On the placing of synchronized vector measurements in network 110 - 330 kV for identification of the Kaliningrad region power system regime

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Abstract. A solution is presented for the problem of placing phasor measurement unit to identify the mathematical model of the electric power system in the state space. The criterion for complete observability of the Kalman dynamic system is taken as a basis. As a method of solution, we use the canonical genetic algorithm. The complete observability of the power system is ensured by the application of the observability rule in the form of a recursive test of observability. The proposed approach is demonstrated by the arrangement of synchronized vector meters in the Kaliningrad region power system.

1 Introduction

Identification of electric power systems (EPS) for a long time was a difficult-solvable problem because of the lack of time-allocated and time synchronized dynamic observations in space. The appearance of synchronized vector meters – phasor measurement unit (PMU) brought this problem to the practical level. Modern PMU allows measuring phase currents along transmission lines, phase voltages on buses of power stations and substations, current frequency, and (indirectly) overflows of active and reactive power. This allows the formation of a system of monitoring for transient regimes, to eliminate the lack of information on transient processes and to realize the identification of EPS [1] – [3].

Identification in the work is the task of determining the parameters of the mathematical model of EPS, which best describes the measurement data. The solution of the identification problem is based on the invariance property of the shift of the Kalman observability matrix [3]. This ensures the identification of the complete and equivalent (reduced) mathematical model of EPS and allows generating, for example, appropriate actions for controlling oscillations in EPS and ensuring a given margin of static stability.

The report shows the problem of placing PMU in the nodes of the electrical network with the purpose of real-time identification of the EPS mathematical model and solving related analysis and synthesis problems of control laws. The canonical genetic algorithm is used as a method of solution, the rule (criterion) observability of it is formulated on the basis of the recursive test analysis of a multidimensional dynamic system observability represented in the state space [4].

A practical example, considered in the paper, is the arrangement of PMU in the 110-330 kV networks of the Kaliningrad region power system.

2 EPS as an object of identification

In the present formulation of the problem, the identification of EPS is reduced to the determination of the elements of numerical matrices: A - the state matrix (Jacobi matrix), B - control effectiveness matrix, C - observation matrix and D – matrix of shunting connections, in vector linear discrete equations [3]

$$x(t+1) = Ax(t) + Bu(t),\ \ y(t) = Cx(t) + Du(t), \tag{1}$$

describing the oscillations in EPS. Here, x (t) is the n-dimensional state vector of the EPS, u (t) is the 1-dimensional vector of control actions (input vector), and y (t) is the m-dimensional vector of the state variables (output vector), t is the discrete time.

The discrete Fourier transform (DFT) of the system (2), taking into account that the input signals are close to periodic and that an entire number of periods of EPS oscillations is observed, yields a system of linear matrix equations with complex numbers [3]:

$$\xi_k X(k) = AY(k) + BU(k),\ \ Y(k) = CX(k) + DU(k). \tag{2}$$

Here ξ_k – is the shift operator, $X(k)$ – is the DFT of the state vector $x(t)$, $Y(k)$ –is the DFT of the output signal $y(t)$, $U(k)$ – is the DFT of the input signal $u(t)$.

The dependence of the second equation in (3) on the first gives the following recursion:

$$W_r(k)Y(k) = O_r X(k) + S_r W_r(k)U(k) \tag{3}$$

where

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$$W_r(k) = \begin{bmatrix} 1 \\ \xi_k \\ \vdots \\ \xi_k^{r-1} \end{bmatrix}, O_r = \begin{bmatrix} C \\ CA \\ \vdots \\ CA^{r-1} \end{bmatrix}, S_r = \begin{bmatrix} D & \cdots & \cdots & 0 \\ CB & D & \vdots & 0 \\ \vdots & \vdots & O & \vdots \\ CA^{r-2}B & CA^{r-3}B & CB & D \end{bmatrix} \quad (4)$$

The matrix O_r in (4)is the Kalman observability matrix, and S_r – is the stabilization matrix [5]. For the observability matrix O_r (5), the following invariance property of the shift is valid [5]:

$$O_{r[1:r-1,:]}A = O_{r[2:r,:]} \quad (5)$$

Here $O_{r[1:r-1,:]}$ – is the matrix obtained from the observability matrix by choosing rows from the first to the (r-1) -th, $O_{r[2:r,:]}$ – the matrix obtained from the choice of rows from the second to the r-th. This fact is indicated by the subscripts of the matrices located in square brackets. A single «: » sign means that all columns of the matrix are selected.

Property (6) is the key and is the basis of identification algorithms. It is necessary that it be completely observable in terms of the condition of Kalman's complete observability [5] for identifying the EPS model (1)

$$\operatorname{rank} O_r = n, \quad \text{при} \quad r < n \quad (6)$$

2 Approach to the solution of the problem of placing PMU

Apparently, the invariance property of the shift of the observability matrix (7) is the fundamental basis of the identification algorithm used, and the Kalman complete observability condition (8) is a necessary condition for the identifiability of EPS. This criterion should be taken into account in the formation of the SMLC, including the placing of SSI.

It is proposed to use the canonical genetic algorithm [6] to search for rational variants of the SVR arrangement.

Genetic algorithms are based on the ideas of population genetics and represent methods of global search for the extremum of the objective function *g*. In this case, this problem is formulated as follows:

$$\Sigma = \sum_{i=1}^{M} z_i \rightarrow \min, \;\; g(Z) = 0, \quad (7)$$

where z_i - is indication of the PMU installation in the i-th node (z_i =1 – SWM is installed, - there is no SWM), M – is total number of nodes in the EPS, $\Sigma = \sum_{i=1}^{M} z_i$ - the total number installed in the EPS PMU, $g(Z)$ – the objective function that determines the condition for the complete observability of the Kalman power plant.

The solution is sought on the basis of repeated cycles of the PMU arrangement options generation, further advancement and elimination of which is carried out on the basis of EPS total observability criterion according to Kalman (6) with the minimum possible number of established PMUs.

Complete observability of EPS in solving this problem is provided by applying the rule (criterion) of observability in the form of a recursive test (algorithm) [4].

The basis for using the recursive test is that applying of the rank test (6) even with low dimensionality of the state vector (more than 10) can lead to false conclusions about the uncontrollability of EPSs due to the deterioration of the numerical conditionality of the analyzed matrix O_r. In this case, a false conclusion about the loss of rank is possible, and, accordingly, the absence of the complete observability property [5].

The algorithm of the recursive test looks like this.

Step 0. An estimation of the observation matrix is formed on the basis of the variant of the PMU distribution set by the genetic algorithm C. The maximum solution is determined as $C^{\perp}$ of the matrix equation $C \cdot C^{\perp} = 0$. If $C^{\perp} = 0$, then the test ends. It is concluded that the system is fully observable. If $C^{\perp} \neq 0$, then the next step is taken.

Step 1. The maximum (maximum rank) solution of the matrix equation is determined.

$$\begin{bmatrix} AC^{\perp} & C^{\perp} \end{bmatrix} \begin{bmatrix} Z_1^{(1)} \\ Z_2^{(1)} \end{bmatrix} = 0 \quad (8)$$

Here A – The state matrix is obtained on the basis of the EPS modeling in Matlab.

If the solution $Z_1^{(1)}, Z_2^{(1)}$ is zero, then the test ends (the system is fully observable).Otherwise, it goes to the next step.

Step 2. The maximum (maximum rank) solution of the matrix equation is determined.

$$\begin{bmatrix} Z_2^{(1)} & Z_1^{(1)} \end{bmatrix} \begin{bmatrix} Z_1^{(2)} \\ Z_2^{(2)} \end{bmatrix} = 0 \quad (9)$$

If the solution $Z_1^{(2)}$, $Z_2^{(2)}$ is zero, then the test ends (the system is fully observable). Otherwise, it goes to the next step.

Step k. The maximum solution of the matrix equation is determined

$$\begin{bmatrix} Z_2^{(k-1)} & Z_1^{(k-1)} \end{bmatrix} \begin{bmatrix} Z_1^{(k)} \\ Z_2^{(k)} \end{bmatrix} = 0 \quad (10)$$

If the solution $Z_1^{(k)}$, $Z_2^{(k)}$ is zero, then the test ends (the system is fully observable). Otherwise, it goes to the next step.

The criterion for stopping the test for observability is the nondecreasing rank of matrices sequence $\begin{bmatrix} Z_2^{(k-1)} & Z_1^{(k-1)} \end{bmatrix}$, $\begin{bmatrix} Z_2^{(k)} & Z_1^{(k)} \end{bmatrix}$.

At each step are sought only in the class of orthogonal matrices [7] to increase the accuracy of the computations using this recursive test of the corresponding matrix equations solutions.

3 Power system of the Kaliningrad region

The Kaliningrad region is separated from the rest of the country by the land borders of foreign states and international sea waters.

The tasks of static stability analysis and provision, evaluation and management of oscillations dominant modes, reserves of regime parameters, damper properties of EPSs acquires a high degree of relevance in conditions of a possible and rather rapid exit from the Interstate Energy Union of the Baltic States.

The initial data for the development of the Kaliningrad region energy system model were taken from the regime model for forecasting the winter maximum of the 2018 load. The total active load of EPS is 985 MW.

Presently, the power system of the Kaliningrad region has the following characteristics: the number of power stations is 5; the number of 330 kV transmission lines is 7; the number of substations is 330/110 kV is 3, the number of substations with a higher voltage of 110 kV is 86. The installed capacity of power plant generators is 923 MW.

The creation of a branched Simulink model of EPS in Matlab made it possible to determine the structure of the state matrix (the Jacobi matrix) in a continuous or discrete form. In this mode, the Jacobi matrix has dimensions of 12 × 12, 22 × 22, 42 × 42, 120 × 120, 273 × 273, 385 × 385, 450 × 450, 510 × 510, depending on the equivalence of the adjacent 110 kV network.

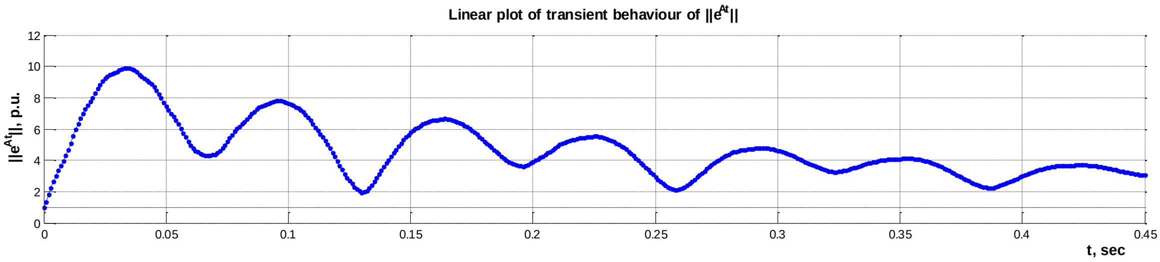

Fig. 1. Generalized transient characteristic of the power system The Kaliningrad Region

The generalized transition characteristic in the form of the norm of the exponential of the Jacobi matrix of size 42×42 $\|e^{At}\|$ [9]**Ошибка! Источник ссылки не найден.** in linear and logarithmic scales is shown in Fig. 1. It characterizes the power system of the Kaliningrad region as statically stable. High-frequency components of electromechanical processes are damped during the first seconds. Further oscillations are low-frequency with periods from one up to tens of seconds. The norms $\|e^{At}\|$ for Jacobi matrices of other sizes are qualitatively equivalent to the characteristic given in Fig. 1.

4 Research results

The sequence of the solution of the problem of placing the PMU in EPS has the form shown in Fig. 2.

The first step is the linearization procedure for the EPS model. At the initial stage of the genetic algorithm work random solutions for distribution of PMU on the on power plant and substation buses are generated randomly using the randomize number operator (sensor). Then, the "survival rate" of the solutions is calculated based on the results of a recursive observability test, which is chosen, as noted earlier, as a rule of observability. These solutions produce offspring (a population). Those decisions that are "stronger", i.e. use a smaller number of PMUs, provided that the observability of the EPS is ensured, selected for further processing, and "weak", using a larger number of PMUs, are excluded.

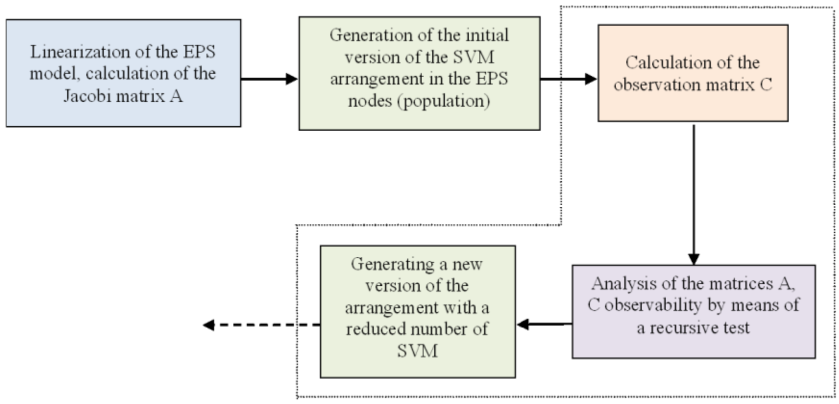

Fig. 2. Sequence of the genetic algorithm work when placing PMU

The process is repeated until a solution is determined in the form of the minimum possible number of PMU that provides observability of the EPS.

At the initial stages of the search, when the number of selected and installed PMU is not less than half the dimension of the identified energy system state space, the step following the zero step of the recursive test is finite in terms of the "survival" of the solution. It consists in verifying the positive definiteness of the symmetric matrix $C^{T}A^{T}E - CC^{\prime T}AC^{\prime} > 0$. This corresponds to the simplified criterion of observability introduced. If this condition is not met, the decision is also considered unacceptable.

The required number of PMUs (fig. 3) and the locations of their arrangement in the power system of the Kaliningrad region were determined, as a result of the genetic algorithm tests in conjunction with the recursive test.

In the fig. 3 a relatively small number of PMUs for high values of the dimensionality of the state space of the mathematical model is explained by the existing multiply connected energy system. At the same time, the growth of the installed PMUs number, depending on the dimensionality of the state space of the mathematical model, is nonpolynomial, which makes it difficult to predict solutions in such problems.

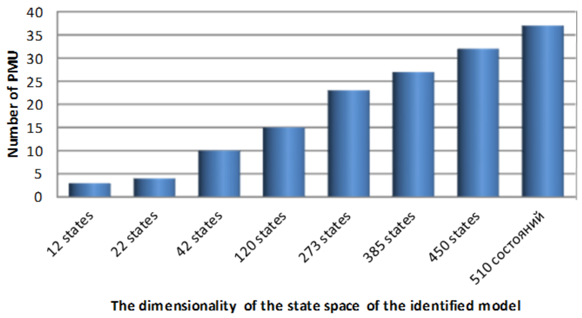

Fig. 3. Distribution of the number of PMUs required for the Kaliningrad region power system

In all the calculated versions of the locations of the PMU, these devices were located in the generator nodes and the most loaded load nodes.

Note that in the post-emergency calculation modes, it is necessary to provide for the appropriate reservation of PMU, which can lead to a twofold increase in the number of meters.

Real-time identification of the simplest power system model, which has the 12th order and takes into account the basic modes of electromechanical oscillations, proves to be sufficient only for 3 PMU, one of which is located at Kaliningradskaya Thermal power station (TPS) – 2, and others at substations 330 kV "Sovetsk" and "Centralnaya".

The general relationship between the practical tasks being solved in the interests of the power systems, and the conditions for the arrangement of the SWMs is shown in Table 1.

We will make the necessary explanations regarding Table1. The authors used models with Jacobi A matrices of 42 × 42 and 450 × 450 sizes for the analysis of the static stability of the power system of the Kaliningrad Region (Task No. 1 in Table 1). In this case, a smaller Jacobi matrix was obtained by reducing the 450 × 450 matrix A based on Krylov subspaces [7] and containing relatively "slow" oscillation modes located near the imaginary axis in the complex plane.

When estimating the dominant oscillation modes (task No. 2 in Table 1), a reduced model with a Jacobi matrix of size 42 × 42 was used, containing, as noted earlier, "slow" oscillation modes. These modes that determine the electromechanical transients and make the main contribution to the fluctuations in the power system of the Kaliningrad region are obtained from the results of mathematical modeling. To estimate the reserves of the regime parameters (Task No. 3 in Table 1), we used the Jacobi A matrices of the entire ruler of the obtained dimensions, i.e. 12 × 12, 22 × 22, 42 × 42, 120 × 120, 273 × 273, 385 × 385, 450 × 450, 510 × 510, in order to determine sufficient conditions for the required dimensionality of the power system model. It was revealed that, starting from the size 42 × 42 and above, the stocks of the regime parameters do not change significantly. Models of smaller dimensions give overestimated (too optimistic) values of the regime parameters reserves.

Table1. Conditions for the arrangement of the PMU

	Class of tasks to be solved	Mathematical Problem	Power system mode	Kind of model and dimension
1	Static stability analysis	The complete problem of the eigenvalues of matrix A	Steady mode	Full high-dimensional model
2	Estimation of dominant modes of oscillation	A partial problem of the matrix A eigenvalues	Electromechanical transients	Reduced modelof smalldimension
3	Estimation of reserves of mode parameters	Analysis of the matrix A pseudospectrum [9]	Steady mode, electromechanical transients	Complete or reduced model
4	Evaluation of damping properties	Calculation of the damping decrement of the vibration modes on the basis of the matrix A eigenvalues	Electromechanical transients	Reduced model
5	Centralized, including emergency control	Synthesis of state observers and laws of centralized control based on matrices A, B, C, D [11]	The steady state, electrical and electromechanical transients	Complete model
6	Control of system stabilizers and reactive power compensation devices	Synthesis of decentralized control laws based on matrices A, B, C, D [12]	The steady state, electrical and electromechanical transients	Complete and reduced model

Models with Jacobi matrices A 12 × 12 and 22 × 22 were used to estimate the damper properties (Task No. 4 in Table 1). These models represented oscillation modes with eigenvalues located in close proximity to the imaginary axis of the complex plane. The degree of damping of these vibration modes was estimated as determining in the damping properties.

The 510 dimension model (the 510 × 510 Jacobi matrix) was used to synthesize the laws of centralized emergency control (Task No. 5 in Table 1). This model allows taking into account the dynamic properties of the power system to the maximum extent and synthesizing the laws of centralized emergency control. These laws provide both specified reserves of static stability, and other important properties: the quality of transient processes, robustness (coarseness, invariance) with respect to perturbations and available information, etc.

When solving the problems of control of system stabilizers and static reactive power compensation devices (Task No. 6 in Table 1), they were used as high-dimensional models (Jacobi A matrixes of sizes 273 × 273, 385 × 385, 450 × 450, 510 × 510) and Reduced models (Jacobi matrices of sizes 12 × 12, 22 × 22, 42 × 42). Such a variety of models makes it possible to use different approaches and synthesis methods (centralized and decentralized synthesis of control, local control, etc.) and to perform a comparative analysis of the results with the choice of the preferred option.

5 Conclusion

The creation of the system of monitoring for transient regimes brought the problem of identifying the energy system to a level where the success of its solution depends on the methods and algorithms used.

The application of discrete algorithms for anenergy system linear mathematical model identification with realization in state space is based on the property of invariance of the observability matrix shift. Ensuring the full observability of the Kalman power system is possible due to the installation of PMU in certain nodes. The number of such nodes is much smaller than the state space dimension of the identified mathematical model.

Determination of the PMUs location and their number allows a genetic algorithm that works together with a recursive test of the dynamic system observability analysis. It is considered as the chosen rule (criterion) of observability.

These devices should be placed on the buses of power stations and substations in all calculated versions of the PMU locations. With the growth of the dimensionality of the state vector by non-linear law, the required amount of PMU also increases.

In all calculated versions of PMU locations, these devices should be placed on power plant buses and power system substations in the Kaliningrad region. At the same time, when the dimension of the state vector increases, the required amount of PMU also increases according to a non-linear (NP) law. To solve the entire range of problems considered in the work, it is sufficient not more than 40 PMUs.

The introduction of a system for managing power systems in real time inevitably leads to high-dimensional dynamic models and the complication of the PMU arrangement task. The nonpolynomial nature of the growth in the number of installed PMU, depending on the dimensionality of the mathematical model state space, makes it difficult to predict the solutions in these kinds of problems. However, the pace of development of mathematical methods and methods of artificial intelligence provides good chances for overcoming this problem.

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