Additional Protection Device for Grid Inverter of Photovoltaic Station

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Abstract: The article describes the large-scale implementation of solar photovoltaic installations and systems in the regions of Uzbekistan, and considers the issues of operation of the component equipment of photovoltaic power plants (PVPP) integrated with the low-voltage electric grid. There is carried out the analysis of the influence of low quality of electric power on the operating modes of the grid inverter in PVPP. There are studied the values of voltage, current and frequency of each phase in the low-voltage electric grid using a two-channel flat-panel oscilloscope FNIRSI -1013D. The voltage deviations of each phase in the low-voltage electric grid are determined; their values are $\delta U^{A}_{m(-)}\ -7{,}8\ \%$, $\delta U^{B}_{m(-)} - 20\%$ and $\delta U^{C}_{m(-)} - 20\%$ under winter conditions, respectively. The archives of most inverters in PVPP integrated with the low-voltage distribution grid in the regions of Uzbekistan are studied and analyzed. The reasons for frequent disconnection and connection of grid inverters have been identified, which include voltage instability in phases, losses in the electrical network, incorrect grounding of the inverter, etc. Additional protective equipment has been developed and created for inverters of the solar power plant integrated with the low-voltage electrical network, distinguished by reliability, automation and availability of electrical components on the domestic market of Uzbekistan.

1 INTRODUCTION

In the world, the use of photovoltaic installations and systems based on renewable energy sources (RES) is one of the promising areas for providing consumers with electric energy. In Uzbekistan, the share of renewable energy sources in electricity production will reach 54% by 2030. The President of the country announced this on December 13 at the launch ceremony of new energy capacities. Additional "green capacities" of 19,000 MW will be built during this period, said the head of state [1].

Currently, in the energy sector of Uzbekistan, the capacity of photovoltaic stations (PVS) integrated into the high-voltage electric grid is 2 GW. Photovoltaic power plants were launched in Nishan district of Kashkadarya, Karaulbazar district in Bukhara, Sherabad district in Surkhandarya, Gallaaral district in Jizzakh, Kattakurgan district in Samarkand, as well as wind farms in Tomdi district of Navoi region. In the republic, low-power photovoltaic power plants with a total capacity of 970 MW are connected to a 0,4 kV low-voltage (local) distribution network at 98,246 different facilities, of which 47,5 MW of capacity were installed at higher educational institutions (according to data from the end of 2023) [2].

One of the main factors for the correct operation of the component equipment (mainly inverters for various purposes) of the PVS connected to the local distribution network is the quality of the electricity supplied by the manufacturer. In this regard, there are a number of problems when connecting these sources to the power grid. The main problems are ensuring the requirements for the quality of electricity, limiting power, security measures, protection systems, the synchronization process, reducing the inertia of the system, etc. [3, 4]. Certain values of quality characteristics are set for the electric grid: in terms of nominal frequency, voltage, current, etc., therefore, the required quality of electricity must be ensured for the normal operation of the components of the PVS. [5]. Deviation of the main indicators of electricity quality from the normalized values can lead to operational disruptions of network inverters, and as a result, losses [6]. Connecting photovoltaic arrays to a grid inverter can be cost-effective, but the service life of a grid inverter is often shorter than that of a photovoltaic plant. This will require replacing the inverter at least once during the lifetime of the solar photovoltaic modules, which will lead to additional costs [7].

In order to ensure safety, network inverters are equipped with protective equipment: in case of significant harmonic changes in the network, i.e. with a strong deviation of the voltage and frequency readings from the permissible limit, the circuit breaker turns off and closes the outlet from the mains. The operation of the protective equipment in this form will depend on the setting of the mains inverter and the quality of the power grid. In the negative case, when the mains voltage decreases by 0.5 V compared to the nominal value, and the frequency deviates from the nominal value by 0.5-0.7 Hz, the mains inverter will stop generating electricity to the electrical network in less than 100 ms [8-10]. Despite equipping the network inverters with a protective device, the task of protecting the inverters from a strong deviation of the main parameters of the electrical network still remains unresolved. A sudden increase in voltage can also damage the integrity of the inverter's memory, as well as prematurely cause it to fail.

The purpose of the research is to develop an additional protective device for a network inverter of a photovoltaic plant connected in parallel to a low–voltage distribution network, as well as to study the main indicators of the quality of electrical energy.

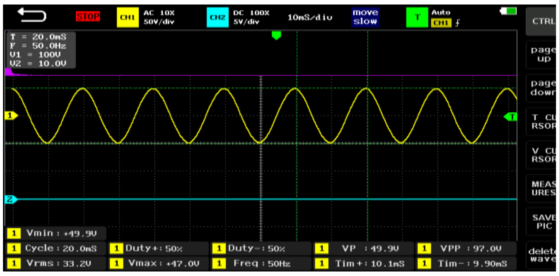
2 MATERIALS AND METHODS

In the course of studying the problems of electricity quality in a low-voltage distribution network, an analysis of waveforms describing voltages, currents and frequency was used. The archive of network inverters of a photovoltaic plant connected in parallel to a low-voltage distribution network during operation has also been analyzed.

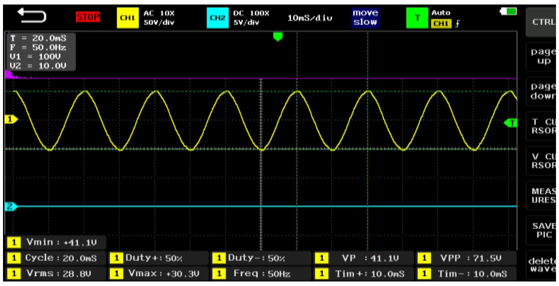
3 RESULTS AND DISCUSSIONS

On January 24-25, 2023, experimental studies were conducted to measure the voltage values of each phase in the low-voltage distribution network of the Faculty of Energy Engineering of Tashkent State Technical University. The voltage, current, and frequency waveforms were recorded using a two-channel FNIRSI -1013D type flat oscilloscope.

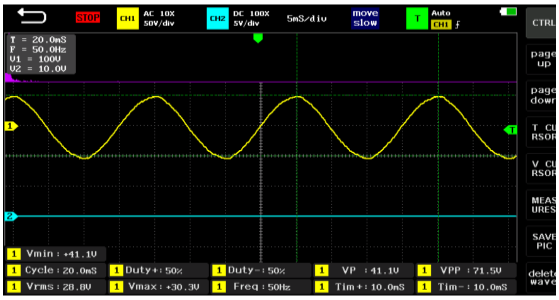
The voltage values for each phase in the low-voltage distribution network, measured and recorded by an oscilloscope at 9:30 a.m. on 01/24/2023 in winter, are shown in Figure 1. The values of the phase voltage in a low-voltage electrical network, respectively, are U_A-202,8 B, U_B – 176 B, U_C- 176 B.



Phase A: oscillation time T=20.0 mS, frequency F=50,0 Hz, U=202.8 B



Phase B: oscillation time T=20.0 mS, frequency F=50,0 Hz, U=176 B



Phase C: oscillation time T=20.0 mS, frequency F=50,0 Hz, U=176 B

Figure 1: Voltage waveforms for each phase in a low-voltage distribution network.

The electric power quality indicators related to slow changes in the power supply voltage are negative $\delta U_{(-)}$ and positive $\delta U_{(+)}$ deviations of the power supply voltage at the point of transmission of electric energy from the nominal agreed value., %:

$$\delta U_{(-)} = \left[1 - \frac{U_{m(-)}}{U_0}\right] \cdot 100\% \qquad (1)$$

$$\delta U_{(+)} = \left[1 - \frac{U_{m(+)}}{U_0}\right] \cdot 100\% \qquad (2)$$

where, $U_{m(-)}$, $U_{m(+)}$- power supply voltage values lower than U_0 and higher than U_0, respectively, averaged over a time interval of 10 minutes in accordance with requirements of GOST 30804.4.30.

According to the indications of the quality of electricity, the following standards are established: positive and negative voltage deviations at the point of transmission of electric energy should not exceed 10% of the nominal or agreed voltage value [11, 12].

Analyzing Figure 1, it can be concluded that in the conditions of the winter and summer period, with an increase in the loads of consumers with a nonlinear characteristic.

It is the nonlinearity of the load that leads to harmonic distortion of the mains voltage. In most cases, consumers of electric energy have a nonlinear volt-ampere characteristic, which leads to a change in the harmonic composition of the voltage and current of the power supply network [13]. Frequent and unpredictable fluctuations in voltage and frequency at the connection point of the PVS lead to exceeding the tolerances for them [14].

It can be seen that (Figure 1) in severe weather in a low-voltage distribution network, the voltage deviation of each phase is less than U_0. According to the results, the interval $U_{m(-)}$ is respectively $\delta U^A_{m(-)}$ −7,8 %, $\delta U^B_{m(-)} - 20\%$ и $\delta U^C_{m(-)} - 20\%$. A strong phase deviation of the voltage in phase B and C in a low-voltage electrical network when connecting the PVS affects the thermal condition of the heated nodes, the insulation strength and the switching apparatus of the central inverter as a whole. Exceeding this indicator ($\delta U_{(-)}$, $\delta U_{(+)}$) will cause frequent failures or accelerated wear of network inverter parts due to increased nonlinear loads.

Due to the fact that frequent failures lead to malfunctions of the electrically erasable programmable permanent storage device (EEPPSD) in network inverters, which is the main memory contained in the working firmware and configuration of the inverter. Restoration and replacement of EEPPSD in a network inverter does not require high costs, but in operation it leads to a significant decrease in the efficiency of the PVS.

Based on the above, for PVS connected in parallel to a low-voltage distribution network, there is an intermediate range of voltage and frequency values at which the network inverters will turn off and turn on again (Table 1). When analyzing the archive, most inverters in PVS integrated with a low-voltage distribution network in Uzbekistan, the number of disconnections and connections of inverters to local electric network, was 1805 times. This was especially observed in a Huawei 30KTL M3 type network inverter with a capacity of 30 kW in the Urgench city in the period from 11/26/2024 to 01/23/2025. Studies show that when analyzing the inverter archive, the reason for frequent disconnection and connection of the protective device to the low-voltage electrical network is the poor quality of electricity: reduction and increase of voltage in phases, losses in the low-voltage electrical network, improper grounding of the inverter, etc.Table 1

Table 1: Requirements for the operation mode of a PVS connected to a low-voltage electrical network [15]

Mode	Requirements
Shutdown Limits:	Voltage drop protection (U <) <184 V Surge protection (U>)> 253 V Surge protection (U >>)> 264.5 V Frequency drop protection (f <) <47.5 Hz Over-frequency protection (f>)> 51.5 Hz
Reconnection Limits:	Voltage greater than 195.5 V and less than 253 V Frequency greater than 47.5 Hz and less than 50.05 Hz

Excessive switching can eventually lead to overheating and wear of relay contacts in network inverters, which are vital for both normal operation and protective functions. Relay failures can cause interruptions in the energy conversion processes, which will lead to unstable power supply or complete disconnection of the PVS from the low-voltage electrical network.

On October 23, 2019, a PVS 10 kW was installed on the Heliopolygon of the Tashkent State Technical University and connected in parallel to the local electric grid [16]. In December 2020, due to a strong phase deviation in the local electrical network, the inverter prematurely failed under normal operating conditions. Was supplied and replaced 10 kW mains inverter from the company that is the customer of the personnel, but more than 1 year passed before the replacement. During this time, the authors managed to develop and create an additional protective device (Figure 3; 3 - protective device) for PVS grid inverter operating in parallel with a low-voltage distribution network.

Figure 3 shows a general schematic diagram of a solar photovoltaic plant connected in parallel to a local distribution network (0.4 kV), in which additional protective equipment of a network inverter is indicated by the number 3. Figure 3 shows an electrical circuit and components of protective equipment for PVS.

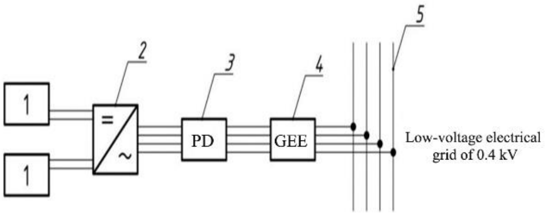


Figure 2. Block diagram of a network photovoltaic plant with a peak power of 10 kW.

In Figure 2: 1 - photovoltaic modules of 20 pieces (total of 40 pieces); 2 - grid inverter; 3 - protective device; 4 - green electricity meter; 5 - low-voltage electrical grid of 0.4 kV.

The solar photovoltaic arrays (1) shown in Figure 3 have an average constant DC voltage of 760 V, a current of 16 A is applied, power is supplied to the mains inverter (2), simultaneously connected to ground (6) and then at a three-phase alternating voltage of ~380 V through the protective equipment (3) of the central inverter through the green electric meter (4) and exported to local electric distribution grid (5). Consumers can import electricity through a green electric meter from the local electric grid [17].

Figure 3 shows in full detail the electrical parts and circuits that make up the protective equipment shown in Figures 2, 3. As noted above, the grid inverter operates in an integrated mode with the local electrical grid, that is, the voltage in the network is synchronized in accordance with the frequency harmonics.

The electrical circuit of the additional protective equipment is switched as follows. The electrical cables are routed from the inverter with three-phase alternating voltage to the input of the SF circuit breaker (3.1), designed for 25A, and are also connected to the neutral (3.5). From the SF circuit breaker, cables are routed to the contactor (3.2) MS and another SF circuit breaker (3.3), rated for a current value of 1A. Current through the SF (3.3) circuit breaker is applied to the input of the RNPP-311 M voltage relay (3.4). In accordance with the requirements of GOST 30804.4.30 the voltage in one or all L1, L2, L3 phases, which is significantly less than or greater than the normalized value of U_0, the smart relay (RNPP-311M – 3.4) disconnects the central inverter from the low-voltage electrical grid and takes control of each phase.

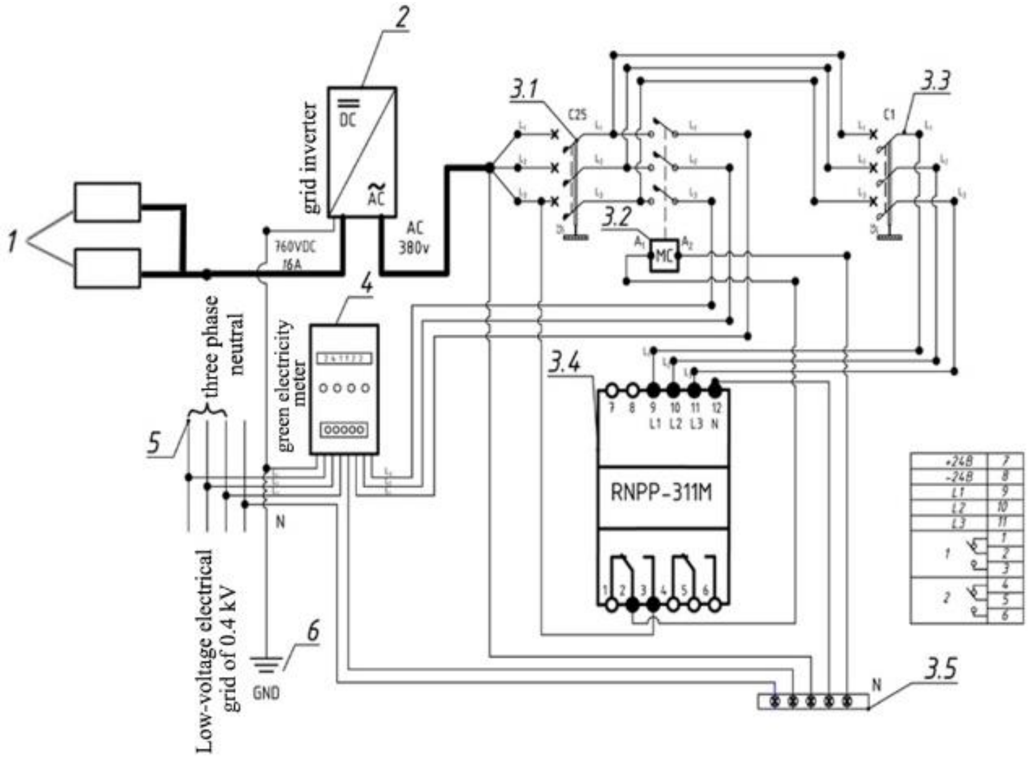


Figure 3: Additional protective equipment for PVS integrated into a low-voltage distribution grid.

In the electrical circuit, the function of the contactor MS (3.2) directly acts as a bridge between the central inverter (2) and the local electrical grid (5), that is, it acts as an automatic switch. The contactor MS (3.2) does not work spontaneously, a signal from the voltage relay RNPP– 311M (3.4) is applied to its operation. It is connected from contact A1 of the contactor MS (3.2) to the voltage relay RNPP– 311M (3.4), and from the other contact A2 it is connected to the neutral (3.5). The RNPP – 311M voltage relay (3.4) issues a signal to disconnect the contacts of the contactor MS (3.2) from the low-voltage distributed network as soon as a defect in the voltage parameters in the electrical grid (5) is detected. Phases L1, L2 and L3 from the MS contactor (3.2), as well as one cable from the neutral (3.5), are connected to the green meter (4) and it is connected in parallel to a low-voltage distributed grid (5).

The following advantages have been identified in the proposed development: it prevents the occurrence of burns and fires caused by overheating of the mains inverter in PVS with low-quality electricity in the local electric grid. The total weight of the development is light, it works without noise, and the cost is very low. There is access to purchase electrical elements and parts in the domestic market of Uzbekistan.

Additional protective equipment is intended for:

- control of the permissible voltage level;
- control of the correct alternation and absence of phase sticking;
- control of the full-phase and symmetry of the mains voltage (phase misalignment);
- disconnecting the load at low-quality mains voltage;
- quality control of the mains voltage after disconnecting the inverter and automatically switching it on after restoring voltage parameters;
- emergency indications in case of an emergency and indication of the presence of voltage in each phase. The development also performs zero control by an indirect method.

4 CONCLUSIONS

In the world, special importance is attached to the issues of electricity generation based on low-power photovoltaic plants and their integration into a low-voltage distribution grid for energy supply to consumers.

The conducted studies allowed us to evaluate the quality of electrical energy in the low-voltage distributed electric grid of Uzbekistan. Based on the results obtained, it can be analyzed that the values of the voltage deviation of each phase in a low-voltage electrical grid are much greater than the nominal value in winter and summer. The voltage deviation of each phase in the low-voltage electrical network and their values, respectively, were $\delta U^{A}_{m(-)} -7{,}8$ %, $\delta U^{B}_{m(-)} - 20\%$ и $\delta U^{C}_{m(-)} - 20\%$ in winter conditions the period in Tashkent. Numerous studies have been conducted on the archives of grid inverters of various types for PVS integrated into the low-voltage electric grid, which are installed in the regions of the country. Data from the memory archive of the grid inverter shows that the reason for frequent disconnection and connection of the inverter to the electrical grid are the following main factors: not phase stability of voltage; losses in the electrical grid; improper grounding of the inverter, etc. Additional protective equipment has been developed and created for PVS inverters integrated with a low-voltage electrical network characterized by reliability, automation and resistance to the thermal condition of heated nodes.

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