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Agricultural Micro Biogas Plants as a Factor in Farm Development—A Case Study

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Abstract: Energy from biogas is one of the most promising renewable energy sources. Significant, for technical, economic, and environmental reasons, is the construction of agricultural microgas plants next to households specialising in cattle rearing. The availability of free substrate makes it possible not only to produce one's electricity and heat but also to produce a more environmentally and human-friendly manure. The operation of biogas plants is, unfortunately, associated with technical problems. This paper presents the results of a study of the quality of electricity generated in an agricultural biogas plant built at a farm specialising in dairy cows, where the owner reported a problem with the voltage in the power supply network. Therefore, selected power quality parameters occurring at the connection point of the biogas plant were analysed in detail. As the authors' research showed, in the case in question, the agricultural biogas plant was connected via a cable with too small a conductor cross-section, which resulted in significant voltage exceedances, making it impossible to switch on the second of the biogas plant's generators. Replacement of the feed-in cable has enabled both generators to run, but significant fluctuations in the feed-in voltage values were still noticeable. Analysis of the subsequent measurements revealed the need for changes in the design of the digester itself. The proposal for change is to replace the two current digester mixers (each rated at 9 kW) with more mixers of lower power. The new mixers would operate in an alternating system, where only one would always be activated. Presenting the proposed solutions to a wider audience may prevent mistakes in constructing micro biogas plants in the future and may even optimise the quantity and quality of electricity produced. It may consequently contribute to faster development of this type of renewable energy source (thanks, among other things, to a shorter payback time), which will translate into both a reduction in the environmental impact of agricultural production and the development of rural areas.

Keywords: agricultural biogas plant; power quality; electricity; farm development; energy independence,

1. Introduction

Renewable energy generation has become an essential factor in the sustainable development of countries, regions, and even individuals in recent years. The use of feedstocks to produce biogas and biomethane has a vast potential, which could cover about 20% of today's global gas demand. Waste from agriculture and industry negatively affects health and the environment, becoming significant emitters of greenhouse gases such as methane and nitrous oxide [1,2]. Methane fermentation is one of the most beneficial technologies for converting organic waste into renewable energy. Agricultural biogas plants reduce the environmental impact of agriculture. The digestate, obtained from the processed substrates, can be effectively used as an organic fertiliser [3,4]. In addition, biogas can contribute to mitigating the harmful effects of using fossil fuels [5], the combustion of which has contributed to a significant increase in CO_2 concentrations in the atmosphere [6]. Biogas can act as an alternative energy source by generating electricity, heat, and cooling and replacing natural gas derived from fossil fuels [7]. Biogas produced in biogas plants mainly contain methane CH_4 and carbon dioxide CO_2 [8]. In addition, biogas also contains water, nitrogen, hydrogen sulphide, ammonia, oxygen, siloxanes, and other particles in smaller proportions [9]. The composition of biogas depends mainly on the substrate used and the technology employed [10].

When building a biogas plant, the location plays a key role, which mainly depends on the availability of input materials (type of farm), the availability of the electricity grid, and the distance from urbanised areas (due to the potential impact of the biogas plant on noise and odours) [11–13]. From the point of view of agricultural development, the most important are micro biogas plants, built directly on farms and fed with waste (e.g., slurry) generated on the farm. A farm with a micro biogas plant is seen as modern and environmentally friendly. The profitability of agricultural biogas plants located at cattle farms depends mainly on the price of electricity and on having the capital to purchase and maintain an electrical generator [14,15]. In addition, suitable technical conditions for connecting such an energy source at the location are necessary [16]. The costs associated with constructing a biogas plant, calculated per cow, decrease with the increase in herd size [17]. When calculating the profitability of an investment in an agricultural biogas plant, the equipment's maintenance and servicing costs should also be considered [18,19]. Various numerical methods, such as AHP [20], Vikor [21], and the numerical taxonomy method [22], can be used to assess the profitability of the investment. The payback period for the construction of an agricultural microbial gas plant is 6-7 years [23] (investments with a payback of up to 8 years are considered financially beneficial [24,25]). In comparison, the payback for a P.V. plant is within 5-6 years [26].

Agricultural biogas plants enable the generation of electricity heat and cooling and have several other advantages, among which are:

- the possibility of using biogas as a fuel for internal combustion engines [27];
- an increase in regional/national energy security through the development of distributed energy [28];
- a reduction in the cost of disposing of organic waste [29];
- mitigation of adverse climate change [30];
- use of local energy resources [31];
- production of wholesome manure [32].

Despite the apparent increase in biogas production, there is often a lack of relevant knowledge and technology in agriculture [33]. Therefore, an essential action is to broker information from agriculture to the technology industry, covering all legal, environmental, administrative, organisational, and logistical aspects, to implement as many biogas plant projects as possible successfully [34]. Many adverse effects, including financial losses, result from investors' ignorance, who often violate the basic principles of biotechnology when selecting substrates for their installations [35]. Existing installations are constantly being improved in terms of their production efficiency and environmental impact [36]. The local use of the generated energy avoids the losses associated with the transmission of energy over longer distances [37].

Biogas power plants are among the renewable energy sources characterised by the constancy of the generated power over time. It was confirmed by the authors' previous studies conducted in biogas plants connected to the medium-voltage grid [8]. However, there is a lack of analysis in the literature of the results of studies that would present an in-depth analysis of the impact of generation in biogas plants on the voltage of the electrical system supplying consumers installed on farms. This topic is all the more important because, in Poland, farmers with small agricultural biogas plants have reported problems with operating some loads, including milking apparatus. Therefore, the authors

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decided to fill this research gap by conducting a comprehensive study in a micro biogas plant in Poland, in the Podlaskie Province. Presenting the proposed solutions to a wider audience may make it possible in the future to avoid mistakes made in the construction of microgas plants and even influence the companies building their components to optimise the amount and quality of energy fed into the grid. It may contribute to a faster development of this type of energy source (thanks, among other things, to a shorter payback time). It is very important for the sustainable development of rural areas. Indeed, agricultural micro biogas plants not only avoid atmospheric emissions of greenhouse gases (through the local production of electricity, heat, and cooling from agricultural waste) but also contribute to making rural areas more attractive (through the reduction of odour emissions from animal production and the generation of additional jobs).

2. Materials and Methods

The study was conducted at a Polish agricultural biogas plant connected directly to a farm installation. The main substrate used in this biogas plant was manure from approximately 120 dairy cows. The agricultural biogas plant had three facilities - a digester, an engine house, and a digestate tank. The digester had a diameter of 15.5 m and a wall height of 3.7 m (the total height, including the biogas tank, was 8.7 m). During regular operation, the digester held approximately 590 m^3 of substrate, mixed by two agitators with a rated power of 9 kW. The engine room was made in the form of a container, in which an internal combustion engine connected to a generator was installed, as well as other technical equipment for pumping and purifying biogas and controlling the biogas plant's technological processes. Biogas purification takes place in a gas filter and an activated carbon filter. The biogas produced is combusted in two combustion engines, type WG1605, each with a power output of 20 kW (with an efficiency of 97 %). A type 4P/IE2 asynchronous generator with a speed of 1,500 rpm is coupled to the engines. The biogas combustion engine was cooled by circulating water in the engine and the cooling block. The final component of the biogas plant was an open concrete digestate tank.

The owner of the biogas plant reported the following problems with its operation:

1. Due to voltage exceedances at the agricultural biogas plant's connection point, it is impossible to run the second generator.
2. Increasingly frequent cluster malfunction - voltage error displayed.

The slurry stayed in the fermenter for an average of two to three weeks, but no less than 12 days. Daily, part of the digested slurry was pumped out of the digester into the digestion tank. The dose of pumped digestate was controlled automatically and depended on the amount of biogas produced, which in turn depended on the parameters of the slurry fed in. A pressure sensor determined the charge level in the reactor. Once the slurry pumping process was complete, when the pressure dropped below the set value, a new portion was pumped from the collection channel to compensate for the substrate's shortfall.

Power quality is defined as a set of parameters describing the characteristics of the power supply process to the user under normal operating conditions, characterising the supply voltage, and determining the continuity of the power supply to the consumer. The following parameters describing power quality were analysed in the study [38,39]:

- **Mains frequency** is the number of repetitions in the time waveform of the fundamental component of the supply voltage measured over a specified time interval. The frequency deviation is the difference between a given value and the rated frequency value exhibited during regular power system operation over at least a few seconds. The frequency deviation should, in most cases, not exceed +/- 1% of the rated grid frequency.
- **Voltage deviation (slow voltage variation)** is the difference between the actual and rated mains voltage values. In most cases, the free voltage variation should not exceed +/- 10 % of the rated mains voltage value.
- **Voltage fluctuations (rapid changes in voltage)**. Indicators that characterise voltage fluctuations include:
  - The amplitude of voltage fluctuations is expressed as the ratio of the voltage variation value to the rated voltage. In most cases, this value should not exceed 3 %,

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- frequency of voltage fluctuation amplitudes or, in the case of periodic fluctuations, the frequency of voltage fluctuations;
- Short-term flicker index P_{st} (index indicating the annoyance of flickering light over a few minutes). $P_{st} = 1$ is the conventional threshold for the annoyance of light flicker;
- the long-term flicker index P_{lt} (an index indicating the annoyance of flickering light over a long period, of the order of a few hours). In most cases, the index P_{lt} should not exceed 1. The value of the index is determined from successive values of P_{st} , according to the relation:

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{12} P_{st_i}^3}{12}} \quad (1)$$

in which P_{sti} (i = 1, 2, 3, ... 12) are successive values of the short-term flicker indices P_{st} .

- **Voltage asymmetry** – unequal voltage values and/or unequal angles between successive phase voltages. The asymmetry of the system of supply voltages results, among other things, in the appearance of symmetrical components of the opposite order. The parameter describing this condition is the voltage asymmetry factor $\alpha_{U\%}$ (opposite voltage asymmetry) [37,40]:

$$\alpha_{U\%} = \left| \frac{\underline{U}_2}{\underline{U}_1} \right| \cdot 100\% \quad (2)$$

where: U_1 , U_2 - the composite values of the symmetrical components of the consensual and opposite order of the voltage
In most cases, the voltage asymmetry factor should not exceed 2 %.

- **The distortion of the voltage waveform**, defined by the total harmonic distortion factor (THD) [41]:

$$THD_U = \frac{\sqrt{\sum_{h=2}^{\infty} U_h^2}}{U_1} \cdot 100\% \quad (3)$$

where: U_1 - rms value of voltage for the first harmonic, U_h - rms value of voltage for the h-th harmonic, h - order of harmonic.

In most cases, the voltage distortion coefficient THD_U in low-voltage networks must not exceed 8 %.

At the agricultural biogas plant under study, electricity was the primary end product, and its production was maintained at the highest possible level. The tests were carried out using a SONEL PQM-701 portable power quality para-meter analyser, performing measurements in accordance with Class A of the EN 61000-4-30 standard [42].

3. Results

3.1. Analysis of the Supply Network Parameters of the Agricultural Biogas Plant under Study

The recorded values of the grid frequencies are shown in Figure 1.

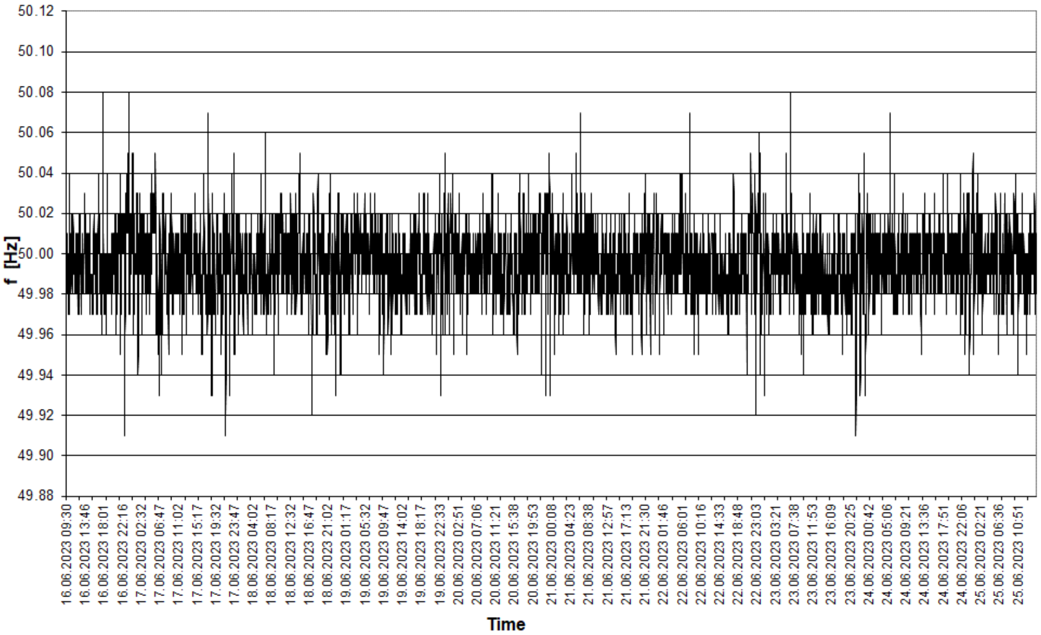

Figure 1. Frequency value variation recorded at the connection point of an agricultural biogas plant.

Although frequent changes in frequency values were recorded, the maximum deviation from the rated value was slight and did not exceed 0.18%. However, it is worth noting that there is a particular recurring regularity. The lowest recorded frequency values were in the afternoon (during maximum load in the electricity network) and then increased as the load decreased.

The waveforms of the variation of voltage levels and the percentage deviation of the voltage from the rated voltage recorded during the tests are shown in Figures 2 and 3.

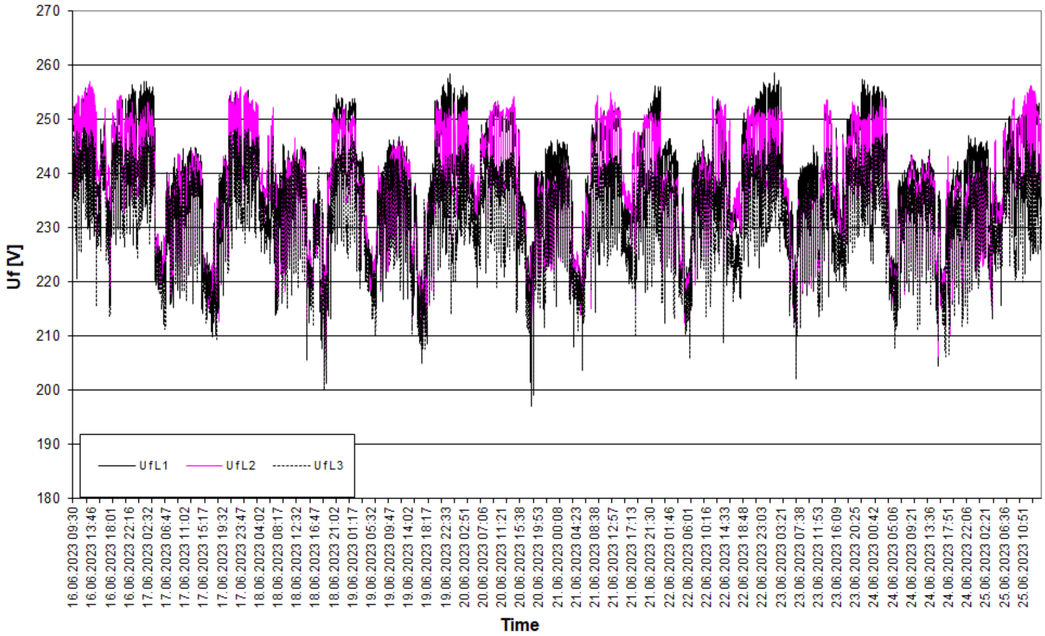

Figure 2. Voltage variation recorded at the connection point of an agricultural biogas plant.

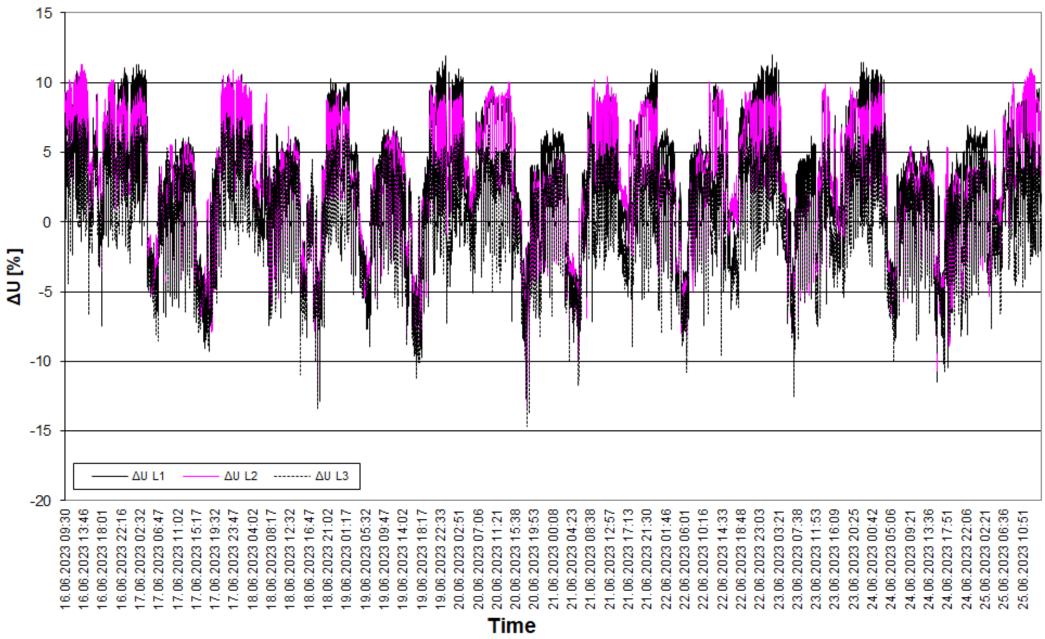

Figure 3. Variation of voltage deviation values recorded at the connection point of an agricultural biogas plant.

When analysing the recorded voltage waveforms, as in the case of frequency, a cyclic pattern of changes can be observed. The voltage changes according to the change in load occurring in the energy system (it decreases as the load increases). Increases in voltage deviation values accompany voltage

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decreases. The voltage value varies from around 200 V to nearly 260 V. Such large changes can cause interference with electronic equipment.

The recorded values of the long-term flicker annoyance factor (Plt) are included in Figure 4.

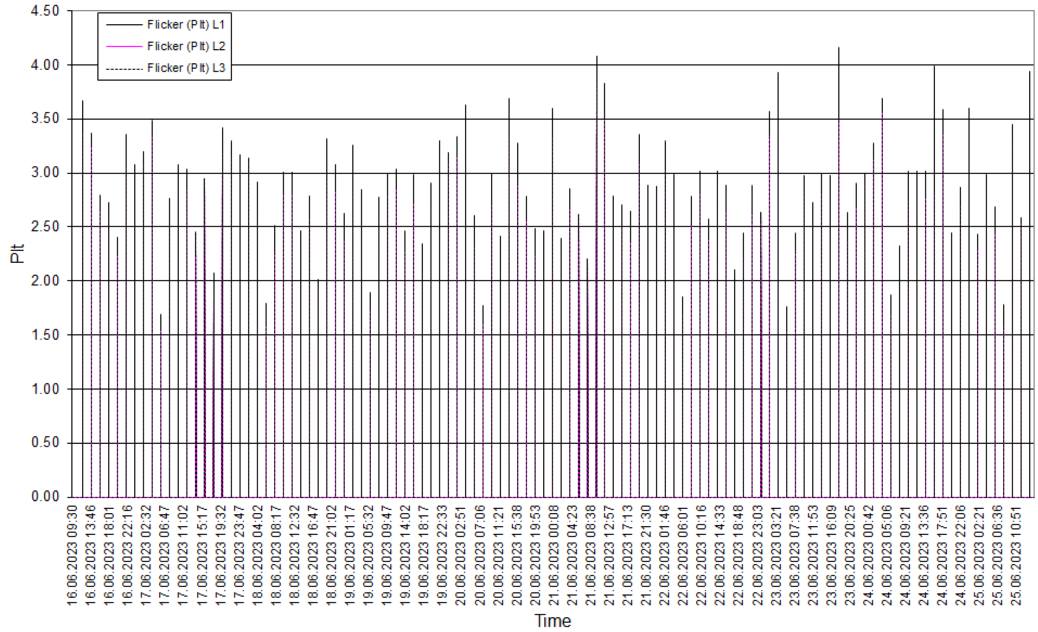

Figure 4. Variation of the long-term flicker nuisance factor (P_{lt}) recorded at the connection point of an agricultural biogas plant.

The values of the long-term flicker annoyance index also vary cyclically. The lowest P_{lt} index occurs at night and the highest in the afternoon. It is usually related to the presence of so-called unstable loads (loads that consume electricity that are significant in value and variable in time) in the power system.

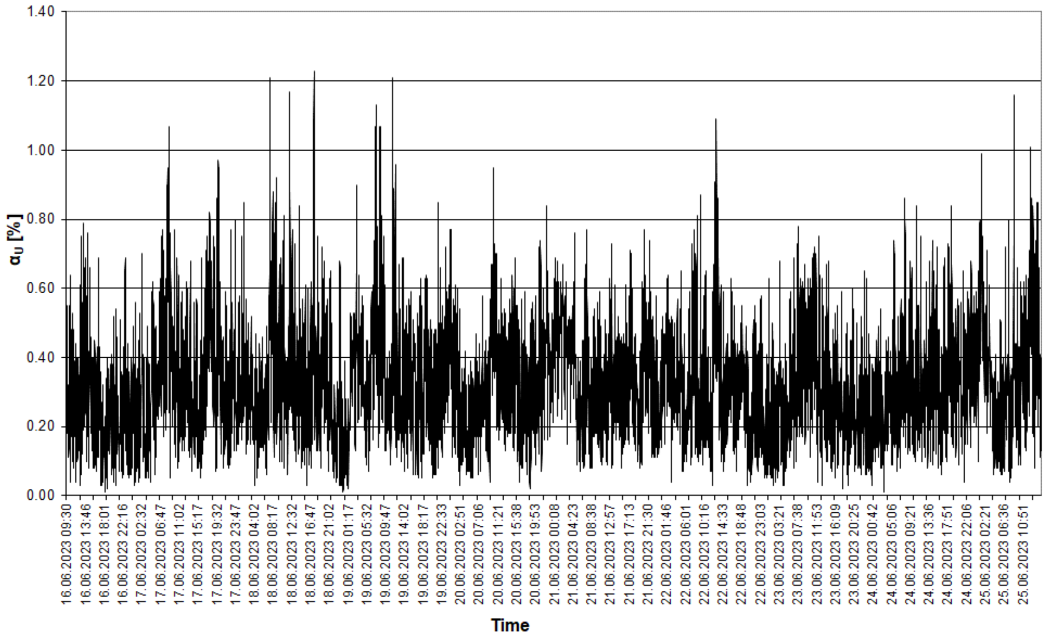

Figure 5. Variation of the voltage asymmetry factor (α_U) recorded at the connection point of the agricultural biogas plant.

The voltage asymmetry factor also varies cyclically. The recorded waveform usually reaches a maximum in the afternoon, while the minimum occurs at night.

The recorded THDU values for each phase are shown in Figure 6.

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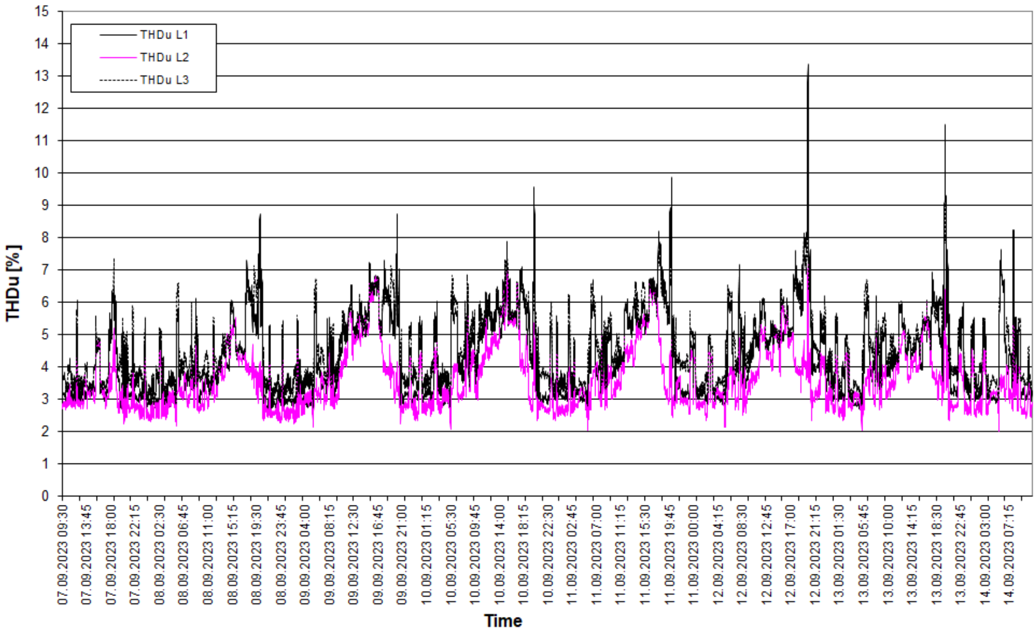

Figure 6. The course of variation of the total voltage distortion coefficient (THDU) was recorded at the connection point of the agricultural biogas plant.

The values of the total voltage distortion coefficient recorded at the biogas plant also vary in the diurnal system, which is mainly due to the cyclic operation of equipment drawing current distorted from the sinusoidal waveform from the grid. The highest values were recorded mainly in the afternoon.

The results of the analysis of the active power levels generated by the agricultural biogas plant are summarised in Figure 7.

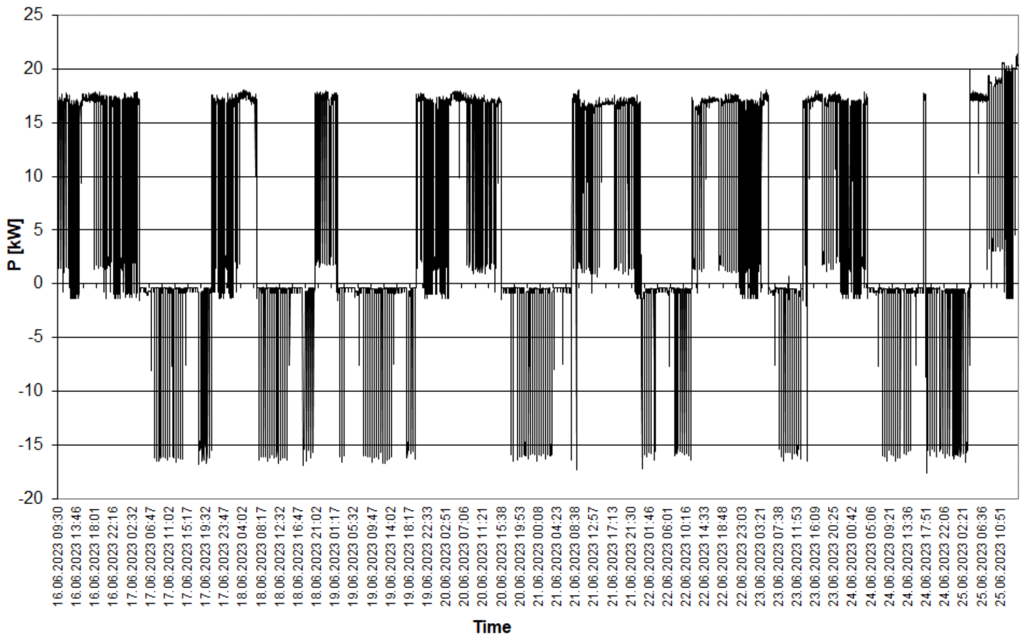

Figure 7. The recorded course of variation of the three-phase active power value generated at an agricultural biogas plant.

As seen from Figure 7 and the information received from the owner, only one turbogenerator is in operation at the agricultural biogas plant. Long periods when the biogas plant is not generating electricity (the power is negative) are also evident. The times when the agitator is running are also clearly visible on the waveform - then the value of the recorded power drops close to zero (when the

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generator is running) or around - 17 kW (when there was no energy production). Therefore, it can be assumed that one generator of 20 kW is necessary to cover the peak needs of an agricultural biogas plant. Without the operation of the agitator, the biogas plant consumes about 1 kW (control systems, monitoring, etc.). The inability to switch on the second generator is due to a voltage in the mains that exceeds the permissible value (253 V). Even with one generator running, voltage exceedances were recorded (Figure 2), which caused this generator unit to be disconnected from the grid (to protect other electrical equipment sensitive to voltage exceedances). The voltage overshoots are also evident in the voltage deviation waveform (Figure 3), which repeatedly exceeds the regulatory limit of 10 %. In order to allow the second generator to operate, an analysis of the power supply system should be carried out to prevent voltage overshoots.

3.2. Analysis of the Feeding System of the Biogas Plant under Study

The original power supply system for the biogas plant under consideration consisted of a 198 m long cable line made using YKY 4x25 mm². As shown in Figure 8, this cross-section does not guarantee that the voltage is maintained within the legal limits.

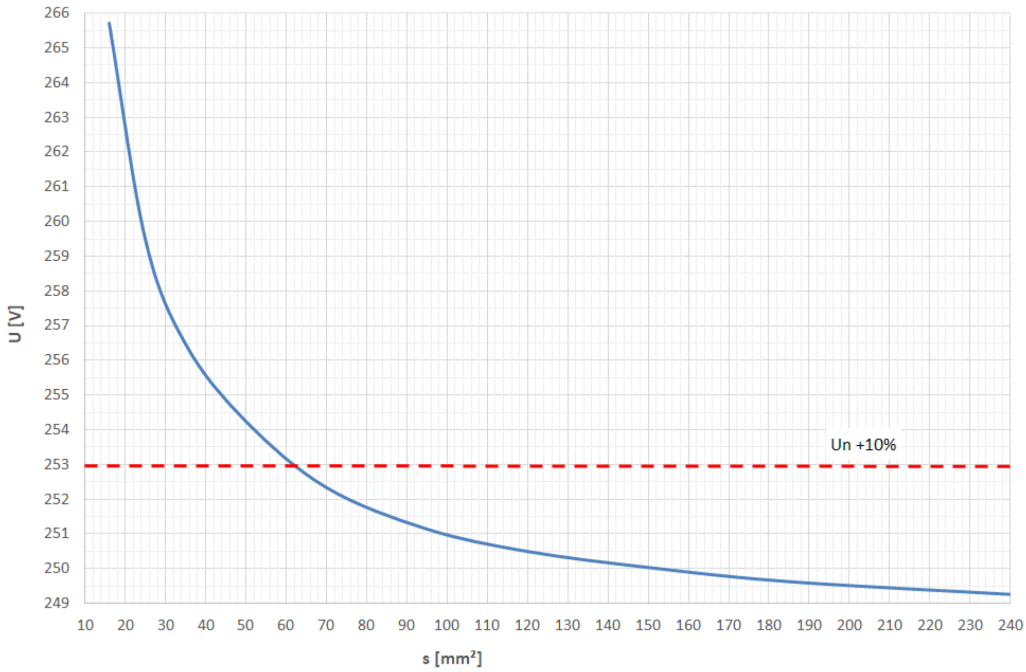

Figure 8. Dependence of the voltage value (U) occurring at the connection point of an agricultural biogas plant as a function of the cross-sectional area (s) of the working conductor of the supply cable.

As can be seen, to meet the voltage requirements, the cable cross-section should be no smaller than 61 mm² (the closest standardised cross-section is 70 mm²). However, due to the reduction of losses occurring in the supply line to the agricultural biogas plant, the supply cable was changed to YKY 4x120 mm².

3.3. Analysis of the Main Supply Parameters of the Studied Agricultural Biogas Plant after Changing the Supply Cable

The recorded values of the mains frequency after the power system conversion are shown in Figure 9.

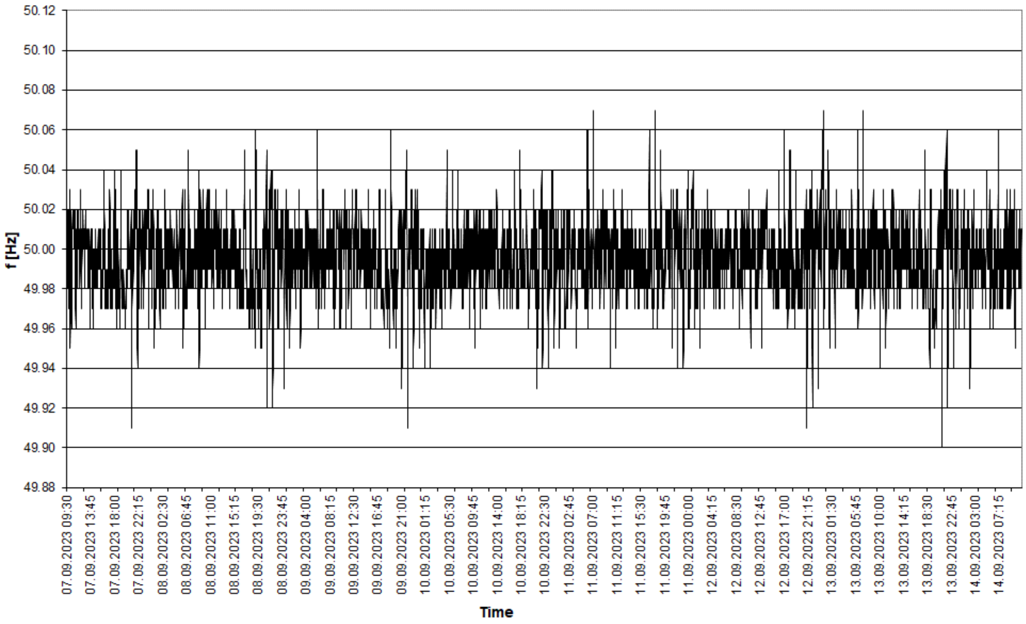

Figure 9. Frequency variation waveform recorded after changing the power cable.

Analysing the course of the variation of the frequency value recorded after the power cable change, repeatability analogous to that before the conversion can be observed.

Analysing the recorded voltage waveforms (Figure 10) and voltage deviation (Figure 11), as in the previous case, it is possible to notice a cyclic variation. However, the variations are noticeably more minor - it is much less frequent for the voltage to take values above 250 V, and only one measurement was recorded in which the voltage dropped below 210 V. This is reflected in the voltage deviation values (Figure 11), which were within +/- 10 % of the rated voltage throughout the recorded period.

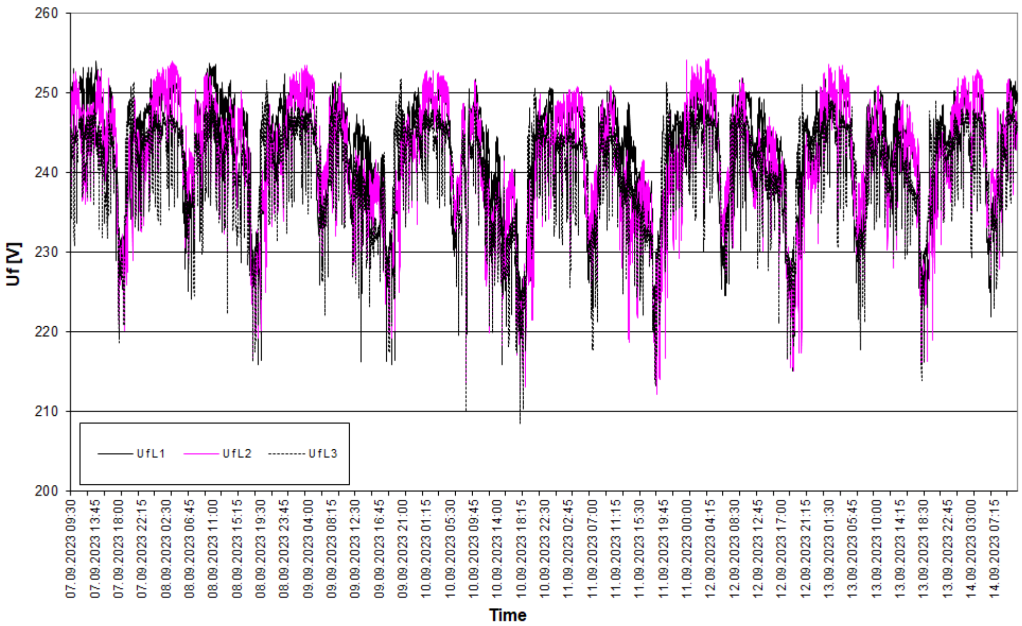

Figure 10. Voltage variation waveform recorded after changing the power cable.

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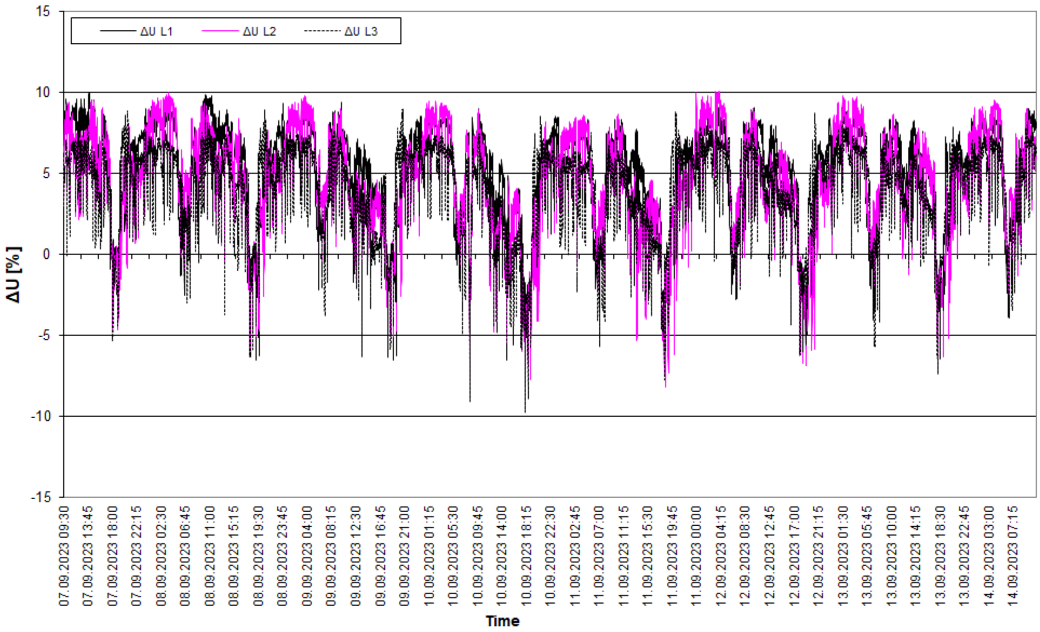

Figure 11. Voltage deviation variation waveform recorded after changing the power cable.

The unstable operation of the agricultural biogas plant is reflected in the recorded values of the flicker nuisance index (Figure 12). These are nearly three times lower than the values found in the system before the power cable change (Figure 4).

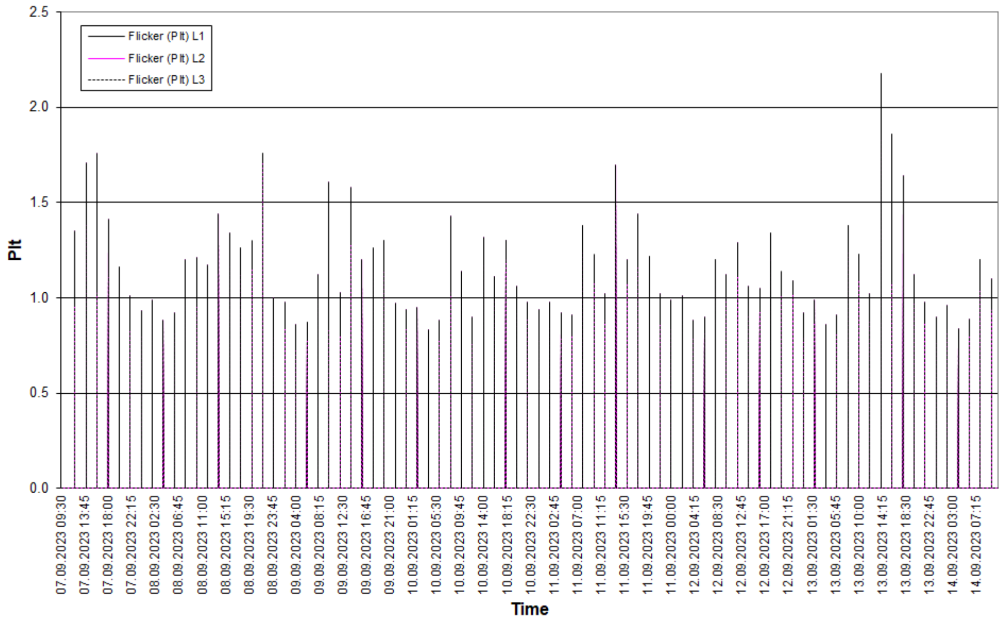

Figure 12. Variation waveform of the long-term flicker nuisance factor (P_{lt}) recorded after changing the power cable.

As with the original system, a cyclic variation of the voltage asymmetry factor was also recorded after changing the power cable (Figure 13). This does not show any significant differences in the values achieved, but comparing the two waveforms (Figure 5 and Figure 13), it is clear that the waveform recorded after the power cable change is less 'jagged.'

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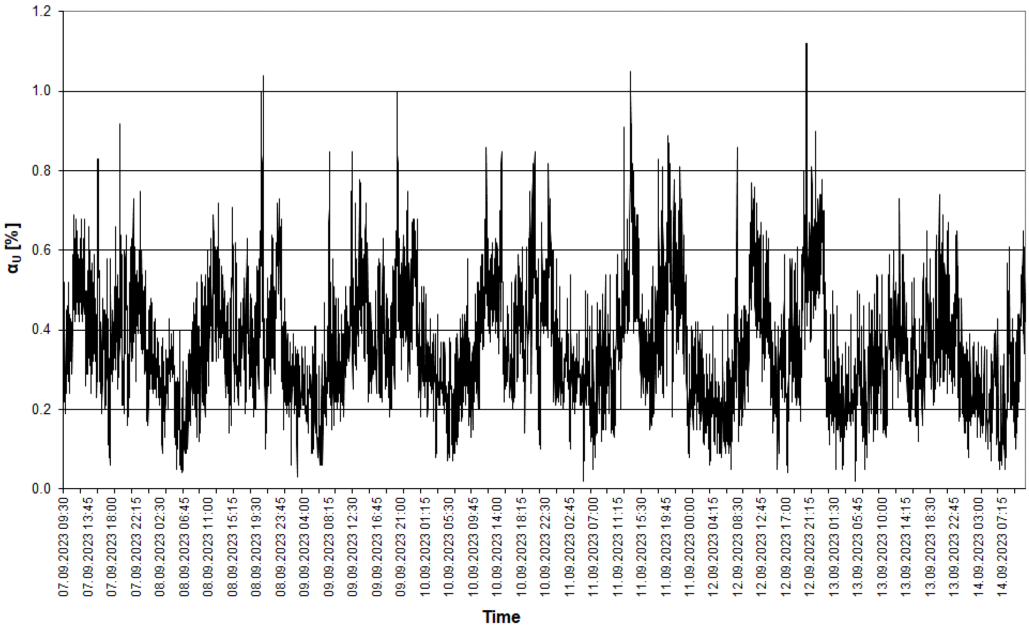

Figure 13. Variation waveform of the voltage asymmetry factor (α_U) recorded after changing the power cable.

As in the original system, the maximum values of the voltage distortion factor occur in the afternoon and evening. However, these values are almost twice as low as the first biogas plant studied.

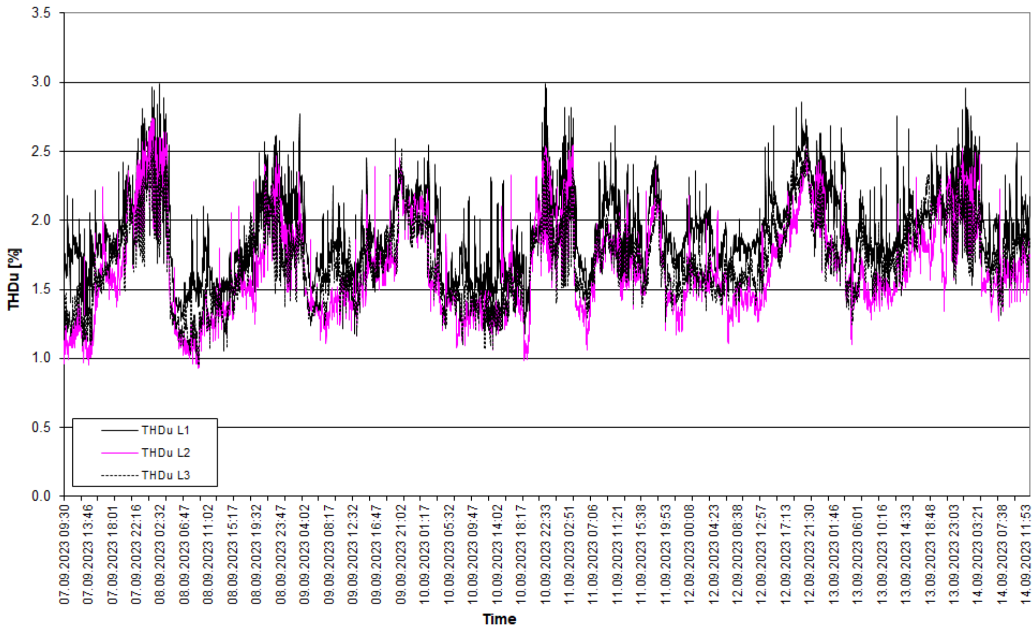

Figure 14. The waveform of the total voltage distortion coefficient (THD_U) variation was recorded after changing the power cable.

The maximum changes in the recorded active power values of the agricultural biogas plant after changing the feed cable (Figure 15) resulted from the operation of the two digester mixers. It is worth noting that at no time during the measurement was the active power equal to the generator's rated power. It was caused by the energy consumption of the equipment installed in the biogas plant.

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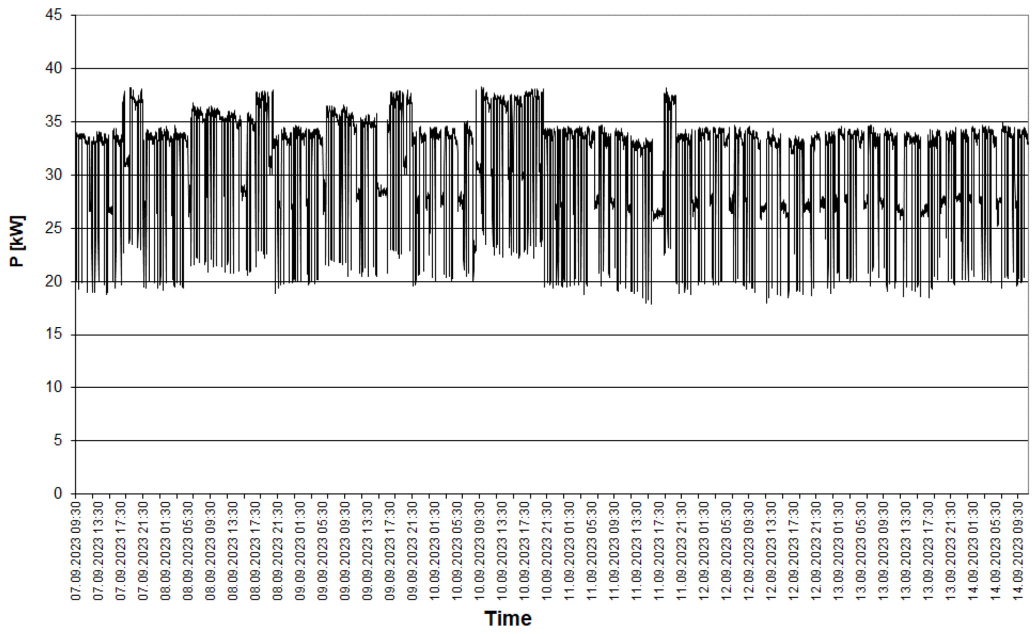

Figure 15. Recorded the course of the variation of the three-phase active power value generated in an agricultural biogas plant.

3.4. Analysis of the Main Supply Parameters of the Studied Agricultural Biogas Plant after Changing the Supply Cable

The value standardised in Polish regulations [38,39] is the 95 % quantile. It is defined in the standard [38] as the highest value obtained from 95 % of the recording time during a week. A summary of the recorded supply voltage frequency values is shown in Table 1.

Table 1. Results of statistical frequency analysis.

Parameter	Before the changes		After changes	
	Frequency [Hz]	Deviation from rated value [%]	Frequency [Hz]	Deviation from rated value [%]
Average value	49.995	-0.010	49.996	-0.008
Minimum value	49.910	-0.180	49.900	-0.200
Maximum value	50.080	0.160	50.070	0.140
Quantile 95	49.970	0.040	49.970	0.040

A summary of the measured voltage levels in each phase of the system supplying the agricultural biogas plant is shown in Table 2. Several relationships emerge from the analysis of the values presented there. In both cases, the asymmetry of the voltages in the individual phases is noticeable. The lowest voltage occurred in the third phase and was most likely due to the asymmetrical connection of single-phase loads to the grid. However, in each phase, the voltage recorded after the power cable change was lower than that of the primary circuit. It translated into voltage deviation values. After the change of the power cable, although momentary exceedances of the permissible voltage deviation values were registered, the regulatory normal quantile of 95 % slightly exceeded 9 %. The operation of the biogas plant causes an increase in the voltage at its point of connection. As can be seen from the measurements taken, this voltage is kept close to the upper limit allowed by the regulations. Switching on the digester mixer reduces generation by almost half, resulting in a drop in voltage values. Turning it off causes the voltage to rise again; this cycle repeats every 30 minutes. It is not a beneficial phenomenon from the point of view of both the quality of the

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generated electricity and the durability of the consumer equipment (the cyclic, step-by-step change in the value of the generated voltage is mainly noticeable as a change in the intensity of the lighting installed on the farm, and can also lead to malfunctioning of voltage-sensitive equipment (mainly electronic), in extreme cases leading to their deactivation or even damage). Table 2 provides the answer to the malfunction of the milking apparatus - its shutdown. Before the power cable was replaced, the lowest recorded voltage value was only 197 V. This is below 200 V, usually accepted as the voltage limit in milking clusters. For this reason, the clusters reported a voltage error and went into emergency mode. After replacing the power cable, the lowest recorded voltage value was 208 V, higher than the minimum value allowed by the regulations. As a result, there were no more emergency shutdowns of the consumers during the test period.

Table 2. Results of statistical analysis of tension levels.

Parameter	L1 phase		L2 phase		L3 phase	
	phase voltage [V]	deviation from the rated voltage [%]	phase voltage [V]	deviation from the rated voltage [%]	phase voltage [V]	deviation from the rated voltage [%]
Before the changes						
Average value	238.913	3.452	238.120	3.109	233.096	0.934
Minimum value	203.260	-11.986	200.130	-13.341	197.070	-14.666
Maximum value	258.650	11.999	257.120	11.336	248.810	7.738
Quantile 95	253.480	9.760	252.110	10.167	244.450	10.850
After changes						
Average value	242.655	5.073	241.368	4.515	240.101	3.967
Minimum value	214.320	-7.197	212.130	-8.145	208.580	-9.682
Maximum value	254.120	10.037	254.280	10.106	251.760	9.015
Quantile 95	250.980	8.678	251.737	9.005	247.690	7.253

A summary of the results of the statistical analysis of the values of the voltage asymmetry coefficient in the power supply system of the biogas plant under study is presented in Table 3. As was shown during the analysis of the recorded waveforms of variation of the asymmetry coefficients, the analysis of the values presented in Table 3 did not reveal any significant differences in the values of this parameter before and after the change of the power supply cable.

Table 3. Results of statistical analysis of voltage asymmetry coefficients.

Parameter	Before the changes α_U [%]	After changes α_U [%]
Average value	0.315	0.350
Minimum value	0.010	0.020
Maximum value	1.230	1.120
Quantile 95	0.610	0.620

A summary of the results of the statistical analysis of the long-term flicker nuisance value (P_{lt}) at the connection point of the agricultural biogas plant during the recording period is presented in Table 4. The values presented there show that the P_{lt} factor in each analysed system exceeds the permissible

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value (1). However, replacing the power cable reduced the value of the 95 % quantile by almost three times.

Table 4. Results of statistical analysis of the long-term flicker annoyance index values (P_{lt}).

Parameter	Before the changes			After changes		
	P_{ltL1}	P_{ltL2}	P_{ltL3}	P_{ltL1}	P_{ltL2}	P_{ltL3}
Average value	2.688	2.762	2.887	0.993	1.141	1.074
Minimum value	1.540	1.620	1.690	0.720	0.830	0.790
Maximum value	3.840	3.960	4.160	2.180	1.830	1.860
Quantile 95	3.500	3.580	3.767	1.384	1.691	1.440

In the primary system, non-compliance with the voltage distortion requirements from the sinusoidal waveform was observed (Table 5). The maximum THDU value is almost 1.7 times higher than the required (8 %) [38,39]. The higher harmonics cause additional voltage and power losses (increased cable heating) in the biogas plant's power supply system. These overshoots are correlated with voltage drops occurring in the electricity network. Changing the power cable reduced the value of the voltage distortion factor by almost half.

Table 5. Results of statistical analysis of the coefficients of higher harmonic content of voltage - THD_U.

Parameter	Before the changes			After changes		
	THD_{UL1} [%]	THD_{UL2} [%]	THD_{UL3} [%]	THD_{UL1} [%]	THD_{UL2} [%]	THD_{UL3} [%]
Average value	4.366	3.641	4.693	2.114	1.821	1.925
Minimum value	2.360	2.020	2.820	1.220	1.010	1.010
Maximum value	13.380	7.190	10.750	7.330	6.050	6.290
Quantile 95	8.557	5.470	7.550	2.760	2.530	2.700

5. Conclusions

As the authors' investigations showed, the power supply voltage problems reported by the owner were technical in origin. The inability to start the second generator was due to an incorrect selection of the cross-sectional area of the cable supplying the biogas plant. A cross-section that was too small was the cause of significant voltage drops, which resulted in high voltage values at the connection point, significantly exceeding the permissible value. Replacement of the power cable enabled the continuous operation of both generators but did not completely solve the voltage problems. The operation of the digester mixers caused the most considerable voltage variations. Simultaneous operation of both mixers resulted in an average drop of about 14.2 kW in the power input to the electrical system. The solution to this problem would be to increase the number of mixers while reducing their power rating. In addition, the mixers should operate in cycles (only one of the mixers would always be switched on). It would allow the system to operate at constant power, significantly reducing voltage variations at the connection point of the biogas plant. In addition, the lower-powered motors would have smaller inrush currents, which would not cause large voltage fluctuations at start-up. In addition, oversizing the generator capacity (relative to the connection capacity) would cover auto consumption and enable power close to the connection capacity to be fed into the grid.

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