Modelling a Small-Size Grid-Connected Solar Photovoltaic Power Plant

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Abstract: The article deals with the modelling and experimental research of a small-size grid-connected solar photovoltaic (SPV) power plant in the power supply network of agricultural consumers to evaluate the power quality parameters. The mathematical model of the parallel operation of the SPV power plant and the distribution network with the subsequent evaluation of the power quality parameters in the power supply network serving agricultural consumers is developed. Based on the presented mathematical model of the SPV power plant, its simulation model is developed in the Simulink software package. The model can be used for designing small-size grid-connected SPV power plants and evaluating the power quality parameters in the designed power supply networks. The conducted experimental research showed the positive effect of the grid-connected SPV power plant on the power quality parameters and confirmed the adequacy of the resulting model.

1 INTRODUCTION

Recently, the power consumers have greatly benefited from using distributed networks. Such networks can ensure reliability and quality of power supplied to consumers according to standards. At the same time, we can reduce the length of power transmission lines and power losses, cost of building and maintaining them, and the cost and consumption of electricity from the centralised network. Non-compliance with the power quality parameters in such networks, compensation to consumers for power quality violations, and accelerated equipment wear can increase diseconomies.

The use of distributed generation networks focuses on renewable energy sources (RES), which, compared to conventional sources, ensure environmentally friendly power generation and the sustainability of the energy resources used.

One of the most promising options for distributed generation networks using renewable energy sources is the direct conversion of solar energy into electrical energy using solar photovoltaic (SPV) power plants. SPV power plants operating in parallel with centralised power supply networks to supply electricity to consumers, their implementation, as well as studies of their effect on the power quality at consumer busbars, and the parameters of centralised power supply networks to which they are connected are topical issues in the modern power supply networks. Therefore, a mathematical and simulation model is needed to study and evaluate the operation of a grid-connected SPV power plant in the power supply network.

By analysing the world experience and international standards, it is possible to identify a number of common patterns that determine the basis of operation of small-size RES power plants in the power supply networks of individual countries (Germany, Japan, USA, Egypt, Israel, Spain, etc.) and

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methods of accounting and payment for the electricity generated by such plants.

In order to regulate the maximum capacity limit of power plants (conventional and alternative) operating in parallel with distributed generation networks, the nominal capacity of medium and low voltage distribution transformers and the permissible throughput of overhead and cable power transmission lines are limited abroad.

In a number of countries, the gross rated output S_{nom} of the transformer to which a low-voltage network is connected limits the load on this network. The most common technical limitation for the connection of consumer power plants is the prohibition of reverse flows of energy through the transformer to the medium-voltage network. The consumption from distributed generation networks at the voltage level to which the power plant is connected is considered acceptable.

European countries limit the capacity of power plants to 35-45% of the nominal capacity of the transformers used. In South Korea, the permissible capacity limit for a distributed generation plant is up to 20% of the low- and medium-voltage transformer capacity. In some countries, utilities permit brief overloading of oil-fired power transformers, provided that this mode of operation does cause prolonged overheating of the equipment. South Africa, South Korea, and the USA limit the permissible plant capacity to 15-25% of the maximum current load of the power transmission line. In Spain it amounts to 50% of the capacity of the medium-voltage network.

In case the capacity of the network is exceeded as a result of connection of a power plant, it is possible to replace the existing wire with a larger cross-section one. This is only possible if the mechanical loads on the line supports do not exceed the permissible values. The limits of the rated current of the substation equipment (circuit breaker, disconnector, current transformer, etc.) are also taken into account when evaluating the load capacity of the network.

In many cases, the effect on network power losses is considered as an additional criterion [14]. Utilities perform additional calculations of electrical modes to determine the effect of the power plant on network losses in different scheme and mode situations. At the same time, the power plant must not lead to increased power losses according to the existing requirements.

In terms of the distribution of power flows in the power supply, the connection of power plants close to the supply centre will have an insignificant effect on power transmission line losses. On the other hand, when power plants are connected to distant feeders, the reverse flow of power can lead to increased losses.

Many foreign researchers study the quality parameters of power from solar power plants (SPPs) and SPV power plants operating in parallel with the network. They consider the quality of power from both SPPs, operating with high-voltage networks, and from SPV power plants, operating to supply power to a specific consumer. Ragab A. EI-Sehlemy et al. study a real section of the 11 kV power supply network of Egypt. The authors simulate four different cases of this section. In the first case, there is no SPV power plant in the power supply network; in the other cases, the SPV power plant is connected to three different line nodes as it moves away from the generation network. The simulation results show that the current and voltage harmonic distortions increase when using a SPV power plant and additional harmonic filters are required to reduce them.

Syed Muhammad Ahsan et al. consider the effect of SPV power plants on harmonic distortion in the low-voltage (400 V) network. The authors also study four variants:

there are no SPV power plants in the network – in this variant, harmonic distortion factor for voltage is $TDH_v = 5.5\%$, for current is $TDH_I = 8.8\%$

33% of the nodes in the network are equipped with SPV power plants ($TDH_v = 5.7\%$, $TDH_I = 10.1\%$)

50 % of the nodes in the network are equipped with SPV power plants ($TDH_v = 5.8\%$, $TDH_I = 12.4\%$)

100 % of the nodes in the network are equipped with SPV power plants ($TDH_v = 6.2\%$, $TDH_I = 13.2\%$)

They conclude that the connection of inverters to the low-voltage network leads to an increase in current and voltage harmonic distortion as the number of inverters increases.

It should be noted that their conclusions are based on the data obtained by simulation. The adequacy of the model used and the mathematical relationships applied will affect the validity of the results obtained.

The aim of the work is to simulate the operation of grid-connected solar photovoltaic power plants in order to assess their effect on the quality of electricity supplied to agricultural consumers.

2 MATERIALS AND METHODS

Before compiling the mathematical and simulation models for the operation of SPV power plants, it is necessary to identify the main elements whose operation will be described. A solar photovoltaic power plant is a standard SPV power plant operating in parallel with a distribution network, whose main components are a photovoltaic (PV) array and an inverter connected to it. The PV array generally consists of photovoltaic (PV) modules connected in a chosen pattern (series, parallel or mixed connection).

In addition to the power electronics (IGBT transistors), the inverter contains a boost converter and a maximum power point tracker.

The study of the modes of the SPV power plant operating in parallel with the network is based on the analysis of the electromagnetic transients at the inverter. In order to describe the processes at the input of the inverter, it is necessary to consider the mathematical description of the operation of the PV modules and the logic of their connection to the array as well as the DC boost converter and the maximum power point tracker.

The inverter input receives DC current from the FB array output. The photovoltaic module model was developed based on the traditional single diode substitution circuit (Figure 1).

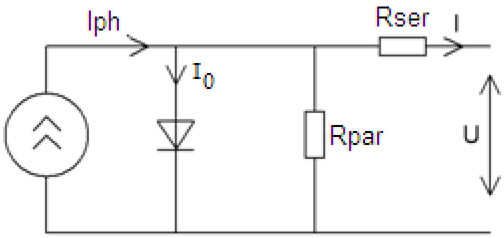

Figure 1: Photovoltaic module substitution schematic diagram.

The current-voltage curve (I-V curve) of the PV module operation can be expressed by the following formula:

$$I = I_{ph} - I_0\left(e^{\frac{q(U+IR_{ser})}{AkT}} - 1\right) + \frac{U + IR_{ser}}{R_{par}} \qquad (1)$$

where I_{ph} is the photocurrent (A); I_0 is the diode saturation current (A); q is the electron charge (C), $q = 1.6 \cdot 10^{-19}$ C; R_{ser} is the series resistance (Ohm); A is the diode non-ideality factor; k is the Boltzmann constant (J/K), $k = 1.38 \cdot 10^{-23}$ J/K; R_{par} is the shunt resistance (Ohm).

The effect of the illumination of the solar module on the photocurrent can be calculated using the following formula [17]:

$$I_{ph} = \frac{E}{E_{STC}}[I_{shc} + \alpha_{shc}(T_i - T_{STC}] \qquad (2)$$

where E is the current irradiance (W/m^2); E_{STC} is the irradiance under the standard test conditions (STCs are 1000 W/m^2, 25°C of the module, Extraterrestrial Solar Radiation 1.5) (W/m^2); I_{shc} is the short-circuit current of the module under STCs (A); α_{shc} is the temperature coefficient of the short-circuit current at STCs; T_i is the current operating temperature of the module under the operating conditions (°C); T_{STC} is the temperature of the module at STCs (T_{STC} = 25°C) (°C).

The effect of the temperature on the solar module operation is taken into account when calculating the saturation current I_0 using the following formula:

$$I_0 = I_{rev}\left[\frac{T_i}{T_{STC}}\right]^3 \cdot e^{\left[\frac{qE_{STC}}{Ak}\left(\frac{1}{T_i} - \frac{1}{T_{STC}}\right)\right]} \qquad (3)$$

where I_{rev} is the reverse saturation current of the diode (A).

As the PV array is connected to the inverter input, the number of PV modules and their connection pattern in the PV array must be taken into account. The number and connection pattern of the PV modules will affect the I-V curve of the PV array (1) according to the following dependencies:

$$\begin{cases} I_{ph.ar} = I_{ph} \cdot N_{par} \\ I_{0.ar} = I_0 \cdot N_{par} \\ R_{ser.ar} = R_{ser}\dfrac{N_{ser}}{N_{par}} \\ R_{par.ar} = R_{par}\dfrac{N_{ser}}{N_{par}} \end{cases} \qquad (4)$$

where N_{ser} is the number of series-connected PV modules in a string (pcs); N_{par} is the number of parallel strings of PV modules (pcs).

Based on the I-V curve of PV module (3) and system (4), the known I-V curve of the PV array is obtained:

$$I = I_{ph.ar} - I_{0.ar}\left[e^{\left(\frac{q\left(\frac{U}{N_{ser}}+\frac{IR_{ser}}{N_{par}}\right)}{AkT}\right)} - 1\right] - \frac{\frac{U}{N_{ser}} + \frac{IR_{ser}}{N_{par}}}{R_{par}} \qquad (5)$$

In formula (5) of the volt-ampere characteristic of the PV array, the current I at the array output is present in both parts of the equation, which complicates the further application of this formula. To describe the dependence of the current at the PV array output on the voltage, formula (5) is transformed with respect to the current I at the PV array output.

The developed mathematical model of the PV array will take the form:

$$I_a = \left(\frac{I_{ph} + I_0}{I_0} - \frac{U}{N_{ser}N_{par}^2R_{par}I_0}\right)e^{\left(-\frac{q}{AkTN_{ser}}\right)U} \qquad (6)$$

где I_a – is the PV array output current (A).

$$I_a = I + \sum_{n=2}^{\infty}\frac{a^{n-1}I^n}{(n-1)!} \qquad (7)$$

The boost converter then raises the low voltage from the PV array to a level corresponding to the maximum (optimum) output of the SPV power plant.

For the first stage of the PV array generation network the boost converter circuit is used as a DC boost converter. The equation describing the operation of the converter can be represented as [18]:

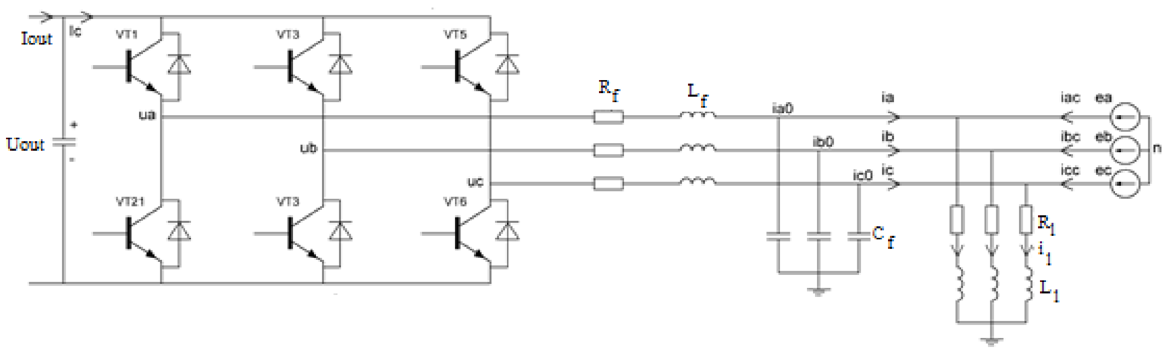

Figure 2: Schematic diagram of a three-phase network inverter.

$$U_{out} = \frac{U_{min}\eta}{1-D} \quad (8)$$

where D is the fill factor;

U_{min} is the minimum input voltage to the boost converter (V);

η is the efficiency of the boost converter.

$$D = 1 - \frac{U_{\text{мин}}\eta}{U_{\text{вых}}} \quad (9)$$

The fill factor can be calculated from formula (24), knowing the voltage value at the output of the boost converter (380 V) and the voltage limit at the input of the boost converter (U_{min}). The value of U_{min} can vary depending on the parameters of the solar panels, so the limits for the small-size SPV power plant are $U_{min} = 110 - 150\,V$. For the calculation, we can use the boost converter efficiency value of 80% (which is a very real efficiency value for the worst-case boost converter), or we can take the efficiency value from the "typical characteristics" section in the specification of the chosen converter. Then, by substituting the values in formula (24) we obtain the fill factor limits $D = 0.68 - 0.76$ for the small-size SPV power plant D=0.68-0.76.

The main requirement for the SPV power plant is to maximise its efficiency and make the best possible use of the energy it generates. The efficient operation of the SPV power plant requires that the output power of the PV array always corresponds to the maximum power point of the I-V curve of the PV array for the given external conditions. Accordingly, the network must be able to track the maximum power point of the PV array. Based on the analysis of the current possibilities of taking into account the factors affecting the operation of photovoltaic equipment and the possible operating conditions of the studied SPV power plant when supplying electricity to agricultural consumers, the effect of the irradiance, the operating temperature of the PV modules/PV array, and the load were directly taken into account. The ambient temperature was considered indirectly.

The output characteristic of the PV array is non-linear and its power output depends on the intensity of the solar radiation, the temperature and the load. Depending on the intensity of the solar radiation and the temperature, the PV array can operate at different output voltages. However, the output power of the solar power plant can only reach its maximum only at a given output voltage. Therefore, an important way to increase the overall efficiency of the PV power generation network is to adjust the operating point of the PV panels in real time so that it always operates close to the maximum output point.

The PV array is connected to the AC network via an inverter with a DC boost converter. The inverter is used to convert the direct current and voltage from the SPV power plant to alternating current and to equalise and modulate the output voltage according to the network voltage. The schematic diagram of the three-phase PWM modulated voltage inverter used to convert the voltage from the SPV power plant is shown in Figure 2.

In this schematic diagram: U_{out} is the inverter busbar voltage on the DC side after the step-up inverter (V), L_f is the network-side filter inductance coil (mH), R_f is the equivalent filter resistance (Ohm), L_l is the load inductance coil (mH), R_l is the equivalent load resistance (Ohm), i_a, i_b and i_c are the inverter output phase current on the network side (A), i_{ao}, i_{bo} and i_{co} are the filter currents (A), e_a, e_b and e_c are the supply voltage (V), u_a, u_b and u_c are the inverter output phase voltages on the network side (V), i_{out} is the current flowing into the inverter from the boost converter side (A), i_c is the current flowing into the network (A), i_l is the total load current of the network and the SPV power plant (A). It is necessary define the switching function of the transistors $S_к$ (к

= a, b, c). When $S_к = 1$, the transistors of the upper arm of the inverter are open. When $S_к = 0$, the lower arm transistors of the inverter are open. Using Figure 2, the phase A substitution diagram is drawn (Figure 3).

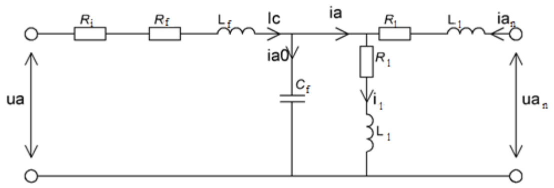

Figure 3: Phase A substitution schematic diagram.

In the substitution schematic diagram, u_{an} is the phase A voltage at the 10/0.4 kV transformer busbars (V).

With the voltage and current directions shown in Figure 3, and in accordance with the first and second Kirchhoff's laws, we present a mathematical model of the inverter phase A based on the switching function of the grid-connected inverter and the inverter input parameters (7, 8):

$$u_l = \frac{1}{2}(u_{\mathrm{a}} + u_{\mathrm{ac}}) - \frac{1}{2}(\Delta U_i + U_f + \Delta U_n) \tag{10}$$

where $u_{\mathrm{a}} = kU_{\mathrm{out}}\sin(\omega t + \varphi_a)$ is the voltage at the inverter output taking into account the switching function of the transistors and the DC voltage at the inverter input (V);

$\Delta U_{\mathrm{i}} = i_{\mathrm{n}} R_{\mathrm{i}}$ is the internal resistance loss of the inverter (V);

$U_{\mathrm{f}} = i_{\mathrm{n}} R_{\mathrm{f}} + \mathrm{L_f}\frac{di_{\mathrm{cn}}}{dt}$ is the passive harmonic filter voltage (V);

$\Delta U_{\mathrm{n}} = i_{\mathrm{an}} R_{\mathrm{l}} + L_{\mathrm{l}}\frac{di_{\mathrm{ac}}}{dt}$ is the power transmission line losses (V).

For phases B and C we obtain similar equations, then the three-phase system equation for the load voltage at the consumer is as follows:

$$\begin{cases} u_{lA} = \frac{1}{2}(u_{\mathrm{A}} + u_{\mathrm{Ac}}) - \frac{1}{2}(\Delta U_i + U_f + \Delta U_n); \\ u_{lB} = \frac{1}{2}(u_B + u_{Bc}) - \frac{1}{2}(\Delta U_i + U_f + \Delta U_n); \\ u_{lC} = \frac{1}{2}(u_C + u_{Cc}) - \frac{1}{2}(\Delta U_i + U_f + \Delta U_n). \end{cases} \tag{11}$$

This system of equations describes the relationship between the DC current and voltage arriving at the inverter from the PV array after the step-up inverter and the AC current and voltage at the inverter output, taking into account the centralised network parameters.

It is necessary to consider the effect of the SPV power plant on the voltage deviation at the power consumer and on the voltage harmonic distortion. The phase A voltage of the inverter and the network voltage are replaced with their respective sinusoidal dependencies.

Based on the equations for the voltage harmonic distortion coefficient, the effect of the SPV power plant on the harmonic component of the consumer voltage can be evaluated:

$$TDH_v = \frac{\sqrt{\sum_{n=2}^{\infty} {U_{cn}}^2}}{kU_{out} + U_{c1}} \tag{12}$$

From the system of equations (11), it can be concluded that the effect of voltage losses in the transmission line on the voltage at the electrical energy consumer is reduced and the voltage deviation at the consumer is reduced. Equation (12) shows a reduction in the harmonic distortion coefficient due to the additional voltage in the first harmonic.

Based on the developed mathematical model in the Simulink software package, a simulation model of the SPV power plant operating in parallel with rural networks has been developed.

The photovoltaic module model is based on the diagram of Figure 1 and consists of a current source, diode, parallel- and series-connected resistors. The operation of the photovoltaic module model is based on equation (1). In this schematic diagram, the ideal current source produces the current I_{f}, which is proportional to the irradiance of the PV array and the ambient temperature. Various defects in the solar module can affect the value of the parallel shunt resistor R_{par}. The value of the series resistance R_{ser} depends on the resistance of the contacts in the PV module and the semiconductor materials from which the module is made.

The output parameters of the PV array unit are calculated on the basis of equation (5) with the given PV array parameters (number of series-connected PV modules in a string and number of parallel strings).

Figure 4 shows a combined schematic diagram of the DC boost converter and the maximum power point tracker. The operation of this unit is based on formula (8).

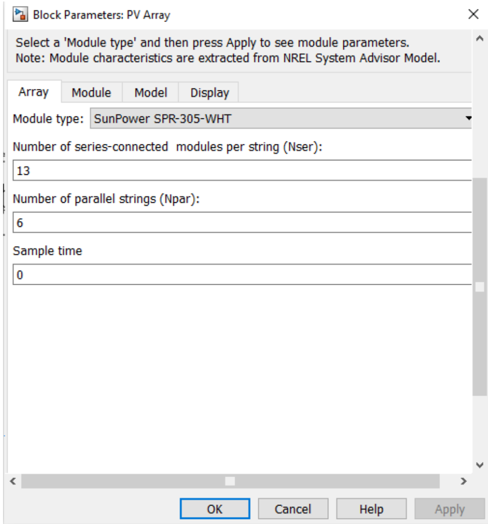

Figure 4: Combined schematic diagram of the boost converter and maximum power point tracker.

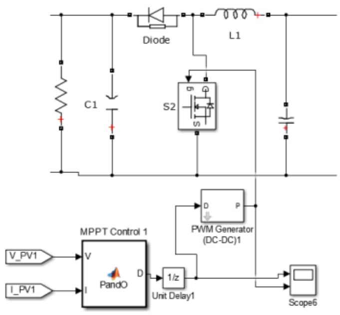

Figure 5: Model screen "Selection of a type of PV modules, their number and connection pattern".

The maximum power point by controlling the duty cycle α is used to control the boost converter. The P&O algorithm is used to find the maximum power point of the SPV power plant. The algorithm is based on tracking the output power of the PV array and selecting the optimum values for current and voltage at the inverter input. The maximum power point tracker (MPPT controller) measures the current and voltage values of the solar panels and controls the S2 switch.

The inverter model is based on the UniversalBridge block provided by the Simulink software. The conventional three-phase voltage inverter diagram presented in the program element is obtained by combining a common input source voltage for three half-bridge single-phase inverters (Figure 8). In this connection, there is no need for a mid-point (zero point) on the output voltage source.

Isolated gate bipolar transistors were chosen for this model as they have low on-state losses and can operate at power levels in excess of 5kW.

3 RESULTS AND DISCUSSION

In the developed model the irradiance and operating temperature of PV modules are manually set by a curve. This type of data setting is chosen in order to be able to evaluate the performance of the PV power plant at different critical and intermediate values of the input signals. The model can be used for selecting PV module types from a suggested list (Figure 5).

When a PV module is chosen, the operating characteristics are automatically modified and can be viewed in the Module section.

The operating characteristics of the PV modules are taken from the data sheet. The model also takes into account the number of PV modules and their connection configuration in the PV array: how many series-connected PV modules are in a string (item "Number of series-connected modules per strings") and how many such strings are parallel-connected (item "Number of parallel strings"). The model currently takes into account the possibility of connecting modules in series, in parallel and in a mixed pattern.

The model determines the effect of the irradiance on the efficiency of PV modules and the PV array based on the I-V curve given set of PV modules in the PV array. The effect of the PV array operating temperature is also taken into account.

The model makes the following assumptions:

- the SPV power plant is designed in such a way that there is no shading from neighbouring objects;
- due to the small total area of the working surface of all PV modules, their location and the peculiarities of their mounting structures, it can be assumed that the operating temperature at any point of the PV modules is equal to the specified value
- deviation of the operating temperature of the modules from the set point is within the permissible limits and can be ignoredin the simulation;
- as required, cleaning procedures are carried out on the PV module working surfaces and other PV module surfaces, whose contamination may affect the performance characteristics (e.g., PV module temperature), and the condition of the

PV module is monitored (damage by birds, hail, etc.).

The modelling and verification of the results obtained were carried out for the grid-connected solar photovoltaic power plant with the capacity of 1.1 kW, operating to supply electricity to a private house with a farm household.

The plant was designed in the developed model and installed in the Saratov region (51.750065N, 42.758712E). According to NASA the number of sunny days in this area is 86, the number of sunny hours per year is 2054.

The solar photovoltaic power plant consists of four TWSolarTW310MWP-60-H monocrystalline silicon solar modules, each with an output of 310W. Each module contains 60 solar cells. The module efficiency is 18.94%. The tilt angle of the modules is 300. The modules are connected in series in the PV array. The surface area of the the PV array is 6.55 m^2. Sofar 1100TL-G3 inverter, manufactured by SofarSolar, was chosen to convert the direct current into alternating current. The installed power of the inverter is 1.1 kW.

The simulations considered two modes of operation of the distribution network: normal (Table 1) and temporary (Table 2).

Table 1: Customer voltage deviations.

SPV power plant is on				SPV power plant is switched off			
Experiment		Modelling		Experiment		Modelling	
min	max	min	max	min	max	min	max
U, Voltage							
215	234	214	234	212	240	212	240
TDH, %							
0.1	4	0.2	4.1	1.2	4.5	0.9	4.3

According to Table 1, a significant reduction in harmonic distortion TDH_U of 1.6% for both even and odd harmonics and a reduction in voltage deviation of 9V can be seen when the SPV plant is operating.

In order to evaluate the effect of the plant on power quality, the plant operation under abnormal operating of the centralised network was studied. This operating mode was provided by a welding transformer.

The results of the experiment on voltage variations with the SPV power plant on and off are shown in Table 2.

Table 2: Customer voltage deviations.

SPV power plant is on				SPV power plant is switched off			
Experiment		Modelling		Experiment		Modelling	
min	max	min	max	min	max	min	max
U, Voltage							
191	234	190	232	212	240	212	240
TDH, %							
2.2	3.4	1.9	3.7	2.7	4.5	2.5	4.3

According to Table 2, the voltage deviation at the consumer is significantly lower (approx. 33V) when the SPV power plant and the welding machine are running. The grid-connected SPV power plant does not switch off when the network voltage drops and continues to produce electricity. In addition, there is a noticeable 1.6% reduction in harmonic distortion when the SPV power plant and the welding machine are running.

The obtained results (Tables 1, 2) show that the grid-connected SPV power plant is able to improve the power quality parameters in the power supply networks of agricultural consumers, but not to reduce them as shown in similar studies.

Table 3 shows the results of the comparison of the power quality parameters at the output of the constructed experimental SPV power plant and the developed model.

Table 3: Comparative analysis of the power quality parameters.

t, hour	SPV		Model		δ,%	
	U, V	TDH %	U, V	TDH %	δ_U	δ_{TDH}
11	227	2.7	230	2.8	1.3	3.
12	227	2.9	231	3	1.5	3.4
13	223	3.4	227	3.6	1.9	5.8
14	232	2.5	229	2.6	1.2	4
15	233	3,1	231	2.9	0.5	6.4
16	227	3	224	3.2	1.3	6.6

The relative error in this case does not exceed 2% when measuring the model voltage and does not exceed 7% when measuring the harmonic distortion coefficient.

4 CONCLUSIONS

The analysis of existing technical solutions, studies and normative documents related to the connection and the parallel operation of small-size solar photovoltaic power plants and the distribution network has shown:

- the main technical and regulatory constraints apply to SPV power plants operating in power supply networks of 6 kV or higher;

- scientists consider the negative impact of grid-connected SPV power plants on the power quality parameters.

The developed mathematical and simulation models of the small-size grid-connected solar photovoltaic power plant can be used for designing a small-size grid-connected solar photovoltaic power plant, namely, for choosing the brand of the solar module (when choosing the brand the working parameters of the module are automatically set according to the ratings), for choosing the connection scheme of the solar array (series, parallel or mixed connection), for choosing the working parameters of the inverter. The model makes it possible to evaluate the efficiency of the grid-connected SPV power plant and the power quality parameters in the power supply network of an agricultural consumer. On the basis of the developed model and the designed and constructed power plant the power quality parameters in the power supply network of the agricultural consumer are studied. The results obtained from the model and from the SPV power plant are compared. According to the data obtained under normal and temporarily allowable modes of the network and the running SPV power plant, a decrease of the voltage deviation by about 9 V and a reduction of the harmonic distortion of the voltage by 1.6% are marked. The evaluation of the model adequacy showed that the simulation error in evaluating the voltage deviation does not exceed 2% and in evaluating the coefficient of harmonic distortion on the voltage it does not exceed 7%.

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