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Study on Energy Efficiency and Harmonic Emission of Photovoltaic Inverters

Krzysztof Chmielowiec [1,*], Łukasz Topolski [1], Aleks Piszczek [1], Tomasz Rodziewicz [2] and Zbigniew Hanzelka [1]

[1] Department of Power Electronics and Energy Control Systems, Faculty of Electrical Engineering, Automatics, Computer Science and Biomedical Engineering, AGH University of Science and Technology, 30-059 Kraków, Poland; topolski@agh.edu.pl (Ł.T.); apiszczek@student.agh.edu.pl (A.P.); hanzel@agh.edu.pl (Z.H.)

[2] TAURON Dystrybucja S.A., 31-035 Kraków, Poland; tomasz.rodziewicz@tauron-dystrybucja.pl

* Correspondence: kchmielo@agh.edu.pl

Abstract: The paper presents the results of an experimental study of 26 brand new photovoltaic (PV) inverters widely available for sale on the EU market; the study was conducted in 2021 by researchers at the AGH University of Science and Technology and Tauron Dystrybucja (Polish DSO). The purpose of the study was to compare and assess PV inverter performances in terms of their DC/AC conversion efficiencies, MPPT efficiencies, and harmonic current emissions. To examine the PV inverters, a laboratory test stand was prepared according to the standard EN 50530 and the technical report IEC/TR 61000-3-15. It was composed of a photovoltaic array simulator, a programmable regenerative AC voltage source, and a power analyzer. Each PV inverter was tested in various operating states determined by the DC voltage levels and the volume of active power generation. The results allowed for a benchmark assessment of PV inverters available on the market. The results showed how various energy efficiency indicators of individual PV inverters changed depending on their operating points. The results also revealed that, based on the performed harmonic emission tests, individual harmonics were within the normative requirements; however, in the case of several PV inverters, attention was drawn to the presence of relatively high switching frequency-related components exceeding permissible levels.

Keywords: photovoltaic inverters; electrical efficency; MPPT tracking; harmonic current emission

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1. Introduction

Energy from solar radiation is an attractive renewable energy source; it is used as a means to reduce fossil fuel use, both in the European Union (EU) and around the world. The growing popularity of solar energy is caused by several factors, inter alia, the growing awareness of about the effects of CO_2 emissions, the rapid increase in electricity prices, and above all, the national directives and EU regulations specifying the desirable national energy mix in the next dozen or so years. One example of such actions is the EU's plan for a green transition [1], which includes directives on energy efficiency and renewable energy sources (RED II) that are primarily aimed at strengthening the achievements of climate goals and increasing the obligation to save energy [2].

Along with the rapid development of PV energy, the market availability of the components of PV installations increases, including one of the key elements—PV inverters that convert direct current(s) (DC) into alternating current(s) (AC).

The basic parameter of a PV inverter is its energy efficiency, which determines what percentage of the energy from PV panels ultimately ends up in the electrical network. The goal is to achieve 100% energy efficiency, but in practice, it will not be possible, due to losses associated with energy conversion and obtaining the maximum power operating points of PV panels. Manufacturers of PV inverters compete with each other (i.e., pertaining to the quality and price of their products). Energy efficiency indicators are some of the most recognizable parameters influencing the choices of specific devices by a prosumer.

Another important factor is the reliable operation of PV inverters depending on the short-circuit power level at the connection point [3]. It consists of harmonic current emissions, including the switching frequency components. If the inverter's harmonic emissions are too high, the risk of an emergency shutdown increases, especially in long, rural, low-voltage lines, where the grid impedance is usually relatively high.

The above-mentioned parameters of PV inverters have been tested and are described in this article in a representative group of commercial products.

2. Scope of the Conducted Research

2.1. Electrical Efficiencies of PV Inverters

European standard EN 50530 [4] provides a procedure for the measurements of the efficiency factors of grid-connected PV inverters. This makes it possible to compare their performances, which have an impact on the financial yields from the PV installations. Determining this efficiency, and reducing it to one universal numerical measure, is not a trivial task, since:

- PV inverters, due to the specificities of their uses, do not work in a steady state, but their operating points depend on the configuration of the installation and the level of insolation, which vary with time throughout the day and have measurable contributions to power quality conditions in distribution networks [5],
- The total efficiency of a PV inverter is the sum of the partial efficiency factors with different determination principles.

In relation to PV inverters, the EN 50530 standard provides the following numerical measures of energy efficiency:

Conversion efficiency [4] is defined by the PV inverter's ability to convert input DC energy into output AC energy within a defined measuring period (1). The efficiency is mainly a measure of the losses released on the semiconductor switching elements.

$$\eta_{conv} = \frac{P_{\mathrm{AC}}}{P_{\mathrm{DC}}} \cdot 100\% \tag{1}$$

Static MPPT efficiency [4] is the PV inverter's control system ability to find the most optimal operating point of the PV inverter under constant supply conditions (temperature and level of irradiation). It is defined as a ratio of the power at the DC terminal to the power accepted at the DC terminal within a defined measuring period (2).

$$\eta_{\mathrm{MPPT}} = \frac{P_{\mathrm{DC}}}{P_{\mathrm{MPPT}}} \cdot 100\% \tag{2}$$

Total efficiency [4] is the product of the conversion efficiency (1) and the MPPT efficiency (2); it measures the ability of the PV inverter to convert the input energy into the output energy (3).

$$\eta_{total} = \eta_{conv} \cdot \eta_{\mathrm{MPPT}} = \frac{P_{\mathrm{AC}}}{P_{\mathrm{MPPT}}} \cdot 100\% \tag{3}$$

The above mentioned efficiency measures (3) relate only to the steady state of the operation of PV inverters and do not consider variations of the irradiation intensity and the resulting transition of the PV inverter to the new operating point. Therefore, an additional measure is used, defining the speed at which the PV inverter sets the operating point with the maximum available active power. This is called Dynamic MPPT efficiency [4] and it is defined as a ratio of the total DC energy delivered at the DC terminal to the total available energy from the photovoltaic cells (which, in principle, varies over time) within a defined measuring period (4).

$$\eta_{\mathrm{MPPT}dyn} = \frac{1}{\sum_j P_{\mathrm{MPP,PV},j} \cdot \Delta T_j} \sum_i U_{\mathrm{DC},i} \cdot I_{\mathrm{DC},i} \cdot \Delta T_i \tag{4}$$

where ΔT_j is the period in which the power $P_{\text{MPP,PV},j}$ is provided and ΔT_i is the period in which the power $U_{\text{DC},i}$ and $I_{\text{DC},i}$ are sampled.

Standard [4] provides specific test profiles that are used for MPPT efficiency testing. They consist of repetitive changes in insolation levels with different gradients of these changes as presented in Figure 1. An extension of the theory dynamic MPPT efficiency indicator can be found in [6,7].

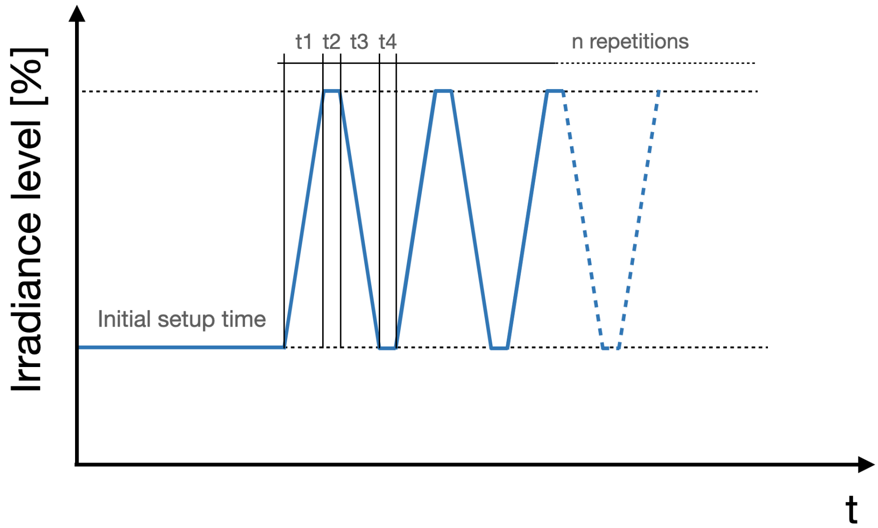

Figure 1. Test sequence for fluctuations of irradiation intensities.

Euro and CEC efficiency [4] are both weighted efficiencies taking into account how often the PV inverter will operate at different states of operation. These measures are generally more useful than maximum efficiency because they measure a PV inverter's performance across the range of its capacity.

Euro and CEC efficiency [4] are both weighted efficiencies, taking into account how often the PV inverter will operate at different states of operation. These measures are generally more useful than maximum efficiency because they measure a PV inverter's performance across the range of its capacity.

Euro efficiency (Euro eff) [4] is the averaged operating efficiency over a yearly power distribution corresponding to a middle-European climate. The value of this weighted efficiency is obtained by assigning a percentage of time that the PV inverter resides in a given operating range. The California Energy Commission efficiency division (CEC eff) [4] is also a weighted efficiency, similar to the European efficiency, but it uses different assumptions on weighting factors.

Euro eff and CEC eff are based only on the conversion efficiency η_{conv}. In calculating them, the efficiency of a PV inverter at different spots, within its operating range, are taken into consideration and balanced against each other. This provides a more comprehensive picture about the PV inverter's operating profile over the course of the day ((5) and (6)).

$$\text{Euro Eff} = 0.03 \cdot \eta_{conv,5\%} + 0.06 \cdot \eta_{conv,10\%} + 0.13 \cdot \eta_{conv,20\%} + 0.1 \cdot \eta_{conv,30\%} + 0.48 \cdot \eta_{conv,50\%} + 0.2 \cdot \eta_{conv,100\%} \quad (5)$$

$$\text{CEC Eff} = 0.04 \cdot \eta_{conv,10\%} + 0.05 \cdot \eta_{conv,20\%} + 0.12 \cdot \eta_{conv,30\%} + 0.53 \cdot \eta_{conv,75\%} + 0.05 \cdot \eta_{conv,100\%} \quad (6)$$

where $\eta_{conv,X\%}$ is the efficiency at generation equal to X% of the rated power of a PV inverter.

In this article, three types of energy efficiencies of PV inverters are examined: conversion efficiency (1), static (2), and dynamic MPPT efficiency (4). The results make it possible to determine the total efficiency (3) and, partially, the aggregated efficiency indicators, Euro (5) and CEC (6).

The reason this research was conducted was due to the lack of similar benchmarking tests carried out on PV inverters (at such a scale), the significant increase in the number of commercial PV installations in central Europe, and the need for more reliable data and literature on the profitability of PV installations, such as in the papers [7,8]. However, the authors mainly focused on describing a modified test stand, the composition of which is clearly defined in the standard [4], and a presentation of a short test of only one efficiency indicator. It is also worth noting that, in the available literature, researchers mainly focused on describing a new type of highly efficient PV inverter [9,10] or the advanced simulation models [11], without focusing on testing commercially available devices, as in [12,13]. In [14], the authors analyzed the effects of temperature on the conversion efficiency of a single-phase PV inverter. Moreover, the number of tested devices was not significant compared to the present study. In addition to the efficiency and harmonic current emission tests, the authors of this article also researched the PV inverter power indications and the power analyzer readings—aspects that have not yet been presented in any of the available literature, but which are very important for PV installation owners.

2.2. Harmonic Current Emissions of PV Inverters

Harmonic current emissions are a part of the electromagnetic compatibility field (EMC). PV inverters—just as with any equipment that is sold in the EU—comply with the requirements established in EMC Directives 2014/30/EU [15] or 2014/53/EU [16] (whichever applies) and the harmonized standards. It is worth noting that there are no standards describing current harmonic limits dedicated solely to dispersed generation (DG) units. The whole EN 61000 series is only dedicated to loads, but it is assumed that there is a substantial commonality between certain types of loads and DG, as far as current harmonic emissions are concerned. Thus, it is reasonable to consider a set of limits based on the standards EN 50439 [17], EN 61000-3-2 [18], and EN 61000-3-12:2011 [19] for DG units. That approach is recommended and presented in the technical report IEC/TR 61000-3-15 [20], which addresses gaps in the existing EMC standards [18,19], providing recommendations on limits and tests for harmonic current emissions for DG.

The technical report IEC/TR 61000-3-15 [20] for product tests (e.g., PV inverter tests) divides current harmonic emission limits to DG—below and above 600 W. For DG below 600 W, the technical report IEC/TR 61000-3-15 [20] uses a set of limits based on the slightly modified standard EN 61000-3-2:2014 [18] for class C equipment (lighting). It is concluded that lighting and small size PV inverters have potentially similar impacts on the network as far as current emissions are concerned. In turn, for DG above 600 W, the technical report IEC/TR 61000-3-15 [20] uses a set of limits based on the slightly modified standard EN 61000-3-12:2011 [19] for R_{sce} = 33 (a short circuit ratio at the point of connection). It is assumed that if DG units meet the proposed limits, they will operate properly in all but the most exceptional cases.

Current harmonics limits for DG units up to 75 A/phase (in percent of I_{rms}) are included in the Technical Report IEC/TR 61000-3-15 [20]. The I_{rms} current is the average rms current level that the DG unit can be operated on a continuous basis in a full load condition. That current is the basis for the limits, even when the unit is tested at lower power e.g., 25% or 50% of full power.

The Technical Report IEC/TR 61000-3-15 [20] also notes that before running the tests, voltage harmonics of a voltage AC source which is simulating public supply shall not exceed the required levels.

The Technical Report IEC/TR 61000-3-15 [20] also describes platform setup for emission tests, which is described in the next section of this article (which is also presented in Figure 2) and which was prepared, for the purpose of this research, at Power Quality Laboratory of AGH University. The difference between platform setup described in the Technical Report IEC/TR 61000-3-15 [20] and setup configuration prepared at AGH University is a impedance unit. The impedance unit was not used, because the authors conducted product tests (i.e. tests which assess the current emissions of PV inverters in worst case conditions, not their impact on a network voltage distortion which is called "system test" in the Technical Report IEC/TR 61000-3-15 [20]).

The technical report IEC/TR 61000-3-15 [20] describes the platform setup for emission tests, as described in the next section of this article (also presented in Figure 2); it was prepared for the purpose of this research at the Power Quality Laboratory of AGH University. The difference between the platform setup described in the technical report IEC/TR 61000-3-15 [20] and the setup configuration prepared at AGH University is an impedance unit. The impedance unit was not used, because the authors conducted product tests (i.e., tests that assess the current emissions of PV inverters in worst case conditions, not their impacts on a network voltage distortion, which is called a "system test" in the technical report IEC/TR 61000-3-15 [20]).

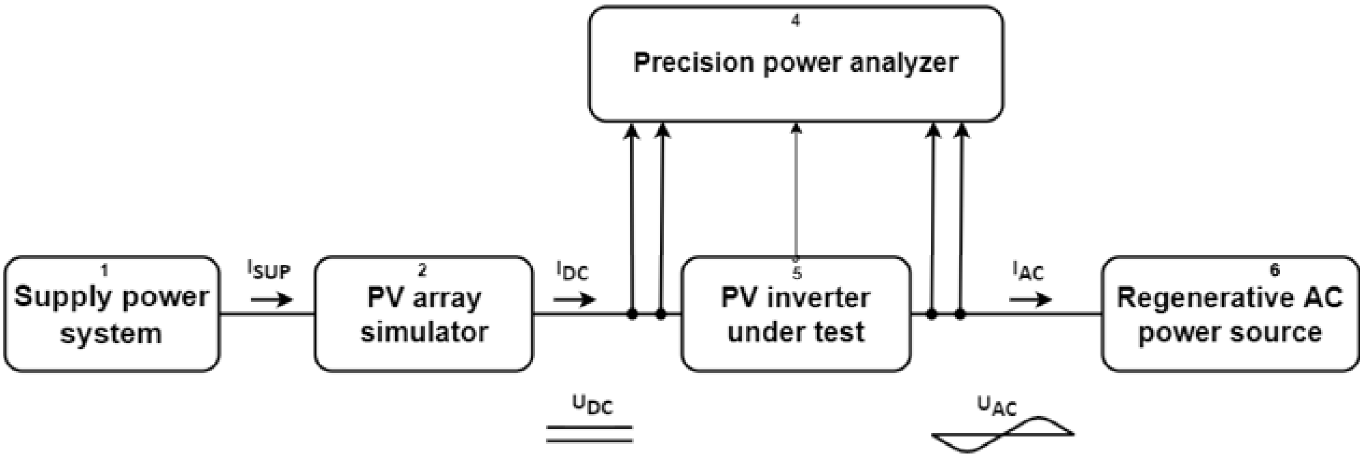

Figure 2. Block diagram of the laboratory stand for tests of PV inverters.

By reviewing the literature, several studies have been performed over the past years regarding harmonic emissions from PV inverters [21–25]. For example, in [21–23,25], the authors carried out analyses of current harmonic emissions from PV inverters while varying the solar irradiation levels. The authors note that, under low power generation periods, current total harmonic distortion (THD_i) is high when compared with high power generation periods, where THD_i is much lower. According to their results, the conclusion can be formulated that there is a strong inversely proportional relationship between solar irradiation levels and THD_i coefficients. The author of [22] also looked into individual RMS values of current harmonics regarding different solar irradiation levels. It can be noted that individual RMS values of current harmonics (3rd, 5th, 7th, 11th, and 13th) increase while the power generation level increases. This observation is the answer as to why the technical report IEC/TR 61000-3-15 [20] suggests that individual current harmonics shall be compared with the RMS current in full load conditions and why there are no requirements for the THD_i levels. An interesting approach to the measurement-based stability analysis of commercially available single-phase inverters in public low-voltage networks is presented in [26]. Its authors validated a commercially available photovoltaic inverter in the laboratory to demonstrate an instability caused by harmonic emissions in low voltage networks that led to a shutdown of the inverter.

The voltage distortion caused by the distorted current is one of the most common disturbances in distribution networks. The issues related to voltage/current distortion are complex [27,28] and the phenomenon itself may intensify other power quality disturbances (e.g., voltage fluctuations [29,30]).

3. Experimental Platform Setup and PV Inverters Under Tests

The test stand was prepared at the power quality laboratory at AGH University and was based on the standard EN 50530 [4], covering the methods of testing the PV inverter efficiency and the technical report IEC TR 61000-3-15 [20], specifying low-frequency electromagnetic compatibility for distributed generation systems. Other similar testing approaches presented in [31,32] were also considered.

The block diagram of the test stand is shown in Figure 2. Each tested PV inverter (3) was supplied on a DC side by the 18 kW photovoltaic array simulator (2), which was a DC source with adjustable current-voltage ($I = f(U)$) characteristics corresponding to the operation of PV arrays. The AC side of the PV inverter was connected to the electrical network simulator (5)—a 15 kW regenerative programmable AC source 3 × 230 V, which allowed to adjust the supply conditions at its output. Power, voltages, and currents on both sides of the tested PV inverter were measured using the power analyzer [33] (4). Figure 3 present the example of the current-voltage characteristics from the PV array simulator and the simulated irradiance changes over time corresponding to different levels of insolation.The blue and yellow points on the presented curves (static graph) correspond to the actual operating points of the tested PV inverter.

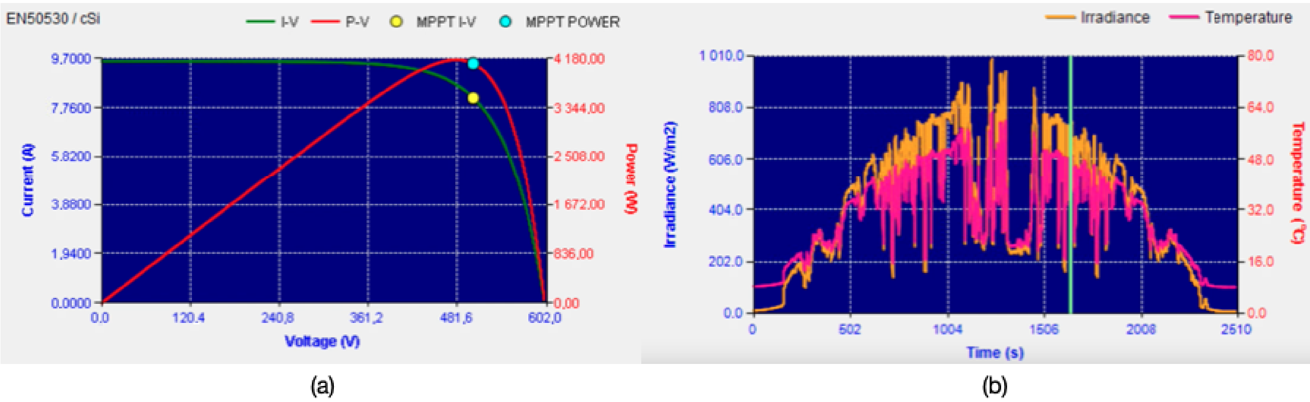

Figure 3. Exemplary current-voltage (**a**) and irradiance-time (**b**) characteristics from the PV simulator.

All tested devices were made available for the purpose of this experiment by their manufacturers or local distributors. The target equipment for the tests were PV inverters that were commonly installed by individual prosumers, i.e., with rated powers ca. 3.5 kW and 5–6 kW for 1-phase and 3-phase, respectively. Before performing the laboratory tests, all PV inverters were properly configured. Table 1 presents the list of tested PV inverters with information about the nominal active power.

Table 1. List of tested 1-phase and 3-phase PV inverters.

PV Model No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
							1-phase inverters										
P_{ac} [kW]	3.0	3.0	3.7	3.6	3.6	3.0	2.5	3.0	3.0								
							3-phase inverters										
P_{ac} [kW]	6.0	5.0	5.0	6.0	6.0	6.0	5.0	5.0	6.0	5.5	6.0	6.0	6.0	6.0	5.0	5.0	5.0

4. PV Inverter Testing Procedures and Obtained Results

4.1. Conversion Efficiency and Static MPPT Efficiency

The signal from the PV array simulator was supplied to the DC terminals of each tested PV inverter in the form of current–voltage characteristics, corresponding to the specific DC power and voltage range of the PV array. Measurement points that determined the operating conditions of the PV array simulator were selected on the basis of the catalog cards provided by the PV inverter manufacturers, whereas the power level for a given DC voltage range was determined as a percentage of the rated power of the AC side of the PV inverter. According to [4], tests were performed for three MPP voltages: $U_{\mathrm{MPP},min}$, $U_{\mathrm{MPP},n}$, and $U_{\mathrm{MPP},max}$. This, given in the matrix of testing points, is presented in Figure 4. Such a matrix of testing points was applied to each PV inverter under testing. The measurements were performed after stabilization of MPP tracking and at a nominal grid voltage in order to avoid any impact of the grid voltage level on the test results.

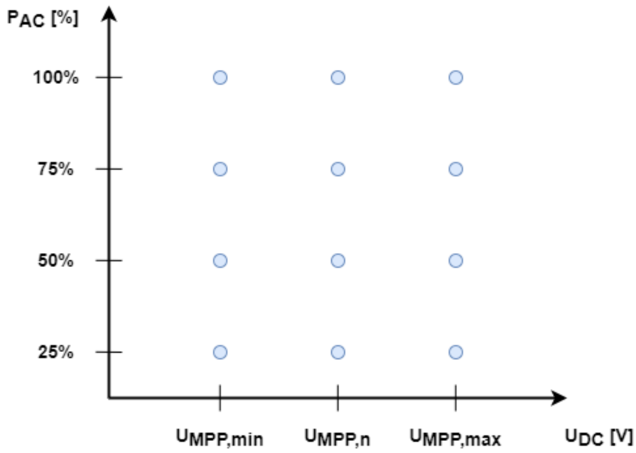

Figure 4. Graphical presentation of the operating point matrix of the tested PV inverters.

Regardless of the number of available MPPT inputs of each PV inverter, the total power was supplied only to a single MPPT. This was a deviation from the test procedure described in [4]; however, it allowed to evaluate the oversizing potential of a single MPPT input, since in practical applications the photovoltaic arrays of prosumer installations are often combined into only one string.

Detailed results of 26 PV inverters tested, 9 of which were 1-phase and 17 were 3-phase, are presented as histograms in Appendix A. Their statistical evaluations are summarized in Table 2 (for conversion efficiency) and Table 3 (for static MPPT efficiency), and are based on calculated medians, to provide the average values more resistant to outliers and standard deviations, and to indicate how widely the individual efficiency values were scattered around the average value. According to [33], the active power measurement accuracy was +/−(0.01% of reading +0.02% of the range).

Table 2. Statistical analysis of conversion efficiency test results.

			PV Inverters			
			1-Phase		3-Phase	
	U_{MPP}	P_{AC}	Median	Standard Deviation	Median	Standard Deviation
η_{conv}	U_{min}	25	94.70	1.23	94.70	4.05
		50	95.20	1.51	95.50	2.83
		75	95.00	1.80	95.70	2.40
		100	95.10	2.25	95.80	2.23
	U_n	25	96.10	1.25	96.30	2.88
		50	96.70	1.05	97.30	1.51
		75	96.80	1.14	97.50	1.08
		100	96.70	1.18	97.50	0.90
	U_{max}	25	95.80	1.62	95.50	2.57
		50	96.40	1.34	96.90	1.34
		75	96.60	1.37	97.30	0.91
		100	96.60	1.37	97.50	0.74

Table 3. Statistical analysis of static MPPT efficiency test results.

			PV Inverters			
			1-Phase		3-Phase	
	U_{MPP}	P_{AC}	Median	Standard Deviation	Median	Standard Deviation
η_{mppt}	U_{min}	25	98.80	17.66	99.20	15.05
		50	81.60	18.66	85.70	18.52
		75	45.90	23.09	56.70	20.54
		100	37.30	25.55	42.80	16.88
	U_n	25	99.70	0.26	99.70	0.30
		50	99.50	0.38	99.70	0.11
		75	99.60	0.24	99.70	0.07
		100	99.50	0.80	99.70	0.23
	U_{max}	25	91.60	7.58	94.40	4.01
		50	91.70	8.44	94.70	4.08
		75	91.50	14.73	94.90	3.93
		100	89.70	18.43	94.80	7.64

Conversion efficiency

When analyzing the conversion efficiency results of PV inverters for $U_{MPP,n}$ and generation ranging from 25% to 100% of the rated power (Figures A1 and A7), one can notice that the conversion efficiencies of the 3-phase PV inverters are in the range of 96.3–97.5%, while the conversion efficiencies of 1-phase PV inverters are in the range of 96.1–96.8%. This means that the 3-phase PV inverters have, on average, approximately a 0.6% greater conversion efficiency than 1-phase PV inverters. It can also be noted that the conversion efficiency decreases along with the reduction of the active power generation by the PV inverter. The maximum differences in conversion efficiency measurements between individual PV inverters amounted to approximately 3% for 1-phase PV inverters and approximately 10% for 3-phase PV inverters.

Both 1-phase and 3-phase PV inverters are on average 1.5% less efficient when operating at $U_{MPP,min}$ (Figures A2 and A8). Moreover, a larger dispersion of conversion efficiency indications was observed compared to the results for $U_{MPP,n}$. The efficiency indicators obtained for $U_{MPP,max}$ (Figures A3 and A9) do not differ significantly (both in terms of median and standard deviations) from those obtained for the rated voltage.

Static MPPT efficiency

When analyzing the static MPPT efficiency results of PV inverters for $U_{MPP,n}$ (Figures A4 and A10), and generation ranging from 25% to 100% of the rated power, one can notice that the median of the static MPPT efficiency is 99.7% for 3-phase inverters and from 99.5% to 99.7% for 1-phase inverters. The results obtained by individual PV inverters are very similar to each other, which is confirmed by relatively small values of standard deviations (up to 0.3).

In the case of tests carried out for $U_{MPP,max}$ (Figures A6 and A12), the systematic reduction in static MPPT efficiency up to 7% can be observed and applies to all 1-phase and most 3-phase PV inverters.

The results obtained for $U_{MPP,min}$ are interesting—a significant reduction in static MPPT efficiency is visible as a result of the generation level increase. Obtaining the rated power generation level with a relatively low voltage of the DC side forces the flow of the increased DC current. The results from Figures A5 and A11 indicate the design differences of the PV inverters related to the applied DC current limitations. It should be emphasized that the results obtained for the lowest voltages are characterized by the greatest dispersions for individual PV inverters, ranging from 15% to 25%.

4.2. Dynamic MPPT Efficiency

The purpose of this test was to compare the effectiveness of MPPT tracking of the PV inverters in variable irradiations and temperatures, as it often occurs during typical operations on days with variable cloudiness. The signal from the PV array simulator, adjusted individually for each PV inverter to $U_{MPP,n}$, was supplied to each tested inverter's DC terminal. Figure 5a presents the irradiation and temperature profiles generated by the PV array simulator for a given PV inverter. The given profile parameters caused variations in the power generated by the simulator, which forced the MPPT algorithm of a PV inverter to constantly search for the maximum power operating point. An example of the result obtained for a 3-phase PV inverter is shown in Figure 5b.

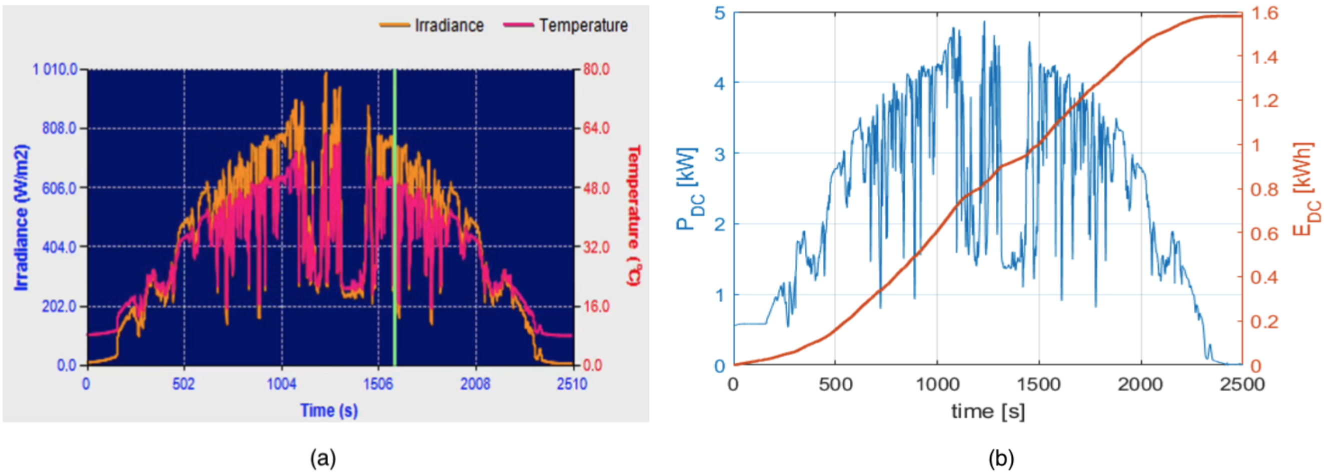

Figure 5. Dynamic MPPT testing procedure (**a**) and sample results of a tested inverter (**b**).

The qualitative indicator of the test was the amount of aggregated energy generated by the PV inverters over the complete test sequence. Eleven 3-phase inverters were tested. Their results are presented in Figure 6. The median of the obtained energies is 1.58 kWh; the individual readings did not differ by more than 2%. However, it should be noted that the energy measured in this test was also influenced by the conversion efficiency (1) and, as demonstrated by further analysis, this energy was the main factor determining the final differences in measurements.

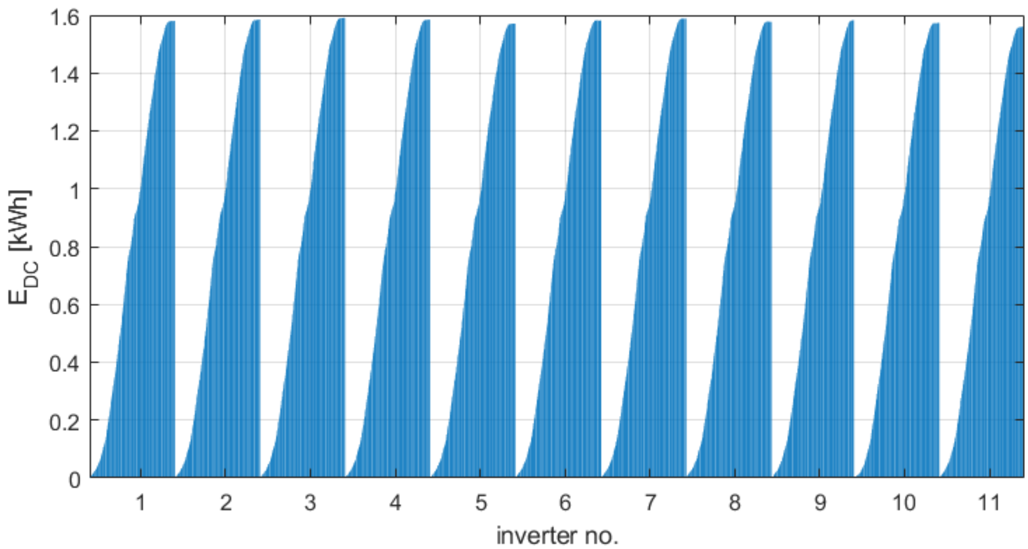

Figure 6. Dynamic MPPT efficiency test results.

4.3. Active Power Masurement

The purpose of this test was to compare the active power readings from the PV inverters with the reference power analyzer (Figure 2, block 4) in order to verify if the amount of energy indicated as generated was in agreement with the energy counted by the analyzer. The test was conducted for 14 3-phase PV inverters operating at $U_{\mathrm{MPP},n}$ and nominal power. The active power was measured by the analyzer as integral of the instantaneous $u(t) \cdot i(t)$ calculation over the 5 sec period and compared with the active power readings provided by the user interface of each PV inverter.

Figure 7 presents the percentage differences between the power readings from individual PV inverters (P_{AC}) and from the reference power meter (P_{ref}). The measured differences were up to 4%. PV inverters in most cases overestimated the amount of generated energy.

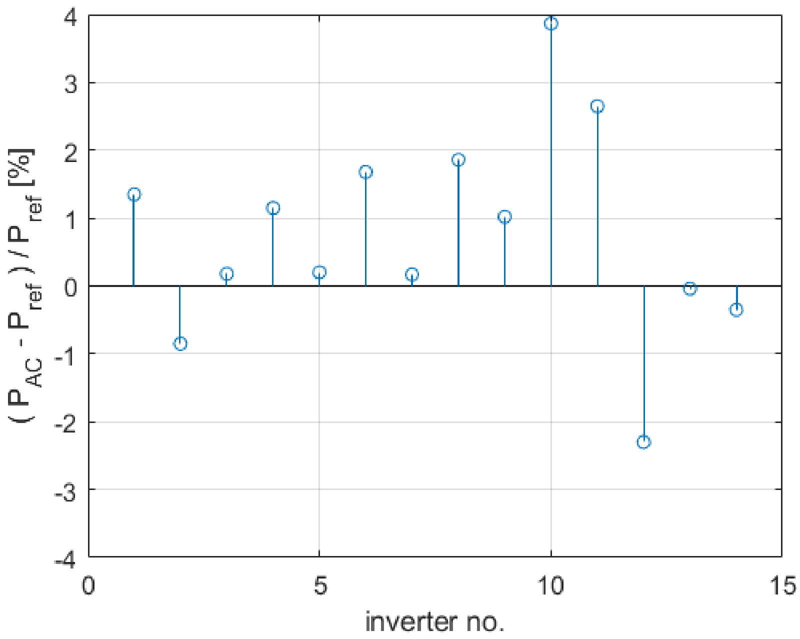

Figure 7. Comparison of power measured by the inverter (P_{AC}) and reference power analyzer (P_{ref}).

4.4. Harmonic Current Emissions

Harmonic current emissions tests were conducted for 17 3-phase PV inverters and 9 1-phase PV inverters according to the product test procedure described in the technical report IEC/TR 61000-3-15 [20], which was as follows:

1. Each tested PV inverter was connected as shown in Figure 2 and supplied with a nominal voltage 230 V AC.
2. The power supply unit was verified to be sufficiently "low-impedance". It was also checked if supply voltage harmonics did not exceed the applicable limits from [18]. This was conducted to exclude the influence of voltage harmonics on the generation of current harmonics in the circuit.
3. The value of I_{rms} was determined for each tested PV inverter as its maximum continuous operating current. This value is a base for the calculation of individual current harmonic limits as shown in Table 1.
4. Individual harmonic current emissions (for selected harmonics: 3rd, 5th, 7th, 9th, 11th, and 15th) were measured at 25%, 50%, 75%, 100% of a PV inverter nominal power and at the following DC voltage levels: $U_{\mathrm{MPP},n}$ and $U_{\mathrm{MPP},max}$. This way, eight results of each considered current harmonic were obtained for each tested PV inverter from which the maximum value was selected and presented in Figure 8 for 3-phase PV inverters and in Figure 9 for 1-phase PV inverters, respectively. According to [33], the harmonic measurement accuracy was 0.01% of reading +0.03% of the range.

From the tests results shown in Figures 8 and 9 can be seen that current emissions for all tested PV inverters are within the applicable limits defined in [20].

Besides individual harmonic current emissions, the THD_i factor was determined. All tested PV inverters were examined at 25%, 50%, 75%, 100% of their nominal powers at $U_{\mathrm{MPP},n}$. The otained results are shown in Figure 10.

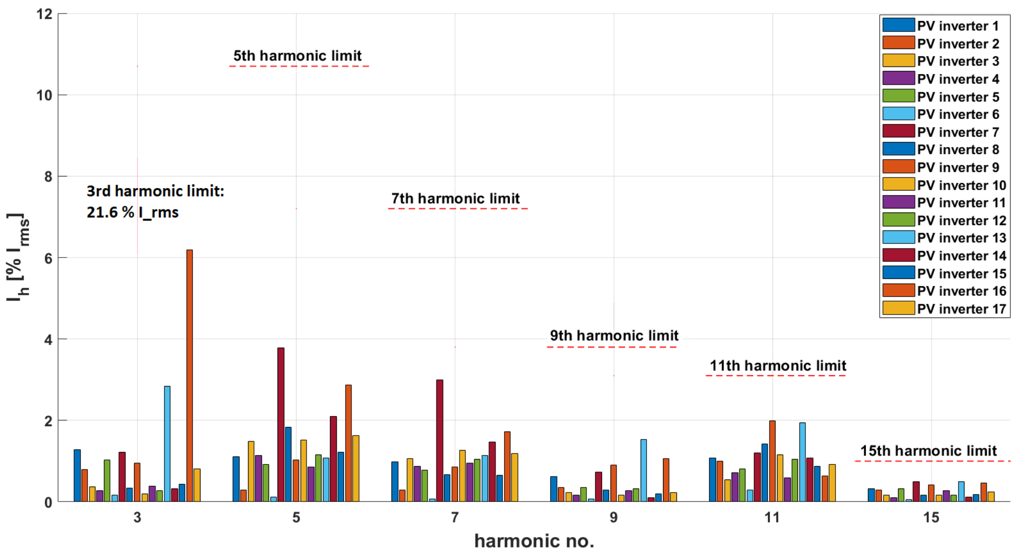

Figure 8. Harmonic current emissions of the tested 3-phase PV inverters.

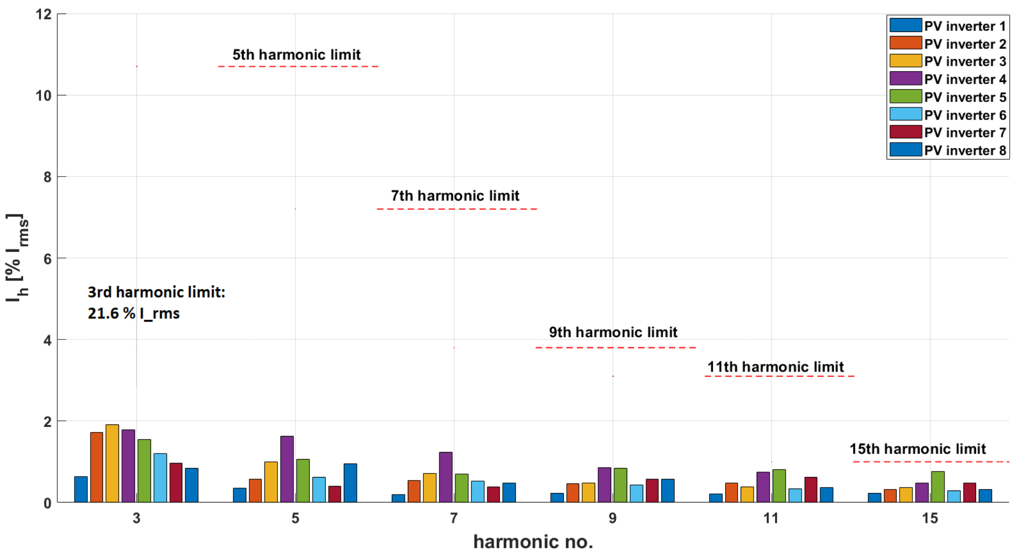

Figure 9. Harmonic current emissions of the tested 1-phase PV inverters.

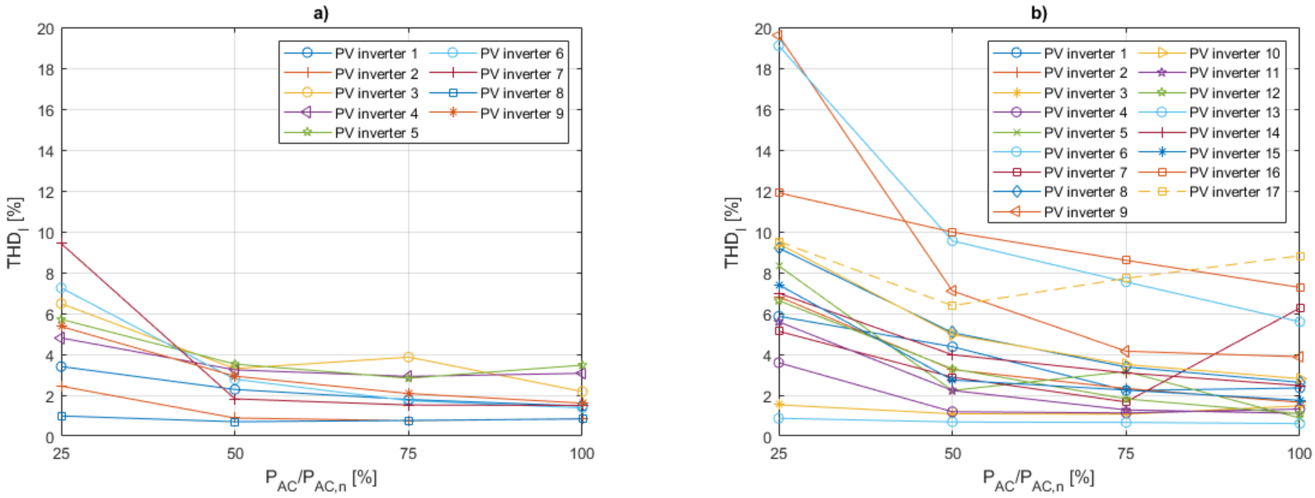

Figure 10. THD_i of the 1-phase (**a**) and 3-phase (**b**) PV inverters in relation to their active power generations.

The general observation that can be formulated is that the current distortion of PV inverters increases with decreasing power generation. For 1-phase PV inverters, maximum THD_i reached almost 10%, and for the 3-phase PV inverters, maximum THD_i reached almost 20%. For most of the 3-phase and 1-phase PV inverters, minimum THD_i was below 4%, but for a few 3-phase PV inverters (the PV inverters 6, 7, 16, and 17), minimum THD_i was equal or above 6%. From the point of view of the impact on the voltage distortion in a low-voltage network, individual maximum harmonic current emissions were much more important than an actual THD_i, because under low load conditions, the RMS current of a PV inverter was also low, so even little RMS values of individual current harmonics can cause the THD_i coefficient to be high, while the impacts of the individual current harmonics on the network are low. Thus, PV inverter manufacturers should draw more attention to meeting individual harmonic current emissions for product tests, according to the report IEC/TR 61000-3-15 [20] and the standard EN 61000-3-12:2011 [19], than showing (in the technical specification sheets) that the product is characterized with a low THD_i coefficient, which does not reflect the true impact of current harmonics on the network.

When examining the emissions of current distortions of PV inverters, attention was also placed on the presence of the switching frequency related components I_{sw}, which were measured as the highest amplitude fringes (around the switching frequencies) in the FFT spectrum obtained with a digital oscilloscope. The frequencies of these components depended on the PV inverter model and ranged from 10 to 32 kHz, i.e., in the band beyond the THD_i calculation. Results are presented in Table 4 (for 3-phase PV inverters) and Table 5 (for 1-phase PV inverters), as well as Figure 11. It should be noted that, in some cases, the values of these components exceeded the maximum levels of the considered harmonics in the band up to 2.5 kHz. This occurred for the 3-phase PV inverter nos. 8 and 12 and for the 1-phase PV inverter nos. 1, 4, 5, 6, 7, and 9. These components were measured at relatively high levels regardless of whether the PV inverters were connected to the grid simulator or directly to the electrical network. Therefore, it can be ruled out that the reason for their formations was not the specific interference of the PV inverter with the grid simulator. It was observed that the presence of these components caused frequent switching off of PV inverters working with the grid simulator, which was not found when connected directly to the electrical network.

Figure 12 presents an example oscillogram of the voltage and current waveforms at the output of the 1-phase PV inverter for which the highest switching frequency harmonic current emission was measured.

Table 4. Switching frequencies of the tested 3-phase PV inverters and corresponding measured values of the switching frequency harmonic current emissions.

Inverter No.	I_{rms} [A]	I_{sw} [A]	I_{sw} [% I_{rms}]	f_{sw} [kHz] (Approx.)
1	7.21	0.12	1.7	20
2	8.6	0.12	1.4	20
3	7.18	0.02	0.3	17
5	7.85	0.12	1.5	16
6	8.62	0.2	2.3	20
7	4.25	0.08	1.9	20
8	8.29	0.6	7.2	20
9	8.42	0.08	1.0	16
10	6.79	0.12	1.8	10
11	8.51	0.08	0.9	20
12	5.07	0.48	9.5	20
13	8.11	0.12	1.5	20
14	7.11	0.08	1.1	16
15	8.5	0.08	0.9	20

Table 5. Switching frequencies of the tested 1-phase PV inverters and corresponding measured values of the switching frequency harmonic current emissions.

Inverter No.	I_{rms} [A]	I_{sw} [A]	I_{sw} [% I_{rms}]	f_{sw} [kHz] (Approx.)
1	15.2	0.44	2.9	18
2	11.9	0.12	1.0	20
3	12.8	0.28	2.2	32
4	11.4	0.44	3.9	20
5	12.7	0.4	3.1	20
6	12.8	1.4	10.9	20
7	15.5	0.44	2.8	20
8	12.5	0.08	0.6	32
9	10.7	0.48	4.5	16
10	12.8	0.04	0.3	21
11	14.9	0.16	1.1	30
12	12.7	0.08	0.6	10

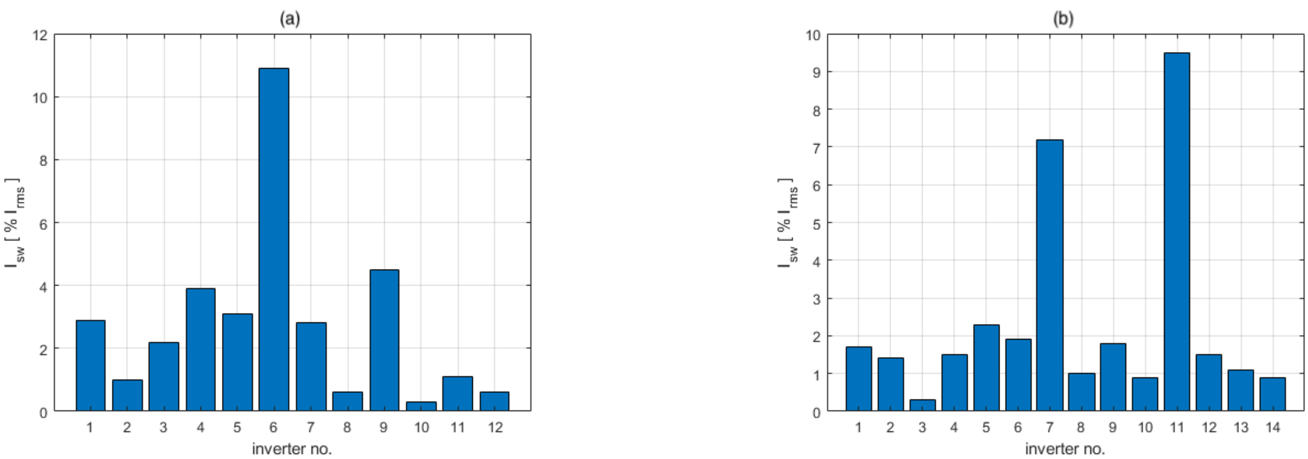

Figure 11. Switching frequency harmonic current emissions of the 1-phase (**a**) and 3-phase (**b**) PV inverters.

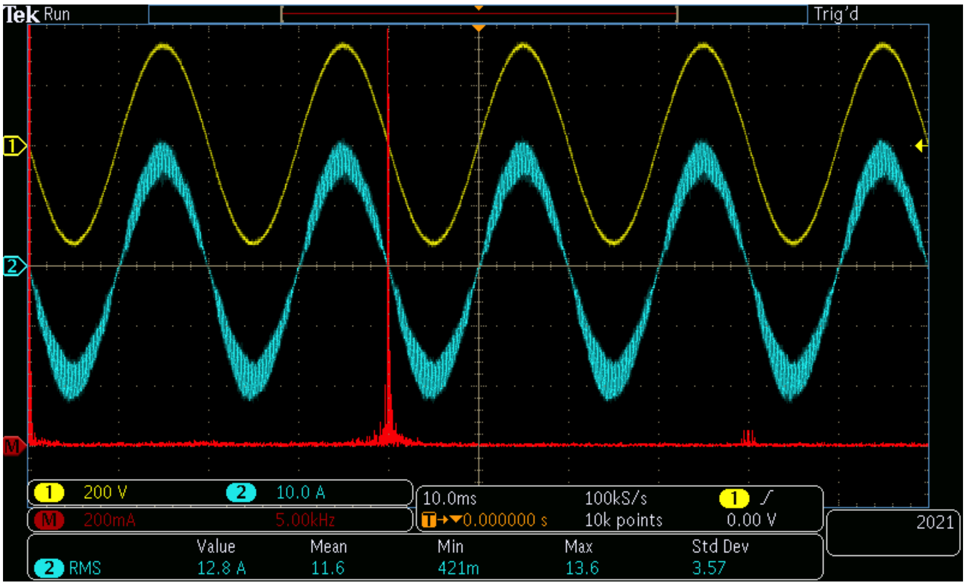

Figure 12. Example waveforms and the current spectrum of a 1-phase PV inverter.

5. Conclusions

In this paper, the essential measures of energy efficiency and current distortion emissions of PV inverters were presented together with a description of their laboratory verification procedures. This technical analysis was followed with a series of experimental laboratory tests performed on 26 brand-new PV inverters widely available on the EU market. These devices were made available (by their manufacturers or official local distributors) for the purpose of this open-ended experiment.

The scope of the laboratory tests included verifications of the key efficiency parameters of PV inverters, as well as their operational stabilities and possible impacts on voltage distortion in low voltage distribution networks:

1. Conversion efficiency;
2. Static and dynamic MPPT efficiency;
3. Current distortion emissions.

The outcome of the presented research is a set of detailed results allowing for a benchmarking assessment of the PV inverters available on the market. We showed how various energy efficiency indicators of individual PV inverters changed depending on their operating points, defined by the connected PV cell configurations and their insolation levels. The results were analyzed using statistical indicators, such as medians, to provide the mean value more resistant to outliers, and standard deviations, to indicate how wide the individual result values were scattered around the mean.

A separate section of the article was devoted toward the study of harmonic current emissions from PV inverters. The requirements and test procedures for such tests, specified in [18,20], were described in detail. The results were presented in the form of individual current harmonics, a current THD indicator, and the share of the switching frequency component in the total phase current of the PV inverters.

Based on the performed tests—individual harmonics were within the normative requirements; however , in the case of several PV inverters, attention was drawn to the presence of relatively high switching frequency-related components reaching even 10% of the fundamental component, as proven by the performed measurements. Regarding these devices, manufacturers should consider some improvements of the switching frequency filters installed on the AC side of PV inverters.

Future research directions will be devoted toward assessing the compliance of PV inverters with the requirements of grid codes of distribution system operators.

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Abbreviations

The following abbreviations are used in this manuscript:

conv	conversion
dyn	dynamic
n	nominal
η	efficiency
ref	reference
sw	switching
AC	alternating current
CEC	California Energy Efficiency
DC	direct current
DG	dispersed genration
EMC	Electromagnetic Compatibility
EN	European Norm
EU	European Union
FFT	Fast Fourier Transform
I	Current
MPP	Maximum Power Point
PV	Photovoltaic
RED	Renewable Energy Directive
RMS	Root Mean Squre
THD	Total Harmonic Distortion
U	Voltage

Appendix A

Appendix A.1. Conversion and MPPT Efficiencies of 1-Phase PV Inverters

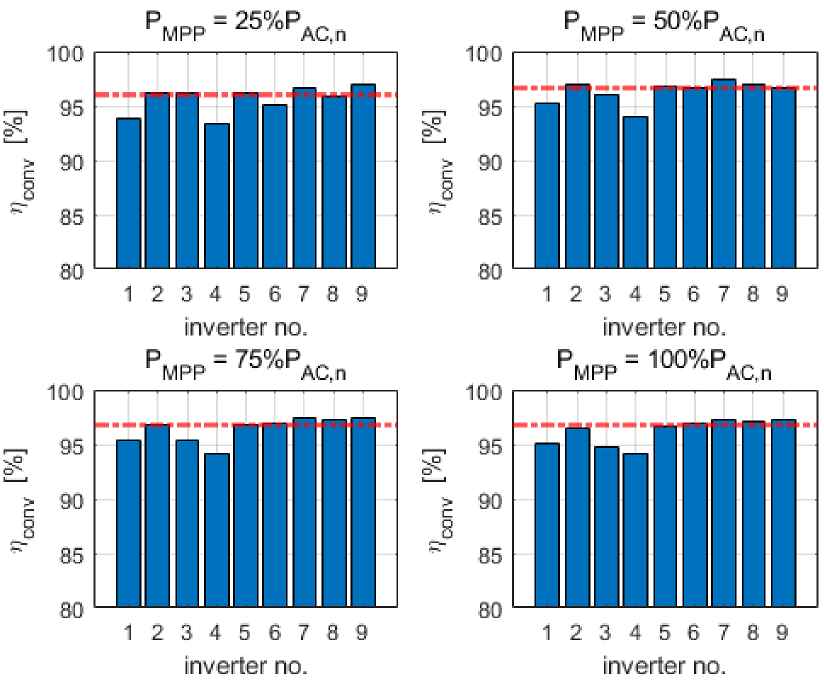

Figure A1. Conversion efficiencies of 1-phase PV inverters at $U_{\mathrm{MPPT},n}$.

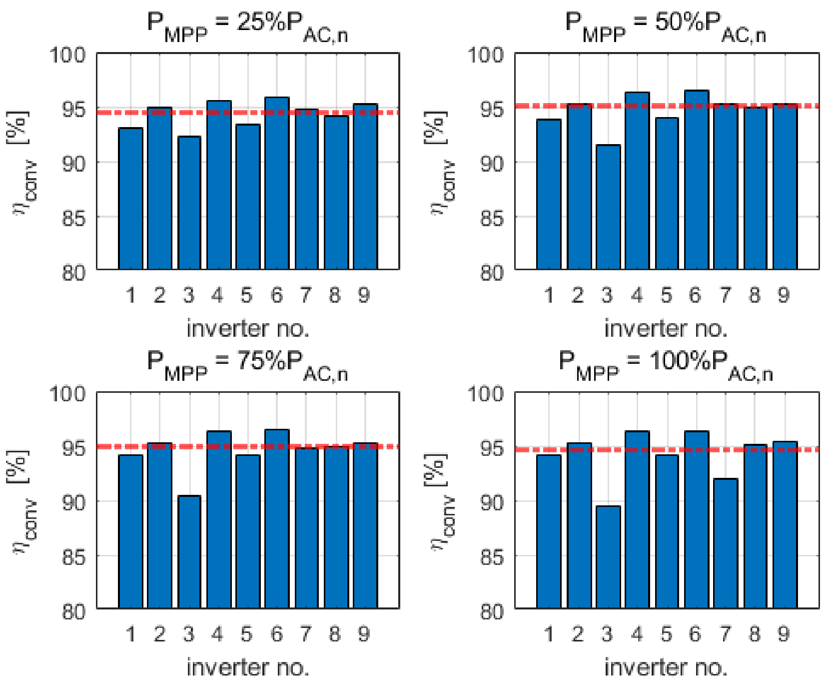

Figure A2. Conversion efficiencies of 1-phase PV inverters at $U_{\mathrm{MPPT},min}$.

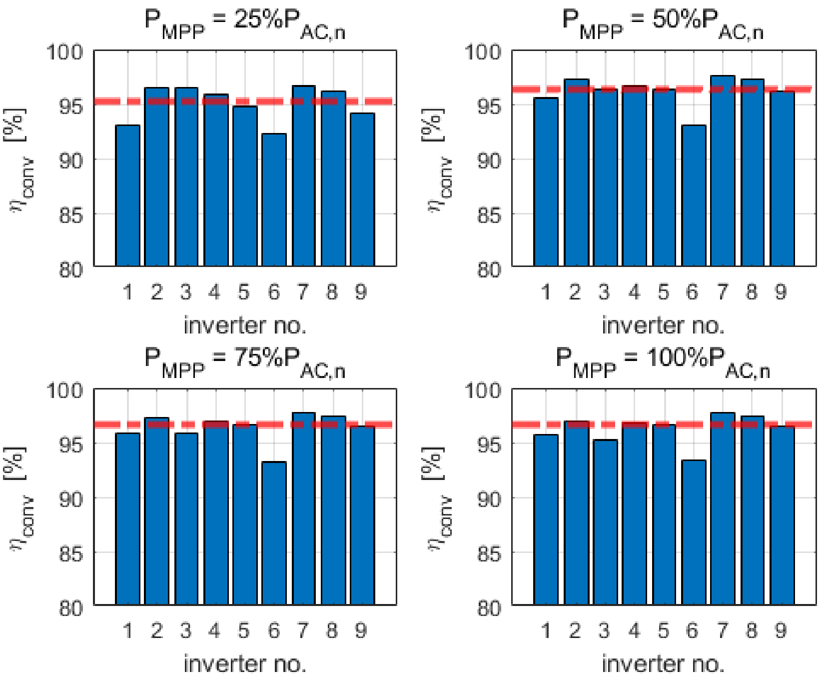

Figure A3. Conversion efficiencies of 1-phase PV inverters at $U_{\text{MPPT},max}$.

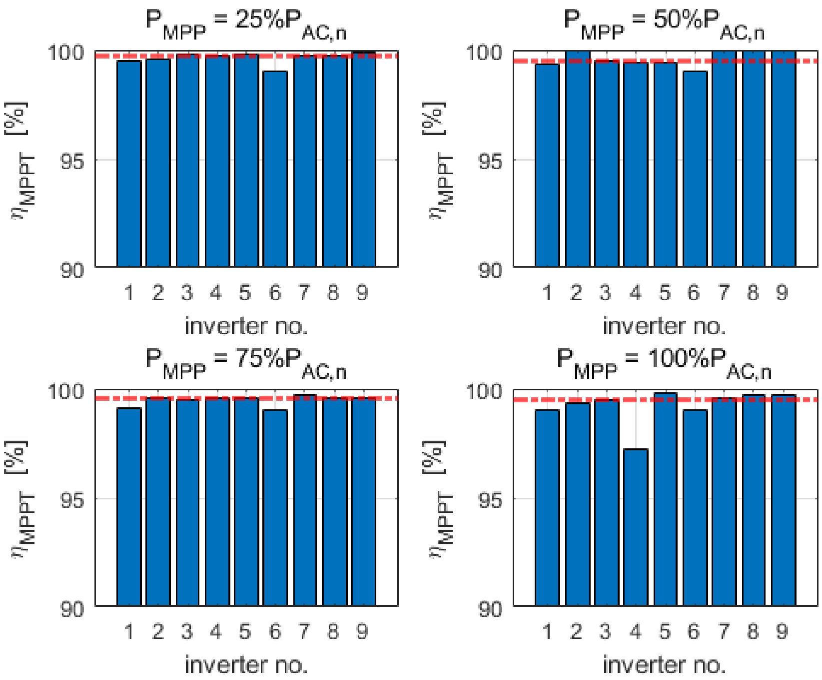

Figure A4. MPPT efficiencies of 1-phase PV inverters at $U_{\text{MPPT},n}$.

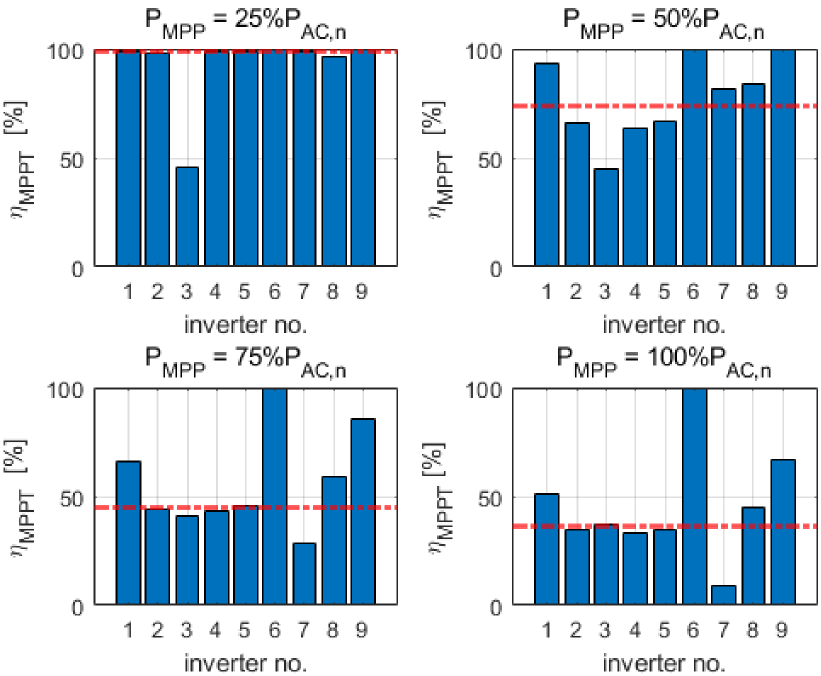

Figure A5. MPPT efficiencies of 1-phase PV inverters at $U_{\mathrm{MPPT},min}$.

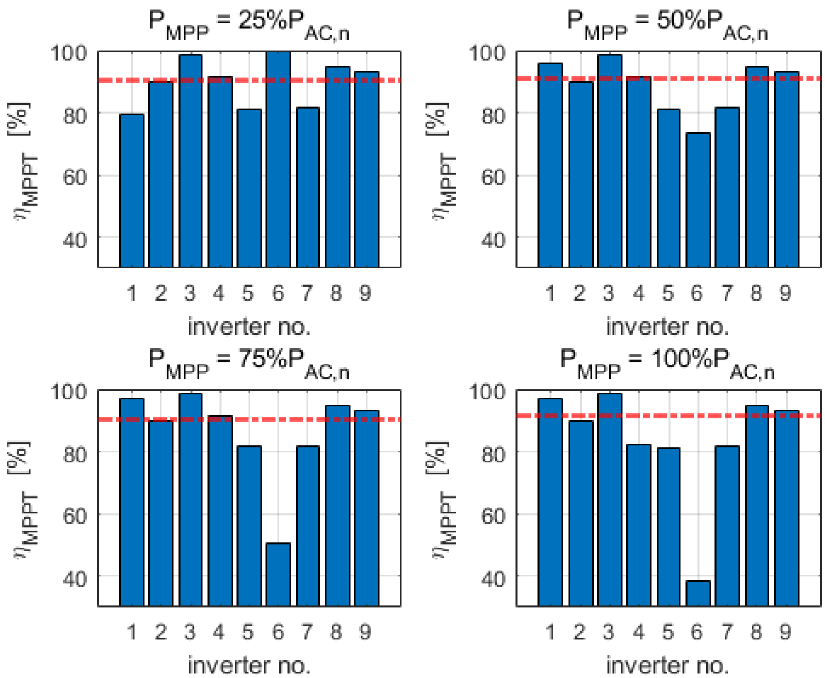

Figure A6. MPPT efficiencies of 1-phase PV inverters at $U_{\mathrm{MPPT},max}$.

Appendix A.2. Conversion and MPPT Efficiencies of 3-Phase PV Inverters

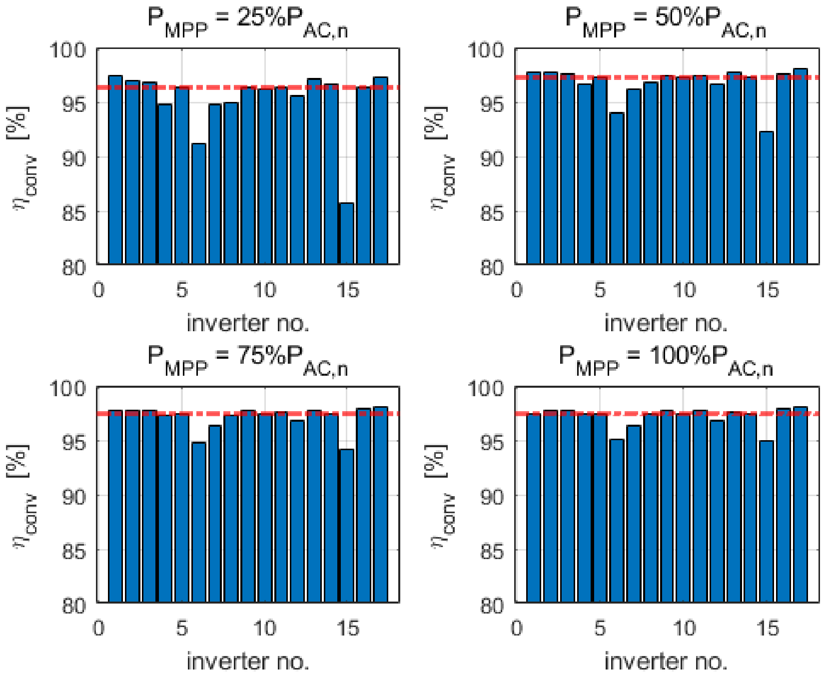

Figure A7. Conversion Efficiencies of 3-phase PV inverters at $U_{\mathrm{MPPT},n}$.

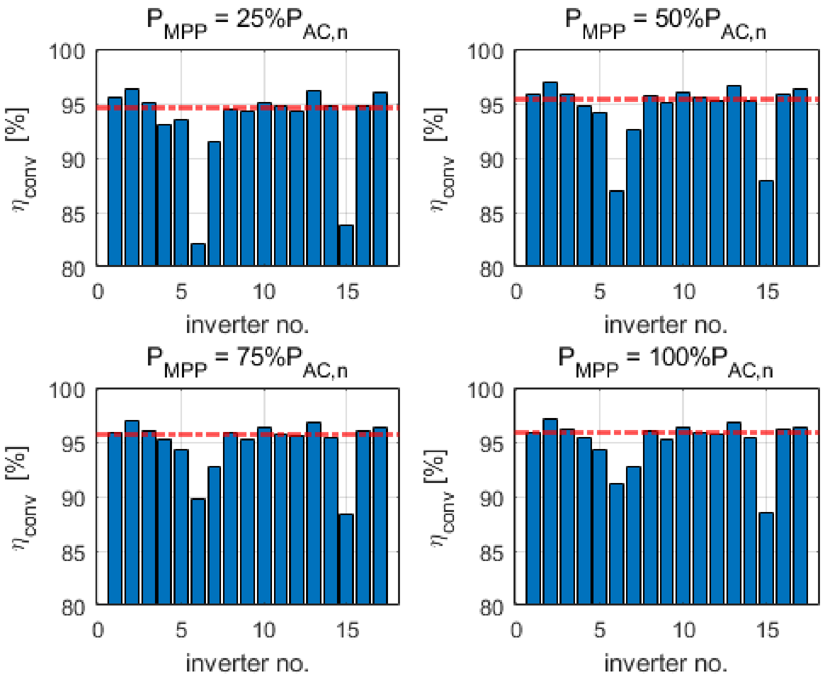

Figure A8. Conversion efficiencies of 3-phase PV inverters at $U_{\mathrm{MPPT},min}$.

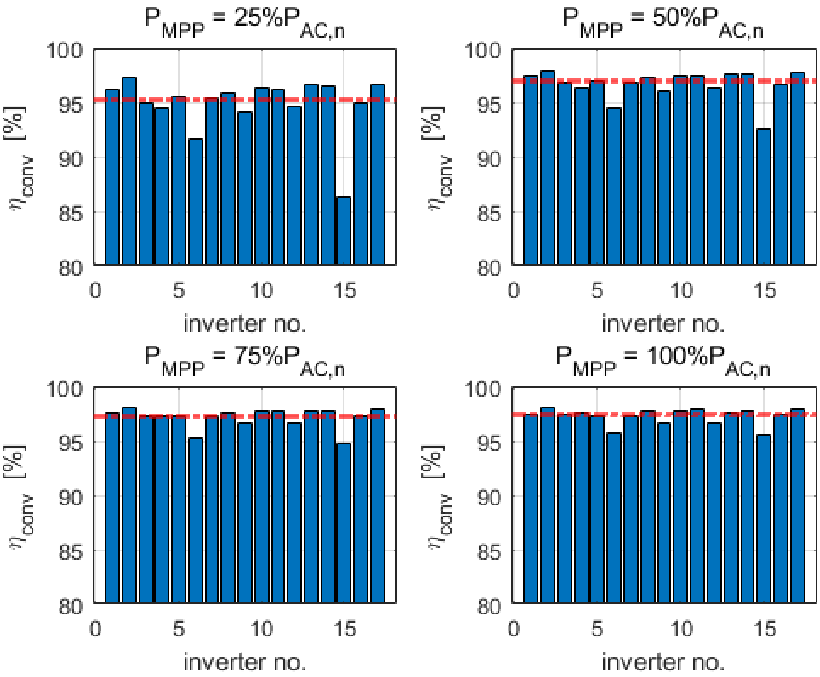

Figure A9. Conversion efficiencies of 3-phase PV inverters at $U_{\mathrm{MPPT},max}$.

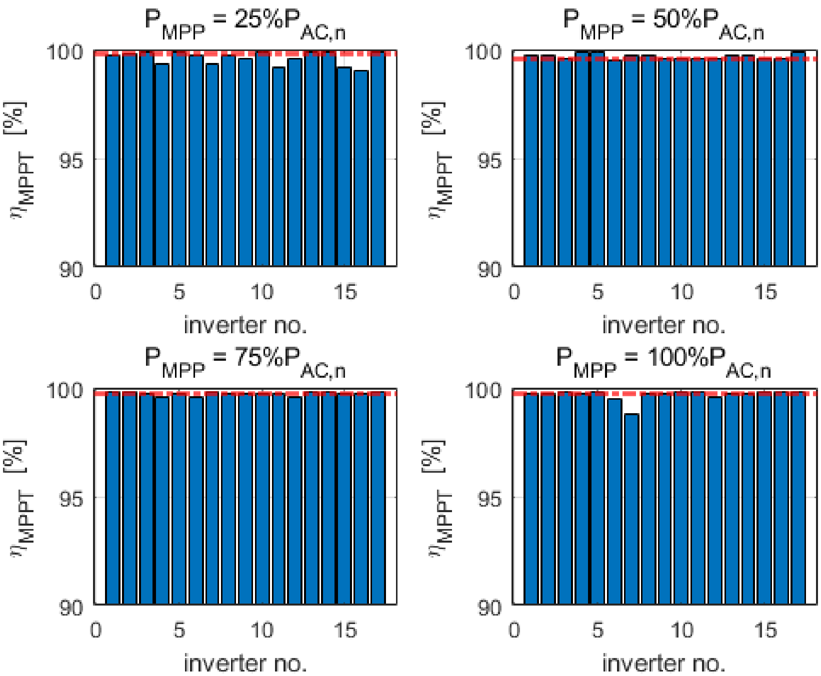

Figure A10. MPPT efficiencies of 3-phase PV inverters at $U_{\mathrm{MPPT},n}$.

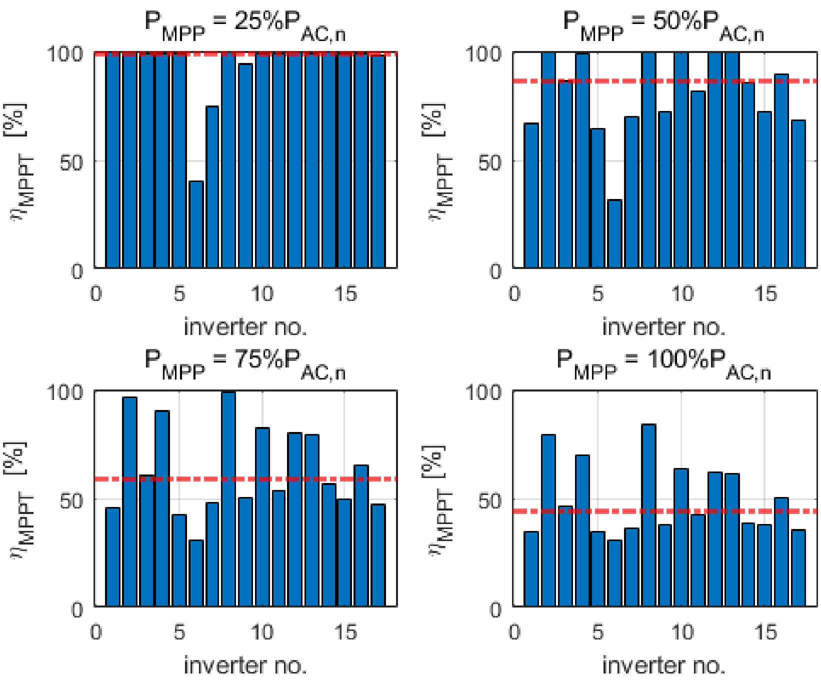

Figure A11. MPPT efficiencies of 3-phase PV inverters at $U_{\mathrm{MPPT},min}$.

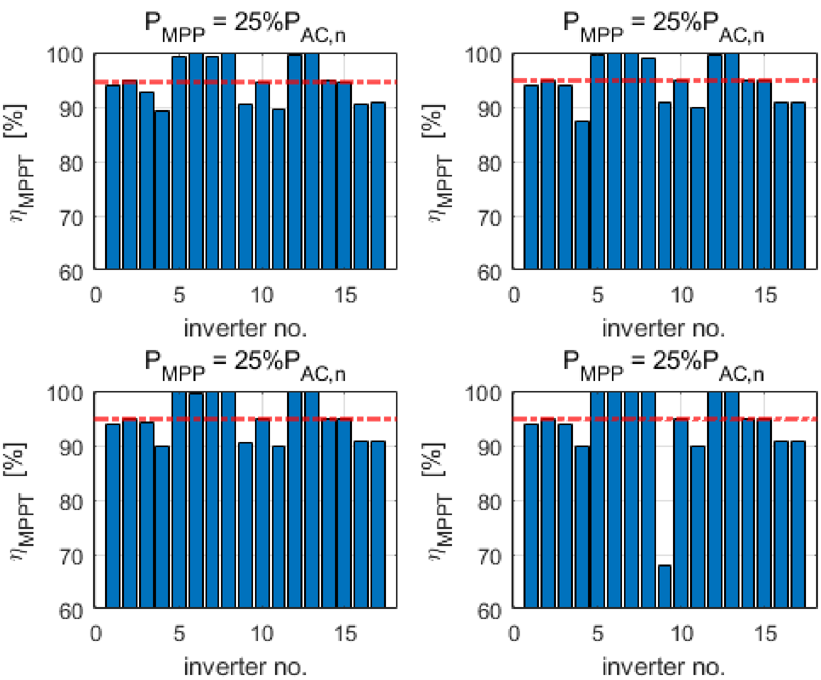

Figure A12. MPPT efficiencies of 3-phase PV inverters at $U_{\mathrm{MPPT},max}$.

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