Development of a centralized control system for alternative thermal energy sources with a predictive assessment of the complex's operating efficiency

Gulmira Abidova[1,a)], Kalizhan Shakenov[2], Saulesh Minazova[2]

[1] *Tashkent state transport university, Tashkent, Uzbekistan*
[2] *Satbayev University, Almaty, Kazakhstan*

[a)] *Corresponding author: abidova_g@tstu.uz*

Abstract. This article focuses on the development of a centralized control system for a hybrid heating complex based on alternative energy sources - solar collectors and heat pumps. A predictive control algorithm is proposed that takes into account weather data and heat consumption dynamics, enabling optimal load distribution between renewable sources and auxiliary units. Simulations have shown that the predictive control system improves the complex's energy efficiency by 13% compared to a traditional cascade system.

INTRODUCTION

Currently, there is a growing adoption of power systems based on alternative energy sources, such as solar collectors, heat pumps, and wind turbines. Despite their widespread use, renewable energy sources have variable and unpredictable energy production due to natural and climatic factors. This leads to instability in energy load coverage and requires integration with other reliable energy sources, such as battery systems or conventional fuel plants. Combining two or more energy sources allows for the creation of a hybrid energy system that compensates for the limitations of individual technologies through complementarity, thereby ensuring a more sustainable and efficient energy supply [1].

Centralized control systems for hybrid energy systems are classified into two main categories: centralized and distributed. Distributed systems are implemented using autonomous controllers integrated with each individual energy module of the system [2]. This architecture provides flexibility in integrating equipment from different manufacturers and simplifies scaling or modifying the system's composition on the fly. However, despite the high reliability and precision of these systems during production, their functionality may be limited due to insufficient information exchange between individual system components. The lack of full communication makes it impossible to dynamically optimize load distribution and coordinate energy source operation based on current consumption requirements. Under these conditions, a cascade algorithm becomes the dominant control strategy, whereby subsequent sources are activated only when the capacity of already-involved elements is exhausted [3]. This, while ensuring basic system stability, reduces the overall efficiency of the system's resource utilization.

Centralized control systems require a single device that implements a control algorithm for all sources within the complex [4]. Such systems are complex to implement, but they improve energy efficiency by optimizing the complex's operating modes. However, implementing an effective control system for the complex requires addressing a number of issues inherent to the centralized structure of an automatic control system [5].

EXPERIMENTAL RESEARCH OF AUTOMATED CONTROL SYSTEM WITH STATE PREDICTION

One of the key challenges facing centralized automatic control systems for hybrid power systems is adaptability to the diverse configurations and technical characteristics of the equipment within the system. In real-world conditions, a system may include a variable number of power units, differing in both design features and operational parameters, such as rated power, efficiency, operating modes, and dynamic characteristics [6]. This variability significantly complicates the development of a universal control algorithm capable of operating effectively in all possible configurations, making the creation of a single, universal power system virtually impossible [7].

Developing a highly effective management strategy requires not only immediate access to current system parameters - such as battery charge level, coolant temperature, current loads, and generator status - but also the implementation of forecasting methods for key factors affecting the performance and operating modes of energy sources. Meteorological parameters are particularly important, as renewable energy sources (solar collectors, wind turbines) are directly dependent on weather conditions. For these purposes, it's advisable to use data from specialized short-term weather forecasting services, which provide detailed information on air temperature, cloud cover, wind speed and direction, and solar radiation intensity [8].

Analysis and integration of these predicted parameters into the control system enable the calculation of the expected energy output of each element of the complex, taking into account upcoming changes in external conditions [9]. This, in turn, enables adaptive scheduling of power plant operating modes, optimizing load distribution and increasing the overall efficiency of the power complex. Thus, forecasting becomes an integral part of management, enabling proactive adjustments to system operating algorithms based on the dynamics of external factors and the internal state of the complex, significantly increasing the reliability and efficiency of hybrid energy solutions [10].

In addition to taking into account the expected efficiency of energy sources, it is also necessary to forecast the consumer's energy needs [11]. Energy consumption analysis allows us to identify peaks and valleys in energy consumption specific to a particular consumer.

Based on the above, the hybrid energy complex control system must have the following characteristics [12]:

- have a centralized automatic control system structure;
- predict key performance indicators for the sources included in the complex, depending on weather conditions;
- accumulate and analyze data on the energy consumption of a specific consumer.

To address these challenges, we propose dividing the control system into two levels [13]:

- the upper level is technically implemented using a dedicated server that calculates system performance and develops a control strategy for the complex;
- the lower level is a programmable logic controller that directly controls the equipment within the complex, according to the strategy developed at the upper level.

The structure of such a system is shown in Figure 1.

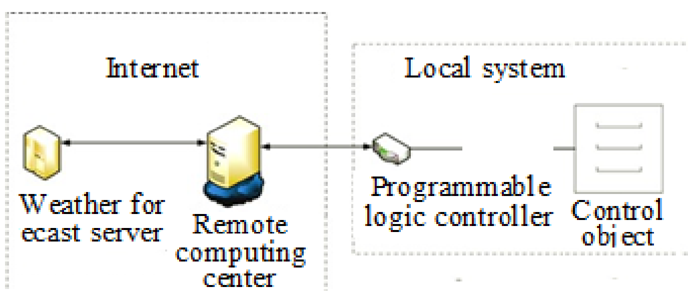

FIGURE 1. Generalized structure of the automated control system

Based on the requirements for the complex's control system, it is necessary to develop an operating algorithm [14]. This article examines a control algorithm for a complex of alternative thermal energy sources, taking into account predicted weather conditions and energy consumer needs, and compares it with a cascade control algorithm widely used in hybrid energy complex control systems [15].

The proposed algorithm for the automatic control system of a hybrid energy complex contains the following sequence of actions.

The algorithm is fed with pre-calculated basic data on the current system state and forecasted weather conditions. The goal of the algorithm is to select the optimal composition of the heat sources used and calculate the required operating time for each source [16]. Based on the summarized energy consumption data, peaks and valleys in consumption are calculated, and a forecasted heat load function is constructed.

The next block calculates the difference between the current amount of stored thermal energy in the storage tanks and the energy required at the next peak in heat consumption. Based on this information, the algorithm's next task is to maximize the required amount of heat to meet the consumer's needs [17].

Next, the amount of energy that can be obtained from the most energy-efficient source is calculated, depending on the predicted weather conditions. In this energy complex, the most energy-efficient source is the solar collector [18]. If the predicted energy from the solar collector is sufficient to cover the consumer's needs, then no other sources are required at this time. This information is transmitted to the local control system.

If the solar collector's energy supply is insufficient, the energy required to supply the required energy in the energy complex is calculated using the heat pump [19]. The heat pump's runtime is then calculated to generate the required amount of heat to meet the next peak demand. The algorithm also determines whether the heat pump can be started at the current ambient temperature. If the heat pump cannot be started under the predicted weather conditions, an electric heater is activated instead. Data on the heat pump or electric heater runtime is transmitted to the complex's local control system. The local control system calculates the optimal start-up time for the heat pump and electric heater, allowing the required energy to be generated when it is needed, rather than maintaining a preset temperature in the storage tanks throughout the entire operation of the complex. This reduces heat loss in the storage tanks by storing water at a lower temperature [20].

RESEARCH RESULTS

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

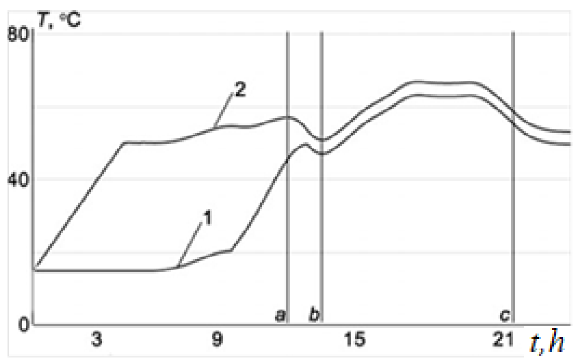

FIGURE 2. The process of changing the water temperature in the tanks:
1 – when the control system with state prediction is operating; 2 – when the cascade control system is operating, where: a – the start point of consumption; b – the point of peak consumption; c – the end point of consumption

Figure 2 shows the process of changing the water temperature in the tanks.

The graph in Figure 2 shows that when the control system is operating with predictive mode, the active process of heating the water to the set temperature of 50°C begins not at the system startup, but at a specific time calculated by the control system based on an analysis of consumer needs [14]. By the time consumption begins, the water temperature in the tanks is 47°C, and at peak demand, it is 43°C. After peak demand is met, the temperature in the tanks is maintained by solar collectors. If the water temperature in the tanks dropped below 40°C, the heat loss would be covered by the heat pump or electric heater. After water consumption ends, the system keeps only the solar collectors on until they become ineffective [13]. The user can optionally set a minimum water temperature, and then the control will be performed in two levels. Let us consider Figure 3, which shows the periods of activation of the complex devices during control with state prediction.

Figure 3 shows that the solar collector pumps were active as long as solar radiation was sufficient for operation. Only one heat pump operation period was required to generate the required amount of heat [12].

Let's examine the results of the cascade control system's operation. In Figure 2, the change in water temperature in the tanks during operation of the cascade control system is shown by curve 2.

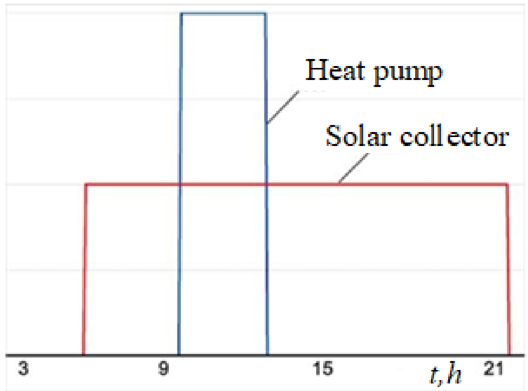

FIGURE 3. Moments of switching on the equipment of the complex, where HP - is the heat pump; SC - is the solar collector pump.

The water heating process begins immediately after the system is turned on and continues until the water temperature reaches the set point. At peak solar collector activity, the temperature exceeds the set point by 10°C. Subsequently, as solar activity declines, the temperature is maintained at the set point.

Figure 4 shows a graph showing the operating time of the system's main equipment under cascade control [20].

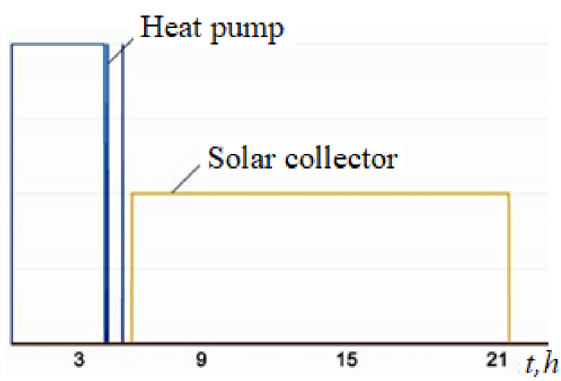

FIGURE 4. Schedule of operating time of the main equipment of the complex with cascade control

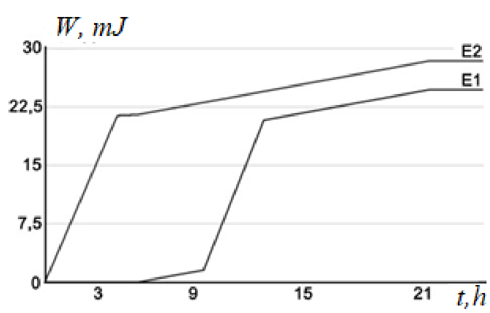

FIGURE 5. Daily energy consumption graph: E1 – energy consumption curve during operation of the state-predictive control system; E2 – energy consumption curve during operation of the cascade control system

The graph shows that when the system starts, the heat pump starts up and, over four hours of operation, transfers enough heat to the system to maintain the temperature. Subsequent short starts are used to maintain the system temperature until the solar collector pump starts up. The solar collector then covers the consumer's needs.

The main criterion for the energy efficiency of the control system is the amount of electrical energy consumed by the system to generate a specified amount of thermal energy.

Figure 5 shows a daily graph of electrical energy consumption. The graph shows that more energy was consumed during operation of the cascade control system than during operation of the state-predictive control system.

CONCLUSIONS

The conducted study demonstrates that the application of a predictive control algorithm in hybrid thermal energy systems with alternative energy sources significantly improves energy efficiency and optimizes the operation of system components. Based on the research, the following key conclusions can be drawn:

1. The predictive control algorithm enables more efficient load distribution between alternative energy sources and auxiliary units.
2. Incorporating weather forecasts and heat consumption analysis allows for advanced planning of the operation times for solar collectors and heat pumps, reducing overall energy consumption.
3. Simulation results indicate a 13% improvement in energy efficiency compared to traditional cascade control methods.
4. Optimizing heat carrier heating times reduces thermal losses in storage tanks by regulating temperature during non-consumption periods.
5. The algorithm's performance depends on the accuracy of weather forecasts; however, the system can safely switch to cascade mode in case of forecast errors without significant efficiency loss.

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