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IDENTIFICATION OF THE MATHEMATICAL MODEL OF FAILURE FREQUENCY OF OVERHEAD LINES OF POWER SYSTEM MAIN GRID

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Abstract

Based on the analysis of accidents of 500 kV overhead lines of the main electric electrical grid of a wide region over a long-time-interval, the failure frequency (failure flux parameter) was determined under the influence of natural and socio-economic factors. It is proposed to consider the indicated failure rate as the output signal of a discrete positive dynamic system with many difficult formalizable inputs. To identify the mathematical model of a dynamic system, it is proposed to use the original method, the identifiability criterion of which is based on the compatibility condition of the linear matrix equation, and the numerical identification algorithm is based on the solution formula using zero-divisors and generalized inverse matrices. The method does not require a priori information about the parameters of the mathematical model of the electric electrical grid, does not involve solving the forecasting problem, and does not apply statistical calculations

Keywords

Overhead lines, accidents, failure frequency (flux parameter), discrete positive dynamic system, mathematical model, identification, matrix equation, compatibility condition, matrix zero divisors, generalized matrix inverse

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Introduction. The causes of major accidents in electric electrical grids with massive damage to overhead lines (OL) are mainly caused by extreme climatic conditions (increased glaze-ice and rime deposition, hurricanes, natural fires, etc.), human activities (unauthorized exposure to OL elements and their poor-quality operation — runover on the supports, wire touching by hoisting devices, untimely detection of defects, etc.). Thus, in the general case, the accident rate of OL depends on the impact of natural and social (socio-economic) factors.

The main reasons for the stable* failure of OL of 500 kV with a total length of about 8.5 thousand km of the European part (Central Federal District) of Russia for the period 2011–2018 are given in Table [1]. According to the presented data, social (paras. 1, 4) and natural impacts (paras. 2–5) almost equally affect the OL accident.

Organizational failure reasons in the period 2011–2018

Failure reason	The number of failures	
	pcs.	%
1. Failure to meet deadlines, failure to meet the required scope of maintenance or repair of equipment and devices	34	12.8
1.1. Untimely detection and elimination of defects (breakage or untwining of wires and cables, destruction of the garland)	17	6.4
1.2. Other violations	17	6.4
2. Bird impacts	5	1.9
3. Excess of impact parameters of natural phenomena concerning project conditions	8	3.0
4. Effects of outsiders and organizations not involved in the technological process	91	34.2
5. Impact of recurring natural phenomena	121	45.5
5.1. Glaze-ice and rime deposition	17	6.4
5.2. Atmospheric overvoltages (thunderstorm)	57	21.4
5.3. Natural fires	17	6.4
5.4. Other effects of adverse natural phenomena (tree fall)	30	11.3
6. Undisclosed reasons	7	2.6
Total	266	100.0

* Failures that cannot be eliminated by the automatic reactivation action.

Accident cycles in electrical grids are considered in [2] by the example of statistical data on unrecoverable failures of OL of 500 kV also of the European part (Central Federal District) of Russia for the period 1974–2001 (specific damage, 1/(year 100 km), more precisely — average flux parameter or failure frequency ω). The authors of the present work have studied the archives of all OL of 500 kV with technological disturbances in the region under consideration for 2002–2018. The failure frequency of non-recoverable OL of 500 kV for the period 1974–2018 is shown on Fig. 1, which is an amplitude-temporal representation of the parameter [1], where failure frequency values have an oscillatory character, varying in a sufficiently large range: from 0.11 1/(year·100 km) in 1980 and 2018 to 0.86 1/(year·100 km) in 1998.

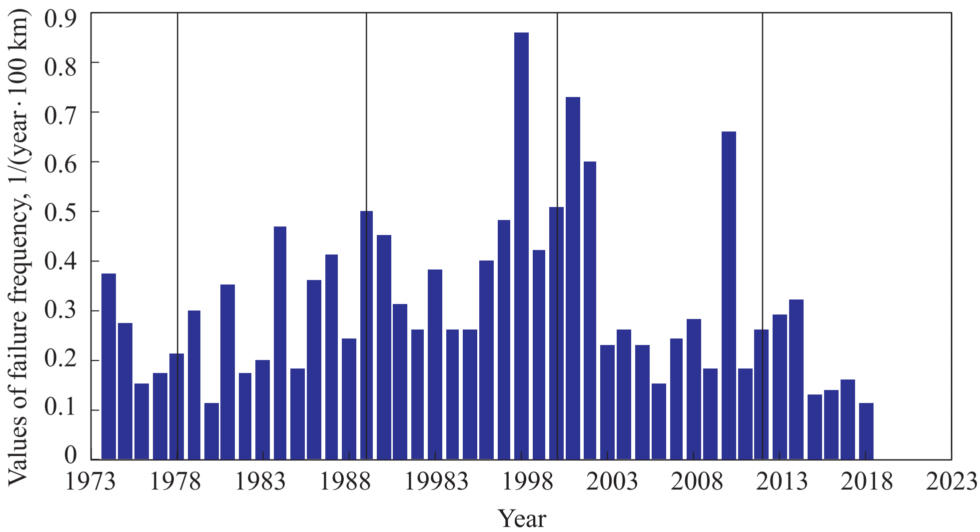

Fig. 1. Values of failure frequency of OL of 500 kV for the period 1974–2018

Causal relationships and their resulting impact on the behavior of failure frequency are determined by the multifactorial and difficult to formalize a combination of environmental influences and socio-economic factors [1]. Nevertheless, regardless of this parameter is not a set of fixed values, depending, for example, on the material of the supports or the nominal voltage of the line, but a dynamic process with a change in the characteristic periods generated by some dynamic systems.

The mathematical model of dynamic systems are conventionally divided into two disjoint classes [3]: 1) autonomous; 2) input-output. In the first class, the system output signals are generated by internal state transitions under the action of nonzero initial conditions. Moreover, all unformalized external influences of such a system are transformed into equivalent initial conditions [4]. In the second class, the system output signals are a homomorphic (not one-to-one) transformation of the corresponding input signals.

Let us formulate the problem: which of dynamic systems reproduces the sequence of output signals with the smallest possible deviations from the observed series in the form of failure frequency (see Fig. 1). The identifiability model should:

– refers to the class of discrete dynamic system, since changes in flux parameter occur discretely with a step of "integration" — year;

– be positive (non-negative), that is, generate only positive values of the output signal, since the flux parameter of failure is at least a non-negative value [5, 6];

– be represented in the state space, that is, described by a combination of physical or abstract variables that characterize the behavior of the system in the future, provided that the state is known at the current moment [3, 4];

– possess the property of non-stationarity, since its parameters change in time, from step to step [7];

– be considered as an autonomous system, since there is no additional information that can be mistaken for input signals.

The method of identification of dynamic systems. Let the mathematical model of a linear discrete dynamic system in the state space have the form

$$\mathbf{x}_{k+1} = \boldsymbol{A}\mathbf{x}_k + \boldsymbol{B}\mathbf{v}_k, \qquad (1)$$

where $\boldsymbol{A}$, $\boldsymbol{B}$ are constant matrices of intrinsic (free) dynamics and inputs; $\mathbf{x}$ is a state vector of a model of a power system of dimension n_x; $\mathbf{v}$ is a vector of input influences of dimension n_v; $k = 0, 1, ..., l$ is discrete time. System (1) is not autonomous since it contains input influences.

According to the results of measurements of the state vector and the vector of input influences, it is required to identify (restore) the mathematical model (1).

Let us consider the matrix equation formed based on (1),

$$\boldsymbol{X}_{k+1} = \boldsymbol{A}\boldsymbol{X}_k + \boldsymbol{B}\boldsymbol{V}_k. \qquad (2)$$

Here

$$\boldsymbol{X}_k = \begin{bmatrix} \mathbf{x}_k & \dots & \mathbf{x}_{k+h} \end{bmatrix}, \qquad (3)$$

$$\boldsymbol{V}_k = \begin{bmatrix} \mathbf{v}_k & \dots & \mathbf{v}_{k+h} \end{bmatrix} \qquad (4)$$

are the matrices compiled based on available data (measurements); h is the number of observation steps.

If discrete equations (3) and (4) one used for solving the problem of parametric identification, i.e., restoration of matrix elements $\boldsymbol{A}$ and $\boldsymbol{B}$, then it is matrices $\boldsymbol{A}$ and B that act as the unknown. In this case, the equation (3) can be rewritten in the equivalent block-matrix form

$$\begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} \end{bmatrix} \begin{bmatrix} \boldsymbol{X}_k \\ \boldsymbol{V}_k \end{bmatrix} = \boldsymbol{X}_{k+1}. \tag{5}$$

To solve block-matrix equations (5) we use the results of [8–10], where it is shown that the linear matrix equation of the type

$$\boldsymbol{YC} = \boldsymbol{D} \tag{6}$$

with known matrices $\boldsymbol{C}$, $\boldsymbol{D}$ is solvable concerning matrix $\boldsymbol{Y}$ than and only then when the compatibility (solvability) condition is fulfilled

$$\boldsymbol{D}\boldsymbol{C}_R^{\perp} = 0. \tag{7}$$

All kinds of solutions of the matrix equation are determined by the formula

$$\boldsymbol{Y} = \begin{bmatrix} \boldsymbol{D}\boldsymbol{C}_R^{-} & \Theta \end{bmatrix} \begin{bmatrix} \boldsymbol{C}_L^{-} \\ \boldsymbol{C}_L^{\perp} \end{bmatrix} = \boldsymbol{D}\boldsymbol{C}^{-} + \Theta \boldsymbol{C}_R^{\perp}. \tag{8}$$

Here Θ is an arbitrary matrix; $\boldsymbol{C}_L^{\perp}$, $\boldsymbol{C}_R^{\perp}$ are left and right zero divisors of maximum rank (matrices for which conditions $\boldsymbol{C}_L^{\perp}\boldsymbol{C} = 0$, $\boldsymbol{C}\boldsymbol{C}_R^{\perp} = 0$ are satisfied); $\boldsymbol{C}_L^{-}$, $\boldsymbol{C}_R^{-}$ are left and right divisors of unity (matrices satisfying the equality $\boldsymbol{C}_L^{-}\boldsymbol{C}\boldsymbol{C}_R^{-} = \boldsymbol{E}$, $\boldsymbol{E}$ is the identity matrix); $\boldsymbol{C}^{-} = \boldsymbol{C}_R^{-}\boldsymbol{C}_L^{-}$ is a semi-inverse matrix satisfying the canonical decomposition

$$\boldsymbol{C} = \begin{bmatrix} \boldsymbol{C}_L^{-} \\ \boldsymbol{C}_L^{\perp} \end{bmatrix}^{-1} \begin{bmatrix} \boldsymbol{E} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{C}_R^{-} & \boldsymbol{C}_R^{\perp} \end{bmatrix}^{-1}. \tag{9}$$

A special case of the semi-inverse matrix is the pseudo-inverse matrix by Moore — Penrose inverse $\boldsymbol{C}^{+}$ [10].

In the general case, the canonical decomposition (9) is not unique and formalizes direct and inverse equivalent matrix transformations [10, 11]. The use of canonical decomposition allows one to obtain in analytic form the set of all solutions of a matrix equation (6), with a minimum rank.

Let us compare the equation (6) with equation (5), used to solve the problem of parametric identification. Then, in accordance with (7) the conditions for solvability (compatibility) of the problems of model identification (1), i.e., the conditions for the presence of at least one solution, are the expressions

$$\boldsymbol{X}_{k+1}\begin{bmatrix}\boldsymbol{X}_k\\ \boldsymbol{V}_k\end{bmatrix}_R^{\perp}=0. \tag{10}$$

Under solvability conditions (10) all identified models according to (8), can be written in the form of sets

$$\begin{bmatrix}\boldsymbol{A} & \boldsymbol{B}\end{bmatrix}=\boldsymbol{X}_{k+1}\begin{bmatrix}\boldsymbol{X}_k\\ \boldsymbol{V}_k\end{bmatrix}_R^{-}+\Theta\begin{bmatrix}\boldsymbol{X}_k\\ \boldsymbol{V}_k\end{bmatrix}_L^{\perp}. \tag{11}$$

Conditions of identifiability [11], i.e., conditions for obtaining a single solution, require equality to zero of the left zero divisor in the formula (11):

$$\begin{bmatrix}\boldsymbol{X}_k\\ \boldsymbol{V}_k\end{bmatrix}_L^{\perp}=0, \tag{12}$$

then the identifiability mathematical model becomes a single form

$$\begin{bmatrix}\boldsymbol{A} & \boldsymbol{B}\end{bmatrix}=\boldsymbol{X}_{k+1}\begin{bmatrix}\boldsymbol{X}_k\\ \boldsymbol{V}_k\end{bmatrix}_R^{+}. \tag{13}$$

Here

$$\begin{bmatrix}\boldsymbol{X}_k\\ \boldsymbol{V}_k\end{bmatrix}_R^{+}$$

is the pseudo-inverse matrix according to Moore — Penrose inverse. The use of the pseudoinverse matrix in (13) provides the problem of identification of dignity, which is inherent to the least-squares method [8].

In fact, the condition (12) also determines the dimension of the state space n_x of the dynamic system (1) [11–18].

Often there is no possibility of measuring input influences in the power system, then instead of (1) as a mathematical model of the normal (pre-accidental) mode of the power system, autonomous dynamic systems can be used

$$\mathbf{x}_{k+1}=\boldsymbol{A}\mathbf{x}_k,\ \ \mathbf{x}_{k=0}=\mathbf{x}_0. \tag{14}$$

In this case, instead of the ratio (2) the following should be written

$$\boldsymbol{X}_{k+1}=\boldsymbol{A}\boldsymbol{X}_k; \tag{15}$$

$$\boldsymbol{X}_{k+1}\boldsymbol{X}_k^{\perp R}=0; \tag{16}$$

$$\boldsymbol{A}=\boldsymbol{X}_{k+1}\boldsymbol{X}_k^{+}. \tag{17}$$

Here $\boldsymbol{X}_k^{\perp R}$ is the matrix — the left zero divisor [13–15].

Example. Let's demonstrate the workability of the proposed method of identification on the example of an autonomous discrete dynamic system of the second order

$$\begin{bmatrix} x_{k+1}^1 \\ x_{k+1}^2 \end{bmatrix} = \begin{bmatrix} a_1 & -a_2 \\ a_2 & a_1 \end{bmatrix} \begin{bmatrix} x_k^1 \\ x_k^2 \end{bmatrix}, \quad \begin{bmatrix} x_0^1 \\ x_0^2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad a_1^2 + a_2^2 < 1. \tag{18}$$

The system (18) is asymptotically stable since the roots of the characteristic polynomial of the matrix $\boldsymbol{A}$ are complex conjugate numbers $a_1 \pm ja_2$, $j^2 = 1$, lying inside the unit circle on the complex plane under the condition $a_1^2 + a_2^2 < 1$ in (18).

Let us consider the solution of the identification problem in steps, thus formulating an identification algorithm.

Step 1. Using a 2 × 3-dimensional matrix:

$$\boldsymbol{X}_k = \begin{bmatrix} \mathbf{x}_{k-2} & \mathbf{x}_{k-1} & \mathbf{x}_k \end{bmatrix}, \tag{19}$$

since the dynamic system (18) has the second order. For example, for $k = 2$ and $k = 3$ following the (18) we get

$$\boldsymbol{X}_k = \boldsymbol{X}_2 = \begin{bmatrix} \mathbf{x}_0 & \mathbf{x}_1 & \mathbf{x}_2 \end{bmatrix} = \left[\begin{array}{c:c:c} 0 & -a_2 & -2a_1a_2 \\ 1 & a_1 & a_1^2 - a_2^2 \end{array}\right]; \tag{20}$$

$$\boldsymbol{X}_{k+1} = \boldsymbol{X}_3 = \begin{bmatrix} \mathbf{x}_1 & \mathbf{x}_2 & \mathbf{x}_3 \end{bmatrix} = \left[\begin{array}{c:c:c} -a_2 & -2a_1a_2 & a_2^3 - 3a_1^2a_2 \\ a_1 & a_1^2 - a_2^2 & a_1^3 - 3a_1a_2^2 \end{array}\right]. \tag{21}$$

Step 2. Calculating the orthogonal right zero divisor of the matrix (20):

$$\boldsymbol{X}_k^{\perp R} = \boldsymbol{X}_2^{\perp R} = \left[\begin{array}{c:c:c} 0 & -a_2 & -2a_1a_2 \\ 1 & a_1 & a_1^2 - a_2^2 \end{array}\right]_R^{\perp} = \frac{\begin{bmatrix} a_1^2 - a_2^2 \\ -a_2 \\ 1 \end{bmatrix}}{\left(a_1^2 - a_2^2\right)^2 + 4a_1^2 + 1}. \tag{22}$$

Step 3. Checking with (21) and (22) the conditions of identifiability (16):

$$\boldsymbol{X}_{k+1}\boldsymbol{X}_k^{\perp R} = \boldsymbol{X}_3\boldsymbol{X}_2^{\perp R} = \frac{\left[\begin{array}{c:c:c} -a_2 & -2a_1a_2 & a_2^3 - 3a_1^2a_2 \\ a_1 & a_1^2 - a_2^2 & a_1^3 - 3a_1a_2^2 \end{array}\right]\begin{bmatrix} a_1^2 - a_2^2 \\ -a_2 \\ 1 \end{bmatrix}}{\left(a_1^2 - a_2^2\right)^2 + 4a_1^2 + 1} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$$

Therefore, we can conclude that it is possible to successfully solve the identification problem.

Step 4. Solving the identification problem using (17) in accordance with (20) and (21):

$$\boldsymbol{A} = \boldsymbol{X}_3\boldsymbol{X}_2^+ = \left[\begin{array}{c|c|c} -a_2 & -2a_1a_2 & a_2^3 - 3a_1^2a_2 \\ a_1 & a_1^2 - a_2^2 & a_1^3 - 3a_1a_2^2 \end{array}\right] \left[\begin{array}{c|c|c} 0 & -a_2 & -2a_1a_2 \\ 1 & a_1 & a_1^2 - a_2^2 \end{array}\right]^+ = \begin{bmatrix} a_1 & -a_2 \\ a_2 & a_1 \end{bmatrix}.$$

This is exactly the same as the right side of the equations of the dynamic system (18).

Identification of the mathematical model of failure frequency. Identification of the flux parameter of the failure change model for 2002–2018 in the class of positive, discrete, non-stationary, autonomous dynamic systems in the state space is made based on the presented method, which is used for each step due to the unsteadiness of the state space. We restrict ourselves to the set of data analyzed since 2002 (see Fig. 1). Otherwise, as shown in [1], the identification results will be significantly affected by the so-called data "tails" from the previous "historical" periods.

As a result of applying (15)–(17) under the above conditions for identifying a non-stationary dynamic system, we obtain discrete equations:

$$\mathbf{x}_{k+1} = \boldsymbol{A}_k\mathbf{x}_k, \;\; \mathbf{x}_{k=0} = \mathbf{x}_0;$$

$$\boldsymbol{A}_k = \boldsymbol{X}_{k+1}\boldsymbol{X}_k^+;$$

$$\omega_k = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}\mathbf{x}_k,$$

where $\omega(t)$ is an output signal of the dynamic system in the form of failure frequency;

$$\mathbf{x}_0 = \begin{bmatrix} \omega_{2002} \\ \omega_{2003} \\ \omega_{2004} \end{bmatrix}, \;\; \mathbf{x}_1 = \begin{bmatrix} \omega_{2003} \\ \omega_{2004} \\ \omega_{2005} \end{bmatrix}, \ldots, \;\; \mathbf{x}_{14} = \begin{bmatrix} \omega_{2016} \\ \omega_{2017} \\ \omega_{2018} \end{bmatrix}$$

are values of the state vector of the dynamic system at the corresponding step of "integration"; $k = 1, \ldots, 14$ is "integration" interval;

$$\boldsymbol{A}_1 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0.4655 & 0.0621 & 0.2404 \end{bmatrix}, \;\; \operatorname{eig}\boldsymbol{A}_1 = \{-0.33264 \pm j0.6439;\;\; 0.8933\},$$

$$A_2 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0.4633 & 0.0600 & 0.2448 \end{bmatrix}, \ \text{eig}\, A_2 = \{-0.3249 \pm j0.6448;\ \ 0.8946\}, ...,$$

$$A_{13} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0.4184 & 0.2301 & 0.1528 \end{bmatrix}, \ \text{eig}\, A_{13} = \{-0,3788 \pm j0.5622;\ \ 0.9104\},$$

$$A_{14} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0.4125 & 0.2326 & 0.1548 \end{bmatrix}, \ \text{eig}\, A_{14} = \{-0.3773 \pm j0.5579;\ \ 0.9093\},$$

are matrices of their own (free) dynamics by the steps of “integration” and corresponding sets of their own values (Fig. 2).

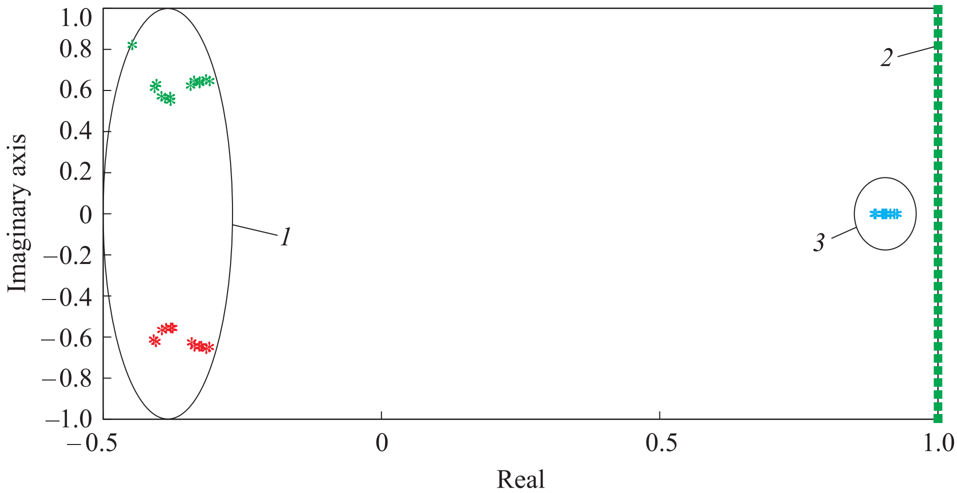

Fig. 2. Eigenvalues of the mathematical model of failure frequency:
1 is complex conjugate pairs of poles; *2* is tangent line to the border of stability; *3* is real poles

According to the above diagram, the identified model is an asymptotically stable (Shurov) system, since to ensure the asymptotic stability of the discrete dynamic system, it is necessary and sufficient to arrange its poles on the complex plane inside the unit circle centered at the origin [4]. Let us note that the robustness of such a dynamic system studied in [1] showed that the stability margin is very small and amounts to approximately 10 % of the nominal values of the elements of matrix $\boldsymbol{A}$. Therefore, the stability of the model is significantly affected by relatively small perturbations of the system parameters. The correlation of this theoretical assumption with the practice of operating the main electrical grids showed the following [1]: about 40 % of OL of 500 kV were built more than 50 years ago, less than 20 % of OL of 500 kV less than 30 years ago. Over the past 30 years, the average duration of a scheduled repair of OLs in the main electrical grids of power systems has grown from 12–17 to 95–149 hours, that is, almost 10 times, and the major part of intentional shutdowns of OL is associated with repairs or maintenance of lines, but not its reconstruction or other external causes. In other words, maintaining the workability of morally and physically worn out electrical grid elements is provided not by reconstruction, but by lengthy repairs.

Conclusion. The existence of significant fluctuations in the failure frequency of OL of 500 kV over the past decades under the influence of natural and socio-economic factors has suggested that this parameter can be described as an output signal of a dynamic system in the class of positive discrete non-stationary autonomous dynamic systems with implementation in state space.

To identify the mathematical model of the dynamic system, it is proposed to use the original method, the identifiability criterion of which is based on the fulfillment of the compatibility condition of the linear matrix equation (7), and the numerical identification algorithm itself is based on the solution formula (8) using zero divisor and generalized matrix inverse. The use of semi-inverse matrix as a pseudo-inverse matrix according to Moore — Penrose inverse provides the considered task of identification of advantages inherent in the method of least squares in terms of data inaccuracy and calculation errors.

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