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Predictive Control Algorithm for a Variable Load Hybrid Power System on the Basis of Power Output Forecast

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ABSTRACT

Harmonious integration of renewable energy sources into current energy systems has taken on increasing importance amid the scarcity of carbon resources. Among the key problems is the imbalance in power consumption, power generation, and significant peak overloads. To deal with this issue, an intelligent software and hardware system is needed, which will effectively implement predictive control algorithms for various energy sources. The research examines the fundamental provisions of the concept of predictive control over a variable load hybrid power system on the basis of power output forecast. The analysis performed has allowed developing a method of predictive control over the power system in a small locality based on machine learning algorithms. The method was tested using an electric power complex simulation, which included four energy sources (solar panel, wind turbines, small hydrogenerator, and standard carbon-fueled generator). The proposed predictive control method has proved to be productive. The algorithms have allowed diversifying the reliability of power supply by ensuring the sustainability of the power grid.

Keywords: Hybrid Power System, Energy Efficiency, Renewable Energy Sources, Power Balance, Decision Tree Methodology
JEL Classifications: L94, Q42, Q47

1. INTRODUCTION

Renewable energy sources (RES) are becoming increasingly widespread (Makarova et al., 2019; Anagnostopoulos et al., 2020). Installations converting the energy of physical processes into electricity are commonplace: wind turbines, solar panels, hydroelectric power stations, geothermal power plants, etc. (Renewables 2021 Global Status Report). The reason behind this trend is the constantly growing consumption of energy, which, in order to be produced, requires a rising amount of expensive fuel resources. The increased use of extractable resources leads to their rapid depletion, and the burning of them causes serious damage to the environment (Rahman et al., 2020).

Electricity generation using RES exhibits a broad spread of time-related characteristics, variable load, and imperfect energy storage systems. In order to tackle these problems, a smart software and hardware system is needed, which will switch automatically between different energy sources based on the results of the generated and consumed power analysis.

The article aims to develop a concept for implementing predictive control of a variable load hybrid energy system including power output on renewable and non-renewable energy sources and batteries. During the study, the following objectives were attained: to develop an algorithm for controlling the power system that provides uninterrupted power supply to a small locality with a hybrid power system; to implement predictive analysis functions based on the machine learning method that automatically selects the best energy sources at a given time under certain conditions; to carry out a predictive assessment of a locality's power consumption.

The forecast results are primarily focused on solving applied problems of resource conservation and reducing the use of non-renewable energy sources for power supply of small and medium-sized localities (SMLs) depending on the consumer value of electricity.

2. LITERATURE REVIEW

Analyze the development of hybrid power systems. In the global practice, there is no clear conventional definition of the term "hybrid power system." It is logical to assume that any power system, which combines several energy sources is considered a hybrid one. A closer study shows that most power systems are of a hybrid nature.

With respect to electric power capacity, the concept of hybrid was first used in the car industry. Hybrid vehicles combine an internal combustion engine and an electric motor. The next step involves the active promotion of electric cars that were able to store more power in batteries due to reverse charging technology (Yaïci et al., 2020). Building upon this, we can make an assumption about significant advantages provided by the hybrid power supply method.

Virtually all renewables-based power supply complexes have energy storage devices that act as an inertial element in the event of short-term power outages, and as sources of stored energy in the event of an increase in their number. Due to changes in natural conditions, the stochasticity of renewables-based power generation is often compensated by traditional fuel generators included in electric power systems. It is quite common to combine wind turbines and solar panels in a single complex; in some cases, small hydroelectric power plants are added to them (Mammadov, 2019).

To determine what energy sources to use, we analyze the advantages and disadvantages of the main methods of industrial renewable electricity generation.

2.1. Solar Energy

There is no need to purchase fuel cells and expensive service equipment to derive it (Helios House, n.d.). Among the key disadvantages are a frequent clean of solar panels from dust and pollution, power harvesting during sun hours, and weather dependency. Figure 1 shows the average energy yield of solar panels per day in central Russia during 1 year.

Insolation varies according to weather conditions and reaches its maximum on clear and cloudless days. Figure 2 presents energy yield of solar panels during a clear/cloudy summer day.

Thus, the efficiency of electricity generation using solar panels is affected by numerous factors, such as the length of the daylight hours and cloudiness. However, with the weather forecast and sun rise and set times known, it is possible to determine the estimated energy yield by solar panels with high accuracy.

2.2. Wind Turbines

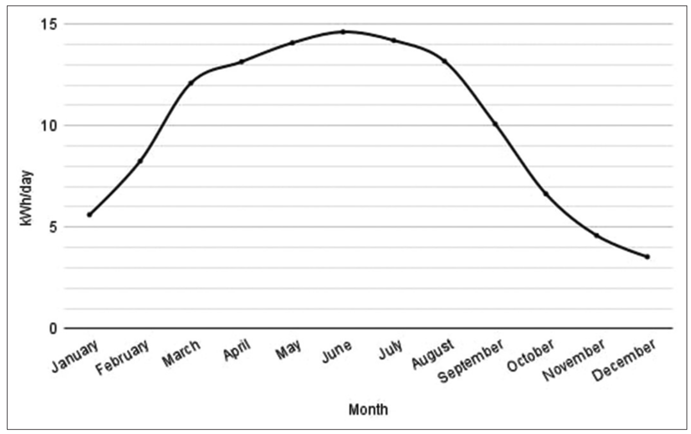
Along with solar energy, wind turbines are also gaining in popularity (Renewables 2021 Global Status Report; Echeistov et al., 2018). To obtain wind energy, an open area with regular abundant air currents is a sufficient criterion. On the other hand, the installation and maintenance of a wind turbine entail considerable costs.

Wind turbine power output is dependent on the strength of the wind. The average energy yield of a HY1000 wind turbine at a height of 15 m per day during 1 year is given in Figure 3.

Wind turbines produce the maximum power output with medium or strong air flows. If wind speeds exceed the cut-out speed, power stops being generated. The relationship between wind speed and the amount of electricity delivered by a turbine is demonstrated in Figure 4.

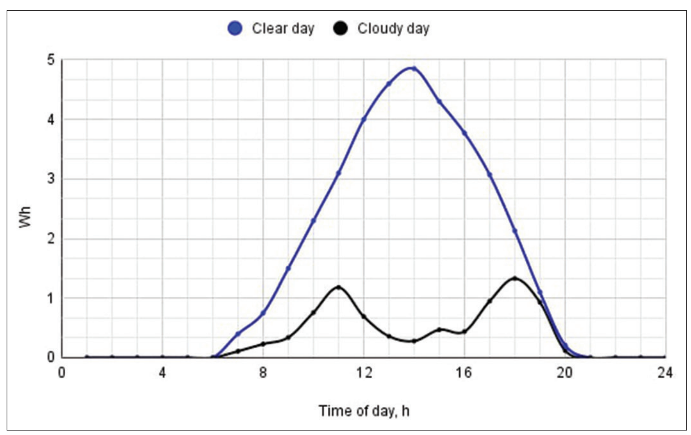
Based on the wind speed data, it is possible to determine the estimated power output.

Figure 1: Average energy yield of solar panels per day during 1 year



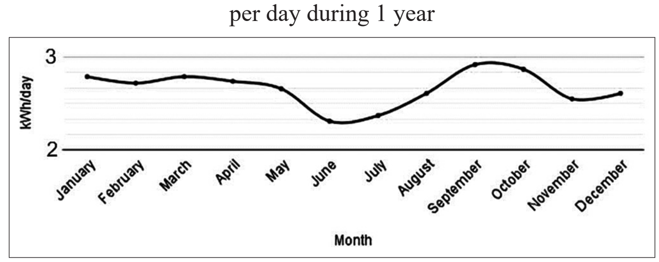
Source: Helios House, n.d.

Figure 2: Energy yield of solar panels during a clear/cloudy summer day



Source: Helios House, n.d.

Figure 3: Average energy yield of a wind turbine at a height of 15 m per day during 1 year



Source: Khan et al., 2019

However, as with solar panels, the wind turbines-based power system should include cyclic energy storage units, i.e. batteries, in order to maintain its sustainability (Renewables 2021 Global Status Report; Todorov et al., 2019).

Renewables-based power generating systems in locations with a significant amount of sunlight (California [USA], Spain) or the active movement of air masses (Norway's shores) can reduce an average household's energy consumption from the central electrical power grid by 20–25%; in some cases, this share reaches up to 80–90% (Todorov et al., 2019; Stave et al., 2021). The types of energy sources used in different countries vary significantly. The structure of production by sources of energy in Russia is represented by thermal power stations (64%), nuclear power plants (19%), hydroelectric power stations (17%), and renewable sources (Kuzmin et al., 2019).

Having analyzed the main sources of energy generation and storage, we can conclude that a complete transition to RES is currently impossible. The best option is to implement a distributed hybrid scheme that provides for the use of alternative sources under favorable conditions, thus supplying SMLs with electricity and, at the same time, storing it in batteries. In situations, where such generation is impossible, it is expedient to use either the charge stored in the batteries or a backup energy source, such as a fuel generator.

It is worth noting that the widespread use of renewable energy has complicated the problem of uneven electricity consumption by adding a new variable, since the amount of electricity generated by renewables-based systems depend on the stochastic nature of weather conditions. However, most electrical grids are designed to deal with a change in capacity of up to 20%. In modern conditions, this interval is far from enough when forming a hybrid energy system.

Despite the recent introduction of smart electricity metering technologies, the problem of imbalanced power consumption during the day and significant peak overloads still persists. Another challenge is a lack of single electrical networks between states and even within one state.

3. METHODS AND DATA

Most renewable energy sources depend on external conditions, so it is reasonable to implement a hybrid system that includes renewables-based generating capacities, storage systems, and backup generating capacities based on non-renewable energy sources. At that, it is of high importance to ensure correct automatic switching between different energy sources using the findings of predictive analytics and smart data processing capabilities (Crespo Márquez et al., 2020; Selivanov et al., 2021; Todorov et al., 2020).

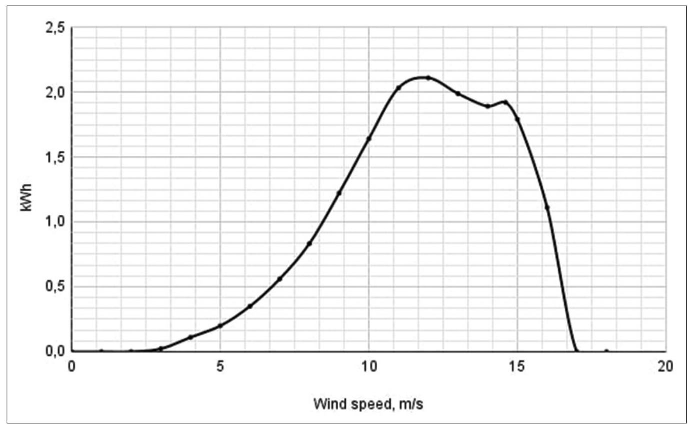
The general model of the hybrid distributed power generation for SMLs is presented in Figure 5.

Determine the conditions for the effective use of various energy sources in a hybrid power supply model.

The power consumption of a locality varies and is dependent on a range of different factors. Production capacities available in the territory are not taken into account as they are designed for special-purpose consumers and recognized as an individual power consumption unit. Figure 6 shows the locality's power consumption per day in summer/winter season.

By distributing data according to the factors that affect generation capacity and power consumption, it is possible to create a smart power management system based on power output, which will determine the best ways to use various energy sources based on

Figure 4: Relationship between the wind speed and the wind turbine power output



Source: Khan et al., 2019

Figure 5: Model of a hybrid power supply station in a small locality

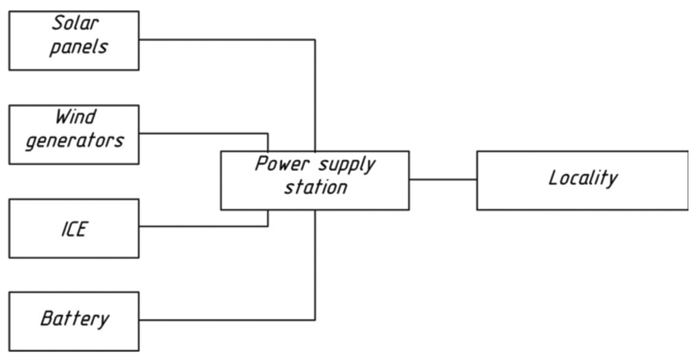
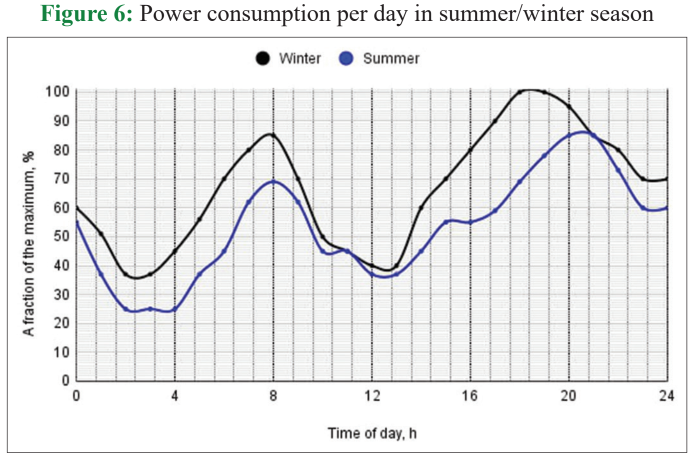


Figure 6: Power consumption per day in summer/winter season



Source: Zhou et al., 2020

input data (Jamil et al., 2021; Shakhnov et al., 2019; Kononov and Kononov, 2018; Hernández-Cedeño et al., 2021).

In the process of constructing an experimental model of a system for predictive control of a hybrid power system, the following provisions were laid down:

1. Possibility of automating the most important control functions, primarily safety functions (automated shutdown of a part of the system)
2. Realization of the power system management based on the function of pollutant emissions minimization (according to the function embedded in the algorithm, the system tends to use renewable energy sources in the first place, and traditional energy sources are utilized on a second-priority basis in the event of a power shortage)
3. Possibility of exercising autonomous control over power sources (the system performs real-time monitoring of the power harvested from renewable energy sources and analyzes power consumption; if the amount of power consumed significantly exceeds the incoming power produced by renewable energy sources, the system automatically enables traditional fuel generators)
4. Possibility of performing predictive analysis of the renewables-generated power based on the weather forecast (the system monitors the weather forecast and estimates power balance on its basis, then it determines the required amount of extra fuel that will be needed to provide the adequate level of power consumption)
5. Possibility of accumulating surplus energy from renewable energy sources and using it when needed (electricity can be stored in batteries or in the form of thermal energy).

4. RESULTS AND DISCUSSION

To realize automatic control of the power supply system in SMLs, a hardware and software complex (Selivanov et al., 2021) is developed that implements the concept of predictive control of energy efficiency based on power output forecast (Shcherbatov, 2019; Arakelian et al., 2019; Shcherbatov et al., 2019). This concept is in line with the trends in infrastructure solutions for the Internet of Things (Yudin et al., 2017; Grigoriev et al., 2018). It allows combining the decision-making module and heterogeneous sensor elements with energy generation and transmission technologies (Figure 7).

The proposed hardware and software complex is classed as embedded solutions, the development and debugging of which imposes a number of requirements. The most relevant issues are the application of basic universal structures, ensuring the flexibility and reconfigurability of the control system used, and the possibility of operational maintenance and predictive repair (Yudin et al., 2017; Khan et al., 2021; Andryushin et al., 2020). The hardware and software complex is built according to the agent-manager scheme; agent applications collect heterogeneous data from the sensor network elements and transfer them to management modules. To serve the smart functions of the system, machine learning algorithms are used, which select the best option for generating electricity based on the input parameters (Sharifzadeh et al., 2019; Prudius et al., 2019).

Predictive control algorithms are designed to increase the efficiency of renewables-based electric power complexes by coordinating the incoming power and the power consumption. If coordination is impossible or the incoming power significantly exceeds the consumed power, predictive control ensures power accumulation. If the incoming power is less than the power consumption, it automatically enacts additional generating capacity to harvest the required amount of electricity and meet energy demands.

The quantitative parameters of the electric power complex (power consumption, power generation, the amount of battery-stored power, generation cost of 1 kW using different methods of electricity generation, etc.) can be considered predicates with their own tolerance range. If the predicates go beyond it, the algorithm will perform necessary control actions to balance the system. Based on the predicates and the established tolerance range, it is possible to form a decision tree, which primarily aims at reaching the maximum efficiency for a given parameter (Yuldashev and Vlasov, 2020; Bakhtadze et al., 2021).

Monitoring data are transferred to a single cloud storage. The key estimated parameters are the following: Hourly costs of active and reactive power (the shift with the highest and lowest power demand during the day); electrical energy quality indicators (voltage deviation, fluctuation, asymmetry, and non-sinusoidal voltage) during the day; load current of electrical networks, transformers and electrical receivers; on/off time of electrical receivers during the day.

General predictive control algorithm for energy efficiency of a variable load hybrid power system based on power output forecast is shown in Figure 8 (Part 1) and Figure 9 (Part 2).

The proposed method was tested using simulation modelling of an electric power complex, which included four power sources (a solar panel, a wind turbine, a small hydrogenerator, and a standard carbon-fueled generator).

First, power consumption and generation are measured and the power balance is calculated. If the power balance is positive (generated power exceeds consumed power), the algorithm evaluates the functioning of a standard carbon-fueled generator and, if it is on, turns it off. If the positive power balance is preserved, the algorithm turns off the hydrogenerator and accumulates excess power in the following order – battery and then kinetic energy of water. Once all energy carriers are charged and the power balance is still positive, generating capacities are gradually shutting down, and solar panels are the first to turn off. To stop power generation completely or maintain it at a low level, the wind turbine is switched to ballast resistance.

If the generated power is not enough to satisfy electricity demand, the algorithm receives and processes the negative power balance. At the first step, all wind generators in the electric power complex are turned on; at the second step, solar panels are activated. With every power generating unit turned on, the algorithm compares the power balance, and, if it is still negative, initiates more expensive power sources. The hydrogenerator is activated following solar panels and wind turbines. The switching sequence is due to the

Figure 7: Concept of a hardware and software complex for predictive control of energy efficiency based on the power output forecast

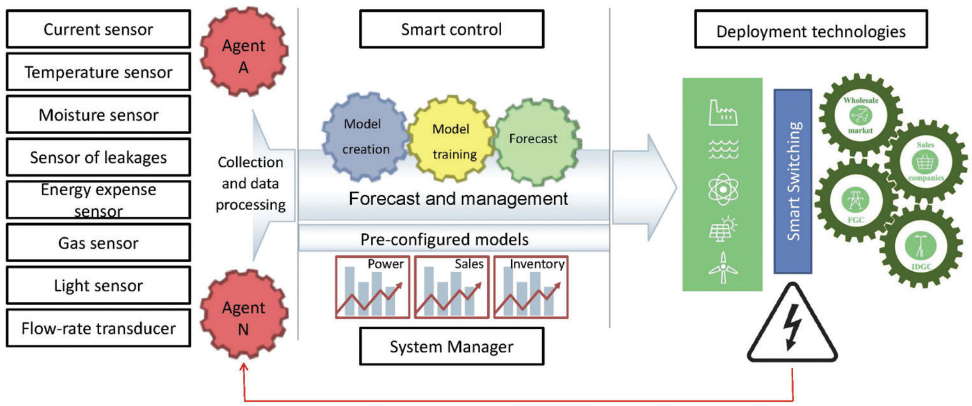
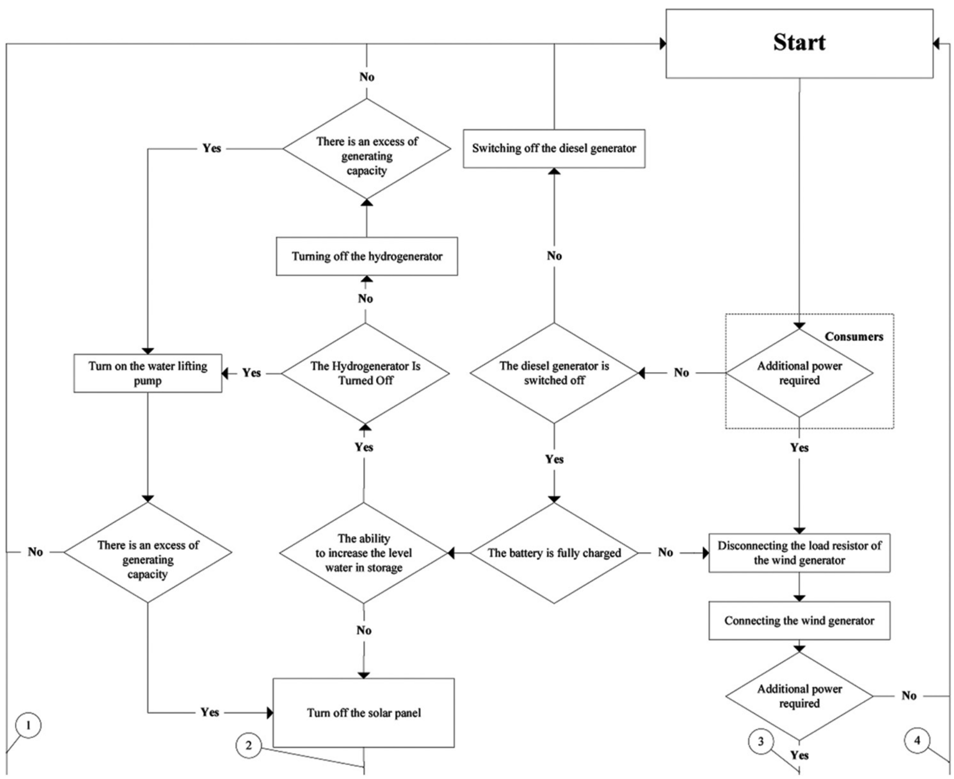


Figure 8: Predictive control algorithm for energy efficiency on the basis of power output forecast (Part 1)



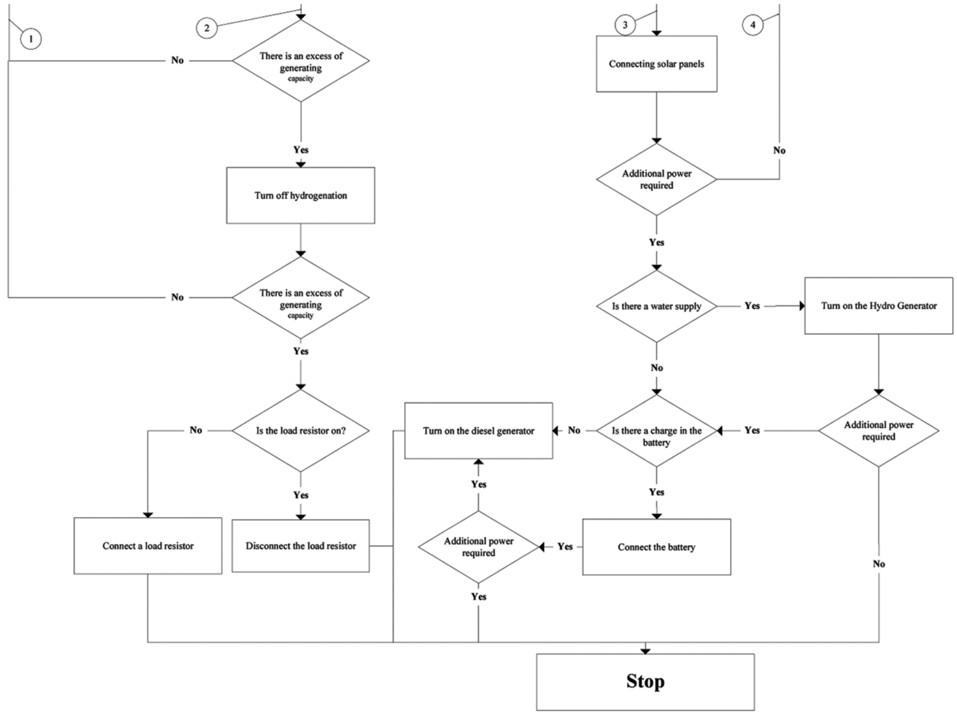
fact that the first two power sources are stochastic, but infinite in terms of incoming power (no fuel is needed). Hydrogeneration is limited by the amount of water stored (if available), and it is mostly recommended to use it sparingly. Next, the battery in power generation mode turns on. If it is impossible to meet the electricity demand after activating all the available alternative energy sources due to insufficiently small power input and/or high peak power consumption, the algorithm switches on the standard carbon-fueled generator.

The cyclic algorithm periodically scans the power balance and, if the power consumption falls, gradually turns off the power sources in reverse order.

The proposed predictive control algorithm for energy efficiency on the basis of power output forecast has demonstrated its productivity in ensuring the power balance, which allowed diversifying the power supply and improving the reliability of power systems (if the centralized power supply system shuts down, renewables-based systems remain operational). Moreover, the batteries embedded in renewables-based power supply systems provide additional energy storage used if all the other energy sources are unavailable. It is noteworthy that the algorithm can be applied in locations with a serious power shortage and the need to purchase it from any producer even with its additional conversion to be transmitted through public power grids.

The algorithm is two-dimensional and controls the power output depending on the power consumption, which imposes a number of restrictions. It does not take into account the possibility to control the load and increase it in case of the incoming power is

Figure 9: Predictive control algorithm for energy efficiency on the basis of power output forecast (Part 2)



significant and energy storage is already filled. Theoretically, the power consumption load can be reduced in case of a shortage of incoming power and then distributed evenly over a certain period of time.

Further research will focus on testing various methods of power matching and power accumulation. Conversion of RES energy into other types of energy suitable for further (delayed) use is of primary interest. At that, attention should be paid to controlling the power balance and a more detailed consideration of the class of consumers whose power consumption can be managed by distributing it over time.

5. CONCLUSION

As found in the research, a complete transition to RES is currently impossible. The best option is to implement a distributed hybrid scheme that provides for the use of alternative renewable energy sources in favorable conditions, thus supplying SMLs with electricity. The quantitative parameters of the electric power complex can be considered as predicates with their own tolerance range. Based on the predicates and the established tolerance range, it is possible to form a decision tree, which primarily focuses on reaching the maximum efficiency for a particular parameter. To realize automatic control of the hybrid power supply system, a hardware and software complex is proposed that follows the established algorithm. Predictive control algorithms are designed to improve the efficiency of renewables-based electric power complexes by coordinating the incoming power and the power consumption load. The proposed method of predictive control has proved its productivity in a simulation model for ensuring energy balance. The algorithm has allowed diversifying the power supply.

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