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INTELLIGENT CONTROL SYSTEM FOR A HYBRID ENERGY COMPLEX BASED ON FORECASTING OF OPERATING CONDITIONS

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Abstract. The paper discusses the development of a control system for a hybrid energy complex that integrates renewable energy sources such as solar collectors, heat pumps, and wind generators. The advantages and disadvantages of centralized and distributed control systems are analyzed. Special attention is paid to the use of forecasting methods for weather conditions and consumer energy demand in order to improve the efficiency of the energy complex. A two-level control architecture is proposed, consisting of a supervisory server responsible for strategy generation and a programmable logic controller that directly controls the equipment. The proposed approach enables optimization of operating modes, improvement of energy efficiency, and adaptation of the hybrid complex to changing operating conditions and consumer requirements.

Keywords: Hybrid energy complex, renewable energy sources, automatic control system, energy forecasting, centralized control, programmable logic controller, energy efficiency, solar collectors, heat pump, wind generator.

INTRODUCTION

Currently, increasing attention is being paid to energy systems based on renewable and alternative energy sources, including solar collectors, heat pumps, and wind turbines. The growing demand for environmentally friendly and sustainable energy technologies is associated with the depletion of conventional fuel resources and the need to reduce harmful emissions into the atmosphere.

Renewable energy sources are widely available; however, their operation strongly depends on environmental conditions and therefore cannot always ensure a stable power supply for consumers. For this reason, such systems are usually supplemented by energy storage devices or backup power units operating on traditional fuels. The integration of several energy sources into a single system forms a hybrid energy complex (HEC), which combines the advantages of different technologies and compensates for their limitations [1].

Automatic control systems for hybrid energy complexes can generally be divided into two main categories: distributed and centralized systems. In distributed control structures, each energy unit is equipped with its own local control system. This approach simplifies the integration of equipment from different manufacturers and facilitates the expansion or modernization of the complex [2]. At the same time, the limited exchange of information between separate subsystems reduces the overall efficiency of the complex and prevents the implementation of optimal operating modes. In many cases, distributed systems use a sequential control algorithm in which additional power sources are connected only when the output of the currently operating units becomes insufficient.

In contrast, centralized control systems employ a single supervisory controller responsible for coordinating the operation of all components of the hybrid complex. Although such systems are more difficult to implement, they provide significantly greater opportunities for optimizing energy production and consumption. Centralized control allows the operating modes of all energy sources to be coordinated according to environmental conditions and consumer demand, thereby improving the overall efficiency and reliability of the system.

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FORECAST-BASED CONTROL SYSTEM

One of the major challenges in designing centralized control systems for hybrid energy complexes is the need to adapt the control strategy to different configurations of equipment. The composition of a hybrid complex may vary depending on the number and type of installed energy units, each having its own technical characteristics and operating requirements. Therefore, the creation of a universal control algorithm suitable for all possible configurations is not feasible [3].

To ensure effective operation of the complex, the control system should analyze not only the current state of the equipment but also predict future operating conditions. Weather forecasting services can be used to obtain short-term meteorological data such as ambient temperature, solar radiation, cloud cover, and wind speed. Based on these parameters, it becomes possible to estimate the expected energy production of each renewable energy source.

Another important aspect of efficient control is the prediction of consumer energy demand. By collecting and analyzing historical consumption data, the system can identify typical load peaks and low-demand periods characteristic of a particular consumer. Such information makes it possible to distribute energy resources more rationally and improve the operational efficiency of the hybrid complex [4].

Considering the above requirements, the proposed hybrid energy complex control system should possess the following features:

– centralized control architecture;
– forecasting of the operating efficiency of energy sources depending on weather conditions;
– accumulation and analysis of consumer energy consumption data.

To achieve these objectives, a two-level control structure is proposed:

– the upper level is implemented on a dedicated server that evaluates system efficiency and generates an optimal operating strategy for the complex;
– the lower level is based on a programmable logic controller that directly controls the equipment according to the commands received from the upper-level system.

The proposed architecture improves the adaptability, reliability, and energy efficiency of

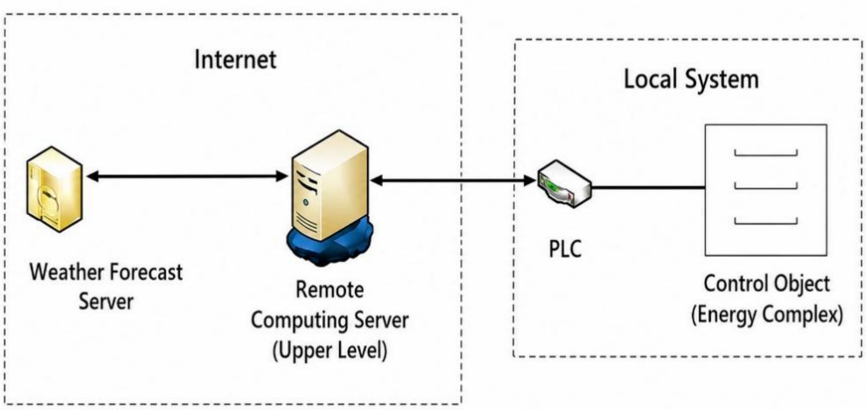

Fig. 1. The generalized structure of the control system

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the hybrid energy complex while enabling intelligent coordination of renewable and conventional

INTELLIGENT CONTROL ALGORITHM FOR A HYBRID THERMAL ENERGY COMPLEX

Based on the requirements imposed on the hybrid energy complex control system, it is necessary to develop an efficient operational algorithm capable of coordinating multiple energy sources. This paper considers a control strategy for a thermal energy complex using alternative energy sources while taking into account predicted weather conditions and anticipated consumer energy demand [5]. The proposed method is compared with the conventional cascade control algorithm widely used in hybrid energy systems.

As an experimental object, a domestic hot water preparation complex operating within the renewable energy research facility of the Volzhsky branch of the Moscow Power Engineering Institute was selected. The research platform is intended for investigating the efficiency of combining different alternative energy sources under varying operating conditions.

The proposed control algorithm includes several consecutive stages. Initially, the system receives calculated data describing both the current operating state of the complex and forecasted environmental conditions. The main objective of the algorithm is to determine the optimal set of active thermal energy sources and calculate the required operating duration of each unit [6].

Using accumulated information about energy consumption, the system identifies periods of peak and reduced demand and generates a predicted thermal load profile. The next stage determines the difference between the currently stored thermal energy in the storage tanks and the amount of heat required during the nearest consumption peak. Based on this analysis, the algorithm aims to accumulate the necessary amount of thermal energy in the most energy-efficient manner.

At the following stage, the system estimates the amount of energy that can be generated by the most efficient renewable source according to forecasted weather conditions. In the considered hybrid complex, solar collectors represent the primary and most efficient energy source. If the predicted thermal output of the solar collectors is sufficient to satisfy consumer demand, additional energy sources are not activated, and the corresponding information is transmitted to the local control subsystem.

If the energy generated by the solar collectors is insufficient, the algorithm calculates the amount of missing heat energy that must be provided by the heat pump. The required operating time of the heat pump is then determined in order to ensure the necessary heat supply before the next peak demand period [7]. The algorithm also evaluates whether the heat pump can operate under the predicted ambient temperature conditions. If operation of the heat pump is impossible due to low outdoor temperatures, an auxiliary electric heater is activated instead. Information regarding the required operating duration of either the heat pump or the electric heater is transmitted to the local control system.

The local control subsystem calculates the optimal switching time for the heat pump and electric heater. This approach allows the system to accumulate the required amount of thermal energy precisely when it is needed instead of maintaining a constant high temperature in the storage tanks throughout the entire operating period. As a result, thermal losses in the storage system are significantly reduced.

The temperature variation process in the storage tanks demonstrates the effectiveness of the proposed forecast-based control method. Unlike conventional control systems, intensive water heating to the target temperature of 50 °C begins not immediately after system startup but at a

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calculated moment determined from predicted consumer demand. By the beginning of the consumption period, the water temperature in the tanks reaches approximately 47 °C, while during the peak demand period it decreases to about 43 °C. After peak consumption is covered, the temperature is maintained mainly by the operation of the solar collectors [8].

If the water temperature falls below 40 °C, the thermal deficit is compensated either by the heat pump or by the auxiliary electric heater. After the completion of the hot water consumption period, only the solar collectors remain active until their operation becomes ineffective due to changing environmental conditions. In addition, the user may define a minimum acceptable water temperature, allowing the system to perform regulation according to two control levels simultaneously.

The proposed control algorithm ensures more rational utilization of renewable energy sources, minimizes unnecessary operation of auxiliary heating devices, and improves the overall energy efficiency of the hybrid
thermal energy complex.

ALGORITHM PERFORMANCE EFFICIENCY

To compare the performance efficiency of the algorithm on a remote server, two control systems were modeled: a cascade control system with predicted weather conditions. The control systems were modeled on the same facility and equipment with identical load characteristics. Both models operated under the same weather conditions.

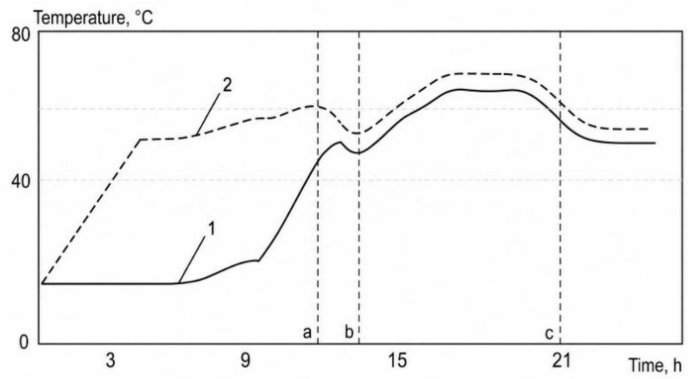

Fig. 2. Process of change the water temperature in the tanks:
1 – when the system with prediction of condition; 2 – during operation of the cascade control system: a – point start of consumption; b – point peak of consumption;

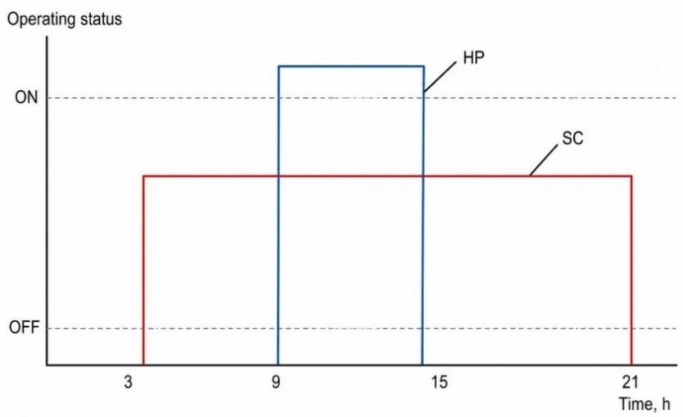

Fig. 3. Timing of switching on the complex equipment, where HP (TH) – heat pump; CP (CK) – solar collector pump.

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According to Fig. 3, it is evident that the solar collector pumps were operational throughout the entire period when solar radiation was sufficient for their functioning. To accumulate the required amount of heat, only one period of heat pump operation was necessary.

Let us examine the performance results of the cascade control system. In Fig. 2, the process of water temperature change in the tanks during the operation of the cascade control system is represented by curve 2.

The water heating process begins immediately after the system starts and continues until the water temperature reaches the setpoint. During the period of maximum solar collector activity, the temperature exceeds the setpoint by 10 °C. Subsequently, as solar activity decreases, the temperature is maintained at the specified level.

Fig. 4 shows a graph representing the operating time of the main equipment of the complex under cascade control.

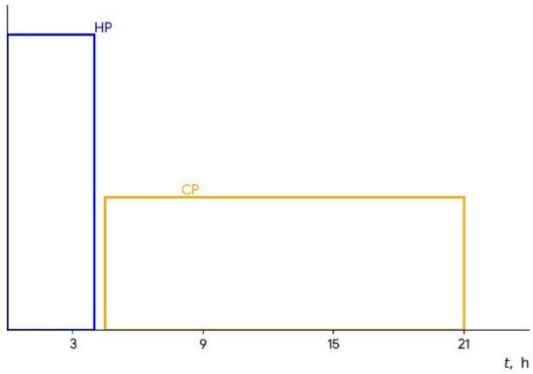

Fig. 4. Moments of enable equipment of the complex with cascade system control

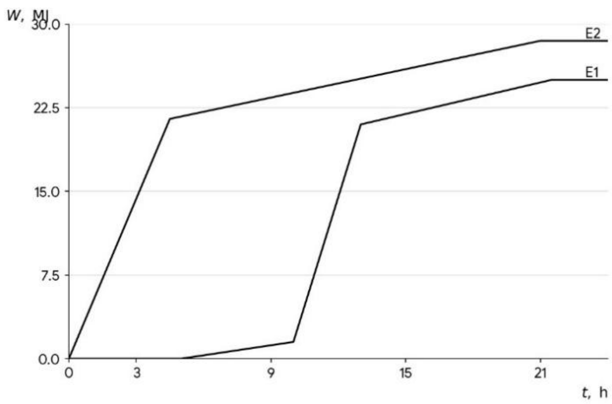

Fig. 5. The daily schedule of electricity consumption:

E1 – consumption line of control system with prediction of a condition; E2 – line of curve of the electricity consumption of the cascade control system

The graph shows that upon system startup, the heat pump is activated and, within four hours of operation, transfers a sufficient amount of heat to the system to maintain the required temperature regime. Subsequent short-term activations are related to maintaining the system temperature until the solar collector pump starts. Further consumer needs are covered by the solar collector.

The primary criterion for the energy efficiency of a control system is the amount of electrical energy consumed by the complex to produce a given amount of thermal energy.

Fig. 5 shows a daily profile of electrical energy consumption. The graph indicates that the cascade control system consumed more energy than the predictive control system.

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CONCLUSIONS

The investigated efficiency of the proposed algorithm in this experiment is 13% higher compared to the cascade control system. This is achieved through several operational features of the algorithm:

− heat accumulation in the system occurs more efficiently because the heat pump is not activated immediately at startup, but at a pre-calculated time required to reach the target temperature.

The disadvantages include the fact that the algorithm's performance is based on parameters such as weather forecasting and thermal consumption analysis, which are inherently imprecise. The control system can handle weather forecast errors by reaching the required temperature in cascade mode, which does not lead to a significant decrease in the efficiency of the hot water production complex.

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