Methodology of synthesis of algorithms for optimal control of adaptive power supply systems with wind power plants

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Abstract. In Russia, relatively new is the development of the use of alternative and renewable energy sources. With scientifically based schemes and volumes of using alternative and renewable energy sources in combination with sources of traditional energy, energy and environmental safety, as well as reliability of power supply systems will increase. That’s why, technologies for using renewable energy sources are becoming the most important innovative direction for improving energy. Power supply systems with wind energy converter of autonomous objects belong to the class of functionally-adaptive systems, the operation of which is ensured by using adaptive optimal algorithms for automatic control and information processing.

Introduction
Currently, there is a diversification of the Russian fuel and energy complex, including the development of decentralized (distributed) energy. Distributed energy is a catalyst and a key element of the “energy transition” from the traditional organization of the power systems of the 20th century to new technologies and practices of the 21st century. The “energy transition” is carried out on the basis of decentralization, digitalization, intellectualization of energy supply systems, with the active involvement of consumers and all types of energy resources and is characterized by increased energy efficiency and reduced greenhouse gas emissions (primarily due to renewable energy sources) [1,9,14]. In Russia, relatively new is the development of the use of alternative and renewable energy sources. With scientifically based schemes and volumes of using alternative and renewable energy sources in combination with sources of traditional energy, energy and environmental safety, as well as reliability of power supply systems will increase. That’s why, technologies for using renewable energy sources are becoming the most important innovative direction for improving energy [2,10]. Power supply systems with wind energy converter of autonomous objects belong to the class of functionally-adaptive systems, the operation of which is ensured by using adaptive optimal algorithms for automatic control and information processing [3,12,16].

An adaptive optimal algorithm is an algorithm that provides the best result, in the sense of a certain quality criterion, in conditions of incomplete information about the properties of an object and the actions of the environment [4,11]. The ability to automatically adapt to unexpected changes in conditions is the most characteristic feature of adaptive algorithms. Adaptive and especially adaptive optimal control algorithms reduce the accuracy requirements of the mathematical description of controlled processes, simplify the process of designing control systems, reduce the time for setting up and testing, reduce the requirements for tolerances on some of the equipment, reduce the required range of automation tools.
In adaptive optimal control algorithms, optimization is applied according to the so-called «generalized work criterion» [5, 6, 13].

**Implementing the algorithm**

Among the areas of optimal control theory, its practical effectiveness is allocated a direction called Analytical design of optimal controllers (control systems). The first formulation of this direction was the Letov-Kalman theorem [4, 15].

For the process described by the equations

\[ \dot{x}_i + f_i(x, \tau) = \sum_{j=1}^{m} \varphi_{ij}(x, \tau) u_j, \quad i = 1, 2, \ldots, n, \]  

optimal in terms of minimizing the functional

\[ I' = V_0(x(\tau_2)) + \int_{t_1}^{\tau_2} Q(x, \tau) \, dt + \frac{1}{q} \int_{t_1}^{\tau_2} \sum_{j=1}^{m} \left( \frac{u_j}{k_j} \right)^q \, d\tau \]  

are controls

\[ u_j = -k_j^p \left( \sum_{k=1}^{n} \varphi_{kj} \frac{\partial \nu}{\partial x_k} \right)^{p-1} \]

where \( V \) is the solution of a nonlinear partial differential equation

\[ \frac{\partial \nu}{\partial \tau} - \sum_{i=1}^{n} f_i \frac{\partial \nu}{\partial x_i} - \frac{1}{p} \sum_{j=1}^{m} \left( k_j \sum_{k=1}^{n} \varphi_{kj} \frac{\partial \nu}{\partial x_k} \right)^p = -Q \]

under the boundary condition \( V_{\tau=\tau_2} = V_0 \), here \( x = (x_1, \ldots, x_n) \) – process state vector; \( f_i, \varphi_{kj} \) – specified continuous functions; \( V_0 \) – given scalar function of the final state of the process \( x(\tau_2) \);

\( Q \) – given positive definite residual function, taking into account the deviation of the process parameters from the specified values;

\( p, q \) – given positive numbers satisfying the relation

\[ \frac{1}{p} + \frac{1}{q} = 1 \]

and such that \( z^p \) – even function \( z \); \( k_j \) – given coefficients.

Thus, the synthesis of optimal controls is reduced in this case to solving a nonlinear partial differential equation (4). Integrating this equation in the design process is very difficult, and in the process of the system functioning, it is practically impossible.

In contrast to the traditional method, optimization by the criterion of a generalized work is reduced to solving a linear partial differential equation of the first order, sometimes called the Lyapunov equation [4]. This greatly simplifies obtaining optimal control laws. In this case, the criterion for generalized work (2) is modified by the introduction of additional optimal controls \( \frac{1}{p} \int_{t_1}^{\tau_2} \sum_{j=1}^{m} \left( \frac{u_{j_0}^{\nu a}}{k_j} \right)^q \, d\tau \) and takes the following form [8]:

\[ I = V_0(x(\tau_2)) + \int_{t_1}^{\tau_2} Q(x, \tau) \, d\tau + \frac{1}{q} \int_{t_1}^{\tau_2} \sum_{j=1}^{m} \left( \frac{u_j}{k_j} \right)^q \, d\tau + \frac{1}{p} \int_{t_1}^{\tau_2} \sum_{j=1}^{m} \left( \frac{u_{j_0}^{\nu a}}{k_j} \right)^q \, d\tau. \]  

In this case, additional optimal controls \( u_{j_0}^{\nu a} \) defined by the formula:

\[ u_{j_0}^{\nu a} = -k_j^p \left( \sum_{k=1}^{n} \varphi_{kj} \frac{\partial \nu}{\partial x_k} \right)^{p-1}, \]

as a result, equation (11) becomes linear:

\[ \frac{\partial \nu}{\partial \tau} - \sum_{i=1}^{n} f_i \frac{\partial \nu}{\partial x_i} = -Q, \]
and the function $V$ is a solution of this linear partial differential equation with the boundary condition $V_{\tau=\tau_2} = V_\tau$. The transition to the criterion of generalized work practically does not change anything in the technical essence of the requirements imposed on an optimal system, since $u_j = u_{jon}$. At the same time, the solution of the problem of obtaining optimal controls is greatly simplified due to the linearity of the partial differential equation for the function $V$.

In the special literature [4, 5, 6], two main optimization methods (algorithms) are considered according to the criterion of generalized work: an operational algorithm and an algorithm with a predictive model. Considering that adaptive Power supply systems with wind energy converter and autonomous objects are sufficiently inertial and do not require high control accuracy at short time intervals, the use of algorithms with a predictive model is most appropriate for optimizing control in such systems.

The algorithm with the predictive model is based on the integration of the equations of free motion (motion with fixed controls) of the controlled object. This integration is carried out on the optimization interval under the initial conditions corresponding to the current state of the object. The optimization interval in this case can be as long as necessary. The algorithm with the predictive model is mainly used to optimize the control itself during the operation of the system.

To solve the equations of the optimal adaptive control of a wind-diesel station, in principle, it was possible to use the mathematical apparatus and software used in the synthesis of optimal motion paths of aircraft. However, the rate of change of the parameters of processes implemented in Power supply systems with wind energy converter, and the requirements for speed and accuracy of calculations of the optimal trajectory are incomparably small compared with similar parameters of the movement of aircraft. Consequently, it is necessary to use simpler methods for synthesizing the control laws of control systems of Power supply systems with wind energy converter. For Power supply systems with wind energy converter autonomous facility, the management of energy supply processes can be divided into the management of energy sources and the management of energy consumption in electrical and heat channels.

One of the effective methods for the synthesis of the laws of optimal control is the synthesis method that is optimal in terms of the functional (criterion) of the generalized work of control. The most constructive results of applying this method relate to dynamic objects with linearly incoming control [4, 5, 6].

It is known [6] that optimal control algorithms with predictive models have the most universal properties.

The content of the algorithm with the predictive model can be interpreted as solving the equations of the characteristics corresponding to the Lyapunov equation in the problem of optimizing control by the generalized work functional, and forming the control by the formula

$$u_{on} = -Ky^\tau \frac{\partial V^\tau}{\partial x},$$

where $K$ is a positive-definite matrix of given coefficients;

$y$ - matrix function $x$ and $\tau$;

$V = V(x, \tau)$ - real scalar function;

$\partial V/\partial x$ - matrix row whose elements are partial derivatives $V(x, \tau)$ by state vector components $x$.

In the case of a numerical implementation, all necessary calculations are performed cyclically with a cycle duration of $\Delta \tau$. The numerical algorithm with a predictive model includes the following operations:

a) measurement or evaluation of the current state of the object in discrete time points corresponding to the beginning of the next cycle management formation;

b) forecasting of free (unmanaged) movement of an object on specified interval $[\tau, \tau_2]$ management optimization (interval forecasting) with initial conditions coinciding with the current in the moment state of the object or lying in some neighborhood of this state;

c) calculation of function gradient change $V(x, \tau)$ for the current state of the object;

d) control signal generation.
Specific capabilities and computational costs depend on the variant of the algorithm with the predictive model.

Considering, as mentioned above, the rather high inertia of technological processes implemented in the power supply systems of autonomous objects, and, accordingly, the availability of time and computing resources of the SAR SEA with wind turbines, it is advisable to further consider the following types of algorithms with a predictive model:

- algorithm with a predictive model and numerical differentiation;
- algorithm with a predictive model modified.

For a wide class of objects, modeling of their functioning in the absence of control actions ($u=0$) on the interval $[\tau, t_2]$ due to difficulties of a computational nature. For example, a neighborhood of the current state of an object containing predictable $[\tau, t_2]$ trajectories may either significantly exceed the region of admissible states in $X$ in size, or not at all intersect with it.

In addition, for nonlinear objects, a significant change in the dynamic properties is possible when the current vector of input variables is replaced by a zero vector ($u = 0$).

When solving the problem of controlling the rate of change of the vector of input quantities, the motion of an object is described by the equations

$$x = f(x, y, \tau), \ y \in u. \quad (9)$$

Minimized functionality is defined as

$$I = V_\alpha[x(\tau_2)] + \int_{\tau_1}^{\tau_2} Q\alpha(x, \tau) d\tau + 1/2 \int_{\tau_1}^{\tau_2} (u^1 K^{-1} u + u_{on}^1 K^{-1} u_{on}) d\tau, \quad (10)$$

Where $f$ – is the vector function;

$V_\alpha$ and $Q\alpha$ - given positive-definite functions.

We will introduce the notation:

$$p_x(\tau) = [\partial V(\tau)/\partial x(\tau)]^T, \ p_y(\tau) = [\partial V(\tau)/\partial y(\tau)]^T.$$  

Then the equations of the characteristics will have the following form:

$$x = f(x, y, \tau), \ y = 0; \quad (11)$$

$$p_x = - \frac{\partial f}{\partial x}^T p_x - \frac{\partial Q}{\partial x}^T; \quad (12)$$

$$p_y = - \frac{\partial f}{\partial y}^T p_y - \frac{\partial Q}{\partial y}^T; \quad (13)$$

$$V = Q(x, y, \tau). \quad (14)$$

Next, we consider the solution of the problem of synthesizing optimal controls using an algorithm with a predictive model and numerical differentiation.

This algorithm is to calculate $V(x(\tau), \tau)$ using integration (14) with conditions $V(x, \tau)_{\tau=\tau_2} = V[x(\tau_2)]$ on simulated in accelerated time $\tau' = \tau/\alpha$ ($\alpha$ - time acceleration scale) the motion of the object (in accordance with (11)) with the subsequent numerical differentiation of this function.

To determine the optimal in the sense of (10) control of the object (9) at the current time (really - on the next cycle of management formation $\Delta \tau_{\text{ui}}$) in control system of Power supply systems with wind energy converter carried out at a minimum $r + 1$ object motion forecasts by integrating model equations

$$\frac{d}{d\tau} x^M = \alpha f^M(x^M, y^M, \tau'), \quad \frac{d}{d\tau'} y^M = 0 \quad (15)$$

in accelerated time $\tau'$ of various initial conditions $y^M(j)(0), j = 1, r + 1$, lying in the vicinity of the current value obtained in the previous cycle. The initial conditions for the first equation (11) are given by

$$x^M(\tau') = x(\tau). \quad (16)$$

Scalar functions are calculated based on these predictions.
where $\tau' = \tau / \alpha$ are integration limits in accelerated time; $x^m(\tau')$ - predicted in accelerated time of the state vector of the controlled object (9); $f^m$ – vector function representing in model (15) the corresponding object function (9).

The calculated values (17) are used further to approximate the differential analog of the partial derivatives in the relation

$$u_{on}(\tau) = -K \left( \frac{\partial y(\tau)}{\partial y(\tau)} \right)^T = -K p_y(\tau).$$

For the synthesis of optimal controls, an algorithm with a predictive model can also be applied. Suppose that the functions $V_\zeta(x, y, \tau) u Q_3(x, y, \tau)$ functional (10) are differentiable on $x(\tau)$ by $X \times Y \times [\tau_1, \tau_2]$.

This algorithm is associated with a solution in accelerated "reverse" time [6]

$$\theta = \tau_2' - \tau_1'\quad (19)$$

changing from 0 to $\theta = \tau_2' - \tau_1'$, equations (12) and (13) with boundary conditions

$$p_x(0) = p_\theta(\tau_2') = \left[ \frac{\partial V_\zeta(x^m(\tau_2'))}{\partial x^m(\tau_2')} \right]^T;$$

$$p_y(0) = p_\theta(\tau_2') = \left[ \frac{\partial V_\zeta(y^m(\tau_2'))}{\partial y^m(\tau_2')} \right]^T.$$

The calculation of these conditions implies knowledge of the state (11) at the end of the optimization interval obtained by preliminary modeling (15) in the accelerated "direct" time $\tau'$ ith the initial conditions (16) and

$$y^m(\tau') = y(\tau).$$

The need to calculate along the predicted trajectory of the function object $\partial f / \partial x, \partial f / \partial y, \partial Q / \partial x$ and $\partial Q / \partial y$ leads either to memorization of the trajectory object in the control system (11), passed during preliminary modeling, or a joint solution in reverse time $\alpha$ of equations

$$\frac{d}{d\theta} x^m = -y^m(x^m, y^m, \alpha), \quad \frac{d}{d\theta} y^m = 0;$$

$$\frac{d}{d\theta} p_x = \alpha \left( \frac{\partial f}{\partial x^m} \right)^T p_x + \alpha \left( \frac{\partial Q_3}{\partial x^m} \right)^T;$$

$$\frac{d}{d\theta} p_y = \alpha \left( \frac{\partial f}{\partial y^m} \right)^T p_y + \alpha \left( \frac{\partial Q_3}{\partial y^m} \right)^T.\quad (22)$$

The resulting vector components $p_y(\theta) = p_y(\tau') = p_y(\tau)$ determining optimal control (18) and used subsequently in the wind turbine control algorithm. Algorithm (18), (22) does not require numerical differentiation and therefore potentially has a higher accuracy.

Thus, for multidimensional objects with a large number of inputs and the impossibility or significant costs of developing an analytical solution, the algorithm with the predictive model is the most preferable in terms of complexity.

The generalized structure of the control system of Power supply systems with wind energy converter control algorithm with wind turbines is presented in Figure 1.

The adaptive control algorithm should contain the following basic typical blocks, which should be eliminated when the control principle changes [7,9]:

1) block input and processing of the source data;
2) current information processing unit;
3) block identification and calculation of control actions;
4) self-adjustment unit (calculation of the quality criteria of regulation based on difference equations);
5) control action generation unit;
6) the block of adjustment of interregulatory connections (adapter).

One of the most important for ensuring effective management is block No. 4 - a self-tuning block (calculation of control quality criteria). This unit in general should consist of the following parts:
- reference model of the control object;
- subprograms of self-tuning parameters;
- subroutines for calculating parameters of regulation quality.

If the SAR includes simply a stabilizing regulator with a corresponding control algorithm, then the parameters of the quality of regulation (the accuracy of energy regulation and the accuracy of measurement of the current values of parameters) are set.

In the case of using the reference model, the quality parameters of the regulation are obtained by calculation from the reference model.

If the most complex control system is applied, the quality parameters of regulation are self-adjusted each time.

Through analog-to-digital converters ADC to the inputs of blocks No. 1 - input and processing of initial data of software-stabilizing regulators for wind turbines, electric and thermal energy transfer channels - the information from the sensors of the current values of object parameters, energy sources and environment.

Then, in each of the mentioned software-based stabilizing regulators, depending on the selected type of control algorithm (identification, stabilizing or direct adaptive control algorithm), sequential processing of information occurs in the blocks participating in the implementation of the algorithm of one type or another. Blocks No. 5 - formations of control actions — through the corresponding digital-to-analog converters of the D/A converter, they generate a formation about the calculated control actions in block No. 6 — corrections of antiregulatory connections, as well as control signals to the actuators of the wind turbine, electric and thermal energy transfer channels.

The software-stabilizing regulator of the wind turbine is the main regulator in the control system of Power supply systems with wind energy converter, which, through the interregulatory connection adjustment unit (adapter), specifies the specified control settings for the electrical and thermal channels. Software-based stabilizing regulators of electric and thermal channels have completely identical sets of information processing units.

Conclusions
1. Energy supply systems with wind-driven installations of autonomous objects belong to the class of functional-adaptive systems.
2. Synthesis of adaptive regulators and structures of control algorithms for Power supply systems of autonomous objects with wind turbines should be based on the principles of adaptive control.
3. The structure of the algorithm of the operation of control system of Power supply systems with wind energy converter with wind turbines should include a predictive model of the functioning of control system, and management optimization should be carried out according to the criterion of generalized work.
4. The control algorithm control system of Power supply systems with wind energy converter with wind turbines, built on the principles of optimal adaptive control, will ensure maximum use of wind energy to power autonomous objects and a significant reduction in the consumption of fossil fuels used for the operation of traditional energy sources.
Figure 1 - The generalized structure of the control algorithm of control system of Power supply systems with wind energy converter
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