculation of the discharge time, with a maximum error of 10 ms, but suboptimal for the analysis of the disconnection voltage. A proof for the inconsistency to detect the disconnection voltage is the presence of data point at voltages above 325 V (peak of the 230 V_{RMS} sine), which are overvoltage values after the disconnection.

Some of the inverters in category A (<= 600 VA) have power values close to 50% of the category limit, and therefore, two inverters could be used for a plug and play system. Figure 12 shows the results of residual voltage tests, where two inverters were operated in parallel on the grid compared to the results of the single operated test. Two out of the three tested inverters show no difference between a single and parallel operation. This can be explained with the time constant of a RC circuit, as Figure 4 shows the voltage decline indicates a capacitor discharge, where further a discharge resistor is assumed to eliminate persistent residual voltages. If two RC circuits are connected in parallel, with the same resistance and capacitance values, the total resistance halves and the capacitance doubles, thus resulting at the same time constant as one RC circuit. In contrary, the times of the two

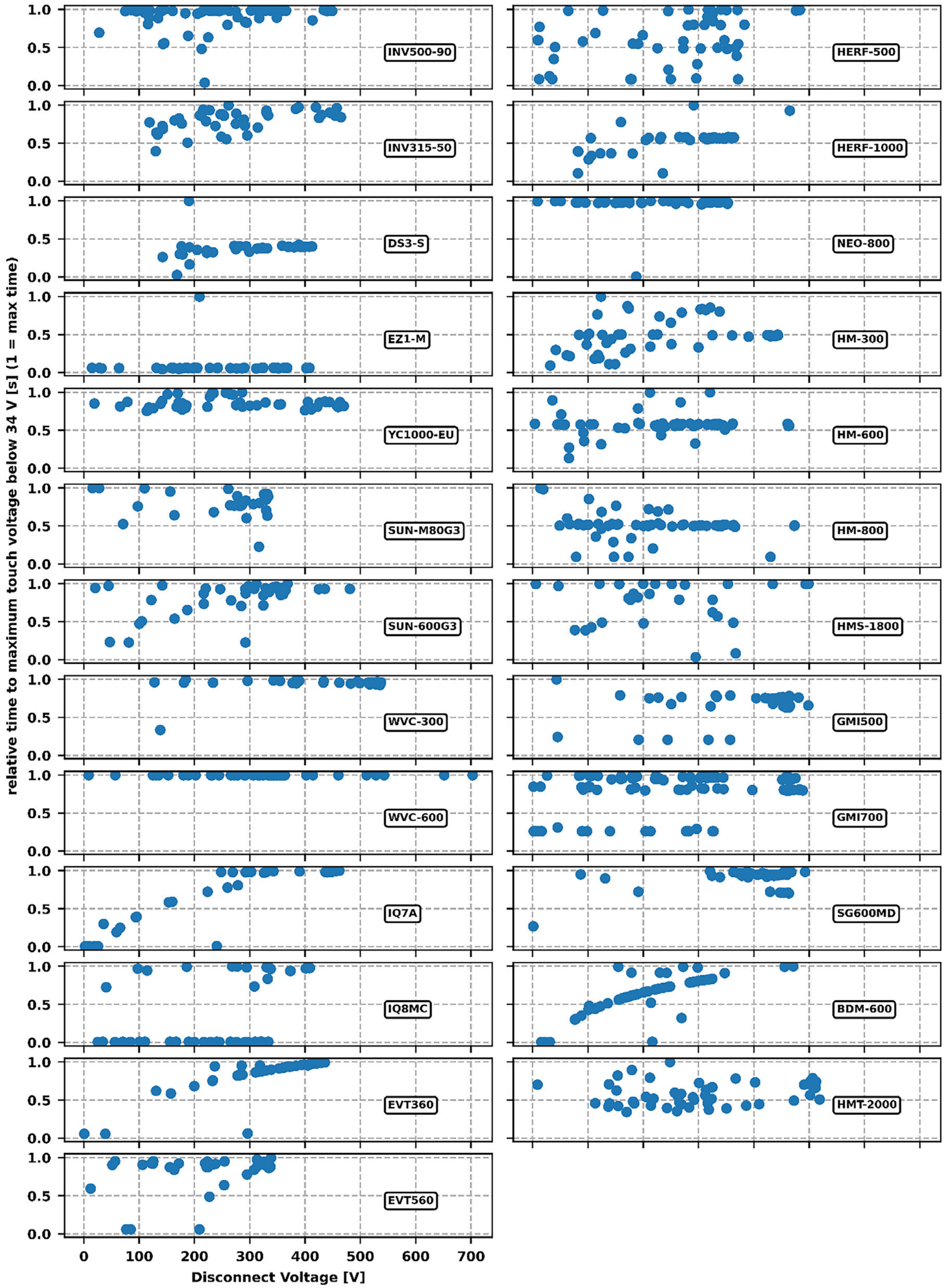

FIGURE 11 | Dependency of disconnect voltage and the discharge time for every inverter.

INV315−50 inverters approximately doubles compared to the single operation. This behavior cannot be explained and seems to be an inverter specific behavior. The exemplary subtests show that the residual voltage test should be applied on the whole system, if it is built with more than one inverter, to ensure a safe operation.

As 44% of the tested inverters exceed the proposed limit of E DIN VDE V 0126-95:2024−6 with a least one measurement, it is further analyzed, if a safety adapter could be used to comply with the standard. The basic functionally of a safety adapter is to ensure compliant residual voltage level after 1 s and provides touch safety in the unplugged state. This could be realized with

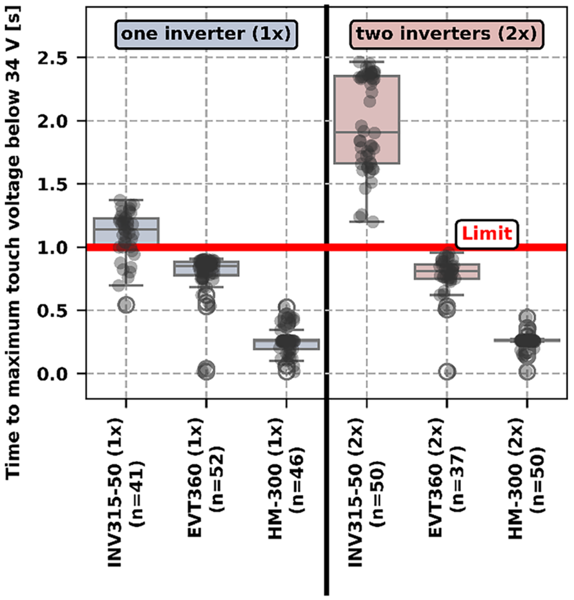

FIGURE 12 | Residual voltage behavior, when two plug and play inverters are operated in parallel to the grid and disconnected (right halve of the figure with (2x) labeling), compared to a single unplug condition (left halve of the figure with (1x) labeling). The red "Limit" line is the residual voltage limit of E DIN VDE V 0126-95:2024–6.

a two-pole relay, which switches off the phase and neutral conductor of the inverter from the mains plug, and therefore, no voltage would be present at the plug pins. A further realization of safety adapter could use a mechanical touch safe mechanism in combination with a discharge resistor, which will be connected between phase and neutral after the grid disconnection to discharge any capacitors and hence achieve compliant residual voltage levels. Due to the novelty of this safety application, it can be assumed that other implementation concepts for the required security function will be developed and that the aforementioned implementation variants serve as examples. The above listing of potential realizations was assembled without checking whether these ideas are under patent protection. For the analysis an exemplary test at one inverter (HMS-1800) is conducted. As an example for a safety adapter, a SEP 1.16 adapter [28] from the company 'Seplugs' is used. This adapter uses the last described method to decrease the residual voltage. Figure 13 shows the results of the residual voltage test without and with a safety adapter. With the safety adapter, the tested inverter complies with the residual voltage limit. This further supports the previously stated conclusion that the system should be evaluated in its entirety rather than testing the inverter alone. Plug and play inverters that exceed the limits without additional system components on the AC side can be combined with a safety adapter to a compliant system. Furthermore, the inverter manufacturer may consider incorporating the safety function (SF) of a safety adapter into the internal circuit during a product revision.

Based on the findings of the residual voltage test, compliancy with the limit of E DIN VDE V 0126-95:2024–6 can be achieved with different system configurations. Figure 14 illustrates three system configuration examples without any claim to completeness. In the first configuration (a), no additional components are needed as the inverter complies with the requirements. In the other two configurations, additional components are necessary. The second configuration (b) uses a safety adapter with a residual voltage safety function. In the third configuration (c), the safety function is provided by the inverter manufacturer (illustrated through the proximity of the function to the inverter) through additional hardware or a functional safety function in the existing inverter.

Since the residual voltages in the measurements always decreased after unplugging, but over varying periods of time, a mechanical touch protection could be used as basic protection

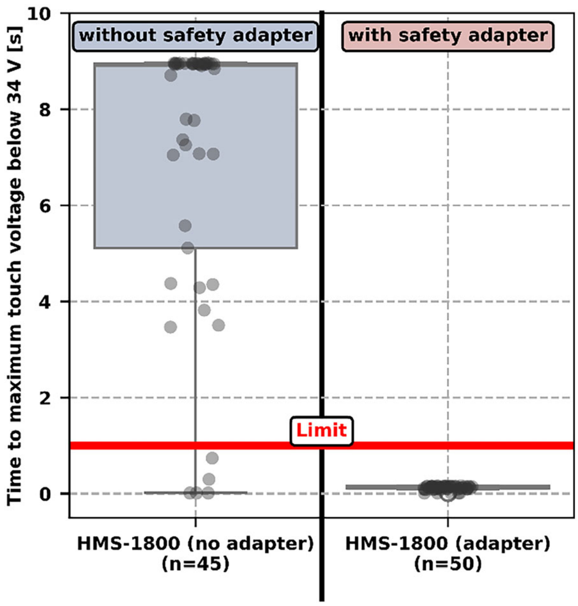

FIGURE 13 | Residual voltage behavior of the HMS-1600 inverter with and without a safety adapter. The red "Limit" line is the residual voltage limit of E DIN VDE V 0126-95:2024–6.

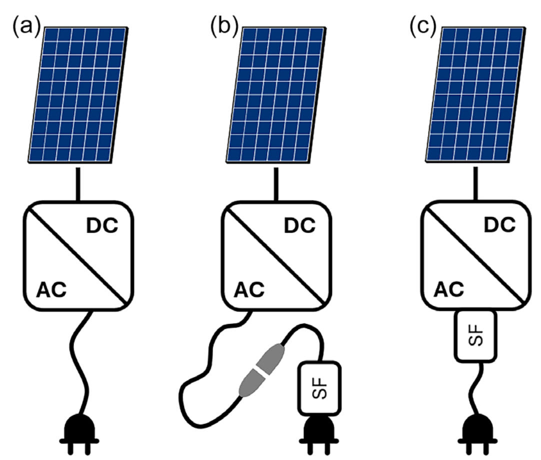

FIGURE 14 | Three versions of exemplary compliant system configurations in context of residual voltage behavior: configuration with no additional components for compliance (a), configuration with an additional component for the safety function (SF) (b) and configuration where the safety function is provided by the inverter manufacturer (additional hardware or functional safety function) (c). Examples without claim to completeness.

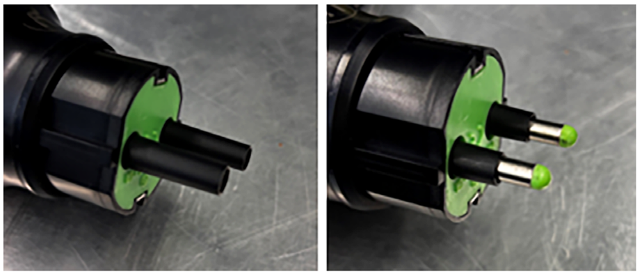

FIGURE 15 | Example of a touch protection at the used SEP 1.16 adapter, which covers the plug pins in the unplugged state.

to prevent directly touching the pins post unplugging, as illustrated in Figure 15. To which extent such a solution provides a sufficient SF without further safety mechanisms, for example, only viable to a certain residual voltage decline times and voltage level, must be evaluated and discussed in a future assessment.

Based on the tested inverter NEO-800, which has the compliance certificate of VDE-AR-N 4105 [29] and a certificate for the network and system protection [30], it can be exemplary stated that these compliances do not ensure a compliant residual voltage behavior in terms of personal safety. The network and system protection relay might reduce the residual voltage behavior due to galvanically disconnecting capacitors, but the compliance condition of the anti-islanding testing according to IEC 62 116 [31] (mandated in VDE-AR-N 4105 [32]) is with 2 s too long and not evaluated in context of residual voltage. The German grid regulation VDE-AR-N 4105 even allows longer compliance condition of up to 9 s. This further highlights the necessity of a standard for plug and play PV inverter and systems.

TABLE 4 | Current, power, and voltage values for each measured single-phase inverter before shutdown in relative values and current and power at the start of the test (30 s steps and 15 min steps).

Inverter	Current at start (A)	Apparent power at start (VA)	Values at shutdown referenced to starting values		
			Voltage (-)	Current (-)	Apparent power (-)
			30 s steps		
WVC-600	2.4	558.0	−24.0%	26.3% (3.06A)	−3.8%
GMI700	2.2	505.5	−23.7%	25.7% (2.76A)	−3.9%
DS3-S	2.6	596.1	−21.5%	25.7% (3.25A)	−0.8%
EZ1-M	2.7	616.8	−15.6%	15.8% (3.1A)	−1.7%
HM-600	2.7	612.5	−16.9%	15.8% (3.08A)	−3.6%
HM-300	1.3	305.4	−16.8%	15.6% (1.53A)	−3.5%
HM-800	3.5	815.3	−17.2%	15.3% (4.08A)	−4.0%
SG600MD	2.5	565.2	−18.2%	15% (2.82A)	−5.5%
INV315-50	1.3	290.9	−20.0%	10.8% (1.4A)	−11.3%
GMI500	2.1	485.3	−20.8%	10.3% (2.33A)	−12.5%
HERF-1000	4.3	988.3	−17.5%	9.5% (4.7A)	−8.9%
SUN-600G3	2.7	615.8	−20.9%	9% (2.95A)	−13.6%
HMS-1800	7.9	1819.1	−17.7%	8.8% (8.58A)	−10.3%
IQ7A	1.6	359.2	−22.8%	8.8% (1.7A)	−15.9%
HERF-500	2.2	498.7	−20.0%	8.7% (2.35A)	−12.9%
EVT560	2.6	593.5	−16.6%	8% (2.78A)	−9.8%
INV500-90	2.1	480.2	−20.0%	7.8% (2.25A)	−13.8%
IQ8MC	1.4	325.1	−20.4%	7.4% (1.52A)	−14.4%
BDM-600	2.5	566.6	−20.1%	6.1% (2.61A)	−14.9%
NEO-800	3.4	792.3	−21.0%	5.9% (3.64A)	−16.2%
EVT360	1.5	347.7	−15.4%	2.9% (1.55A)	−12.8%
SUN-M80G3	3.5	794.3	−21.8%	1.7% (3.55A)	−20.0%
			15 min steps		
EZ1-M	2.7	606.3	−15.1%	16.2% (3.09A)	−1.2%
SUN-M80G3	3.5	796.4	8.7%	−7.6% (3.21A)	0.6%
HM-800	3.5	813.4	–	–	–

3.2 | Limitation of Feed-in Current at Low Grid Voltage

The results of the test determining, if the inverters increase their feed-in current at a low grid voltage are presented in Table 4. For comparable results the values at the point of inverter shutdown are shown as relative values referenced to the RMS starting values. Additionally, the maximum absolute current values are shown as well. The current increase of the tested inverters ranges from 1.7% to 26.3% in reference to the nominal current.

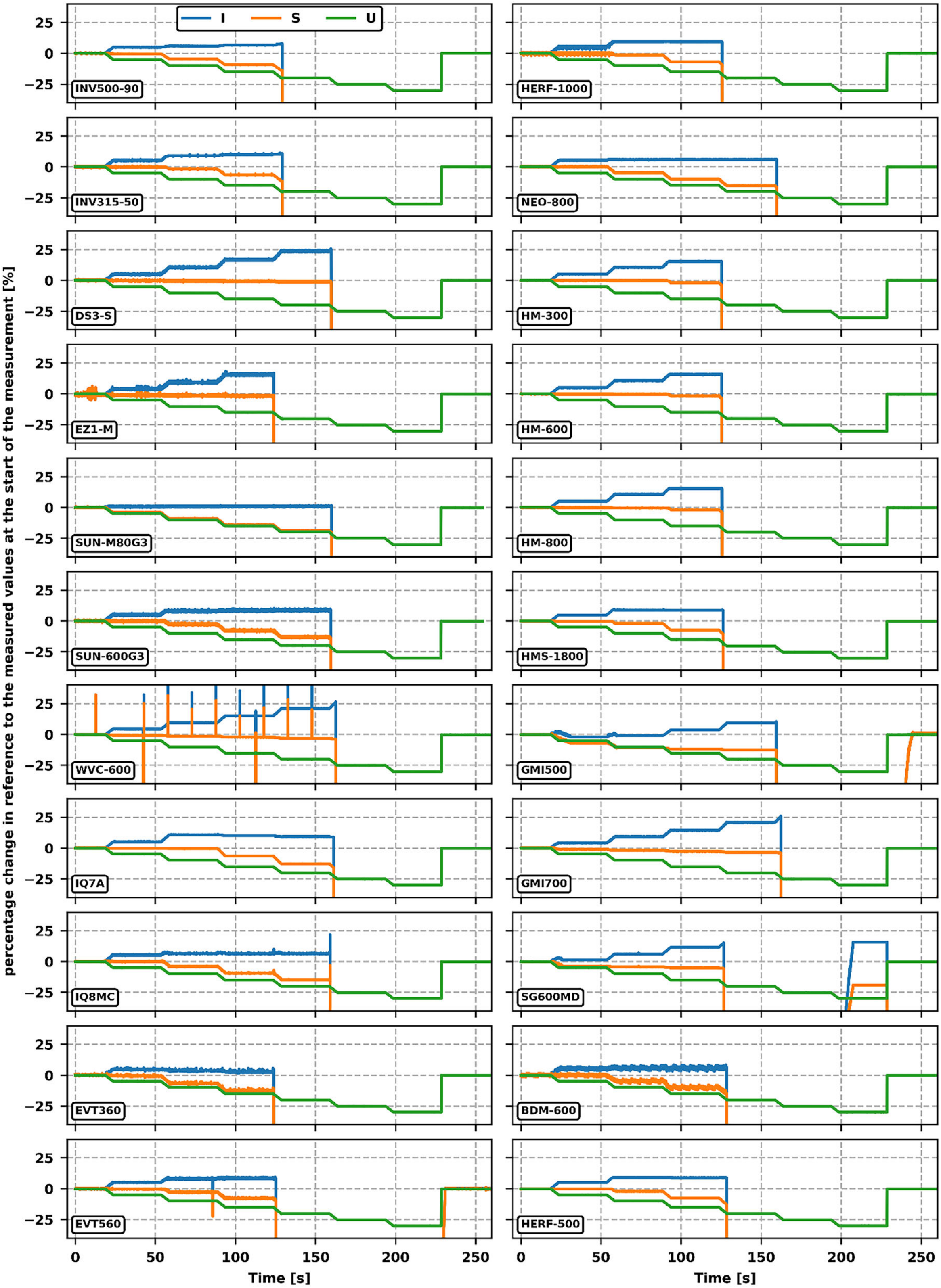

FIGURE 16 | Feed-in current and feed-in power (apparent and active power) during the voltage steps (30 s steps) of all measured single-phase inverters.

Two of the three inverters (HM-800, NEO-800, SUN-M80G3), that have a nominal power of 800 VA, exceeded the limit of 3.5 A (including the 2% tolerance) and thus would not comply with E DIN VDE V 0126-95:2024–6. Even though the other inverters of category A and B increased their feed-in current, they did not exceed the absolute current limit. To uniform the feed-in current regulation for plug and play systems a relative current limit, for example 'The maximum feed-in current must not exceed 2% of the nominal feed-in current', could be proposed to preplace the absolute limit. This would allow for simpler system configurations where two or more inverters of the same type are combined into a plug and play system with a single mains plug, if the inverter is known to meet the 2% limit. An absolute limit is a more complex solution in this aspect. Under a relative limit only one of the tested inverters would comply.

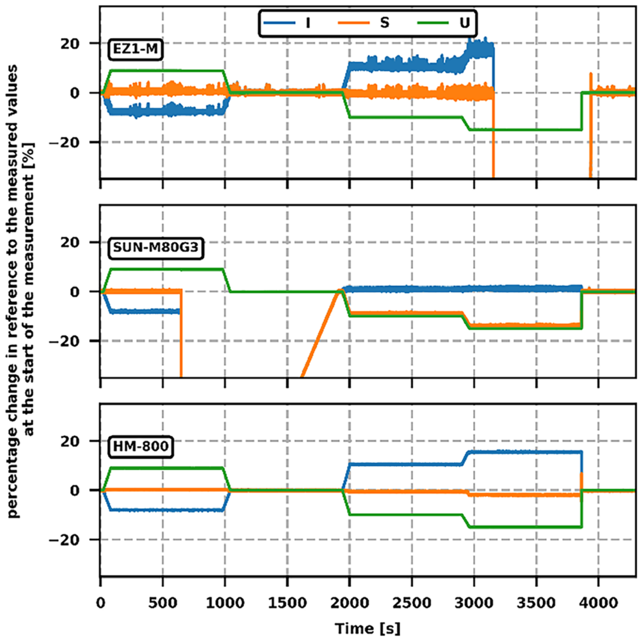

FIGURE 17 | Feed-in current and feed-in power (apparent and active power) during the voltage steps according to DIN VDE V 0124–100 (15 min steps) of three single-phase inverters.

The comparison of the results of the 30-second steps and the 15 min steps (see Table 4) shows that the EZ1-M microinverter switches off at the same voltage. The SUN-M80G3 microinverter switched of at overvoltage and the HM-800 didn't switch off as the shutdown voltage is below the 15% voltage reduction.

Figures 16, 17 illustrates the current, voltage, and power curves over the test duration for the 30 s and 15 min step tests of each inverter. The illustrations do not include any limit indications due to the relative value representation and the previous discussion about absolute versus relative limit.

The identical behavior and lack of a stabilization phase for the three sample inverters confirm the validity of the reduced step time. The figures further show that some inverters restart in the time window of the measurement after switching off due to the voltage levels. In Figure 17, the SUN-M80G3 resumes feed-in at nominal voltage after shutting down at overvoltage and the EZ1-M resumes after the voltage returns to the nominal value. Five inverters restart in the measurement time of the 30 s-steps tests (see Figure 14). The inverters EVT360 and GMI500 reach nominal power shortly after the voltages returns to the nominal value, while the inverters EVT560 and GMI 700 are still in ramp-up phase (not seen in the figure due to axis scaling). One inverter (SG600MD) restarts at the lowest voltage level and reaches the same current value as before the shutdown, indicating that the system controller requires adjustments for this operating condition.

TABLE 5 | Phase current, phase voltage, and power values for each measured three-phase inverter before shutdown.

Inverter		Current at start (A)	Apparent power at start (VA)	Values at shutdown referenced to starting values (-)		
				Voltage (-)	Current (-)	Apparent power (-)
Voltage profile at all phases						
YC1000-EU	L1	1.41	935.6	−21.2%	26.4% (1.78A)	0.3%
	L2	1.37		−21.2%	27.2% (1.75A)	
	L3	1.36		−21.2%	27% (1.72A)	
HMT-2000-4T	L1	2.96	2043.9	−16.9%	8.4% (3.2A)	−9.6%
	L2	2.96		−16.9%	8.4% (3.21A)	
	L3	2.96		−16.9%	8.3% (3.2A)	
Voltage profile only on L3						
YC1000-EU	L1	1.38	936.8	−0.1%	3.7% (1.44A)	−0.2%
	L2	1.35		−0.1%	3.4% (1.4A)	
	L3	1.33		−21.1%	16.5% (1.55A)	
HMT-2000-4T	L1	2.96	2046.8	−0.1%	−9.5% (2.68A)	−9.3%
	L2	2.96		−0.1%	−9.4% (2.68A)	
	L3	2.96		−17.1%	9.5% (3.24A)	

Table 5 and Figure 18 show the results of the feed-in current tests for the two tested three-phase inverters. Two tests per inverter are conducted to analyze if the inverter behave differently, when the voltage profile is only applied to one phase (the other two remain at nominal value) compared to all phases. The current increases of all three-phase measurements range from 3.4% to 27.2% and thus are not complying with the standard draft, if the abovementioned relative limit is applied. If the absolute limit of 3.5 A is used and applied to all three phases, the inverters are within the limit.

The results further illustrate that the inverters shutdown at the same voltages, even if the voltage profile is only applied to one phase. A different behavior can be identified for the phase currents. The YC1000-EU inverter has a lower current increase on L3 compared to the test on all phases, but the current also increases on L1 and L2. Contrary to that behavior, the HMT-2000 inverter increases the current on L3 with the same value as he is reducing the currents on L1 and L2. The power values at shutdown are on the same level for the two inverters in both tests, suggesting that the controller regulates to a constant output power.

3.3 | Maximum Touch Temperature

The maximum measured temperatures of the maximum touch temperature test are presented in Table 6. The maximum measured touch temperatures range from 43.40 to 80.33°C. Of the 24 inverters tested, 18 (75%) comply with the maximum temperature limits of IEC 62 109–1. As the touch temperature is dependent on the ambient temperature, Table 6 also shows the maximum ambient temperature values for a compliance with IEC 62 109–1. These values range from 13.80 to 50.48°C. If a scenario with 35°C ambient temperature is assumed, 11 of the 24 inverters (46%) do not comply with the temperature limits.

Figure 19 shows the temperature (front, back, and ambient) and power curves of the measured inverters during the test duration. The majority of the evaluated inverters demonstrated stable thermal behavior, with front and back surface temperatures gradually rising and reaching a steady-state condition. In most cases, the front surface temperature exceeded the rear temperature, because the cooling fins are mounted on that side. Several inverters, such as the IQ7A, IQ8MC, and INV500–90, maintain moderate surface temperatures and deliver a constant relative power output, suggesting efficient thermal management. In contrast, certain models—most notably the GMI500, GMI700, and SG600MD—exhibited significant cyclical fluctuations in both temperature and relative power. This pattern indicates active thermal derating mechanisms, likely triggered by internal temperature limits. In addition, the WVC-600 inverter showed an early power drop, potentially due to protective shutdown or inadequate thermal performance. These observations highlight that, while many inverters perform reliably under thermal stress, some devices experience limitations related to thermal protection strategies or insufficient

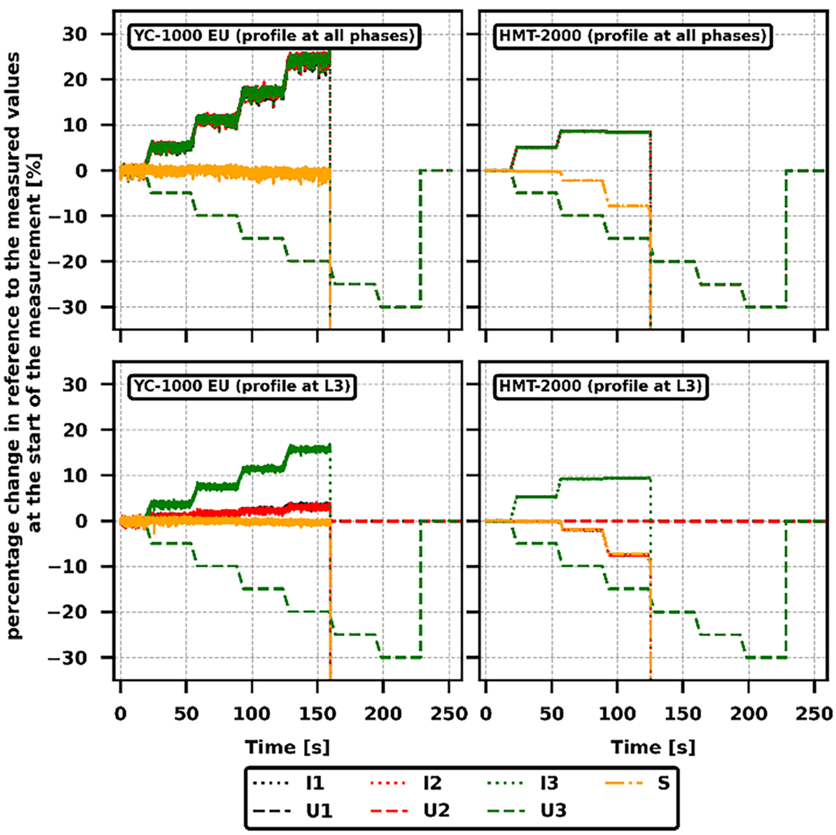

FIGURE 18 | Feed-in current per phase and total feed-in power during the voltage steps (30 s steps) of two three-phase inverters for voltage steps at all three phases and only one phase.

TABLE 6 | Maximum measured temperatures of the maximum touch temperature test, compliance verification with IEC 62 109–1, and maximum ambient temperature to comply with the mentioned standard for every tested inverter.

Inverter	Test duration (hh:mm:ss)	T_{max} (°C)	Timestamp of T_{max} (hh:mm:ss)	Compliance with IEC 62 109–1	ΔT_{max} ($T_{max}-T_{amb}$) (°C)	Max T_{amb} for compliance with IEC 62 109–1 (°C)
HM-300	07:15:00	43.40	06:54:20	yes	19.52	50.48
IQ8MC	07:15:00	49.09	07:06:00	yes	26.43	68.57
INV500-90	07:15:00	49.11	07:01:50	yes	25.41	44.59
INV315-50	07:15:00	49.37	04:21:00	yes	27.27	42.73
DS3-S	07:15:00	50.31	04:05:40	yes	27.14	42.86
HM-600	07:15:00	50.53	06:56:20	yes	27.89	42.11
EVT360	07:15:00	51.70	06:16:10	yes	27.71	42.29
IQ7A	07:15:00	53.06	02:32:10	yes	28.82	66.18
SUN-600G3	07:15:00	53.39	07:01:20	yes	29.70	40.30
NEO-800	07:15:00	55.96	02:54:50	yes	33.59	36.41
EVT560	07:15:00	56.58	02:52:00	yes	33.99	36.01
HERF-500	07:15:00	56.90	03:31:10	yes	32.97	37.03
BDM-600	07:15:00	57.90	07:00:50	yes	33.86	36.14
HM-800	07:15:00	58.30	06:54:40	yes	35.65	34.35
EZ1-M	07:15:00	61.99	04:49:40	yes	38.79	31.21
SUN-M80G3	07:15:00	62.39	04:55:50	yes	39.38	30.62
HERF-1000	07:15:00	63.80	03:24:00	yes	40.74	29.26
SG600MD	07:15:00	65.76	07:00:50	yes	41.55	28.45
WVC-600	04:08:20	70.08	03:38:20	no	45.84	24.16
HMS-1800	07:15:00	73.45	05:15:50	no	49.17	20.83
GMI700	07:15:00	76.58	00:40:30	no	52.50	17.50
YC1000-EU	07:15:00	77.07	06:05:00	no	51.94	18.06
GMI500	07:15:00	77.63	06:07:20	no	52.91	17.09
HMT-2000	07:15:00	80.33	06:56:40	no	56.20	13.80

cooling capabilities. From a systems performance perspective, this thermal derating behavior would result in a decreased system yield.

The two inverters, INV315−50 and YC1000-EU, show an increase in power when the profiles reach the 1500 W/m^2 test phase (see Figure 9). As the INV315−50 never reaches the nominal power in the first test phase, it can be deducted that the supplied DC power in the 1000 W/m^2 phase is not enough for the inverter to reach nominal power. The YC1000-EU inverter, which reached nominal power in the first phase, increased the output power to a stable value and held it till the end of the measurement. This shows that the maximum peak power value in the datasheet can be held constantly for a considerable amount of time, not only for a short period. For a system configuration with considerable high module power, compared to the AC power (i.e. overpaneling), no negative temperature increases could be observed.

The reason why microinverters that have valid IEC 62 109–1 certificates (e.g. SUN-M80G3) would still exceed the touch temperature limit in a configuration with sufficient available DC power and at certain ambient temperatures is most likely due to the considerate mounting situation in the certification test. The usual mounting situation for most of the systems, which are not purely designed for plug and play systems, is behind the module. Therefore, no inverter surfaces are accessible during the operation and high temperatures are only a concern for the component lifetime and not in terms of safety. This aspect should be considered in the safety standard for plug and play PV systems.

Figure 20 shows the correlation between the maximum power dependent temperature increase (maximum touch temperature minus ambient temperature) and the power density of the tested inverters, where a positive correlation can be observed. Inverters with a lower power (e.g. in category A) have a lower power density, and thus, a lower power dependent temperature increase. The spread in the datapoints is influenced by the fact that the power density was calculated with the datasheet dimensions, which do or do not include the dimensions of the mounting points. Further influencing factors are the inverter efficiency

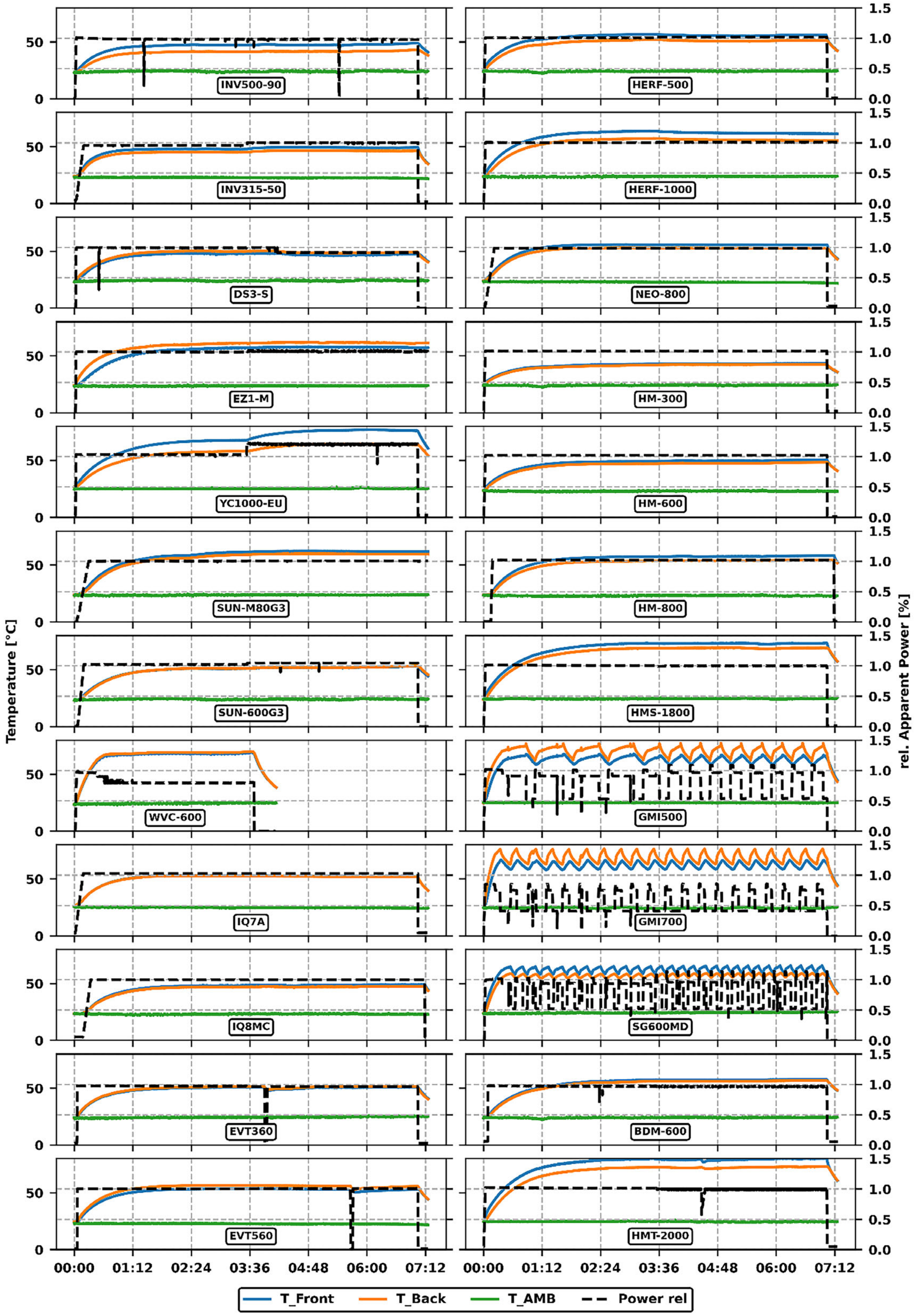

FIGURE 19 | Measured temperatures (at the front and back of the inverter), ambient temperature, and relative power (measured apparent power divided by the nominal apparent power) during the maximum touch temperature test. The front of the temperature measurement is defined as the surface of the inverter most distant from the mounting point in depth dimension.

and the heat transfer area (i.e. cooling fin design). Except for the two outliers of category A, the figure shows that it is better to use two or more smaller inverters with lower power density than one inverter with a higher power density, with regard to the maximum touch temperature. This would not only reduce the risk of elevated contact temperatures but could also extend the service life of the inverters, as component aging (e.g., capacitors, relays) is temperature dependent.

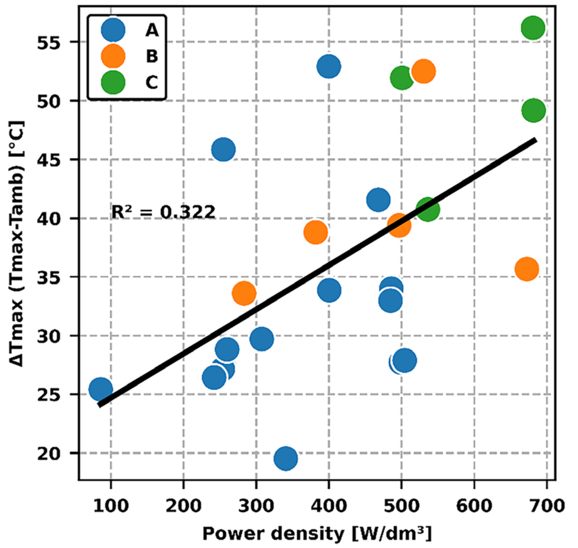

FIGURE 20 | Correlation between the maximum temperature difference (maximum touch temperature minus ambient temperature) and the power density (nominal inverter power/datasheet volume). The categories A, B, and C are the previously mentioned power categories (A: <=600 VA, B: <=800 VA and >600 VA, and C: >800 VA).

4 | Conclusion and Outlook

This article analyzes three safety concerns of plug and play inverters using a black box approach. The analysis provides a data foundation for the current discussion on safety standards for plug and play systems. In addition, the conducted methods and procedures can be used for future compliance testing.

In the residual voltage testing, 56% of the analyzed inverters did comply with the proposed limit of the latest official draft (2024–06) of E DIN VDE V 0126–95. Regarding the 11 noncompliant inverters, it must be stated that an exceedance of the residual voltage limit should not be directly linked to a safety risk without taking the severity of the exceedance (time and number of occasion) into account and conducting further assessments. A future assessment should include the analysis of the body current that is present when the pins are touched after 1 s. Due to the limited energy stored in the nondisconnectable capacitors, contact with the plug pins after disconnection is expected to result in a transient, pulse-shaped body current rather than a continuous one. For this reason, a remaining charge limit additionally to the residual voltage limit after 1 s could be considered after thorough analysis.

The test further demonstrates that system testing is advised with systems of more than one inverter, due to the possibility of a longer residual voltage time compared to a single inverter. With an exemplary test, it was shown that by adding an additional safety relay, actively reducing the residual voltage to a compliant level after disconnection, noncomplying inverters can achieve compliance. The general requirement of such an adapter could be a cost-effective solution for the residual voltage risk, as the discharge times can have a high device dependance and hence require many repeated tests, leading to a longer test duration and probably higher costs.

Future work in the context of residual voltage testing could focus on the validation of the results of this analysis with tests via a triggered relay and assess methods to further reduce the test time. In addition, tests at other power levels (50% of nominal power or minimal operating power, as required in E DIN VDE V 0126-95:2024–06) should be conducted to analyze if these conditions have considerable influence on the residual voltage behavior.

The second test found that several inverters exceed the feed-in limit at low grid voltages, with the number of noncompliant devices varying depending on whether an absolute or relative limit is applied. To ensure consistent regulation across devices of different power ratings, the implementation of a relative limit is recommended. In context of severity, this safety aspect has the lowest real-world effect on occurrence of the three tested, since low voltages during sun hours are very unlikely. Nevertheless, the appropriate control of the feed-in current has to be taken into account when assessing inverters for plug and play PV systems. It can be assumed that this feed-in behavior of the inverters can be adjusted via a firmware update, and hence, a verification of those updates should be carried out in the future.

The last test shows that under full load conditions and high ambient temperatures, assumed to be the most severe condition, plug and play inverters could reach touch temperatures that exceeded the limit of IEC 62 109–1. To mitigate a high touch temperature in these situations, the use of two or more smaller inverters, rather than one, is suggested for the system design.

Future studies assessing the thermal behavior of power-limited inverters (e.g. category C inverters limited to 800 VA) may offer guidance for system design, as their larger housing volume could enhance heat dissipation.

The results and findings of this article show that safety risks may be present at certain plug and play inverters under the tested conditions and should be considered for market entry and surveillance. However, these issues can be addressed with technical adaptations and system engineering adjustments leading to a save use of plug and play PV systems.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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