Computer System for Energy-saving Control of Electrotechnological Chemical Plants

Tamara Chistjakova
Computer Design and Control Department
Saint-Petersburg State Institute of Technology
Saint-Petersburg, Russia
chistb@mail.ru

Olga Ershova
Computer Design and Control Department
Saint-Petersburg State Institute of Technology
Saint-Petersburg, Russia
erol@rambler.ru

***Abstract*—The architecture of a computer system for controlling electrotechnological chemical plants in an energy-saving mode is presented. The system is a flexible configurable environment for different types of equipment, using different raw materials, the required quality of the target products and productivity. The core of the system is mathematical models that are reconfigured for various equipment, raw materials, products obtained and productivity. Databases and mathematical software have been developed that allow determining the values of control actions. To develop control interfaces as close as possible to real objects, a SCADA system was used. The development is tested on the example of energy-intensive production of aluminum, calcium carbide and phosphorus, for which energy-saving management is relevant. The system forms control tips for production personnel that ensure safe, energy-saving modes of operation of plants. Testing based on experimental and literary data confirmed the adequacy of the models and the effectiveness of the system due to the reduction of development time and the convenience of software implementation. The efficiency is confirmed by the results of approbation and certificates of implementation at Russian industrial enterprises, in scientific and educational organizations.**

Keywords—computer system; energy-saving control; electrotechnological plants

I. Introduction

The object of the study is electrotechnological plants (EP), in which electric energy is used to perform technological processes (TP). The electrotechnological processes occurring in EP, including the processes of electrochemical and electrothermal production, have common features: energy-intensive, have a large number of parameters that depend on each other, the chemical reactions that are carried out in them occur at high temperatures due to electric current heating, chemical and phase transformations occur in the reaction zone, control actions with different degrees of influence and frequency of application are used to maintain TP [1-3]. Since the objects under consideration are energy-intensive, energy-saving control is relevant.

The expediency of creating a unified functional structure of a computer control system (CS) that provides safe, energy-saving operating modes, the required quality of the products obtained and performance is due to the presence of common features of the EP.

The issues of conducting processes in resource-saving and energy-saving modes are disclosed in [4-9]. It is noted that this is "A set of diverse research, educational, production, economic, control activities, using information technologies, to ensure optimal spending of all types of natural and material resources (raw materials, fuel and energy resources, water, air), labor resources necessary for the production of the required type and quality in the required quantity of products in compliance with the conditions of national and international legislation." In addition, the tasks of energy saving are regulated by the Federal Law of the Russian Federation No. 261 of 23.11.2009 "On energy saving and on improving energy efficiency and on amendments to certain legislative acts of the Russian Federation".

CS is programmatically implemented in the SCADA HMI environment, which significantly reduced the development time and created interfaces for production personnel that visually display control objects [10].

II. Information Description Of The Control Object

For the analysis of EP as objects of control, database development and mathematical description, the classification of variables characterizing TP is carried out, presented in the Fig. 1.

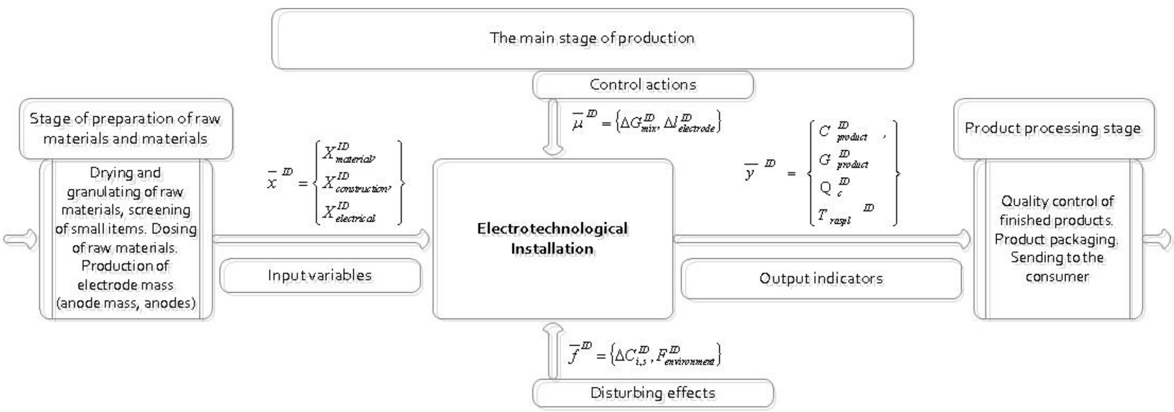

Fig. 1. Variable classification of the objects of control

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***ID* – process identifier:** ID = 1– aluminum production, ID =2 – production of calcium carbide, ID = 3– phosphorus production;

$\bar{x}^{ID} = \{X^{ID}_{material}, X^{ID}_{construction}, X^{ID}_{electrical}\}$ – **input variables**: $X^{ID}_{material}$ – raw material properties (concentration of the *i*-th chemical component in the s-th input stream, density, granulometric composition); $X^{ID}_{construction}$ – geometric characteristics of the EP (diameter / length and width, height, diameter of the electrode / anode); $X^{ID}_{electrical}$ – electrical indicators of the plant; I – current strength, A.; cosφ – power coefficient.

$\bar{\mu}^{ID} = \{\Delta G^{ID}_{mix}, \Delta l^{ID}_{electrode}\}$ – **control actions**: ΔG^{ID}_{mix} – raw material consumption, t/h; $\Delta l^{ID}_{electrode}$ – position of the electrodes (anodes), m;

$\bar{f}^{ID} = \{\Delta C^{ID}_{i,s}, F^{ID}_{environment}\}$ – **disturbing effects**: $\Delta C^{ID}_{i,s}$ – fluctuations in the chemical composition of the *i*-th component in the *s*-th input stream of raw materials; $F^{ID}_{environment}$ – fluctuations in environmental parameters (temperature, humidity);

$\bar{y}^{ID} = \{C^{ID}_{product}, G^{ID}_{product}, T^{ID}_{raspl}, l_{mpr}, Q^{ID}_{c}\}$ – **output indicators** $C^{ID}_{product}$– concentration of the key component in the melt, mass fraction; $G^{ID}_{product}$– quantity of the received product, kg/s; T^{ID}_{raspl} – melt temperature, °C; l_{mpr} – interpolar distance, m; Q^{ID}_{c} – the amount of electricity consumed for the production of products, Wh.

All variables are stored in databases (DB):

- The DB of administrative and production personnel contains information about all registered users with the appropriate access rights;
- The DB of TP variables;
- The DB of raw materials includes the type of raw materials of a certain deposit, the density of raw materials components, the decomposition coefficients of components, stoichiometric coefficients;
- The DB of the equipment includes EP types, structural characteristics, current strength, coefficients that determine the type and structural features of the EP;
- The DB of products of various brands [11].

The problem of energy-saving control: for a given vector of input variables X^{ID} under the influence of disturbances f^{ID} by varying the values of control actions $\boldsymbol{\mu}^{ID}$ in the regulatory ranges { $\Delta l^{ID}_{min} \le \Delta l^{ID} \le \Delta l^{ID}_{max}$, $\Delta G^{ID}_{\min} \le \Delta G^{ID} \le \Delta G^{ID}_{max}$ }, depending on the types of equipment and raw materials, find such a vector of control actions $\mu^{ID}_{opt} = \{\Delta G^{ID}_{opt}, \Delta l^{ID}_{opt}\}$, which provides the minimum amount of electricity consumed Q_c^{min}, that is, maintaining an energy-saving mode, and the required values of production indicators - productivity ($G^{ID}_{product}{}^{min} \le G^{ID}_{product} \le G^{ID}_{product}{}^{max}$) and the specified quality of the target product being produced ($C^{ID}_{product}{}^{min} \le C^{ID}_{product} \le C^{ID}_{product}{}^{max}$), subject to restrictions on security indicators

$l^{ID}_{electrode}{}^{min} \le l^{ID}_{electrode} \le l^{ID}_{electrode}{}^{max}$,

$T_{raspl}{}^{min} \le T_{raspl} \le T_{raspl}{}^{max}$.

III. Mathematical description

The mathematical description necessary for calculating the values of control actions that provide the minimum amount of electricity consumed includes the functional relations of the equations of mathematical models (MM) reflecting the dependencies between the input, control and output variables TP, which are presented in the form $\bar{y} = \varphi(\bar{x}, \bar{\mu}, \bar{A})$, where A – the coefficients of the model. Ensuring the accuracy of MM is achieved by adjusting the values of A in the permissible ranges of coefficient changes $A^{min} \le A \le A^{max}$ [11,12,13,14].

The system of MM equations allows solving the problem of energy-saving control.

Calculation of the concentration of the key component of raw materials in the product $C^{ID}_{product}$ it is produced from the material balance equation:

$$m^{ID}_{raspl} \cdot \frac{dC^{ID}_{product}}{dt} = \Delta G^{ID}_{mix} - k^{ID}_{r} \cdot G^{ID}_{product} \quad (1)$$

where $G_{product}$ – the amount of the resulting product, kg/s.

$$G_{product} = k_{elchem} \cdot I \cdot \eta \quad (2)$$

I – current strength, A; η – current output; k_{elchem} – electrochemical equivalent of the key component, kg/(A·s); m_{raspl} – melt mass, kg; ΔG_{mix} – consumption of loaded raw materials, kg/ s; k_r – stoichiometric coefficient of decomposition reaction.

Vector of coefficients A_1 { $k_{r,}$, k_{elchem} }.

The initial data for the calculation (1) are: m_{raspl}, G_s, k_r.

Calculating of the inter-pole distance l_{mpr} is:

$$\frac{dl^{ID}_{mpr}}{dt} = v^{ID}_{el} - v^{ID}_{product}, \quad (3)$$

where $v^{ID}_{el} = \frac{G^{ID}_{el}}{\rho^{ID}_{el} \cdot S^{ID}_{el}}$ – the rate of combustion of the electrodes/anodes due to their consumption, m/s.

Product level change rate, m/s:

$$v^{ID}_{product} = \frac{G^{ID}_{product}}{\rho^{ID}_{product} \cdot S^{ID}_{raspl}}$$

where ρ_{el}– density of electrodes/anodes, kg/m^3; $\rho_{product}$– product density, kg/m^3; G_{el} – consumption of electrodes/anodes, kg/s; S_{el} – cross-sectional area of the electrodes/anodes, m^2; S_{raspl} – melt cross-sectional area, m^2.

The initial data for the calculation (3) are: $G_{product}$, G_{el}. , S_{el}, S_{raspl}

The temperature of the melt T_{raspl} is calculated by the equation of the thermal balance of the melt zone:

$$m^{ID}{}_{raspl} \cdot c^{ID}{}_{raspl} \cdot \frac{dT^{ID}{}_{raspl}}{dt} = I^{ID^2} \cdot R^{ID}{}_{mpr} - \\ - \alpha^{ID}{}_{raspl} \cdot S^{ID}{}_{raspl} \cdot (T^{ID}{}_{raspl} - T^{ID}{}_{smelt}) - \\ - k^{ID}{}_{bottom} \cdot S^{ID}{}_{bottom} \cdot (T^{ID}{}_{raspl} - T^{ID}{}_0) \quad (4)$$

where c_{raspl} – T_{raspl} – melt temperature, °C; heat capacity of the melt, J/(mol K); α_{raspl} – heat transfer coefficient from the melt to the melting zone, W/m^2°C; R_{mpr} – melt resistance, Ohm; S_{raspl} – melt cross-sectional area, m^2; T_{smelt} – temperature in the melting zone, °C; k_{botton} – heat transfer coefficient from the melting zone to the environment, W/m^2°C; S_{botton} – total area of the spring and electrodes/anodes, m^2; T_o – temperature, °C .

Equation for calculating the speed of movement of electrodes/anodes Δl_{el}:

$$\frac{d\Delta l^{ID}{}_{el}}{dt} = v^{ID}{}_{el} - v^{ID}{}_{product} + K^{ID}{}_{ctrl} l^{ID}{}_{ctrl} \quad (5)$$

where l_{ctrl} – speed of movement of the electrode/anode during control, m/s; K_{ctrl} – accepts values –1, 0, +1.

The voltage at the installation and the current passing through it, measured automatically, are connected to the state variables through resistance and reverse EMF:

$$U^{ID} = I^{ID} \cdot R^{ID} + E^{ID} \quad (6)$$

$$R = R_{nom} + k_{R_l} \cdot (l_{mpr} - l_{mpr_{nom}}) - k_{R_T} \cdot (T_{raspl} - T_{raspl_{nom}}) + k_{R_C}(C_S - C_{S_{nom}}),$$

$$E = E_{nom} - k_{E_T} \cdot (T_{raspl} - T_{raspl_{nom}}) - k_{E_C} \cdot \ln \frac{C_S}{C_{S nom}},$$

where U – operating voltage, V; R – resistance, Ohm; E – reverse EMF, V; index nom – nominal values;

Vector of coefficients A2 {k_{Rl}, k_{RT}, k_{Rc}, k_{ET}, k_{Ec}} – reflects the coefficients of the influence of the type and features of the equipment, its geometric characteristics on the electrical parameters.

Initial conditions for solving a system of equations:

$$t_0 = 0; \; C_{product}(t_0) = C_{product\,0}; \; T_{raspl}(t_0) = T_{raspl\,0};$$
$$\Delta l_{el}(t_0) = \Delta l_{el\,0}; \; t_0 \le t \le t_k .$$

Calculation of the amount of electricity Q_c, consumed for the production of the product:

$$Q_c{}^{ID} = U^{ID} \cdot J^{ID} \cos \varphi^{ID} \quad (7)$$

where $\cos\varphi$ – the power factor defined for a specific EP.

It follows from the above that equation (7) is a dependency $Q_c = f(U, J, T_{raspl}, C_{product}, \Delta G_{mix}, \Delta l_{el})$, so Q_c depends on the values of the control actions μ^{ID} .

When reconfiguring CS to different sources of raw materials to determine the values of control actions $\boldsymbol{\mu}^{ID}$, vector of coefficients A3 {k_{elchem}, k_r, , G_{el}, ρ_{el}}. When reconfiguring CS to different types and geometric characteristics of plants, the vector of coefficients is A4 {η, J, k_{Rl}, k_{RT}, k_{Rc}, k_{ET}, k_{Ec}} [14,15].

The adequacy of the models is verified by the literature and experimental data presented by S.Ltd "GIPROCHIM-TECHNOLOG" and Ltd "RUSAL-VAMI" and is confirmed by the fulfillment of the adequacy condition according to the Fisher criterion.

IV. Software implementation of CS

SCADA-HMI was chosen for the software implementation of CS, because it is universal, modern, convenient, has a lot of graphic, animation, software and other development tools, which allows you to create calculation modules by writing scripts, dynamic visualization, controls, time and archive trends, ergonomic interfaces. The CS architecture is shown in Fig. 2.

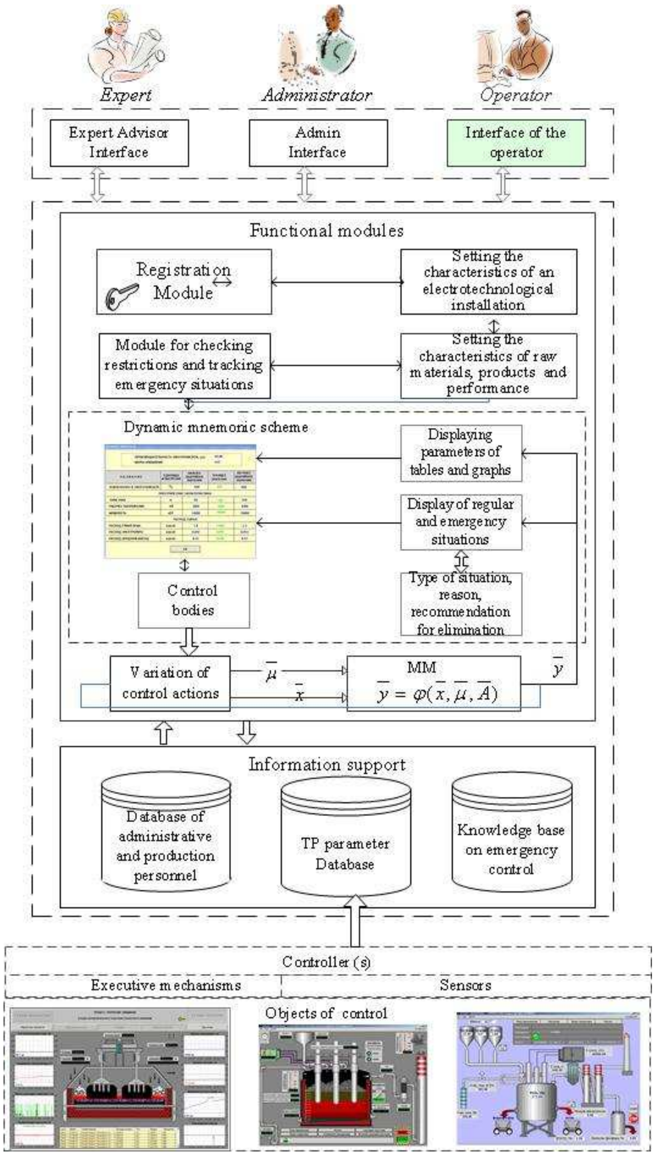

Fig. 2. Architecture of computer system on the example of the electrotechnological production of aluminum, calcium carbide and phosphorus

SCADA implements an architecture that includes DB, MM scripts, information visualization modules in the form of interfaces, tables and graphs, dynamic controls), etc.

The InTouch SCADA-system was used as a tool for the software implementation of CS, since the university has a license for scientific and educational purposes. CS can be programmatically implemented in other environments [13].

V. Conclusion

A special CS is proposed, which is a flexible customizable environment for various types and configurations of equipment, using different raw materials, the required quality of the target products and productivity. The CS forms tips on controlling processes in an energy-saving mode for production personnel. The functional structure of the CS, including databases and mathematical models, is programmatically implemented in the SCADA HMI environment.

Testing based on experimental and literary data confirmed the adequacy of the models and the effectiveness of the system due to the reduced development time and ease of software implementation. The development method is tested on the example of the production of aluminum, calcium carbide and phosphorus. The CS is implemented in the educational process of the St. Petersburg Institute of Technology and other universities, research and production activities.

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