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Integrated Power Quality Assessment of Photovoltaic Plants Using Field and Background Measurements, Network Modeling, and Unsupervised Analysis

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Abstract

This paper presents an integrated procedure to support the assessment of power quality at the points of connection of photovoltaic power plants to medium-voltage distribution networks. The study covered 20 power plants in Poland, for which seven-day power quality measurements were conducted, supplemented by measurements of background grid conditions with the installations disconnected. The proposed procedure combines compliance assessment against the requirements of EN 50160 and the applicable IRiESD, a synthetic power quality index, modeling in DIgSILENT PowerFactory, and multivariate analysis using principal component analysis (PCA) and the Isolation Forest algorithm. The results revealed significant discrepancies between the compliance assessments based on the two sets of requirements: 19 out of the 20 power plants met the EN 50160 requirements for harmonics, whereas all installations exceeded the applicable harmonic limits under the IRiESD requirements. Measurements of the grid background confirmed the presence of elevated levels of certain harmonics even when the power plants were disconnected, highlighting the necessity of accounting for grid conditions when interpreting results. Modeling enabled the analysis of harmonic characteristics, while PCA and Isolation Forest facilitated the preliminary identification of installations with atypical harmonic characteristics. The article describes the measurement and computational methodology, presents the results from the measurements, modeling, and multivariate analysis, and concludes with a discussion on the limitations of the proposed approach. The findings demonstrate the value of integrating these methods into a procedure to support power quality diagnostics.

Keywords: power quality; photovoltaic plants; medium-voltage networks; harmonics; Isolation Forest; background-grid analysis

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1. Introduction

The ongoing transformation of the power sector is leading to a systematic increase in the share of distributed energy resources, particularly installations using renewable energy sources (RES). The transition from an electricity generation structure based primarily on large, centralized generating units to one characterized by a significant share of distributed generation is causing substantial changes in power system operating conditions [1–4]. The development of distributed generation is also closely associated with the smart grid concept, in which bidirectional power flows, measurement systems, and advanced methods for processing information on grid conditions are becoming increasingly important [5].

The development of photovoltaic generation plays a particularly important role in this transformation. The growing number of PV installations means that distribution networks, originally designed for unidirectional power delivery to consumers, are increasingly operating under bidirectional power flow conditions [6–8]. During periods of high generation and limited local demand, power flow may reverse and the voltage profile may change. High penetration of photovoltaic generation may also affect distribution network operating conditions, including voltage levels, protection coordination, and selected power quality parameters [9]. The increasing share of distributed generation therefore requires not only the expansion of grid infrastructure but also the development of methods for monitoring, modeling, and assessing power system operating conditions [10,11].

One of the key issues associated with the integration of PV installations into the power system is ensuring the required level of power quality. The connection of photovoltaic sources may affect, among other parameters, RMS voltage, voltage fluctuations and voltage unbalance, and harmonic distortion [12,13]. Power electronic converters, which provide the interface between photovoltaic generators and the grid, are particularly important in this context. Their operation may result in the generation of harmonic components, whose levels depend, among other factors, on converter topology, control algorithms, filter parameters, and grid operating conditions [14].

However, power quality assessment at the point of connection of a renewable energy source should not be limited to identifying specific disturbances or exceedances of applicable limits. An important issue is determining the origin of these disturbances. The voltage parameters recorded at the point of common coupling are influenced simultaneously by the investigated source, other sources and loads, and the characteristics of the grid itself [15]. Therefore, the observation of an exceedance of a specified limit during PV plant operation does not provide sufficient evidence to attribute a given disturbance to the investigated plant. This is particularly important for voltage harmonics, whose levels depend both on disturbance sources present in the grid and on the grid impedance characteristics and harmonic propagation conditions [16]. For this reason, characterizing the background grid conditions can provide useful information when assessing the potential impact of a PV installation on the grid. In this study, the background grid conditions are defined by the levels of the analyzed power quality parameters recorded at the point of connection when the investigated plant is disconnected. Comparing measurements obtained during normal plant operation with those performed after its disconnection provides information on differences in disturbance levels between the two operating states, although changes in grid conditions between the measurement periods must be considered. This approach provides additional information that helps identify disturbances that are also present when the investigated installation is disconnected, without conclusively identifying their sources [17].

The assessment of supply voltage characteristics in public distribution networks is primarily based on the EN 50160 standard [18]. When assessing generating units, the provisions of EN 50160 are considered alongside national regulations and documents issued by distribution system operators, including the Regulation of the Minister of Climate and Environment on detailed conditions for the operation of the power system and the Distribution Network Operation and Maintenance Instructions (IRiESD). The European Network Code on Requirements for Generators (NC RfG) is also relevant, as it specifies requirements for the connection of generating units to the power system, particularly with regard to their capability to interact with the system and their behavior during disturbances [19]. Conventional compliance assessment primarily provides information on whether individual parameters meet the applicable requirements. When comparing a larger number of installations, it may be useful to complement this assessment with a synthetic power quality index that enables the combined evaluation of multiple parameters. Such an index should,

however, serve as a tool supporting the interpretation of the results rather than replacing direct compliance assessment.

Additional information can be obtained through computer modeling. From a metrological perspective, mathematical models can be used to analyze the properties of measurement systems and the influence of their dynamic characteristics on measurement results [20]. An appropriately developed model of the investigated power system can, in turn, be used to analyze its behavior and compare simulation results with measurements from the actual system [21,22]. For large installations, aggregation methods are required to reduce model complexity while preserving an appropriate representation of the components that significantly affect the phenomena under investigation, particularly power electronic converters [23,24]. The DIgSILENT PowerFactory environment enables power system modeling and, among other functions, power flow and harmonic analyses [25].

At the same time, the development of digital measurement systems is generating multidimensional power quality datasets. Conventional data analysis methods can be complemented by machine learning techniques applied, among other areas, to the diagnosis and classification of power quality disturbances [26], load profile analysis [27], and the analysis of photovoltaic systems [28]. When comparing multiple plants, unsupervised methods may be particularly useful [29]. Principal component analysis (PCA) enables dimensionality reduction and the identification of dominant directions of variability, whereas Isolation Forest can support the detection of plants characterized by unusual combinations of parameters. However, outlier detection does not automatically establish non-compliance or identify the causes of observed disturbances; therefore, these methods should support rather than replace conventional engineering analysis [30,31].

Existing research on power quality in grids with photovoltaic installations provides significant insights into the occurrence of disturbances and the methods available for their analysis. A fundamental limitation of approaches based primarily on measurements taken during plant operation is the difficulty of distinguishing between disturbances caused by the source under investigation and those that occur independently of its operation [15]. Computer modeling methods, in turn, allow for the analysis of harmonic characteristics and their propagation mechanisms; however, the reliability of the results depends on the simplifications adopted and the accuracy with which actual grid operating conditions are represented [21]. Meanwhile, multivariate data analysis methods can identify atypical characteristics of the systems under study, yet they do not, by themselves, establish the physical causes of the observed disturbances [29]. These limitations highlight the need for an integrated approach that combines measurement data, analysis of the grid background, computer modeling, and statistical methods. Consequently, the methodological gap concerns not the development of additional independent analytical tools, but their integration into a procedure that enables a more comprehensive and cautious interpretation of power quality assessment results.

Although individual measurement techniques, modeling methods, and data analysis tools are well-established, their independent application does not always yield a coherent interpretation of power quality disturbances at the point of common coupling. In particular, while traditional compliance assessment against applicable requirements can identify instances where parameter values exceed permissible limits, it cannot definitively determine whether these exceedances result from the operation of the photovoltaic installation under study or from pre-existing disturbances within the distribution network. The methodological challenge addressed in this work therefore concerns the development of an integrated diagnostic procedure that combines regulatory compliance assessment, analysis of background grid conditions, modeling of harmonic propagation, and multivariate analysis to identify installations requiring further investigation. The value of the proposed approach

lies primarily in the complementary interpretation of the results obtained through these methods, rather than in the novelty of any individual analytical tool.

The aim of this study is to develop and demonstrate the applicability of an integrated diagnostic approach to power quality assessment at the points of connection of PV plants to medium-voltage networks. The study covered 20 operating PV plants, at which seven-day measurements of power quality parameters were conducted and compliance with the requirements of EN 50160 and the applicable IRiESD was assessed. For each of the analyzed plants, an additional measurement campaign was conducted with the PV installation disconnected to characterize the background grid conditions. A detailed model of one of the plants was developed in DIgSILENT PowerFactory, enabling comparison of measured and simulated results as well as analysis of harmonic analysis. The data obtained for the investigated plants were also subjected to multivariate analysis using PCA and the Isolation Forest algorithm.

The primary methodological contribution of this work is the development and application of a multistage diagnostic procedure that combines traditional power quality assessment with an analysis of grid conditions when a PV installation is disconnected and supplements it with numerical and statistical analyses. A key feature of this approach is the use of measurement data collected while the installation is disconnected as an additional diagnostic reference when interpreting limit violations recorded during normal operation. The procedure is further supported by a synthetic power quality index, modeling of harmonic propagation, and the identification of installations with atypical harmonic characteristics using unsupervised learning methods. Integrating the results of the individual stages yields additional diagnostic information that cannot be obtained through a standard compliance assessment against regulatory requirements. The applicability of the proposed procedure is demonstrated using real-world measurement data and simulation results from 20 photovoltaic power plants, while accounting for the inherent limitation that harmonic emissions cannot be reliably quantified and attributed to individual installations.

2. Materials and Methods

The study employed an integrated procedure comprising field measurements of power quality parameters, background grid measurements with the PV installations disconnected, computer modeling, and multidimensional data analysis. The adopted approach was intended not only to assess whether voltage parameters comply with the applicable standard and the relevant distribution system operator requirements, but also to compare the conditions observed during PV plant operation with those observed after disconnection and to identify plants exhibiting unusual harmonic characteristics.

2.1. Characteristics of the Investigated Plants and Measurement Methodology

The study was conducted using data from 20 operating PV plants connected to medium-voltage networks in Poland. The plants were located within the service areas of three distribution system operators: Enea Operator S.A., Energa-Operator S.A., and TAURON Dystrybucja S.A. [32–34]. The maximum connection capacities of the analyzed plants ranged from approximately 0.8 MW to 8.4 MW, while the total rated power of the inverters installed at individual plants ranged from approximately 0.8 MW to 10 MW. The investigated plants were equipped with Huawei SUN2000-215KTL-H (Huawei Technologies Co., Ltd., Shenzhen, China) or Sungrow SG350HX inverters (Sungrow Power Supply Co., Ltd., Hefei, China). Due to confidentiality requirements, the names and locations of the plants, as well as other potentially identifying information, were withheld; the plants were designated as Plants 1–20.

Power quality measurements were performed using Sonel PQM-710 analyzers (Sonel S.A., Świdnica, Poland) [35]. During the measurement campaigns, all analyzers had valid calibration certificates issued by an accredited laboratory. The analyzers perform power quality measurements in accordance with Class A requirements specified in IEC 61000-4-30 [35,36]. Sonel CA-6 current clamps were used for current measurements, while voltage measurements were performed using probes dedicated to the PQM-710/711 analyzers. The measurements were carried out using the existing Class 0.2 or 0.2S current and voltage transformers installed at the plants. At each plant, the power quality analyzer was connected to the secondary circuits of the instrument transformers, with its settings configured according to the corresponding transformation ratios.

The analyzer was installed as close as practicable to the point of common coupling (PCC) between the PV plant and the distribution network, taking into account the technical conditions at each plant and the accessibility of the measurement circuits. In most cases, the analyzer was installed in the metering cabinet of the relevant bay at the main substation or in the metering bay of the customer-owned transformer substation. For each plant, the primary measurement campaign was conducted continuously for seven days. This enabled the assessment of voltage parameters in accordance with EN 50160 [18] and the requirements of the applicable distribution system operator's IRiESD [32–34]. The measurement campaigns were scheduled during the summer period in coordination with the relevant distribution system operators. This period was selected to enable measurements across a broad range of PV generation levels, including conditions of relatively high power output. The seven-day measurement period was consistent with the arrangements agreed upon with the operators.

In addition, background grid measurements were performed for each of the analyzed plants. For this purpose, the circuit breakers on the low-voltage side were opened so that the PV plant converters were isolated from the grid, while the power supply to the equipment required for data recording was maintained. At each plant, the background grid measurement lasted at least 24 h. Measurements performed during normal PV plant operation and with the installation disconnected correspond to mutually exclusive operating states and therefore cannot be performed simultaneously at the same point of connection. The duration of the background grid measurement campaigns was also constrained by operational and economic considerations, since prolonged disconnection of a PV plant would interrupt electricity generation and require approval from the plant owner and the relevant distribution system operator. The resulting data were used to characterize the conditions occurring at the PCC with the investigated source disconnected, rather than as an invariant characteristic of the grid itself. Due to the differing durations of the measurement campaigns and the fact that they were conducted during different periods, comparing the results obtained during normal operation with those recorded when the installation was disconnected did not constitute an experiment capable of definitively determining the impact of the source under study on the levels of individual harmonics. The primary objective of the background grid measurements was to establish whether elevated harmonic levels were also present when the installation in question was disconnected. Consequently, the results obtained were treated as supplementary diagnostic information regarding grid conditions, rather than as a basis for directly quantifying the harmonic emissions produced by the photovoltaic power plant under investigation.

The parameters recorded during the measurements, together with their units and aggregation intervals, are summarized in Table 1.

Table 1. Parameters recorded during the power quality measurements.

Parameter	Unit	Aggregation Interval
Supply voltage frequency	Hz	10 s
RMS line-to-line voltage	V	10 min
Short-term flicker severity index, Pst	–	10 min
Long-term flicker severity index, Plt	–	2 h
Voltage unbalance	%	10 min
THDU	%	10 min
Voltage harmonics from the 2nd to the 50th order	V or %	10 min

2.2. Data Processing and Power Quality Assessment

Data from the analyzers were downloaded and reviewed using Sonel Analiza software (Sonel 5.0.1) [35] and subsequently exported to CSV files. Due to differences in file structure arising, among other factors, from differences between software versions, a custom Python 3.15.2 program was developed to automatically identify and normalize variable names, standardize the data, and perform further processing. For each measurement series, the arithmetic mean, minimum, maximum, median, 5th and 95th percentiles, standard deviation, variance, and coefficient of variation were calculated. The maximum values shown in the harmonic characteristic plots help identify the highest recorded harmonic levels but do not reflect their variability over the entire measurement period. Consequently, these values should be interpreted with caution, considering the possible influence of isolated extreme values and differences in the durations of individual measurement campaigns. The proportion of samples meeting the applicable limit requirements was also determined.

Compliance was assessed separately against the requirements of EN 50160 [18] and the IRiESD requirements of the distribution system operator to whose network the respective plant was connected [32–34]. The two sets of requirements were considered separately because of differences in the applicable limits and in the assessment procedures for individual parameters, particularly voltage harmonics. The synthetic assessment did not replace the conventional assessment of each parameter against the applicable requirement. Compliance with the requirements of EN 50160 and the applicable IRiESD was assessed independently for each power quality parameter under analysis. This process utilized the limit values, aggregation intervals, and statistical criteria specific to each document. For individual voltage harmonics, the analysis focused on the relative magnitudes of individual harmonic components, expressed as a percentage of the fundamental component. For EN 50160, the assessment was based on comparing the 95th percentile calculated from ten-minute values over a one-week observation period with the permissible limit for the respective harmonic order. In the case of the IRiESD, the requirements of the relevant distribution system operator (to whose network the installation was connected) were applied, including the 0.5% limit for individual voltage harmonics applied in this study. Compliance results were determined separately for each document, without using the synthetic power quality index as a normative criterion.

Particular attention was paid to comparing the voltage harmonics levels recorded during normal PV plant operation with those obtained during background grid measurements. For the harmonic of order h, a comparative quantity was defined as the difference between the maximum values recorded under the two operating conditions:

$$\Delta H_{\mathrm{h}} = H_{\mathrm{h}}{}^{\mathrm{PVmax}} - H_{\mathrm{h}}{}^{\mathrm{BGmax}} \quad (1)$$

where $H_{\mathrm{h}}{}^{\mathrm{PVmax}}$ denotes the maximum level of the h-th harmonic recorded during normal operation of the PV installation, whereas $H_{\mathrm{h}}{}^{\mathrm{BGmax}}$ denotes the corresponding maximum value obtained during the background grid measurement. The quantity ΔH_{h} was treated

solely as a comparative indicator rather than as a direct measure of harmonic emissions from the investigated source. This qualification is necessary because the primary measurement campaign covered seven days, whereas the background grid measurement lasted at least 24 h, and the grid configuration and loading conditions could have changed between the two measurement periods. Therefore, a positive value of ΔH_{h} indicates only that a higher maximum was recorded during PV plant operation; by itself, it does not establish a causal relationship.

To facilitate comparison among the investigated plants, a custom synthetic power quality index ranging from 0 to 100 was also applied. The preliminary index value was calculated as a weighted average of the partial scores assigned to seven parameters: voltage, total harmonic distortion of voltage (THDU), voltage harmonics, the long-term flicker severity index P_{lt}, voltage unbalance, the short-term flicker severity index $P_{st,}$ and frequency. The nominal weights were 0.25, 0.20, 0.15, 0.15, 0.10, 0.10, and 0.05, respectively. The assigned weights were determined on the basis of expert assessment of the significance of individual parameters in power quality assessment in medium-voltage networks. The highest weight was assigned to voltage magnitude, given its fundamental importance for the operation of electrical equipment. A significant weight was also assigned to parameters characterizing harmonic distortion, a factor of particular importance for photovoltaic installations that utilize power electronic converters. The remaining weights were selected by considering the diagnostic relevance of voltage flicker, voltage unbalance, and frequency. The proposed weighting scheme is based on expert judgment and serves as a tool for comparative assessment rather than as a direct reflection of regulatory requirements. If measurement data were unavailable for a given parameter or no corresponding limit value was specified, that parameter was omitted and the remaining weights were normalized so that their sum equaled 1. The preliminary value of the index was calculated as follows:

$$W_{\mathrm{r}} = \frac{\sum_i w_i S_i}{\sum_i w_i} \tag{2}$$

where S_i denotes the partial score for the i-th parameter and w_i denotes its weight. The partial scores were determined on the basis of the normalized deviation of the measured value from the corresponding limit value. If the parameter value did not exceed 50% of the allowable range, a score of 100 points was assigned. For parameter values between 50% and 100% of the limit, the score decreased linearly, whereas for values exceeding the limit, it decreased exponentially, using a decay coefficient of 3.0. The partial score was further reduced by penalties accounting for the proportion of time during which the limit was exceeded, the mean magnitude of exceedances, and the number of distinct exceedance events.

A more restrictive algorithm was applied to voltage harmonics. For each harmonic–phase pair, the 95th percentile was calculated and normalized with respect to the corresponding limit value. In this case, the full score was assigned only for values not exceeding 30% of the limit, whereas above the limit value the score decreased exponentially using a decay coefficient of 6.0. The overall harmonic score accounted for both the mean score across all analyzed harmonic–phase pairs and the lowest score obtained for an individual pair, with both components contributing equally:

$$S_H = 0.5\overline{S}_H + 0.5\overline{S}_{H\min} \tag{3}$$

The score determined in this manner was further reduced by a penalty depending on the number of harmonic–phase pairs exceeding the applicable limit. This approach increased the influence of particularly high harmonic levels on the final power quality score.

Separately from the partial scores, an additional critical penalty was applied to account for the duration and amplitude of particularly significant exceedances. The duration

threshold was set at 5% of the total measurement period, while the amplitude threshold was set at 150% of the corresponding limit value. The critical penalty was capped at 50 points. The introduction of a "critical penalty" was intended to increase the sensitivity of the index to particularly significant exceedances of permissible power quality parameter values exceedances whose impact might otherwise be diminished during the aggregation of partial scores. The duration threshold of 5% of the measurement period was selected with reference to the statistical approach commonly used in power quality assessment, while the amplitude threshold of 150% of the permissible value was intended to identify particularly severe exceedances. The maximum penalty of 50 points was selected as part of the proposed diagnostic procedure to ensure that such exceedances substantially influence the final assessment. However, this mechanism can strongly influence the final index value; therefore, both the index value before applying the penalty and the value after its application should be considered when interpreting the results. The selected threshold values and the maximum penalty are not directly derived from regulatory standards and require further validation. The final value of the index was calculated as follows:

$$W = \max(0, W_r - P_{crit}) \quad (4)$$

where P_{crit} denotes the critical penalty. The index was calculated separately for each set of applicable requirements and was treated as an auxiliary comparative measure. The formal assessment of compliance for each plant was based on the individual power quality parameters rather than on the value of the synthetic index.

2.3. Modeling in DIgSILENT PowerFactory

Computer modeling was performed using DIgSILENT PowerFactory 2024 [37]. The models were developed using the available technical documentation, connection conditions, electrical diagrams, and equipment ratings. Components relevant to the phenomena under investigation were represented, including the external grid, medium-voltage cable connections, transformers, busbars, and PV plant converters. The use of PowerFactory for power flow and harmonic analyses is consistent with established practice in modeling power systems with distributed generation [21,25].

Simulated harmonic spectra were obtained for all 20 analyzed plants and subsequently used in the multidimensional data analysis. A detailed model was developed, and an analysis of system behavior and a comparison of the simulation results with field measurements were performed for Plant 7, which served as the reference plant. This distinction is important: the PCA and Isolation Forest analyses used simulation data for the entire set of 20 plants, whereas the detailed comparison between the modeling results and field measurements was performed for one selected plant. It should be emphasized that a detailed comparison of simulation results with field measurement data was conducted exclusively for Plant 7, which was selected as a reference installation. For the remaining power plants, the simulation results were used for a multidimensional analysis of harmonic characteristics, without independently verifying the models quantitatively. Consequently, the obtained results do not provide a basis for generalizing the accuracy with which the models reproduce actual harmonic levels across all the installations analyzed. The modeling was used primarily to support the analysis of spectral characteristics and harmonic propagation, rather than as a standalone method for predicting actual harmonic levels at the points of connection.

The model of Plant 7 comprised 20 inverters, each with a maximum apparent power of 352 kVA. To reduce computational complexity, the inverters were aggregated into groups of 10 units while preserving the electrical parameters relevant to the phenomena under investigation [24,38]. The analysis included power flow, the effects of changes in active and reactive power on voltage, and the harmonic spectrum at selected points in the system.

The model of Plant 7 was examined by comparing the simulation results with field measurements. For the harmonic analysis, the difference ΔH_h between the maximum value recorded during PV plant operation and the maximum value obtained during the background grid measurement was used as a comparative quantity. This comparison was intended to assess whether the model reproduced the dominant components of the harmonic spectrum and the overall spectral pattern observed at the plant; it was not treated as a quantitative attribution of harmonic emissions to the investigated source.

2.4. Data Analysis Using PCA and Isolation Forest

Principal Component Analysis (PCA) and the Isolation Forest algorithm were applied to perform a multidimensional comparison of the investigated plants. Both methods are unsupervised learning techniques and were used as supporting tools for power quality data [29–31]. The methods were implemented in Python using the scikit-learn library [39]. The choice of PCA and Isolation Forest was driven by the exploratory nature of the analysis and the absence of a labeled reference dataset that would allow for the definitive classification of installations as either functioning correctly or incorrectly. PCA was employed to reduce dimensionality and visualize similarities among harmonic characteristics, while Isolation Forest was used to identify outliers in a multidimensional feature space. Other outlier detection methods, such as Local Outlier Factor, One-Class SVM, or autoencoders, are also documented in the literature. The selected methods offer relatively low computational complexity and enable preliminary analysis without the need for labeled examples of faulty system operation. It should be noted, however, that the objective of this study was not to compare the performance of different outlier detection algorithms, but rather to utilize unsupervised learning methods as tools to support power quality diagnostics.

The maximum level of voltage harmonics from the 2nd through the 50th orders were used as input features. Thus, a 49-feature vector was constructed for each plant. Prior to applying the algorithms, the data were standardized to reduce the influence of differences in scale between variables. Four datasets were analyzed: (i) differences between the maximum harmonic values measured during PV plant operation and those obtained from background grid measurements, (ii) simulated harmonic spectra, (iii) background grid harmonic spectra, and (iv) a combined dataset comprising the measurement differences and simulation results. PCA was used for dimensionality reduction and for visualizing similarities and differences among the plants. The analysis focused primarily on the first three principal components and the proportion of total variance explained by these components. Isolation Forest was applied independently in the original standardized feature space rather than to the PCA-transformed data. The contamination parameter, representing the assumed proportion of outlying observations, was set to 0.20. Using maximum harmonic values as input features allows the most adverse conditions recorded during measurements to be taken into account; however, it also increases the sensitivity of the analysis to individual extreme values and differences in the durations of measurement campaigns. An additional limitation is the relatively small number of installations analyzed (20) compared to the number of features used to describe their harmonic characteristics (49). The selected contamination parameter of 0.20 specifies an assumed proportion of anomalous observations, rather than their actual frequency of occurrence within the studied population. Consequently, the results obtained using PCA and Isolation Forest were used for the preliminary identification of installations that stand out from the rest of the dataset, rather than for a definitive classification of their power quality characteristics.

The PCA and Isolation Forest results were not interpreted as an automated assessment of compliance with EN 50160 or the applicable IRiESD requirements, nor as evidence of the physical origin of a disturbance. Instead, these methods were used to identify

plants exhibiting unusual multidimensional harmonic characteristics and to indicate cases requiring further engineering analysis.

2.5. Integrated Diagnostic Procedure

The proposed methodology can serve as a basis for a multi-stage diagnostic procedure designed to assist distribution system operators in assessing power quality and interpreting harmonic disturbances at the connection points of photovoltaic power plants. The procedure comprises the following stages:

Initial compliance assessment.

Based on power quality measurements performed at the connection point, individual parameters are evaluated against the requirements of EN 50160 and the relevant IRiESD. Harmonic levels exceeding the permissible limits are identified; however, the mere fact that a limit is exceeded does not, in itself, constitute grounds for attributing responsibility to the installation under analysis.

Assessment of the background grid.

For installations where limit exceedances are detected, measurement data obtained while the PV inverters are disconnected are analyzed. This helps determine whether elevated levels of specific harmonics are also present when the investigated source is disconnected.

Comparison of measurement results.

Harmonic characteristics recorded during the operation of the installation are compared with those recorded after its disconnection, with a focus on identifying similarities and differences. This comparison must account for the duration of the measurements and the operating conditions of the grid. In the absence of sufficiently comparable data, it is not possible to quantitatively determine the contribution of the PV installation to the observed disturbances.

In-depth diagnostic analysis.

In cases requiring further verification, a synthetic power quality index incorporating partial scores is used as an auxiliary comparative measure, together with DIgSILENT PowerFactory modeling, where justified. Methods such as PCA and Isolation Forest can assist in the preliminary identification of installations with atypical harmonic characteristics. The results obtained serve as supplementary information and do not, on their own, constitute a sufficient basis for determining the source of disturbances.

Additional verification in ambiguous cases.

If the available results do not allow the origin of the disturbances to be established, it may be necessary to conduct further measurements under comparable grid operating conditions. This should include controlled changes to the installation's operating state and, where feasible, the simultaneous recording of parameters at additional points within the grid. Further analysis should also take into account load conditions and the grid configuration.

Final diagnostic interpretation.

The results obtained at each stage are combined to distinguish between the mere occurrence of an exceedance of permissible limits and the identification of its underlying causes. If elevated harmonic levels are also detected when the photovoltaic installation is disconnected, the compliance assessment result alone should not be considered sufficient evidence to hold the operator of that installation responsible. Any attribution of responsibility for the disturbances requires further technical justification, taking into account applicable requirements and grid connection conditions.

The procedure presented here is intended to structure the diagnostic process and reduce the risk of misinterpreting exceedances of permissible limits. However, it does not replace the detailed investigations necessary to quantitatively determine the contribution of individual sources to the observed disturbance.

3. Results

This section presents the results obtained for the 20 analyzed PV plants. The results are presented according to the successive stages of the research procedure: assessment of power quality parameters based on field measurements, analysis of the background grid conditions, comparison of field measurements with simulation results obtained using DIgSILENT PowerFactory, and multidimensional analysis of the harmonic spectra using PCA and the Isolation Forest algorithm. The interpretation of the mechanisms underlying the observed differences and the limitations of the adopted methodology are discussed in the Discussion section.

3.1. Power Quality Assessment Based on Field Measurements

The seven-day measurements performed at the points of connection showed that the main voltage parameters presented a high degree of compliance for most of the analyzed plants. The greatest differences among the plants were observed in the flicker severity indices and, in particular, in individual voltage harmonic levels. The primary compliance assessment was performed against the IRiESD requirements, which are more restrictive than EN 50160 with respect to voltage harmonics, particularly because they specify a fixed limit of 0.5% for generating units, whereas EN 50160 specifies separate limit values for individual harmonic orders. When individual voltage harmonics were excluded from the assessment, 13 of the 20 plants complied with the IRiESD requirements, whereas seven plants (1, 2, 13, and 17–20) failed to meet at least one requirement for the remaining parameters. Detailed results of this assessment are presented in Table 2.

Table 2. Percentage of measurement time satisfying selected IRiESD requirements in the weekly measurements (excluding individual harmonic assessment).

Plant	U [%]	f [%]	Pst [%]	Plt [%]	THDU [%]	Unbalance [%]	IRiESD
1	99.90	100.00	95.54	89.32	100.00	100.00	No
2	99.90	100.00	98.23	92.86	100.00	100.00	No
3	100.00	100.00	99.81	96.43	100.00	100.00	Yes
4	100.00	100.00	99.90	98.81	100.00	100.00	Yes
5	100.00	100.00	100.00	100.00	100.00	100.00	Yes
6	100.00	100.00	99.90	98.81	100.00	100.00	Yes
7	100.00	100.00	99.90	98.81	100.00	100.00	Yes
8	100.00	100.00	99.81	96.43	100.00	100.00	Yes
9	100.00	100.00	100.00	100.00	100.00	100.00	Yes
10	100.00	100.00	100.00	100.00	100.00	100.00	Yes
11	100.00	100.00	99.96	100.00	100.00	100.00	Yes
12	100.00	100.00	100.00	100.00	100.00	100.00	Yes
13	25.89	100.00	97.36	91.67	100.00	100.00	No
14	100.00	100.00	99.94	97.53	100.00	100.00	Yes
15	100.00	100.00	99.90	98.81	100.00	100.00	Yes
16	100.00	100.00	100.00	100.00	100.00	100.00	Yes
17	99.40	100.00	96.14	88.10	100.00	100.00	No
18	85.12	100.00	99.83	98.81	100.00	100.00	No
19	68.16	99.83	99.83	98.44	100.00	100.00	No
20	78.89	100.00	100.00	100.00	100.00	100.00	No

Significant differences between compliance assessment results obtained using EN 50160 and the IRiESD requirements arise primarily from the distinct limit values established for individual voltage harmonics. EN 50160 specifies permissible levels for individual harmonics according to their harmonic order, whereas the IRiESD requirements impose a more stringent limit of 0.5%. Consequently, while 19 of the 20 analyzed installations met the EN 50160 requirements for individual voltage harmonics, all 20 installations exceeded at least one applicable IRiESD limit for individual voltage harmonics. For example, at Plant 7, the IRiESD limits were exceeded for the 5th, 7th, 11th, and 13th voltage harmonics. These findings demonstrate that discrepancies in compliance assessments depend not only on the recorded harmonic levels but also on the limit values and evaluation methodologies adopted in the respective documents.

The analysis of individual voltage harmonics yielded a more restrictive compliance assessment. During the seven-day measurement campaigns, exceedances of the IRiESD limits were observed for individual harmonic orders. For Plant 7, selected as the reference installation, exceedances were identified for the 5th, 7th, 11th, and 13th harmonics. The maximum values of individual voltage harmonics of orders 2 through 50, recorded during the seven-day power quality measurement campaign for this plant, are presented in Figure 1. Particular attention should be paid to the 13th harmonic, whose level increased during periods of higher active power generation. However, the observed co-variation between the harmonic level and power generation alone does not provide sufficient evidence to attribute the disturbance to the investigated PV plant. Therefore, an additional background grid measurement was performed, the results of which are presented in Section 3.2.

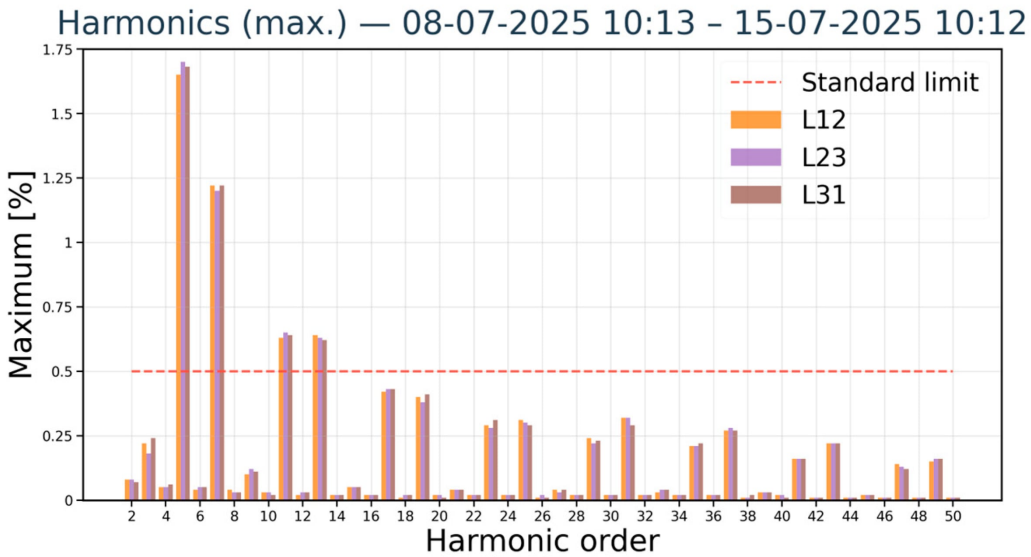


Figure 1. Maximum values of individual voltage harmonics recorded during the power quality measurements for Plant 7.

The custom synthetic power quality index demonstrated the dominant influence of individual harmonics on the final score. For Plant 7, the index calculated using the IRiESD requirements was 27.9/100, compared with 77.9 before the application of the critical penalty. The 50-point penalty resulted from the exceedance associated with the 5th harmonic. At the same time, voltage magnitude, frequency, and voltage unbalance received very high partial scores. Across the entire set of 20 plants, only two plants achieved a final score above 50 out of 100 against the IRiESD requirements, highlighting the strong influence of individual exceedances on the proposed index.

3.2. Background Grid Measurements and Harmonic Distortion Assessment

To assess whether the harmonic level exceedances recorded during normal operation of the PV installations could be directly associated with their impact on the grid, the results of the seven-day power quality measurements were compared with those obtained from background grid measurements performed with the PV converters disconnected. The conventional assessment of compliance with the IRiESD requirements for voltage harmonics showed that, during normal plant operation, none of the 20 analyzed plants complied with the requirements for individual voltage harmonics. However, the same result was obtained for the background grid measurements: all 20 measurement points also exhibited non-compliance with the IRiESD requirements for voltage harmonics. Moreover, for some plants, particularly Plants 3, 5, and 7, the proportion of samples exceeding the applicable limits for selected harmonics was higher during the background grid measurement than during the seven-day measurement campaign conducted with the PV plant in operation. These results indicate that the mere observation of a harmonic limit exceedance at the point of connection during plant operation is insufficient to attribute the disturbance to the investigated PV plant. At the same time, the different observation periods should be taken into account when interpreting this comparison, since the power quality measurements were conducted over seven days, whereas the background grid measurements lasted at least 24 h. For Plant 7, selected as the reference installation, the maximum values of the individual voltage harmonics recorded during the background grid measurement are presented in Figure 2. In contrast to the results presented in Section 3.1 for normal PV plant operation, the background grid measurement was performed under conditions in which the PV converters were disconnected from the grid.

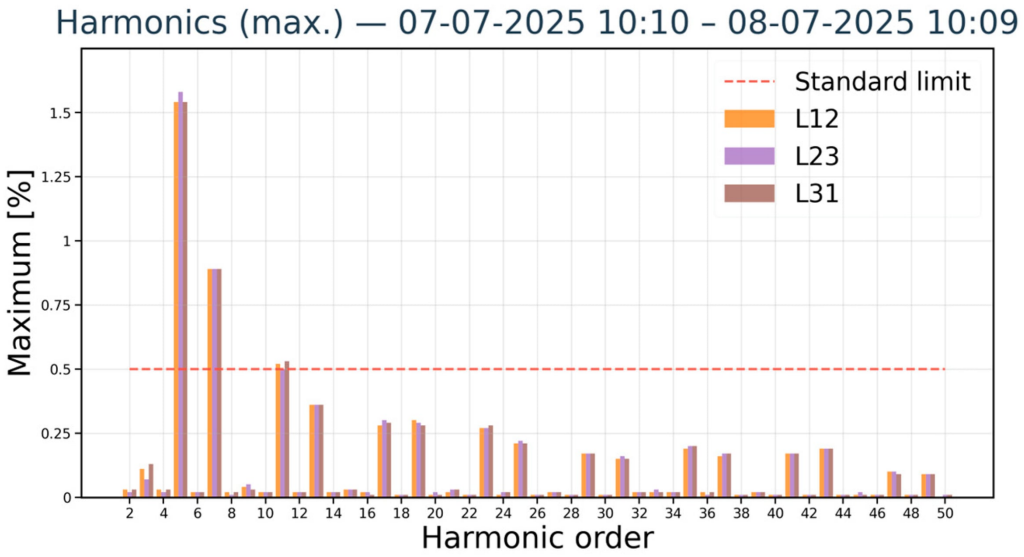


Figure 2. Maximum values of individual voltage harmonics recorded during the background-grid measurement for Plant 7.

The results of the background grid measurements indicated that elevated levels of certain harmonics were present even when the photovoltaic installation was disconnected. This observation suggests that exceedances of permissible limits at the point of connection cannot be automatically attributed to the power plant under analysis. At the same time, it should be noted that the measurements performed during normal operation of the installation and those performed after its disconnection covered different observation periods, which prevents the assumption that the grid operating conditions were equivalent. Consequently, the obtained results do not allow the contribution of the photovoltaic instal-

lation to the observed harmonic levels to be quantified, nor do they exclude its possible influence on these levels during normal operation. They do, however, confirm that harmonic disturbances can occur at the point of connection independently of the operation of the investigated source, a factor that must be taken into account when interpreting the results of power quality assessments.

For Plant 7, the synthetic power quality index calculated using the IRiESD requirements was 35.8/100 for the background-grid measurement, compared with 27.9/100 for the seven-day measurement campaign conducted during normal plant operation. In both cases, the final index value was reduced by 50 points due to the critical penalty associated with an exceedance of the applicable limit for the 5th harmonic. At the same time, the partial score for harmonics increased from 38.39 during normal operation to 41.62 for the background grid measurement, while the index value before application of the critical penalty increased from 77.9 to 85.8, respectively.

However, the difference in the duration of the two measurement campaigns should be taken into account. Power quality measurements during normal plant operation were conducted over seven days, whereas the background grid measurements lasted at least 24 h. Consequently, a direct comparison of the maximum values obtained over the two periods should be treated as a comparative indicator rather than as a basis for quantitatively determining the contribution of the PV installation to the levels of individual harmonics. Nevertheless, the presence of elevated harmonic levels during the background grid measurement provides important evidence that conditions in the supply grid contribute to shaping the harmonic spectrum observed at the point of connection.

3.3. Simulation Results and Measurement-Based Assessment of the PowerFactory Model

To complement the field measurement results, a simulation analysis was performed using PV plant models developed in DIgSILENT PowerFactory. Harmonic spectrum simulation results were obtained for all 20 analyzed plants and subsequently used in the PCA and Isolation Forest analyses. A detailed comparison of the simulation results with the field measurements was performed for Plant 7, which was selected as the reference plant. The harmonic spectra generated by the converters were defined based on models provided by the equipment manufacturers, whereas the short-circuit power values at the points of common coupling (PCCs) were determined from the connection conditions of the individual plants. The model enabled analysis of the distribution and propagation of individual voltage harmonics within the investigated system and at the point of common coupling.

The maximum values of the individual voltage harmonics obtained from the simulations at the PCC are presented in Figure 3. The simulated spectrum shows pronounced components at selected odd harmonic orders, with the 13th harmonic being particularly prominent. Elevated values are also observed for the 11th, 15th, and 17th harmonics. The distribution of harmonic components around the 13th harmonic may be related to the resonance characteristics of the investigated system; however, confirmation of this phenomenon would require additional impedance analysis. At the same time, none of the harmonics exceeded the applicable limits in the simulation results, which may be partly attributed to the idealized supply-grid conditions assumed in the model.

To provide a more detailed assessment of harmonic propagation, the harmonic levels at selected points in the model were also analyzed. Figure 4 presents the harmonic spectra on the low- and medium-voltage sides of the transformer and at the PCC. This comparison allows changes to be examined changes in the levels of individual harmonic components across successive parts of the modeled system and to identify harmonics components that are particularly significant in the analyzed system.

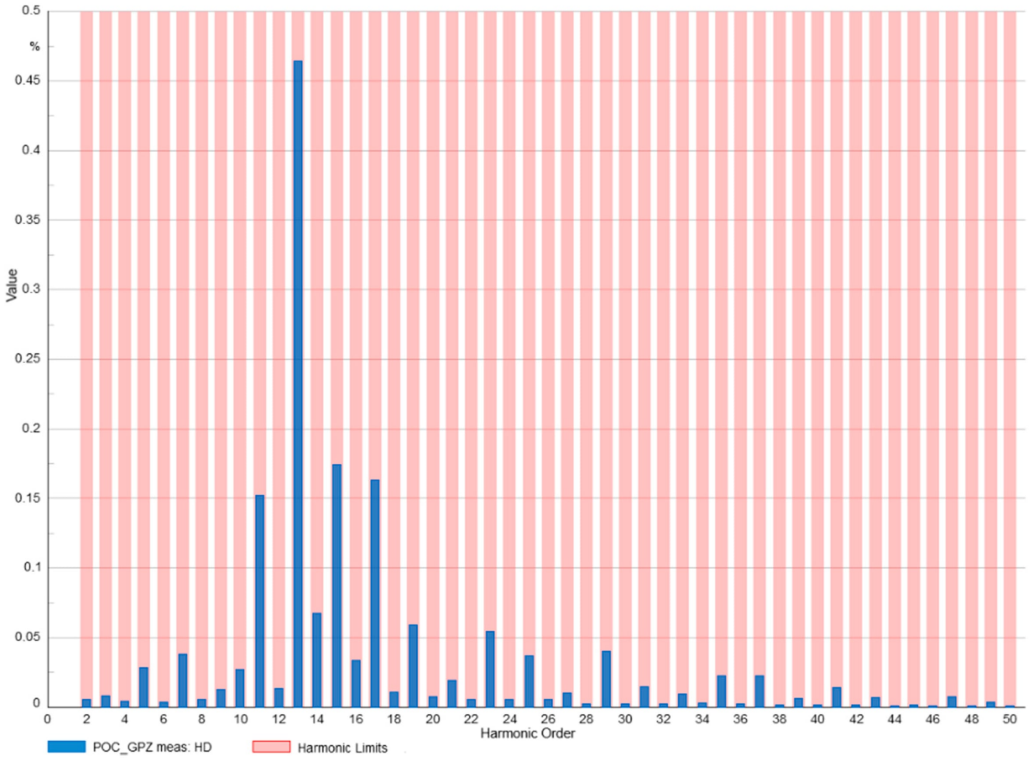


Figure 3. Maximum values of individual voltage harmonics obtained from the PowerFactory simulation at the PCC of Plant 7.

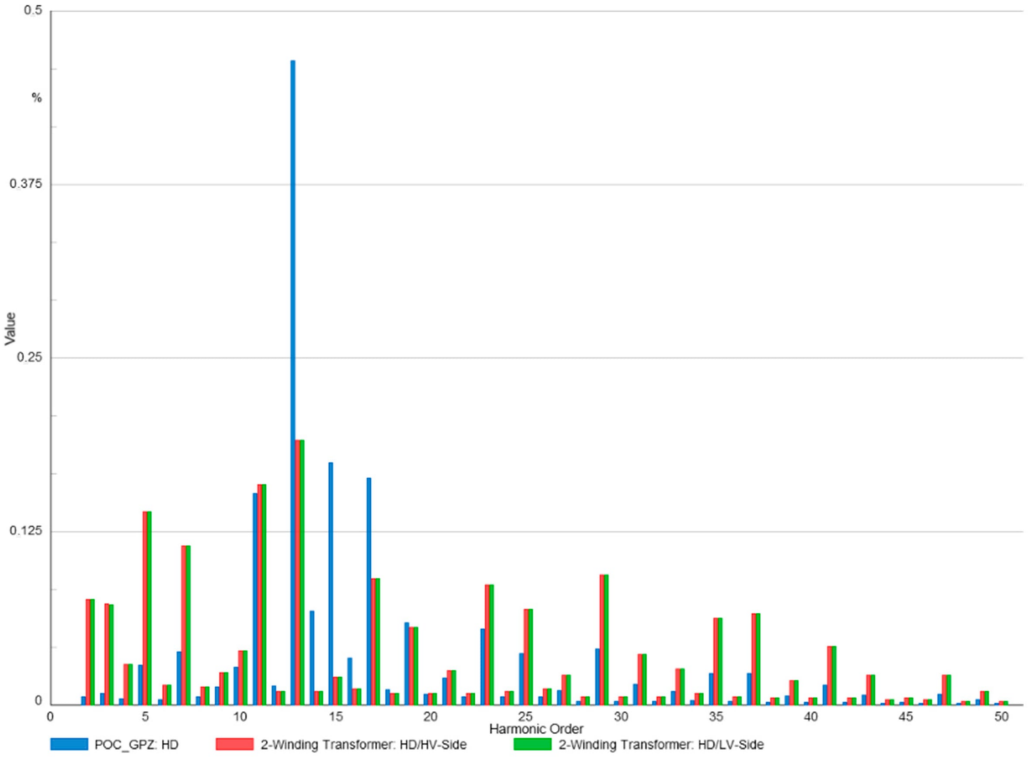


Figure 4. Voltage harmonic spectra obtained at selected points of the PowerFactory model for Plant 7.

In the analyzed model, the power grid is represented by an ideal voltage source; this means that background harmonic distortion present at the point of connection when the photovoltaic power plant is disconnected is not taken into account. This assumption constitutes a significant model simplification, especially in light of the background grid mea-

surements, which revealed elevated levels of certain harmonics even when the installation was disconnected. Consequently, discrepancies between measured and simulated values may stem not only from simplifications in the model parameters but also from the omission of background voltage harmonic distortion in the supply grid. Therefore, the simulation results should be interpreted primarily as a qualitative characterization of the dominant harmonics and their propagation within the modeled system, rather than as a quantitative representation of the actual voltage harmonic distortion at the point of connection.

The use of an ideal voltage source was a deliberate modeling assumption, adopted to examine the harmonic characteristics associated with the modeled PV installation without including background harmonic distortion in the external grid. Consequently, the simulations were not intended to reproduce the complete harmonic conditions at the actual point of connection.

3.4. PCA-Based Analysis of Harmonic Distortion Patterns

To identify similarities and differences among the harmonic spectra of the analyzed plants, Principal Component Analysis (PCA) was applied. The analysis was performed separately for four datasets: the spectrum of differences between the maximum harmonic values obtained from the power quality measurements and the background grid measurements, the simulated harmonic spectra, the background grid measurement results, and a combined dataset comprising the measurement differences and simulation results. For each plant, harmonic values of orders 2 through 50 were used, corresponding to 49 input variables. Prior to PCA, the data were standardized.

The proportions of total variance explained by the first three principal components for the individual datasets are presented in Table 3. The highest proportion of total variance explained by the first three principal components was obtained for the background grid data, for which the first three principal components explained a total of 72.2% of the variance. For the simulated harmonic spectra, the corresponding value was 68.9%. Lower proportions of variance explained by the first three principal components were obtained for the differences between the power quality and background grid measurements (54.8%) and for the combined dataset comprising the measurement differences and simulation results (51.4%).

Table 3. Explained variance of the first three principal components for the analyzed datasets.

Dataset	PC1 [%]	PC2 [%]	PC3 [%]	PC1–PC3 [%]
PQ–background difference	28.8	15.8	10.2	54.8
Combined PQ–background difference and simulation	29.1	13.3	9.0	51.4
Simulation	47.7	12.2	9.0	68.9
Background	42.5	19.1	10.6	72.2

The largest proportion of variance explained by the first three principal components was obtained for the background grid data (72.2%) and the simulation results (68.9%). In both cases, the first principal component alone explained more than 40% of the total variance. Analysis of the PCA loadings showed that PC1 in both datasets was primarily associated with higher-order harmonics, particularly those of the 25th order and above, which exhibited the highest loading values, with the exception of selected lower-order harmonics. For the datasets comprising the differences between the power quality and background grid measurements, the variance explained by successive principal components was distributed more evenly.

The distribution of the 20 analyzed plants in the space defined by the leading principal components was then used to assess the similarity of their harmonic profiles. Figure 5

presents the PCA projection for the simulation results. Most plants formed a relatively compact cluster, whereas Plants 13, 18, 19, and 20 showed more pronounced separation from the main group, particularly in the projection defined by PC1 and PC3.

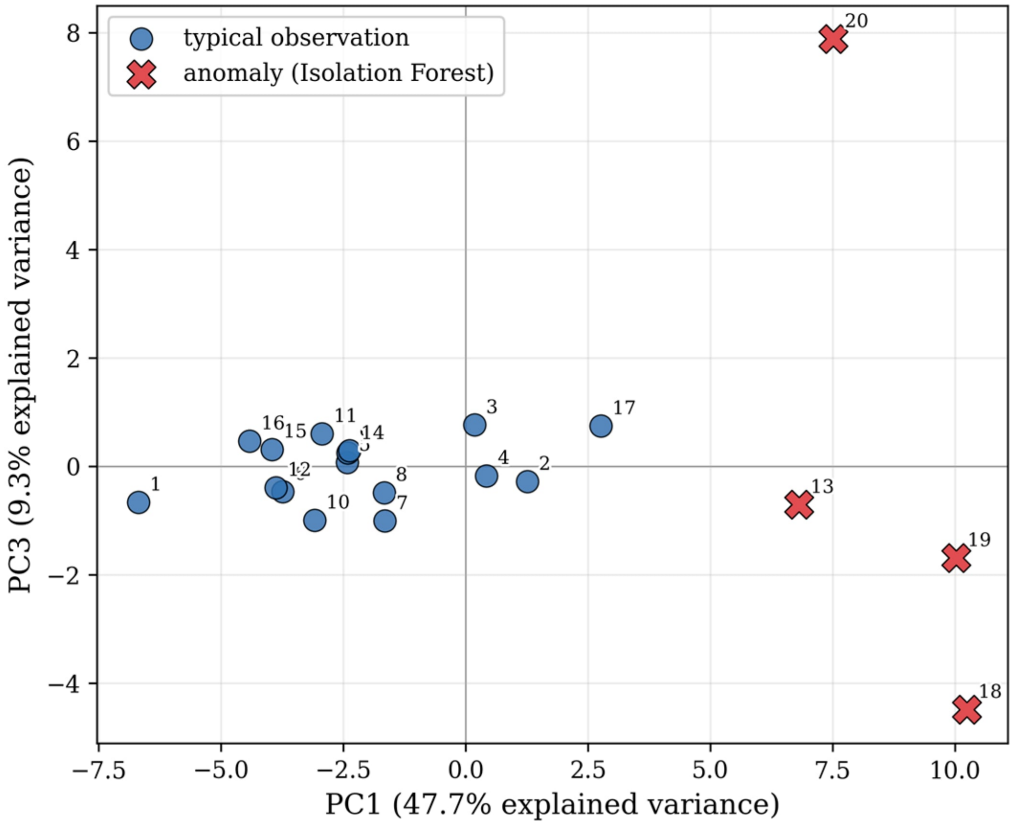


Figure 5. PCA projection of the harmonic spectra obtained from the PowerFactory simulations for the analyzed PV installations.

A different distribution of plants was observed for the background grid measurement data. Figure 6 presents the PCA projection for this dataset. Most plants again formed a main cluster, whereas some plants, particularly Plants 5 and 7, showed greater separation from the main group. This indicates that the harmonic profiles present in the grid with the PV converters disconnected also exhibited substantial variation among the investigated locations.

The PCA revealed differences in the harmonic spectra among the individual plants for both the simulation results and the background grid measurements. At the same time, the limited proportion of variance explained by the first two or three principal components, particularly for the datasets comprising the differences between the power quality and background grid measurements, indicates that a two-dimensional PCA visualization does not fully represent the variability present in the 49-dimensional harmonic feature space. Therefore, the identification of unusual plants was complemented by an independent analysis using the Isolation Forest algorithm, the results of which are presented in Section 3.5.

3.5. Outlier Detection Using Isolation Forest

To complement the PCA analysis, the Isolation Forest algorithm was applied to identify plants with harmonic profiles differing from those of the other installations. The algorithm was applied independently to the four datasets previously analyzed using PCA. The contamination parameter was set to 0.20. This parameter specifies the assumed proportion of outlying observations in the analyzed dataset and, on this basis, affects the determination of the decision threshold used to classify observations. Unlike PCA, Isolation Forest operated

directly in the original standardized 49-feature space corresponding to harmonics from the 2nd to the 50th order. Therefore, the results of the two methods should be interpreted in the context of their different approaches to data analysis rather than regarded as two alternative classifications of the same two-dimensional projections.

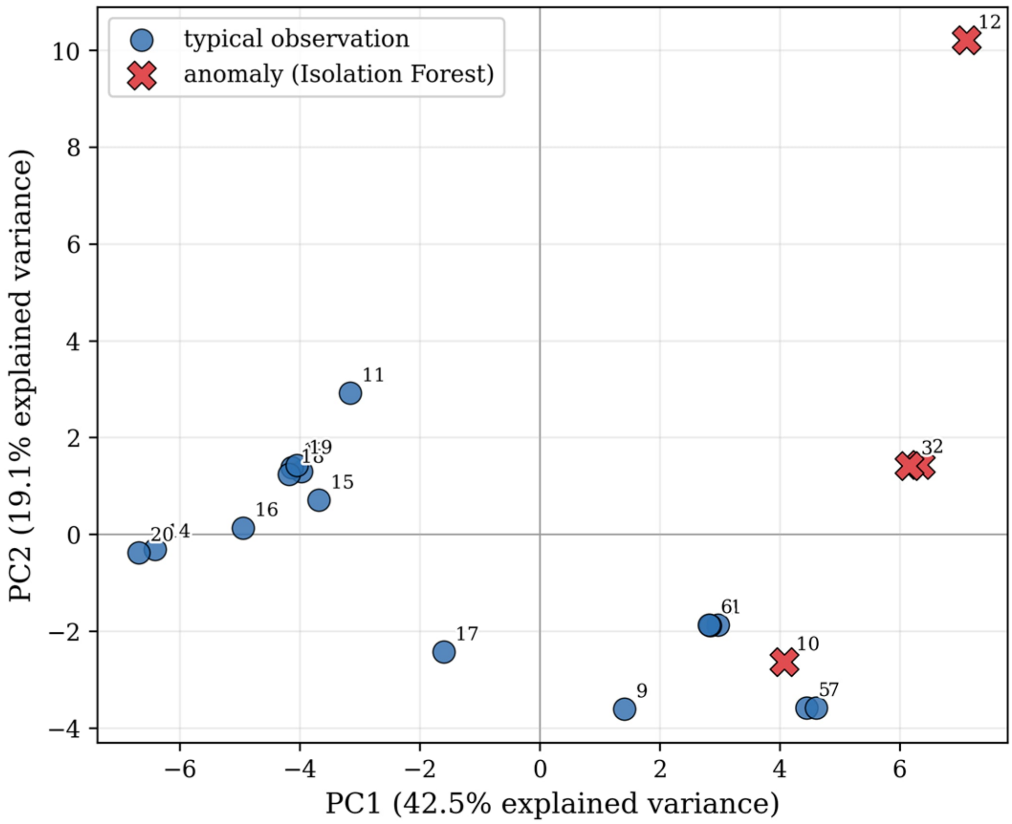


Figure 6. PCA projection of the harmonic spectra obtained from the background grid measurements for the analyzed PV installations.

The plants identified as outliers by Isolation Forest for the individual datasets are summarized in Table 4.

Table 4. Plants identified as anomalous by the Isolation Forest algorithm for the analyzed datasets.

Dataset	Plants Identified by Isolation Forest
PQ–background difference	7, 11, 12, 13, 17
Simulation	13, 18, 19, 20
Background	2, 3, 10, 12
Combined PQ–background difference and simulation	13, 18, 19, 20

The results presented in Table 4 indicate that the identification of unusual plants depended on the type of data analyzed. For the simulation results, Isolation Forest identified Plants 13, 18, 19, and 20 as outliers. The same plants were identified for the combined dataset comprising the simulation results and the differences between the maximum harmonic values obtained from the power quality and background grid measurements. In contrast, the background grid measurements alone yielded a different group of anomalous plants, comprising Plants 2, 3, 10, and 12.

The distribution of the plants in the PC1–PC2 space is presented in Figure 7. Plants 13, 18, 19, and 20, identified as outliers by Isolation Forest, are clearly separated from the main cluster. In addition, Plant 10 also appears somewhat separated from the main cluster

in the PCA projection, although it was not classified as an outlier by Isolation Forest for this dataset.

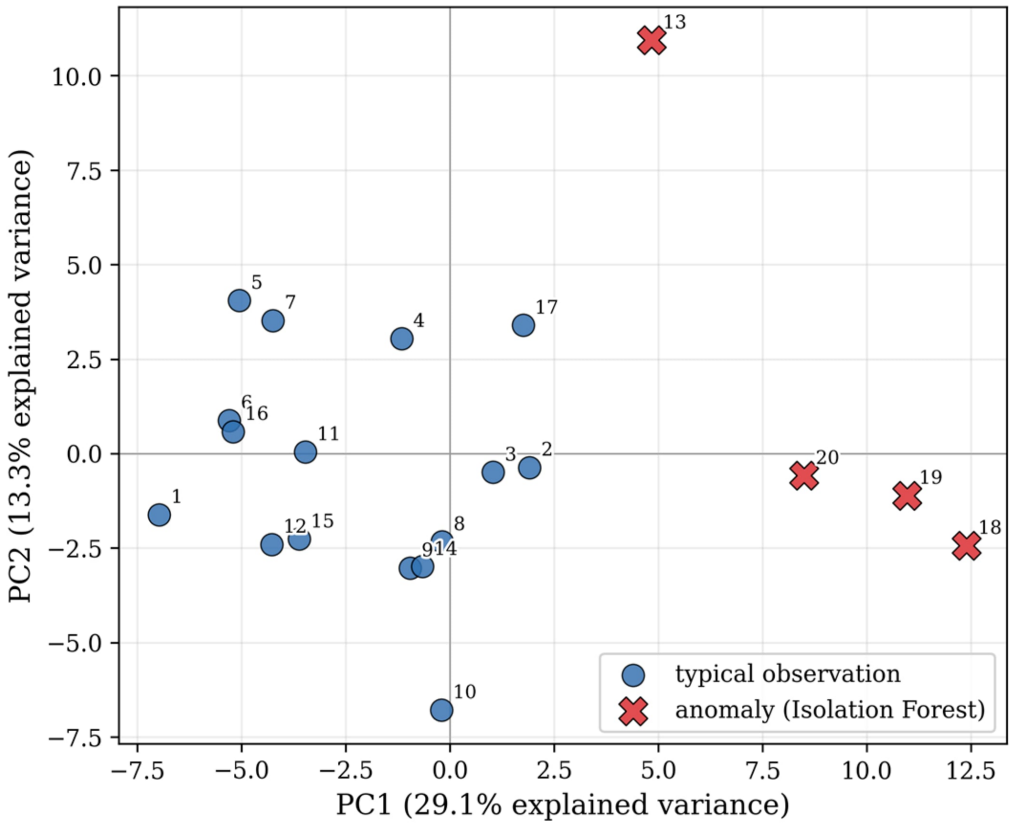


Figure 7. PCA projection of the combined dataset comprising the difference between power quality and background grid measurements together with simulation results (PC1–PC2 plane); plants identified as anomalous by Isolation Forest are highlighted.

Including the third principal component enabled a more detailed assessment of the structure of the analyzed dataset. Figure 8 presents the projection onto the PC1–PC3 plane, with the plants identified as outliers by the Isolation Forest algorithm highlighted additionally. Plants 13, 18, 19, and 20, identified as outliers by Isolation Forest, are also clearly separated from the main cluster in the PCA projection. At the same time, Plants 4 and 7 show some separation from the main cluster in the PCA projection, although they were not classified as outliers by Isolation Forest.

A comparison of the results presented in Table 4 and Figures 7 and 8 indicates that PCA and Isolation Forest provide complementary perspectives on the analyzed dataset. PCA enables the visualization of similarities among harmonic profiles in a reduced-dimensional space, whereas Isolation Forest identifies unusual observations based on the full set of standardized features. Consequently, a plant that appears clearly separated in a two-dimensional PCA projection is not necessarily identified as an outlier by Isolation Forest. This was observed for Plants 4 and 7 in the PC1–PC3 projection of the combined dataset.

3.6. Additional Diagnostic Information Obtained Through an Integrated Power Quality Assessment

To illustrate the additional diagnostic value of the proposed procedure, the information obtained from a conventional compliance assessment was compared with that provided by supplementary stages of analysis. While a conventional assessment can determine whether the values of the analyzed parameters meet the applicable requirements, it does not provide sufficient information to establish the origin of observed disturbances.

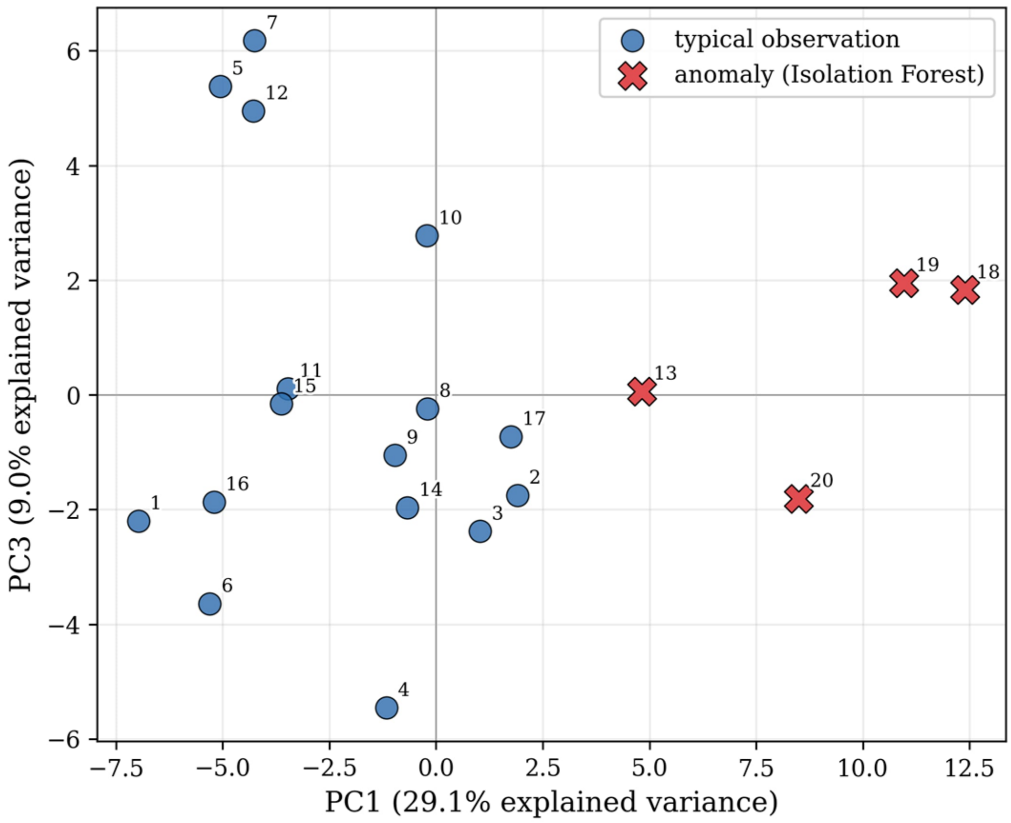


Figure 8. PCA projection of the combined dataset comprising the difference between power quality and background grid measurements together with simulation results (PC1–PC3 plane); plants identified as anomalous by Isolation Forest are highlighted.

At the connection points of all 20 analyzed installations, the limits for individual voltage harmonics specified in the applicable IRiESD requirements were exceeded during normal operation of the photovoltaic power plants. Significantly, these limits were also exceeded at all 20 connection points during background grid measurements, which were conducted with the inverters of the analyzed installations disconnected. These findings broaden the interpretation of conventional compliance assessments, indicating that the occurrence of limit exceedances during power plant operation cannot be automatically attributed to the installation itself.

For Plant 7, selected as the reference installation, a simulation analysis provided further insight, making it possible to identify dominant harmonic components and assess their propagation within the modeled system. Furthermore, the use of a synthetic power quality index helped identify the parameters and penalty mechanism contributing to the lower final index value. The application of Principal Component Analysis and the Isolation Forest algorithm allowed the analysis to be extended to the entire group of installations, identifying those characterized by atypical multidimensional harmonic profiles. The results indicate that the integrated application of these methods provides complementary diagnostic information, including an assessment of compliance with requirements, characterization of background grid conditions, analysis of harmonic propagation, and identification of installations requiring further investigation. However, the results obtained do not provide a basis for quantifying the specific contribution of individual photovoltaic power plants to the levels of harmonic distortion present in the network.

4. Discussion

The results indicate that power quality assessment at the points of connection of PV installations to medium-voltage networks should not be based solely on measurements performed during normal plant operation. Most of the analyzed power quality parameters exhibited a high level of compliance with the applicable requirements, whereas a more restrictive assessment was obtained for individual voltage harmonics. At the same time, parameters such as the total harmonic distortion of voltage (THDU) and voltage unbalance generally remained within the applicable limits. This indicates that relying exclusively on aggregate voltage distortion indices may fail to reveal exceedances associated with individual harmonics. Therefore, power quality assessment should also include an analysis of the individual components of the harmonic spectrum.

An important finding of this study is that background harmonic distortion in the grid should be taken into account. Exceedances of the applicable harmonic limits were also observed during background grid measurements performed with the power electronic converters of the investigated PV installations disconnected from the grid. For some plants, including Plants 3 and 5, the proportion of samples exceeding the applicable limits during the background grid measurements was even higher than that observed during normal plant operation. This indicates that harmonic disturbances recorded at the point of connection cannot be directly attributed to the investigated PV installation without considering the grid conditions when the investigated installation is disconnected.

This finding is particularly well illustrated by the reference Plant 7. During the seven-day power quality measurement campaign, exceedances of the requirements were identified for the 5th, 7th, 11th, and 13th harmonics. However, significant harmonic levels were also observed during the background grid measurement, when the PV converters were disconnected. Comparing the results obtained during normal operation of the installation with those obtained after its disconnection provides additional insight into the presence of harmonic distortion in the grid—information that cannot be obtained solely from measurements performed during normal plant operation. However, because the two measurement campaigns were conducted during different periods and had different durations, this comparison is qualitative in nature; it does not allow for a definitive determination of the specific contribution of the investigated installation to individual harmonic levels. Quantifying this contribution would require measurements conducted under controlled and comparable grid operating conditions, supported by appropriate statistical analysis. Nevertheless, this limitation does not invalidate the observation that permissible limits may be exceeded even when the photovoltaic installation is disconnected.

From a methodological standpoint, the results highlight the potential diagnostic value of the proposed integrated procedure. The additional diagnostic value does not stem from the development of a new measurement technique or a novel harmonic analysis algorithm, but rather from the integration of complementary sources of information within a coherent process of interpreting the results. Conventional compliance assessment allows for the identification of instances where permissible limits are exceeded; background grid measurements help identify disturbances present when the investigated installation is disconnected; simulation modeling supports the interpretation of harmonic propagation; and multivariate data analysis facilitates the identification of installations with atypical characteristics. Combining these sources of information can reduce the risk of drawing unsubstantiated conclusions regarding the extent to which a photovoltaic installation is responsible for disturbances recorded at the point of connection. At the same time, this approach should be viewed as a diagnostic support procedure rather than a method capable of definitively attributing disturbances to a specific source.

When comparing these results with previous studies, it should be noted that the literature presents various approaches to analyzing power quality in networks with distributed generation. For example, the study reported in [17] examined the impact of photovoltaic system operating conditions on harmonic levels at the point of connection, while the study reported in [23] employed synthetic power quality indices and cluster analysis to evaluate the time-varying operating conditions of networks with distributed generation. Furthermore, the research presented in [29] focused on the application of data clustering methods, while the study reported in [30] explored the use of outlier detection in power quality analysis. In contrast to these approaches, the primary objective of this work was to integrate compliance assessment, background grid measurements, harmonic modeling, and multivariate data analysis into a single diagnostic procedure. A key finding from the analysis of 20 photovoltaic power plants is that harmonic levels can exceed permissible limits at the points of connection even when the investigated installations are disconnected. Supplementing conventional compliance assessments with information obtained from the other stages of the analysis thus enables a more comprehensive interpretation of observed disturbances. At the same time, the proposed approach is not intended as an alternative to methods for the quantitative identification of harmonic sources; rather, it serves as a diagnostic tool for identifying cases requiring further investigation.

The proposed synthetic power quality index further highlighted the significance of exceedances associated with individual harmonics. For Plant 7, the final index value was substantially reduced by the penalty associated with the exceedance of the applicable limit for the 5th harmonic, despite the high scores obtained for the remaining parameters. A similar effect was observed for the background grid measurement. This demonstrates the high sensitivity of the proposed index to individual exceedances. At the same time, the assessment improved markedly when the less restrictive limits specified in EN 50160 were applied instead of the IRiESD requirements, which was particularly evident for the index values calculated before application of the critical penalty. This shows that the index value depends not only on the actual power quality parameters but also on the set of limit values adopted as the basis for its calculation. The results of this study confirm the magnitude of this difference: according to EN 50160, 19 of the 20 plants complied with the harmonic requirements, whereas the assessment based on the IRiESD requirements was considerably more restrictive.

The critical penalty algorithm also has a significant influence on the final index value. In the analyzed cases, this penalty could reduce the score by as much as 50 points and could therefore largely determine the final assessment. For this reason, the parameters of the critical penalty algorithm should be further validated using a larger dataset to ensure adequate sensitivity to significant exceedances without allowing them to disproportionately dominate the final index value. On the one hand, the high sensitivity of the index is beneficial for identifying plants requiring detailed analysis, because a significant disturbance is not masked by high scores for the remaining parameters. On the other hand, the index value should not be interpreted independently of the partial scores. The index should therefore be regarded primarily as a tool supporting the identification of parameters responsible for power quality deterioration and the comparison of plants, rather than as a substitute for the analysis of individual parameters.

The measurement-based analysis was complemented by simulation studies performed in DIgSILENT PowerFactory. The model developed in detail for Plant 7 reproduced the main features of the observed harmonic spectrum, particularly the increased contribution of selected odd-order harmonics and the significant contribution of the 13th harmonic. Analysis of the results at different points in the model also revealed changes in the relative levels of individual harmonics as they propagated between the PV installation and the PCC.

This indicates that the harmonic levels recorded at the point of connection depend not only on the emission characteristics of the converters but also on the electrical parameters of the grid and the propagation of the disturbances.

However, quantitative differences were observed between the measured and simulated values. These differences may result, among other factors, from uncertainties in the parameters of the modeled network, including the lengths and parameters of the cable lines, differences between the aggregation of the measurement data and the conditions assumed in the simulations, and limited knowledge of the internal control and filtering algorithms implemented in commercial PV inverters. Another important limitation of the model is the representation of the supply grid as an ideal voltage source, which means that the model does not account for the actual background harmonic distortion identified during the field measurements. Despite these limitations, the simulation results showed qualitative similarity to the field measurement results and enabled the identification of harmonics that were particularly relevant to the analyzed system. Modeling should therefore be regarded as a tool that complements field measurements and enables the analysis of harmonic propagation mechanisms rather than as a direct substitute for measurements. To improve the predictive reliability of the developed models, it would be necessary to validate them against field measurements from a larger number of photovoltaic power plants and to incorporate background voltage harmonic distortion present in the supply grid. These steps would enable a more robust comparison between simulation results and field measurements, as well as an assessment of how background grid conditions affect the accuracy with which individual harmonic levels are reproduced. In their current form, the models complement the diagnostic procedure by providing insights into spectral characteristics and harmonic propagation, although their ability to predict harmonic levels quantitatively under actual grid operating conditions remains limited.

The developed models could also be used to analyze various operating scenarios for photovoltaic power plants. The first scenario concerns the influence of grid parameters, specifically grid impedance and short-circuit capacity at the point of connection, on the levels and propagation of individual harmonics. The second scenario involves evaluating changes in harmonic characteristics under different operating conditions of photovoltaic inverters, corresponding to variations in active and reactive power output. The third scenario addresses the interaction between the harmonics generated by the installation and background voltage harmonic distortion in the supply grid, a matter of particular significance in light of the background grid measurement results. Analyzing such cases could provide further insight into the mechanisms of harmonic generation and propagation, while also enhancing the utility of these models for power quality diagnostics. It should be noted, however, that these scenarios represent potential directions for extending the current research; a quantitative assessment would require appropriate model modifications, as well as additional simulations and experimental verification.

The measured harmonic characteristics presented in the figures are based on the maximum values recorded during the analyzed measurement periods. While this approach identifies the harmonics that reach the highest levels, it limits the ability to assess their variability over time. Specifically, similar maximum values may correspond to different statistical distributions of the recorded harmonic levels. Although measures of dispersion were calculated during the data processing stage, they are not shown in the charts, which should be considered a limitation in the presentation of the results. In future research, it would be appropriate to supplement the harmonic characteristics with percentile ranges or standard deviations, allowing for a more comprehensive assessment of the variability of the observed disturbances.

The application of PCA and Isolation Forest extended the conventional analysis by enabling the comparison of harmonic profiles of all 20 investigated plants. The PCA results showed that the data structure depended on the type of dataset analyzed. The first three principal components explained a larger proportion of the total variance for the background grid measurement and simulation datasets than for the datasets incorporating the differences between the power quality and background grid measurements. This finding indicates a greater concentration of variance in the first three principal components for the background grid and simulation data, whereas the differences between normal plant operation and background grid conditions exhibit a more distributed variance structure.

Isolation Forest enabled the identification of PV plants with harmonic profiles differing from those of the majority of the analyzed plants. The set of plants classified as outliers depended on the type of data analyzed. For the differences between the power quality and background grid measurements, Plants 7, 11, 12, 13, and 17 were identified as outliers. In contrast, for the simulation data and for the combined dataset comprising the simulation results and the differences between the power quality and background grid measurements, the same four plants (Plants 13, 18, 19, and 20) were consistently identified. The identification of the same group of plants in both cases indicates that their distinct harmonic profiles remain apparent when the data representation is extended to include the differences between the power quality and background grid measurements. However, this result should not be regarded as independent confirmation of the unusual characteristics of these plants, because the combined dataset also contains the simulation data.

Nevertheless, the identification of a plant as an outlier does not imply non-compliance with the applicable requirements, nor does it provide a basis for determining the impact of that plant on the grid. Given the limited sample size of 20 plants, PCA and Isolation Forest should be regarded solely as supporting methods for the preliminary identification of plants requiring further investigation, rather than as tools for assessing their impact on power quality in the grid.

The differences between the sets of installations identified as outliers may result not only from the limited number of plants analyzed but also from the nature of the input data and the selected approach to representing harmonic characteristics. Each dataset captures different aspects of the investigated phenomena, including background grid conditions, simulation results, and differences between measurements performed during normal plant operation and after disconnection. Consequently, a given plant may be identified as an outlier in one dataset but not in others. Furthermore, the use of maximum harmonic values makes the results highly sensitive to isolated extreme events, while the small number of observations relative to the number of features limits the ability to assess the stability of the identified outliers. For these reasons, the findings should not be interpreted as definitive evidence that the identified installations are operating improperly. Future research would benefit from using larger datasets and more robust statistical representations of harmonics, such as percentiles or a combination of several descriptive statistical measures, along with a formal stability analysis of the identified outliers.

Comparison of the PCA and Isolation Forest results indicates that the two methods characterize the analyzed dataset from different perspectives. PCA enables dimensionality reduction and visualization of similarities among harmonic profiles, whereas Isolation Forest identifies unusual observations in the full standardized feature space. Consequently, a plant that is clearly separated from the main cluster in a two-dimensional PCA projection is not necessarily identified as an outlier by Isolation Forest. Examples include Plants 4 and 7 in the PC1–PC3 projection of the combined dataset. The differences between the results of the two methods reflect their distinct approaches to representing and analyzing the data structure and should not be interpreted as a direct measure of power quality or the impact

of a given plant on the grid. A significant limitation of the analysis presented here is the lack of a direct comparison of Isolation Forest results with those obtained using other outlier detection methods or simple diagnostic criteria based on threshold values for individual harmonics. While such criteria allow for the clear identification of instances where specific thresholds are exceeded, they do not fully account for the multidimensional relationships between the various components of the harmonic spectrum. Conversely, unsupervised learning methods can identify unusual combinations of feature values, though the physical significance of the identified patterns often requires further interpretation. Consequently, the results obtained using PCA and Isolation Forest should be viewed as a supplement to conventional assessment of individual power quality parameters, rather than as evidence that these methods are superior to other diagnostic approaches. Future research should include a comparative evaluation of alternative outlier detection algorithms and threshold-based criteria applied to the same input data.

An important direction for further development of the proposed methodology would be to establish a sufficiently large reference dataset comprising PV plants with well-characterized and stable harmonic profiles to serve as a benchmark for the analyzed plants. The absence of such a reference dataset was one of the reasons for using unsupervised learning methods in this study. Expanding the available database and establishing such a reference dataset would make it possible to assess the applicability of more advanced classification methods in future studies and increase the reliability of the automated identification of plants requiring detailed analysis. The results obtained provide a basis for proposing a multistage procedure to support power quality assessment at the points of connection of photovoltaic power plants. Within this framework, PCA and Isolation Forest can be used for the preliminary identification of installations with atypical harmonic characteristics, while a synthetic power quality index, considered together with its partial scores, can help identify parameters that require special attention. However, the final interpretation should be based on the analysis of individual power quality parameters, supplemented by background grid measurement data and, where justified, simulation modeling. It should be emphasized that the proposed procedure offers a structured diagnostic approach whose applicability has been illustrated using data obtained under the specific measurement conditions of this study. The results obtained do not, however, provide a basis for confirming its universal effectiveness across various seasonal and operational conditions.

From a practical perspective, the value of the proposed procedure lies in distinguishing between the assessment of compliance with power quality requirements and the identification of the sources of observed disturbances. This approach can help distribution system operators determine whether further investigations are needed, while also reducing the risk of unjustifiably attributing harmonic disturbances to photovoltaic power plants, particularly when elevated harmonic levels are also observed with the investigated installations disconnected. At the same time, it should be emphasized that the proposed procedure remains a diagnostic approach, and its effectiveness in broader applications requires further experimental verification.

However, the limitations of the study should be taken into account when interpreting the results. First, the background grid measurements were shorter than the seven-day power quality measurement campaigns; therefore, the difference between the maximum harmonic values recorded under the two operating conditions should not be regarded as a direct quantitative measure of harmonic emissions from the PV installation. The background harmonic spectrum may be affected by changes in grid loading, the operation of other distributed energy resources, and the current network configuration. Moreover, the detailed PowerFactory model was developed, and its results were compared with field measurements primarily for Plant 7, which limits the extent to which conclusions regarding

the agreement between measured and simulated results can be directly generalized to all the analyzed plants. The study included only 20 PV plants operating under specific conditions in Polish distribution networks, and the PCA and Isolation Forest analyses were based on the maximum values of individual harmonics. The results of these methods should therefore be used solely to support the identification of plants requiring further investigation rather than as a basis for assessing their impact on the grid.

These limitations also indicate directions for future research, including additional measurements during normal plant operation and with the installation disconnected, conducted under grid operating conditions that are as comparable as practicable, validation and parameterization of the critical penalty algorithm, validation of simulation models for a larger number of plants, the use of more statistically robust representations of harmonic spectra, and the establishment of a sufficiently large reference dataset comprising plants operating under different network configurations and employing different converter technologies.

5. Conclusions

The primary achievement of this work is the development and application of an integrated diagnostic procedure for assessing power quality at the points of connection of photovoltaic power plants to medium-voltage networks. Unlike the conventional approach, which focuses primarily on verifying whether parameters comply with specific requirements, the proposed procedure combines compliance assessment with an analysis of background grid conditions, modeling of harmonic propagation, an assessment based on a synthetic power quality index, and a multidimensional analysis of harmonic characteristics. Its main methodological value lies in the integrated interpretation of these analyses, which provides additional insight into observed disturbances and helps identify installations that require detailed diagnostics. Applying this procedure to 20 operating photovoltaic power plants revealed that harmonic levels can exceed permissible limits even when the installations in question are disconnected; this underscores the importance of accounting for background grid conditions when interpreting power quality assessment results.

Accounting for background harmonic distortion in the grid is of particular importance in the proposed approach. Exceedances of the applicable harmonic limits recorded during normal operation of the PV installations were also observed during background grid measurements, with the converters of the investigated installations disconnected. With respect to the IRiESD requirements, exceedances of the applicable harmonic limits were identified at the connection points of all 20 analyzed plants during background grid measurements, and for some plants, the proportion of samples exceeding the applicable limits was higher than during measurements performed with the PV sources in operation. These results demonstrate that the mere observation of a limit exceedance at the PCC during plant operation does not provide sufficient evidence to attribute the disturbance to the investigated source. Background grid measurements therefore constitute an important element supporting the interpretation of power quality measurement results.

The synthetic power quality index complemented the binary compliance assessment by providing a relative assessment of the analyzed plants and identifying the parameters that had the greatest influence on the final score. At the same time, the analyses revealed a very strong influence of the critical penalty algorithm on the final index value. In some cases, the penalty reached the adopted maximum of 50 points and could therefore largely determine the final assessment of a plant. Moreover, the index values before the application of the critical penalty were clearly higher when assessed against EN 50160 than against the more restrictive IRiESD requirements. This indicates the need for further validation and parameterization of the critical penalty mechanism using a larger dataset. The index should therefore be interpreted together with its component scores, primarily as a tool supporting

the identification of parameters responsible for reducing the overall score rather than as a standalone measure of power quality.

The detailed model of Plant 7 developed in PowerFactory reproduced the main features of the harmonic spectrum observed in the measurements and enabled analysis of the propagation of individual harmonics within the PV installation. However, the quantitative differences between the measurement and simulation results may be partly attributed to the adopted model simplifications, particularly the representation of the supply grid as an ideal voltage source and, consequently, the omission of the actual background harmonic distortion. Modeling should therefore be regarded as a complement to field measurements, particularly useful for analyzing the structure of the harmonic spectrum and harmonic propagation.

The application of PCA and Isolation Forest enabled the comparison of the multidimensional harmonic profiles of all 20 analyzed PV plants and the preliminary identification of plants with atypical harmonic characteristics. However, the results of these methods should be interpreted with caution. The analysis was conducted on a relatively small number of plants, and the maximum harmonic values were used as input features, which may increase the sensitivity of the results to individual extreme values. Moreover, the sets of plants identified as unusual varied depending on the dataset analyzed. For the differences between the measurements obtained during plant operation and the background grid measurements, Plants 7, 11, 12, 13, and 17 were identified, whereas the analysis of the background grid data resulted in a different group of plants being identified. These differences indicate that, given the currently available dataset, PCA and Isolation Forest should primarily be used as preliminary screening tools to identify plants requiring further investigation rather than as a basis for assessing the impact of PV installations on the grid.

In this context, the identification of Plants 13, 18, 19, and 20 in both the simulation dataset and the combined dataset comprising the simulation results and the differences between the measurements obtained during plant operation and the background grid measurements should be interpreted with caution, because the two datasets are not independent. The repeated identification of these plants indicates only that their distinct harmonic profiles were also identified when the data representation is extended to include information derived from the comparison between the measurements obtained during plant operation and the background grid measurements. However, this does not constitute independent confirmation of their unusual characteristics or provide a basis for drawing conclusions about their impact on the grid.

The results therefore provide a basis for proposing a practical hierarchy for applying the individual elements of the methodology. PCA and Isolation Forest can be used for the preliminary screening of a larger number of plants and for identifying installations requiring more detailed analysis. For such plants, the synthetic power quality index, considered together with its partial scores, can support the identification of problematic parameters. However, the final interpretation should remain based on the analysis of individual power quality parameters, supplemented by background grid measurements and, where appropriate, simulation modeling.

When interpreting the results, the measurement conditions should also be taken into account. The measurements were conducted during the period from June to September, which is favorable for high levels of photovoltaic generation. However, they were not performed synchronously for all 20 plants, but rather on different days and in different months. This limits the possibility of directly comparing the plants under identical grid operating and generation conditions. In addition, the background grid measurements were shorter than the seven-day power quality measurement campaigns, which should be considered both when comparing maximum harmonic values and when calculating the components of the synthetic index that depend on the duration of exceedance events.

An additional limitation of the study is that the measurements were conducted between June and September, a period characterized by generally favorable conditions for photovoltaic power generation. Although the seven-day measurement period allows the assessment of certain power quality parameters in accordance with the requirements of EN 50160, it does not fully capture seasonal or long-term variations in grid operating conditions. Furthermore, the lack of synchronization between measurements performed at different power plants limits the possibility of directly comparing the results under identical operating conditions. Consequently, the presented results should be regarded as an illustration of the applicability of the proposed approach to the analyzed dataset, rather than as a comprehensive validation of its diagnostic effectiveness. Confirming the suitability of the proposed procedure for broader applications would require further research encompassing different seasons, longer observation periods, and comparable measurement conditions.

Future research should therefore include additional background grid measurements performed under grid operating conditions as similar as practicable to those observed during normal plant operation, measurements performed in different seasons, the validation of detailed simulation models for a larger number of plants, and expansion of the database beyond the 20 installations analyzed in this study. Further validation of the synthetic index parameters, particularly those governing the critical penalty mechanism, is also warranted, as is an assessment of the stability of the PCA and Isolation Forest results using a larger and more representative dataset. Establishing a reference dataset comprising PV plants with well-characterized harmonic profiles could facilitate the development of a more reliable tool for the preliminary screening of PV installations and the identification of plants requiring detailed power quality analysis.

From a broader perspective, an important direction for further development of the proposed methodology is the transition from the analysis of individual measurement campaigns to periodic or continuous power quality monitoring, while taking into account the temporal variability of harmonic characteristics. Further development could include integrating measurement data with updated grid models, as well as developing methods for the automated identification of atypical operating conditions in photovoltaic installations. A particularly promising avenue is the development of a decision-support tool for distribution system operators that would combine the assessment of compliance with regulatory requirements, analysis of background grid conditions, and the identification of cases requiring detailed diagnostics. However, the practical implementation of such a solution would require validation using larger measurement datasets encompassing diverse grid operating conditions and various photovoltaic converter technologies.

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