

SCIENTIFIC BACKGROUND FOR THE DEVELOPMENT OF INTELLIGENT ELECTRIC DRIVES FOR OIL AND GAS PROCESS UNITS

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The article suggests theoretical justification for the development of power efficient electric drives for the crude hydrocarbons transport process units based on intelligent control and monitoring systems. The strategies of electric drives multifactorial optimization are reviewed under the conditions of stochastic technological and natural disturbances. The resulting invariant systems and regression control algorithms for the variable-frequency drives of technologically interrelated units are presented. The neuro-fuzzy technical state prediction principles for the development of the in-built electromechanical systems control systems are suggested.

Keywords: automatic electric drive, scientific justification, intelligent control system, invariant system, monitoring, forecast.

Introduction

Addressing the issue of power efficiency, reliability and ecological compatibility improvement of crude hydrocarbons production, transport and distribution operating procedures, is connected with the modernization of automatic electric drives technology with their integration within unified resource-saving concept of oil and gas transport systems. The downward tendencies in energy intensity and emergency risks determine the necessity to create self-optimizing and intelligence systems with forecasting the technical state and equipment parameters based on new object-oriented electric drives. Meanwhile the implementation of minimally manned or unmanned operations resolves a spectrum of problems on maximum integration of electric machine systems with actuators, their frequency control and coordination of operation of technologically interrelated units, and also power consumption optimization for the main pipelines linear sections.

To provide for the theoretical justification of the development and creating a new electric driven equipment and operation algorithm of process units of compressor and pumping stations of main transport a common methodological approach [1, 2] is suggested. It is based on the structural synthesis of intelligent electric drives based on systemic optimization within the experimental design theory [3, 4] and procedures of neuro-fuzzy process identification in the main transport facilities [1, 5].

1. Crude Hydrocarbons Transport Optimization Strategy

Let us consider the crude hydrocarbons transport optimization principles as exemplified with the natural gas main transport [6, 7].

According to the codes of main gas pipelines (GM) process engineering, the automation facilities complex are provided in the automatic control systems in compressor stations (CS), which ensure maintaining of the desired gas pressure and temperature values at the station output, and anti-surge control and protection devices of electric driven gas compressor units (EGCU) [1, 8]. However the existing automatic tools mostly operate independently from the units in manual mode, executing mainly protective functions, and do not ensure power efficient modes. At the same time, the capabilities of the controlled electric drive EGCU nowadays allow optimizing CS power consumption with automatic tracking deterministic and stochastic disturbances [9, 10].

In accordance with the invention patent [11] the author suggests the method of gas main transport, ensuring the highest possible power efficiency under any gas pipelines modes (Fig. 1). It is achieved thanks to the fact that the compressed gas temperature and pressure at the output of all CS at the beginning of each linear section are measured and automatically controlled under the condition of their keeping at the optimum level according to the task and values of external disturbances, influencing the gas flow parameters inside the gas pipelines [12].

The analysis of this method, consisting in compressible gas flow pressure and temperature generation along the whole GM route by means of EGCU and ACU blowers, installed at all CS at the beginning of each GM linear section, with analogues demonstrates that the suggested method of gas main transport differs from the known one as the gas pressure and temperature values are automatically set up and continuously adjusted by means of controlled EGCU and ACU, depending on current gas pressure and tempera-

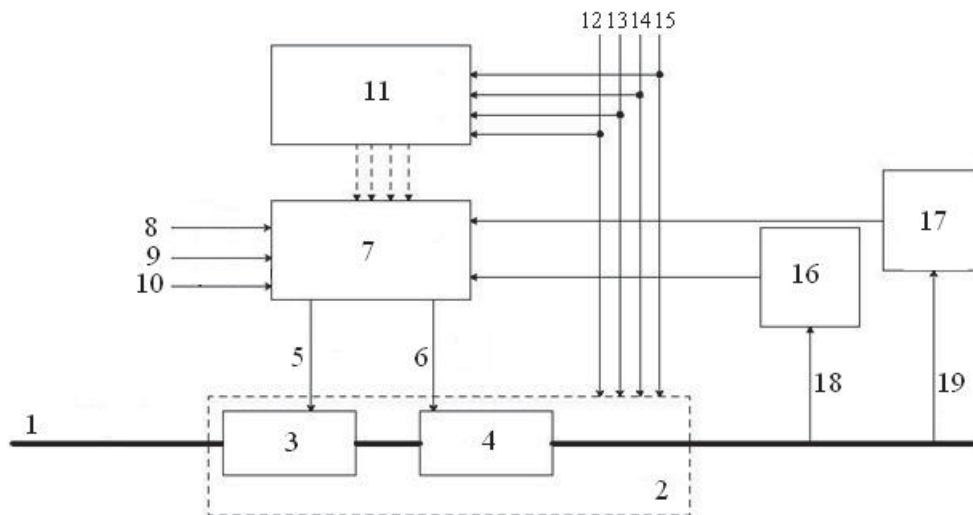


Fig. 1. The structure of power efficient gas transport via an electric driven compressor station: 1 – GM linear part; 2 – CS; 3 – EGCU; 4 – gas ACU; 5 and 6 – rotary speed of EGCU ($\omega_{\text{завл}}^{\text{EGCU}}$) and ACU blowers ($\omega_{\text{завл}}^{\text{ACU}}$); 7 – control parameters calculation block; 8, 9, 10 – desired values of gas flow rate, pressure and temperature; 11 – external actions gauges; 12 – air humidity (β); 13 – air temperature (θ); 14 – temperature differential (Δt) or pressure differential at CS (Δp); 15 – CS output (Q); 16 and 17 – gas pressure and temperature sensors; measuring 18 and 19 – actual gas pressure and temperature values at CS

ture values in GM, measured accordingly by gas pressure and temperature sensors, preset pressure and temperature parameters of GM section, and also values of perturbation influences of stochastic nature, and thereby parametrical changes of gas pipeline pressure and temperature are minimized, therefore its operational reliability improves, and also integrated power inputs for EGCU drive and gas ACU blowers are minimized.

The required initial condition of optimization the intervals of values of continuously changing variables and value sets of discrete variables should be selected. The possible values of variables are analyzed at gradual tree derivation the branches of which are connected to the nodes describing the considered values combinations, using the technology of separation of variables, i.e. separation, leading to the generation of new tree nodes, and the evaluation, i.e. determination with a high probability of tree branches, that can lead to the leaves corresponding to the final optimized solution. Thus, the branches with the greatest probability of successful solution have a priority, and the target values are considered as optimum ones if the restrictions, set in advance, are not broken or are broken to the minimum degree. At this the minimum of target function is reached, that has the following three-factor form:

$$G = \alpha \times R + \beta \times W + \gamma \times C, \quad (1)$$

where α , β and γ – weight coefficients, R – “mode” factor, i.e. minimization (maximization) of pressure in certain GTS points, such as any points, located upstream or downstream CS or control valve, and gas consumption device, W – “energy” factor or electric energy consumption minimization for gas compression and cooling in ACU before its input to the pipe-

line, C – “target” factor, i.e. maximization (minimization) of gas flow rate at the system section, located between two GM points, or pressure in a certain connecting point.

Besides the indicated restrictions encompass the equality restrictions, the number of which comprises the law of pressure loss in the pipelines and the first Kirchhoff rule, determining networks calculation, and restrictions of inequality, the number of which comprises the restrictions for minimum and maximum gas flow rate values, the restrictions for minimum and maximum pressure in active or passive objects and CS EGCU power limiting.

The optimum configuration of CS active objects KC is modelled in the form of P program of optimization in the following view:

$$\begin{cases} \min_{\{x,s,e\}} f(x,s) = G(x) + \alpha \cdot \|S\|, \\ P = C_I(x) + \beta \cdot e \leq S_I, \\ C_E(x) = S_E, \end{cases} \quad (2)$$

where $x \in R^n$, $S_I \in R^p$, $S_E \in R^q$, $e \in \{0,1\}$; x – set of variables of gas flow rate Q and pressure P ; $G(x)$ – target function, representing economic criterion of optimization; $C_I(x)$ – a set of p linear and non-linear restrictions of inequality for active objects; β – vector, the coefficients of which are equal to zero or maximum values of restrictions; e – vector of binary variables; $C_E(x)$ – a set of q linear and non-linear restrictions of equality; s – deviation variable, that non-zero value means restriction violation; α – coefficient, corresponding to admissible degree of restriction violation.

As a result with the preset gas flow rate 8 (Fig. 1) gas pressure 19 and temperature 18 at CS output are

set up and stabilized at the preset optimum level of CS power consumption. The given method of the main gas transport represents a reliable and long-life system, limiting gas overpressure and over-temperature above and below limiting values.

The use of the suggested gas main transport method as compared to the existing methods provides the automatic stabilization of gas pressure and temperature at CS outlet and thus eliminates inadmissible deformations and stress conditions of the pipeline and possible destructions of its anticorrosive isolation almost completely, as a result the operational reliability improves, along with the optimization of the integrated power inputs for EGCU drive and gas ACU blowers of main gas pipelines are optimized.

2. Intellectualization of Control Functions in the Process Units Electric Drives

To implement the given power effective process scheme, the EGCU electric drive system should be frequency-regulated [1, 13] and invariant to all parameters of deterministic and stochastic disturbances, i.e. combined ACS (by deviation and disturbance) with negative feedback according to the main process variable – gas pressure at the outlet of compressor station. Such system developed with the assistance of the author [14], is shown in Fig. 2.

Gas compressor unit 5 is the object of control for the electric drive PCH-SD 4, to the inlet of which gas is supplied. Gas pressure increase (compressing) is effected by means of polytropic operation of GCU compressors. The gas compressor unit rotation is provided by a synchronous motor with a device changing its rotation frequency (PCH) with the control law

$U/f^2 = \text{const}$. The signals of values of disturbing influences and pressure setting signal p_{targ} come to the inlet of block 2 of the required fan rotation speed calculation from the external influences measuring gauges 1. The signal from the outlet of block 2 of the required electric drive rotation speed calculation is received by the adder unit 7 where it is corrected by a signal from the pressure gauge 6. The signal from the adder unit is received by the PI-controller 3 at the outlet of which U_{given} signal is generated, proportional to the synchronous motor required speed of rotation. Gas compressor unit 5 rotated by electric drive PCH-SD 4, creates the required gas pressure at the compressor station outlet p_{outlet} .

The given combined system consisting of ACS on deviation (of the gas pressure) and ACS on disturbance (stochastic disturbances), provides gas compressing process automation up to the optimum stable pressure in the conditions of various random influences by means of an invariant control system of variable frequency EGCU. So the required task of improvement of accuracy of the required value of gas pressure at CS outlet and gas compressing process stabilization by EGCU means is solved. It is facilitated by the strict observance of basic gas compressing process parameters, that allows improving gas pipeline productive capacity and reliability in the conditions of disturbance influences.

If transferring EGCU in turbo expanding operating mode is necessary, it is required to provide voltage parameters at the outlet of the converter by means of entering an external negative feedback on output voltage as it is described in the papers by the author [1, 15].

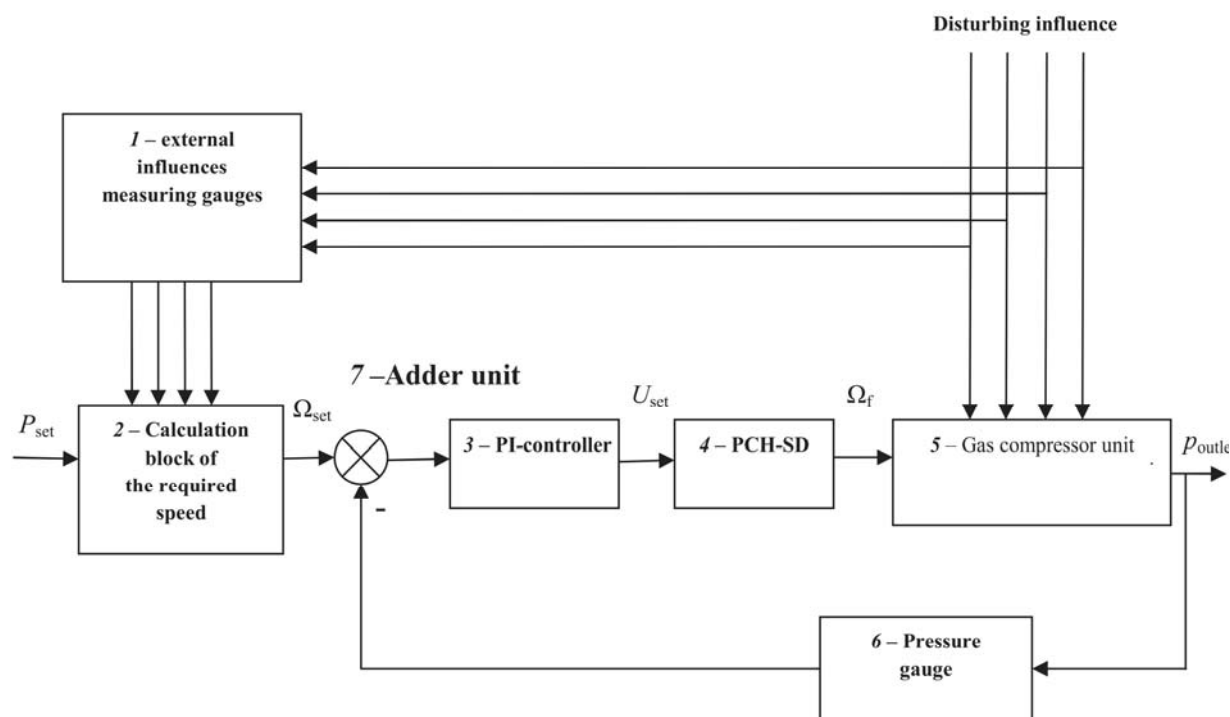


Fig. 2. Structure of invariant system of frequency-controlled EGCU

3. Theoretical Justification of Regression Algorithms Generation

The obvious stochastic nature of influence the technological and climatic factors have on optimum modes of natural gas transport suggests the need to apply corresponding statistical techniques for their handling and formalization. The general experimental design theory, first stated by English statistician R. Fisher in his work [16], constitutes a set of these methods based on the appendices of the central theorem of the theory of probability. Indeed, all basic disturbances influencing the units, valves and pipelines, have random character, they are independent from each other and each of them makes up for an insignificant share in the general change of gas transport parameters. Therefore it is necessary to receive the required multiparameter dependences in the form of nonlinear and linearized regression models using the least squares matrix methods [1, 17].

The regression analysis method, being the basis of many sections of the experimental design theory and statistical data processing, should be used in invariant EGCU design practice in two basic cases:

- when, after carrying out of experiments, there are curves or tables with the numerical values characterizing the change of the recorded indications (received data files are processed with a personal computer and then entered in a DBMS);
- when directly during operation of EGCU ACS the signals picked off from sensors with a certain discreteness, are processed with a control industrial computer based on neurotechnologies algorithms.

While developing new process ACS of CS facilities, the processing of initial experimental data of a prototype refers to the tasks of the first type, and their analysis at the active GM and adjustment refer to the second one.

For experimental data processing it is possible to use model of linear regression in a matrix form

$$Y = X \cdot a + \zeta, \quad (3)$$

where Y – system output parameters matrix (rate of AED rotation or process parameters); X – matrix of input influences (parameters of the task and external disturbing influences); a – parameters of the transformation mechanism in the system; ζ – matrix of disturbances (not considered factors).

Thus it is possible to solve two assigned applied problems simultaneously:

1) forecasting (restoration of) the unknown values from the whole actual range of control of individual $Y(X)$ or average $Y_{av}(X)$ values of the studied resultants according to the preset values of corresponding variables. It is necessary for the estimation of technical and economic indices of automation by means of EGCU (range, smoothness, control accuracy, efficiency and project payback);

2) eliciting cause- and-effect relations between input X and output Y indices, Y values control by variables adjustment. It is required for the program reali-

zation of optimum algorithms of calculation of the set rotation rate of the driven electric motor, providing an optimum gas flow from CS outlet via GM.

4. Electric Drives State Control and Prediction

All the main gas pipelines of the Russian Federation and those of the neighboring countries are classified as the high-risk industrial facilities [18, 19] and irrespective of the electric driven CS operating modes, the requirements to the enhanced reliability and fail-safety operation of all the equipment established by the federal and sectoral normative and technical documents become stricter every year.

Thus the development of universal systems of oil and gas facilities reliability monitoring functioning in the real time mode allowing performing the control and management at various levels and system-wide, is a top-priority task in terms of the energy systems reliability and safety improvement.

As shown above, it is not the STD diagnosis, but the verifiable forecast of its technical condition and the estimation of a residual lifetime of the unit, allowing to prevent sudden non-standard accidents and to pass from scheduled preventive procedures MRO to servicing on an equipment actual state, are more effective procedures of EGCU monitoring. Operating in the real time mode, it is reasonable to use fuzzy logic algorithms, which unlike the boolean two-level logic is multi-level with the language syntax using linguistic variables and levels. Smart sensors based on serial thermal converters may serve as primary information sources for such systems, while furtheron the data is processed with fuzzy controllers [5, 20]. The monitoring algorithm is compiled based on the preliminary fuzzification of the current measured variables and their change rate of. Based on the resulting linguistic estimations of the current parameter value and its change rate the forecast value of each factor is determined.

The database is created and the statistical analysis is performed for the failures of more than 60 electric motors of STD-12500 and SDG-12500 type for the operation period from 1987 to 2010. The most typical kinds of damage are revealed. The key parameters of electric motors operation in various operating modes under the conditions of active compressor shops are measured. A complex analysis is carried out and 4 groups of the operational factors influencing EGCU electric motor resource are specified.

To compare the reliability of EGCU technical condition forecast results delivered by various methods, we shall consider the trend describing daily temperature fluctuations of STD-12500-2 stator during EGCU operation (Fig. 3, a curve) and analyze the efficiency of the inertial prognostic methods. For this we shall break the known time series, describing the temperature change, in two parts, first of which will serve as a basis for the forecast, and the second one will be used to check the posterior accuracy of the forecast.

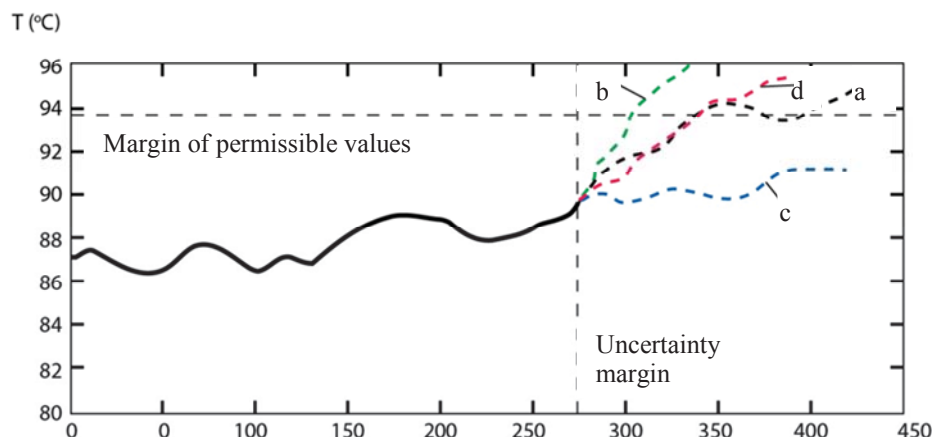


Fig. 3. STD-12500-2 electric motor stator temperature prediction: a – actual temperature series, b – prediction, received with ANN application (Ward network), c – prediction, received with Box-Jenkins model application, d – prediction, received with SCDA (spectral components dynamic analysis) method application

Based on the research conducted it is possible to make a conclusion that the use of the time series method allows for more precise forecasting of the temperature drift of STD-12500-2 stators as compared to the applied methods based on predictive models and ANN.

The developed functional flow diagram presenting the system of analysis of STD operational factors influence on stator isolation resource and prediction algorithms of EGCU motor states based on fuzzy-logic and artificial neural networks allows:

- getting reliable data on the technical condition of the driven motor in the on-line mode;
- planning capital and operating repairs of the electric motor based on the actual state, reducing

the idle time due to repair from 12,000 hours to 2,000–3,000 thousand hours;

- eliminating the heating effect of current and decreasing the cost of capital repairs thrice due to prevention of the in-operation STD damage;
- carrying out current repairs instead of overhauls featuring the replacement of defective cores (4 times lower cost) on SM with flexible multilayered mica winding;
- controlling STD cooling system operation and maintaining optimum operation modes, allowing for the increase of the isolation lifetime;
- improving EGCU maintenance level and, consequently, cutting down the operating costs total.

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НАУЧНАЯ БАЗА СОЗДАНИЯ ИНТЕЛЛЕКТУАЛЬНЫХ ЭЛЕКТРОПРИВОДОВ ТЕХНОЛОГИЧЕСКИХ УСТАНОВОК НЕФТЕГАЗОВОГО КОМПЛЕКСА

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Предложено теоретическое обоснование разработки энергоэффективных электроприводов технологических установок транспорта углеводородного сырья на базе интеллектуальных систем управления и мониторинга. Рассмотрены стратегии многофакторной оптимизации электроприводных агрегатов в условиях действия стохастических возмущений технологического и природного характера. Получены инвариантные системы и регрессионные алгоритмы управления частотно-регулируемыми электроприводами технологически связанными агрегатами. Предложены принципы нейро-нечеткого прогнозирования технического состояния для разработки встроенных систем мониторинга электромеханических систем.

Ключевые слова: автоматизированный электропривод, научное обоснование, интеллектуальная система управления, инвариантная система, мониторинг, прогнозирование.

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