

Article

Testing Photovoltaic Power Plants for Participation in General Primary Frequency Control under Various Topology and Operating Conditions

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Abstract: The energy transition is accompanied by developing a digital decentralized low-carbon energy infrastructure with renewable-based generating plants as its main elements. In 2020, 15 photovoltaic power plants (PVPs) with an installed capacity of 364 MW were commissioned in Russia, which is 21.08% of the total installed PVP capacity of Russia. The findings of an analysis of Russia's current regulatory and technical documents (RTD) concerning the frequency and active power flow control are presented. They indicate that all PVPs must participate in the general primary frequency control (GPFC). This requirement is due to large frequency deviations of transient processes resulting from an emergency active power shortage, which can shut down frequency-maintaining generating plants by relay or process protection devices and industrial consumers with significant damage to them. The requirements suggest full-scale tests of PVP to confirm their readiness for participation in GPFC. The program and results of checking the algorithm of change in the PVP active power, depending on frequency, are demonstrated with an example of one PVP. The full-scale tests confirmed the compliance of the certified PVP with this requirement. The plans for involving PVPs in the power flow control under various topology and operation conditions are considered.

Keywords: photovoltaic power plant; general primary frequency control; off-grid operation; emergency active power shortage; full-scale tests; power flow control

1. Introduction

Currently, the world is undergoing an energy transition, which involves the development of a digital decentralized low-carbon energy infrastructure. The energy transition is based on the elements of the sixth wave of innovation and technologies of the fourth industrial revolution.

In this context, new types of power systems with distributed energy resources are emerging. These systems are complex heterogeneous facilities, as a rule, with decentralized control systems, including local generating units mainly based on renewable energy sources (RES), energy storage systems (ESS), and load-controlled consumers. Such facilities are saturated with various technical (new types of equipment and automatic systems) and organizational (new services and market models) innovations [1–3].

The weighty reasons contributing to the intensive construction of renewable energy facilities in the world are their high energy and environmental efficiency, a decrease in the dependence on gas and oil imports from oil/gas producing countries, and a persistent trend towards a reduction in specific capital investment in their construction [4,5].

The massive integration of decentralized RES-based generation into distribution networks leads to a significant increase in the number of energy sources operating for a common electrical network. This causes a variety of possible topologies and operating conditions, leads to the impossibility of visual recognition of operating conditions and their manual control, and complicates the problem of control due to an increase in its dimensions [6,7].

According to expert estimates, the proportion of renewable energy facilities in electricity production will increase worldwide to 27.1% by 2030 and up to 48.8% by 2050. At the same time, wind energy will prevail in the renewable energy structure in 2030 (70%), but by 2050 its share will go down to 47% due to an increase in the share of solar energy, given the decrease in the cost of photovoltaic modules. Some countries plan to completely transition to electricity generation from renewable energy facilities, for example, Sweden by 2040, and Canada by 2050. According to the European Photovoltaic Industry Association, SolarPower Europe, the share of solar energy in world electricity production is currently about 2.6% [8].

Research carried out by the International Energy Agency shows that when the amount of RES electricity in the power system exceeds 15% of the annual value, the algorithms designed to control the operation of power systems have to be thoroughly revised, and new technical facilities have to be introduced to provide reliable operation of the power systems [9–11].

The world has tremendous potential for further expansion of PVPs, both large ones integrated into power systems and small ones connected to the internal power supply networks of households [12,13].

According to the System Operator of the Unified Energy System of Russia (UES of Russia), as of 1 January 2021, the total installed capacity of PVPs operating as part of power systems was 1726.72 MW or 0.7% of the installed capacity of all power plants. The support program RES 1.0 2014–2024 is expected to raise the output from renewable energy facilities (excluding large hydroelectric power plants) to 1% of the total generation in the UES of Russia by 1 January 2025, and the installed capacity of renewable energy facilities will exceed 2.2% of the installed capacity of all power plants.

In the interconnected power systems (IPSs), the PV installed capacities are distributed as follows: 145 MW in IPS of the Middle Volga, 399 MW in IPS of the Urals, 822.52 MW in IPS of the South, and 300.2 MW in IPS of Siberia. Thus, IPS of the Center, IPS of the North-West, and IPS of the East do not have PVPs that function as part of these power systems and supply power to them. In 2020, the amount of electricity generated by PVPs in Russia was 1982.3 million kWh, i.e., 54.3% more than in 2019. The number of hours of the PVP installed capacity utilization was 1324 h (15.08% of the calendar time).

Thus, in 2020, 15 photovoltaic power plants or their parts (when constructed in stages) were commissioned in the UES of Russia with a total installed capacity of 364 MW, that is 21.08% of the total installed capacity of PVPs in the UES of Russia, which indicates a high rate of their construction [14].

In 2021–2024, Russia is planning to introduce PVPs with a total installed capacity of more than 800 MW under the mechanism designed to support the RES-based facilities through the Capacity Supply Agreements that provide investors with a guaranteed highly profitable return on investment for 15 years due to a special premium to the capacity price for the buyers of the wholesale electricity and capacity market [15].

Russia has considerable potential for commissioning new PVPs, since the amount of solar energy coming to the country's territory in three days is comparable to the annual electricity generation [16]. The insolation level varies from 810 kWh/m² per year in remote northern regions to 1400 kWh/m² per year in the southern regions, Siberia, and the Far East. In the Moscow and Leningrad regions, having many cloudy days, the PVP output is about 1000 kWh per 1 kW of installed capacity per year [8].

In 2020, the Ministry of Energy of Russia proposed a new large-scale support program RES 2.0 2025–2035, which is a logical continuation of the current one. This program focuses

not only on RES construction but also on the RES efficiency enhancement and stimulation of the equipment manufacture for renewable energy facilities in Russia and its export to other countries [17]. The total investment support under the RES 2.0 program until 2035 will amount to RUR 360 billion. The plans for 2023–2035 include the commissioning of 2.4 GW capacities at new PVPs (0.3 GW were transferred from the RES 1.0 program) [18].

It is worth noting that the UES of Russia has its historical features associated with the existing structure of the electric power industry. We will consider those of them that have a significant impact on the possibility of connecting PVP to the power system and controlling its operation:

- Historically, power flows were unidirectional from the transmission to distribution networks and, further, to internal networks supplying power to consumers. Consequently, the distribution networks were not designed for large-scale integration of PVPs and reversible power flows occurring depending on the generation and consumption. For this reason, the relay protection devices need to be reconstructed;
- Widespread use of main and backup protection with long time delays in 6–110 kV distribution networks lead to the PVP shutdown until the damage is eliminated. PVP disconnection causes an active power shortage in an amount equal to the PVP power in the pre-emergency condition, which is why it is necessary to carry out a massive reconstruction of relay protection and emergency control devices, as well as algorithms for their operation in adjacent networks;
- Insufficient transfer capability of 220–750 kV transmission networks (loading up to the maximum allowable flows), which does not allow compensating for stochastic electricity production at PVPs due to the flows from the UES of Russia;
- Insufficient transfer capability of 35–110 kV distribution networks, which is due to the historically low power available per consumer (the specific power per point of connection was 3–10 times lower). This affects the possibility of connecting high-power PVP or limiting the power output from PVP in the case of overloaded power lines and power transformers;
- Thermal power plants account for the largest proportion (66.2%) in the mix of generating capacities in the UES of Russia, and about 80% of thermal power plant equipment is steam turbine units (STUs). Even a short-term increase in frequency by 10–12% of f_{rated} or up to the value specified by the manufacturer leads to the operation of the safety circuit breaker that turns off STU, without time delay;
- All power plants, regardless of the type, including PVPs, must participate in the general primary frequency control;
- A small number of flexible generating capacities (short duration of start-up operations; extended control range; high permissible speed of load surge/shedding), for example, of peak gas turbine units (GTUs). Given the stochastic nature of PVP electricity generation, it is necessary to continuously maintain a balance between generated and consumed electricity, which requires highly flexible gas turbine units or energy storage systems [19];
- Energy storage systems were not used in distribution networks to compensate for the intermittent renewable generation and to cover active power shortage while actuating the secondary frequency and active power control reserve;
- The demand response mechanism, which makes it possible to reduce the magnitude of peak loads during the hours of morning and evening highs, is in the initial stage of its development in Russia. It began to function in 2017 and until July 2019 was available only to large industrial enterprises. A considerable effect for the UES of Russia (reduction in electricity consumption by 5–6%) can be achieved by attracting the demand response aggregators that consolidate small and medium-sized consumers. As of June 2021, the total volume of demand response services was no more than 1.86 GW with a potential of at least 7–9 GW;
- A high share of large-scale renewable energy facilities in the structure of generating capacities: photovoltaic power plants with an installed capacity of 10–75 MW,

wind power plants with a capacity of 15–150 MW, and wind farms with a capacity of 40–460 MW, with an increasing but insignificant proportion of microgeneration in households;

- Poor availability of high-speed cyber-protected communication channels. The high-speed digital network for data collection and transmission is a mandatory condition for the functioning of the Distribution Management System (DMS) in the distribution networks to which the PVPs are connected;
- The UES of Russia has an established hierarchical model of operational and dispatch control, in which normal operating conditions of power systems tend to be controlled by the dispatching personnel through voice commands, while the extent to which the automated control systems provided is insignificant. In the context of large-scale integration of renewable energy facilities, some European countries have transformed their vertically oriented model into a distributed one;
- According to statistical data, various parts of the power system located in the centralized power supply zone can be switched to islanded operation more than 50 times a year [20].

In world practice, automatic frequency control is used to maintain frequency in power systems within an acceptable level. It consists of two main components: primary frequency control and secondary frequency control [21–23]. The automatic frequency control is activated spontaneously to stop the frequency decline below the nominal value after emergency disturbances. This task is implemented by synchronous generators regardless of their location and the location of the emergency disturbance. Automatic frequency control consists of inertial response and response of speed controllers of synchronous generators [24].

An increase in the share of PVPs affects the normal functioning of power systems, which is primarily associated with a decrease in the value of mechanical inertia in the power system [25,26]. In turn, low mechanical inertia significantly affects the primary frequency response of the power system. Conventional electricity sources provide an instant reaction to a decrease in frequency in the power system, releasing the energy accumulated in their rotating masses [27,28].

Currently, PVPs are designed to operate at the maximum power point and are power sources with no energy buffer. Therefore, they are ineffective for participation in the mechanism of automatic frequency control [29]. For this reason, a dynamic stability issue arises in the power system since low mechanical inertia makes it difficult to overcome emergency disturbances accompanied by significant frequency deviations. At the same time, the rate of frequency change in transient processes increases significantly, which can result in the disconnection of both synchronous generators and a load of consumers [30].

Many technical measures are proposed to eliminate the negative consequences of low mechanical inertia in power systems using energy storage devices [31–36].

The earlier studies analyze the effectiveness of various types of energy storage systems in microgrids. They show that the energy storage systems are economically impractical because of their short service life and high investment costs [37]. The possibility of using primary frequency response for PVPs without energy storage is analyzed in [38–40]. The researchers propose reducing the amount of PVP generation when the frequency in the power system rises above the rated value, thus preventing system frequency collapse. In [41,42], the authors investigate the possibility of using the inertial response of PVPs relying on the load shedding mechanism.

Nevertheless, today, the application of these technologies in Russia is an acute issue. It is essential to take into account the technological features of the UES of Russia and regulatory control. This work aims to substantiate the need to adapt PVP equipment to Russian conditions.

2. Technical Requirements for Photovoltaic Power Plant Participation in General Primary Frequency Control

The large-scale commissioning of large-capacity renewable energy facilities, as noted earlier, requires their guaranteed participation in the control of power systems operation under various topology and operating conditions. We will analyze the regulatory and technical documents regarding the PVP participation in the frequency and active power flow control, which are in force in Russia.

The PVP equipment made by foreign manufacturers, even when manufactured in Russia under the localization program, meets the technical requirements of the country (group of countries) where it is designed. To prevent its damage and exclude it from the list of equipment for use in Russia, it is necessary to thoroughly analyze the technical requirements for the equipment based on the results of the accident investigation.

Technical requirements are developed at the national level and may gradually become stricter with the growing number of renewable energy facilities in the mix of generating capacities. This approach is justified and applied in many countries since the widespread use of renewable energy facilities can damage power grid equipment and cause accidents with disruption of power supply to consumers due to improperly solved technical issues.

The main regulatory and technical documents governing the technical requirements for the equipment of renewable energy facilities, including photovoltaic power plants, in Russia, are:

- the Standard of the System Operator of the UES of Russia “Control of the frequency and active power flows in the UES of Russia. Standards and requirements” [43];
- Procedure for Establishing Compliance of Generating Equipment of Wholesale Market Entities with Technical Requirements [44];
- Technical Requirements for Generating Equipment of Wholesale Market Entities [45];
- National Standard “Unified Energy System and Off-grid Power Systems. Operational dispatch control. Regulation of frequency and active power flows. Standards and requirements” [46];
- rules for the technological functioning of electric power systems [47];
- Order of the Ministry of Energy of Russia on the approval of requirements for the generating equipment participation in general primary frequency control and the amendment to the Rules for the technical operation of electric power plants and networks in Russia [48].

The mandatory participation of PVPs in general primary frequency control is implemented by automatically reducing active power supplied to the network under frequency increases in the power system [49–51]. This function can be performed by the generating equipment control devices, DC link, or through the disconnection of part of PVP generating equipment [52–54].

To participate in the general primary frequency control, the PVP inverters should have the following settings:

- the drop of primary frequency control should be in the range of 4–5%;
- the upper limit of the primary control deadband should be no more than 50.1 Hz;
- the required value of the decrease in the PVP primary power output is determined based on the magnitude of frequency deviation above 50.1 Hz and the actual PVP power output at the time of frequency deviation beyond the deadband;
- with a stepwise change in frequency above 50.1 Hz, the PVP active power should decrease to the value of the required primary power after 10 s. The change in the PVP active power in the case of PVP participation in general primary frequency control should take no more than 5 s and be aperiodic;
- the PVP control system must provide a frequency-tracking primary control and change the active power output in proportion to the current frequency deviation beyond 50.1 Hz.

PVPs are tested for readiness to participate in the general primary frequency control by full-scale tests according to individual programs for each PVP, which are agreed with the System Operator of the UES of Russia [55].

With the high probability of islanding some parts of the power system, it is necessary to analyze the features of transient processes in the islanded conditions. This will make it possible to assess the PVP readiness to participate in the control of operating parameters and in the maintenance of power quality parameters [56,57].

3. Features of Transient Processes in Islanded Conditions

According to statistical data, some parts of the power system can transition to islanded operation more than 50 times a year. This transition, as the analysis shows, most often results from emergency outages of power lines under network repair conditions.

We will dwell on the features of transient processes during islanding and islanded operation of a part of the power system as these processes affect the operation of PVPs and technical requirements for them:

- Depending on parameters of pre-emergency conditions, islanding can make power balance vary from an excess, which requires disconnection of some generating units, to a shortage exceeding 50%.
- Emergency shutdowns of a generating unit or a group of generating units (connected to one busbar section) during islanded operation can result from a short circuit at generating unit, a short circuit at buses, a generating unit overload, or a breaker failure of one generating unit (the busbar section is disconnected by a circuit breaker failure protection).
- Technical characteristics of generating units installed at the gas turbine, gas reciprocating, wind power, and photovoltaic plants differ significantly from the characteristics of steam turbine generating units, which determine the parameters of transient processes during emergency disturbances.
- The equivalent mechanical constant of inertia in the UES of Russia is $T_j \text{ eq} \approx 10$ s. Islanding can occur in the power system with advanced generating units with low T_j values (for gas-reciprocating three-shaft gas turbine gensets $T_j = 1\text{--}2$ s, for powerful gas-reciprocating two-shaft gas turbine gensets $T_j = 3\text{--}4$ s), which is due to the design features of drive engines. Emergency disturbances and load surges/shedding associated with connection/disconnection of electrical installations of consumers will cause significant short-term frequency deviations due to an increase in the rate of electromechanical transient processes.
- Short-term increases in frequency are most dangerous for steam turbine units, as they lead to safety circuit breaker operation without time delay and shutdown of the steam turbine. Modern steam turbine units have very high mechanical stresses from centrifugal forces in the blades and disks, and in some parts at normal rotational speed, the safety margin versus the yield strength is 1.6–1.8 p.u. Since the mechanical stresses from centrifugal forces with the increase in frequency rise in proportion to its square, this can destruct blades and discs.
- When the frequency decreases in the islanded conditions, compressor surge may occur in single-shaft gas turbine genset. Compressor surge is a form of unstable operation of a gas turbine engine. It represents an aerodynamic phenomenon in the form of a self-oscillating process of air mass movement inside the compressor. A surge of the compressor significantly deteriorates its efficiency, causes fluctuations in gas turbine engine power, increases vibration and dynamic stresses in the rotor blade, and may result in compressor destruction. In this case, the gas turbine genset alarm is triggered at $f = 49\text{--}49.5$ Hz, and emergency shutdown occurs at $f = 47.5\text{--}48.5$ Hz without time delay.
- With a large number and capacity of renewable energy facilities, including PVPs integrated into the network through frequency inverters, under the islanded conditions, active power shortages will be compensated for by frequency-independent gensets,

which must have available power margin. Otherwise, this can lead to the shutdown of frequency-independent gensets with complete termination of power supply in the islanded part of the power system.

- With the wrongly chosen load shedding amounts under active power shortage in the islanded operation, the first half-wave of the electromechanical transient process (frequency decrease) is less dangerous than its second half-wave (frequency increase), i.e., the frequency decrease is lower than the increase.
- There can be unnecessary shutdowns of contemporary gensets due to lower indices of thermal resistance to overloads, resulting from a decrease in weight and size characteristics. The manufacturers of gensets seek to improve their efficiency and cost-effectiveness, which requires time reduction for emergency disturbance elimination and an increase in the restoration speed of normal operating parameters. To this end, relay protection needs to be reconstructed using absolute selectivity protections and emergency control throughout the entire adjacent network.

Since the algorithms for PVP voltage, frequency, and power control are implemented in inverters, the control signals in them (during electromechanical transient processes), are implemented almost instantly.

PVPs normally employ frequency-dependent inverters because their power is delivered to an energy system, where the frequency is almost independent of the PVP operation. Thus, PVP provides active power output at the current value of frequency in the network, which affects the parameters of transient processes (Figure 1).

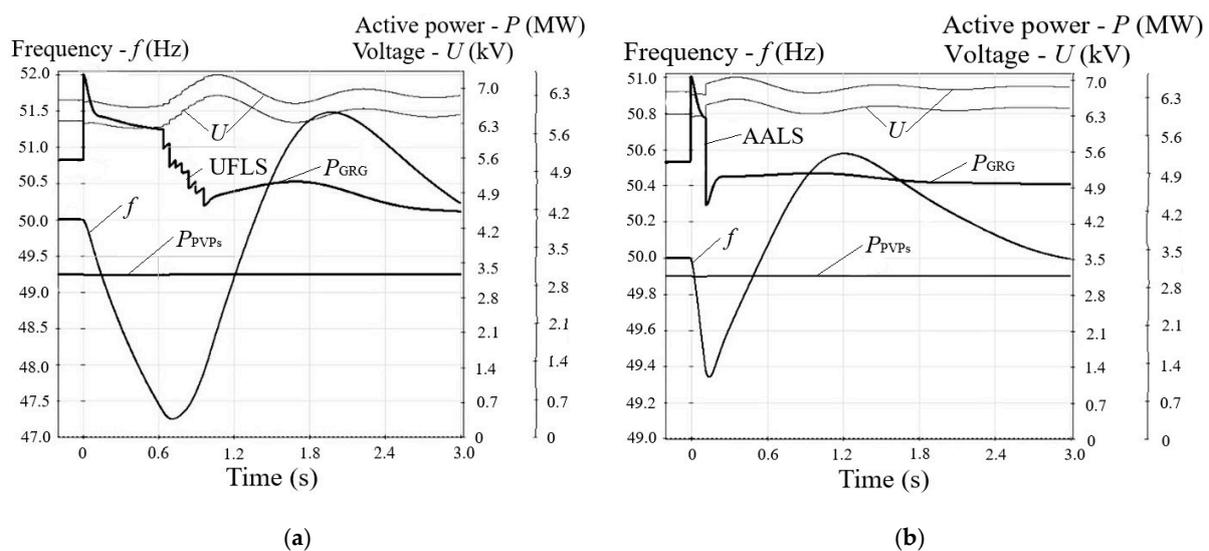


Figure 1. Transient processes: (a) a disconnection of three gas-reciprocating gensets and operation of UFLS; (b) a disconnection of three gas-reciprocating gensets and operation of AALS.

Figure 1a shows a transient process caused by the disconnection of several gensets (three gas-reciprocating gensets, 2 MW each) in an islanded operation. One 2 MW gas-reciprocating genset (GRG) and two photovoltaic power plants with frequency-dependent power control with a capacity of 2 MW each remain in operation. This situation causes a significant active power shortage and frequency decrease to 47.3 Hz, which triggers 13 stages of under-frequency load shedding (UFLS) with a disconnection of 29% of load with respect to the initial value.

Figure 1b shows a transient process with a similar disturbance, but an additional automatic load shedding (AALS) function operates instead of UFLS, which is triggered with a command to turn off three gas-reciprocating gensets. The response time of AALS was $t_{AALS} = 0.1$ s, therefore the transient process causes smaller frequency deviations. The AALS action disconnects 24% of the load (5% less than the UFLS), then the frequency decreases to 49.4 Hz (2.1 Hz higher than in Figure 1a) and recovers much faster [58].

Analysis of transient processes (Figure 1a,b) allows the following conclusions to be made:

- electromechanical transient processes in islanded conditions, given the types of gensets used, can run much faster, which is due to 3–10 times lower values of genset T_J ;
- in the case of emergency power shortages, transient processes in islanded conditions with the frequency-dependent inverters used at PVPs cause more severe consequences for gensets and consumer loads (significant deviations of operating parameters from the rated values for a longer time);
- particular attention should be paid to the design of emergency control systems, factoring in the pre-emergency operating parameters and the magnitude of the actual power shortage. It is also necessary to identify parts of power systems to be islanded to make a list of power consumers whose disconnection by UFLS (AALS) action is sufficient to normalize operating parameters;
- in the islanded operation with PVP, it is necessary to prevent the load surges that can lead to the shutdown of frequency-dependent gensets, or to provide a guaranteed and uninterrupted power supply system for essential consumers, thus preventing grave consequences of a blackout;
- the AALS allows minimizing frequency deviations in the islanded conditions and reducing the recovery time of the rated frequency after elimination of emergency power shortage;
- during the UFLS operation ($f_{\min} = 47.3$ Hz), if single-shaft gas turbine gensets operated instead of gas-reciprocating gensets, they would be disabled by the compressor surge protection with a complete shutdown of the power supply in the islanded part of the power system;
- if the UFLS did not operate in the islanded conditions, and steam-turbine gensets were in operation instead of gas-reciprocating gensets, then in the second half-wave of the transient process, they could be turned off without time delay by safety automatic systems;
- the use of algorithms of control in the PVP inverters, i.e., active power control under varying frequency $P(f)$, minimizes the disconnections of frequency-independent gensets when frequency deviates from f_{rated} ;
- The current settings of protection for PVP inverters are $1.3\text{--}1.4 I_{\text{rated}}$ ($t_{\text{ps}} = 10\text{--}100$ s); $1.4\text{--}1.6 I_{\text{rated}}$ ($t_{\text{ps}} = 0.1\text{--}10$ s); $1.6\text{--}1.8 I_{\text{rated}}$ ($t_{\text{ps}} = 0.1$ s) and $4.5 I_{\text{rated}}$ ($t_{\text{ps}} \leq 1$ ms), which is due to the low thermal inertia of IGBT transistors. To prevent their unnecessary tripping, special attention should be paid to their configuration, parameterization, and coordination with algorithms and settings of relay protection devices in the adjacent network.

With the above said in mind, participation of PVP inverters in the control of operating conditions makes it possible to minimize shutdowns of other gensets when the frequency in the network increases under parallel operation with the UES of Russia, to help to prevent outages of frequency-independent gensets and to ensure reliable power supply to consumers under islanded conditions.

4. Initial Conditions, Program and Results of Full-Scale Tests of Photovoltaic Power Plant

Basic data on the equipment and operating conditions of PVPs include the following:

- The rated power of PVP equipment (P_{rated}) is 20.56 MW.
- The voltage of power supply from PVP to network is 10 kV.
- The mains voltage to inverter stations is 0.345 kV.
- The number of inverter units is 31 pcs.
- The unit power of inverter is 630 kW.
- The upper limit of the regulation range (according to the total rated power of inverters) is 19.53 MW.

- The lower limit of the regulation range, given the setting of the PVP technological protection at a frequency of 51.5 Hz is 56% of P_{rated} .
- The PVP power is supplied to the power system by four 10 kV cable lines through a 10/110 kV substation.
- The drop of primary control of inverters when calculated based on the current active power is 5%.
- The full-scale tests were carried out following the instructions for operation of PVP equipment with all the necessary technological protection devices and algorithms of control systems put into operation.
- The change in active power in the process of PVP participation in the general primary frequency control should take no more than 5 s.
- In the case of frequency change in the network, active power is regulated at inverters relative to the initial active power (P_{in}), which depends on the amount of insolation, with a minimum step of 4%/0.1 Hz.
- After a decrease in the value of quasi-steady-state frequency below 50.1 Hz, the limitation of the PVP active power should be automatically removed.
- After an increase in the value of quasi-steady-state frequency above 49.9 Hz, an increase in the PVP active power should be automatically removed.
- The PVP regulation system must ensure its participation in the general primary frequency control in the tracking mode when the frequency goes beyond the deadband of the primary control, through the change in the power output in proportion to the current frequency deviation from f_{rated} , given the specified drop.
- During the time of the quasi-steady-state frequency value exceeding 50.1 Hz PVP must automatically limit the generated power to the design value, as per Table 1 and Figure 2.
- During the time of the quasi-steady-state frequency value being lower than 49.9 Hz, PVP must automatically increase the generated power relative to the given initial active power (P_{in}) to the design value, as per Table 2 and Figure 3.
- The amount of primary power output to be generated by PVP to participate in the general primary frequency control is determined by the expression (1):

$$P_{\text{PVP}} = P_{\text{in}} \pm \frac{100}{S} \cdot \frac{P_{\text{rated}}}{f_{\text{rated}}} \cdot \Delta f_{\text{des}} \quad (1)$$

where S is the drop of general primary frequency control, %; P_{rated} is the rated power of PVP equipment, kW; f_{rated} is rated network frequency, Hz; Δf_{des} is the design value of frequency deviation beyond the deadband, Hz. The minus sign in expressions (1) and (2) is used when frequency increases with respect to f_{rated} , and the plus sign is used when it decreases. The calculations assume that when the frequency rises above f_{rated} , $P_{\text{in}} = P_{\text{rated}}$, and when the frequency decreases below f_{rated} , $P_{\text{in}} = 0.5 P_{\text{rated}}$.

- The value of primary power output from PVP in the percentage of P_{in} is calculated by expression (2):

$$P_{\text{PVP}} = P_{\text{in}} \pm \frac{200}{S} \cdot \Delta f_{\text{des}} \quad (2)$$

For PVP, we assume $\Delta f_{\text{des}} = 0$ with frequency deviations not exceeding the deadband ($f_{\text{in}} = \pm 0.1$ Hz), i.e., the deadband of general primary frequency control; $\Delta f_{\text{des}} \neq 0$ with frequency deviations exceeding the deadband.

- The number of full-scale tests is 2;
- The operating parameters (network frequency, PVP power output) were recorded at the 10/110 kV substation.

Table 1. PVP primary power for the frequency increase above 50.1 Hz.

Frequency Settings	Frequency, Hz	PVP Primary Power, %	PVP Primary Power (P_{PVP}), kW
f_0 setting (deadband)	50.1	100	630
f_1 setting (Zone A)	50.2	96	604.8
f_2 setting (Zone B)	50.6	80	504
f_3 setting (Zone C)	51.1	60	378
f_0 setting	50.1	100	630

Inverter power - P (kW)

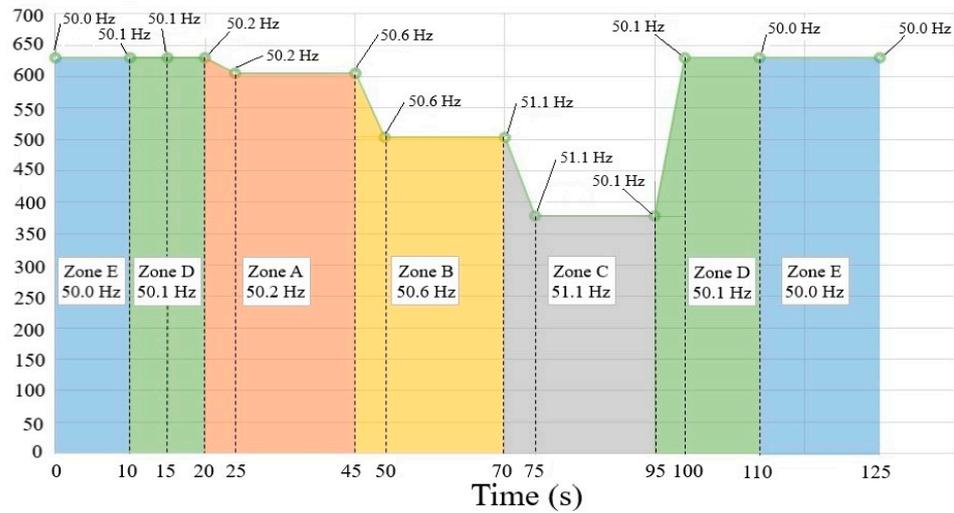


Figure 2. Diagram of PVP power limitation under the frequency rise ($P_{in} = P_{rated}$).

Table 2. The PVP primary power for the frequency decline below 49.9 Hz.

Frequency Settings	Frequency, Hz	PVP Primary Power, %	PVP Primary Power (P_{PVP}), kW
f_0 setting (deadband)	49.9	100	315
f_1 setting (Zone A)	49.8	104	327.6
f_2 setting (Zone B)	49.4	120	378
f_3 setting (Zone C)	48.9	140	441
f_0 setting	49.9	100	315

Inverter power - P (kW)

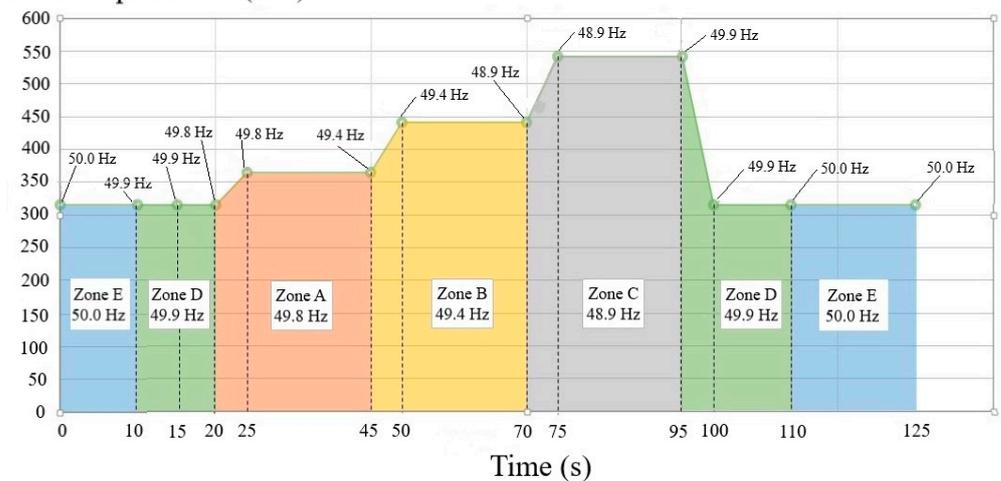


Figure 3. Diagram of increase in PVP power under frequency rise.

The waiting time until the value of the PVP power output decreases from $P_{\text{rated}}(t_0)$ under the frequency rise above 50.1 Hz is $t_0 = t_1 = t_2 = t_3 = 5$ s.

Zone E (Figure 2) corresponds to the deadband, i.e., PVP power output is not limited. Zone D is the frequency value going beyond the deadband up to $f_1 = 50.2$ Hz (a 5 s waiting until the power limitation starts); PVP power restoration to P_{rated} without waiting at a frequency decrease to $f_0 = 50.1$ Hz.

The waiting time before the increase in the value of the PVP power output from $P_{\text{in}}(t_0)$ under the frequency decline below 49.9 Hz is $t_0 = t_1 = t_2 = t_3 = 5$ s.

Zone E (Figure 3) corresponds to the deadband, i.e., PVP power is supplied according to the specified initial active power ($P_{\text{in}} = 0.5 P_{\text{rated}}$). Zone D covers the frequency values going beyond the deadband down to $f_1 = 49.8$ Hz (a 5 s waiting until the increase in power output starts), and restoration of PVP power to P_{in} without waiting at a frequency rise to the boundary of the deadband, i.e., 49.9 Hz.

Involvement of PVPs in the general primary frequency control when PVPs are connected to the UES of Russia increases the system reliability under frequency deviations from f_{rated} in emergency conditions. This is especially significant in the context of the growing number and installed capacity of PVPs [59–61].

The first stage of the full-scale tests involved simulating a jump-like change in frequency at the inlet of the PVP central control device and recording corresponding changes in the active power output. This made it possible to prove the technical feasibility of the PVP participation in the general primary frequency control at specified time intervals. Testing is associated with the reconfiguration of all PVP inverters in accordance with the specified settings for droop and the deadband of the general primary frequency control. This test is a simulation, and it is implemented using the “SolarPowerSet” software (SIGMA LLC, Russia).

Following are the program and the results of the full-scale tests.

Test 1. Initial state: inverter operates with active power output $P_{\text{in}} = P_{\text{rated}} = 630$ kW.

1. The upper limit of the deadband is tested. The personal computer (PC) is connected to the inverter using the “SolarPowerSet” software, and the parameters of settings are set according to Table 1 and Figure 2. After the start and the expiration of time delay $t_0 = 5$ s, the inverter active power output $P_{\text{in}} = 630$ kW must not be limited since the set value $f_0 = 50.1$ Hz is the upper limit of the deadband of the general primary frequency control (Figure 4a).
2. Next settings are set with the “SolarPowerSet” software, following Table 1 (Zone A). After the start and expiration of the time delay $t_1 = 5$ s, the inverter must limit the active power output to $P_{\text{PVP1}} = 604.8$ kW (96% of $P_{\text{in}} = 630$ kW). Since $f_1 = 50.2$ Hz is higher than $f_{\text{rated}} = 50.00 \pm 0.05$ Hz, the inverter limits active power output to 604.8 kW (Figure 4b).
3. The next parameters of settings are set with the “SolarPowerSet” software, following Table 1 (Zone B). After the start and expiration of the time delay $t_2 = 5$ s, the inverter must limit active power output to $P_{\text{PVP2}} = 504$ kW (80% of $P_{\text{in}} = 630$ kW). Since $f_2 = 50.6$ Hz is higher than $f_{\text{rated}} = 50.00 \pm 0.05$ Hz, the inverter limits active power output to 504 kW (Figure 5a).
4. The next parameters of settings are set with the “SolarPowerSet” software, following Table 1 (Zone C). After the start and expiration of the time delay $t_3 = 5$ s, the inverter must limit active power output to $P_{\text{PVP3}} = 378$ kW (60% of $P_{\text{in}} = 630$ kW). Since $f_3 = 51.1$ Hz is much higher than $f_{\text{rated}} = 50.00 \pm 0.05$ Hz, the inverter limits the active power output to 378 kW (Figure 5b).
5. The next parameters of settings are set with the “SolarPowerSet” software, following Table 1. After the expiration of time delay $t_0 = 5$ s, the inverter will restore active power output to $P_{\text{in}} = 630$ kW since the set value $f_0 = 50.1$ Hz is the upper limit of the deadband of the general primary frequency control.

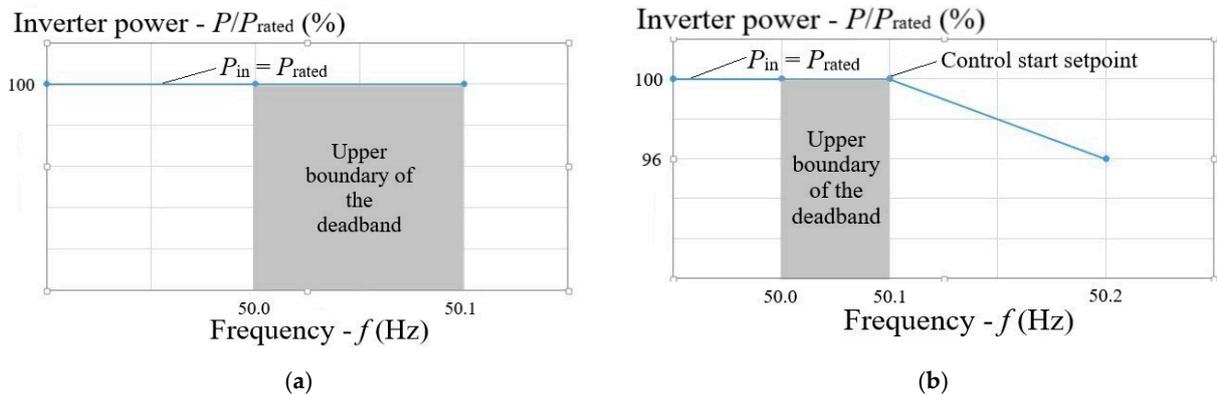


Figure 4. (a) A graph of testing the upper boundary of the deadband of the general primary frequency control; (b) a graph of power limitation by the inverter at $f_1 = 50.2$ Hz.

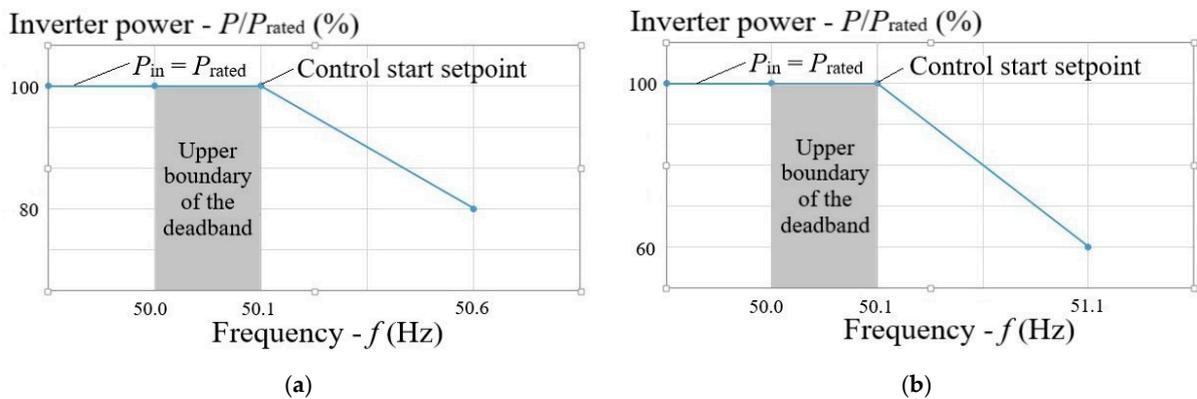


Figure 5. Graphs of power limitation by inverter: (a) at $f_2 = 50.6$ Hz; (b) at $f_3 = 51.1$ Hz.

Test 2. The initial state is as follows: the inverter operates with active power output $P_{in} = 0.5P_{rated} = 315$ kW (power is limited by the operator).

1. The lower boundary of the deadband is tested. The PC is connected to the inverter with the aid of the “SolarPowerSet” software and the settings are set following Table 2 and Figure 3. After the start and expiration of the time delay $t_0 = 5$ s, the power of inverter $P_{in} = 315$ kW should not change since the set value $f_0 = 49.9$ Hz is the lower limit of the deadband of the general primary frequency control (Figure 6a).
2. The next settings are set with the “SolarPowerSet” software, according to Table 2 (Zone A). After the start and expiration of the time delay $t_1 = 5$ s, the inverter must increase active power output to $P_{PVP1} = 327.6$ kW (104% of $P_{in} = 315$ kW). Since $f_1 = 49.8$ Hz is lower than $f_{rated} = 50.00 \pm 0.05$ Hz, the inverter increases active power output to 327.6 kW (Figure 6b).
3. The next settings are set with the “SolarPowerSet” software according to Table 2 (Zone B). After the start and expiration of the time delay $t_2 = 5$ s, the inverter must increase active power output to $P_{PVP2} = 378$ kW (120% of $P_{in} = 315$ kW). Since $f_2 = 49.4$ Hz is lower than $f_{rated} = 50.00 \pm 0.05$ Hz, the inverter increases the active power output to 378 kW, as shown in Figure 7a.
4. The next settings are set with the “SolarPowerSet” software according to Table 2 (Zone C). After the start and expiration of the time delay $t_3 = 5$ s, the inverter must increase active power output up to $P_{PVP3} = 441$ kW (160% of $P_{in} = 315$ kW). Since $f_3 = 48.9$ Hz is significantly lower than $f_{rated} = 50.00 \pm 0.05$ Hz, the inverter increases the active power output to 441 kW (Figure 7b).
5. The next settings are set with the “SolarPowerSet” software according to Table 2. After the expiration of time delay $t_0 = 5$ s, the inverter will restore active power output

to $P_{in} = 315$ kW since the set value $f_0 = 49.9$ Hz is the lower limit of the deadband of the general primary frequency control.

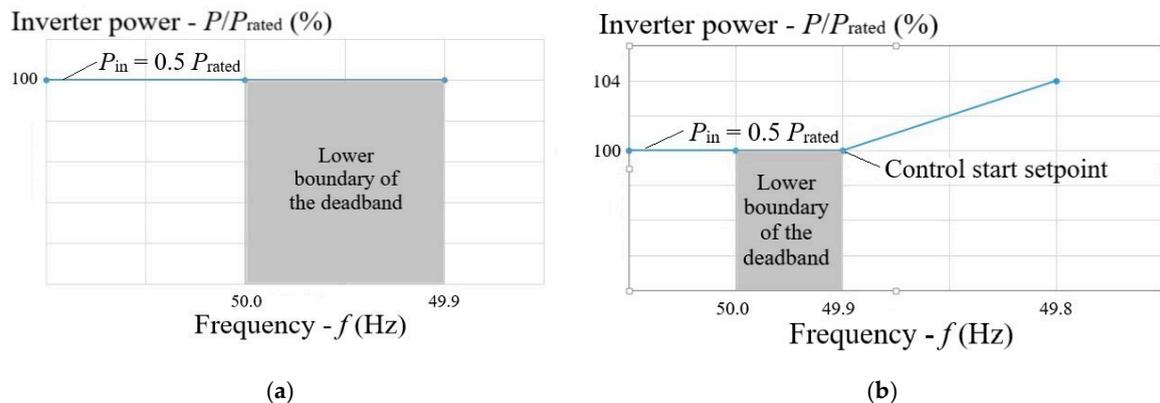


Figure 6. (a) A graph of testing the lower boundary of the deadband of the general primary frequency control; (b) a graph of the inverter power increase at $f_1 = 49.8$ Hz.

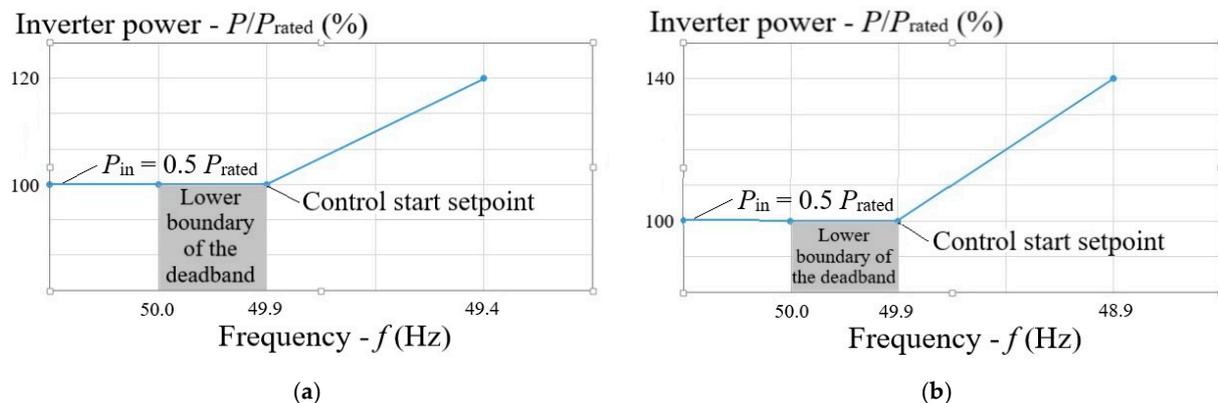


Figure 7. Graphs of the inverter power increase: (a) at $f_2 = 49.4$ Hz; (b) at $f_3 = 48.9$ Hz.

All results of tests No. 1 and No. 2 were recorded at the control panel of inverters, the automated workstation of the PVP operator, and the analyzer of power quality indices.

The results of the first stage of the full-scale tests indicate that there is a technical possibility for the PVP generating equipment to participate in the general primary frequency control at specified time intervals.

The second stage of the full-scale tests at the PVP was performed in the first half of the day as part of a global experiment, which involved islanding a large part of the power system, where two thermal power plants with combined-cycle gas turbines were designated as frequency-independent ones.

The weather during the second stage of the full-scale tests was good with stratocumulus clouds, as shown in Figure 8 [62,63].

Under the disturbances initiated for the islanded part of the system, the current frequency values went beyond the upper limit of the deadband of the general primary frequency control three times, $f = 50.1$ Hz (Figure 9). In these cases, the PVP had to limit the active power output according to Table 1.

Figure 9 also indicates that the current value of frequency went below the lower boundary of the deadband of the general primary frequency control twice, $f = 49.9$ Hz. In these cases, the PVP had to increase active power output following Table 2.



Figure 8. Weather conditions in the PVP area during the full-scale tests.

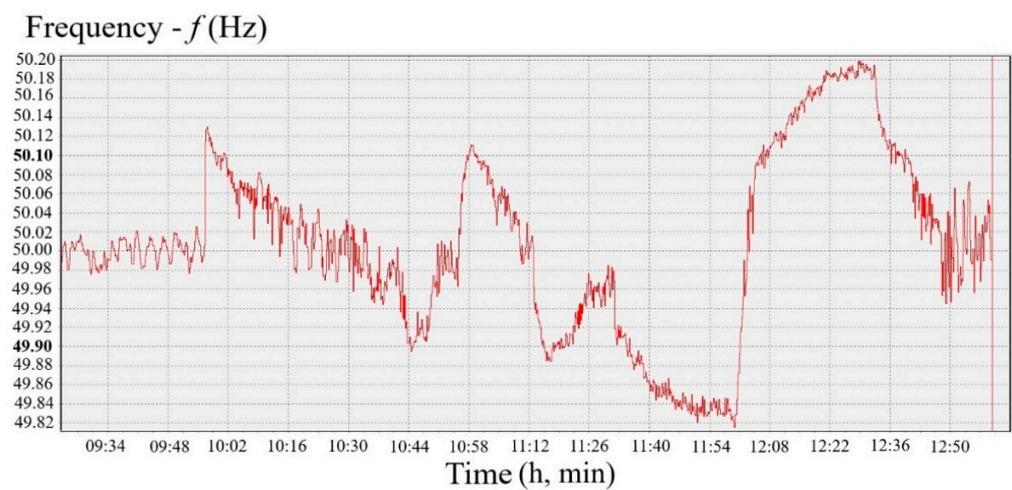


Figure 9. Graph of a frequency change after islanding part of the power system.

Figure 10 shows how the PVP limited and increased active power output to the power system, following the given algorithms (one case is given).

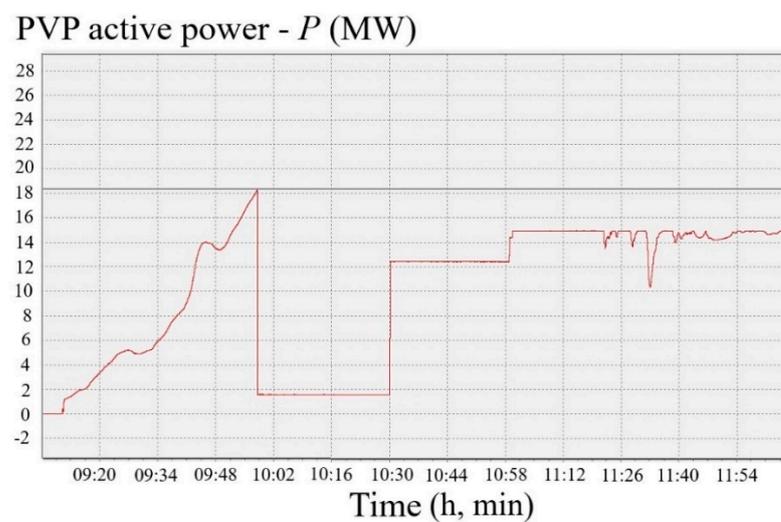


Figure 10. Graph of changes in the PVP active power output with frequency changes in the islanded part of the power system.

Due to the time scale selected, it is not seen in Figure 10 that the PVP power limitation or increase occurs not instantly, but rather in 5 seconds, according to the given algorithm.

The second stage of the full-scale tests confirmed the readiness of the PVP generating equipment to participate in the general primary frequency control. These results can be used to improve the regulatory and technical documents that determine the requirements for the PVP generating equipment, and the procedure for testing PVPs for their participation in general primary frequency control.

The participation of all photovoltaic power plants in general primary frequency control will lessen the flexibility requirements for frequency-independent gensets at conventional power plants and reduce the deviation of operating parameters due to emergency disturbances, including those under islanded conditions [30,64].

The growing number and installed capacity of RES-based facilities, including PVPs operating as part of power systems, change the mix of generating capacities and their behavior. The consumers seek to vary power consumption from the power system depending on price signals, which leads to a change in the load behavior. If we do not develop and implement compensatory organizational and technical measures, these factors can become a threat to the stable and reliable operation of the UES of Russia. Then, electrical installations of consumers can face massive outages with significant damage.

It is worth noting that Russia has enormous potential for microgeneration for households (power up to 15 kW), and in the coming years the development of this trend will significantly change distribution networks of medium and low voltage, for which some regulatory acts were passed [65,66].

To ensure the free integration of various types of distributed energy resources (including microgeneration facilities), reliable functioning of distribution networks, and power supply to consumers, it is necessary to carry out a phased reconstruction of medium- and low-voltage distribution networks through the revision of their construction principles and the adoption of automated control systems. It is also essential to develop guidelines for the design of medium- and low-voltage networks, which would simultaneously envisage a Distribution Management System for optimal control of distribution networks with integrated MicroGrids/Multimicrogrids and Minigrids.

The international experience of developing regulatory acts and regulatory and technical documents for renewable energy facilities focuses on ensuring a reliable operation of energy systems with a large proportion of renewable energy sources in the mix of generating capacities and maintaining power quality indices in medium- and low-voltage networks, according to the requirements. Therefore, RES facilities to be connected to work as part of power systems must comply with the mandatory technical requirements imposed on them.

An increase in the share of renewable energy facilities in Russia, given the stochastic nature of electricity generated by them, requires:

- organizing the monitoring of the available power margin in power systems, with the aid of tools for short-term and operational projection of electricity generation from renewable energy facilities;
- providing capacity redundancy for renewable energy facilities by traditional generating units or energy storage systems;
- revising flexibility requirements for generating units at conventional power plants;
- changing the approaches to planning the transfer capability of transmission lines;
- involving the maximum number of load-controlled consumers in demand response;
- involving renewable energy facilities in the control of power flows in distribution networks.

The development and adoption of tools for forecasting electricity output from RES facilities, capable of providing reliable data, will reduce the magnitude of the spinning reserve at conventional power plants, minimize the time of uneconomical operation of generators, and decrease the redundant transfer capability in transmission and distribution networks.

Today, there are difficulties in involving renewable energy facilities in voltage regulation at the distribution network nodes. This is because manufacturers of inverters, for the

sake of saving, choose their power according to the active power of the primary source of electricity. The analysis of the inverter PQ -diagram shows that the output of rated active power is possible only at $\cos \varphi = 1$, which does not allow the output of reactive power without reducing active power. Therefore, now, the possibilities for the participation of renewable energy facilities, including PVPs, in the control of power flows are limited, and reactive power boost is only possible with the inverters of higher power or in the presence of a reserve.

In Russia, the formulation of technical requirements for RES facilities to provide their participation in the power flow control is in the early stage. They need to be developed relying on the international experience, historical features of the UES of Russia, and using ranking by voltage class, type of RES facilities, and their capacity.

To accomplish the objectives set, Russia is planning to create a testing ground with a hybrid energy system (photovoltaic installations, wind power plants, energy storage systems, diesel generator sets, STATCOM). This ground will make it possible to develop optimal algorithms for controlling the hybrid energy system components to work out a mechanism for involving renewable energy facilities in control of power system operation. The cost-effective technical solutions will be developed based on the capabilities of RES facilities to take part in the frequency and voltage control by changing the generation/consumption of active/reactive power and minimization of power and capacity of the energy storage system.

5. Conclusions

The increasing number and installed capacity of RES facilities, including PVPs operating as part of power systems, change the structure and behavior of generating capacities. Therefore, it is necessary to involve them in the power flow control, including general primary frequency control in power systems.

Foreign manufacturers of equipment for photovoltaic power plants will find it instrumental to familiarize themselves with the features of the Unified Energy System of Russia and distribution networks, to be aware of the conditions in which their equipment will function. This will help both prevent damage to PVP equipment and avoid situations when it will cause damage to other power grid equipment in adjacent networks or disruption of power supply to consumers.

When supplying equipment for photovoltaic power plants, foreign manufacturers must know current technical requirements for equipment in Russia, including the procedure for testing the PVP readiness to participate in general primary frequency control, which relies on full-scale tests.

It is necessary to ensure reliable operation of PVPs both as part of the power system and as an island, considering that in the case of emergency-related active power shortages, transient processes are accompanied by large frequency deviations.

Since the technical requirements for PVP equipment in Russia are under development, foreign manufacturers should constantly monitor regulatory and technical documents for changes (tightening) in the technical requirements. This will ensure the compliance of the PVP equipment with the current technical requirements and its admission to parallel operation with the UES of Russia.

To prevent unnecessary shutdowns of PVP inverters, it is necessary to pay special attention to their configuration, parameterization, and coordination with algorithms and settings of relay protection devices in the network. This will make it possible to avoid considerable fluctuations in operating parameters in the case of shutdown of powerful PVPs, which can provoke the onset and development of an accident with significant active power shortages, especially under islanded conditions.

The above program and results of the full-scale tests for the participation of PVPs in general primary frequency control give an idea of how these tests are conducted. They will allow foreign manufacturers of photovoltaic power plant equipment to prepare for these tests and provide the compliance of the equipment with the current technical requirements.

The results of the full-scale tests indicate that the equipment of most PVPs can effectively participate in the control of frequency and active power flows, which creates favorable conditions for the reliable operation of power systems.

The implementation of long-term plans will contribute to the development of cost-effective technical solutions for the participation of renewable energy facilities, including PVPs, in the frequency and voltage control by changing the generation/consumption of active/reactive power, and minimizing the power and capacity of energy storage systems. These technical solutions will be in demand in Russia soon.

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