APPLICATION OF QUANTUM PHOTON–SPIN CONTROL ALGORITHMS FOR THERMAL ENERGY SYSTEMS

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Abstract: In modern process automation, the main objective is to develop control systems that enhance regulation quality and energy efficiency. Since most technological systems are complex, multidimensional, and nonlinear, quantum computing algorithms provide an effective solution. Although intelligent control methods exist, they often have limitations in adaptability and resource efficiency. This study proposes a quantum–fuzzy control system for the evaporation process — a key stage in thermal power plants aimed at improving energy efficiency by removing moisture from steam. The approach integrates quantum algorithms with photon polarization and spin-state mechanisms to optimize control while minimizing energy consumption. A computer model of the quantum–fuzzy system was developed, and computational experiments demonstrated a 1.6% reduction in energy usage, confirming the effectiveness of the proposed method.

Keywords: quantum photon–spin method; superposition; interference; photon polarization; qubit.

Annotatsiya: Zamonaviy texnologik jarayonlarni avtomatlashtirishda bosh maqsad — boshqarish jarayonining sifati va energiya samaradorligini oshiruvchi tizimlarni ishlab chiqishdir. Ko‘pchilik texnologik obyektlar murakkab, ko‘p o‘lchovli va noxatolik xususiyatiga ega bo‘lgani sababli, kvant hisoblash algoritmlaridan foydalanish samarali yechim hisoblanadi. Mavjud intellektual boshqaruv usullari esa moslashuvchanlik va energiya tejamkorligi nuqtai nazaridan cheklovlarga ega. Ushbu tadqiqotda issiqlik energetika tizimlaridagi bug‘ni namlikdan ajratish bosqichiga oid bug‘lanish jarayoni uchun kvant–loyqa (fuzzy) boshqaruv tizimi taklif etildi. Taklif etilgan yondashuv kvant algoritmlari, foton polarizatsiyasi va spin holati usullarining integratsiyasiga asoslanib, boshqaruvni energiya sarfini kamaytirgan holda optimallashtirish imkonini beradi. Kvant–loyqa boshqaruv tizimining kompyuter modeli ishlab chiqildi va hisoblash tajribalari o‘tkazildi. Natijada energiya sarfi 1,6 % ga qisqarishi aniqlanib, taklif etilgan usulning samaradorligi tasdiqlandi.

Kalit so‘zlar: kvant foton–spin usuli; superpozitsiya; interferensiya; foton polarizatsiyasi; kubit..

Аннотация: В современной автоматизации технологических процессов основное внимание уделяется разработке систем управления, повышающих качество регулирования и энергетическую эффективность. Поскольку

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большинство технологических объектов являются сложными, многомерными и нелинейными, применение квантовых алгоритмов вычислений представляет собой эффективное решение. Несмотря на существование интеллектуальных методов управления, они часто ограничены по адаптивности и энергоэффективности. В данной работе предложена квантово-нечеткая система управления процессом испарения — ключевым этапом в тепловых энергетических установках, направленным на повышение эффективности за счёт удаления влаги из пара. Подход основан на интеграции квантовых алгоритмов с методами поляризации фотонов и спиновых состояний, что позволяет оптимизировать управление при минимальных энергетических затратах. Создана компьютерная модель квантово-нечеткой системы и проведён ряд вычислительных экспериментов. Результаты показали снижение энергопотребления на 1,6 %, что подтверждает эффективность предложенного метода.

Ключевые слова: квантово-фотонно-спиновый метод; суперпозиция; интерференция; поляризация фотонов; кубит.

Introduction

Currently, one of the most urgent tasks is to create highly efficient and safe control systems for thermal power plants, to develop models and algorithms for synthesizing intelligent control systems that operate stably against various external and internal disturbances. Since thermal power plants are multi-parameter, nonlinear and multi-stage systems, it is difficult to constantly ensure optimal control in them. Traditional methods for their effective control cannot provide sufficient speed and stability. Therefore, the use of quantum technologies, in particular the quantum photon-spin method, is of great importance in control processes. Using quantum photon-spin, it is possible to safely and quickly transmit technological parameters with high accuracy through photon polarization and develop optimal control signals using quantum algorithms. Therefore, the use of quantum technologies is an effective solution for increasing the speed and efficiency of control [1].

Therefore, in conditions of uncertainty of the initial data, the use of quantum photon-spin technologies is of great importance in improving the technological units of thermal power plants with modern control methods. Quantum photon–spin enables secure and fast transmission of high-precision technological parameters via photon polarization, and the development of optimal control signals using quantum algorithms. This allows quantum algorithms to perform certain types of calculations exponentially faster than their classical counterparts, making them attractive for optimization tasks in control systems [2].

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The development of quantum algorithms for optimization, such as Grover's algorithm for search problems and the Quantum Approximation Optimization Algorithm (QAOA), has led to significant advances in control applications. By enabling fast data processing and decision making, quantum computing offers a means to overcome the inherent limitations of classical systems when dealing with multidimensional data sets. In control system engineering, the integration of fuzzy logic with quantum computing has demonstrated the potential for controlling uncertain and nonlinear systems. Fuzzy logic models human thinking by using linguistic variables and inference rules to process uncertain data. Fuzzy control systems incorporating quantum photon spin method computing capabilities enhance decision making and achieve real-time accuracy and flexibility. Quantum fuzzy control systems combine the flexibility of fuzzy logic with the computational efficiency of quantum algorithms, resulting in robust frameworks capable of optimizing control decisions under uncertainty [3].

Traditional neural network control systems, while effective in certain contexts, face limitations related to the complexity of structural identification, sensitivity to learning parameters, and the need for large volumes of reliable data. These limitations restrict their performance when dealing with poorly defined, stochastic, or uncertain environments. Moreover, the lack of comprehensive methodologies that integrate chemical, physical, and informational dependencies of technological objects further reduces the reliability of classical modeling approaches [4].

The implementation of quantum fuzzy control systems involves building a hybrid architecture that combines classical and quantum components. The classical component handles sensor data acquisition, blurring, and defuzzification, while the quantum component performs fast optimization and decision-making. Quantum gates are used to represent possible control states, and quantum superposition allows for the evaluation of multiple control scenarios simultaneously. The fuzzy inference engine develops control rules based on expert knowledge and past observations, and the quantum optimizer refines these rules to ensure optimal performance[5].

This study also aims to evaluate the practical feasibility of quantum fuzzy control systems in industrial settings by conducting computational experiments and simulations. The main focus is on comparing the energy consumption, impurity reduction and control stability between the proposed system and traditional control methods. Preliminary results show that the quantum photon spin method can achieve significant improvements in energy efficiency and process stability, which will help reduce the overall manufacturing cost [6].

Research Methods and the Received Results

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Quantum computing methods are based on the principle of quantum superposition. In a quantum computing scheme, these two states ($|0\rangle$ and $|1\rangle$ can exist in a superposition state, meaning that the most general state of a quantum bit can be written as follows [7]:

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad (1)$$

where, α and β are a complex numbers.

The spin–photon interface consists of two quantum systems. Let the spin qubit ($|\uparrow\rangle$, $|\downarrow\rangle$) states and the photon qubit polarization states ($|H\rangle$, $|V\rangle$) be given. The general system state is expressed in tensor product space as:

$$|\psi(t)\rangle = \alpha(t)|\uparrow\rangle\otimes|H\rangle + \beta(t)|\uparrow\rangle\otimes|V\rangle + \gamma(t)|\downarrow\rangle\otimes|H\rangle + \delta(t)|\downarrow\rangle\otimes|V\rangle \; |\Psi(t)\rangle \quad (2)$$

where α, β, γ, δ – are complex amplitudes, and their total sum is as follows::

$$|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1 \quad (3)$$

The interaction between spin and photon is expressed by the Jaynes–Cummings Hamiltonian operator [8]:

$$H = \hbar\omega_c a^{\perp}a + \frac{h\omega_s}{2}\sigma_z\hbar g(a\sigma_+ + a^{\perp}\sigma_-) \quad (4)$$

where: $a^{\perp}a$ – photon operators, $\sigma_z;\sigma_+;\sigma_-$ – spin Pauli operators, ω_c – photon frequency, ω_s – spin frequency, g – spin–photon coupling strength.

The spin state is encoded into the photon state by the following quantum

$$|\psi_s\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle:$$

$$|\uparrow\rangle|0\rangle \to |\uparrow\rangle|H\rangle, \qquad |\downarrow\rangle|0\rangle \to |\downarrow\rangle|V\rangle \quad (5)$$

The resulting photon polarization encodes and transmits the measured parameters.

The mathematical model of the evaporation process consists of three main components. The material balance equation describes the change in the concentration of sulfur-containing compounds and other reactants in the reactor volume over time[9]. This equation ensures that the total flow of reactants into the system is balanced by the reaction consumption and the outflow of products. It is expressed as:

$$C\frac{dT(t)}{dt} = Q_y(t) - Q_{out}(t) \quad (6)$$

where:C- heat capacity, $T(t)$— temperature of the working medium, $Q_{yoq}(t)-$ heat flow resulting from fuel combustion, $Q_{out}(t)-$ heat loss.

The dynamics of a heating boiler are expressed in a simplified form by the transfer function [10]:

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$$G(s) = \frac{K}{Ts+1} e^{-Ls} \quad (7)$$

wherea: K- gain, T- time constant, L- delay time.

The quantum photon–spin control system combines PID and quantum inference blocks. The quantum interface optimizes the actuator parameters in real time using the superposition of photon and spin states:

$$|\psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle \quad (8)$$

from this $\alpha, \beta \in C, \quad |\alpha|^2 + |\beta|^2 = 1$ Taking into account that, the control signal will be as follows:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (9)$$

where $K_p, K_i, K_d -$ — regulator coefficients.

To analyze the dynamic properties of each control channel shown above, the experimental data obtained in production were approximated [11]. As a result, the transfer functions of the control channel, which relate each input-output variable in the boiler unit, are found. This relationship can be written in matrix form as follows.

$$W_0(s) = \begin{bmatrix} W_{11}(s)W_{12}(s)W_{13}(s) \\ W_{21}(s)W_{22}(s)W_{23}(s) \\ W_{31}(s)W_{32}(s)W_{33}(s) \end{bmatrix} \quad (10)$$

To create a highly effective control system, it is necessary to study the properties and dynamic characteristics of the control process.

In this study, the quantum control method is implemented by integrating a quantum decision-making module into a fuzzy inference system [12]. The design is based on a quantum approximate optimization algorithm that uses quantum schemes to search for near-optimal solutions in a discrete optimization space. Initially, fuzzy rules derived from expert knowledge and empirical process data are encoded as quantum states. These states are controlled using unitary transformations represented by a combination of Hadamard, phase, and controlled NOT (CNOT) gates to simultaneously explore multiple control trajectories through quantum superposition [13].

An important aspect of a quantum controller is its ability to handle uncertainty and nonlinearity in real time. The quantum layer calculates the expected values of different control scenarios by applying measurement operators to the quantum state vector. These expected values represent the cost function that the system seeks to minimize—typically energy consumption or the level of impurity. The result of the quantum computation drives the defuzzification process

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to produce precise control actions that dynamically adapt to the process environment [14].

The MATLAB software package was used to implement the mathematical model of the evaporation process [15,16]. The block diagram of the MATLAB model is presented in Figure 1, which represents the computational structure of the evaporation process.

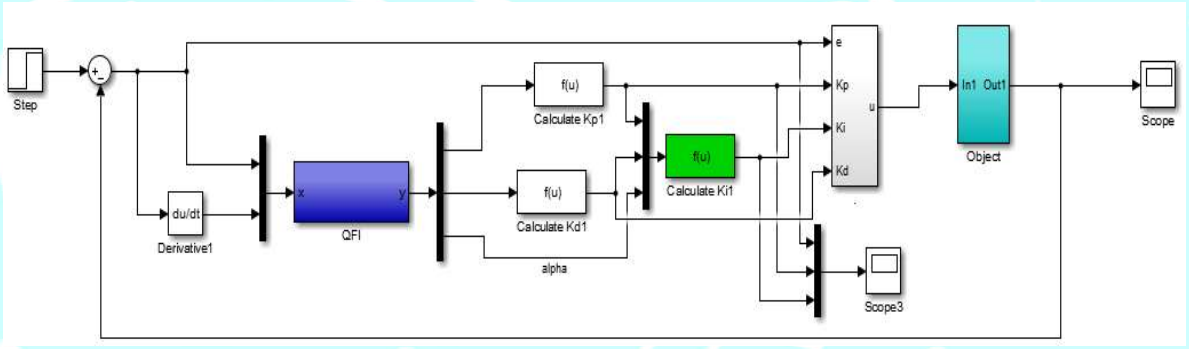


Figure 1. Computer model of the evaporation process.

The results of simulation and computational experiments conducted on the quantum fuzzy control system for the evaporation process show significant improvements in process efficiency, stability, and product quality. Figure 4a depicts the temporal characteristics of the output parameters, which show the temperature changes over time. The quantum controller effectively maintained the reactor temperature within the optimal range and demonstrated high stability despite external disturbances. Figure 4 depicts the output signal of the quantum controller during temperature control, which highlights its fast response and adaptability to changing process conditions [17,18].

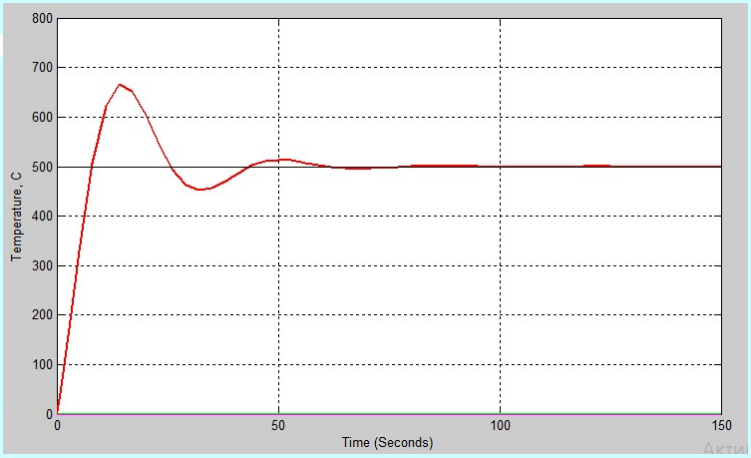


Figure 2. Heater temperature control

Similarly, Figure 4 shows the temporal characteristics of the process, depicting the output signal of the quantum controller corresponding to the temperature control, demonstrating the ability of the controller to dynamically adjust its decisions in real time [19,20].

Conclusion

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This study developed a quantum fuzzy control system for diesel fuel hydrotreating, which significantly improves the stability, efficiency, and energy consumption of the process.

The quality of the steam entering the turbine increases, which means that the turbine efficiency increases. The generator produces more electricity and fuel consumption is reduced by 1.8%. Since the heating system has an economizer and condenser, the waste heat is reused. The result is fuel savings, with overall efficiency increasing from 30–40% to 45–50%.

Using the quantum photon spin method, the system enabled real-time optimization and outperformed traditional control methods in terms of computational efficiency. These findings highlight the potential of quantum fuzzy control systems to revolutionize process automation, making operations more sustainable and cost-effective. Future research should focus on further refinement and real-world implementation.

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