Торайғыров университетінің хабаршысы
ҒЫЛЫМИ ЖУРНАЛЫ

НАУЧНЫЙ ЖУРНАЛ
Вестник Торайгыров университета

Торайғыров университетінің ХАБАРШЫСЫ

Энергетикалық сериясы

1997 жылдан бастап шығады

ВЕСТНИК Торайгыров университета

Энергетическая серия

Издается с 1997 года

ISSN 2710-3420

№ 4 (2020)

Павлодар

НАУЧНЫЙ ЖУРНАЛ
Вестник Торайгыров университета

Энергетическая серия
выходит 4 раза в год

СВИДЕТЕЛЬСТВО
о постановке на переучет периодического печатного издания, информационного агентства и сетевого издания
№ 14310-Ж
выдано
Министерство информации и общественного развития Республики Казахстан

Тематическая направленность
публикация материалов в области электроэнергетики, электротехнологии, автоматизации, автоматизированных и информационных систем, электромеханики и теплоэнергетики

Подписной индекс – 76136

SRSTI 44.29.29

https://doi.org/10.48081/WDDO6475

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ALGORITHM FOR OPTIMAL CONTROL OF ELECTRIC POWER SYSTEMS

This paper provides information about the current state of the energy system in Kazakhstan. Also, analyzing the technical condition of the structure of the Kazakhstan electro power station, a mathematical model for complex power systems is developed. Algorithms of control with Adams-Bashforth multistep method are developed. There has been conducted the analysis and assessment of significant factors affecting the forecasted dynamics of electric power consumption, built based on multivariate regression and cointegration models.

Keywords: electric power industry, power system, mathematical model.

Introduction

Currently, a series of processes is present that change the most important physical parameters of the power system. Predominantly, it is interconnection of electricity grids, distributed power generation and infrastructure aging. Since the original power systems were designed and built without taking into account these changes, now it is required to ensure their efficiency in new and changing conditions. The primary task, however, remains the same: controlling the power flow from suppliers to consumers and maintaining the stability of the power system. Therefore, one of the most important problems in the power sector is to establish control systems to ensure long-term stability of the system, since the loss of stability may result in economic losses and devastating damage to the power system.

Object of research: electric power systems.

Subject of research: modern methods of electric power systems management.

Aim: Methods of mathematical optimization (algorithmic) have been used for many years for many tasks of planning, operation and control of power systems. The mathematical formulations of real problems are derived under certain assumptions, and even under these assumptions, the solution of large-scale power systems is not simple. On the other hand, there are many uncertainties in the power system problems, because the grid systems are large, complex and geographically widely distributed.

Table 1 – Electric power generation in Kazakhstan, million kWh [1]

The structure of power generation	Electricity production by year					
	2014 y.	2015 y.	2016 y.	2017 y.	2018 y.	2019 y.
Thermal power station	78772,9	74091,8	74702,8	82424,8	86795,1	88625,2
Gas turbine power station	6915,8	7279,5	7407,6	8372,6	9119,3	9367,0
Hydroelectricity	8235,8	9250,3	11605,9	11157,9	10343,0	10412,0
Wind farm, Solar power station	10,6	175	360,2	428,3	539,7	579,9
Total	93935,2	90796,6	94076,5	102383,6	106797,1	108984,1

With the expansion of the power station scale in Kazakhstan, the control problems of its modes are becoming more complex due to the large extent of the electrical network, the uneven distribution of energy resources and productive units across the territory of the country, the structure complexity of generating capacities and schemes of backbone electric grids. The liberalization and restructuration of power industry leads to a radical change in organizational structure of power station which does not coincide with its technological structure and the structure of mode control system.

Presently, in the world, and also in Kazakhstan, new concepts of development of the electric power system are studied and formed in the global and national level, which correspond to the new goals and development trends of the global and national economies, and the new nature of threats to economic, environmental and social character. The technological infrastructure of modern electric power systems is complex and it includes a set of different spatially distributed but related technical elements, which perform in real-time processes of generation, power transmission and distribution and realize the common strategic goal - to provide reliable power energy supply for consumers (table 2). To do this, there are several methods of forecasting energy consumption. Whereas, all of them are based on the information coming from each point of consumption using counters, which are able to transmit information about the instantaneous values of power consumption in data centers. But Kazakhstan does not have such a well-developed infrastructure, which makes it impossible to use foreign techniques.

Table 2 – Expected electrical energy balance of Kazakhstan UPS during years 2020–2026 [1]

Name	Predicts, milliard kWh						
	2020 y.	2021 y.	2022 y.	2023 y.	2024 y.	2025 y.	2026 y.
Electricity consumption	110,1	112,2	114,1	115,4	117,7	120,9	124,1
Electricity production	116,4	119,7	122,4	123,4	129,4	135,0	128,5

On this basis, it is necessary to develop models and methods for optimal control of power systems that fully comply with the requirements of the Kazakhstan.

Issue: Development of a mathematical model of a multi-machine power system.

Materials and methods

Consider a classical mathematical model of multi-machine system. Figure 1 shows the electrical diagram of the system of n machines. All voltages are measured with respect to node 0 (neutral). Nodes 1,2, ... n - bus of corresponding machines or connection point of e.m.f. for transient reactance. Various nodes are connected together and to node 0 by passive elements represented with impedances. Initial values $E_1, E_2, ..., E_n$ are determined from the conditions of pre-emergency mode. Values $E_i\,(i = 1,2,...,n)$ in the transitional regime are assumed to be constant.

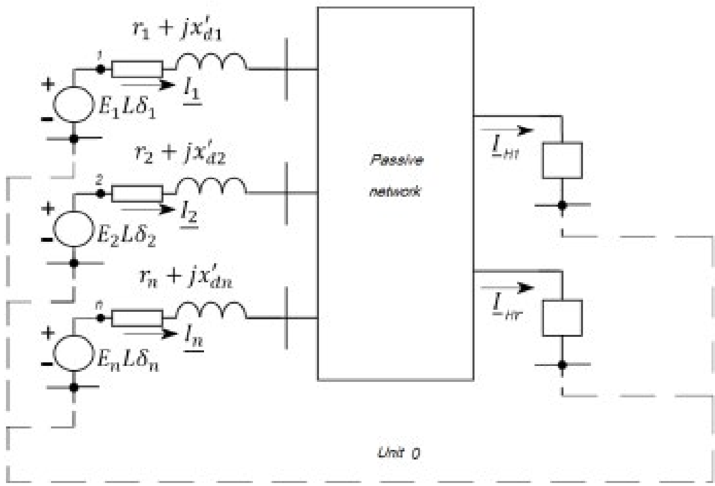

Figure 1 – The classical model of multi-machine system

Matrix of conductivities n-pole from generator terminals is defined by the expression $I = YE$ where, Y has the diagonal elements Y_{ii} and the off-diagonal elements of Y_{ij}. By definition, $Y_{ii} = Y_{ii} < \theta_{ii} = G_{ii} = jB_{ii}$ is equal to its own node conduction i, but $Y_{ij} = Y_{ij} < \theta_{ij} = G_{ij} = jB_{ij}$ is equal to the mutual conductance between nodes i and j with a minus sign.

Power, flowing in the network in node i and equivalent to electric power of i-th machine, is determined by the expression

$$P_i = \operatorname{Re} E_i I_i^*$$

$$P_{э,i} = E_i^2 G_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{n} E_i E_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) =$$

$$E_i^2 G_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{n} E_i E_j Y_{ij} \left[B_{ij} \sin(\delta_i - \delta_j) + G_{ij} \cos(\delta_i - \delta_j) \right]$$

$$i = 1, \ldots, n$$

The equations of motion are given in the following form [4]:

$$\frac{\tau_{J,i}}{\omega_{ном}} \frac{d\omega_i}{dt} + D_i \omega_i = P_{MX,i} - \left[E_i^2 G_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{n} E_i E_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j) \right]$$

$$\frac{d\delta_i}{dt} = \omega_i - \omega_{ном}, i = 1, 2, \ldots, n$$

It should be noted that at the time preceding the emergency perturbation (t = 0),

$$P_{MX,i,0} = P_{э,i,0},$$

$$P_{MX,i,0} = E_i^2 G_{ii,0} + \sum_{\substack{j=1 \\ j \neq i}}^{n} E_i E_j Y_{ij,0} \cos(\theta_{ij,0} - \delta_{i,0} + \delta_{j,0}).$$

In some standard assumptions dynamics of *n* interconnected generators through a communication network can be described in the classical model with dynamics of the flow decay [5]. The network has been reduced to the representation of the internal bus, assuming that the load impedances are constant and they take into account the presence of the transfer conductance. A dynamic model of the *i*-th machine is represented by the classical model of the third order

$$\dot{\delta}_i = \omega_i - \omega_s$$
$$\dot{\omega}_i = \frac{\omega_s}{2H_i}\left(P_{m_i} - D_i(\omega_i - \omega_s) - E'_{q_i} I_{q_i}\right)$$
$$\dot{E}'_{q_i} = \frac{1}{T'_{d_i}}\left(E_{f_i} - E'_{q_i} - \left(X_{d_i} - X'_{d_d}\right) I_{d_i}\right)$$

where,

$$I_{q_i} = G_{ii} E'_{q_i} + \sum_{j=1, j\neq i}^{n} E'_{q_j} \left\{G_{ij}\cos\left(\delta_j - \delta_i\right) - B_{ij}\sin\left(\delta_j - \delta_i\right)\right\}$$
$$I_{d_i} = -B_{ii} E'_{q_i} - \sum_{j=1, j\neq i}^{n} E'_{q_j} \left\{G_{ij}\sin\left(\delta_j - \delta_i\right) + B_{ij}\cos\left(\delta_j - \delta_i\right)\right\}$$

$I_{q_i}(t)$ and $I_{d_i}(t)$ are currents in *d–q* reference frame of *i*-th generator, $E_{q_i}(t)$ – transient e.m.f. in the quadrature axis, $E_{f_i}(t)$ - equivalent e.m.f. in the excitation coil, X_{d_i} and X'_{d_d} - reactance of straight axis and transient reactance of straight axis, respectively; P_{m_i} – mechanical input power, received by the constant, D_i – damping coefficient; H_i – represents the inertia constant in seconds; T'_{d_i} – time-constant of short circuit on the straight axis in seconds; $\delta_i(t)$ – rotor angle in radians; $\omega_i(t)$ represents the relative speed, $\omega_s = 2\pi f_s$ – synchronous speed of the machine, in rad / s; G_{ij} and B_{ij} represent the *i*-th element of row and *j*-th element of column for nodal conduction matrix and nodal susceptibility matrix, respectively, which are symmetrical in the internal nodes after eliminating all physical bus. Consider $E_{f_i}(t)$ as an input system of signal.

This flowchart starts with a source of fuel, which is then burned to provide steam. This steam rotates the turbine, which drives a generator. Generators, installed in power plants, are mainly synchronous machines. Synchronous machine converts the mechanical power provided by turbine into electric power that is then distributed to the network with loads. In the loads power is consumed, and it closes the circuit block of power allocation. All system components are controlled by an energy control center for reliable operation.

Mathematical models for the problems of stability, optimal control and stabilization of electric power systems are developed to describe the operation of electric power systems.

The following shows a general mathematical model of the complex electric power systems, which is described by a set of nonlinear differential equation:

$$\begin{aligned} &\frac{d\delta_i}{dt} = S_i, \\ &\frac{dS_i}{dt} = w_i - D_i S_i - f_i(\delta_i) - \psi_i(\delta_{i^*}), \quad w_i = C_i^* x_i, \\ &\frac{dx_i}{dt} = A_i x_i + q_i S_i + b_i u_i, \quad i = \overline{1,l}, \end{aligned} \tag{1}$$

where the function

$$\psi_i(\delta_{i^*}) = \sum_{\substack{k=1,\\ k\neq i}}^{l} P_{ik}(\delta_{ik}), \qquad \delta_{ik} = \delta_i - \delta_k \tag{2}$$

A function $\psi_i(\delta_{i^*})$ describes the interaction between generators and expands in the following way:

$$\psi_i(\delta_{i^*}) = \sum_{\substack{j=1,\\ j\neq i}}^{l} \frac{1}{T_i}\left[P_{ij}\sin(\delta_{ji0} + \delta_{ji} - P_{ij}\sin\delta_{ij0})\right] \tag{3}$$

A periodic continuously differentiable function $f_i(\delta_i)$ is determined using the following formula:

$$f_i(\delta_i) = \frac{1}{T_i}[P_i \sin(\delta_{i0} + \delta_i) - P_i \sin\delta_i] \quad i = \overline{1,l}, \tag{4}$$

In the system (1), δ_i – rotation angle of the rotor of *i*-th synchronous generator with respect to a rotational axis; S_i – slip of *i*-th generator; $D_i > 0$ – damping coefficient.

To ensure reliable operation of electric power systems for system (1), it is required to define the area, where the phase trajectories tend to a particular stable equilibrium position. Investigation of stability «in the large» of the system (1) is done in the band $G_{0i} = \{(\delta_i, S_i, x_i) | \delta_{-1i} < \delta_i < \delta_{0i}, \quad S_i \in R_i^1, \quad x_i \in R_i^{n_i}\}$ using the second method of Lyapunov.

Consider an insulated subsystem of the second order

$$\frac{d\delta_i}{dt} = S_i, \quad \frac{dS_i}{dt} = -D_i S_i - f_i(\delta_i) \tag{5}$$

for which M_i stationary set in the phase plane $R_i^2(\delta_i, S_i)$ consists of alternating points of stable and unstable equilibrium. To estimate the attraction regions of stable equilibrium positions using Lyapunov second method, it is possible to study the stability «in the large» of only one point of stable equilibrium (e.g., the origin $O(0,0)$), because of the periodicity on the angular coordinate of δ_i phase diagram of the system on the plane $R_i^2(\delta_i, S_i)$.

Consider the function $v_{0i}(\delta_i, S_i)$ defined in the band $\overline{G_{0i}}$ in the following way:

$$v_{0i}(\delta_i, S_i) = \frac{1}{2}(S_i + \alpha_i D_i \delta_i)^2 + \frac{1}{2}\alpha_i D_i^2 (1 - \alpha_i) \cdot \delta_i^2 + F_i(\delta_i) + \\ + 2D_i\sqrt{\alpha_i(1 + \alpha_i)}\widetilde{F}_i(\delta_i) = \frac{1}{2}(S_i + \alpha_i D_i \delta_i)^2 + \int_0^{\delta_i} N_i(\delta_i) d\delta_i, \tag{6}$$

where,

$$\alpha_i = const(0 < \alpha_i < 1), F_i(\delta_i) = \int_0^{\delta_i} f_i(\delta_i) d\delta_i \,,$$

$$\widetilde{F}_i(\delta_i) = \int_0^{\delta_i} \sqrt{\delta_i f_i(\delta_i)} d\delta_i \,, N_i(\delta_i)$$

$$= \alpha_i D_i^2 (1-\alpha_i)\delta_i + f_i(\delta_i) + 2D_i\sqrt{\alpha_i(1-\alpha_i)}\sqrt{\delta_i f_i(\delta_i)}.$$

Functions $F_i(\delta_i).\tilde{F}_i(\delta_i)$ are continuous in the band $\overline{G_{0\iota}}$.

A mathematical model of optimal control problem for electric power system is described in the following way:

$$\frac{d\delta_i}{dt} = S_i,$$
$$H_i \frac{dS_i}{dt} = -D_i S_i - f_i(\delta_i) - N_i(\delta_i) + v_i, \qquad (7)$$
$$\delta = (\delta_1, ..., \delta_l), \qquad S = (S_1, ..., S_l),$$

For full description of control problem, a system of equations (7) is supplemented by initial conditions

$$\delta_i(0) = \delta_{i0}, \quad S_i(0) = S_{i0}, \quad i = 1,...,l. \qquad (8)$$

Theorem 1. In order to obtain the optimum control $v_i^0(S_i, t) = -\left[w_{v_i}\right]^{-1} \exp\{-\gamma_i t\} S_i, \quad i = 1,...,l,$ and the corresponding solutions $\{\delta^0(t), S^0(t)\}$ for the system (7) – (8), it is necessary and sufficient to

$$\Lambda(\delta(T), S(T)) = K(\delta(T), S(T)),$$
$$w_{S_i}(t) = 2D_i \exp\{-\gamma_i t\} + \left[w_{v_i}\right]^{-1} \exp\{-2\gamma_i t\} > 0, \qquad i = 1,...,l,$$

where,

$$K(\delta, S) = 0.5\sum_{i=1}^{l}\left[H_i S_i^2 + \int_0^{\delta_i} f_i(\delta_i)d\delta_i\right] + \sum_{\substack{i=1,\\ \delta_j=0,\\ j>i}}^{l}\int_0^{\delta_i} N_i(\delta_1,...,\delta_{i-1},\delta_{i+1},...,\delta_l)d\xi_i \quad (9)$$

Bellman-Krotov function, and

$$J(v^0) = \min_v J(v) = K(\delta^0, S^0)$$

A mathematical model for motion stabilization of the power system for two synchronously running generators is developed and it is described by the following system of differential equations:

$$\begin{aligned}
\frac{d\delta_1}{dt} &= S_1, \\
\frac{d\delta_2}{dt} &= S_2, \\
\frac{dS_1}{dt} &= c_1x_1 - K_1S_1 - f_1(\delta_1) - P_{12}, \\
\frac{dS_2}{dt} &= c_2x_2 - K_2S_2 - f_2(\delta_2) - P_{12}, \\
\frac{dx_1}{dt} &= A_1x_1 + u_1, \\
\frac{dx_2}{dt} &= A_2x_2 + u_2,
\end{aligned} \qquad (10)$$

where, first 4 equations describe the operation of the system, and last 2 equations describe the state of the regulator. Also x_1, x_2 – phase variables; c_1, c_2 – scalars; u_1, u_2 – controls; δ – rotor rotation angle; S – slip of generator;

$$f_1 = \Gamma_0(\sin(\delta_1 + \theta_0) - S_1);$$
$$f_2 = \Gamma_0(\sin(\delta_2 + \theta_0) - S_2);$$

$$P_{12} = \Gamma_1\left((\delta_1 + \delta_2 + 2\theta_0) - S_2\right).$$

The following algorithms are employed for the numerical implementation for the problems of stability, optimality and stabilization of electric power systems. These algorithms provide more accurate solutions to the studied problems. Consider these algorithms in the example of the stabilization problem for electric power systems with two synchronous generators.

1-algorithm. Adams–Bashforth multistep method.

1-step. The initial values δ, S, x at $t = 0$ and c, K, P, A are known.

2-step. To find δ, S, x at points 1,2,3,4, use Runge-Kutta method of 4th order.

$$\delta_{i+1} = \delta_i + \frac{1}{6}\left(m_1 + 2m_2 + 2m_3 + m_4\right)$$

$$m_1 = \Delta t(S_i)$$

$$m_2 = \Delta t\left(S_i + \frac{1}{2}m_1\right)$$

$$m_3 = \Delta t\left(S_i + \frac{1}{2}m_2\right)$$

$$m_4 = \Delta t\left(S_i + \frac{1}{2}m_3\right)$$

$$S_{i+1} = S_i + \frac{1}{6}\left(m_1 + 2m_2 + 2m_3 + m_4\right)$$

$$m_1 = \Delta t((cx_i - KS_i - f_i(\delta_i) - P_{12}))$$

$$m_2 = \Delta t\left((c(x_i + \frac{1}{2}m_1) - K(S_i + \frac{1}{2}m_1) - f_i(\delta_i + \frac{1}{2}m_1) - P_{12})\right)$$

$$m_3 = \Delta t\left((c(x_i + \frac{1}{2}m_2) - K(S_i + \frac{1}{2}m_2) - f_i(\delta_i + \frac{1}{2}m_2) - P_{12})\right)$$

$$m_4 = \Delta t\left((c(x_i + \frac{1}{2}m_3) - K(S_i + \frac{1}{2}m_3) - f_i(\delta_i + \frac{1}{2}m_3) - P_{12})\right)$$

$$x_{i+1} = x_i + \frac{1}{6}\left(m_1 + 2m_2 + 2m_3 + m_4\right)$$

$$m_1 = \Delta t((Ax_i + u)$$

$$m_2 = \Delta t\left(A(x_i + \frac{1}{2}m_1) + u \right)$$

$$m_3 = \Delta t\left(A(x_i + \frac{1}{2}m_2) + u \right)$$

$$m_4 = \Delta t\left(A(x_i + \frac{1}{2}m_3) + u \right)$$

3-step. To find δ, S, x starting from $i = 4$ and up to $i = n$, use Adams–Bashforth multistep method. Coefficients for Adams–Bashforth multistep method [6] are shown in [6].

$$\delta_{i+1} = \delta_i + \Delta t\left(\frac{1901}{720} S_i - \frac{1387}{360} S_{i-1} + \frac{109}{30} S_{i-2} - \frac{637}{360} S_{i-3} + \frac{251}{720} S_{i-4} \right)$$

$$S_{i+1} = S_i + \Delta t\left(\begin{aligned} &\frac{1901}{720}(cx_i - KS_i - f_i(\delta_i) - P_{12}) - \frac{1387}{360}(cx_{i-1} - KS_{i-1} - f_{i-1}(\delta_{i-1}) - P_{12}) + \\ &+ \frac{109}{30}(cx_{i-2} - KS_{i-2} - f_{i-2}(\delta_{i-2}) - P_{12}) - \frac{637}{360}(cx_{i-3} - KS_{i-3} - f_{i-3}(\delta_{i-3}) - P_{12}) + \\ &+ \frac{251}{720}(cx_{i-4} - KS_{i-4} - f_{i-4}(\delta_{i-4}) - P_{12}); \end{aligned} \right)$$

$$x_{i+1} = x_i + \Delta t\left(\frac{1901}{720}(Ax_i + u) - \frac{1387}{360}(Ax_{i-1} + u) + \frac{109}{30}(Ax_{i-2} + u) - \frac{637}{360}(Ax_{i-3} + u) + \frac{251}{720}(Ax_{i-4} + u); \right)$$

2-algorithm. Adams–Moulton multistep method.

1-step. The initial values δ, S, x at $t = 0$ and c, K, P, A are known.

2-step. To find δ, S, x at points 1,2,3,4, use Euler method.

$$\delta_{i+1} = \delta_i + \Delta t(S_i)$$

$$S_{i+1} = S_i + \Delta t(cx_i - KS_i - f_i(\delta_i) - P_{12})$$

$$x_{i+1} = x_i + \Delta t(Ax_i + u)$$

3-step. To find δ, S, x starting from i = 4 and up to i = n, use Adams–Moulton multistep method. Coefficients for Adams–Moulton multistep method [5] are shown in the [5].

$$\delta_{i+1} = \delta_i + \Delta t\left(\frac{251}{720}S_i + \frac{323}{360}S_{i-1} - \frac{11}{30}S_{i-2} + \frac{53}{360}S_{i-3} - \frac{19}{720}S_{i-4}\right)$$

$$S_{i+1} = S_i + \Delta t\left(\begin{array}{l}\frac{251}{720}(cx_i - KS_i - f_i(\delta_i) - P_{12}) + \frac{323}{360}(cx_{i-1} - KS_{i-1} - f_{i-1}(\delta_{i-1}) - P_{12}) + \\ -\frac{11}{30}(cx_{i-2} - KS_{i-2} - f_{i-2}(\delta_{i-2}) - P_{12}) + \frac{53}{360}(cx_{i-3} - KS_{i-3} - f_{i-3}(\delta_{i-3}) - P_{12}) + \\ -\frac{19}{720}(cx_{i-4} - KS_{i-4} - f_{i-4}(\delta_{i-4}) - P_{12});\end{array}\right)$$

$$x_{i+1} = x_i + \Delta t\left(\frac{251}{720}(Ax_i + u) + \frac{323}{360}(Ax_{i-1} + u) - \frac{11}{30}(Ax_{i-2} + u) + \frac{53}{360}(Ax_{i-3} + u) - \frac{19}{720}(Ax_{i-4} + u);\right)$$

Conclusion

The modeling process of technical, biological, economic and other processes requires a preliminary study of the data structure, the stationarity nature, the presence of anomalous observations. A special feature of energy consumption indicators is divergent trends of the seasonal and cyclical fluctuations, structural breaks, which cause their unsteadiness and causes autocorrelation, heteroscedasticity and the lack of normal distribution of residuals models constructed from these data. This makes it impossible to use classical statistical tools and actualizes the search for methods and models that reduce the negative impact of aforementioned problems to obtain better mathematical models and reliable forecasts.

This paper describes the process of optimal control of complex electric power systems. We found a continuous Bellman function that has continuous partial derivatives everywhere over all its arguments. The solution of the problem is obtained. The implicit Adams method was used to solve this problem.

The article was prepared within the framework of the project of grant financing AR05132020 “Development of an intelligent information complex and mathematical models for modern electric power systems” of the Institute of information and computing systems.

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Material received on 11.12.20.

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Электр энергетикалық жүйелерді оңтайлы басқару алгоритмі

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Материал баспаға 11.12.20 түсті.

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Материал поступил в редакцию 11.12.20.

Бұл мақалада Қазақстанның энергия жүйесінің ағымдағы жағдайы туралы деректер ұсынылған. Сондай-ақ, қазақстандық ЭЭК құрылымының техникалық жай-күйін талдай отырып, күрделі электр энергетикалық жүйелер үшін математикалық модель әзірленді. Адамс-Башфорттың көп сатылы әдісін қолдана отырып, басқару алгоритмдері жасалды. Көп факторлы регрессиялық және коинтеграциялық модельдерді құру электр энергиясын тұтыну көлемінің болжамды динамикасына әсер ететін маңызды факторларға талдау және бағалау жүргізілді.

Кілтті сөздер: Электр энергетикасы, энергия жүйесі, математикалық модель

В данной статье предоставлены данные о текущем состоянии энергосистемы Казахстана. Также, анализируя техническое состояние структуры Казахстанского ЭЭС, разработана математическая модель для сложных электроэнергетических систем. Разработаны алгоритмы управляемости с использованием многошагового метода Адамаса-Башфорда. Проведен анализ и оценка значимых факторов, влияющих на прогнозную динамику объемов потребления электроэнергии построение многофакторных регрессионных и коинтеграционных моделей.

Ключевые слов: электроэнергетика, энергосистема, математическая модель

Теруге 11.12.2020 ж. жіберілді. Басуға 17.12.2020 ж. қол қойылды.
Электрондық баспа
3,99 Mb RAM
Шартты баспа табағы 26,6. Таралымы 300 дана. Бағасы келісім бойынша.
Компьютерде беттеген: А. К. Шукурбаева
Корректор: А. Р. Омарова
Тапсырыс № 3715

Сдано в набор 11.12.2020 г. Подписано в печать 17.12.2020 г.
Электронное издание
3,99 Mb RAM
Усл. печ. л. 26,6. Тираж 300 экз. Цена договорная.
Компьютерная верстка: А. К. Шукурбаева
Корректор: А. Р. Омарова
Заказ № 3715

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