

The Synthesis of Nonlinear Hyperstable Adaptive Control Systems of Multiple Connected Electric Drives of Robotic Technological Equipment for arc Plasma Coating

Oleg Khasanov
Ufa State Aviation Technical University
 Ufa, Russia
 legnix@mail.ru

Zimfir Khasanov
Ufa State Aviation Technical University
 Ufa, Russia
 zimfirm@list.ru

Alexey Lutov
Ufa State Aviation Technical University
 Ufa, Russia
 lutov1@mail.ru

Sergey Aksenov
Ufa State Aviation Technical University
 Ufa, Russia
 kafedra_pb@mail.ru

Abstract—The issues related to the research and development of a new method for designing of hyper-resistant robust adaptive multiple connected automatic control systems (ACS) of complex spatial movements of dynamic moving objects of robotic technological equipment for arc plasma spraying are considered in the paper. The proposed approach implies the integration of the robust control principles, implemented by the main control loop, and the principles of adaptive self-tuning using dynamic identifiers in non-linear models of control objects. Systems of equations describing the dynamics of the movement of complex multiple connected dynamic control objects are essentially nonlinear and non-stationary ones. Furthermore, all the studied robust adaptive multiple connected ACS has been shown to be able to significantly compensate for the interaction of both complex dynamic effects from the actuators of a multiple connected electric drive and the interaction of control channels, as well as the variability of the gravity of the load in these complex interrelated mechanisms. Moreover, recommendations for performing dynamic acceleration, dynamic deceleration and movement at a steady speed for all multiple connected electric drives of robotic technological equipment has been given. The results of numerical calculations have been provided, which indicate the effectiveness of the numerical algorithms for solving the problems based on the proposed method. It is concluded that the developed structures of robust adaptive multiple connected ACSs not only provide high-quality control, but also they are rather convenient in practical implementation. Finally, a comparative analysis of computational and experimental studies has been given.

APC) is the development of new research methods for nonlinear multiple connected (MC) dynamic automatic control systems (ACSs) and improvement of existing ones. Moreover, these systems operate under conditions of a priori uncertainty and existing perturbation influences, nonstationarity of interconnected parameters, time delays and impossibility of measuring variable parameters of MC control objects. Due to the intensive development of flexible ACSs the creation of new methods for the synthesis of multiple connected electric drives (MCED) are needed in order to increase their performance and accuracy of operation. Adaptive and robust digital control algorithms are carried out taking into account the implementation of their transient characteristics without retuning. Electric drives are created which are able to position the working body at any intermediate point of the motion and implement the specified movement program. Unfortunately, so far only prototypes of such electric drives are available. In complex MCED, the rate of acceleration and deceleration, and transient time have a significant impact on their dynamics. All this stimulates the development and study of new methods for the dynamic calculation of multiple connected adaptive robust ACSs with distributed parameters. Furthermore, this activates the research, where the study process takes into account inherent for them substantial nonlinearity and nonstationarity.

Keywords—*adaptive control system, robotic technological equipment, nonlinear adaptive structure*

I. INTRODUCTION

One of the main tasks of automation of technological equipment for arc plasma coating (TE

Mathematical models of interconnected valve asynchronous electric drives contain a complex of nonlinearities, for example: quantization nonlinearity, nonlinear friction, dead zone, saturation nonlinearity, sigmoid and exponential nonlinearity, multiplication and the sum of these nonlinear variables, etc. When synthesizing digital adaptive ACSs the presence of such nonlinearities in the descriptions of interconnected asynchronous electric drives generates

“substantially nonlinear phenomena”. Examples of such phenomena are: the multiplicity of the equilibrium state; solving problems on an infinite plane; limit or adjustable problem solving cycle; subharmonic, harmonic and almost periodic oscillations; chaos and multiplicity of behaviours.

Therefore, one of the most important tasks in designing high-precision adaptive MC ACSs for interconnected asynchronous electric drives is the development of high-speed robust terminal-type ACSs that use a priori information about temporal changes of parameters and their current values, while ensuring the necessary stability of all control subsystems. In addition, when developing adaptive control algorithms for robust ACSs, it is necessary to take into account the real limitations on the performance of control forces and the energy resources of the drives.

The requirement of simultaneous operation of all interconnected asynchronous valve electric drives is equivalent to reducing the system of differential equations [1-4] to multiple connected independent equations, each of which contains only generalized coordinates and their derivatives. This requirement can be realized by choosing the structure of ACS of electric drives and using dynamic decoupling techniques in the structure of electric drive transmissions.

To assess the movement dynamics of the electric drive's working mechanism, its forces of inertia $F_i(t)q(t)$, damping $F_d(t)q(t)$ and elasticity $F_e(t)q(t)$ are compared. When summing these forces and taking into account external forces of drive control $F_c(t)$, then for given dimensions $F_i(t)$, $F_d(t)$, $F_e(t)$, the movement dynamics of the electric drive's working mechanism is described by the following equation

$$(F_i p^2 + F_d p + F_e) q = F_c,$$

where q is the generalized coordinate; $p = \frac{d}{dt}$ is an operator.

To evaluate movement in MCED, it is necessary to determine the static and dynamic modes of each electric drive in a multiple connection concept. Moreover, the performance and movement stability of all interconnected mechanisms in MCED are also important for this concept.

II. PROSPECTS FOR THE SYNTHESIS OF ADAPTIVE MULTIPLE CONNECTED ACSs OF INTERCONNECTED ASYNCHRONOUS ELECTRIC DRIVES

Mathematical and simulation modelling is one of the most important methods used to assess the dynamic characteristics and obtain fundamental design solutions when creating control systems for technological equipment for an APC. The development of appropriate methods for the synthesis of adaptive MC ACSs of asynchronous drives and software is a very time-consuming task. This is due to the complexity of MC nonlinear dynamic systems of technological equipment for APC, which includes complex mechanical and electrical elements.

The wide development of asynchronous valve electric drives and flexible ACSs has led to the need to create a methodology for calculating MCED in order to increase their performance and accuracy of operation. Algorithms of optimal and adaptive control are developed, taking into account the implementation of their transient characteristics without retuning. Asynchronous valve drives are created which are able to position the working body at any point and implement the specified movement program of adaptive high-speed controller.

The above-mentioned features of asynchronous interconnected electric drives in combination with the specific requirements of APC TE to a large extent influence the future development of adaptive, hyperstable and high-speed MC ACSs. Based on the analysis of recent publications, the authors has been found to relate the improvement of characteristics of asynchronous interconnected electric drives of the APC TE to consideration of all changes in the parameters of interconnected electric drives in time and space in the control algorithms. This is mainly in regard to all changes in the dynamic properties of electric drives. Timely consideration of changes in these parameters makes it possible to compensate for their influence and thereby increase the accuracy and performance of all units of the APC TE.

In [5-8], algorithms have been proposed for adaptive control of ACSs of electric drives that use dynamic models of interconnected electric drives to predict and compensate for the inertial properties of drives. The synthesizing of hyperstable adaptive ACSs will be achieved through special programs and hardware. In general, the design basis for hyperstable adaptive ACSs will be structural design, i.e. hierarchization and decomposition of control, monitoring and measurement functions that multiple connected adaptive ACSs will implement between separate autonomous digital controllers connected with each other through corresponding interfaces.

At present, in the synthesis of MC ACSs, methods of the theory of optimal, adaptive and robust control are preferred. The performance-optimal control algorithms for all interconnected drives should be determined taking into account the restrictions on the phase coordinates of the system, the limiting dynamic capabilities of all drives, and the technological requirements for APC TE. The maximum speed of the actuators, positioning accuracy, uniform acceleration and deceleration should be limited for all electric drives. In addition, adaptive and robust control algorithms should take into account possible deviations from the optimal trajectory of drive movement. Furthermore, they should provide both acceleration in minimum time and deceleration at steady rate in a short time, taking into account all established restrictions without retuning in speed and path length.

The need to increase the speeds of the working mechanisms of interconnected drives and the increasingly stringent requirements to reduce the size

and weight of the drives determined the need to create dynamic methods for the synthesis of robust adaptive ACSs of electric drives, operating under conditions of a priori uncertainty and in the presence of operating perturbations. The methods of robust ACS synthesis are based on the theory of hyperstability and positivity of dynamic control systems and are described in detail in the research of V. M. Popov.

Development of robust control algorithms for high-speed controllers of adaptive automatic control systems under conditions of a priori uncertainty should ensure high dynamics of movement of all interconnected drives at specified parameters of accuracy, speed and stability of ACSs. The desired dynamics in such controllers is formed using the reference model. A further increase in the efficiency of using robust controllers in high-speed adaptive ACSs is associated with the development of explicit and implicit reference models [9-15]. In addition, the development of a robust control system cannot be effectively implemented without information on the variable states of the control object for the purpose of generating feedback. The results of the theory of robust control systems make it possible in many cases to synthesize robust control algorithms using digital adaptive state inspectors. They guarantee stability and provide estimates of the variables state of the control object during processing the information in the system that is available for measurement.

III. SYNTHESIS AND STUDY OF HYPERSTABLE ADAPTIVE ACS

Among other methods for the synthesis of adaptive sustainable ACS, the approach based on the criterion of stability in general has at least two important properties which are its systematic nature and guaranteed ensuring the stability for any initial conditions of input effects. The greatest successes in the development of methods for the synthesis of adaptive stable ACSs were obtained in the theory of hyperresistance by V.M.Popov. One of the first works concerning this research is the paper by I. Landau. He proposed a rather general algorithm for the synthesis of ACS of this type. This approach was then modernized and used by other authors for solving various problems of identification and control. The most complete and detailed procedures and algorithms for the synthesis of adaptive ACS based on the theory of hyperresistance are given in [16].

The general structure of an adaptive hyperstable ACS with a reference model is presented in Fig. 1. In [17], a method for the transformation of the structural scheme (shown in Fig. 1) to a hyperstable linear adaptive ACS with nonlinear adaptive feedback (Fig. 2).

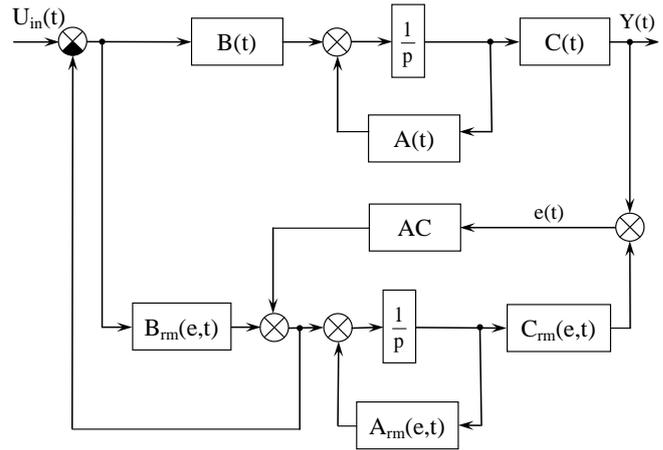


Fig.1. The structure of an adaptive hyperstable ACS with a reference model

For the synthesis of a hyperstable adaptive ACS of an electric drive, it is necessary that the functions $F_1(\cdot)$, $F_2(\cdot)$, $G_1(\cdot)$ and $G_2(\cdot)$ satisfy the following ratios:

$$\begin{cases} F_1[v(\tau), t] = f_A(t - \tau) \cdot v(\tau) [g_A \cdot y(\tau)]^T \\ F_2[v(\tau), t] = f_B(t - \tau) \cdot v(\tau) [g_B \cdot y(\tau)]^T \\ G_1[v(\tau), t] = f_{A_i}(t - \tau) \cdot v(\tau) [g_{A_i} \cdot y(\tau)]^T \\ G_2[v(\tau), t] = f_{B_i}(t - \tau) \cdot v(\tau) [g_{B_i} \cdot y(\tau)]^T \end{cases} \quad (1)$$

where $f_A(t - \tau)$ and $f_B(t - \tau)$ are matrix definitely positive kernels, the Laplace transformation of ones are real positive transfer matrices with one zero pole; g_A and g_B are the constant definitely positive matrices; $f_{A_i}(t - \tau)$ and $f_{B_i}(t - \tau)$ are the variable definitely positive matrices; $v(\tau)$ is linear transformation of the error vector.

In the well-known approach of synthesizing a robust adaptive ACS, determining the linear part of the adaptation mechanism was reduced to finding the matrix D [6]. The technique, based on the simultaneous solutions of the Lyapunov and Yakubovich-Kalman equations, has the greatest application. However, in practice, due to the mathematical complexity of solving these equations, the known results are limited mainly by systems described by state's differential equations of relatively low dimension.

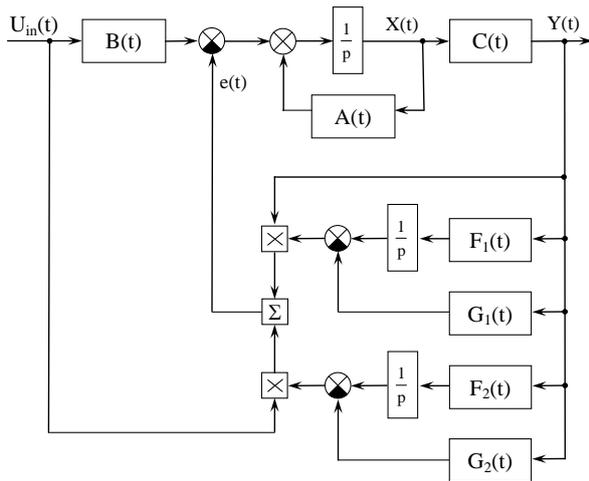


Fig. 2 The structure of a hyperstable linear adaptive ACS with nonlinear adaptive feedback

The second important factor limiting the practical use of well-known methods for solving complex synthesis problems of digital adaptive robust ACSs of high-speed MCED is the need to use the desired input signal at identifying the parameters of the control object; the generation of the input signal is not always possible in real time.

These circumstances will limit the practical significance of known results and will not allow them to be used in solving problems of the synthesis of automatic control systems with adaptive identification and control algorithms. The goal is to synthesize a robust adaptive ACS of MCED of the APC TE with a reference model in a control loop based on a combination of hyperstability conditions defined by system of equations (1) and modal and adaptive control algorithms without solving identification problems.

When studying the movement dynamics of electric drives in the ranges of a given movement, the required parameter deviations never go beyond small values, therefore, a linear type control system can be used as a model of the dynamics of objects of movement of MCED.

The state of movement of MCED is described by the following equations:

$$\begin{cases} \frac{d x_i(t)}{d t} = A_i(\eta, t) \cdot x_i(t) + B_i(\eta, t) \cdot u_i(t) + \omega(t) \\ \frac{d \eta(t)}{d t} = D_i(\eta, t) \cdot \eta_i(t) + \xi(t) \\ z(t) = C_i(\eta, t) \cdot x_i(t) + \vartheta(t) \end{cases}, (2)$$

where $x_i(t)$ is the state vector, $u_i(t)$ is the control, $\eta_i(t)$ is the vector of object's random parameters, $\omega(t)$, $\xi(t)$, $\vartheta(t)$ are Gaussian random processes such as white noise with zero average and variable

intensities. Here, some of the components $\omega(t)$ can be determining signals, and some can be perturbations, $A_i(\eta, t)$, $B_i(\eta, t)$, $C_i(\eta, t)$, $D_i(\eta, t)$ are known matrix functions of time t .

Feedback equations or measurement equations are represented in the form

$$y_i(t) = C_i(t) \cdot x_i(t) + D_i(t) \cdot u_i(t). (3)$$

Each control vector $u_i(t)$ will be always assumed as a deterministic one and as a function of the state vector $x_i(t)$.

It is required for each actuator of the MCED to find an admissible piecewise-continuous vector function $u_i(t)$ so that at any time the location of the roots of the characteristic equation of an adaptive closed-loop ACS agrees with the specified (desired) distribution.

In accordance with the well-known results, optimal control in linear adaptive systems of control the MCED is ensured at

$$u_i(t) = M_i(t) \cdot x_i(t), (4)$$

where $M_i(t)$ is the matrix of optimal gains of the control loop i of the electric drive.

For ACS with closed feedback, the movement of the control object is as follows:

$$\frac{d x_i(t)}{d t} = [A_i(t) - B_i(t) \cdot M_i(t)] x_i(t). (5)$$

The possibility to solve equations (5) determines the conditions of controllability of the MCED in the complex of the entire technological equipment for the APC [5].

The electric drive with a precision plasma torch feed with matrices of fast $A_1(t) \cdot B_1(t)$ and slow $A_2(t) \cdot B_2(t)$ movement of the plasma torch carriage along the sprayed part requires highly accurate complex dynamic tuning of all matrix elements $A_1(t) \cdot B_1(t)$ and $M_1(t)$ and all elements $A_2(t) \cdot B_2(t)$ and $M_2(t)$ in order to ensure the required dynamic parameters of this electric drive.

It is assumed that the ACS is entirely controllable and has full information about its state vector with a given accuracy, and the parameters of the matrices $A_i(t)$ and $B_i(t)$ change slowly.

In accordance with the approach based on Popov's hyperstability theory, all the elements of the matrices $A_i(t)$ and $B_i(t)$ are changed so that the ACS is hyperstable and it provides a generalized error $e_i(t) = 0$ for all given $t \rightarrow t_{3ад}$.

With regard to MCED of APC TE, changing the elements of the matrices $A_i(t)$ and $B_i(t)$ according to the desired program of the technological process of the ACP is not always possible, and changing the elements of the matrices $M_i(t)$ according to the desired program will be carried out according to the proposed algorithm.

In regards to the formation of the equations of the tuning on the elements of the matrix $M_i(t)$, the equations of the adaptive controller are taken into consideration:

$$\frac{dx_{ac}(t)}{dt} = [A_{ac}(t) - B_{ac}(t) \cdot M_{ac}(t)] x_{ac}(t), \quad (6)$$

here $A_{ac}(t)$ and $B_{ac}(t)$ are $(n \times m)$ – dimensional matrices of the state of the regulated controller and the reference model.

The quality indicator is set in an explicit form by the state of the reference model.

$$\frac{dx_{rm}(t)}{dt} = [A_{rm}(t) - B_{rm}(t) \cdot M_{rm}(t)] x_{rm}(t) \quad (7)$$

where $A_{rm}(t)$ and $B_{rm}(t)$ are $(n \times m)$ – dimensional matrices of the reference model.

Then the goal of adaptive ACS control is determined as follows

$$\lim_{t \rightarrow t_{зад}} e(t) = 0, \quad \text{при } t \rightarrow t_{зад},$$

where $e(t) = x_{ac}(t) - x_{rm}(t)$; $A_{ac}(t)$ and $B_{rm}(t)$ meet the Hurwitz's requirements, they are calculated from a priori known requirements for the desired dynamics of a closed ACS; $M_{rm}(t)$ is software adaptive control law.

The linear equation of the adaptation law (algorithm) in accordance with [6] and equation (1) can be obtained as follows

$$v(t) = D \cdot e(t), \quad (8)$$

and its matrix transformation

$$v_1(t) = J^T \cdot v(t), \quad (9)$$

where $D(n \times n)$ and $J(n \times m)$ are the matrices of the linear part of the ACS adaptation mechanism and the linear transformation.

Identically, the equation of matrix tuning $M_i(t)$ will be represented in the following form

$$m_i(t) = L v_1(t) (Q x_{ac})^T + \int L_1 v_1(t) (Q_1 x_{ac})^T dt, \quad (10)$$

where $m_i(t)$ is the current change of tuning $M_i(t)$; the parameters L, Q, L_1 and Q_1 – are given positive weighing matrices.

It should be noted that for practical implementation of the above-described algorithm in the structures of MC controllers, it is sufficient to provide stepless in wide range regulations of linear and adaptive (from tuned inspectors) amounts of feedbacks of ACS by experimentally tuning directly on the objects of ACP TE, which will make it possible to achieve efficient operation of all MC adaptive controllers.

As mentioned above, due to the force of the introduced matrix $J(n \times m)$, all necessary changes for each column of the matrix $A_{ac}(t) - B_{ac}(t) \cdot M_{ac}(t)$ as a linear combination of these changes are introduced into those elements in the column of the matrix in which the elements of the matrix $M_i(t)$ appear, which guarantees the stability of the digital adaptive control algorithms.

These properties determine the main advantage of the proposed adaptive control algorithms, which consist in the convenience of tuning the matrix $M_i(t)$, their high degree of flexibility and equivalently adapting to the desired changes of the control matrices and state matrices. The reasonable choice of elements in the matrix of the linear transformation J allows ensuring the requirements for adaptation quality and optimizing the procedure for the functioning of the new proposed adaptive control algorithms.

The advantage of the proposed approach is that the tuneable parameters are determined not only by estimating the parameters of interconnected electromechanical systems, but also taking into account the accuracy of these estimates, i.e, taking into accounts all covariance matrices $P_x, P_\eta, P_{x\eta}$.

To obtain estimates $\dot{x}_i(t), \dot{\eta}_i(t), \Delta \dot{x}_i(t)$ and matrices $P_x, P_\eta, P_{x\eta}$, nonlinear second-order digital filters are used, in which the filter x , the identifier η , and the covariance numerator Δx can be roughly identified. Synthesis of adaptive ACS is carried out using the methods of digital dynamic programming and sensitivity theory.

In fig. 3 ÷ 5 the estimation of the control error e in the simulation on PC of dynamic processes in adaptive robust ACS with feedback are shown. The purpose of the adaptive ACS is to suppress the elastic oscillations in the MCED, which makes it possible to increase the quality factor of the ACS loops, and hence the accuracy of the adaptive control by 2 ÷ 3 times in comparison with the values achieved within the framework of the subordinate regulation and with the algorithms of continuous tuning. Fig. 3 shows the error vector estimates e for given external perturbation ω on the controlled system. Here: 1 – in the absence of algorithms for adaptive tuning of the matrix $M_{rm}(t)$ and 2 – in the presence of algorithms for adaptive tuning of the matrix $M_{rm}(t)$.

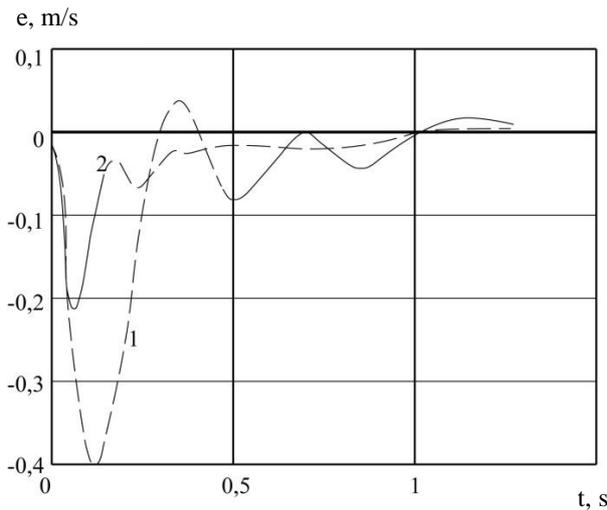


Fig. 3. The estimation of the control error results for given external perturbation

Fig. 4 shows the study of variations of matrix of the linear transformation J on the dynamic characteristics of adaptive control devices for electric drives. It should be noted that in the presence of an a priori preliminary assessment of the nature and form of the current perturbation, it is possible to provide the specified or required parameters of the adaptive control algorithms with wide variations of the matrix of linear transformation J within fairly wide range.

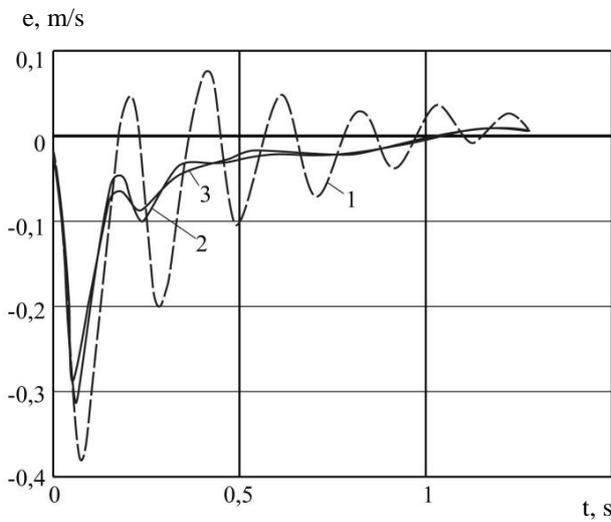


Fig. 4. The variations of matrix of the linear transformation on the dynamic characteristics of adaptive control devices for electric drives

Fig. 5 shows the assessment of the influence on the process of deviations of the electric drive control elements δ in the dynamics of adaptive switching. The research results confirm that during transient processes even the abrupt actions of external perturbations ω keeps the dynamic error δ of the adaptive controller within the linearity zone.

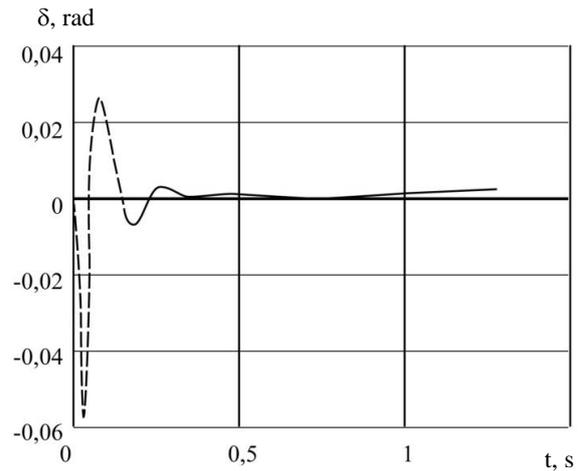


Fig. 5 The influence on the process of deviations of the electric drive control elements in the dynamics of adaptive switching

The proposed approach to solving the problem of synthesizing adaptive robust MC ACSs of interconnected electric drives with tuneable reference models in control loops differs from those known ones by the absence of complex digital identifiers and devices for adaptive tuning of parameters of interconnected MCED models with adaptive, high-speed control algorithms. All this caused great difficulties in the technical implementation of the control subsystems responsible for acceleration, deceleration and stabilized movement of MC working mechanisms in interconnected electric drives of an ACP TE.

IV. CONCLUSION

The theoretical and practical results obtained were tested on the example of studying the dynamic parameters of adaptive robust ACS with tuneable reference models for controlling the movement of the working mechanisms of interconnected electric drives of an ACP TE, their performance and effectiveness in the production conditions are illustrated. The proposed approach is free of some disadvantages of the well-known technical solutions for error assessment of adaptive automatic control systems. The use does not have limitations on the dimension of adaptive models of the system and opens up broad prospects for the synthesis of adaptive robust automatic control systems of interconnected electric drives with control algorithms during acceleration, stable speed and instant deceleration of the MCED, i.e. operating under conditions of uncertainty.

Synthesis of adaptive algorithms for instant acceleration and deceleration is carried out taking into account the adopted restrictions and requirements of the ACP TE. Deceleration and acceleration at steady speed are performed at an adaptive, adjustable rate. The access to the position point is achieved at low speed and acceleration, which provides the required accurate dynamics of movement of all working mechanisms in interconnected electric drives.

When choosing control algorithms, the above-mentioned requirements for MC adaptive robust automatic control systems and interconnected electric drives of ACP technical equipment should be taken into account. High-speed MCED with frequency vector control allow good regulating of the speed at low frequencies, which improves control accuracy in this range. Furthermore, the use of vector control allows improving the dynamic characteristics of asynchronous electric drives, expanding the range of speed control and limiting the moment at a given level.

ACKNOWLEDGEMENTS

The work was supported by the Russian Foundation for basic research (PFFI Grant № 19-08-01122 A).

REFERENCES

- [1] Z. M. Khasanov, O. Z. Khasanov, R. M. Guzairov, "Mathematical model of movement of multiple connected systems of electric drives for technological processes of arc plasma spraying", in *Mechatronics, automation, control*, No. 2, vol. 16, 2015, pp. 116–122.
- [2] M. Araki, K. Yamamoto, "Multivariate multirate sampled-data systems: state-space description, transfer characteristics and nyquist criterion", *IEEE Trans. AC*. 1986. vol. 31, № 2, Feb. pp. 145–154.
- [3] Stefan Almer, Ulf Johanson. *Dynamic Phasor Analysis of Periodic Systems // IEEE Transactions on automatic control*. 2009 Vol. 54 N 8
- [4] Chiang C. Robust adaptive fuzzy control of uncertain nonlinear systems with unknown deadzone // *Amer. Journ. Intelligent Systems*. 2012. N 2(7). P. 191–199.
- [5] Z. M. Khasanov, "Automated technological equipment for arc plasma spraying", in *Svarochnoe Proizvodstvo*, 2006, No. 5, pp. 44–50.
- [6] Shinji Hara, Yutaka Yamamoto, Tohru Omara, Micho Nakato. Repetitive Control System: A New Type Servo System for Periodic Exogenous Signals // *IEEE Transactions on automatic control*. 1988. – Vol. 33, N 7. – P. 659–668.
- [7] Ramon Costa-Castello, Danwei Wang, Rodert Grino. A Passive Repetitive Controller for Discrete-Time Finite-Frequency Positive-Real Systems // *IEEE Transactions on automatic control*. 2009 Vol. 54 N 4
- [8] Zhen Zhang, Andrea Serrani. Adaptive Robust Output Regulation of Uncertain Linear Periodic Systems // *IEEE Transactions on automatic control*. 2009. – Vol. 54, N 2. – P. 266–278.
- [9] Z. M. Khasanov, O. Z. Khasanov, "Self-tuning information and control system with a model for dynamic control of electric drives in high-temperature technological processes", in *Automation and modern technologies*, 2008, No. 12, pp. 23–32.
- [10] Markov A.Yu., Fradkov A.L. Adaptive synchronization of chaotic systems based on speed gradient method and passification // *IEEE Trans. Circ. and Syst.* 1997. № 11. P. 905–912.
- [11] Luis T. Aguilar, Igor Boiko, Leonid Fridman, Rafael Iriarte. Generating Self-Excited Oscillations via Two-Relay Controller // *IEEE Transactions on automatic control*. 2009 Vol. 54.N 2
- [12] Pashilkar A.A., Sundararajan N. Adaptive backstepping neural controller for reconfigurable flight control systems // *IEEE Trans. Contr. Syst. Technol.* – 2006. – V. 14, No. 3. – P. 553–561.
- [13] Ge S.S., Hang C.C., Tao Zhang. Adaptive Neural Network Control of Nonlinear Systems by State and Output Feedback // *IEEE Transactions on systems, man, and cybernetics*. – Part B: cybernetics. – 1999. – Vol. 29, No. 6. – P.818–828.
- [14] Byrnes C.I., Isidori A., Willems J.C. Passivity, feedback equivalence, and the global stabilization of minimum phase nonlinear systems. *IEEE Trans. AC*. Vol.36. 1991. № 11, P. 1228–1240.
- [15] Decarlo R.A., Branicky M.S., Pettersson S., Lennartson B. Perspectives and results on the stability and stabilizability of hybrid systems // *Proc. Of the IEEE*, Vol. 88, №7, 2000, p. 1069–1082.
- [16] G. Abdelmajid, B.S. Mohamed, T. Mohamed, S. Ahmed, M. Youcef, "An improved stator winding fault tolerance architecture for vector control of induction motor: theory and experiment", *Electric Power Systems Research*, 2013, vol. 104, pp. 129–137.
- [17] Khasanov Z. M., Yakimovich B. A., Guzairov R. M. Position-adaptive control of multiple connected electric drives of technological equipment of arc plasma spraying. *Bulletin of Izhevsk State Technical University*, № 4, 2014. pp. 41–49.