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A Novel Approach of Synchronization of Microgrid with a Power System of Limited Capacity

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Abstract: Currently, active networks called microgrids are formed on the basis of local power supply systems with a small share of distributed generation. Microgrids operating in an island mode, in some cases, have the ability to transfer electricity excess to an external network leading to a synchronization requirement; thus, the optimization task in terms of the system's synchronization must be considered. This paper proposes a method for obtaining synchronization between microgrids and power systems of limited capacity based on a passive synchronization algorithm, allowing us to connect a microgrid to an external power system with a minimum impact moment on the shaft of the generating equipment. The algorithm application was demonstrated by considering a real-life object in Tajikistan. The simulation was carried out on RastrWin3. The obtained results show that the microgrid generator is connected to an external power system at an angle of 0.3° and a power surge of 29 kW, unlike the classical synchronization algorithm with an angle of 6.8° and a power surge of 154 kW (a reduction of the shock moment by more than five times). The proposed synchronization method allows us to reduce the resource consumption of the generating equipment and increase the reliability and efficiency of the functioning units of the examined power system.

Keywords: decentralized management; microgrid; passive synchronization; power system of limited capacity; recloser

1. Introduction

Nowadays, the traditional electricity grid has been transformed into smart infrastructure. The main driving force is related to the integration of renewable energy sources (RESs) at both transmission and distribution levels. However, the distribution network requires to be more "smartness" since it implements a transformation from passive to active networks in terms of power flow direction (bidirectional), decision, control, and protection functions (distributed). When the distribution network functions under real-time conditions, the power generation should match consumer demands. To realize such a service, new system concepts are required. Microgrid systems are considered one of the optimal, beneficial, and practically realized solutions available since they incorporate different RESs with energy storage options [1–6].

The transition from a centralized to a decentralized system of consumer power supply based on microgrids is relevant; it allows the efficient use of power energy sources distributed over the grid, including RES. Both the analysis of achieved research results and forecasts of RES development show that the power energy systems of many countries in the world are undergoing significant changes, the purpose of which is to ensure universal access to inexpensive, reliable, sustainable, and modern energy sources. This goal is achieved by active integration of various traditional and renewable energy sources in a wide range of capacities, from small and distributed generation facilities to large power plants, which entails the transformation of power energy systems [7]. While the costs of traditional energy sources continue to grow and the costs of distributed generation continue to decrease, the latter is becoming more affordable. The RESs are not only environmentally friendly but also create an opportunity to reduce consumer costs when they can generate more electricity than needed and sell the leftovers to energy supply companies [8].

Microgrids combine small generation sources, consumers, and energy storage as well as control devices to form a holistic controlled energy supply system (Figure 1).

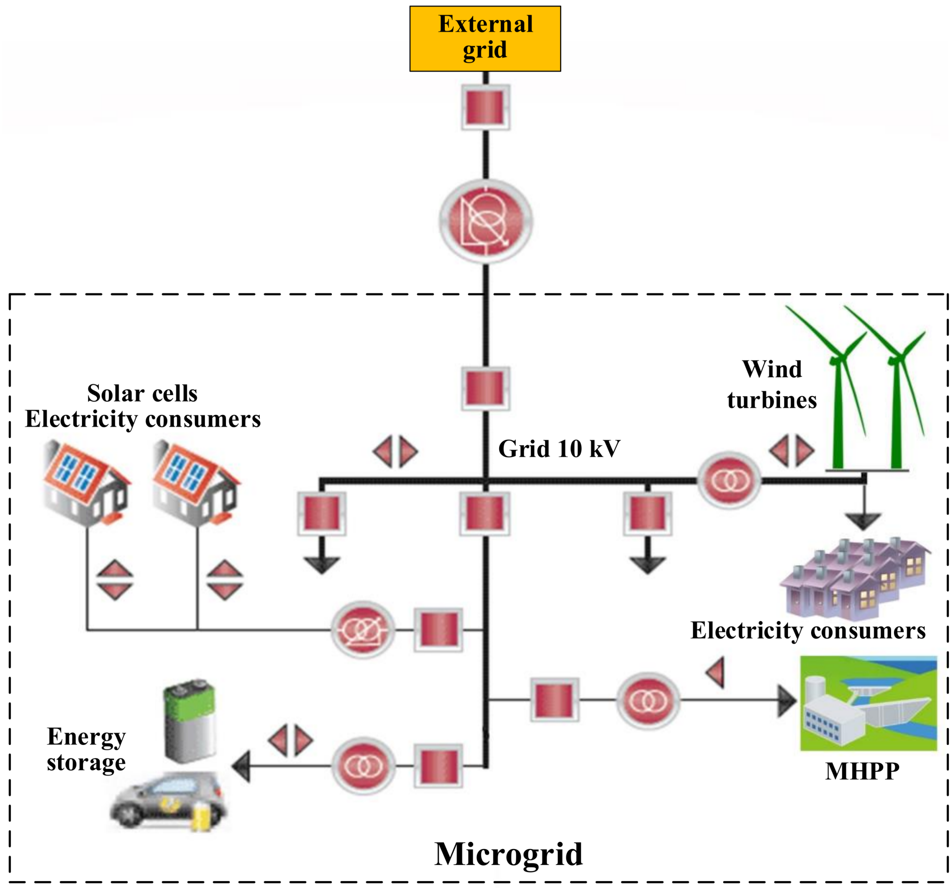

Figure 1. The basic structure of the hybrid microgrid.

An important property of microgrids is that despite functioning as a part of a distribution system, they can also automatically switch to an isolated operating mode in the case of occurring accidents in the network and restore synchronous operation with the network after the accident is eliminated while maintaining the required quality of power energy. Being autonomous or connected to the national power grid, distributed generation facilities (DGFs) are located in close proximity to consumers (small towns, villages, factories) and can produce electricity "on the spot", thus significantly reducing transmission line losses and increasing the reliability of power supply. The power energy produced by the DGFs directly depends on the demand of local consumers; those, in turn, have an opportunity to adjust energy supplies in accordance with their needs, which leads to an increase in their role in power system management [9]. Therefore, microgrids are intelligent automated systems that independently reconfigure the infrastructure and manage the balance and distribution of power flows, ensuring both a smooth transition to isolated mode and automatic resynchronization.

However, the integration of microgrid systems faces great challenges in terms of operation, control, and protection, including load frequency control issues, protection issues related to the inverter presence, the failure of protection schemes, the requirement of fast response protection, low levels of fault currents because of the presence of power electronic devices, various interfacing issues, the need for the electricity demand forecasts, synchronization issues, and many others [10–12].

One of the important tasks of ensuring the normal functioning of small and distributed generation facilities is synchronization and their further parallel operation with other small generation facilities or with a high-power network to achieve maximum system effects and to ensure high reliability in consumer power supply [13,14].

When studying microgrid objects, it is necessary to distinguish between the synchronization of power station generators with an external network (the classical approach) and the synchronization of microgrids with each other or with an external network (microgrid participation).

It should be noted that many scientific studies have been devoted to the synchronization issue between microgrids and the external power system. Let us discuss some existing studies in this regard. For example, an active method of automatic synchronization is proposed in [15]. Active synchronization control forces several generators to actively change the voltage and frequency in microgrids to reconnect to the external network. The proposed synchronization control algorithm is applied for each type of generation source in the examined microgrid. The principle of frequency control in microgrids is analyzed detailed in [16], where a pre-synchronization strategy is proposed to achieve a smooth transition from island to parallel operation with the network. Another study has proposed algorithms for the control and identification of the island state, frequency unloading during the transition to the island mode, and an intelligent synchronization algorithm for reconnecting microgrids to the network [17]. A new method based on the combined use of various phase automatic frequency tuning systems to synchronize the phase and frequency of microgrids with the distribution network was proposed in [18]. The authors in [19] considered another problem that has been underestimated or ignored in other studies, namely, the fact that during synchronization, the communication channels may become subject to time delays; thus, it must be considered in the design of the synchronizers and load share controllers.

This work presents the modified approach of the synchronization between a microgrid and an external isolated power system, considering recloser use. The study examines a transient process during the realization of such synchronization based on a real-life object (isolated power system) located in Tajikistan. The proposed synchronization algorithm minimizes generator failure and diminishes the probability of fault current appearance.

The paper is organized as follows. The next section includes the theory of synchronization concerns. Section 3 describes the examined object applied for the proposed approach's validation. Section 4 discusses methods and proposed approaches for the considered synchronization scope. Section 5 presents both the obtained modeling results and a discussion. Conclusions are drawn in Section 6.

2. Synchronization Concerns

2.1. Generator Synchronization

As it is known, the inclusion of power plant generators for parallel operation with the power system requires the fulfillment of synchronization conditions [20]. For instance, the equalizing current on the unifying switch at switching time should not exceed the permissible value. In practice, the method of precise synchronization and self-synchronization has become widespread.

The realization of switching by the method of precise synchronization is assumed under conditions that are close to ideal, where, at the moment of closing the switch contacts, the amplitudes, frequencies, and phases of the generator voltages and the system are identical.

The precise synchronization of the power station generators consists of:

- Equalizing the voltage (electrodynamic force) of the synchronized generator with the system voltage ($E_g = U_s$);
- Bringing the frequency of the generator as close as possible to the frequency of the system ($f_g \approx f_s$);
- Capturing the moment when the phase shift angle between the generator voltage vector and the system voltage is zero ($\delta = 0$).

Self-synchronization is carried out by connecting a generator without excitation. The generator switch turns on at the moment close to a synchronous rotational speed fg < fs, then the excitation is applied to the rotor, and the generator is pulled into synchronism. Dynamic effects may occur when generators are switched to the parallel operation [21] (Figure 2).

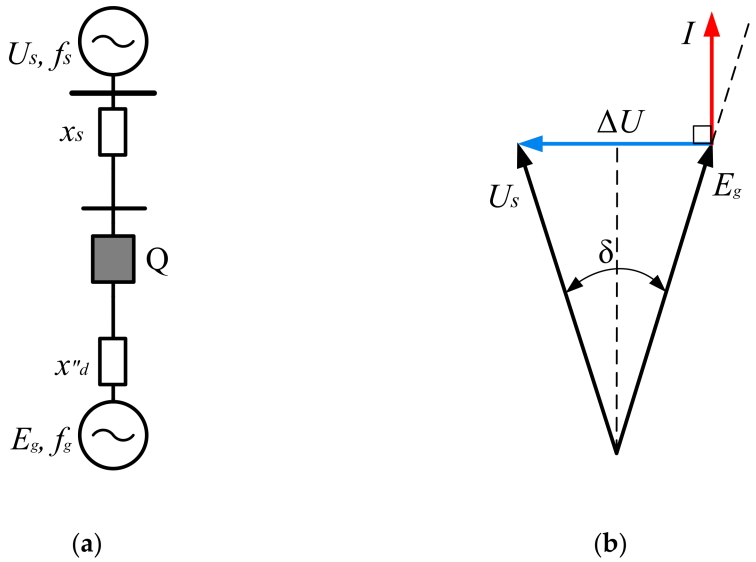

Figure 2. Diagram of the electrical connections (**a**) and a vector diagram (**b**) of a generator synchronized with the network.

If the phase angles of the generator voltage vectors and the network do not match at the moment of switching on ($\delta_g \neq \delta_s$), the generator system connection is under a voltage difference (ΔU), causing an equalizing current according to the following expressions:

$$\Delta U = 2Esin\frac{\delta_{turn}}{2} \quad (1)$$

$$I''_{eq} = \frac{\Delta U}{x''_d + x_s} \quad (2)$$

The initial periodic component of this current creates a sudden surge of active power on the generator shaft and an electromagnetic moment equal to it, as follows:

$$P = M = EI''_{eq}cos\frac{\delta_{turn}}{2} = E\frac{2E}{x''_d + x_s}sin\frac{\delta_{turn}}{2}cos\frac{\delta_{turn}}{2} = \frac{E^2}{x''_d + x_s}sin\delta_{turn} \quad (3)$$

The optimal moment when the synchronized generator is switched on to the network is the moment when the angle passes through zero, and it takes some time to turn on the switch. This means that the synchronizer must provide an impulse to turn on the switch with some advance in time. The advance time should be equal to the proper time of the switch operation and other auxiliary relays and contactors located in the circuit between the synchronizer and the switch. Only in this case will synchronization occur with a minimization of the equalizing current.

Depending on how the advance is created, the synchronizers are divided into two types: synchronizers with a constant advance time—the moment of operation of which is determined directly by a given advance time, and synchronizers with a constant advance angle—the moment of operation of which is determined by a given angle.

Figure 3 shows a change in the effective values of the peak voltage (or sliding voltage) that occurs when there is a frequency difference between the generator voltage and the network. Two cycles of peak voltage U_s changes, corresponding to the two values of the angular frequency ω_s, are given, and the greater the sliding speed, the shorter the sliding period T_s. In order to turn on the generator at the optimal time (at Point 2), the pulse to the switch must be applied earlier than this moment and correspond to the turn-on time. This time is called the advance time $t_{adv.}$. The moment when the pulse is applied to the switch is indicated by Point 1. The advance time corresponds to the angle between the generator voltage vectors and the network, called the advance angle $\delta_{adv.} = \omega_s t_{adv.}$ (Figure 4).

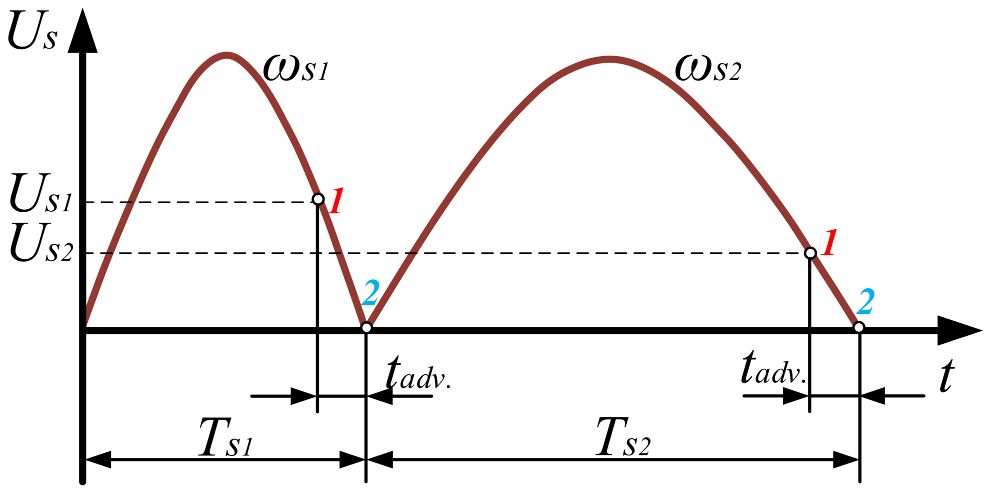

Figure 3. A graph of the peak voltages.

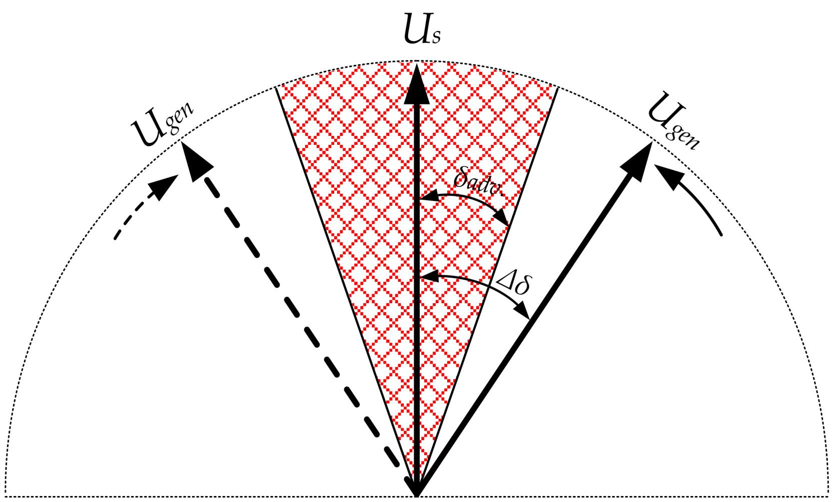

Figure 4. A graph that explains the actions' algorithm in a case of classical synchronization of the generators.

It becomes obvious that the signal to turn off the recloser should be given at the angle $\delta_{adv.}$ and the time $t_{adv.}$ equal to it. This allows us to connect the power station generator to the network without power surges.

2.2. Microgrid Synchronization

Microgrid synchronization is different from single-machine synchronization. Microgrids consist of a variety of generators, including RESs, as well as consumer loads that are highly variable in real-time. Consequently, the nature of changes in both power energy sources and consumer loads strongly affects the synchronization process because of constantly changing synchronization parameters (frequency, angle, and voltage amplitude); it is almost impossible for microgrid systems to get into synchronous conditions.

Using only an auto synchronizer is not enough for microgrid synchronization. The manual synchronization method is usually applied, which, while maintaining microgrid frequency and voltage values, waits until the synchronization criteria are met. However, the manual method does not always give the expected results. In particular, when the frequency difference between the two systems is very small, it takes a long time until the phase difference corresponds to an acceptable value.

To synchronize a microgrid with an external network, the following methods are used [22,23]:

- Passive synchronization method—when the measured synchronization parameters on both sides of the switching device are equal or close to each other. This type is easy to implement; however, there are cases when the synchronization process can be delayed [24,25];
- Active synchronization method—uses additional control to get the synchronized parameters into the acceptable range, and this ensures a faster and smoother connection of the microgrid to the external network [15,26–28].

Low inertia of generator rotors and high stochasticity of consumer loads are the main factors affecting the synchronization process in microgrids. Figure 5 shows an example of the frequency fluctuations in microgrids in parallel operation with the power system and after separation (island mode).

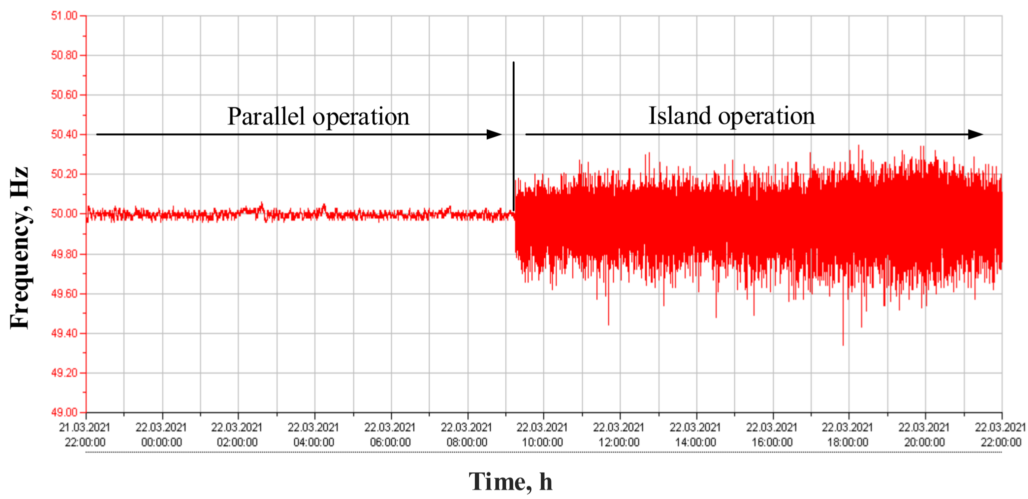

Figure 5. Frequency fluctuations in microgrids in both parallel and island operation modes.

Therefore, the intensity of the frequency and mutual angle fluctuations creates an urgent task in establishing a smooth synchronization nowadays, the solution of which would contribute to an extended service life of the generating equipment operating as a part of the microgrid.

3. The Real-Life Object of Research

The object of the study is an isolated power system in the Gorno-Badakhshan Autonomous Region (GBAR) in Tajikistan. The territory of this region, as well as almost the entire territory of the country, is a mountainous area. Power energy production is mainly carried out based on RESs, i.e., hydropower plants [29–32]. Pamir Energy is engaged in power supply for consumers in the GBAR, consisting of eight districts. The company has 11 small hydroelectric power plants (SHPPs) with a total capacity of 43.5 MW [33,34].

One of the localities of the Rushan region, in which small-generation sources are operating, is the mountainous area of Shujand. In this area, there is a Shujand SHPP, built according to the derivational type on the Bartang River (Figure 6).

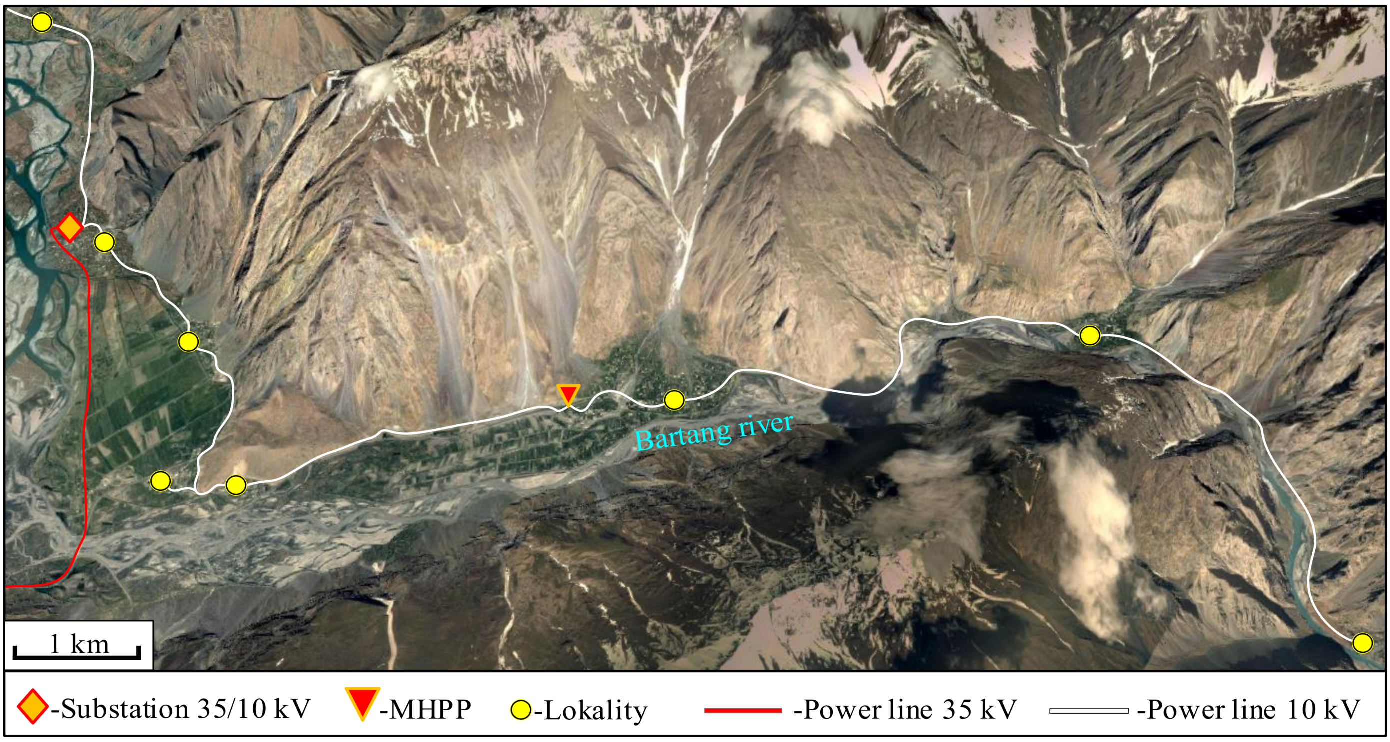

Figure 6. Geographical map of the Shujand network location, presenting its generation.

The Shujand SHPP feeds this area's consumers by forming a local power supply network [35]. Since this local system operates in the island mode from the rest of the Rushan network, in most months of the year, the electricity production by the MSPP is limited to the loads consumed only in this area. The station has two generator units with a capacity of 500 kW each. Figure 7 shows the schedule of the power energy production of the Shujand SHPP in 2019.

As can be seen from Figure 7, the maximum energy production (W_{max}) at the SHPP can reach about 0.725 million kWh. However, the actual power energy production does not correspond to the established one. The reasons for a decrease in power energy generation are mainly the following: the units' operation in only island mode is limited to a small number of consumers; there are frequent emergency disturbances in the external network, leading to the shutdown of both the power units of this SHPP and local consumers; the influence of external factors such as seasonal changes in water flow. The listed disadvantages do not allow the SHPP to properly supply the local consumers and transfer (sell) the electricity excess to the external network.

Another raised task is the synchronization and connection of this local network to parallel operation with the rest of the Rushan network. The procedure for the parts' synchronization with the sources under conditions of constant load fluctuations is impossible due to the non-fulfillment of synchronization conditions. To ensure switching to parallel operation mode, de-energizing local consumers is required by disconnecting the single source (the SHPP) and then connecting to the local network through a switching device to the main network after connecting the SHPP units to the network by performing a synchronization process. This whole procedure is laborious and consumes a lot of time.

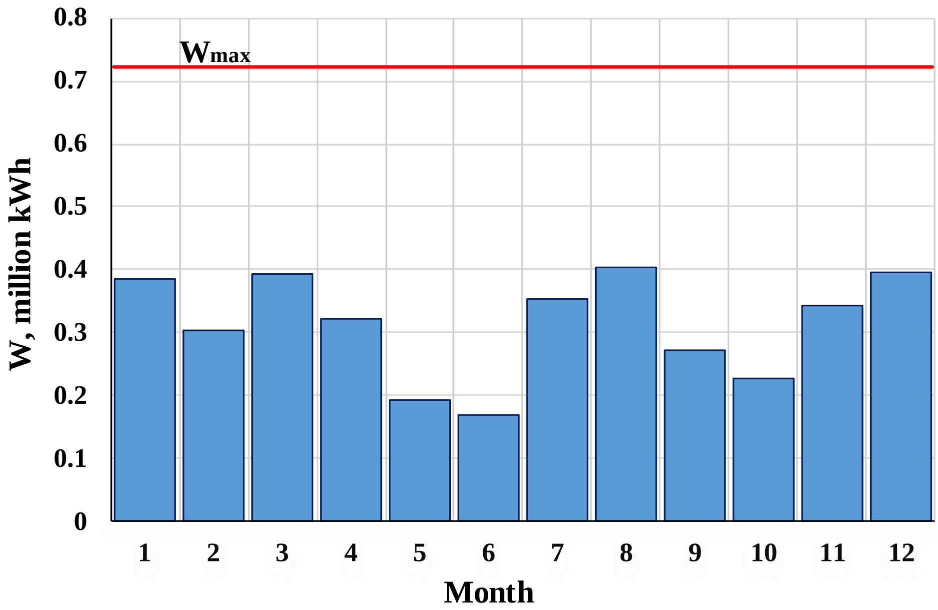

Figure 7. Energy production profile of Shujand SHPP.

Therefore, due to both the low inertia of the power units of the SHPP and the stochasticity of the loads in the Shujand local network, this study considers the problem of the large shock moment occurrence on the shaft of the generating units of the power plant. This essential issue occurs when synchronization is carried out with the subsequent connection of the SHPP, together with the consumers, for parallel operation with an external network.

4. Methods and Proposed Approaches

4.1. Combined Use of Both the Special Automation and Intelligent Reclosers

To prevent an emergency shutdown of the local power supply network (microgrid) due to emergency disturbances in the external network, special automation is used—the automation of outstripping balanced division (AOBD) [36]. This automation has shown its effectiveness and can be used at both planned facilities with low generation and existing facilities, whose operation in such modes was not originally intended. To ensure the safe parallel operation of the microgrid, a special method of emergency mode control with an auto operator was proposed and implemented [37]. The idea of this method is an outstripping balanced separation of the microgrid according to a priori fixed network sections in the case of normal mode violations with the transition to an autonomous operation mode and subsequent automatic restoration of a synchronism as well as a normal mode with the required equipment loading.

It is well known that in networks with generating devices, when the connection line with the external network is disconnected, it is prohibited to turn it back on. Every time such lines are switched on, the synchronization conditions must be satisfied. If these rules are not followed, when the generating device is switched on asynchronously, significant dynamic moments may occur, which will pose a threat of damage to both the generators and their primary motors [38].

Today, reclosers are widely used as a unifying element of network parts with the sources [39]. Reclosers are elements that perform the separation functions, reserving parts of 6–10 kV electrical networks with long power lines of a trunk-radial configuration. The recloser combines the following units: a vacuum switch; a system of current and voltage converters; an autonomous operational power supply system; microprocessor relay protection and automation; a system of ports for connecting telemechanic devices; a software package. Most modern reclosers do not have the synchronizing functionality necessary for operation in networks with the presence of generators. Since the reclosers are installed in different network places remotely from the generators, synchronization will be performed on them but not on the generator switches. An improvement in the reclosers' functionality was proposed in [40], where a synchronization unit was added to the recloser control cubicle, transferring it to the category of intelligent network elements.

4.2. Microgrid Synchronization Algorithm

As noted earlier, the synchronization of microgrids with an external network or with each other has its own characteristics, and, in most cases, it is difficult to fulfill the synchronization conditions. The reason is the frequent change of the load power in the microgrid itself. There are cases when the conditions are met, a signal is issued to turn on the unifying switch, and, at this moment, the load power changes, which leads to an unacceptable mismatch of synchronization conditions (usually the phase shift angle between the microgrid voltage vector and the voltage of the external network) even before the unifying switch is fully turned on. Thus, the phase shift angle exceeds its permissible value, leading to the occurrence of a shock moment under the action of the equalizing current, which can result in a disconnection of microgrid generators by protection operation, shortening their service life and even causing damage.

To minimize the shock moments when connected to a parallel operation, the novel algorithm for the operation of auto-synchronizers on reclosers is proposed and presented in the block diagram shown in Figure 8.

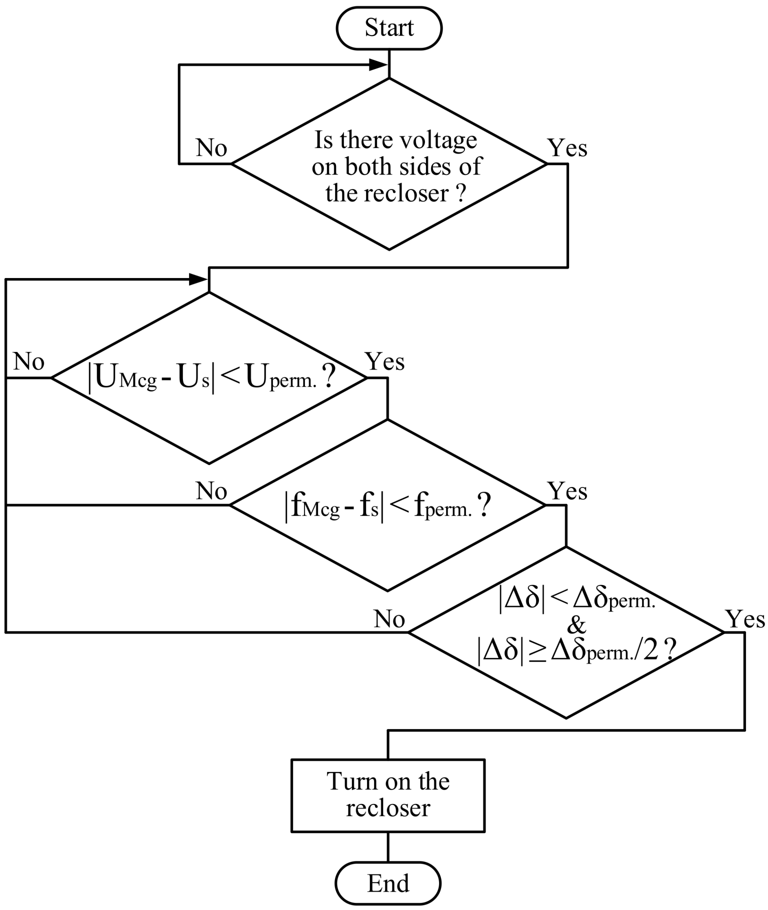

Figure 8. Block diagram of the proposed synchronization algorithm.

Figure 8 includes the following parameters: U_{Msg}–a voltage in the microgrid, kV; U_s–a voltage in the external network, kV; $U_{perm.}$–a permissible voltage difference, kV; f_{Msg}–a frequency in the microgrid, Hz; f_s–a frequency in the external network, Hz; $f_{perm.}$–a permissible frequency difference, Hz; $\Delta\delta$–a mutual voltage angle, °; $\Delta\delta_{perm.}$–a permissible mutual voltage angle, °.

The essence of the proposed algorithm states the following: when the first two synchronization conditions are met, the third condition is expected to be met. When the voltage phase shift angle reaches the value $|\Delta\delta| < \Delta\delta_{perm.}$ and until this angle is equal to $|\Delta\delta| \geq \Delta\delta_{perm.}/2$, the command to turn on the recloser is not issued (Figure 9).

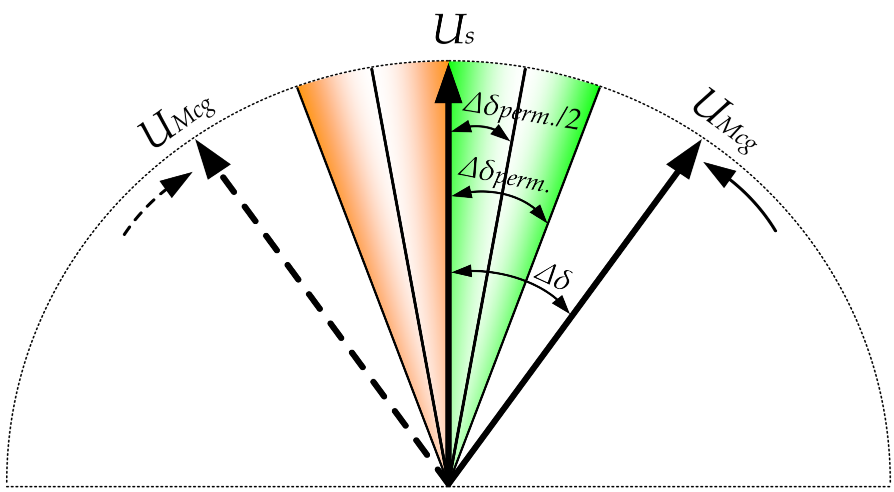

Figure 9. An explanation of the proposed synchronization algorithm.

Considering the change of the slip(s) sign, the third synchronization condition can be written as follows:

$$-\frac{\Delta\delta_{perm.}}{2} \leq \Delta\delta \leq 0, \tag{4}$$

when $s \geq 0$ or where s is the slip, $s = f_{msg} - f_s$

$$\frac{\Delta\delta_{perm.}}{2} \geq \Delta\delta \geq 0, \tag{5}$$

when $s \leq 0$.

It is required to have a margin for the full turn-on time of the recloser t_R and, at the moment when the command to turn on is given, $\Delta\delta$ does not exceed $\Delta\delta_{perm.}$ (Figure 9). In all other cases, the command to turn on the recloser is blocked. The microgrid is not turned on for parallel operation with the external network.

5. Obtained Simulation Results and Discussion

A simulation was performed for the power supply scheme for consumers in the mountainous area of Shujand, Rushan Region, GBAR in Tajikistan. In the scheme of the local network of this area, its source is the SHPP. Power supply to consumers is carried out either in island mode or in power supply mode from an external network at 10 kV. The power supply mode exists because of the frequent disturbances that occur in the external network. In the case of parallel operation of the SHPP with the external network, the synchronous operation of the generators is often disrupted, leading to the de-energization of consumers of the whole feeder. Considering the high accident rate in the examined scheme, causing many outages, prolonged downtime, and an undersupply of power to consumers, as well as performing a remote synchronization, the installation of the reclosers in different places of the considered scheme is proposed (Figure 10).

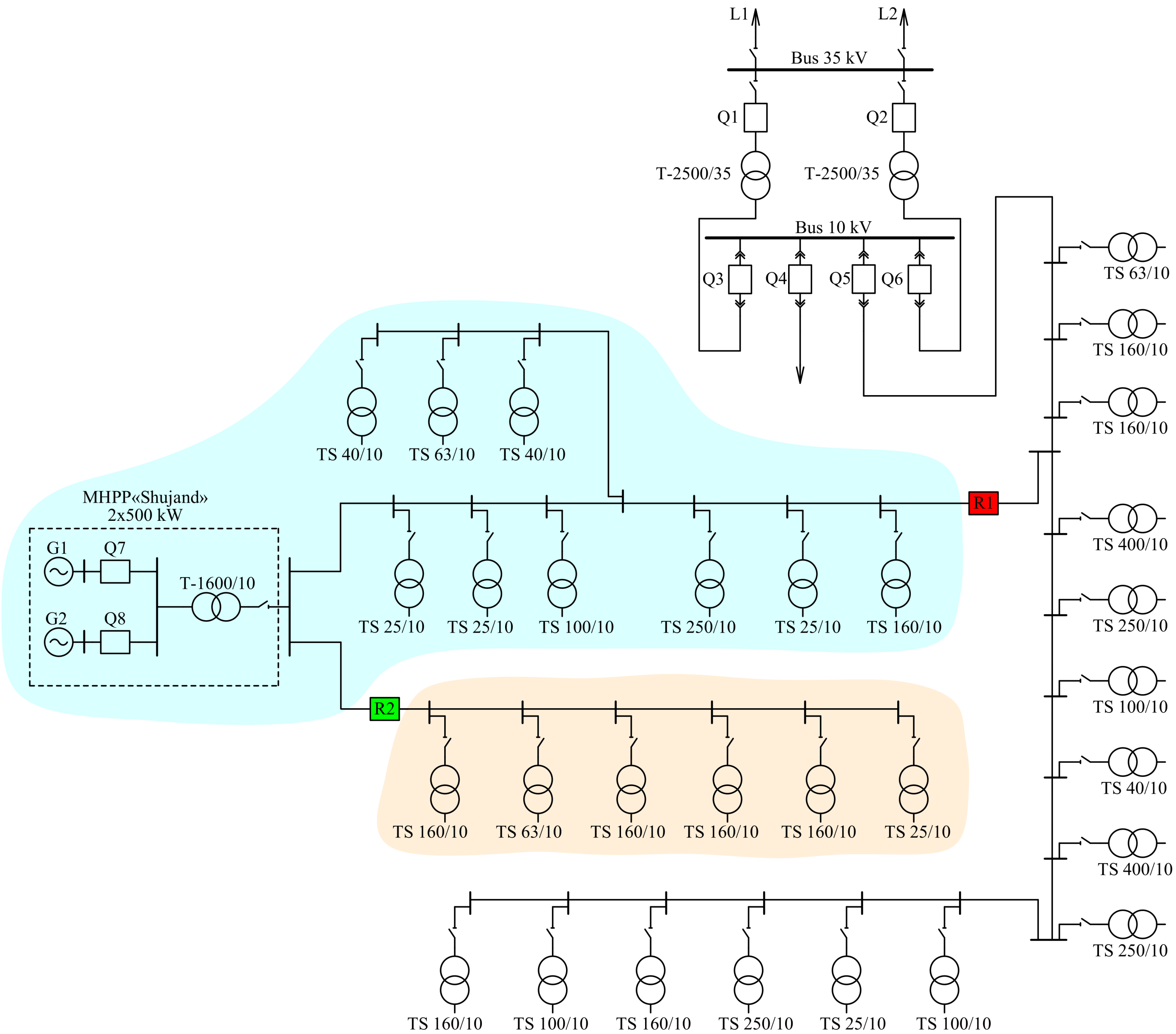

Figure 10. Power supply scheme of the Shujand area.

During the simulation, the installation locations of the reclosers (R1, R2) in the considered scheme were selected based on the balance conditions between capacities of the SHPP generating devices and the consumer loads. This arrangement allows the microgrid to disconnect from the external network automatically and quickly in emergency modes and continue its operation in the island mode. An automation of AOBD was used as emergency automation that performs the separator function, and the proposed algorithm was applied to restore normal parallel operation between the microgrid and the external network.

As shown in Figure 10, the recloser R1 is designed to separate the microgrid from the external network and enables it to work in parallel with the network (the area highlighted in blue). The recloser R2 is used to perform an automatic frequency unloading (AFU) of a part of the consumers (the area highlighted in orange) in cases when the power of the consumer loads exceeds the generation capacity of the SHPP (sometimes this can happen during the winter period). The simulation was carried out on RastrWin3—Rustab for both the software and computing complex [41].

The parameters of the algorithm were selected manually by means of simulation modeling. The proposed algorithm can operate under different options of the synchronization conditions' settings. However, the maximum permissible deviations for the values of the synchronized parameters should be limited to the IEEE 1547 standard [42].

In practice, due to restrictions on dynamic impacts from manufacturers of the generating equipment and to increase service life, more stringent requirements are imposed. For example, the difference in angles when switching on should not be more than 3–5°.

Therefore, an acceptable deviation of the parameters, such as the permissible voltage difference, the permissible frequency difference, and the mutual voltage angle, are assumed as follows (according to the constraints mentioned in [42]):

$$\begin{array}{c} |U_{Msg} - U_s| < \Delta U_{perm.} = 0.1\ \text{kV}; \\ |f_{Msg} - f_s| < \Delta f_{perm.} = 0.08\ \text{Hz}; \\ |\delta_{Msg} - \delta_s| < \Delta \delta_{perm.} = 5^\circ; t_R = 0.1\ \text{s}. \end{array} \quad (6)$$

Another important parameter affecting algorithm accuracy is the proper turn-on time of the recloser. The shorter the turn-on time, the more accurate the result will be, and there will probably be a lower shock moment on the generator shaft and vice versa; the longer the turn-on time, the lower the accuracy, i.e., the greater the error, and thus, a greater shock moment on the generator is likely.

Figure 11 shows an example of the behavior of the mutual angle of the microgrid with an external network. As can be seen, a stochastic change of the load power leads to a change in the slip sign; therefore, the advanced synchronization algorithm given in Figure 4 cannot be used in such situations.

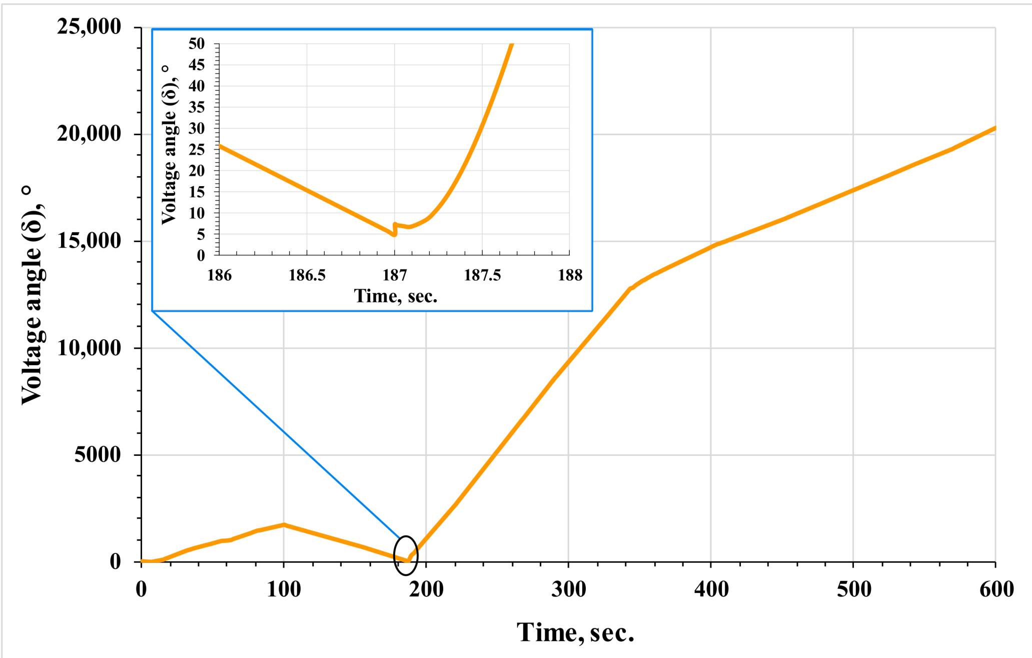

Figure 11. A graphical example of changing the mutual angle in a case of a sign change during forbidden synchronization.

To exclude the large shock moments on the generator, we will use the algorithm proposed in this work (Figures 8 and 9). The simulation results, both with and without the algorithm, are shown in Figures 12 and 13.

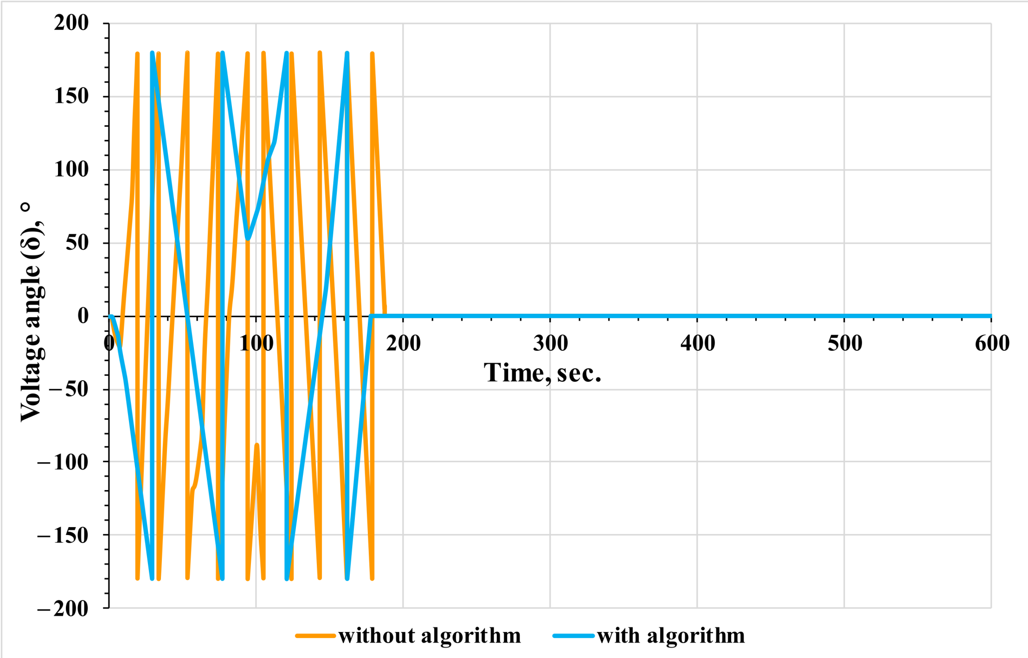

Figure 12. A graph of the mutual angle changes during synchronization (angle displayed in the range of $\pm$ 180°).

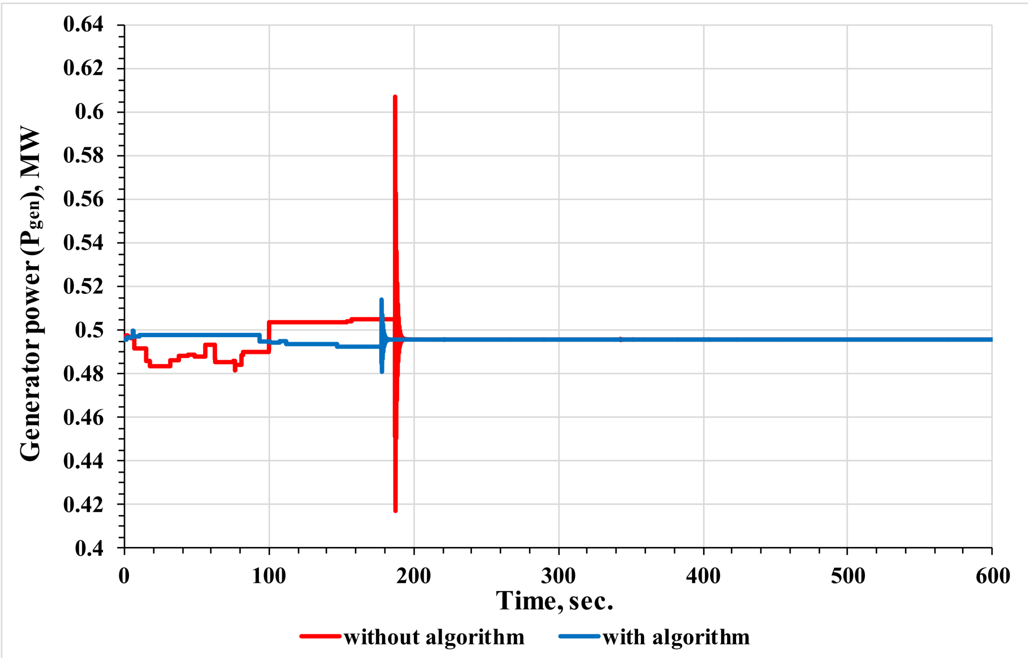

Figure 13. A graph of the power change of the generator (G1) during synchronization.

The nature of the change of the mutual angle and power of the microgrid generator during synchronization is shown in Figure 14.

It is obvious from the simulation results that the use of the classical synchronization algorithm (Figure 4) in the microgrid objects leads to erroneous angle connections. An example of such a case is presented by the graphs in Figure 14a, where the microgrid is connected to the external network at the angle $\delta = 6.8^{\circ}$ and power surge $\Delta P = 154kW$.

The result of solving this problem is illustrated in Figure 14b, where error-free synchronization is achieved by using the proposed algorithm (Figures 8 and 9). The microgrid is connected to the external network at an angle $\delta = 0.3°$, while the power surge is $\Delta P = 29kW$.

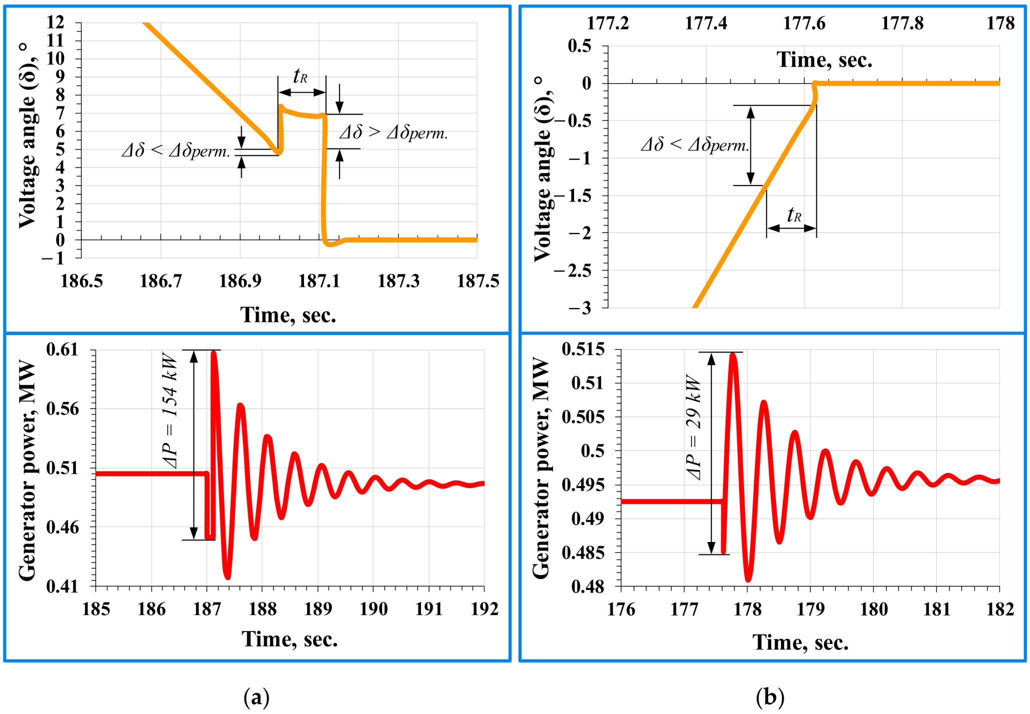

Figure 14. Graphs of both the angle and power of the generator (G1) (**a**) without using and (**b**) using the synchronization algorithm.

The proposed algorithm was tested under the same synchronization conditions, and, based on the experimental results, the statistical data were obtained, which indicated a solution to the considered problem. A chart of the obtained statistical data is given in Figure 15. Based on analysis of the statistical data results, the average statistical switching on angle $\delta = -0.83°$ and $\delta = 0.68°$ was determined for negative and positive sliding, respectively.

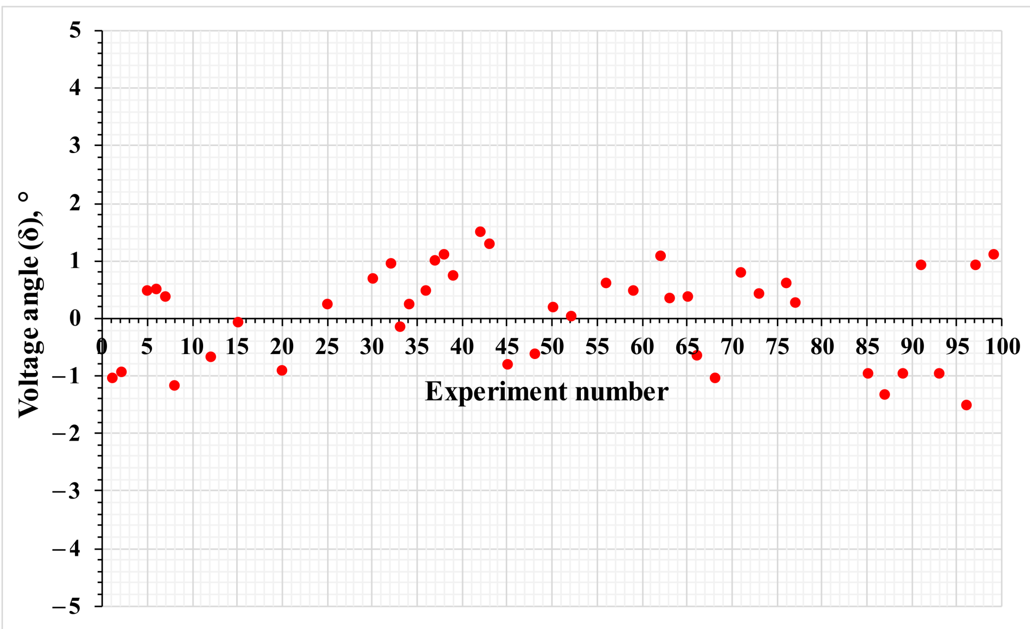

Figure 15. A chart of the statistical data.

As a result, the proposed algorithm demonstrates the solution of the synchronization issues between microgrids and the external network. The proof of the method's operability can be considered as a reduction of the impact moment on the generator by more than five times. Naturally, the reduction of the impact moment has a positive effect on the service life of the generating equipment.

6. Conclusions

The low inertia of power units and the stochasticity of the microgrid's own loads can lead to erroneous connections to the external network, with unacceptable misalignments of synchronous conditions, the consequences of which may be the shutdown of the microgrid generators by protection functions, a reduction in their service life, and even damage to the latter.

The synchronization issue of microgrid facilities is an urgent task, and its solution will ensure the quality of the supplied power and a proper degree of power supply reliability as well as the synchronization with a smooth connection, which contributes to prolong the service life of the generating equipment.

This study presents a modified algorithm for synchronizing the Shujand microgrid with a limited power network. The simulation results show that the microgrid is connected smoothly at an angle $\delta = 0.3°$, while the power surge to the generator is $\Delta P = 29$ kW. The proposed synchronization method, according to the results of the study, made it possible to reduce the impact moment on the microgrid generators by more than 5 times. Consequently, this leads to a decrease in the resource consumption of the generating equipment operability of the Shujand local network, an increase in the reliability and efficiency of the functioning of the isolated power system parts of the GBAR in Tajikistan. The proposed approach is relevant for adaptation and integration in expanding the number of intelligent power systems.

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