METHOD FOR DETERMINING THE PERMISSIBLE POWER OF HYBRID INVERTERS FOR OPERATION IN ISOLATED SYSTEMS WITH SIGNIFICANT REACTIVITY

Roman Hrytsak, postgraduate student, Vitalii Tsykh, PhD, associate professor
Ivano-Frankivsk National Technical University of Oil and Gas, Ukraine;
e-mail: roman27gri@gmail.com

https://doi.org/10.23939/istcmtm2025.04.

Abstract. The article presents an improved method for determining the permissible power generated by photovoltaic power plants, taking into account the influence of load and power converter parameters. The proposed approach is based on the construction of diagrams in active and reactive power coordinates (P-Q) with the allocation of areas of permissible and prohibited operating modes according to the criterion of total harmonic distortion of voltage. To verify the method, a series of mathematical simulations were performed in the MATLAB/Simulink environment, where a model of a hybrid PV power plant with an inverter, a storage battery, filter elements and a unit for measuring the main indicators of electricity quality was implemented.

The simulation results showed that the shape of the diagram of permissible operating modes depends on the parameters of the LCL filter and the nature of the load (resistive, capacitive or inductive). It has been established that the existing technical limitations of inverters specified by manufacturers do not always allow compliance with regulatory requirements for the level of harmonic distortion, which confirms the need to improve control algorithms and filtration mechanisms. A comparison of the simulation results with the measurement data showed a high degree of correspondence, confirming the correctness of the proposed method.

The results obtained are of practical importance for the design and operation of microgrids where PV systems are the main source of power. The proposed method can be used as a basis for creating new or updating existing regulatory documents that regulate the requirements for electricity quality in the context of integrating renewable energy sources.

Keywords: Photoelectric system; harmonic distortion; MATLAB/Simulink model; voltage distortion; higher harmonic filtering; mathematical modelling; method; power quality; power limitation; photoelectric power station; harmonics.

1. Introduction

In today's environment of rapid development of renewable energy, microgrids — autonomous or semi-autonomous power supply systems based on PV systems with inverters and storage batteries — are becoming increasingly widespread. Their introduction has enabled residential and industrial consumers to switch partially or completely to their own generation. At the same time, the increase in the number of inverter sources with a capacity of up to 5–7 kW is accompanied by an increase in nonlinear effects and a deterioration in power quality — an increase in voltage fluctuations, harmonic distortions, and overloads in reactive power compensation circuits [1]. The problem is particularly acute in Ukraine, where microgrids are often the only source of power during emergency outages.

At the same time, one of the key aspects of the development of power quality (PQ) systems is the improvement of metrological and information-measuring technologies aimed at increasing the accuracy of PQ parameter control in hybrid systems [2]. In this context, the proposed method and the conducted research correspond to the current trends in the metrology of energy processes, as they combine mathematical modelling, automated measurement tools and analysis of harmonic components, which form the basis for an objective assessment of the energy characteristics of inverter systems.

The power quality is determined not only by the source parameters, but also by the load characteristics. Modern household consumers, among which pulse power supplies, computer equipment, and LED lighting systems account for a significant share, have low power factors (cosφ ≤ 0.5–0.7) and generate significant harmonic components [3–5]. This leads to additional reactive currents and increased active power losses, which negatively affects the operation of inverters in connected microgrids [1].

According to international and national standards, in particular EN 50160:2022 [6], power quality is determined by the maximum deviations in voltage, frequency, harmonic distortion factors and other standardised indicators. However, inverter manufacturers usually provide only information on the permissible values of the power factor (cos φ) in their technical documentation, which does not allow for a comprehensive assessment of their ability to operate with loads that contain a significant reactive component and higher harmonics [7]. International studies confirm that deviations of the power factor from unity significantly reduce the reliability and shorten the service life of inverter converters [8]. Thus, to assess the real operating conditions of inverters in domestic microgrids, it is not enough to analyse only the power factor. It is necessary to apply methods that take into account the total impact of active and reactive power on the system.

In view of this, there is a need for a metrologically sound approach to determining the permissible load level of inverters in P–Q coordinates. Modern electricity metering and control devices already allow simultaneous measurements of active and reactive power, power factor and power quality indicators [7]. This creates a basis for supplementing new methods for testing hybrid inverters in isolated operation modes, which makes it possible to determine critical load conditions and set limits for their reliable operation in conditions of significant reactive power levels.

2. Disadvantages

Existing methods for assessing power quality indicators in microgrids are mainly focused on standardising individual parameters, such as power factor (cos φ), crest factor or total harmonic distortion. However, providing only the acceptable cos φ range or crest factor does not give a complete picture of the actual operating conditions of the inverter, since these indicators only characterise the phase shift or current waveform, but do not take into account the simultaneous interaction of active, reactive power and harmonic components, which determines the stability and reliability of the inverter when connected to loads with a significant reactive energy content.

In addition, there are currently a number of standards describing methods for testing inverters in various aspects, including operation at different power levels, overload conditions, output voltage quality, and electromagnetic compatibility requirements. These documents include IEC 62109-2 [9], EN 50530 [10], IEEE 1547-2018 [11], IEC 61000-3-2:2018 [12], IEC 61000-4-30 [13] and others. However, none of these standards contains a methodology that would allow determining the permissible load of an inverter when operating in isolated AC networks with increased reactivity, where the interaction of active and reactive power significantly affects the level of harmonic distortion and the ability of the inverter to operate without overloads. The absence of such a methodology complicates the prediction of inverter behaviour in real microgrid conditions. As a result, there is a need to develop an approach that would allow determining the permissible load of the inverter in the P–Q coordinate plane, taking into account the critical operating modes characteristic of isolated networks.

3. Objective

The aim of the work is to develop and verify an improved information and measurement method for determining the permissible load of hybrid inverters in isolated AC networks with increased reactivity, which can serve as a basis for further improvement of regulatory provisions describing the procedures for testing and inspecting such systems.

4. Description of the method

Currently, the available standards governing the testing of inverters focus primarily on safety parameters, conversion efficiency and interaction with the electrical grid. At the same time, the issue of assessing the actual operating power of an inverter, including determining it under conditions of acceptable harmonic distortion, is considered mainly indirectly when checking its compliance with requirements for operating stability, thermal limitations, safety requirements, etc. At the same time, the passport data provided by manufacturers can be used to find out the nominal or full output power of the equipment for standard conditions (most often at cos φ = 1) and the permissible power factor range, which sets key power limitations and on the basis of which it is possible to partially understand the parameters of the networks in which the equipment can be used. To do this, using the well-known relationships between active, reactive, total power and power factor, you can construct a Q-P diagram showing the permitted operating modes. For example, Fig. 1 shows a diagram for inverters with a total power of 2 kW, an output voltage of 230 V, a frequency of 50 Hz, and a permissible power factor of ± 0.8.

Thus, since the inverter is limited by nominal voltage and current values, the permissible combinations of active and reactive power (P and Q) form a limited area on the P–Q diagram, which is further narrowed by power factor requirements. These limits, set by the manufacturer, are related to the design features of the inverter and the need to ensure stable operation and reduce losses. In particular, power factor limitations are aimed at reducing reactive energy flows, but they do not guarantee compliance with all power quality requirements, as they do not take into account harmonic distortion, flicker or voltage asymmetry. At the same time, in domestic conditions, power factor control is complicated by the lack of measuring equipment, and modern consumers (LED lamps, power supplies, etc.) often have a low power factor, which further worsens the power quality [3–5].

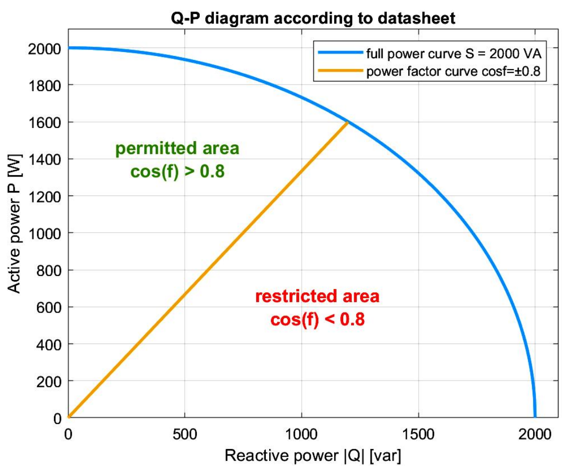


Fig. 1. Diagram of permissible operating modes of a hybrid inverter according to the passport data

One way to solve this problem is to improve existing inverter testing methods by supplementing traditional measurements with advanced power quality analysis. This approach allows for the consideration of acceptable power quality indicators, such as harmonic content, as well as specific inverter limitations and load characteristics.

The improved approach involves, in addition to conducting classic tests for safety, efficiency, resistance to various disturbances and influences, a series of additional measurements of voltage, current, total harmonic distortion (THD), active and reactive power, and cos φ with a gradual change in the reactive component of the load. In this case, it is assumed that the greatest distortions will be observed in the case of parallel connection of R-C loads, when the capacitive reactive power in the network increases sharply, leading to an increase in harmonic components and a deterioration in the stability of the inverter. On the other hand, in the presence of an inductive component, reactive currents are partially compensated, and power quality indicators improve. Thus, the R-C load mode is the most critical for hybrid inverters. Requirements for the permissible level of distortion are regulated by the EN 50160 standard [14].

This approach makes it possible to determine and verify not only the basic characteristics but also the limits of the permissible values of the active and reactive power of the inverter by stepwise changing P and Q until the THD limit values are reached. The results obtained form a P-Q diagram taking into account the peculiarities of the hybrid inverter operation in an autonomous network, and the superimposition of power factor isolines allows identifying loads that lead to exceeding current limits or voltage deviations.

The proposed addition can be summarised as follows:

1. Preliminary measurements in the microgrid for which the use of a hybrid photovoltaic system is envisaged: at this stage, the existing consumers in the isolated system, their active and reactive powers, power factors and load shapes are determined. Measurements are carried out using a network analyser or a wattmeter of at least 0.5 class. This step allows you to establish which combinations of P and Q are characteristic of the existing load and to determine the ranges of test loads.

2. Inverter testing: To accurately determine the limits of the permissible active and reactive load (P–Q) of a hybrid inverter in an isolated microgrid, a comprehensive series of tests is proposed, involving systematic investigation of the inverter's behaviour under various combinations of active and reactive power. These tests include the following steps:

2.1 Setting initial values: The base active resistance (resistive load) corresponding to the nominal power of the inverter with zero or minimum reactive component is set. The THD level is checked and, if it does not exceed the permissible values, the output parameters of the inverter are recorded: U, I, P, Q, cos□ ,φTHD. Otherwise, the measurements are repeated with a lower base resistance.

2.2 Step-by-step addition of the reactive component: The reactive component is gradually connected to the base load via an adjustable capacitor (or parallel-connected R–C elements). At each new step, the capacitance value (or the ratio of R and C in parallel) is changed, which leads to an increase in Q with a constant (or known adjusted) total power S.

2.3 Measurement of characteristics: At each step, the same parameters (U, I, P, Q, cosφ, THD) are recorded. The moment when the permissible THD values exceed 8% is determined [14].

2.4 Recording of boundary conditions: In addition, the boundary limits set at the beginning (e.g., rated current or maximum total power of the inverter) are monitored to ensure that they are not exceeded. In such cases, the values are recorded and the measurements are stopped.

2.5 Construction of the permissible power curve: Based on the collected data, a P-Q diagram is constructed, where the area under the curve shows the permissible power combinations. This diagram takes into account the current and voltage limitations of the inverter.

2.6 Checking ‘negative scenarios’: if necessary, in addition to capacitive loads, inductive modes or asymmetrical loads can be investigated, but in hybrid systems, inductive reactive power is often compensated by capacitors. Non-standard cases can also be tested additionally: intermittent loads, uncharacteristic frequencies, etc.

The detailed algorithm for testing the inverter is shown in Fig. 2.

To apply this method, it is necessary to use measuring equipment that fully complies with the requirements of regulatory documents regarding accuracy class and functional capabilities. In particular, during testing, it is mandatory to use a power quality analyser that must comply with at least standard S according to EN 61000-4-30 [13], ensure the recording of actual voltage and current values, determine active and reactive power, power factor, and harmonic distortion with an accuracy class of at least 0.5. The quality analyser must be able to store data in real time and support the functions of constructing histograms, time series, and P-Q curves for further analysis of the permissible operating modes of the inverter. The shape of the current and voltage curves is monitored using an oscilloscope that must comply with the requirements of IEC 61010-2-030 [15] to ensure safety when taking measurements in experimental electrical circuits. The oscilloscope provides a high sampling frequency (at least 1 MHz) and the ability to measure short-term current peaks, as well as to monitor the occurrence of high-frequency harmonics, which are not always detected by quality analysers. Active and reactive power is determined during testing using a wattmeter/clear wattmeter with an accuracy class of at least 0.5–1, which ensures the measurement of three-phase and single-phase systems, the recording of instantaneous and averaged values of P and Q, and also supports the functions of recording energy flows for constructing P–Q diagrams and analysing the permissible load modes of the inverter. It is advisable to monitor instantaneous current and voltage values in critical test modes using an ammeter and voltmeter with an accuracy class of at least 0.5, which allow for additional monitoring during overloads or sudden load changes, as well as refining the cos φ value at each stage of testing. All measuring instruments must undergo periodic verification in accordance with current standards and international recommendations for metrological control of electrical equipment, which ensures the reliability and reproducibility of test results. Thus, the use of measuring equipment with appropriate characteristics allows for accurate determination of the permissible P–Q load limits, control of the power factor, and identification of critical inverter operating modes, which is especially important for microgrids based on hybrid PV systems.

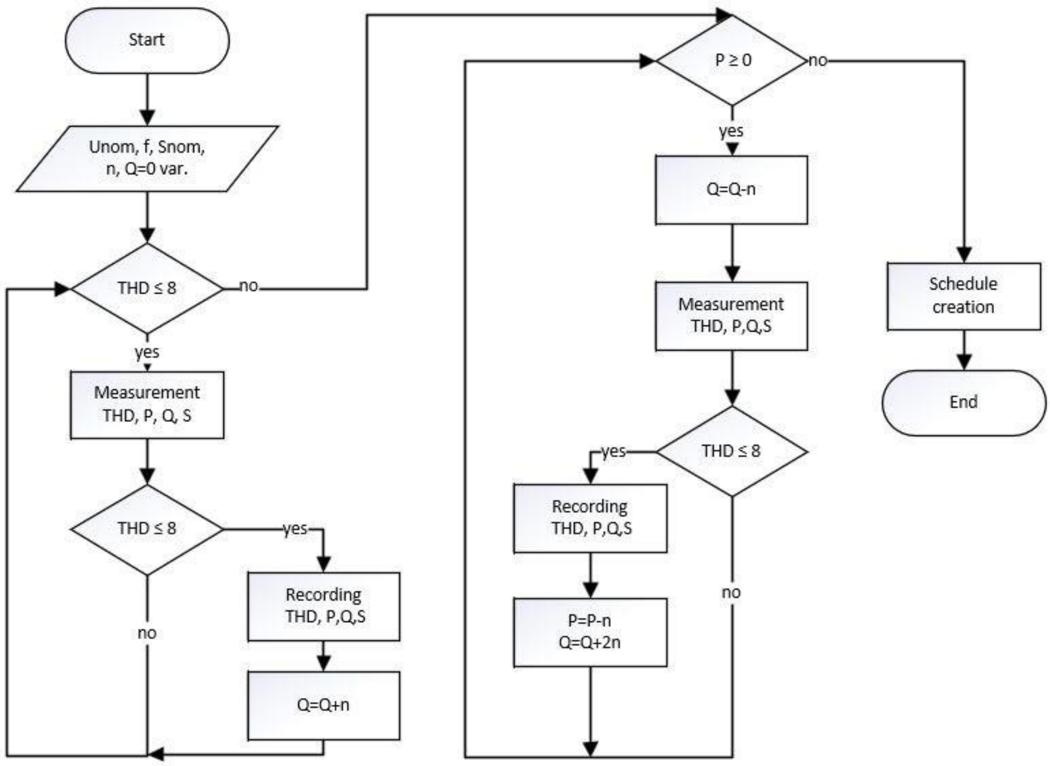


Fig. 2. Block diagram of the algorithm for measuring and constructing the permissible power curve of the inverter

The test itself must be carried out under standard conditions (ambient temperature approx. (20±5)°C (minimal impact of thermal conditions on the inverter), stable frequency of 50 Hz). After each load adjustment, it is necessary to wait for the system to stabilise (~30–60 s) before recording the readings, i.e. until the transient processes are complete. The observation time in each mode is at least 10 minutes for averaging measurements, which meets the requirements of EN 61000-4-30 [13] and allows for the correct determination of harmonic distortion of current and voltage (THD) in the stable operating mode of the inverter. This interval provides a sufficient number of measurements for accurate averaging, reduces the influence of short-term pulsations, and allows obtaining representative THD values for analysing permissible P–Q modes.

The advantages of the proposed approach over traditional methods for determining the permissible power of an inverter in autonomous mode are its comprehensiveness and proximity to real conditions. Instead of simple passport testing for active load (cosφ=1) or conservative calculations based on nominal values, the method uses direct measurements of dynamic modes. This provides:

- determination of the actual load limit, taking into account the need to ensure power quality (high THD is immediately detected);
- the ability to identify ‘unsuitable’ modes – for example, when the inverter fails not due to exceeding the nominal active power, but due to load characteristics;
- adaptability to a specific microgrid by taking into account previous load indicators and network operating conditions.

Thus, the approach allows for a more accurate justification of the limit values of P and Q, and therefore increases the reliability and safety of the autonomous hybrid source without excessive underestimation or overestimation of its permissible load.

The analysis method is based on proven electrical engineering laws and is performed using standard measuring equipment.

5. Modelling

5.1 Description of the mathematical model

To verify the proposed method for determining the permissible P–Q load of a hybrid inverter, mathematical modelling was performed in the MATLAB Simulink environment. The improved mathematical model of a hybrid PV system is distinguished by the fact that it allows modelling the joint operation of hybrid voltage inverters with nonlinear electrical loads of active, reactive-inductive and reactive-capacitive nature. This approach makes it possible to conduct experiments under controlled conditions without the need for physical testing of equipment, which is especially important for low-power domestic microgrids, and allows for the investigation of critical combinations of active and reactive power, which are often accompanied by increased harmonic distortions. The schematic diagram of the electrical circuit and the mathematical model are shown in Fig. 3-4.

A hybrid PV system structure was used to build the model, which includes an array of photovoltaic modules, a DC-DC converter, a battery with a charge controller, an inverter, and an LCL filter at the output. The photovoltaic array simulates electricity generation depending on the level of illumination and temperature, the DC–DC converter maintains a stable voltage on the DC buses, and the inverter together with the LCL filter generates a sinusoidal AC voltage for the load. The storage battery allows you to study the system's operating mode at different charge and discharge levels, simulating the real operating conditions of microgrids. The main parameters of the model are given in Table.

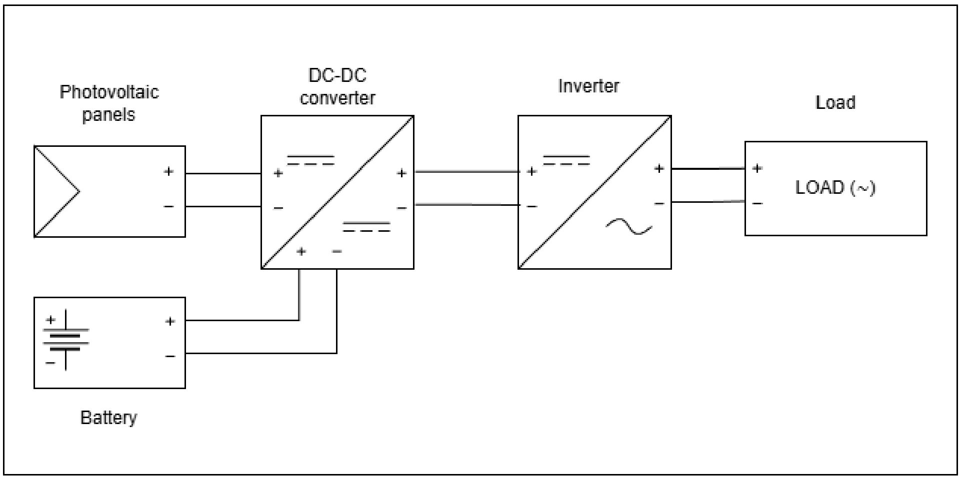


Fig. 3. Schematic diagram of a hybrid wind farm

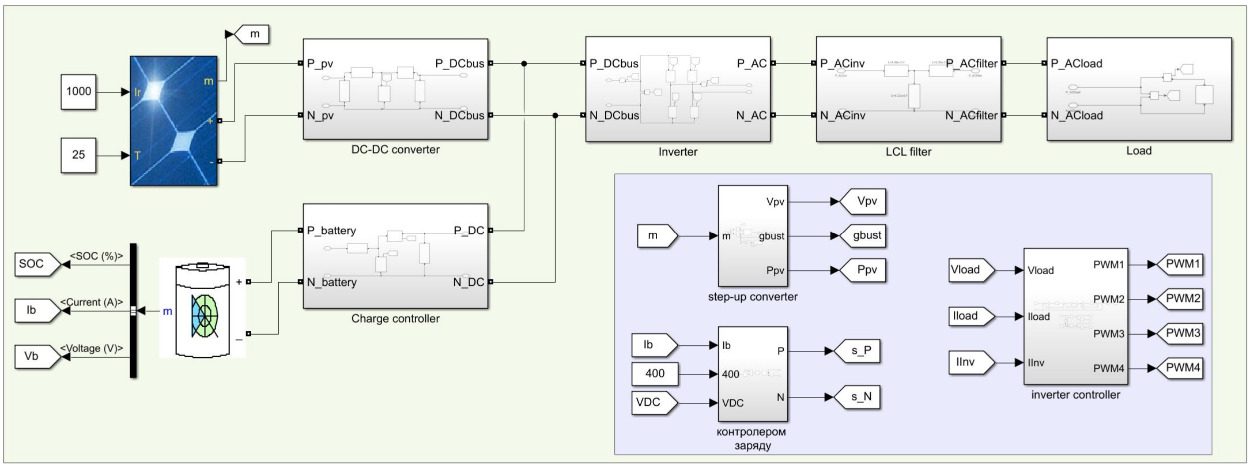


Fig. 4. Mathematical model of a hybrid PV system in MATLAB Simulink

Table. Main parameters of the Simulink model of a hybrid PV system

Parameter	Value
Nominal power of the photovoltaic array (W)	2094
DC bus voltage (V)	400
Battery capacity (Ah)	100
Nominal power of the inverter (VA)	2000
Filter type	LCL filter
Model sampling frequency (Ts)	$10e^{-6}$
Test mode duration	2,5

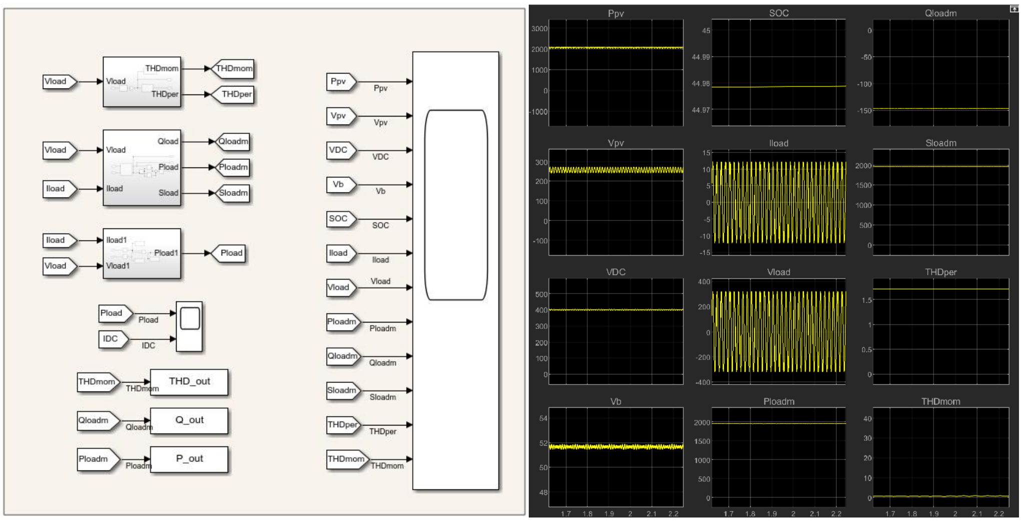


Fig. 5. Measurement block of the constructed model in MATLAB Simulink environment

Load simulation was implemented using Serial and Parallel RLC-branch blocks, which allow you to specify various combinations of resistive, inductive, and capacitive elements in the network. This makes it possible to change the load power factor, analyse the effect of reactance on the stability of the inverter, and construct P–Q diagrams for different system operating modes. The model also supports the collection of data on instantaneous and averaged values of voltage, current, and power, which is necessary to verify the correctness of the proposed method and evaluate the power quality. In turn, the parameters of the R, L, and C elements were determined according to the known relationships between active, reactive, and total power for sinusoidal AC circuits [16], which are given in formulas 1 and 2. For the serial connection of all elements:

$$R = \frac{P \cdot U^2}{S^2};\ L = \frac{Q \cdot U^2}{2\pi f S^2};\ C = \frac{S^2}{2\pi f Q U^2} \qquad (1)$$

where – R is active resistance, Ohm; L is inductance, H; C is capacitance, F; f is frequency, Hz.

For parallel connection of all elements:

$$R = \frac{U^2}{P};\ L = \frac{U^2}{2\pi f Q};\ C = \frac{Q}{2\pi f U^2} \qquad (2)$$

An important component of the constructed model is the measurement unit, which is designed to obtain key characteristics of the inverter and load operation. This unit is shown in Fig. 5.

The measurement unit acts as a centralised monitoring tool, providing simultaneous tracking of key parameters of the constructed model and control of various stages of energy conversion. It allows monitoring the state of the storage battery (in particular, the direction and magnitude of the charge or discharge current), the parameters of the energy flow at the output of the photomodules, the characteristics after the operation of the DC-DC amplifier, and the output values of the inverter. In addition, the unit displays instantaneous power changes, providing an idea of the dynamics of the hybrid station's operation in real time.

This unit implements a comprehensive system for measuring the main electrical quantities necessary for a reliable assessment of the system's operating modes. The multi-channel data collection structure allows information to be obtained in parallel from the load and photovoltaic subsystems, transmitting the measured signals to the digital processing and visualisation units, where oscillograms and other parameter displays are generated.

This block also implements the determination of active, reactive and total power based on voltage and current measurements at the inverter output. Mathematical subsystems calculate instantaneous, root mean square and averaged values, while the accuracy of parameter determination is ensured by sample synchronisation, phase shift compensation and high-frequency interference filtering. Additionally, the calculation of total harmonic distortion (THD) is implemented, which is used to analyse power quality in accordance with international standards and allows assessing the impact of load modes on the stability of the hybrid converter.

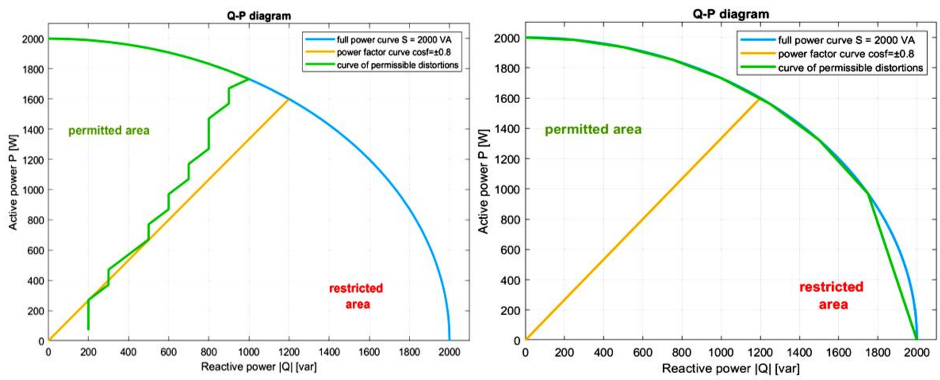
The model is controlled in the MATLAB/Simulink environment by a specialised script that automates the change of load parameters, the calculation of RLC elements according to formulas (4–9), and the collection of simulation results. The program code verifies intermediate results and generates data arrays for further analysis. After the simulation is complete, the script plots a diagram of the relationship between reactive and active power (Q–P) with curves for total power and power factor limits. The results are automatically saved in the form of tables and graphs, which simplifies further processing and use for verification of the proposed method.

5.2 Modelling results

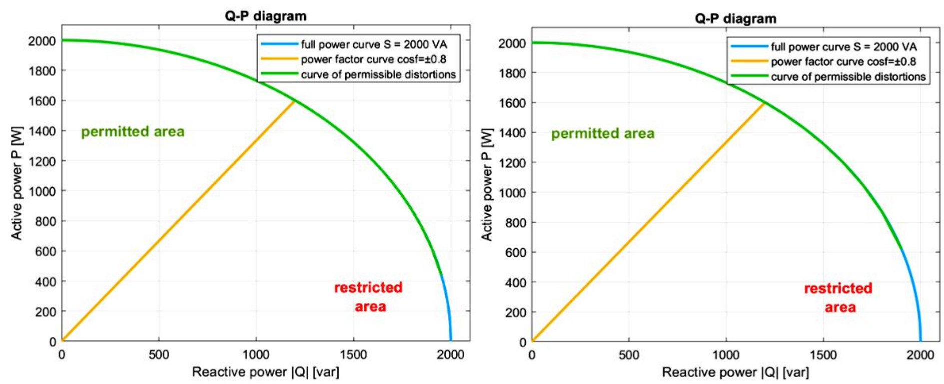
In order to verify the performance of the proposed method, a series of simulations were performed in the MATLAB/Simulink environment. The main focus was not on recreating the complete microgrid model, which had already been considered earlier, but on testing the algorithm for determining the permissible P–Q load of the inverter. To this end, a series of scenarios were implemented with variations in load parameters, power quality determination, and the construction of operating curves. Thus, the simulation served to verify the adequacy of the developed method and allowed its accuracy to be assessed in different modes.

First, the task was set to check which combination of connected RLC loads achieves the greatest distortion of electricity quality. As mentioned above, theoretically, the greatest distortion should be achieved with parallel connection of R-C elements. To confirm this, modelling was carried out with different combinations of active resistance, inductance and capacitance parameters, which made it possible to trace the influence of the load characteristics on the harmonic composition of voltage and current. Standard settings and parameters of the hybrid PV system, which are listed in Table 1, were used for modelling, while only the load characteristics were changed. The results obtained, which are shown in Fig. 6, made it possible to determine the critical mode that must be used when evaluating the permissible load of the inverter.

The simulation results confirm the assumption that the level of harmonic distortion depends on the nature of the load. In particular, in the case of parallel connection of the capacitive component (R–C), the permissible values are exceeded, which manifests itself in the formation of a prohibited zone. This fully corresponds to the predicted results, since the resonance effects during the interaction of the inverter with the capacitive load amplify the harmonic components.



Parallel connection of R-C and R-L



Series connection of R-C and R-L

Fig. 6. Results of constructing Q-P diagrams for different configurations of connected loads

On the other hand, for parallel or series connection of an inductive load (R–L) or series connection of R–C, harmonic distortions remain within acceptable limits. This is because the inductive component acts as a natural filter for higher harmonics, and in a series R–C connection, there are no conditions for a sharp increase in resonance phenomena. Thus, the obtained curves of acceptable distortions are physically justified and confirm the correctness of the approach used.

Further simulations were aimed at verifying the correctness of the inverter operating curve formation according to the proposed method. For this purpose, with the same initial model parameters, a simulation was performed to determine the voltage harmonic distortion factor for the entire load variation range. In parallel, in accordance with the method algorithm, a P–Q dependence diagram was constructed taking into account THD limitations. This made it possible to compare the results of numerical experiments with the data obtained using the method and to evaluate the accuracy of the curve construction. The resulting diagram is shown in Fig. 7.

The resulting graph, formed by superimposing the simulation results on the P–Q plane, demonstrates the correctness of the proposed method. It can be seen that the curve of permissible distortions, constructed according to the algorithm, practically coincides with the results of calculating the total harmonic distortion of voltage, determined in the process of complete modelling for the entire load plane with a step of 250 W. This confirms that the method allows you to accurately reproduce the boundary between the zones of permissible and impermissible inverter operation without the need for a significant number of separate simulations. The coincidence of the calculated and experimentally obtained curves indicates the correctness of the algorithmic dependencies embedded in the method and their correspondence to physical processes. In particular, there is a clear reproduction of the boundary line in those ranges where resonance effects and R-C load combinations could lead to an increase in harmonic distortion.

Additionally, in order to verify the correctness of the results obtained and confirm the proposed method, a comparison of the initial characteristics of the model with the experimental data obtained in the article was carried out.[2] The superimposition of both curves demonstrated their similarity and confirmed the adequacy of the model; in particular, the values of harmonic distortions obtained during the experimental test practically correspond to those obtained from the mathematical model, and the slight error is due to the physical characteristics of the inverter under study. The results confirm that the method can be used for a quick assessment of the electromagnetic compatibility of photovoltaic inverters in a wide range of loads.

Particular attention was paid to verifying the correct operation of the proposed method for different inverter configurations. For this purpose, a series of simulations were carried out in which the load remained unchanged, but the parameters of the inverter's LCL filter, which is directly designed to reduce higher harmonics in the output voltage, were changed. The results obtained are shown in Fig. 8.

A series of simulations confirmed that the shape of the resulting curve significantly depends on the parameters of the hybrid photovoltaic system, in particular on the characteristics of the LCL filter. This is fully consistent with known studies, which emphasise that the efficiency of filtering harmonic components determines not only the level of electromagnetic compatibility of the system, but also the possibility of ensuring a wider operating range under variable loads [17,18]. Thus, the key assumption that optimisation of filter parameters is a determining factor in reducing distortion and forming an acceptable operating range in Q-P coordinates has been confirmed.

According to the results obtained, it is clearly evident that the restrictions currently imposed by equipment manufacturers do not allow full compliance with the requirements for the level of harmonic distortion. This discrepancy has been repeatedly noted in international publications, which emphasise that the actual operating conditions of microgrids differ significantly from those of laboratory tests, and therefore regulatory approaches need to be revised [19]. At the same time, the results of modelling show that improving the algorithms for determining the permissible operating modes of inverters in networks with significant reactance content can solve this problem.

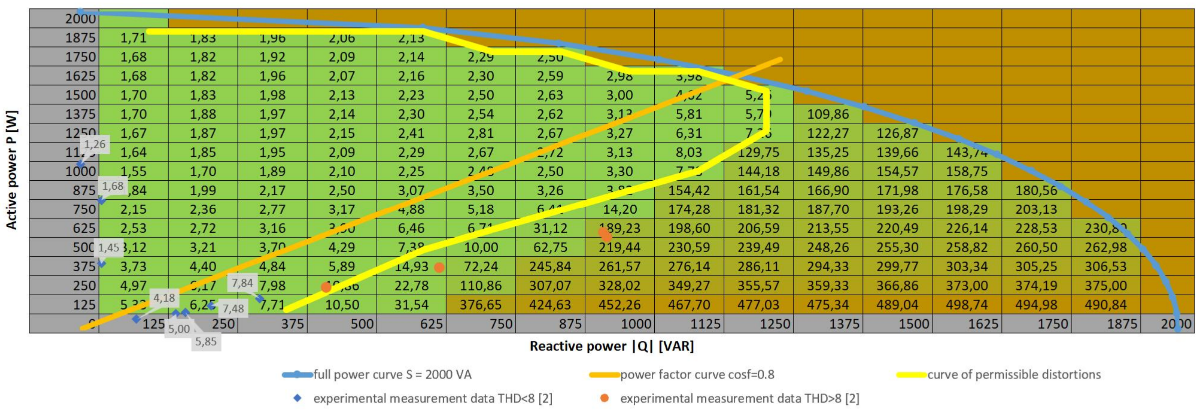
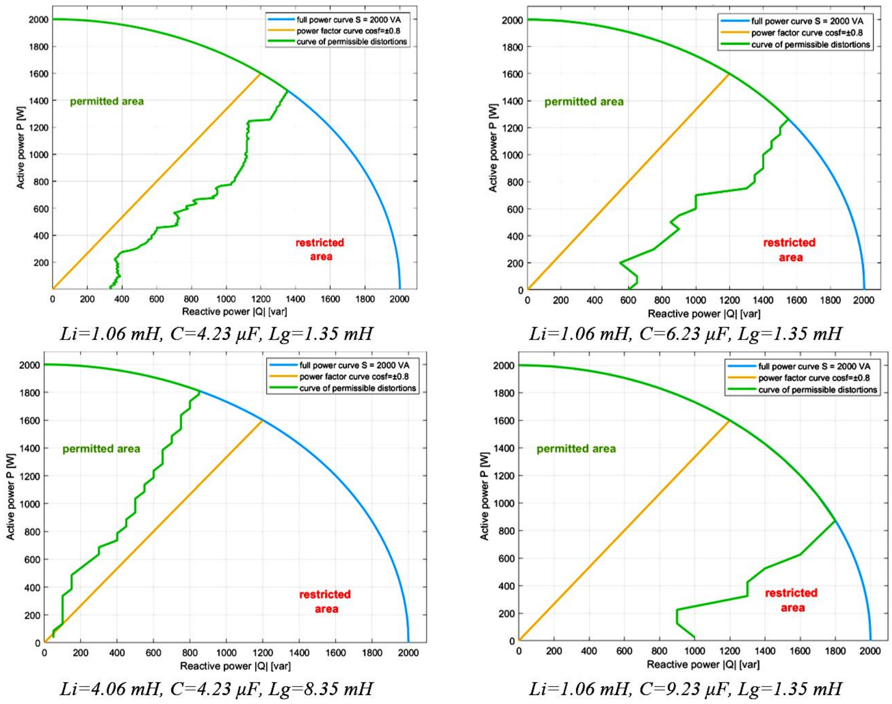


Fig. 7. Results of determining the total harmonic distortion coefficient on a plane and constructing a curve of permissible distortions



Li=1.06 mH, C=4.23 µF, Lg=1.35 mH

Li=1.06 mH, C=6.23 µF, Lg=1.35 mH

Li=4.06 mH, C=4.23 µF, Lg=8.35 mH

Li=1.06 mH, C=9.23 µF, Lg=1.35 mH

Fig. 8. Results of constructing a curve of permissible distortions at different LCL filter parameters

It is important to note that high filtration efficiency expands the range of acceptable operating modes, which increases the flexibility of the system when working with different types of loads. On the other hand, low filtration levels have the opposite effect: a reduction in the operating range and restrictions on the use of the inverter in certain Q-P combinations. This confirms the need to integrate more sophisticated active harmonic suppression mechanisms, such as adaptive current control algorithms and digital compensation methods [20].

The results of the work also indicate the need to improve existing methods for determining the permissible load of hybrid inverters when operating in isolated general-purpose networks. This is due to the fact that existing methods for assessing the permissible power of an inverter are focused primarily on basic procedures for testing compliance with safety requirements and general power quality criteria. In particular, existing documents such as IEC 62109-2 [9], EN 50530 [10], EN 50160 [14], IEEE 1547-2018 [21] and IEC 61000-4-30:2015 [13], do not contain provisions for a comprehensive analysis of the interaction of active and reactive power with the level of harmonic distortion across the full load range, which is a key element of the proposed improved method. Accordingly, the inclusion of the described test in the structure of existing standards would require a significant revision and would violate their logical consistency.

In view of this, it is advisable to develop a separate regulatory document in the form of a standard or industry methodology that would contain the complete procedure for applying the method: the order of measurements, requirements for measuring instruments, data processing algorithms, and evaluation criteria. This will ensure the reproducibility and accuracy of testing in laboratory and field conditions and lay the foundation for its further implementation in future editions of national or industry standards.

6. Conclusions

The method for determining the permissible load of hybrid inverters has been improved, provided that the quality indicators of electrical energy are mandatory in the autonomous mode of operation of a microgrid with hybrid photovoltaic systems. The method is based on the analysis of the limit value of the total harmonic distortion factor (THD) in order to correctly select the permissible load of the inverter, which allows taking into account the type and nature of the connected load. The application of this method will ensure that the quality of electrical energy complies with current standards by selecting an inverter of the appropriate power. In addition, it provides an objective assessment of the impact of consumers on the quality of electricity and the stability of inverters in autonomous systems.

An improved mathematical model of a hybrid PV system has also been developed, which allows the joint operation of hybrid voltage inverters with nonlinear electrical loads of active, reactive-inductive and reactive-capacitive nature to be simulated. The model provides an assessment of system operating modes, including critical ones, and allows predicting the impact of nonlinear effects on power quality in real operating conditions.

The proposed approach allows combining mathematical modelling, metrological control and harmonic distortion analysis, which is important for optimising the operation of autonomous microgrids. The modelling results can be used to design systems with increased resistance to load fluctuations, to verify the permissible operating modes of inverters and to plan energy management strategies.

The improved method for determining the permissible load power of hybrid inverters is the basis for the development of draft regulatory documents, in particular, internal regulations or industry guidelines, since the current standards (IEC 62109-2 [9], EN 50530 [10], EN 50160 [14], IEEE 1547-2018 [21], IEC 61000-4-30:2015 [13]) do not take into account a comprehensive analysis of the interaction of active and reactive power with the level of harmonic distortion. Given the impossibility of integrating this procedure into the structure of existing standards without a major revision, it is advisable to develop a separate regulatory document that will ensure the reproducibility and correct application of the method.

Acknowledgements

The authors would like to thank Lviv Polytechnic National University for publishing the article and Ivano-Frankivsk Technical University of Oil and Gas for assisting in conducting the research.

Conflict of Interest

The authors declare that there are no financial or other potential conflicts of interest with respect to this work.

References

[1] A. Mohammed, E. K. Sakr, and M. Abo-Adma, "A comprehensive review of advancements and challenges in reactive power planning for microgrids," Energy Informatics, vol. 7, no. 1, p. 63, Aug. 2024. [Online]. Available: https://doi.org/10.1186/s42162-024-00341-3.

[2] R. I. Hrytsak and A. V. Yavorsky, "Problems of Power Quality in Microgrids Based on Hybrid Photovoltaic Systems," Visnyk VPI, no. 4, pp. 22–31, Aug. 2025.

[3] A. A. Zhirnova, V. V. Zhirnov, and S. N. Tkachenko, "The Influence of LED Lighting Sources on the Nature of Power Consumption and Power Quality Indicators," Energies, vol. 11, no. 6, p. 1479, Jun. 2018, doi: 10.3390/en11061479.

[4] A. S. Lapacheva, A. V. Lebedev, and A. S. Lebedeva, "Research of the Negative Influence of Dimmed LED Lighting on Power Quality Indicators," Sustainability, vol. 13, no. 17, p. 9753, 2021, doi: 10.3390/su13179753.

[5] I. P. Kaur, M. Aggarwal, and A. L. Sharma, "Effects of Waveform Distortion for Household Appliances on Power Quality," Journal of Electrical Engineering & Technology, vol. 14, pp. 2137–2147, Sep. 2019, doi: 10.1007/s42835-019-00227-3.

[6] European Committee for Electrotechnical Standardization (CENELEC), "EN 50160:2022 - Voltage characteristics of electricity supplied by public electricity networks," Dec. 2022. [Online]. Available: https://standards.iteh.ai/catalog/standards/clc/083c552d-f4b8-4373-a5ec-8a27b6c8d37d/en-50160-2022

[7] R. Haghighi, V.-H. Bui, M. Wang, and W. Su, "Survey of reliability challenges and assessment in power grids with high penetration of inverter-based resources," Energies, vol. 17, no. 21, p. 5352, Nov. 2024. [Online]. Available: https://doi.org/10.3390/en17215352.

[8] R. Thiagarajan, A. Nagarajan, P. Hacke, and I. Repins, "Effect of reactive power on photovoltaic inverter reliability and lifetime: Preprint," National Renewable Energy Laboratory, Golden, CO, NREL/CP-5D00-73648, Sep. 2019. [Online]. Available: https://docs.nrel.gov/docs/fy19osti/73648.pdf.

[9] IEC 62109-2:2011, Safety of power converters for use in photovoltaic power systems – Part 2: Particular requirements for inverters. International Electrotechnical Commission, 2011.

[10] EN 50530:2010, Overall efficiency of grid connected photovoltaic inverters. European Committee for Electrotechnical Standardization (CENELEC), 2010.

[11] IEEE Std 1547-2018, IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. IEEE Standards Association, 2018.

[12] IEC 61000-3-2:2018, Electromagnetic compatibility (EMC) – Part 3-2: Limits – Limits for harmonic current emissions (equipment input current ≤16 A per phase). International Electrotechnical Commission, 2018.

[13] International Electrotechnical Commission (IEC), "IEC 61000-4-30:2015 - Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods," Feb. 2015. [Online]. Available: https://webstore.iec.ch/en/publication/21844.

[14] European Committee for Electrotechnical Standardization (CENELEC), "EN 50160:2022+A1:2025 - Voltage characteristics of electricity supplied by public electricity networks," Jan. 10, 2023. [Online]. Available: https://standards.iteh.ai/catalog/standards/clc/c8691375-8082-4c4c-8a5d-01b79af10f85/en-50160-2022-a1-2025.

[15] IEC 61010-2-030:2021, Safety requirements for electrical equipment for measurement, control, and laboratory use – Part 2-030: Particular requirements for testing and measuring circuits. International Electrotechnical Commission, 2021.

[16] S. I. Bielov, Teoriia elektrychnykh kil. Kyiv: Vyshcha shkola, 2009.

[17] B. Singh, S. Singh, A. Chandra, and K. Al-Haddad, "Power quality issues and their mitigation in microgrids: A comprehensive review," IEEE Transactions on Industry Applications, vol. 56, no. 4, pp. 4012–4029, Jul.-Aug. 2020. [Online]. Available: doi: 10.1109/IICPE.2016.8079543.

[18] Y. Yang, H. Xiao, L. Lu, and F. Blaabjerg, "LCL filter design and control in grid-connected converters: An overview," Renewable and Sustainable Energy Reviews, vol. 109, pp. 1–15, Feb. 2019. [Online]. Available: https://doi.org/10.1016/j.rser.2019.04.043.

[19] D. Graovac, M. Knezović, and D. Žarko, "Harmonic mitigation challenges in microgrids," Electric Power Systems Research, vol. 195, p. 107155, Mar. 2021. [Online]. Available: https://doi.org/10.1016/j.epsr.2021.107155.

[20] M. Liserre, F. Blaabjerg, and S. Hansen, "Active power filters and modern control strategies for power quality improvement," IEEE Industrial Electronics Magazine, vol. 12, no. 2, pp. 20–31, Jun. 2018. [Online]. Available: https://doi.org/10.1109/MIE.2018.2813278.

[21] IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE Std. 1547-2018, Jul. 27, 2018. [Online]. Available: https://standards.ieee.org/standard/1547-2018.html.