Application of algorithms with a predictive model in solving the problem of regulating the rotational speed of the wind turbine of autonomous wind energy converters

V K Averyanov¹, G I Sidorenko², V N Tolmachev¹, A A Shapovalo¹

¹Gazprom, BOX 1255, St. Petersburg, 190900, Russian Federation
²Peter the Great St.Petersburg Polytechnic University, Polytechnicheskaya, 29, St.Petersburg, 195251, Russia

Abstract. The effective use of wind energy converters in the composition of the energy supply systems of autonomous objects largely depends on the type of algorithms used for optimal control of automatic control systems. As you know, the universal properties have optimal control algorithms with predictive models.

Introduction

Specific features and computational costs essentially depend on the variant of the algorithm with a predictive model, the main ones being the following [1-4]:
- algorithm with numerical differentiation;
- modified algorithm;
- algorithm with sensitivity matrix;
- algorithm with synchronous detection;
- an algorithm with an analytical solution.

In implementing the algorithm are also possible combinations thereof.

In [5] is noted that all known variants of the algorithm with a predictive model lead to essentially one solution and differ only in computational procedures. In this case, the first four options are algorithms for the numerical solution of the problem, and the fifth is an analytical solution. The use of the latter in the process of management will require highly skilled developers and considerable labor costs in the preliminary preparation of the control algorithm, but the costs of forming management during the operation of the system will be insignificant. The remaining options almost all the complexity of the focus on the stage of formation of management in the process of functioning of the control system.

Main part

Given the relatively 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 automatic control systems of the power supply system with wind power plants, it is advisable to use only the first two types of algorithms with a predictive model.[6-7]

Consider as an example the application of an algorithm with a modified predictive model for solving the problem of speed control wind-driven propeller to ensure maximum power output or the maximum wind energy use factor. Control actions in solving the above problem will assume the load on the wind-driven generator and excitation current wind energy converter.
The equations of the mathematical model of wind energy converter is recorded as follows [8-10]:
\[
\begin{align*}
M_b &= \bar{M}_b \cdot \pi \cdot R^3 \cdot \rho \cdot \frac{v^2}{2}; \\
\omega_b &= z \cdot \frac{v}{R}; \\
P_b &= M_b \cdot \omega_b; \\
P^r_b &= P_{ap} + P_{np},
\end{align*}
\]
(1)

Where \( \bar{M}_b \) — relative moment;
\( \omega_b \) — wind turbine speed, rad / s;
\( R \) - wind turbine radius, m;
\( \rho \) - air density, kg / m³;
\( P_b \) - load on the wind-driven generator, kW;
\( P_{ap} \) - unregulated part of the load on the wind-driven generator, kW;
\( P_{np} \) - Consumer-load regulators (adjustable part of the load on the wind-driven generator) kW.

It is known [3] that the maximum use of wind energy, i.e. generating the maximum possible power can be achieved by changing the rotational speed of the wind turbine in accordance with the ratio
\[
\omega_b = z_n \cdot \frac{v}{R},
\]
(2)

where \( z_n \) — nominal number of wind turbine modules.

Power generated by the wind-driven generator \( P_b \), will have the highest possible value \( P_{bm} \) for the current wind speed, if the operating points will be on curve 1 (Figure 1). Curve 1 - is the locus of points corresponding to maximum values of power generated by wind-driven generator, with the current values of wind speed (wind speed function).

Figure 1 shows the generalized mechanical characteristics of the wind turbine of wind energy converter - power dependencies \( P_b \), produced by wind power plants, and the moment \( M_b \) on the wind wheel shaft from wind speed. Characteristics are built for four wind speeds, selected from the range of operating speeds by wind power plants, according to the condition:
\[
v_{pmin} < v_1 < v_2 < v_3 < v_4 < v_{p max}.
\]
(3)

Considering the discrete nature of the load change at the wind power plants generated by the consumers of electric power of an autonomous object. Figure 1 shows the zone of possible deviations of power values generated by the wind power plants when the load power of the wind power plants deviates \( \pm \Delta P_{ap}, \pm \Delta P_{np} \) from a given optimal load value \( P_b \).

Since when wind speed changes during wind energy converter operation, it is necessary to control the rotational speed in accordance with curve 1, to develop a control algorithm and determine control actions, you can apply the mathematical apparatus of algorithms with a predictive model for the problem of optimizing software trajectories using the criterion (functional) of the generalized work.

The terminal part of the minimized functional of the generalized work expresses its dependence on the constraints that ensure the quality parameters of the electricity generated by wind power plants:

- for electric channel
\[
V_{TRK} = \frac{1}{2} \gamma_{11} (\omega_i - \omega_{ai})^2 + \frac{1}{2} \gamma_{22} (U_{ci} - U_{cai})^2 + \frac{1}{2} \gamma_{33} (f_{ci} - f_{cai})^2, \quad (4)
\]
where \( \omega_{ai}, U_{cai}, f_{cai} \) - given values of speed, voltage and current frequency of the generator stator;
- for heat channel
\[
V_{TRK} = \frac{1}{2} \gamma_{44} (\omega_i - \omega_{ai})^2. \quad (5)
\]

For consumers of electric power of the thermal channel, unlike consumers of the electric channel, the introduction of restrictions on the stator voltage and the stator current frequency of the generator by wind power plants is not required. If it is necessary to provide power from one wind power installation at the same time to consumers of electrical and heat channels, the terminal part of the functionality can be specified as (4). Maximum allowable errors to ensure the set values of the rotational frequency \( U_{ci} \) and the stator voltage \( f_{ci} \) for the electrical channel can be denoted by \( \Delta \omega_{ai}, \Delta U_{cai}, \Delta f_{cai} \).
Then the expression of equal contributions of maximum deviations will be obtained in the form [10]
\[ \gamma_{11} \cdot \Delta \omega_{\text{м}}^2 = \gamma_{22} \cdot \Delta U_{\text{см}}^2 = \gamma_{22} \cdot \Delta f_{\text{см}}^2. \] (6)
From the expression (6) up to a common factor, you can determine the values \( \gamma_{ii} \).

**Figure 1**  Generalized mechanical characteristics of the wind wheel wind turbines

As the integrand function of the minimized functional for the electric channel, we will use the following function:
\[ Q_{\text{эк}} = Q_{\text{шт}} + 1/2 \beta_{55} \cdot \Delta P_{\text{рп}}^2 + 1/2 \beta_{66} \cdot \Delta I_{\text{в}}^2, \] (7)
where \( Q_{\text{шт}} \) - penalty function;
\( \Delta P_{\text{in}} \) and \( \Delta I_{\text{in}} \) – control actions for the trajectory movement (the corresponding changes in the load of consumers-regulators and the excitation current of the generator by wind power plants).

For a thermal channel, the integrand function of the minimized functional will have the following form:

\[
Q^T_{\text{WT}} = Q_{\text{WT}} + 1/2\beta_{55} \cdot \Delta P_{\text{in}}^2. \tag{8}
\]

The penalty function in expressions (7) and (8) should minimize the load deviations on a wind power plant from a given zone of maximum values of power generated by wind power plants at different wind speeds \( P_{3m} \pm \Delta P_3 \) (Figure 1), those. from the optimal trajectory of movement, and can be represented as follows:

\[
Q^T_{\text{WT}} = Q^T_{\text{WT}} = \beta_p (P_{3m} - P_{3m}) \text{ when } P_{3m} < (P_{3m} - \Delta P_3) \text{ u } P_{3m} > (P_{3m} + \Delta P_3);
\]

\[
0 \text{ when } P_{3m} - \Delta P_3 \leq P_{3m} \leq P_{3m} + \Delta P_3. \tag{9}
\]

Relations between \( \beta_p, \beta_{55} \) and \( \beta_{66} \) for the electrical channel can be determined based on the principle of equal contributions

\[
\beta_p \cdot \Delta P_{\text{in}} = 1/2 \beta_{55} \cdot \Delta P_{\text{in}}^2 = 1/2 \beta_{66} \cdot \Delta I_{\text{in}}^2. \tag{10}
\]

For the heat channel the ratio between \( \beta_p \) and \( \beta_{55} \) determined in a similar way:

\[
\beta_p \cdot \Delta P_{\text{in}} = 1/2 \beta_{55} \cdot \Delta P_{\text{in}}^2. \tag{11}
\]

In this case, \( \beta_{55} > 0 \) – is large enough, but \( \Delta P_{\text{in}} \), as a rule, is assigned rather small [4].

Equations of the process of regulation by wind power plants on the time interval \( \Delta \tau = \tau_2 - \tau_1 \) may be given (14) are presented in the following form:

\[
\begin{align*}
\frac{d\tau}{d\tau} &= \frac{\pi}{2} R^3 \cdot \rho (v_1^2 - v_2^2); \\
\frac{d\omega}{d\tau} &= \frac{v}{R} (v_1 - v_2); \\
\frac{dp}{d\tau} &= \frac{dP_{\text{in}}}{d\tau} + \frac{dP_{\text{in}}}{d\tau}.
\end{align*}
\]

(12)

For further reasoning, we introduce the notation

\[
x_{T1} = \omega, x_{T2} = U_{ci}, x_{T3} = f_{ci}, x_{T4} = P_{\text{in}}, x_{T5} = M_{\text{in}}, x_{T6} = P_{\text{in}}, y_1 = \Delta P_{\text{in}}, y_2 = \Delta I_{\text{in}}, y_3 = u_1, y_4 = u_2.
\]

We write equations (12) and the minimized functional for the electric channel in the form

\[
\begin{align*}
x_{T1} + f_{T1}(x_{T4}, x_{T5}, y_1) &= 0; \\
x_{T2} + f_{T2}(x_{T1}, x_{T2}, y_2) &= 0; \\
x_{T3} + f_{T3}(x_{T1}, x_{T2}, x_{T4}, x_{T5}) &= 0; \\
x_{T4} + f_{T4}(x_{T6}, y_1) &= 0; \\
x_{T5} + f_{T5}(x_{T1}, x_{T4}, x_{T6}, y_1) &= 0,
\end{align*}
\]

\[
I_{\text{tr}}^{2} = 1/2 y_{11} (x_{T1}(\tau_2) - \omega_{\text{in}})^2 + 1/2 y_{22} (x_{T2}(\tau_2) - U_{\text{cii}})^2 + 1/2 y_{33} (x_{T3}(\tau_2) - f_{\text{cii}})^2 +
\]

\[
1/2 f_{T1}^{T2} [Q_{\text{WT}}(x_{T1} - P_{\text{ini}}) + 1/2\beta_{55} \cdot y_1^2 + 1/2\beta_{66} \cdot y_2^2] d\tau +
\]

\[
1/2 f_{T1}^{T2} \left( u_1^2 + u_2^2 \right) d\tau. \tag{14}
\]

For the thermal channel, equations (12) and the minimized functional can be written in the following form:

\[
\begin{align*}
x_{T1} + f_{T1}(x_{T4}, x_{T5}, y_1) &= 0; \\
x_{T2} + f_{T2}(x_{T1}, x_{T4}, x_{T5}) &= 0; \\
x_{T4} + f_{T4}(x_{T6}, y_1) &= 0; \\
x_{T5} + f_{T5}(x_{T1}, x_{T4}, x_{T6}, y_1) &= 0,
\end{align*}
\]

\[
I_{\text{tr}}^{2} = 1/2 y_{11} (x_{T1}(\tau_2) - \omega_{\text{in}})^2 + f_{T1}^{T2} [Q_{\text{WT}}(x_{T1} - P_{\text{in}}) + 1/2\beta_{55} \cdot y_1^2] d\tau +
\]

\[
1/2 f_{T1}^{T2} \left( u_1^2 + u_2^2 \right) d\tau, \tag{16}
\]
where $\tau_2$ – point in time for which controls are defined.

Analytical solution of the systems of equations (13), (14), (15), (16) and the synthesis of optimal controls in real time during the operation of the system seems to be quite a complicated and time-consuming process.

Analytical solution of the systems of equations (13), (14), (15), (16) and the synthesis of optimal controls in real time during the operation of the system seems to be quite a complicated and time-consuming process.

A block diagram of a numerical algorithm for synthesizing optimal controls of automatic control systems of an Energy supply system with wind power plants with a Numerical differentiation is performed by rerunning the model with modified initial conditions $\hat{x}, y_{np}, y_b$. In this case $\hat{x}$ - evaluation of the state of the object obtained from the sensors $(\omega_i, U_{ci}, f_{ci})$, when $y_{np}$ and $y_b$ - respectively, the vectors that control the impact of changing the regulated part of the load on wind power plants $\Delta P_{np}$ and generator excitation current by wind power plants $\Delta I_e$.

After calculating the gradient components $u_{np}$ and $u_b$ the value of the vector of control actions for the next cycle is calculated. This control action is introduced into the controlled process and remains unchanged during the next cycle. This completes the functioning of the algorithm on this cycle. On the next cycle, the current state of the process is again measured, repeated start ($m + 1$, where $m$ is the number of components of the control gradient) of the model is performed at an accelerated time and other operations are repeated in accordance with Figure 2.

If one does not take into account the errors of the numerical implementation, the algorithm gives an exact solution of the optimal control problem under very general conditions.

The mathematical model and the minimized functional in this task can be practically any within the framework of the uniqueness of free propagation and the uniqueness of the functional.
Raw data block matrix, $\sigma$; arguments $K_j, \Delta \tau_{\nu}, \Delta P_{np}, \Delta I_v$.

Object

\[ \dot{x} = ax + by, \quad \dot{y}_{np} = u_{np}, \quad \dot{y}_b = u_b \]

Evaluation system through each cycle $\Delta \tau_{\nu}$ gives to the object model $\tilde{x}, \tilde{y}_{np}, \tilde{y}_b$

1st launch of the “free” movement of the model in accelerated time (15) for a period $\Delta \tau_{\nu}$

\[ \frac{dx_m}{d\tau} = \varphi(ax_M + by_M) \]

with simultaneous calculation of the functional $I_2$ (36) or (38)

2nd launch of the “free” movement of the model in accelerated time (15) for a period $\Delta \tau_{\nu}$

\[ \frac{dx_m}{d\tau} = \varphi(ax_M + by_M) \]

with simultaneous calculation of the functional $I_2$ (36) or (38)

3rd launch of the “free” movement of the model in accelerated time (15) for a period $\Delta \tau_{\nu}$

\[ \frac{dx_m}{d\tau} = \varphi(ax_M + by_M) \]

with simultaneous calculation of the functional $I_3$ (36) or (38)

The control unit for the next cycle

\[ u_{np} = -k_{np} \frac{I_2 - I_1}{\Delta P_{np}}, \quad u_B = -k_B \frac{I_3 - I_1}{\Delta I_B}. \]
Figure 2 - Block diagram of a numerical algorithm for the synthesis of optimal controls of automatic control systems Power supply systems with wind farms with a predictive model

The proposed approach to the synthesis of optimal control algorithms for adaptive power supply systems with wind power plants should be considered when determining the optimal composition of power complexes using renewable energy sources [11 - 13].

Conclusions

1. The effective use of wind power plants in the composition of the energy supply systems of autonomous objects largely depends on the type of algorithms used for optimal control of automatic control systems.

2. When solving the problem of regulating the rotational speed of the wind wheel by wind-electric installations, in order to ensure the maximum power generated or the maximum wind energy utilization ratio, optimal control algorithms with predictive models should be applied.

3. Considering the complexity and laboriousness of the synthesis of optimal controls in real time during the operation of the automatic control system, the use of a numerical method is most appropriate for calculating optimal controls.

4. The proposed approach to the synthesis of optimal control algorithms for adaptive power supply systems with wind power plants will provide a reasonable choice of the optimal composition and high efficiency of functioning of power supply systems using renewable energy sources.

References

[1] Spravochnik po teorii avtomaticheskogo upravleniya / Pod. red. A.A.Krasovskogo - M.: Nauka, Gl. red. fiz.-mat. lit.,1987. – pp 270

[2] Adamyan, Y., Krivosheev, S., Minevich, T. Investigation of the wind generator blades material resistance to the lightning current action (2018) MATEC Web of Conferences, 245, art. no. 15001, DOI: 10.1051/mateconf/201824515001

[3] Panfilov, A.A. Features of Calculation Schemes and Methods for Design of Wind Turbine Foundations for Arctic Conditions (2018) Proceedings - 2018 International Ural Conference on Green Energy, UralCon 2018, art. no. 8544376, pp. 122-126, DOI: 10.1109/URALCON.2018.8544376

[4] Sidorenko, G.I., Ahmad, A.J. Method of Assessing the Economic potential of Wind Energy in the Region (case study Syria) (2018) Journal of Physics: Conference Series, 1087 (2), art. no. 022016, DOI: 10.1088/1742-6596/1087/2/022016

[5] Titkov, V.V., Bekbayev, A.B., Munsybai, T.M., Shakenov, K.B. Construction of autonomous buildings with wind power plants (2018) Magazine of Civil Engineering, 80 (4), pp. 171-180, DOI: 10.18720/MCE.80.15

[6] V.N.Tolmachev, A.V.Orlov, V.A.Bulat. Effektivnoe ispol'zovanie energii vetra v sistemah avtonomnogo energoobespecheniya. - Spb., VITU, 2002. – pp 203

[7] Vashkevich K.P. Aerodinamicheskie harakteristiki vetrovogvitelej vetroelektricheskikh ustanovok// Izv. AN «Energetika». – 1997. - №3. -S.4-17.

[8] Krasovskij A.A., Bukov V.N., SHendrik V.S. Universal'nye algoritmy optimal'nogo upravleniya nepreryvnymi processami / Pod. red. A.A.Krasovskogo- M.: Nauka,1977. – pp. 272

[9] Tolmachev V.N., Kiryuhin S.N., Sibgatullin A.R. Opredelenie optimal'nogo sostava energokompleksov s ispol'zovaniem vozobnovlyaemykh istochnikov energii // Nauka i tekhnika v gazovoy promyshlennosti. - 2014. - № 3. - S. 81-89.Artur Sibgatullin, Vladimir Tolmachev. Justification of the Parameters of RES Based Energy Complexes for Trunk Gas Pipeline Consumers // Proceedings 2018 International Ural Conference on Green Energy (UralCon). – 2018. – P. 114 – 121. doi: 10.1109/URALCON.2018.8544285.
[10] Kozinec G. L. Generalization of the Methodology of Studying the Durability of Segmental Gates //Power Technology and Engineering. – 2018. – pp. 1-5.

[11] Makarichev, Y.A., Anufriev, A.S., Zubkov, Y.V., Didenko, N.I. Energy efficiency of the wind power generator (2019) Proceedings of the 2019 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering, ElConRus 2019, art. no. 8657095, pp. 1011-1015, DOI: 10.1109/ElConRus.2019.8657095

[12] Makarichev, Y.A., Anufriev, A.S., Ivannikov, Y.N., Didenko, N., Gazizulina, A. Low - Power wind generator (2018) International Conference on Information Networking, 2018-January, pp. 671-672, DOI: 10.1109/ICOIN.2018.8343203

[13] Ljovkina, A.O., Dusseault, D.L., Zaharova, O.V., Klochkov, Y. Managing innovation resources in accordance with sustainable development ethics: Typological analysis (2019) Resources, 8 (2), art. no. 82, DOI: 10.3390/resources8020082