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Optimal amount of information determination for power system steady state estimation

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Abstract

On the basis of literature sources analysis, the paper provides the rationale for the necessity of considering the limited digital devices capabilities when designing closed digital control systems for the complex electrical power grids. The problem of design is decomposed into two subproblems: design of current state observation vector digital transmission systems and current controlled process state estimation; design of digital systems for optimal control vector calculation, transmission and control actions realization.

The paper presents consideration of the former problem, i.e. design of current state observation vector digital transmission systems and current controlled process state estimation: the mathematical model of digital system of information transmission and state estimation considering speed and reliability of technical means of implementation is presented; the functional structure of simulation complex is developed; the paper provides the formulation of the problem of estimating the optimal amount of information about the control object state, resulting in a solution of computational experiments simulating complex.

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Keywords: Power systems state estimation; Optimal amount of information; Digital systems; Automation of control processes; Information gathering; Mathematical modeling and simulation; Observation vector

1. Introduction

With the advent of modern digital means of transmission and processing of information, methods of technical cybernetics and mathematical programming [1–6], and on the basis of the achievements of theoretical and applied

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research in the field of digitalization in the electric power industry [7–14], it became possible to fully automate the complex power grid control systems by creation and implementation of closed digital control systems.

The main object of the article is to study the problem of data transmission and coding. The results of the paper could be utilized for the task of dynamic state estimation. The dynamic state estimation was initially mentioned decades ago, but research began to find its relevance only in recent years due to the widespread implementation of modern measuring instruments, such as phasor measurements. As a conclusion, the problem of reliable and fast data transmission both from measuring devices to data processing facilities and during data exchange between processing servers has become urgent, which, in turn, leads to the problem of optimal data coding.

The problem of designing closed digital control systems for the power grid complex can be divided into two subproblems on the basis of the principle of state assessment and control decomposition [15]:

- design of digital systems for the transmission of the observation vector and optimal estimation of the controlled process current state, where the components of the observation vector are the measurements of the current and voltage sensors at the control points;
- design of digital systems for calculating the vector of optimal control, transmission and implementation of it at the facility, where the components of this vector, depending on the particular power grid complex under consideration, are the values of the transformers transformation ratios, reactors inductances, etc.

Features of the power grid complex, as a control object, are: a large number of elements distributed over a large territory and interconnected with each other by power lines in a complex way, a large number of points for monitoring the state of the system and points for controlling the processes taking place in this system [7–14].

All methods of the optimal control systems theory used in practice are developed under the following idealized assumptions [1–6,15,16]:

- it is assumed that the technical means of the control process automation are absolutely reliable. Rejection of this assumption led to the emergence of works on the synthesis of control systems, considering the reliability of elements of technical means, in some of which the higher efficiency of systems with a partially decentralized hierarchical structure is strictly proved;
- it is assumed that the properties of the object and the disturbances are strictly consistent with those adopted in the synthesis of optimal algorithms. The rejection of this assumption led to the emergence of works on the synthesis of stiff systems, systems with robust properties, in some of which engineering methods of lowering the order of object models for synthesizing a control law, as well as calculating estimates of state variables are rigorously substantiated;
- infinitely high speed of data collection, processing and issuance of control actions is assumed, i.e. it is assumed that the control process proceeds instantly. Rejection of this assumption led to the need to introduce a new concept, such as system speed in the form of a pair of values (τ, ν) in the problem of designing digital control systems, where τ is the delay brought by digital means into the control loop; ν — interval of the controlled object state monitoring and control actions realization. These time parameters are related to each other in the form of inequality $\nu \geq \tau$.

Therefore, it follows: for the developed control system of complex technological processes to be physically realizable, it is necessary to reject the above idealized assumptions at the design stage.

One of the main characteristics of digital control systems for complex power systems, from the point of view of control quality, is the system speed, which is determined by the values of the delays τ in the devices for collecting information, controlling, transmitting and implementing control actions and the time periodicity for measuring and issuing control actions. The system speed depends on the amount of digital information about the state of the controlled process and control actions, on the computational complexity of information processing, estimation and control algorithms, on the adopted structure of the control process organization and on the speed of the technical means used. With an increase in the number of control points and binary digits of digital sensors, the amount of information about the current state of the controlled process increases, which has a positive effect on the quality of the closed control system functioning. However, an increase in the amount of transmitted digital information leads to an increase in transmission time, which negatively affects the quality of operation. This implies the problem of assessing the optimal amount of information about the state of the power grid.

This paper describes the problem of estimating the optimal amount of information about the current state of the power grid, the solution of which is carried out by means of a simulating complex computational experiment.

2. Simulating complex description

2.1. Mathematical model of the control object

The mathematical model of the control object can be written as follows:

$$\frac{dx_0(t)}{dt} = f(x_0(t),\ u(t),\ \upsilon(t))$$

where $x_o(t) - (n \times 1)$ is the vector of control object state; $u(t) - (q_u \times 1)$ is the control action vector; $\upsilon(t) - (d \times 1)$ is the disturbance vector.

Building a control object model is a laborious task due to the large dimension of the real power systems. Therefore, in the modeling complex there is a subsystem of control object model formation. In the process of modeling, it is solved by the fourth order Runge–Kutta method.

2.2. Mathematical model of the information gathering process (IGP)

The mathematical model consists of the digital information transfer process equation and the condition of this process physical feasibility on technical means with limited speed and reliability (when constructing the IGP model, the basic fundamental concepts and formulas from the theory of error-correcting coding and transmission of discrete information were used).

• digital information transfer process equation.

$$y_0(t) = C_0 x_0(t), \qquad y_0 = (y_{01}, \ldots,\ y_{0j}, \ldots,\ y_{0q_y})^T; \tag{1}$$

$$y_{\tau j}(\theta_s) = y_{0j}(\theta_s - \tau_{yj}(\theta_s)), \quad j = 1, 2, \ldots,\ q_y; \tag{2}$$

$$y_{kj}(\theta_s) = K(y_{\tau j}(\theta_s),\ \varepsilon_{yj}); \tag{3}$$

$$\sum_{a=1}^{k_y} 2^{a-1} \cdot \beta_{j,a-1}(\theta_s) = \left[\sum_{a=1}^{k_y} 1 \cdot 2^{a-1}/(y_{\max j} - y_{\min j})\right] \cdot (y_{kj}(\theta_s) - y_{\min j}), \tag{4}$$

$$y_{ej}(\theta_s) = \frac{\left[\sum_{a=1}^{k_y} 2^{a-1} \cdot (\beta_{j,a-1}(\theta_s) \oplus e^y_{j,a-1}(\theta_s))\right](y_{\max j} - y_{\min j})}{\sum_{a=1}^{k_y} 1 \cdot 2^{a-1}} + y_{\min j}; \tag{5}$$

$$y_j(\theta_s) = \Lambda^y_j(\theta_s) y_{ej}(\theta_s) + (1 - \Lambda^y_j(\theta_s)) \cdot \widehat{y}_j(\theta_s \,|\theta_{\,s-1}); \tag{6}$$

$$\theta_{s+1} = \theta_s + \nu(\theta_s), \qquad s = 0, 1, 2, \ldots; \qquad \theta_0 = T_0; \qquad \Lambda_j(\theta_s) \in \{0, 1\}; \tag{7}$$

where $y_0 - (q_y \times 1)$ is the observation vector of the x_0 state; q_y — dimension of the observation vector; $C_0 - (q_y \times 1)$ observation matrix; τ_{yj} is the lag of jth element y_{0j} of the observation vector y_0; $K(.)$ — operator characterizing the process of quantizing the value of each jth element of the observation vector y_τ by level; y_k — level-quantized observation vector; $\{\beta_{j,a} : a = 0, \ldots, k_y - 1\}$ – k_y bit binary code transmitted over an equivalent communication channel I_{eq}; $\left\{e^y_{j,a} : a = 0, \ldots,\ k_y - 1\right\}$– equivalent channel error code combination I_{eq}; $[y_{\min j},\ y_{\max j}]$ — change interval of each jth observation vector element value; $y - (q_y \times 1)$ vector of outputs of the information collection system; $\widehat{y}$ — predicted y vector value; ε_y — level quantization step; $\nu(\theta_s)$ — time quantization step; θ_s — discrete time moments with discrete $\nu(\theta_s)$.

• condition of physical feasibility of the process of transmitting digital information on technical means with limited speed and reliability

$$\tau_{yj}(\theta_s) = \tau_{yj}(t_y(\theta_s),\ q_y), \qquad t_y(\theta_s) = \left\{t_{yj}(\theta_s) : j = 1, \ldots,\ q_y\right\}; \tag{8}$$

$$t_{yj}(\theta_s) = t_{yj}(n_y,\ k_y,\ S_{yj}(\theta_s)); \tag{9}$$

$$\nu(\theta_s) \geq \tau_y(\theta_s) = \max \tau_{yj}(\theta_s) \colon j = 1, 2, \ldots, q_y; \tag{10}$$

$$\varepsilon_{yj} = (y_{\max j} - y_{\min j})/(N_y - 1); \tag{11}$$

$$k_y = \log 2N_y; \tag{12}$$

$$S_{yj}(\theta_s) = \begin{cases} 1, & \textit{when error correction decoding is adopted}, \\ S'_{yj}(\theta_s), & \textit{when error detection decoding is adopted}; \end{cases} \tag{13}$$

$$e^{y}_{j,a}(\theta_s) = \begin{cases} 1 & \textit{with the probability } \widetilde{P}_y = 1 - P_y^{1/k_y}, \\ 0 & \textit{with the probability } P_y^{1/k_y}; \end{cases} \tag{14}$$

$$a = 0, 1, \ldots, \; k_y - 1;$$

$$P_y = \begin{cases} 1 - \dfrac{P_{ue}}{P_{we} + P_{ue}}, \; \textit{when error correction decoding is adopted}, \\ \displaystyle\sum_{m=0}^{r_y} C^m_{n_y} P^m (1-P)^{n_y - m}, \; \textit{when error detection decoding is adopted}; \end{cases} \tag{15}$$

$$2 \cdot r_y + 1 \leq d_{\min};$$

$$P_{we} = (1-P)^{n_y}; \quad P_{ue} = \sum_{m=d_{\min}}^{n_y} C^m_{n_y} \cdot P^m (1-P)^{n_y - m}; \tag{16}$$

$$\Lambda^y_j(\theta_s) = \begin{cases} 0, \; \textit{if } \; t_{yj}(\theta_s) > \bar{t}_{yj}(\overline{S}_{yj}) \textit{ or } \alpha^y_j(\theta_s) = 0, \\ 1, \; \textit{otherwise}; \end{cases} \tag{17}$$

$$S'_{yj}(\theta_s) = \begin{cases} 1 & \textit{with probability} \;\; P(1) = P_{we} + P_{ue}, \\ 2 & \textit{with probability} \;\; P(2) = P_{de}(P_{we} + P_{ue}), \\ 3 & \textit{with probability} \;\; P(3) = P^2_{de}(P_{we} + P_{ue}), \\ \vdots & \qquad \vdots \qquad\qquad \vdots \\ \overline{S}_{yj} & \textit{with probability} \; P(\overline{S}_{yj}) = P_{de}^{\overline{S}_{yj}-1}(P_{we} + P_{ue}), \\ \vdots & \qquad \vdots \qquad\qquad \vdots \\ \infty & \textit{with probability} \;\; P(\infty) = 0; \end{cases} \tag{18}$$

$$\alpha^y_j(\theta_s) = \begin{cases} 0, & \textit{in the case of failure of jth measuring device} \\ & \textit{and/or jth communication channel} \\ 1, & \textit{otherwise}; \end{cases} \tag{19}$$

$$P_{de} + P_{we} + P_{ue} = 1, \tag{20}$$

$$\bar{t}_{yj} = t_{yj}(n_y, \, k_y, \, \overline{S}_{yj}), \tag{21}$$

where the form of the delay function $\tau_{yj}(t_y(\theta_s), q_y)$ depends on the adopted organization structure of the processes of measurement and transmission of the observation vector y_0 elements values (vector elements y_{0j} can be transmitted in the following ways: sequential measurement and transmission; simultaneous measurement of all vector elements values and sequential transmission; parallel method of measurement and transmission; combined method); $t_{yj}(n_y, k_y, S_{yj}(\theta_s)$ — transmission time of each jth element of the observation vector y_0; S_{yj} — code combination retransmissions number of the code $(n_y, k_y,)$; n_y — codeword length of the $(n_y, k_y,)$ code; k_y — information symbols of $(n_y, k_y,)$ code; N_y — the quantization level points number of each observation vector element; P — the probability of binary symbols distortion in the I_p communication channel; P_{we} — probability of receiving a $(n_y, k_y,)$ code codeword without errors; P_{ue} — probability of receiving a $(n_y, k_y,)$ code codeword with an undetected error; P_{de} — probability of receiving a $(n_y, k_y,)$ code codeword with detected error; $d_{\min}$– minimum $(n_y, k_y,)$ code distance; r_y — code $(n_y, k_y,)$ packing radius.

2.3. Object state estimation process mathematical model

The mathematical model consists of the digital information transfer process equation and the condition of this process physical

• state estimation process equation:

$$\widehat{x}_0(\theta_s) = G_{\widehat{x}}(z(\theta_s)),\, z(\theta_s) = G_{z,s}(z(\theta_{s-1}),\;\; u(\theta_{s-1}),\;\; y(\theta_{s-1} - \tau_{\widehat{x}})),\, \widehat{y}(\theta_s\,|\theta_{s-1}) = G_{\widehat{y},s}(z(\theta_{s-1})), \tag{22}$$

where $\widehat{x}_0 - (n \times 1)$ estimation of the x_0 control object vector; $z - (n_z \times 1)$ observer state vector; $G_{\widehat{x}}(.)$ — conversion operator $z(\theta_s)$ in $\widehat{x}_0(\theta_s)$; $G_{z,s}(.)$ — observer algorithm; $G_{\widehat{y},s}(.)$ — predictive value $\widehat{y}(\theta_s\,|\theta_{s-1})$ of state vector $y(\theta_s)$ estimation algorithm. The actual $\{G_{\widehat{x}},\;\; G_{z,s},\;\; G_{\widehat{y},s}\}$ form depends on the estimation method.

• condition of physical realizability of the estimation process on technical means with limited speed and reliability

$$\nu(\theta_s) \geq \tau_{\widehat{x}},\, \tau_{\widehat{x}} = \tau_{\widehat{x}}(W_{\widehat{x}}),\;\;\; W_{\widehat{x}} = W_{\widehat{x}}(n_z,\; n,\; q_y,\; q_u), \tag{23}$$

where $\tau_{\widehat{x}}$ — state estimator lag; $W_{\widehat{x}}$ — computational complexity of the state estimation algorithm $\{G_{\widehat{x}},\;\; G_{z,s},\;\; G_{\widehat{y},s}\}$.

The computational complexity $W_{\widehat{x}}$ is determined by the number of processor operations, the number of calls to external memory, and the amount of information transferred per call. Therefore, in the general case, $W_{\widehat{x}}$ is a vector quantity. The forms of $\tau_{\widehat{x}}(.)$, $W_{\widehat{x}}(.)$ functions from (23) depend on the organization structure of computational process in the state estimator.

2.4. The functional structure of the simulation complex (Fig. 1) contains the following blocks

Block 1 — power grid elements graphical input; if necessary, the block program requests the input of the parameters of the entered circuit elements.

Block 2 — based on the information of Block 1, a database is formed on the topological structure and parameters of the power grid elements.

Block 3 — the topological structure of the power grid is analyzed and a mathematical model is formed on the basis of it.

Block 4 — simulation of the process in the control object is performed.

Block 5 — initial data of the IGP model.

Block 6 — control object state observation Eq. (1). The structure of $(q_y \times n)$ observation matrix C_0 reflects the location of power system state measurement sensors, where q_y — sensors number, n — system state vector dimension. Observation vector $y_0(t)$ from Block *6* enters the Block *7*.

Block 7 — simulation of the time quantization process with a step $\nu(\theta_s)$ (7) and lag process (2) for the value of each jth element of the observation vector y_0 for time $\tau_{yj}(\theta_s)$, $j = 1, 2, \ldots, q_y$. Observation vector $y_\tau(\theta_s)$ from this block enters the Block *8*.

Block 8 — simulation of the process of level quantizing of each jth element $y_{\tau j}(\theta_s)$ value of the observation vector $y_\tau(\theta_s)$ with the ε_y step (3). The level-quantized observation vector $y_k(\theta_s)$ enters the Block *9*.

Block 9 — simulation of the distortion process of the value of the jth element $y_{kj}(\theta_s)$ of the observation vector $y_k(\theta_s)$ in the communication channel. Based on (4), the value $y_{kj}(\theta_s)$ is converted into a k_y bit binary code combination $\{\beta_{j,a} : a = 0, 1, \ldots, k_y - 1\}$ (decimal to binary conversion), where $\beta_{j,a} \in \{0,1\}$, $a = 0, 1, \ldots, k_y - 1$, $j = 1, 2, \ldots, q_y$. The codeword $\{\beta_{j,a} : a = 0, 1, \ldots, k_y - 1\}$ transmitted over the equivalent communication channel I_{eq} is added to the error codeword $\{e^y_{j,a} : a = 0, 1, \ldots, k_y - 1\}$ bitwise modulo 2, and in the general case, another, distorted codeword $\{\beta_{j,a} \oplus e^y_{j,a} : a = 0, 1, \ldots, k_y - 1\}$ is received. Based on (5), a conversion is made from the binary number system to decimal. In bits β_{ja} of the transmitted (through the channels I_{eq}) codeword corresponding to $e^y_{j,a} = 1$, errors occur. The probability that $e^y_{j,a} = 1$, is equal to the error probability of binary symbols in an equivalent communication channel I_{eq} (see (14)). The distorted observation vector $y_e(\theta_s)$ enters Block 10.

Block 10 — simulation of the information transmission process under conditions of failures (6) of measuring devices and communication channels and failures due to exceeding $t_{yj}(\theta_s)$ the standard transmission time $\bar{t}_{yj}$ of the value of the jth element of the observation vector ($j = 1, 2, \ldots, q_y$). The missing (due to failures) element $y_{ej}(\theta_s)$

of the observation vector $y_e^{(\theta_s)}$ is equated to the predicted value $\widehat{y}_j(\theta_s|\theta_{s-1})$ calculated in the device for evaluating the state of the object. The output vector of the information dumping system $y(\theta_s)$ enters the estimation device.

Block 11 — calculation of delays $\{\tau_{yj}(\theta_s)$: $j = 1, 2, \ldots, q_y\}$ (8) and checking the fulfillment of (10) condition. If (10) holds, then ν and $\{\tau_{yj}(\theta_s)$: $j = 1, 2, \ldots, q_y\}$ enter block 7.

Block 12 — performing a quantization step ε_y by level (11) (ε_y enters Block *8*).

Block 13 — simulating the process of errors $\{e^y_{j,a} : a = 0, 1, \ldots, k_y - 1\}$ in an equivalent communication channel I_{eq} (14), $j = 1, 2, \ldots, q_y$.

Block 14 — simulating of failures of measuring devices and communication channels and failures due to $\bar{t}_{yj}$ excess (17), $j = 1, 2, \ldots, q_y$.

Block 15 — calculating the observation vector the jth element value transmission time (9) $j = 1, 2, \ldots, q_y$. If the jth measuring device and (or) the jth communication channel fails, i.e. if $\alpha^y_j(\theta_s) = 0$, then $t_{yj}(\theta_s) = t_g = const$.

Block 16 — calculating the number of code information symbols (n_y, k_y) (12). $\alpha^y_j(\theta_s) \in 0, 1$ enters the Block 14.

Block 18 — retransmission sensor S_{yj} (θ_s), (13), (18).

Block 19 — calculating P_{we}, P_{ue}, P_{de} (16), (20).

Block 20 — calculating the probability P_y of correct decoding (15) (error detecting, or error correcting).

Block 21 — calculation of standard time $\bar{t}_{yj}$ (21).

Block 22 — processing the power system state estimation on the basis of the algorithm obtained from Block 23.

Block 23 — synthesizing the power system state estimation on the basis of database.

Eq. (6) of the information transmission process under failure conditions corresponds to the case when the estimation algorithm requires a constant number q_v of observation vector components $y(\theta_s)$, i.e. when the algorithm has a constant structure.

For the case when the structure of the estimation algorithm is tunable, i.e. the algorithm allows a vector $y(\theta_s)$ with variable dimension q_y (θ_s), where $1 < q_y$ $(\theta_s) < q_y$, then the equation of the information transfer process under failure conditions will take, instead of (6), the following form:

$$y(\theta_s) = \widetilde{\Lambda}(\theta_s) y_e(\theta_s), \tag{24}$$

where $y = (y_1, \ldots, y_j, \ldots, y_{q_y(\theta_s)})^T$; $y_e = (y_{e1}, \ldots, y_{ej}, \ldots, y_{eq_y})^T$; $(q_y(\theta) \times q_y)$ dimension matrix $\widetilde{\Lambda}(\theta_s)$ is formed from a diagonal matrix

$$\widetilde{\Lambda}(\theta_s) = diag\{\Lambda^y_1(\theta_s), \ldots, \Lambda^y_j(\theta_s), \ldots, \Lambda^y_{q_y}(\theta_s)\} \tag{25}$$

by deleting those rows that consist only of zero elements. In this case, in block 10 (Fig. 1), expression (24) is used instead of (6).

3. Formulation of estimating the optimal amount of information about the state of a controlled object problem

The dimension q_y of the observation vector y_0 (rows number of the observation matrix) is determined by the number of control points for the current state of the ESC, and the structure of filling the observation matrix C_0 is determined by the location of the control points in the power system. As can be seen from the IGP model (1)–(21), each jth element of the observation vector is transmitted in the form of a binary error-correcting code (n_y, k_y). Expressions (15), (16) show the important role of the minimum distance $d_{\min}$ and packing radius r_y as the main indicators of the correcting and detecting properties of the (n_y, k_y) code. The larger $d_{\min}$ and r_y, the less the probability P_{ue} of receiving a codeword with an undetected error and the greater the probability P_y of correct decoding (with error detection, with error correction). By increasing the length n_y of the code (n_y, k_y) and keeping the number of code combinations 2^{ky}, it is possible to obtain arbitrarily large values of the parameters $d_{\min}$, r_y. However, as can be seen from (9), with an increase of n_y, the transmission time t_{yj} of each jth element of the observation vector y_0 increases. If the length n_y is specified, then one can get any $d_{\min}$, r_y parameters values (within the (n_y, k_y) code length) reducing the number of combinations 2^{ky} by reducing the number of information symbols k_y. However, as can be seen from (11), (12), as the number of information symbols k_y decreases, the level quantization accuracy deteriorates, i.e. the quantization step ε_y increases. With an increase in the points of control over the power system, i.e. dimension q_y, the amount of information about the state of the power system increases, which has a positive effect on the accuracy of the state estimation. However, an increase in the amount of

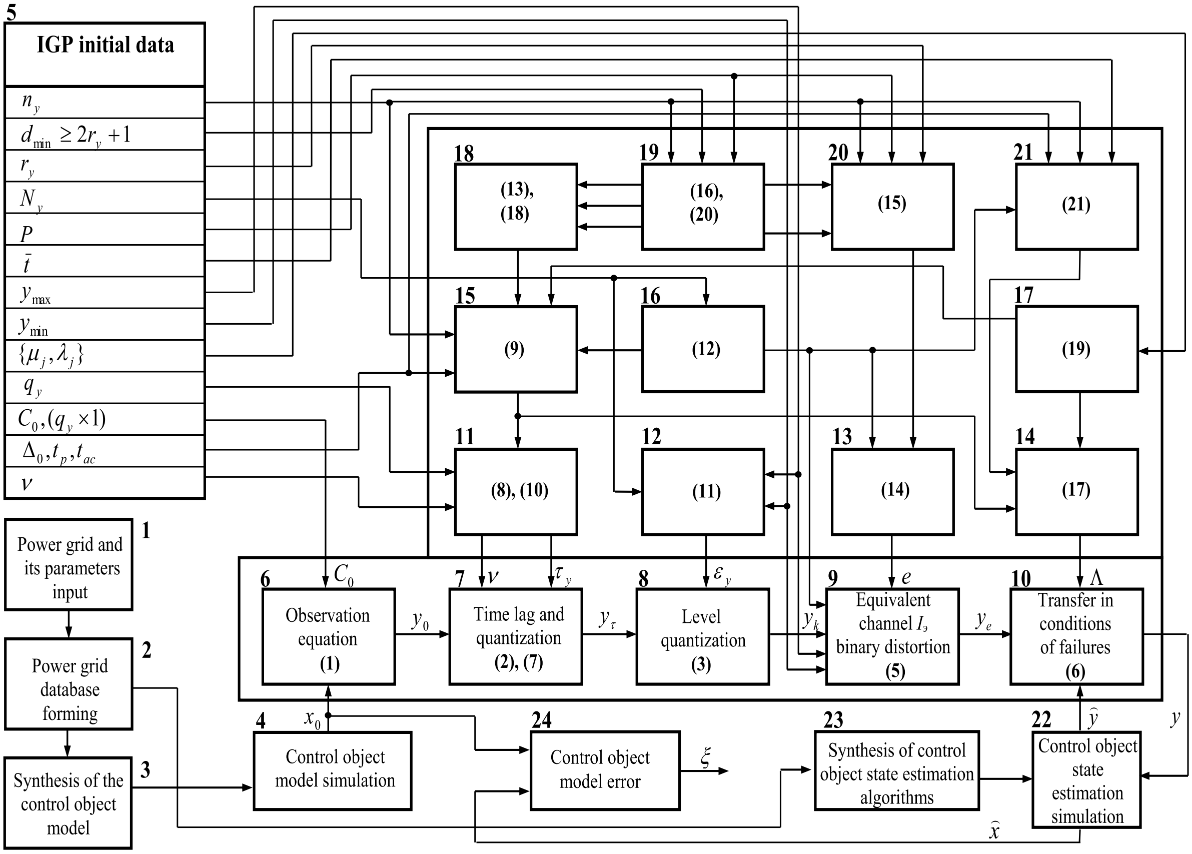

Fig. 1. Functional structure of the simulation complex.

transmitted information, as can be seen from (8), leads to an increase in the transmission time τ_{yj}, which negatively affects the accuracy of the power system state estimation.

From the above, the following problem of estimating the optimal amount of information about the current power system state follows: it is required to find such a dimension value q_y (number of control points) of the observation vector y_0, such a structure of the observation matrix C_0 (location of control points) and select a code (n_y, k_y) with the appropriate parameters for which the estimation error (Fig. 1, Block 24) of the power system state will take a minimum value.

4. Conclusion

On the basis of literature sources analysis, the rationale for the necessity of considering the limited digital devices capabilities when designing closed digital control systems for the complex electrical power grids is provided.

The problem of designing digital systems for transmitting the observation vector and optimal estimation of the current state of the controlled process, taking into account the limited capabilities of digital means of implementation, is considered:

- the mathematical model of a digital system for transmitting information and state estimation of the power grid complex has been developed, taking into account the speed and reliability of technical means of implementation;
- the functional structure of the modeling complex has been developed;
- the problem of estimating the optimal amount of information about the state of the controlled object is formulated, the solution of which is obtained as a result of computational experiments on the modeling complex.

The results of this work will be further used in the development of computer-aided design systems (CAD) of closed-loop digital systems for optimal control (CLDSfOC) of complex power grids, both in normal and emergency operational conditions. The main mathematical apparatus in the development of CAD CLDSfOC complex is the Petri computer network (VSP) [17–19], which is a further development of the classical theory of Petri nets [20].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Gimpel H, Roglinger M. Digital transformation: Changes and chances–insights based on an empirical study. Augsburg/Bayreut: Fraunhofer Institute for Applied InformationTechnology; 2015.
[2] Vyboldin YuK, Krivosheikin AV, Nurmukhamedov LKh. Signal processing methods in discrete information transmission systems. St. Petersburg: St. Petersburg State Institute of Cinema and Television; 2015.
[3] Stepanchenko IV. Investigation of the influence of limited parameters of technical means on the choice and implementation of algorithms for controlling dynamic processes. Volgograd: Volgograd State Technical University; 2002.
[4] Pupkova KA, Egupova ND. Methods of classical and modern theory of automatic control. Moscow: MSTU; 2004.
[5] Roedder N, Dauer D, Laubis K, Karaenke P, Weinhardt C. The digital transformation and smart data analytics: An overview of enabling developments and application areas. IEEE Int Conf Big Data 2016;2795–802.
[6] Narka BC. Theory and applications of automatic controls. New Delhi: New Age Publisher; 2009.
[7] Mozokhin AE, Shvedenko VN. Analysis of directions for the development of digitalization of domestic and foreign energy systems. Sci Tech Bull Inform Technol Mech Optics 2019;19(4):657–72.
[8] Semenenko SI. Development of algorithms for placing synchronized vector measurements to improve the efficiency of assessing the state of the EPS. Yekaterinburg: Ural Federal University named after the first President of Russia Boris N. Yeltsin; 2019.
[9] Strasser T, Siano P, Ding Y. Methods and systems for a smart energy city. IEEE Trans Ind Electron 2019;66(2):1363–7.
[10] Veselov FV, Dorofeev VV. Intelligent energy system of Russia as a new stage in the development of the electric power industry in the digital economy. Energy Policy Mag Digital Energy 2018;5:43–52.
[11] Tomsovic K, Bakken D, Venkatasubramanian V, Bose A. Designing the next generation of real-time control, communication and computations for large power systems. Energy Infrastruct Syst 2005;93(5):965–79.
[12] Lee MMoon, Chu J, Mun M. Control system for power grids. IEEE Int Conf Robot Autom 2005;2649–54.
[13] Keating D, Warwick K. Smart cities with efficient power distribution. IEEE Int Conf Syst Man Cybern 2013;489–93.
[14] Immonen A, Kalaoja J. Requirements of an energy data ecosystem. IEEE Access 2019;7:111692-111708.
[15] Zhao J, et al. Roles of dynamic state estimation in power system modeling, monitoring and operation. IEEE Trans Power Syst 2020. (early access).
[16] Burghes DN, Graham A. Control and optimal control theories with applications. Cambridge: Woodhead Publishing Limited; 2005.
[17] Asanov MS, Asanova SM, Satarkulov KA. Structural model of computational Petri nets. Izvestiya KSTU 2008;13:78–85.
[18] Asanov MS, Asanova SM, Satarkulov KA. Computing components, description language and rules for the functioning of Petri networks. Izvestiya KSTU 2008;13:85–95.
[19] Asanov MS, Kokin SE, Asanova SM, Satarkulov K, Dmitriev SA, Safaraliev MKh. The use of Petri computing networks for optimization of the structure of distribution networks to minimize power losses. Energy Rep 2020;6:1337–43.
[20] Peterson JL. Petri net theory and the modeling of systems. Prentice-Hall: Englewood Cliffs; 1981.