Experimental Studies of Power Quality Indicators of Autonomous Low-Power Generators

Ivan Hlad, Vitalii Tsykh*, Yaroslav Batsala

Ivano-Frankivsk National Technical University of Oil and Gas, 15 Karpatska St., Ivano-Frankivsk, 76019, Ukraine

Received: April 16, 2025. Revised: May 21, 2025. Accepted: June 17, 2025.

Abstract

Experimental studies of the main indicators of power quality at the terminals of autonomous low-power generators were carried out. The content of higher voltage harmonics, as well as voltage and frequency deviations from the nominal value were determined. In the course of the research, the technical means of data collection and analysis by National Instruments were used. The main indicators of the power quality of autonomous inverter generators are shown to fully comply with the EN 50160-2022 standard. It is established that the voltages of even harmonics of the studied autonomous generators are absent in all operating modes. As a result of the experimental studies, it was found that with an increase in the connected load, the content of higher harmonics in inverter generators slightly increases, but the amount of distortion does not exceed the permissible values. It has also been found that with an increase in the electrical load of synchronous generators, the magnitude of voltage curve distortions is significantly reduced compared to the no-load voltage. Based on the studies, to reduce the content of higher voltage harmonics, it is advisable to connect electrical consumers with an active load character, which will allow powering parallel devices sensitive to higher harmonics.

Keywords: power quality; measurements; synchronous generator; inverter; harmonics.

1. Definition of the problem to be solved

As a result of the military aggression by the Russian Federation, Ukraine's power system suffered many critical damages that significantly affected its overall operation. Emergency power outages were observed in almost all settlements, and later scheduled hourly power outages were introduced. To ensure the operation of critical consumers, the use of mobile autonomous power sources became an urgent issue. The main emphasis was placed on the most widespread segment, namely stand-alone generators of low power. Among these power sources, generators driven by internal combustion engines have the longest battery life: synchronous and inverter generators. However, during their operation, there were frequent cases of incorrect operation of household and office equipment. The likely reason for this is the deviation of certain indicators of the quality of electricity produced by such generators. Therefore, an urgent task is to conduct experimental studies of the power quality parameters of low-power generators and formulate basic recommendations for their improvement. Identification of key parameters of power quality control and electromagnetic compatibility of local generation sources will reduce problems with switching on low-power generators and avoiding failures during operation.

2. Analysis of the recent publications and research works on the problem

Currently, there is a significant amount of research on the operation of high-power synchronous generators installed at power plants (transients, accuracy of maintaining the voltage at the terminals, rotor speed, etc.) [1], [2], [3]. These studies are important due to the assessment of the electromagnetic compatibility of power system components and

* Corresponding author. Email address: vitalii.tsykh@nung.edu.ua

This paper should be cited as: I. Hlad, V. Tsykh, Y. Batsala. (2025) Experimental studies of power quality indicators of autonomous low-power generators. *Energy Engineering and Control Systems*, Vol. 11, No. 1, pp. 27 – 32. https://doi.org/10.23939/jeecs2025.01.027

the proposed intelligent methods of power system coordination, which improves the stability and controllability of such systems. However, the results obtained for large generators cannot always be directly applied to low-power generators, especially those operating in stand-alone or hybrid mode. A feature of high-power synchronous generators is that they provide an almost sinusoidal voltage waveform at the terminals in the range from no-load to rated load. This is due to the fact that the large size of the magnetic system and windings of high-power synchronous generators allows us to take into account most of the factors that affect the content of higher voltage harmonics. In such systems, power quality issues, such as voltage stability, frequency accuracy, and the impact of higher harmonics, become critically important, requiring separate studies taking into account the specifics of operating modes and control schemes. Among these factors are the uneven distribution of magnetic induction in the air gap between the poles and the generator armature, the value of the maximum magnetic induction in the teeth and the stator back, and the generator winding dissipation inductance [4]. The author used the idea of invariants of the sums of squares of winding coefficients to analyze the harmonic composition of currents in the windings of electric machines. Their existence determines the limitation on the value of the fundamental harmonic and the possibility of compensating for harmful harmonics arising in multiphase winding circuits, which was introduced by Willem Klima in 1979. The paper considers the case of symmetrical three-phase currents in single- or double-layer winding schemes consisting of four sections in 24 slots. The peculiarity of the presentation is that the authors of the publication not only repeat Klima's conclusions, but also generalize the approach by applying mathematical and structural transformations to modern winding configurations. The ideas for harmonic spectrum analysis can be applied to low-power generators, and the invariance of winding coefficients can explain the limitations in reducing harmonic distortion in systems with a fixed winding structure. This is the basis for optimizing the winding layout of inverter-synchronous generators to improve the quality of electricity.

As for low-power electric machines, they are designed to strike a balance between the price of the product and operational parameters, including the quality of electricity. This is due to the fact that it is difficult to ensure a uniform magnetic field in the magnetic system because this requires increasing the number of winding grooves and, accordingly, stator teeth. Since stators are made of electrical steel plates by stamping, it is technologically impossible to produce narrow teeth. Thus, there is a limitation on the maximum number of stator winding slots and teeth for low-power synchronous generators [5].

The maximum magnetic induction in the magnetic system of a low-power synchronous generator is often located at the limit of the linear section of the magnetization curve of electrical steel. Therefore, the transition to the nonlinear part of the magnetization curve usually causes nonlinear distortions of the magnetic flux and, consequently, the voltage at the generator terminals. If a low-power synchronous generator is designed and manufactured to ensure that there is no distortion in the voltage curve, its cost increases significantly, or, otherwise, at the optimal cost, we will have a reduction in its rated power.

Today, a variety of models of stand-alone low-power synchronous generators are available on the market, both single-phase and three-phase. Most of them belong to the budget price range. At the same time, such generators have become the most widespread in our country over the past few years and are used to power important consumers, including public buildings, residential buildings, and medical facilities. Given that low-cost generators can deviate from certain power quality indicators in different operating modes, this can lead to the failure of expensive equipment that is sensitive to deviations in power quality indicators. Such equipment includes transformerless power supplies for gas boilers, individual power supplies for LED lamps, and medical equipment with sensitive sensors.

Leading manufacturers of stand-alone power supplies have invented a way to significantly improve the quality of electricity by incorporating a built-in voltage inverter into the design of an autonomous generator [5]. In inverter generators, the alternating voltage is first generated by a synchronous generator, then rectified, filtered from ripples, and inverted by a built-in inverter into a nearly sinusoidal alternating voltage. At the same time, the frequency, rms value and content of higher harmonics of the alternating voltage in the circuit between the synchronous generator and the built-in voltage inverter are not normalized. The main disadvantage of inverter generators is their low resistance to overloads caused, for example, by the starting currents of electric motors.

The issue of voltage control in distribution power grids is addressed in [7]. However, these studies concern only the analysis of voltage control methods in distribution networks, and do not contain studies on the voltage quality of autonomous low-power generators.

Work [8] contains a study of methods for improving the quality of electricity from diesel generators with millisecond pulse load, which were carried out by mathematical modeling of diesel generator transients and do not contain experimental voltage measurements.

Paper [9] contains the results of measuring the higher harmonics of currents and voltages at the points of joint connection of distribution power grids, which show a significant increase in the content of higher current harmonics in distribution power grids.

Article [10] discusses the impact of the transition to low-inertia systems on frequency stability in power systems. The authors analyze the interaction between synchronous machines and grid-forming inverters, which can ensure system stability in the absence of traditional sources of inertia.

Article [11] emphasizes the relevance of electromagnetic compatibility of power devices in local power grids, especially in conditions of high-frequency and fast electromagnetic processes. The authors analyze the mechanisms of overvoltage occurrence during switching and propose effective ways to limit them with the help of properly selected protective equipment, as well as the problem of protecting power electronic converters based on thyristors with forced shutdown (GTO) from switching overvoltage. The presence of autonomous inverter and synchronous low-power generators in local networks necessitates experimental studies, and their inconsistency can lead to malfunctions, overheating, or even equipment failure.

The peculiarities of diesel generators, an assessment of existing variable speed technologies and their evaluation according to a number of performance criteria are described in detail in [12]. The authors consider harmonics, frequency stability, voltage, etc., which are the main indicators of electricity quality, and discuss the impact of inverter control algorithms on these indicators.

In [13], the developers propose technical and system solutions (monitoring of diagnostic symptoms) to minimize the likelihood of power supply failure and its timely restoration. In [14], the authors propose to use the electrical parameters of a generator as an indicator of the technical condition of an energy source, which may be relevant for autonomous low-power systems, for example, in microgrids or backup systems.

3. Formulation of the goal of the paper

The aim of this paper is to conduct experimental studies of the main indicators of power quality of low-power autonomous synchronous and inverter generators. Such a study is necessary to assess the possibility of connecting electrical consumers that are sensitive to the content of higher harmonic components, frequency deviations, and supply voltage. To increase the reliability of the results obtained, it is necessary to use the hardware and software complex developed by the authors, which is based on the technology of virtual devices, simultaneously with the specialized power quality analyzer Metrel MI2892. It is worth noting that for the completeness of the research, it is necessary to measure the quality of electricity at the terminals of autonomous power generators with a power range from 3 to 10 kVA, both single-phase and three-phase, including inverter ones.

4. Presentation and discussion of the research results

The research methodology involved measuring and recording instantaneous voltage values at the terminals of autonomous generators in the idle mode, as well as in the mode close to the nominal active load. Household heating appliances such as electric convectors and electric kettles were used as a load. The set of electrical appliances used provided a power range of 0.7 - 0.9 of the rated power of the autonomous generators. A Metrel MI2892 power quality analyzer was used to measure the frequency, rms voltage, harmonic content, and total harmonic distortion.

The disadvantage of this Metrel MI2892 device is the difficulty of obtaining oscillograms with instantaneous voltage values. Therefore, we used primary voltage converters CV3-1000 from LEM, an analog-to-digital converter NI USB-6210, and a laptop with software developed by the authors for the rapid recording of instantaneous voltage values with the ability to save them to a hard disk. The ADC sampling rate is 10 kHz (200 points per period of 50 Hz industrial frequency for each channel), the bit depth is 16 bits of bipolar signal (±32768 discrete samples), the bandwidth of the measuring channels is in the range from 0 to 2 kHz. This made it possible to obtain informative voltage waveforms at the terminals of autonomous generators (Figures 2, 3).

Metrel MI2892 device uses digital signal processing, in particular the fast Fourier transform, to determine the higher harmonic voltages contained in the voltage at the terminals of autonomous generators, as well as the voltage frequency, its rms value, and total harmonic distortion according to EN 50160:2022 [15].

As a result of the experimental studies, it was found that the main indicators of the power quality of autonomous inverter generators fully comply with the EN 50160:2022 standard [15]. However, attention should be paid to the voltage spectral composition of low-power autonomous synchronous generators, which contains an unacceptably high total harmonic distortion and significant odd harmonic voltages in the off-load mode (Table 1). In Table 1, the models of synchronous generators are shown conventionally, indicating the value of the rated total power and the number of phases.

In particular, Table 1 shows that the voltage and frequency deviations, total harmonic distortion, and higher harmonic components of all the studied generators, except for the Gen8500 generator, are within the permissible limits according to EN 50160-2022 [15]. However, the total harmonic distortion of the Gen8500 single-phase synchronous generator with a rated full power of 8.5 kVA in the no-load mode is 16.2%, which is twice the value allowed by EN 50160-2022 [15].

Table 1. Power Quality parameters of single-phase autonomous generators (idle mode).

Name of parameter	Measured Values				Allowed Values EN 50160:2022
	Gen8500 single-phase	Gen3000 single-phase Invertor	Gen6000 three-phase	Gen10000 three-phase	
U, V	226.9	230.9	235.0	226.7	207-253
f, Hz	54.1	50.1	52.6	53.3	42.5-57.5
Total Harmonic Distortion (THD), %	16.2	0.3	6.6	7.8	8
$U_{(3)}$, %	4.0	0.16	1.5	2.9	5.0
$U_{(5)}$, %	5.4	0.11	5.4	4.4	6.0
$U_{(7)}$, %	0.6	0.1	1.0	2.4	5.0
$U_{(9)}$, %	1.5	0.05	0.6	2.1	1.5
$U_{(11)}$, %	1.1	0.04	1.1	1.8	3.5

Table 2 shows the results of measuring the above-mentioned power quality indicators when supplying consumers with an active load and power close to the nominal value.

Table 2. Power Quality parameters of single-phase autonomous generators (nominal active load mode).

Name of parameter	Measured Values				Allowed Values EN 50160:2022
	Gen8500 single-phase	Gen3000 single-phase Invertor	Gen6000 three-phase	Gen10000 three-phase	
U, V	229.1	224.7	240.0	224.2	207-253
f, Hz	48.9	50.1	52.0	51.8	42.5-57.5
Total Harmonic Distortion (THD), %	17.7	2.6	9.9	6.7	8
$U_{(3)}$, %	17.2	0.9	7.5	2.5	5.0
$U_{(5)}$, %	2.0	0.1	5.0	3.8	6.0
$U_{(7)}$, %	0.58	1.9	1.0	2.1	5.0
$U_{(9)}$, %	0.9	0.8	0.7	1.4	1.5
$U_{(11)}$, %	0.76	0.8	1.0	1.2	3.5

Table 2 shows that when operating under load in autonomous low-power generators, except for the inverter generator, the content of higher-order harmonics decreases, but the percentage of the third harmonic voltage and, accordingly, the total harmonic distortion increase. This is probably due to the peculiarities of the stator winding schemes and their design, changes in the saturation of the magnetic system when operating under load, as well as the settings of automatic excitation controllers.

The voltage waveforms at the terminals of the studied generators in the idle mode are shown in Fig. 1. As can be seen, the voltage curve of the inverter generator has practically no nonlinear distortions, the voltage curve of the single-phase generator with a capacity of 8.5 kVA contains higher-order harmonics, and the voltage curve of the three-phase generator with a capacity of 6 kVA contains higher harmonic distortions, approximately the same in the frequency spectrum that was studied.

The voltage waveforms at the terminals of the investigated generators under an active load are shown in Fig. 2. As can be seen, the voltage curve of the inverter generator contains minor nonlinear distortions, the voltage curve of the single-phase generator with a capacity of 8.5 kVA does not contain higher-order harmonics, and the voltage curve of the three-phase generator with a capacity of 6 kVA contains higher harmonic distortions, approximately the same in the frequency spectrum under study.

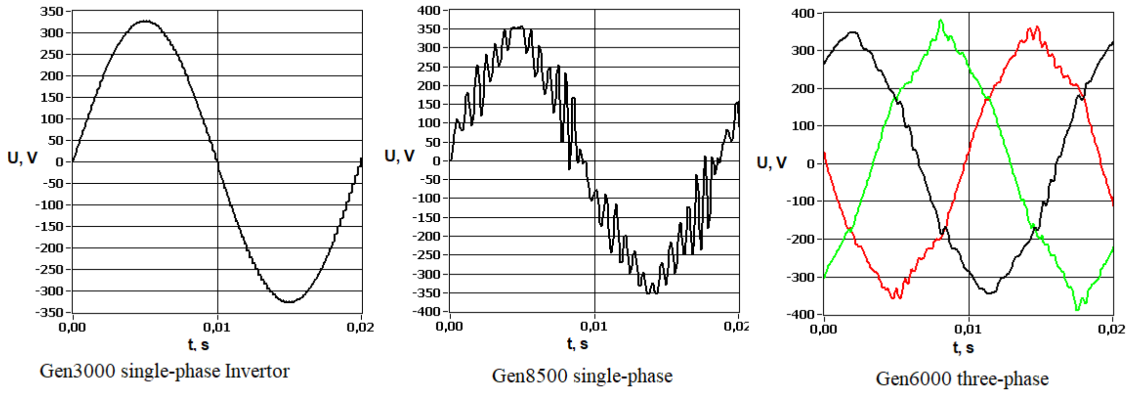

Fig.1. Waveforms of generator voltages in idle mode.

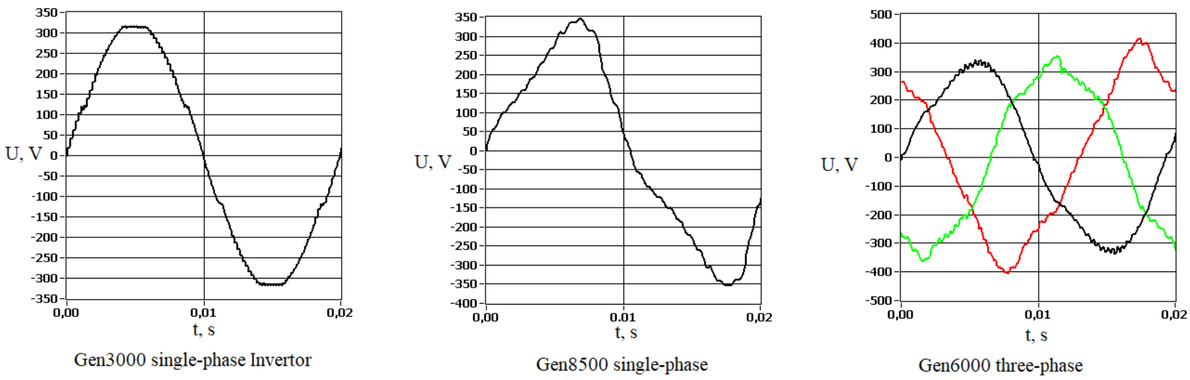

Fig.2. Waveforms of generator voltages in nominal active load mode.

Also, Fig.2 shows that a three-phase synchronous generator with a capacity of 6 kVA does not provide sufficient symmetry of phase voltages when operating with a load, so in the future it will be advisable to conduct experimental studies to determine the asymmetry factor and its impact on the power consumer.

5. Conclusion

The publication highlights the results of experimental studies of low-power autonomous synchronous and inverter generators. For this purpose, the measurement methodology used with the Metrel MI2892 power quality analyzer, CV3-1000 high-precision voltage converters, NI USB-6210 ADC, and specialized software made it possible to perform a detailed spectral analysis of the voltage with the determination of higher harmonics, frequency, and rms value.

The results of the analysis showed that inverter generators provide high power quality indicators that fully meet the requirements of EN 50160-2022 with a load ranging from idle to rated. At the same time, low-power synchronous generators demonstrate significant voltage quality violations in the idle mode: elevated values of total harmonic distortion and unpaired harmonic voltages were found, which can negatively affect the operation of sensitive electronic equipment.

The results obtained indicate the feasibility of optimizing the winding design, excitation schemes, or implementing filtration measures to improve the quality of electricity in synchronous generators. In particular, the connection of an active load reduces the content of higher harmonic components in low-power autonomous synchronous generators.

References

[1] Mugarra, A.; Guerrero, J.M.; Mahtani, K.; Platero, C.A. Synchronous Generator Stability Characterization for Gas Power Plants Using Load Rejection Tests. Appl. Sci. 2023, 13, 11168. https://doi.org/10.3390/app132011168.

[2] Varetsky, Y.; Gajdzica, M. Power Compatibility of Induction Motors in Industrial Grids Containing Synchronous Generators. Energies 2024, 17, 1066. https://doi.org/10.3390/en17051066.

[3] Khezri, Rahmat & Oshnoei, Arman & Yazdani, Amirmehdi & Mahmoudi, Amin. (2020). Intelligent coordinators for automatic voltage regulator and power system stabiliser in a multi-machine power system. IET Generation, Transmission and Distribution. 10.1049/iet-gtd.2020.0504.

[4] Gavrilyuk R. B. Secrets that preserve the harmonics of the magnetizing force of symmetrical multiphase winding circuits (2009) Electrotekhnika i Elektromechanika. 2009. No. 1, National Technical University "KhPI", P. 5-8.

[5] Rasilo, Paavo. (2007). Low-Voltage Synchronous Generator Excitation Optimization and Design. PP. 1-70. https://www.researchgate.net/publication/27516626.

[6] Shpenst, Vadim & Belsky, Aleksey & Orel, Evgeny. (2023). Improving the efficiency of autonomous electrical complex with renewable energy sources by means of adaptive regulation of its operating modes. Journal of Mining Institute. 261. 479-492.

[7] Kosareva IV, Shcherbak IE Analysis and practice of voltage control in distribution networks. Electric power engineering, electromechanics and technologies in the agro-industrial complex: materials of the International scientific and practical conference, December 22, 2022, State Biotechnology University, Kharkiv: 2022. C. 9-10.

[8] Hai-Chao Li et al 2023 J. Phys.: Conf. Ser. 2452 012032. DOI 10.1088/1742-6596/2452/1/012032.

[9] Solomchak O.V., Solomchak A.O. Measurement of higher harmonics of currents and voltages at the points of joint connection of distribution electrical networks. P. 194-201. DOI https://doi.org/10.32782/2663-5941/2024.4/29.

[10] A. Tayyebi, D. Groß, A. Anta, F. Kupzog and F. Dörfler, "Frequency Stability of Synchronous Machines and Grid-Forming Power Converters," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 8, no. 2, pp. 1004-1018, June 2020, doi: 10.1109/JESTPE.2020.2966524.

[11] Y. Fediv, O. Sivakova, V. Lysiak, M. Korchak. Switching overvoltages protection of power electronics converters with gate turn-off thyristors. Energy Engineering and Control Systems, 2021, Vol. 7, No. 2, pp. 103 – 110. https://doi.org/10.23939/jeecs2021.02.103.

[12] Grzeczka, Grzegorz & Piłat, Tomasz & Polak, Adam. (2017). The parameters of excitation current of ship synchronous generator as the diagnostic symptoms of the propelling IC engine. Journal of Marine Engineering & Technology. 16. P. 1-5. 10.1080/20464177.2017.1381063.

[13] Mobarra, M.; Rezkallah, M.; Ilinca, A. Variable Speed Diesel Generators: Performance and Characteristic Comparison. Energies 2022, 15, 592. https://doi.org/10.3390/en15020592.

[14] Y. Shelekh, M. Sabat, V. Lysiak, L. Parashchuk. Enhancing safety and reliability of electric power supply to consumers through safe electricity networks of up to 1 kV. Energy Engineering and Control Systems, 2021, Vol. 7, No. 2, pp. 97 – 102. https://doi.org/10.23939/jeecs2021.02.097.

[15] EN 50160:2022 Voltage characteristics of electricity supplied by public electricity networks. Online: https://standards.iteh.ai/catalog/standards/clc/083c552d-f4b8-4373-a5ec-8a27b6c8d37d/en-50160-2022?srsltid=AfmBOoq4zJRM8sYUfwnN2YpKAha3Rv57nlK5kZ2Qb6kvVkLsSbhaUAs-.

Експериментальні дослідження показників якості електричної енергії автономних генераторів малої потужності

Іван Гладь, Віталій Цих, Ярослав Бацала

Івано-Франківський національний технічний університет нафти і газу,
вул. Карпатська, 15, Івано-Франківськ, 76019, Україна

Анотація

Проведено експериментальні дослідження основних показників якості електричної енергії на затискачах автономних генераторів малої потужності. Визначено вміст вищих гармонік напруги, а також відхилення напруги і частоти від номінального значення. В ході досліджень використано технічні засоби збору та аналізу даних компанії National Instruments. Показано, що основні показники якості електроенергії автономних інверторних генераторів повністю відповідають стандарту EN 50160-2022. Встановлено, що напруги парних гармонік автономних генераторів, які досліджувалися, відсутні у всіх режимах роботи. В результаті проведених експериментальних досліджень виявлено, що при зростанні підключеного навантаження в інверторних генераторах дещо збільшується вміст вищих гармонік, однак величина спотворень не перевищує допустимих значень. Також встановлено, що при збільшенні електричного навантаження синхронних генераторів, величина спотворень кривої напруги суттєво знижується, порівняно із напругою неробочого ходу. На основі проведених досліджень показано, що для зменшення вмісту вищих гармонік напруги доцільно приєднувати електроспоживачі із активним характером навантаження, що дозволить живити паралельно приєднані чутливі до вищих гармонік пристрої.

Ключові слова: якість електроенергії; вимірювання; синхронний генератор; інвертор; гармоніки.