

Article

The Effect of Biogas Generation and Fermenter Mixer Operation on Power Quality in a Local Power System

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Abstract

This study analyses the effect of an agricultural biogas plant on power quality at the connection point of a dairy cattle farm. The main objective was to determine how power generation and fermenter mixer operation affect selected power quality parameters. Four characteristic operating states of the system were analysed, differing in terms of power generation and mixer operation. The measurement results showed that generator operation stabilised the voltage in the low-voltage network. When the generator was switched off, the voltage decreased from approximately 234 V to approximately 226 V, confirming the clear effect of local generation on the supply voltage level. At the same time, the analysis of total harmonic distortion (THD_U) showed that the greatest differences occurred when the generator was switched off, particularly between states with the fermenter mixers operating and inactive. In this case, the mean difference (Δ_{mean}) in phase L3 reached 0.31, indicating increased susceptibility of the system to non-linear loads in the absence of local generation. Mixer operation caused only a moderate voltage reduction and minor changes in power quality parameters. Its effect was therefore weaker than that of power generation. Statistical analysis, including the Games–Howell test, confirmed significant differences among most operating states, particularly between states with and without generation.

Keywords: power quality; agricultural biogas plant; low voltage; voltage distortion factor; voltage asymmetry



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1. Introduction

Energy generated by biogas plants is one of the most promising alternative energy sources [1], alongside wind and solar energy [2,3]. Compared to other renewable energy sources, agricultural biogas plants generate energy continuously, regardless of weather conditions, thereby improving the stability of rural electricity grids [4]. For this reason, their role in the power system goes beyond energy production itself and includes effects on power quality parameters and integration with the low-voltage network. Biogas is an environmentally friendly energy source that can be produced from various raw materials, such as manure, sewage sludge, industrial waste, and energy crops [5,6]. An additional advantage is its environmental benefit: the use of renewable energy sources helps reduce

greenhouse gas emissions [7] and achieve sustainable development goals [8,9]. The efficiency of the process depends on several key factors, such as fermentation temperature, pH, retention time, and dry organic matter concentration [10,11].

Biogas can be used in the same way as natural gas, including applications such as heating, electricity generation, and, following appropriate modifications, as a vehicle fuel [12,13]. Continuous technological progress enables the use of biogas in the energy sector—from simple gas boilers to fuel cells. Its potential includes the production of heat in adapted gas boilers and electricity in internal combustion engines or turbines [14]. These processes are characterised by low efficiency, rarely exceeding 40%, suggesting that biogas should be burned in combined heat and power (CHP) engines that simultaneously generate electricity and heat [15,16].

Agriculture generates a variety of by-products, including plant residues, manure, and other organic waste, which can be converted into bioenergy. The presence of biogas plants on farms simultaneously reduces waste and greenhouse gas emissions [17]. Biogas plants also bring economic benefits, improving the profitability of both agricultural production and the processing industry [18]. Properly processed fermentation slurry can partially replace mineral fertilisers, providing macro- and micronutrients [19]. Key advantages include reduced fertiliser costs, lower CO₂ emissions associated with synthetic fertiliser production, increased soil biological activity, and improved water retention capacity. These factors contribute to increased crop drought resistance [20].

The literature indicates that the presence of distributed sources affects voltage regulation, which is associated with a change in the voltage profile in low-voltage networks [21]. At the same time, these sources may affect the level of harmonic distortion, especially when interacting with non-linear loads and power electronic converters [22]. Moreover, the influence of distributed generation on voltage unbalance is observed, especially in networks with uneven phase load [23]. The scale of these impacts depends largely on the network configuration and load structure. Additionally, it is emphasised that in low-voltage networks using distributed sources, there may be local exceedances of permissible voltage levels and increased variability in power quality parameters [24]. The important role of interactions between generating sources and loads is also pointed out, which may lead to an increase in the content of higher harmonics and deterioration of the operating states of electrical devices [25]. At the same time, the nature of these impacts depends on the local operating states of the network and the method of source control [26], and their importance in agricultural systems remains insufficiently recognised. Power quality in a system with an agricultural biogas plant depends not only on the efficiency of the generator, but also on the parameters of the plant's own equipment. The largest energy consumers in such plants are the fermenter mixers [27]. The geometric parameters of the mixers should be tailored to the specific nature of the mixing process and the tank shape [28]. Preliminary simulations are an essential tool for achieving optimal efficiency, which means minimising energy consumption while maximising mixing efficiency [29].

A biogas power plant designed for the agricultural sector, like any other energy source, is installed close to the consumer, which can significantly affect the quality of the power supplied to the agricultural enterprise [30]. Poor quality of this energy can lead to failures in sensitive equipment and, in extreme cases, even cause damage [31]. The main factors contributing to deterioration in power quality parameters are the increasing number of non-linear loads, renewable energy sources, and power electronic systems [32]. The increased concern for these parameters stems from the drive to improve the reliability, efficiency, and safety of power supply systems [33]. Consequently, before widespread implementation of such installations, it is essential to analyse power quality parameters [34,35]. One of the key parameters of power quality is the deviation of the supply voltage from a sinusoidal

waveform, most commonly expressed by the total harmonic distortion (THD) [36,37]. Another important indicator of power quality is voltage asymmetry, i.e., a condition in which voltage values or the angles between successive voltages are not equal [38]. A distinction is made between zero-sequence asymmetry [39] and phase-sequence asymmetry [40]. The assessment of these phenomena should be carried out in relation to applicable power quality standards, such as EN 50160 [41] and the IEC 61000 series of standards [42], which specify permissible levels of voltage deviations, unbalance and harmonic distortions. Referring the measurement results to these standards allows for a clear interpretation of the power quality and an assessment of the compliance of the system with operational requirements. The presented results are based on measurements carried out in a single local system with a rated source power of 20 kW. Therefore, the conclusions are primarily of a qualitative nature and refer to the specific operating states of the analysed facility.

Grid electricity supply in rural areas is often associated with technical problems, such as sudden voltage fluctuations and unexpected power outages [43]. These phenomena may disrupt the operation of modern equipment and production lines on the farm [17]. In turn, energy production in currently popular renewable installations, such as photovoltaic panels or wind farms, is completely dependent on the weather. The energy they produce is intermittent and often does not meet the actual daily demand of the farm, which makes it necessary to purchase expensive energy storage systems or purchase additional electricity from the grid. Against this background, an agricultural biogas plant, as a controllable source, can provide constant and predictable energy production with stable parameters, regardless of the time of day or weather conditions [44].

Issues relating to power quality have been described many times in the international literature. However, the number of publications on the impact of agricultural biogas plants on voltage parameters at farm connection points is limited. In particular, the simultaneous impact of various operating states of biogas plants, including both the presence of generation and the operation of auxiliary devices, on parameters such as voltage level, unbalance and harmonic distortions remains insufficiently recognised.

This study addresses this gap by testing selected power quality parameters in real operating states of a farm with a biogas plant. Unlike previous analyses, this study includes a comparison of several characteristic operating states of the system, which enables a more comprehensive assessment of the effects of both generation and auxiliary devices on power quality. The aim of the study was to analyse how power generation and mixer operation in an agricultural biogas plant affect power quality in the local power system and to determine how various operating states of the installation affect selected parameters of power quality.

The article is organised as follows. Section 2 presents research materials and methods, including the characteristics of the analysed object, description of the measuring equipment and the adopted operating states of the biogas plant, along with the applied methodology of statistical data analysis. Section 3 presents the research results and their discussion, including the analysis of the waveforms and statistical characteristics of selected power quality parameters, such as voltage level, unbalance and harmonic distortions, in various operating states of the system. Section 4 presents the final conclusions, summarising the results obtained, their practical significance, the research limitations, and directions for further work.

2. Materials and Methods

The methodology was based on a comprehensive analysis of power quality parameters at the connection point of a dairy cattle farm, equipped with an agricultural biogas plant. Measurements were taken under four operating conditions of the power supply system:

T1—power generation in the agricultural biogas plant without the fermenter mixers running;
 T2—power generation in the agricultural biogas plant with the fermenter mixers operating;
 T3—no power generation in the biogas plant and no operation of the fermenter mixers;
 T4—no power generation in the biogas plant while the fermenter mixers are operating.

Power quality measurements were conducted for a total period of one week, during normal, actual operation of the agricultural biogas plant. This made it possible to isolate the above four operating states of the power supply system. Due to the natural operation of the biogas plant, the number of samples differed between operating states and was as follows: 2211 for T1, 611 for T2, 4126 for T3, and 3870 for T4. The four analysed operating states (T1–T4) were selected as representative of typical operating states of the studied farm and biogas plant. They include all important combinations of system operation, i.e., the presence or absence of generation and the operation or standstill of mixers, which enables the separation of the influence of the generating source (including auxiliary devices) and the main energy consumers. Measurements for individual operating states were carried out under comparable conditions, at a similar load level, which helped limit the influence of external factors and ensure a reliable comparison of the obtained results.

An agricultural biogas plant has been installed on the farm to process slurry from the dairy cows reared there. The basic technical parameters of the combustion engine and the generator installed in the analysed agricultural biogas plant are presented in Table 1.

Table 1. Primary technical specifications of the generation equipment used in the analysed agricultural biogas plant.

Internal Combustion Engine	
Engine type/cycle	WG1605/Otto
Number of cylinders	4
Speed	2700 rpm
Rated active power	20 kW
Nominal apparent power	26 kVA
Primary energy consumption	62.5 kW
Electrical efficiency	32%
Total efficiency	97%
Thermal power	40.9 kW
Rated voltage	400 V
Rated current	29 A
Power factor $\cos \phi$ rated	0.97
Generator	
Type	Asynchronous 4P/IE2
Rated speed	1500 rpm
Rated frequency	50 Hz
Rated voltage	3×400 V
Winding connection	triangle

The measurements were recorded using a SONEL PQM-710 power quality analyser operating at a 1-min measurement interval, which enabled a large number of samples and statistically reliable estimates of variability characteristics to be obtained. This device meets the requirements of measurement class A in accordance with the IEC 61000-4-30 standard [45], which ensures high accuracy and repeatability of measurement results of power quality parameters. Harmonic and interharmonic measurements were carried out in accordance with the IEC 61000-4-7 standard [42], while other power quality parameters were recorded in accordance with the requirements of the IEC 61000-4-30 [45] and EN 50160 [41] standards. In the first stage, an analysis was carried out of the time wave-

forms of the phase voltages (U_{L1} , U_{L2} , U_{L3}), the zero-sequence (k_{U0}) and negative-sequence (k_{U2}) voltage unbalance factor, and the voltage distortion factor (THD_U). A statistical analysis was then performed on all measured quantities, enabling a quantitative assessment of the stability and distribution characteristics of power quality parameters. To determine the significance of differences between individual operating states, an ANOVA analysis was used, followed by the Games–Howell post hoc test. Before applying one-way analysis of variance (ANOVA), the basic assumptions of this statistical method were verified. The normality of the distribution of the analysed variables was assessed using the Shapiro–Wilk test, while the homogeneity of variance was checked using the Levene test. The results indicated that the assumption of homogeneity of variances was only partially met, which justified the use of an analytical variant resistant to this limitation. One-way analysis of variance was selected as an appropriate tool to compare the mean values of power quality parameters between the four system operating states, which is a standard approach in the analysis of multi-group experimental data. Due to the differences in variance and sample size, the Games–Howell post hoc test was used for detailed comparisons between pairs of states, which does not require homogeneous variances and is recommended in this type of analysis. This approach enables reliable identification of significant differences between the analysed operating states, while limiting the risk of incorrect interpretation caused by violations of the assumptions of classical analysis of variance.

In addition to the p -value, the statistical analysis also included effect size measures and confidence intervals, which allowed for the assessment of the practical significance of the observed differences. In particular, the effect size measure η^2 was used for the analysis of variance and 95% confidence intervals for the mean values. This approach enables not only the identification of statistically significant differences between the analysed operating states, but also the assessment of their significance from the perspective of power system operation.

The statistical analysis employed a one-way ANOVA to determine whether the mean values of the power quality parameters differed significantly between the four operating states of the system (T1–T4). The test was based on a comparison of between-group and within-group variances, with the F statistic calculated in accordance with the classical formula [46]:

$$F = \frac{MS_{between}}{MS_{within}} \quad (1)$$

where $MS_{between}$ —mean square of deviations between groups, and MS_{within} —mean square of deviations within groups.

The MS values were determined from the equations:

$$MS_{between} = \frac{SS_{between}}{k - 1} \quad (2)$$

$$MS_{within} = \frac{SS_{within}}{N - k} \quad (3)$$

where $SS_{between}$ —sum of squares of deviations between groups, SS_{within} —sum of squares of deviations within groups, k —number of groups (in the case of the present analysis, $k = 4$), and N —total number of observations.

The ANOVA test verified the null hypothesis [47]:

$$H_0 : \mu_1 = \mu_2 = \mu_3 = \mu_4 \quad (4)$$

where μ_i denotes the mean value of the parameter in operating state T_i . Rejection of the hypothesis indicated the existence of significant differences between the operating states of the biogas plant.

Due to heterogeneity of variances and differences in sample sizes, the Games–Howell post hoc test was used to compare pairs of means without the assumption of homogeneity of variances. In this test, the generalised standard error was calculated as [48]:

$$SE_{ij} = \sqrt{\frac{s_i^2}{n_i} + \frac{s_j^2}{n_j}} \quad (5)$$

where s_i^2 , s_j^2 —variances in groups i and j , and n_i , n_j —numbers of observations in the respective groups.

The comparative statistic was determined as:

$$p\text{-value} = \frac{\Delta\text{mean}}{SE_{ij}} = \frac{\bar{x}_i - \bar{x}_j}{SE_{ij}} \quad (6)$$

where $\bar{x}_i$, $\bar{x}_j$ —the mean in groups i and j , and SE_{ij} —the standard error of the difference in means.

The effective degrees of freedom were calculated using the Welch–Satterthwaite formula [48]:

$$df = \frac{\left(\frac{s_i^2}{n_i} + \frac{s_j^2}{n_j}\right)^2}{\frac{s_i^4}{n_i^2(n_i - 1)} + \frac{s_j^4}{n_j^2(n_j - 1)}} \quad (7)$$

which ensured the validity of the inference despite unequal variances. The Games–Howell test was applied separately to phase voltages, the THD_U coefficient, the power factor $\cos\varphi$, and active and reactive power, enabling the precise identification of pairs of states for which there are statistically significant differences. The interpretation of the Games–Howell test results presented in the tables involved analysing the differences in means (Δmean) and the corresponding p -values. Large Δmean values indicate significant differences between operating states, while a $p\text{-value} < 0.05$ indicates that the difference is statistically significant. The combination of measurement, statistical, and graphical methods allowed for a comprehensive, multidimensional assessment of the impact of biogas plant operation and fermenter mixers on the power quality in the local power supply system.

The analysis of the impact of agricultural biogas plant operation on power quality parameters should be supplemented with basic dependencies resulting from the theory of power flow in power systems. In the steady state, the complex power flow can be described by the relationship:

$$S = P + jQ = V \cdot I^* \quad (8)$$

where P , Q —active and reactive power, respectively, and V , I^* —complex values of voltage and current.

For a simplified model of a line with an impedance consisting of resistance (R) and reactance (X) and small phase shift angles, the voltage change in the receiving node can be approximated by the following relationship:

$$\Delta U \approx \frac{R \cdot P + X \cdot Q}{U_n} \quad (9)$$

where U_n is the rated voltage of the network.

This equation indicates that both active and reactive power flow directly affect the voltage level at the connection point [21,24].

In the case of operation of an agricultural biogas plant, the presence of a generation source leads to a change in the direction of active power flow. When energy is fed back into the network ($P < 0$ is assumed), the R-P component becomes negative, which results in an increase in voltage at the connection point. This mechanism explains the increase in voltage observed in the tests during generator operation and its decrease when the generation is turned off. At the same time, the impact of reactive power can be considered through a differential relationship:

$$\frac{\partial U}{\partial Q} \approx \frac{X}{U_n} \quad (10)$$

which indicates an important role of the nature of the load, especially in the case of inductive consumers, such as motors driving mixers [21,23].

Harmonic distortion is an important element of power quality analysis and arises from the non-linear nature of electrical loads. The voltage waveform in such a system can be written as a Fourier series expansion:

$$u(t) = U_1 \sin(\omega t) + \sum_{h=2}^{\infty} U_h \sin(h\omega t + \varphi_h) \quad (11)$$

where h is the harmonic number.

The total voltage distortion factor is defined as:

$$\text{THD}_U = \frac{\sqrt{\sum_{h=2}^{50} U_h^2}}{U_1} \quad (12)$$

The level of harmonic distortion depends on the value of harmonic currents and network impedance for a given frequency, which can be written as:

$$U_{Uh} = Z_h \cdot I_h \quad (13)$$

where Z_h —the network impedance for harmonic order h , I_h —the current flowing in the network for the harmonic of order h .

In practice, this means that the presence of a local generation source increases the effective voltage “stiffness” of the system, limiting the impact of harmonics on the voltage, which is confirmed by analyses reported in the literature [25,49].

Another issue is voltage unbalance, which can be described using the symmetric components method. The Fortescue transformation has the form:

$$\begin{bmatrix} V_0 \\ V_1 \\ V_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_{L1} \\ V_{L2} \\ V_{L3} \end{bmatrix} \quad (14)$$

where V_0 , V_1 , V_2 —voltage components, respectively: zero, positive and negative; V_{Li} —voltage in individual phases (L1-L3); and a —the phase-rotation operator in the complex plane described by the equation:

$$a = e^{j\frac{2\pi}{3}} \quad (15)$$

The zero-sequence component is particularly sensitive to the presence of single-phase loads, while the negative-sequence component reflects the uneven distribution of loads between phases [22,39].

From the point of view of the theory of power systems, the concept of voltage stiffness is also important, which describes the ability of the system to maintain a stable voltage

level with changing load. It can be approximated as the inverse of the impedance seen from the connection point:

$$S_k \approx \frac{U_n^2}{Z_{eq}} \quad (16)$$

where S_k —the short-circuit power at the connection point, and Z_{eq} —the network equivalent impedance.

The increase in short-circuit power caused by the presence of a local generation source leads to increased voltage stiffness and reduced voltage variability [34,36].

The presented theoretical relationships allow for a mechanistic explanation of the observed measurement results. In particular, the increase in voltage in states with generation is a direct consequence of the reversal of the direction of active power flow, while its decrease in states without generation results from the dominance of loads. The higher harmonic distortion values observed in these states can be interpreted as resulting from the greater influence of non-linear loads under conditions of lower voltage stiffness. In turn, voltage unbalance remains primarily a function of the load structure, which indicates the dominant role of single-phase loads. Taking into account the above dependencies makes it possible to link experimental observations with fundamental physical mechanisms occurring in the power system, which significantly strengthens the interpretation of the results and goes beyond purely statistical analysis.

3. Results and Discussion

3.1. Variability Graphs of the Analysed Parameters

The recorded phase voltage waveforms at the connection point of a farm with an operational agricultural biogas plant (Figure 1a) show variations in supply parameters typical of low-voltage networks, resulting from the combined effects of a local generation source and a variable load. The voltages in the individual phases (U_{L1} , U_{L2} , U_{L3}) varied smoothly and in a correlated manner, confirming the dominant influence of the biogas plant's operation on all phases. Voltage waveforms analysed in the time domain showed no significant deviations from mean values or sudden, large-amplitude changes, which indicates the stable nature of the system operation in the analysed time scale. Additionally, the analysis of the minimum and maximum values in one-minute measurement intervals (not included in this study due to their small deviations from the mean values) did not show any significant deviations from the mean values, which confirms the lack of significant slowly changing voltage disturbances. It should be noted, however, that the time resolution of the measurements used does not allow the identification of short-term dynamic phenomena, therefore the conclusions refer to the long-term stability of the system. The differences in phase voltages were minor and did not indicate any significant power supply asymmetry. The results indicate that the biogas plant operated in a manner that stabilised the local voltage, and its impact on power quality at the connection point was beneficial, helping maintain stable power supply parameters.

The phase voltages recorded at the farm's connection point during biogas plant operation with active fermenter mixers (Figure 1b) show increased variability compared to the period without the additional load from the mixers. The voltage waveforms remained smooth and changed in parallel, confirming the stable operation of the biogas plant generator and the absence of sudden grid disturbances (most of the recorded voltage values remained within the $\pm 10\%$ U_n range specified by the relevant standards). The increase in voltage variability was mainly due to the additional inductive load; however, the power supply parameters remained stable and fell within the typical range for a low-voltage grid. During periods when the mixers were not in operation, voltages in all

phases remained higher, and after the mixers were switched on, the values decreased by approximately 2–2.5 V.

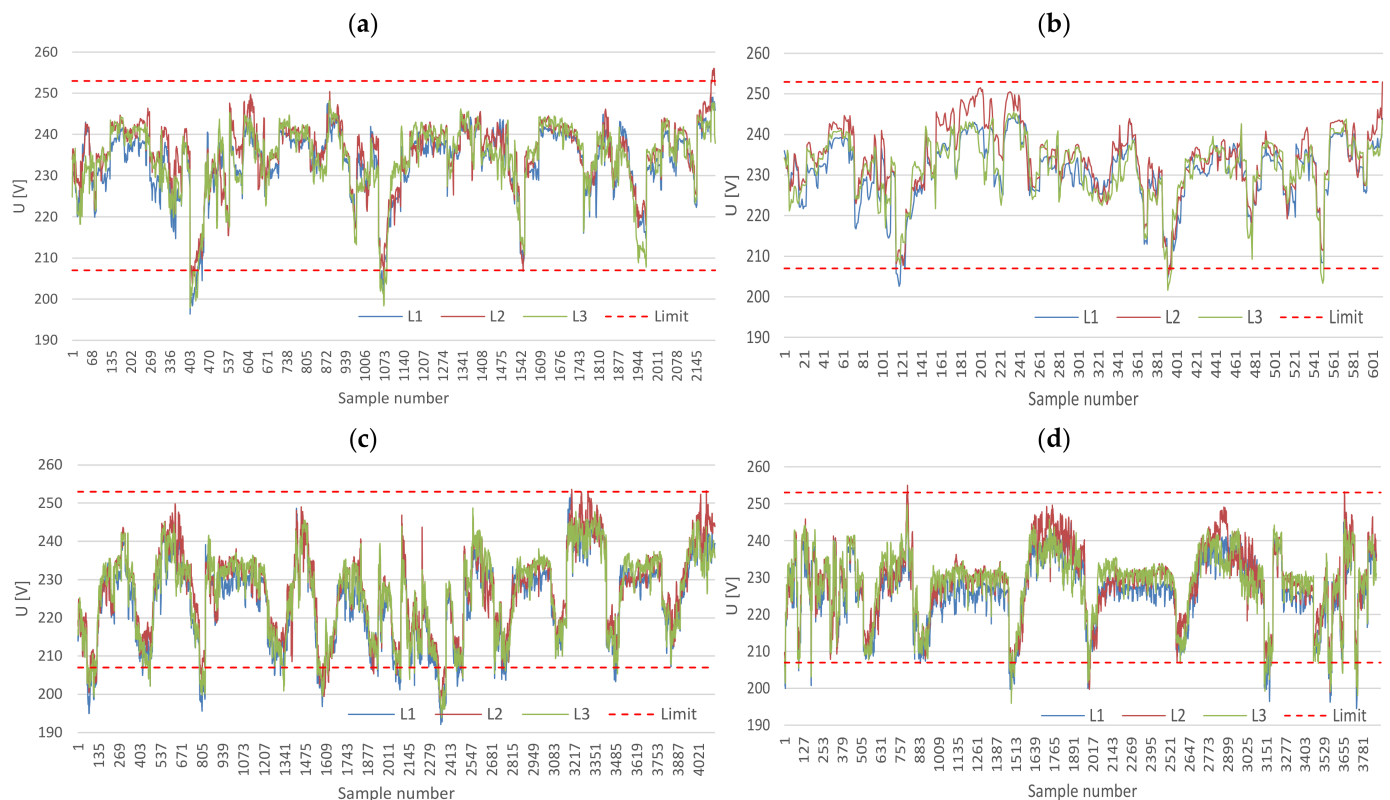


Figure 1. Waveform of phase voltage variations recorded during (a) operation of the agricultural biogas plant generator, with the fermenter mixers switched off; (b) operation of the agricultural biogas plant generator, with the fermenter mixers switched on; (c) the agricultural biogas plant generator at a standstill, with the fermenter mixers switched off; (d) the agricultural biogas plant generator at a standstill, with the fermenter mixers switched on.

Voltage variability during the period when the biogas plant was not operating was significantly greater than during operation, both with the mixers (Figure 1d) and without them (Figure 1c). Compared to earlier measurements, the voltage when the biogas plant was not operating was lower, more variable and less predictable, confirming that the operation of the biogas plant—both on its own and with the mixers—has a stabilising effect on the local low-voltage grid. Voltage variability during the period when the biogas plant was not generating power but the fermenter mixers were operating was significantly greater than during generator operation, though lower than when neither the biogas plant generator nor the mixers were operating. The average voltage was approximately 3–5 V lower than during biogas plant generator operation but higher than when neither the generator nor the mixers were operating.

When the agricultural biogas plant generator was operating with the fermenter mixers switched off (Figure 2a), the zero-sequence voltage unbalance (k_{U0}) showed marked variability, with numerous short-term fluctuations and periodic increases (from 0.5% to 3.6%). This variability, observed despite relatively stable process conditions, may indicate the influence of local asymmetric single-phase loads occurring in the system. However, it should be emphasised that this is an interpretation based on the observed nature of changes, and not a direct result of measuring the sources of unbalance. In contrast, the negative-sequence voltage unbalance (k_{U2}) remains at a low, stable level, indicating the absence of dynamic sources of asymmetry and the uniform nature of the phase load when

the mixers are not operating. Consequently, the zero-sequence component remains the main source of voltage asymmetry variation, while the negative-sequence component reflects only the system's constant, minor impedance differences.

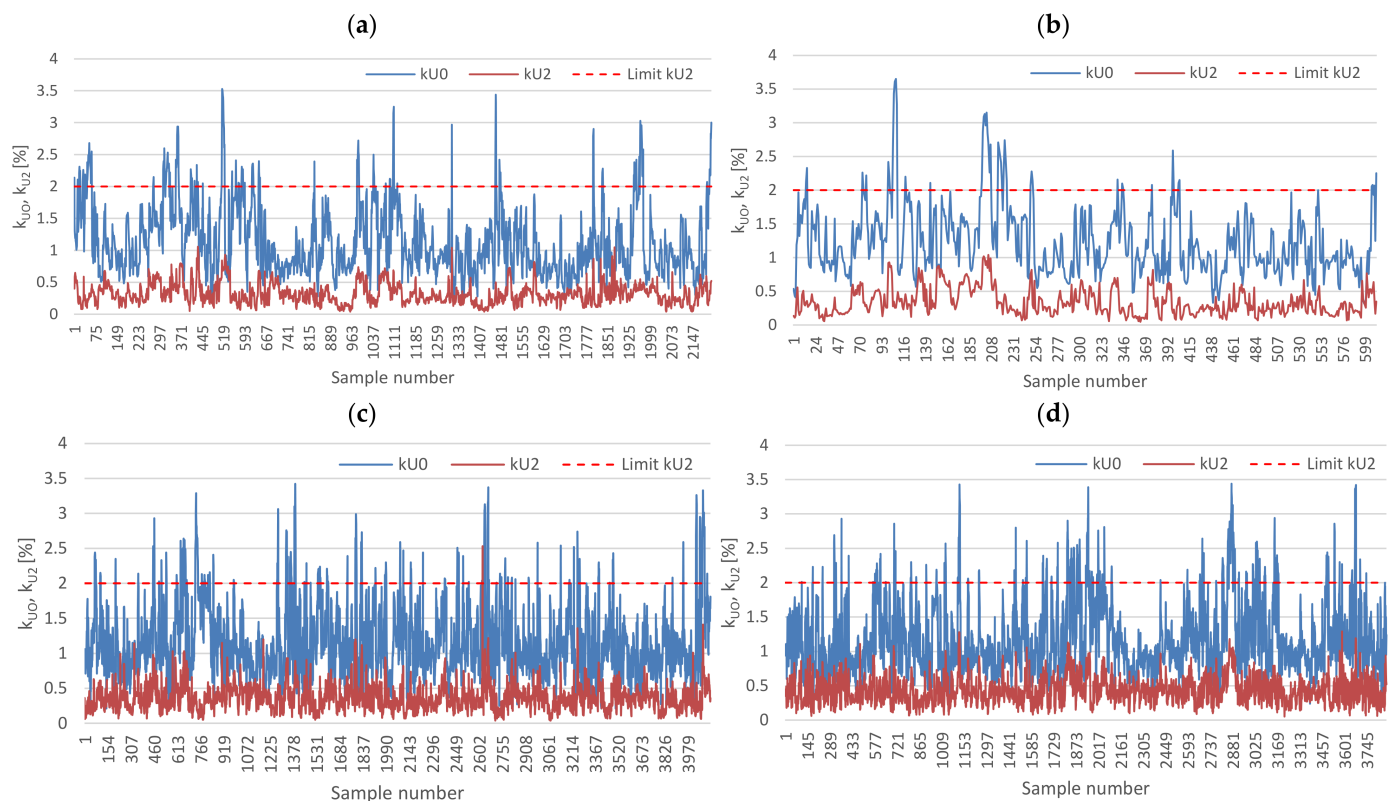


Figure 2. Variation in zero-sequence (k_{U0}) and negative-sequence (k_{U2}) recorded during (a) operation of the agricultural biogas plant generator, with the fermenter mixers switched off; (b) operation of the agricultural biogas plant generator, with the fermenter mixers switched on; (c) when the agricultural biogas plant generator was shut down, with the fermenter mixers switched off; (d) when the agricultural biogas plant generator was shut down, with the fermenter mixers switched on.

The fluctuations in the zero-sequence voltage unbalance factor observed during operation of the biogas plant generator with the mixers switched off are consistent with results reported in the literature on low-voltage networks with distributed energy sources. As Liao and Milanović [22] point out, the zero-sequence component is particularly sensitive to local, irregular single-phase loads, which can generate short-term asymmetry pulses even under stable operating conditions of a three-phase source. The authors emphasise that in networks with distributed generation, zero-sequence asymmetry more often reflects the nature of the loads rather than the operation of the source itself.

When the biogas plant generator was operating with the fermenter mixers switched on (Figure 2b), the variability of the asymmetry factors was similar to the previous condition without mixers. Both the zero-sequence and negative-sequence voltage unbalance factors reached values similar to those described earlier, despite the operation of the fermenter mixer motors (approximately 1.25% and 0.5%, respectively). The negative-sequence voltage component remains relatively stable, but its level is slightly higher than before, indicating increased, though still moderate, phase asymmetry. The variability of the voltage asymmetry coefficients during the period when the biogas plant generator was switched off, and the fermenter mixers were not operating (Figure 2c), was clearly greater than in the other operating states. The zero-sequence asymmetry coefficient remained at a similar level across all analysed cases. The negative-sequence voltage unbalance factor showed

significant deviations (up to 2.5%). The absence of power generation and the absence of additional load from the mixers did not lead to a more predictable, static asymmetry profile, confirming that this value is primarily influenced by the loads operating on the analysed farm. The variability of voltage asymmetry coefficients during the period when the biogas plant was not generating power but the fermenter mixers were operating (Figure 2d) was similar to that in the previous case (Figure 2c). The measurement results indicate that the operation of the mixers in the analysed farm does not increase the voltage unbalance occurring in its power supply system.

A comparison of the biogas plant generator's operation with and without the mixers running indicates that the presence of the mixer motors does not significantly affect the level of voltage asymmetry. This is consistent with the findings of Liao and Milanović [22], who demonstrated that induction motors operating in steady state rarely generate significant negative-sequence components, and that variable single-phase loads remain the dominant factor shaping asymmetry. The slight increase in k_{U2} during mixer operation can be interpreted as the effect of an additional, yet still symmetrical, three-phase load, as confirmed by the observations of Nandini et al. [38], who reported a moderate influence of three-phase loads on the formation of phase asymmetry. The greatest variability in the asymmetry coefficients was observed when the generator and mixers were switched off. In this case, the voltage asymmetry profile was more dynamic, and k_{U2} reached up to 2.5%. This result is consistent with the analyses by Hołdyński [50], who emphasises that the absence of a local generation source increases the grid's susceptibility to asymmetry originating from single-phase loads, particularly on farms with a varied load structure. A similar level of asymmetry variability when the generator was switched off but the mixers were operating confirms that the mixers themselves do not constitute a significant source of asymmetry, which is consistent with the findings of Jarrar et al. [9], who indicate that biogas plant equipment has a limited impact on power quality compared to farm loads. This pattern is also confirmed by Shin et al. [33], who emphasise that the negative-sequence component is particularly sensitive to asymmetrical single-phase loads, rather than to three-phase loads with stable operating characteristics.

The variability in the voltage distortion factor during biogas plant operation without fermenter mixers (Figure 3a) was moderate, and the waveforms were stable across all three phases. In each phase, THD_U fluctuated within a few per cent, with low variability and waveforms free of sudden spikes.

Switching on the fermenter mixers did not cause any significant changes in the voltage distortion factor (Figure 3b). When the biogas plant generator was switched off, and the mixers were not operating (Figure 3c), the voltage distortion factor remained at the lowest and most stable level among the four analysed operating states. In the operating state in which the biogas plant generator was switched off but the fermenter mixers were operating (Figure 3d), the THD_U waveforms were more dynamic than in the no-load condition—periodic increases and decreases were visible, and the values frequently exceeded 4%. Nevertheless, the recorded values of the total harmonic distortion of voltage in all analysed operating states were below the 8% limit specified in the standard [41], with the highest recorded value being 7.02%.

The stable, moderate level of the voltage distortion factor (THD_U) during biogas plant operation without mixers is consistent with results from studies on the operation of synchronous and induction generators under constant load conditions. As Shin et al. [33] point out, in systems without dynamic loads, harmonic distortion waveforms exhibit low variability and lack sudden spikes, resulting from the dominance of harmonics originating in the grid rather than in local process equipment. The absence of significant changes in THD_U following activation of the fermenter mixers suggests that the mixer motors do not

contribute significantly to harmonics. This is consistent with the observations of Oubrahim et al. [8], who emphasise that induction motors with soft start-up and steady-state operation contribute little to harmonic distortion, and that their impact on THD is usually marginal compared to power electronic converters. Jarrar et al. [9] indicate that biogas plants in a no-load condition exhibit voltage waveforms dominated by harmonics originating from the main grid, which are typically characterised by greater stability. Conversely, the increase in THD_U dynamics with the generator switched off but the mixers running is consistent with the findings of Servati and Hajinezhad [28], who demonstrated that motors operating under variable hydraulic load can generate periodic variations in currents and voltages, leading to an increase in the proportion of higher harmonics.

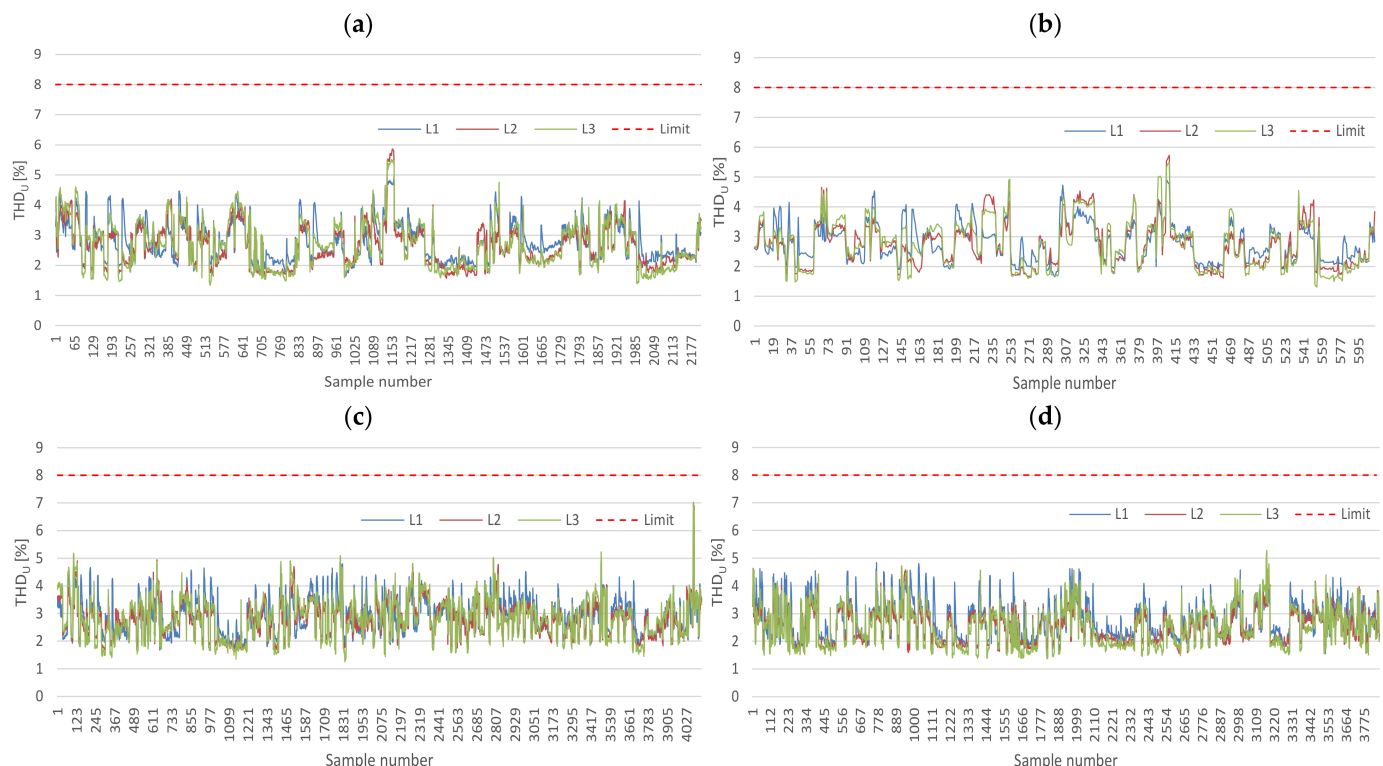


Figure 3. Variation in the voltage distortion factor THD_U recorded during (a) operation of the agricultural biogas plant generator, with the fermenter mixers switched off; (b) operation of the agricultural biogas plant generator, with the fermenter mixers switched on; (c) the agricultural biogas plant generator at a standstill, with the fermenter mixers switched off; (d) the agricultural biogas plant generator at a standstill, with the fermenter mixers switched on.

3.2. Statistical Analysis of the Results

The statistical data presented in Table 2 enable an assessment of power quality and the operating conditions of the farm's power supply system across four characteristic operating states of the biogas plant. Mean values and measures of variability, including variance and standard error, are important for assessing the level and stability of the analysed quantities and for interpreting power quality. The median, skewness, and kurtosis coefficients were also analysed, but they play an auxiliary role in interpreting data distributions.

The mean voltage values recorded during operation of the biogas plant without mixers indicate a slight increase relative to the rated value, with good interphase balance. Switching on the mixers reduced the voltage in the first and third phases by approximately 2.2 V, with a change of only 1.3 V in the second phase. Switching off the generator reduced the voltage in the farm's power supply system under analysis. During generation at the biogas plant, all voltages are characterised by a strongly negative skew (from approximately

−0.6 to −1.5), which means that the distributions are skewed towards lower values, with most observations clustered above the mean. This is also confirmed by median values that are higher than the mean values. In conditions without the generator running (T3 and T4), the skewness of the voltages is lower in absolute terms (from approximately −0.2 to −0.97), indicating more symmetrical distributions, though still with a slight predominance of the tails on the lower voltage side. The kurtosis of voltages with the generator operating (T1 and T2) is positive, often exceeding 1, indicating more leptokurtic distributions with a greater proportion of extreme values. In T3, the kurtosis of voltages is slightly negative, suggesting distributions close to normal or slightly flattened, whereas in T4, the kurtosis is slightly positive, indicating a moderate concentration around the mean. Voltage variances are clearly greater in states without generation (T3 and T4) than when the generator is running, indicating greater voltage variability when powered solely by the external grid. However, the standard error of the mean remains small (0.15–0.35 V), indicating a large sample size and high reliability of the estimates.

Table 2. Results of the statistical analysis of parameters describing the farm power supply system in four characteristic operating states of the biogas plant: T1, T2, T3, and T4. THD_{UL1}, THD_{UL2}, THD_{UL3}—voltage distortion factor in individual phases, P—three-phase active power, Q—three-phase reactive power, cosφ—power factor.

Parameter	Mean				Median				Skewness			
	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
U _{L1}	233.2	231.0	224.4	226.4	234.9	232.0	227.3	227.0	−1.47	−0.98	−0.32	−0.63
U _{L2}	235.3	234.0	227.1	229.0	236.6	234.5	228.8	229.6	−1.23	−0.61	−0.2	−0.38
U _{L3}	234.0	231.7	226.1	228.7	235.6	233.3	228.9	230.3	−1.52	−1.06	−0.44	−0.97
THD _{UL1}	2.76	2.78	2.87	2.7	2.6	2.64	2.83	2.56	0.81	0.64	0.55	0.65
THD _{UL2}	2.64	2.72	2.78	2.52	2.52	2.68	2.79	2.46	1.06	0.81	0.65	0.6
THD _{UL3}	2.68	2.74	2.83	2.52	2.61	2.71	2.85	2.48	0.64	0.45	0.40	0.49
cosφ	−0.39	−0.15	0.38	0.59	−0.85	−0.48	0.84	0.92	0.93	0.52	−0.88	−1.5
P	−7385	−2616	3441	5973	−9544	−4855	3711	7450	0.57	0.41	−0.34	−0.91
Q	4457	6590	2053	1688	4162	5973	861	91.26	0.98	0.08	1.03	1.14
k _{U0}	1.14	1.24	1.15	1.18	0.99	1.12	1.05	1.05	1.15	1.28	1.14	1.18
k _{U2}	0.32	0.34	0.36	0.42	0.29	0.29	0.34	0.39	1.02	1.06	1.54	0.95

Parameter	Kurtosis				Variance				Standard error			
	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
U _{L1}	2.67	1.21	−0.59	0.17	69.96	62.53	130.82	84.05	0.18	0.32	0.18	0.15
U _{L2}	1.92	0.79	−0.58	0.04	68	73.81	120.99	87.39	0.18	0.35	0.17	0.15
U _{L3}	2.64	1.61	−0.74	0.6	77.80	61.41	126.81	82.11	0.19	0.32	0.18	0.15
THD _{UL1}	0.20	−0.11	0.03	−0.39	0.39	0.41	0.44	0.44	0.013	0.026	0.01	0.011
THD _{UL2}	2.38	0.55	1.61	−0.08	0.47	0.58	0.39	0.33	0.015	0.031	0.01	0.009
THD _{UL3}	0.19	−0.3	0.75	−0.42	0.62	0.68	0.52	0.48	0.017	0.033	0.011	0.011
cosφ	−0.81	−1.32	−0.97	0.71	0.54	0.51	0.56	0.40	0.016	0.029	0.012	0.01
P	−0.6	−0.51	−0.27	1.64	91 × 10 ⁶	90 × 10 ⁶	77 × 10 ⁶	53 × 10 ⁶	203.42	385.15	136.67	118.01
Q	1.33	−0.65	0.96	1.76	21 × 10 ⁶	27 × 10 ⁶	14 × 10 ⁶	13 × 10 ⁶	99.30	212.26	59.68	59.03
k _{U0}	1.37	2.46	1.54	1.49	0.29	0.28	0.25	0.25	0.011	0.021	0.008	0.008
k _{U2}	1.28	0.73	7.4	1.21	0.03	0.04	0.03	0.03	0.003	0.008	0.003	0.003

In the graphs shown in Figure 4, a higher voltage in phase L2 is evident. The spread of voltage values is significantly smaller when the generator is operating in an agricultural biogas plant. The voltage decrease recorded when the generator was switched off is also noteworthy. The activation of the fermenter mixers did not cause significant changes in voltage across the individual phases.

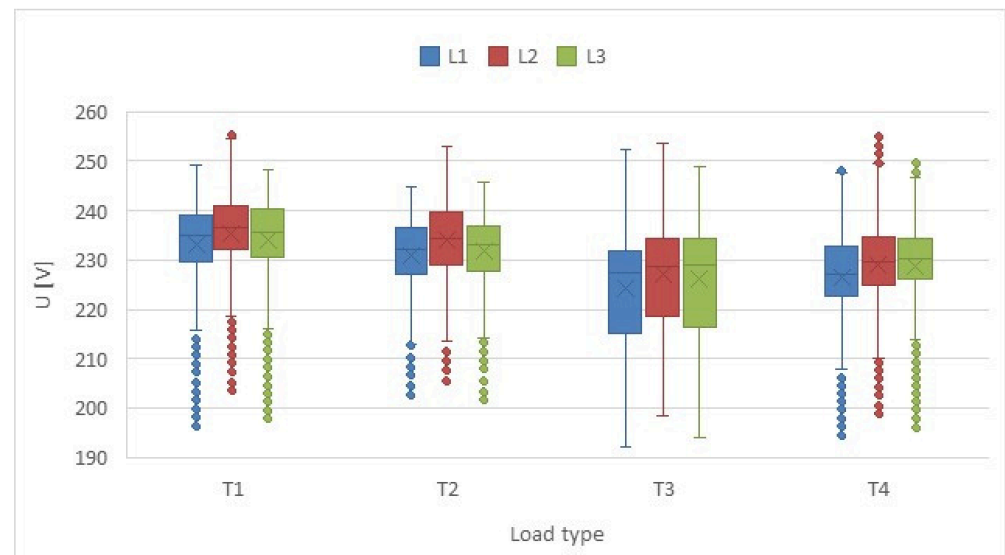


Figure 4. Voltage distributions for individual phases under the four operating states of the power supply system.

To determine the exact influence of the mixers and generator operation on the voltage at the connection point of the analysed farm, an ANOVA supported by the Games–Howell method was performed (Table 3). Due to the large sample size, the statistical analysis could indicate significance even for small differences between the analysed operating states. Changes exceeding the natural variability of a given parameter and those that may affect consumer operation or compliance with the requirements of power quality standards were considered important from a practical point of view [41]. In particular, differences in mean values were analysed in relation to variance and standard error, assuming that consistent and repeatable changes, and not only those that are statistically significant, have operational significance.

Table 3. Results of the post hoc analysis using the Games–Howell method for phase voltages at the farm’s connection point for four operating states of the power supply system.

Operating States Compared	Δ Mean			p-Value			Significance	
	Phase	L1	L2	L3	L1	L2	L3	L1, L2, L3
T1 vs. T2	2.15	1.29	2.29	3.72×10^{-8}	0.005	4.58×10^{-09}	$p < 0.001$ for L1 and L3, $p < 0.01$ for L2	
T1 vs. T3	8.74	8.2	7.87	6.15×10^{-14}	6.15×10^{-14}	6.15×10^{-14}	$p < 0.001$	
T1 vs. T4	6.79	6.24	5.34	6.15×10^{-14}	6.15×10^{-14}	6.15×10^{-14}	$p < 0.001$	
T2 vs. T3	6.60	6.91	5.58	4.3×10^{-14}	2.3×10^{-13}	2×10^{-13}	$p < 0.001$	
T2 vs. T4	4.65	4.95	3.05	4.71×10^{-14}	6.5×10^{-14}	9.96×10^{-14}	$p < 0.001$	
T3 vs. T4	1.95	1.96	2.53	6.22×10^{-14}	6.2×10^{-14}	6.2×10^{-14}	$p < 0.001$	

The results in Table 3 indicate that both power generation and mixer operation influence the phase voltage level. The greatest changes are observed between the states of power generation and no power generation. The greatest difference in mean voltage values was observed between state T1—power generation without operation of the fermenter mixers—and state T3—no power generation and no mixer operation (for all phases), while the smallest difference was between states T1 and T2 for phases L2 and L3, and T3 and T4 for phase L1.

Another important aspect is the analysis of voltage distortion coefficient THD_U . The mean voltage distortion coefficient in the individual states falls within approximately 2.5–2.9%, which is typical for low-voltage networks with power electronic converters and non-linear loads [49,51,52]. The skewness of the THD_U distributions is positive in all states, indicating a predominance of observations below the mean and occasional higher distortion levels. The highest skewness value (1.06) occurs in phase L2 during generator operation, indicating a distinctly elongated tail towards higher distortion levels in this phase. The standard deviations of THD_U are relatively small (of the order of 0.3–0.7), which indicates moderate variability in the distortion coefficients. The standard errors of the THD_U averages are very small (of the order of 0.01–0.03), confirming the stability of the estimates and allowing reliable comparisons between states T1–T4. Figure 5 shows scatter plots of the total harmonic distortion of voltage (THD_U) coefficient for each phase, for the four operating states of the power supply system (T1–T4).

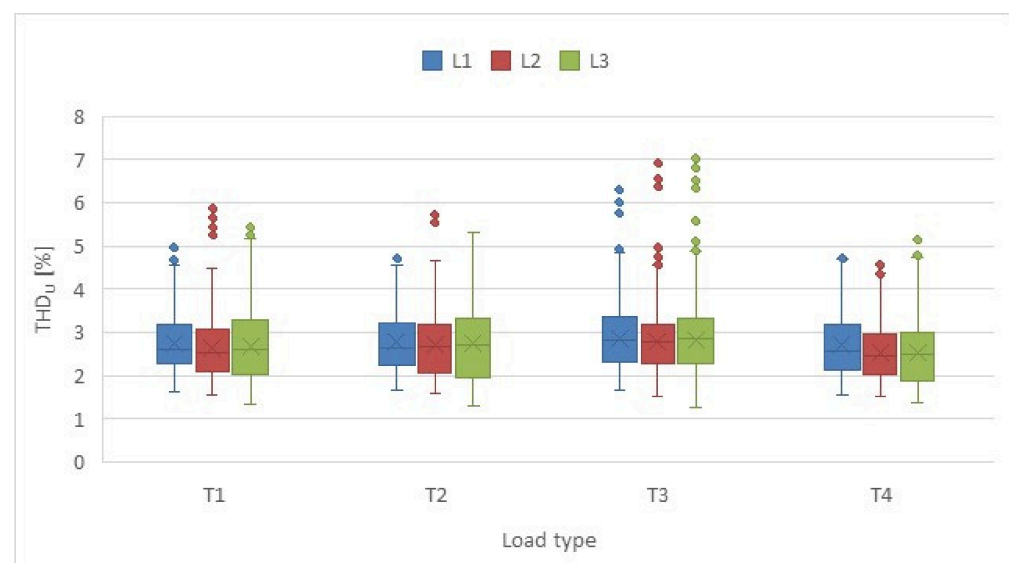


Figure 5. Scatter plots of the voltage distortion coefficient THD_U in individual phases under the four operating states of the power supply system.

For the voltage distortion factor THD_U , the Games–Howell test revealed differences between most of the analysed operating states of the biogas plant (Table 4). No significant differences in THD_U values were found across all phases when comparing T1—power generation without the fermenter mixers operating, with T2—power generation with mixers operating. The greatest difference in mean values was observed between conditions T3—no power generation and no mixer operation and T4—no power generation with mixers operating. The results indicate that the highest values of the voltage distortion coefficient occurred in the operating state involving the operation of the mixers without local generation. However, it should be emphasised that this is an interpretation based on a comparison of statistical results, and not direct evidence of a cause-and-effect relationship. This observation suggests that the lack of generation in the presence of non-linear consumers may contribute to an increase in the harmonic level.

Of particular interest from the point of view of power quality is the power factor $\cos\varphi$ and the associated powers: active P and reactive Q . The analysis adopted a standard sign convention used in the power industry and consistent with the IEC 61000-4-30 and EN 50160 standards. Active power P assumes positive values when energy is consumed from the network and negative when it is released by the generator. Similarly, positive $\cos\varphi$ values correspond to the flow of power to consumers, while negative values indicate the

export of energy to the grid. This interpretation results from the adopted measurement methods and reflects the direction of power flow, not the quality of energy. In each of the analysed cases, the dominant power factor is inductive.

Table 4. Results of the post hoc analysis using the Games–Howell method of the voltage distortion coefficient THD_U in individual phases, for four operating states of the power supply system.

Operating States Compared	Δ Mean			p-Value			Significance
	Phase	L1	L2	L3	L1	L2	L3
T1 vs. T2	0.02	0.08	0.06	0.896	0.0856	0.323	$p > 0.05$
T1 vs. T3	0.11	0.14	0.15	2.52×10^{-10}	6.51×10^{-14}	4.29×10^{-13}	$p < 0.001$
T1 vs. T4	0.05	0.12	0.16	0.0147	6.65×10^{-11}	6.87×10^{-14}	$p < 0.01$ for L1, $p < 0.001$ for L2 and L3
T2 vs. T3	0.09	0.06	0.09	0.0059	0.21	0.0598	$p < 0.01$ for L1, $p > 0.05$ for L2 and L3,
T2 vs. T4	0.07	0.20	0.23	0.0523	6.45×10^{-9}	1.65×10^{-9}	$p > 0.05$ for L1, $p < 0.001$ for L2 and L3
T3 vs. T4	0.16	0.26	0.31	6.2×10^{-14}	6.15×10^{-14}	6.15×10^{-14}	$p < 0.001$

While the generator is operating (T1 and T2), the average $\cos\phi$ takes on negative values, which means that the direction of active power flow is reversed—the farm, together with the biogas plant, feeds active power into the grid. At the same time, the median $\cos\phi$ is even more negative, indicating that, most of the time, the power factor is strongly inductive with power flowing from the local source to the grid. The skewness of the power factor is then positive (0.93 and 0.52), indicating a distribution skewed towards higher values (closer to zero), with most observations clustering around more negative values. In the non-generation system (T3 and T4), the power factor takes on positive values: on average, 0.38 in T3 and 0.59 in T4, with medians of 0.84 and 0.92, respectively. This means that in these states, the farm draws active power from the grid, and the power factor is relatively favourable, particularly in T4, where the values are high (close to 1). The skewness of $\cos\phi$ in T3 is negative (−0.88), indicating a predominance of higher values (closer to unity) and the occasional occurrence of lower values, whereas in T4 the skewness is strongly negative (−1.5), confirming the dominance of high power factor values and a small number of instances where it deteriorates. The kurtosis is negative in T1–T3, suggesting flatter distributions, whereas in T4 it is positive (0.71), indicating greater concentration around high-power-factor values.

The plots shown in Figure 6 demonstrate a clear change in the nature of the power transmitted via the supply line to the analysed farm. In most of the analyses cases, the power factor took on both positive and negative values. Only when the generator was switched off, and the fermenter mixers were operating, did the power factor predominantly exhibit an inductive character. In each case, pronounced fluctuations are visible, indicating high variability in the power factor. This information is relevant from the perspective of reactive power compensation, which enables not only a reduction in charges related to reactive power consumption or injection, but also a reduction in power losses in the farm's electrical system. Farms equipped with agricultural biogas plants may require separate compensation strategies: one to compensate for the reactive power generated/consumed by the biogas plant, and the other to compensate for the reactive power consumed by the loads installed on the farm. The variability in the power factor observed in the tests constitutes important information from the perspective of analysing system operation, but

the conclusions regarding reactive power compensation and loss reduction have general engineering implications. This study did not include a detailed analysis of reactive power flow or optimisation of compensation systems, therefore recommendations regarding the use of specific solutions, such as separation of compensation systems, should be treated as engineering guidelines based on interpretation of the results rather than as direct conclusions from the measurements performed.

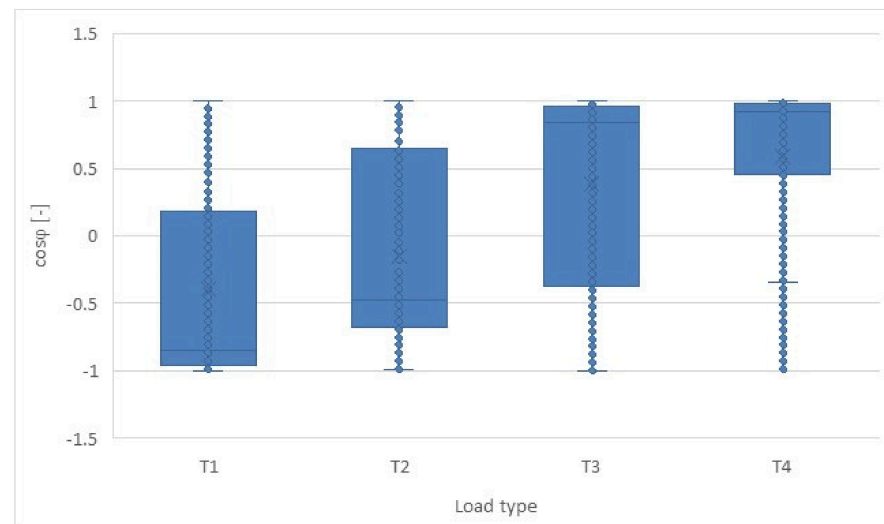


Figure 6. Scatter plots of the power factor $\cos\phi$ for four operating states of the power supply system.

A post hoc analysis using the Games–Howell method revealed differences among all analysed operating states of the biogas plant for the power factor $\cos\phi$ (Table 5). The greatest difference in means was observed between operating conditions T1 and T3, while the smallest was between conditions T3 and T4. The results indicate a clear relationship between the power factor and the operating condition of the analysed plant. The differences in the mean power factor values (Δmean) presented in Table 5 should be interpreted not only in the context of statistical significance, but primarily in the context of their practical engineering significance. Larger Δmean values (above approximately 0.5) correspond to substantial changes in system operation, in particular the transition between the energy consumption and generation modes, which is of significant operational importance. In turn, smaller differences, although statistically significant, reflect only limited changes in operating parameters and are of less practical importance.

Table 5. Results of the post hoc analysis using the Games–Howell method for the $\cos\phi$ parameter for four operating states of the power supply system.

Operating States Compared	Δ Mean	p -Value	Significance
T1 vs. T2	0.244	1.43×10^{-12}	$p < 0.001$
T1 vs. T3	0.775	6.15×10^{-14}	$p < 0.001$
T1 vs. T4	0.983	6.15×10^{-14}	$p < 0.001$
T2 vs. T3	0.53	2.43×10^{-13}	$p < 0.001$
T2 vs. T4	0.739	7.18×10^{-12}	$p < 0.001$
T3 vs. T4	0.208	6.15×10^{-14}	$p < 0.001$

Active power P reflects the direction and intensity of energy exchange between the biogas plant, the farm, and the grid. During generator operation, the average power values are negative (approximately -7.4 kW and -2.6 kW, respectively), confirming that in these

states the system acts as an energy source. Switching on the mixers resulted in partial consumption of the generated power for internal use, reducing the power fed into the grid. When the generator is idle, the average power is positive, indicating power consumption from the grid, and activating the mixers further increases this consumption. The skewness of power during generator operation is positive (0.57 and 0.41), indicating that the distribution is skewed towards higher values (closer to zero and positive), while the majority of observations cluster around more negative power values, which is typical of stable generation. In the absence of generation, the skewness is negative (approximately -0.34 and -0.91), indicating a predominance of higher active power values (greater consumption) and occasional lower loads. The kurtosis of active power is negative in T1–T3, suggesting flatter distributions, whereas in T4 it is positive (1.64), indicating greater concentration around typical power consumption values and a more frequent occurrence of extreme values. The variances of active power are very large (of the order of 5.3×10^7 – $9.1 \cdot 10^7$), reflecting significant variability in load and generation over time; however, the standard error of the mean (of the order of 120–390 W) remains relatively small in relation to the power level, indicating good precision of the estimates.

When the biogas plant generator is operating without fermenter mixers, the box plot shows the widest distribution, indicating the greatest variability in active power and a more variable operating pattern (Figure 7). The median lies closer to the highest negative values, suggesting a distribution closer to the generator's rated power. In states T2 and T3, the range of values is significantly smaller. During periods of no generation and with the fermenter mixers switched off (T3), the median is in the middle of the box, indicating a symmetrical distribution of active power. In contrast, switching on the mixers with the generator switched off (T4) shows the least asymmetry in the distribution, with a narrow range of values.

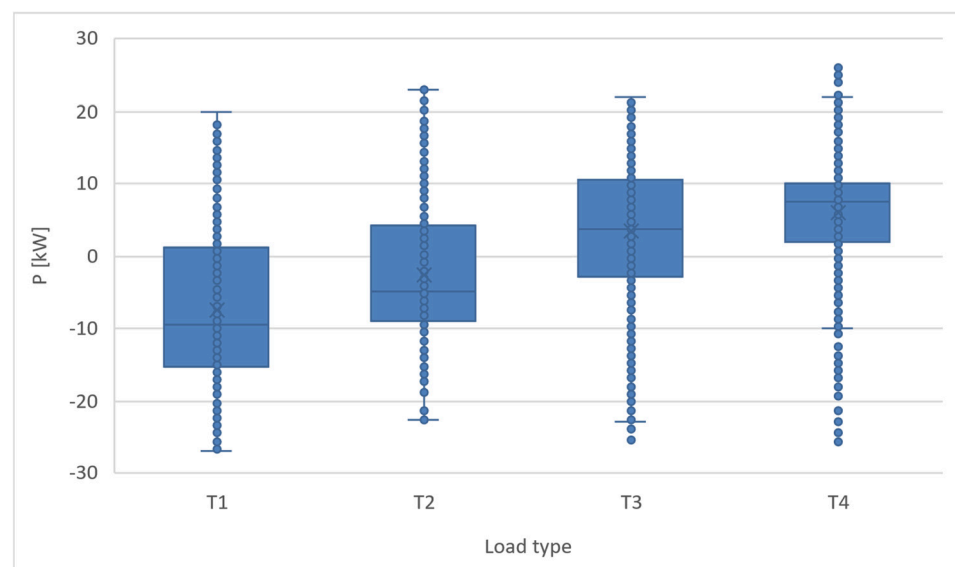


Figure 7. Scatter plots of three-phase active power for four operating states of the power supply system.

A post hoc analysis of active power P using the Games–Howell method (Table 6) revealed differences between all analysed operating states of the biogas plant ($p < 0.001$). The greatest differences in means were observed between states T1 and T4, and the smallest between states T3 and T4. This shows that both power generation and mixer operation influence the level of active power in the analysed energy system.

Table 6. Results of the Games–Howell post hoc analysis of three-phase active power for the four operating states of the power supply system.

Operating States Compared	Δ Mean	p -Value	Significance
T1 vs. T2	2506.803	4.2×10^{-13}	$p < 0.001$
T1 vs. T3	5726.191	8.2×10^{-14}	$p < 0.001$
T1 vs. T4	7777.353	5.73×10^{-14}	$p < 0.001$
T2 vs. T3	3219.389	8.3×10^{-13}	$p < 0.001$
T2 vs. T4	5270.551	3.37×10^{-13}	$p < 0.001$
T3 vs. T4	2051.162	5.8×10^{-14}	$p < 0.001$

Reactive power Q also shows clear variation between states. During generator operation, the average reactive power values are positive and relatively high (approximately 4.5 kvar and 6.6 kvar), which means that the system is associated with substantial inductive reactive power, typical of generator and motor operation. After the generator is switched off, the average reactive power values are lower (approximately 2 kvar and 1.7 kvar), indicating a lower reactive load in the absence of generation, although in T3 the median Q is even lower (approximately 861 var), and in T4 very low (approximately 91 var), suggesting that the Q distribution is strongly asymmetric. The skewness of reactive power in states T1, T3, and T4 is positive (approximately 1), indicating a predominance of lower values and the occasional occurrence of higher reactive power values, whereas in T2, the skewness is close to zero (0.08), indicating a distribution close to symmetric. The kurtosis of reactive power is positive in all states, indicating leptokurtic distributions with a high concentration around typical values and a greater frequency of extreme values. The variances of Q are very high (of the order of 1.3×10^7 – 2.7×10^7), reflecting the high variability of reactive power; however, the standard errors of the mean (approximately 60–210 var) are relatively small.

During operation of the biogas plant generator, the reactive power box is relatively narrow (Figure 8), and the median lies in the upper part of the interquartile range, indicating moderate reactive power generation and a stable operating profile. The generation system with the mixers in operation is characterised by far the greatest range of values—both in terms of the width of the interquartile range and the number of outliers. The high median and high variability indicate a load of a strongly inductive nature and dynamic changes in reactive power demand. Operating states without generation show a lower median level and a moderate box width, which indicates lower variability of the reactive power flow in the system.

A post hoc analysis using the Games–Howell method for reactive power (Q) also revealed differences across all analysed operating states of the biogas plant (Table 7). The greatest differences in mean values were observed between states T1 and T4, while the smallest differences occurred between states T3 and T4. Therefore, both power generation and mixer operation influence the level of reactive power in the analysed system.

The mean values of zero-sequence voltage asymmetry across all operating states fall within narrow ranges of approximately 1.14–1.24 in T1–T2 and 1.15–1.18 in T3–T4, indicating a moderate level of zero-sequence voltage asymmetry. The medians are close to the means, suggesting relatively symmetrical distributions. The skewness of kU_0 is positive in all states (approximately 1.14–1.28), indicating a predominance of lower values of the coefficient and occasional higher levels of asymmetry. The kurtosis is positive, indicating distributions with a high concentration around the mean and more frequent extreme values. The variances of the zero-sequence voltage unbalance are small (approximately 0.27), and

the standard errors are very small (of the order of 0.008–0.021), indicating the stability of this parameter.

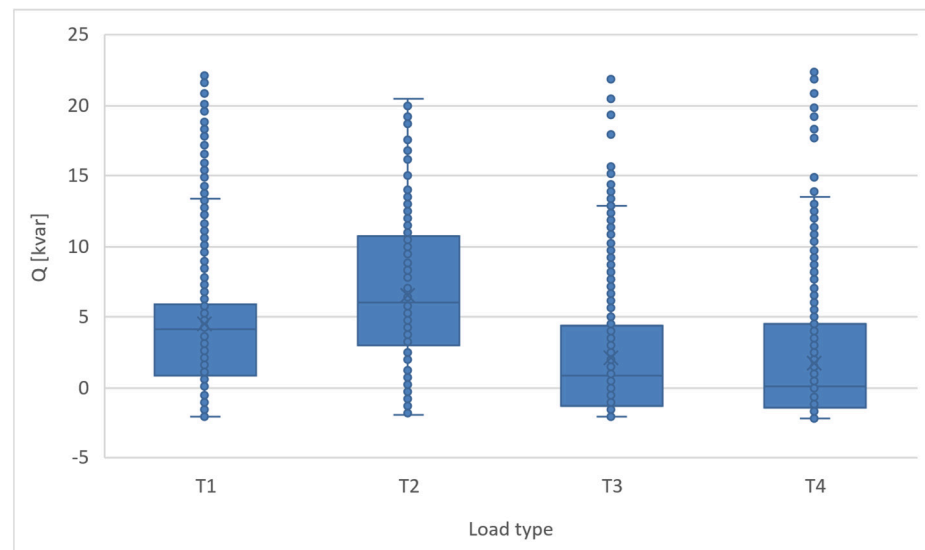


Figure 8. Scatter plots of three-phase reactive power for four operating states of the power supply system.

Table 7. Results of the post hoc analysis using the Games–Howell method for three-phase reactive power, for four operating states of the power supply system.

Operating States Compared	Δ Mean	p -Value	Significance
T1 vs. T2	2153.166	3×10^{-12}	$p < 0.001$
T1 vs. T3	1812.548	5.3×10^{-13}	$p < 0.001$
T1 vs. T4	1115.261	6.15×10^{-14}	$p < 0.001$
T2 vs. T3	3965.715	4.4×10^{-13}	$p < 0.001$
T2 vs. T4	3268.428	9×10^{-13}	$p < 0.001$
T3 vs. T4	697.287	6.15×10^{-14}	$p < 0.001$

As shown in Figure 9, the statistical parameters describing the zero-sequence voltage unbalance factor are very similar: the medians, interquartile ranges, and whisker ranges are almost identical. This means that the analysed parameter k_{U0} behaves stably and shows no significant differences between operating states, and any spikes in values are incidental rather than systemic. In each case, the whiskers range from values close to zero to approximately 3.5, indicating that in every state there are periods with a significantly increased proportion of the zero-sequence component. The numerous outliers visible in the data indicate sporadic but distinct deviations from the typical range, which may result from short-term disturbances in voltage asymmetry. It can also be observed that the operation of the fermenter mixers leads to a slight increase in the zero-sequence voltage unbalance.

A post hoc analysis using the Games–Howell method of the zero-sequence voltage unbalance factor (Table 8) revealed differences for most of the analysed operating states of the biogas plant. No significant differences were found between T1 and T3, or between T3 and T4 ($p > 0.05$). The greatest difference in means was observed between states T1 and T2. The results indicate that the effect of the analysed operating states on the zero-sequence voltage component is unclear, and some comparisons do not reach statistical significance. At the same time, the operating state with mixer operation (T2) shows significant differences

from the other states, which suggests that mixer operation may be an important factor shaping the value of the voltage zero-sequence unbalance factor.

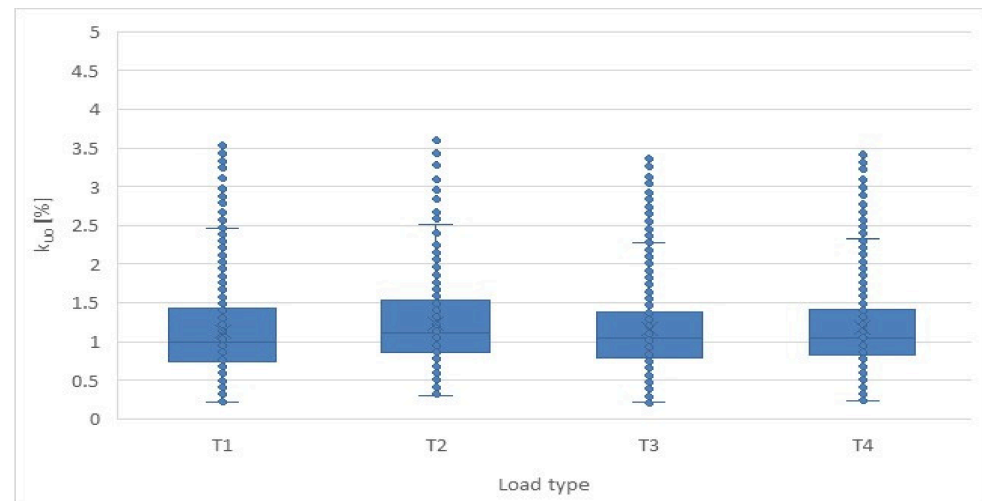


Figure 9. Scatter plots of the zero-sequence voltage unbalance factor for four operating states of the power supply system.

Table 8. Results of the post hoc analysis using the Games–Howell method of the zero-sequence voltage unbalance factor for four operating states of the power supply system.

Operating States Compared	Δ Mean	p -Value	Significance
T1 vs. T2	0.099	0.0002	$p < 0.001$
T1 vs. T3	0.018	0.5606	$p > 0.05$
T1 vs. T4	0.04	0.0217	$p < 0.05$
T2 vs. T3	0.081	0.0019	$p < 0.01$
T2 vs. T4	0.059	0.0453	$p < 0.05$
T3 vs. T4	0.022	0.2017	$p > 0.05$

The negative-sequence voltage unbalance factor increased from 0.32 in T1 to 0.34 in T2 and from 0.36 in T3 to 0.42 in T4. This means that the highest level of negative-sequence voltage unbalance occurred when the generator was not operating and the fermenter mixers were running. The medians of the k_{U2} coefficient are slightly lower than the averages in T1–T3 (0.29–0.34), whereas in T4 the median is 0.39, confirming a higher typical level of unbalance. The skewness of k_{U2} is positive in all analysed cases, indicating a predominance of lower values of the coefficient and occasional higher levels of unbalance. The particularly high skewness in T3 (1.54) indicates a distribution with a long tail towards higher k_{U2} values, even though the average level of unbalance is lower there than in T4. The kurtosis of k_{U2} is positive in all states, reaching a very high value (7.4) in T3, indicating a strongly leptokurtic distribution with a high concentration around typical values and sporadic, but clearly elevated, episodes of unbalance. The variances are very small (0.03–0.04), and the standard errors are of the order of 0.003–0.008, which confirms the high stability of this parameter over time.

The outlier clusters of the negative-sequence voltage unbalance factor visible in Figure 10 are similar across the analysed operating modes, indicating a wide range of observed values. The numerous outliers shown in the figure indicate that episodes of significantly increased negative-sequence voltage unbalance occurred in each state. Compared with the zero-sequence voltage unbalance factor, the number and spread of these points are

greater, suggesting that the negative-sequence voltage unbalance factor is more susceptible to short-term disturbances.

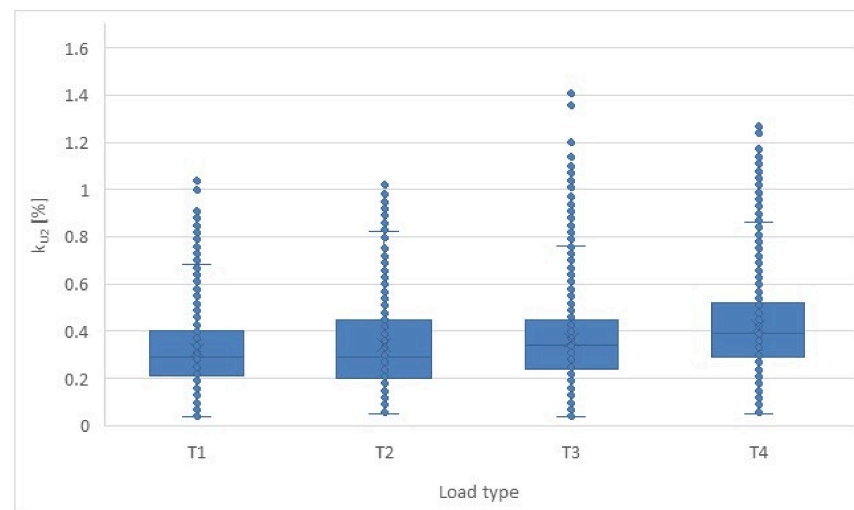


Figure 10. Scatter plots of the negative-sequence voltage unbalance factor for four operating states of the power supply system.

A post hoc analysis using the Games–Howell method for the negative-sequence voltage unbalance factor revealed the greatest difference in mean values between states T1 and T4, and the smallest between states T1 and T2 (Table 9). The results indicate that the negative-sequence voltage unbalance factor depends on the operating state of the analysed system. At the same time, both power generation and mixer operation influence changes in voltage asymmetry. The greatest differences occurred between states with power generation and those without.

Table 9. Results of the post hoc analysis using the Games–Howell method of the negative-sequence voltage unbalance factor for four operating states of the power supply system.

Operating States Compared	Δ Mean	p -Value	Significance
T1 vs. T2	0.022	0.047	$p < 0.05$
T1 vs. T3	0.046	6.2×10^{-14}	$p < 0.001$
T1 vs. T4	0.103	6.15×10^{-14}	$p < 0.001$
T2 vs. T3	0.024	0.024	$p < 0.05$
T2 vs. T4	0.081	9.48×10^{-12}	$p < 0.001$
T3 vs. T4	0.056	6.15×10^{-14}	$p < 0.001$

The observed effects, in particular the increase in the voltage level during generator operation and changes in the level of harmonic distortion depending on the system configuration, remain consistent with the theoretical relationships describing the power flow in power networks. This indicates that the identified mechanisms are not accidental or exclusively local, but result from the general properties of power systems. The results indicate that the effect of biogas plant operation on power quality parameters varies and depends on both the presence of generation and the nature of local loads. In the analysed system, voltage stabilisation related to generator operation does not always translate into a clear reduction in the level of disturbances, such as unbalance or harmonic distortions, which is consistent with research results indicating the important role of non-linear consumers and power electronic converters in shaping power quality [23,25,52]. These results are also confirmed by observations regarding distributed generation systems, where the local

network configuration and load structure may have an effect on power quality parameters comparable to that of generation itself [21,34,36]. At the same time, it should be emphasised that in the analysed case, the characteristics of the system result from the interaction of the generating source and end consumers, which is typical for systems with a large share of renewable sources and power electronic technologies [8,30]. From a practical point of view, the results indicate that improving power quality in this type of systems requires simultaneous consideration of both the generating source and the loads, in particular in the context of their impact on the level of harmonics and voltage unbalance [25,34,51]. Although the study was carried out in one facility, the analysed system is representative of the class of small distributed sources used on farms. Installations of this type, with rated powers ranging from several to several dozen kW, are commonly used in low-voltage networks, which increases the practical usefulness of the results obtained.

4. Conclusions

The study indicates that the operating state of an agricultural biogas plant significantly influences the power quality parameters at the farm's connection point. Analysis of time-domain waveforms, variability characteristics, and statistical parameters indicates that power generation by the biogas plant acts as a stabilising factor, limiting voltage fluctuations, the variability of asymmetry factors, and the amplitude of harmonic distortions. During periods when the generator was in operation, phase voltages exhibited higher mean values, lower variability, and distinctly leptokurtic distributions, indicating a stable power supply profile. Shutting down the generator, however, led to reduced voltage levels, increased variability, and more symmetrical but less stable statistical distributions. The operation of the fermenter mixers resulted in a slight reduction in voltage and a moderate increase in the variability of selected parameters; however, its impact was clearly weaker than that of power generation alone.

The voltage asymmetry coefficients showed high stability of the zero-sequence component and greater susceptibility of the negative-sequence component to short-term disturbances, particularly in non-generation states. Post hoc analyses indicated that the greatest differences in asymmetry values occurred between generation and non-generation states, while the effect of the mixers was noticeable but moderate. For the voltage distortion coefficient THD_U , the values fell within the typical range for low-voltage networks, and significant statistical differences occurred mainly between states with and without generation. The greatest increase in distortion was observed in the no-generation state with the mixers operating, indicating greater system sensitivity to non-linear loads under grid-only supply conditions.

A summary of the Games–Howell test results for all analysed parameters confirms that both power generation and mixer operation cause statistically significant changes in most quantities describing power quality. The greatest differences were observed between the generation and non-generation states, which suggests that generator operation is the key factor in stabilising the local low-voltage grid. Mixer operation affects power quality parameters in a noticeable but secondary manner relative to generation.

The scientific contribution of this study lies in the comprehensive separation of the effects of generation and auxiliary devices on power quality parameters under real farm operating conditions, based on the analysis of several characteristic operating states of the system. All of the analyses conducted indicate that agricultural biogas plants, in addition to their energy production function, also play an important role in shaping the quality of farm power supply. However, the study has several limitations, including the analysis of a single facility, the lack of identification of disturbance sources and the limited time resolution of the measurements. Future research should extend the analysis to a larger number of

facilities, examine dynamic changes in power quality parameters, and include power-flow analysis, which would allow for a more comprehensive assessment of the impact of biogas plants on power quality.

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