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Monitoring of Power System Operating Conditions with the Methods of Distributed and Dynamic State Estimation

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Power system state estimation, SCADA, PMU, WAMS, distributed state estimation, the structural and functional decomposition of SE problem, forecasting of EPS operating conditions.

1 INTRODUCTION

An important step in development of a new technology intended to control operating conditions of Russia' unified power system (UPS) on a market basis but without damage to system reliability and survivability is the systems for monitoring and short-term forecasting of state variables of electric power systems (EPS) and their interconnections [1]. Such systems of monitoring and forecasting of the EPS normal, pre-emergency and post-emergency operating conditions should be capable of solving the following problems:

- 1) Distributed state estimation (static);
- 2) Forecasting the parameters of expected operating conditions (dynamic state estimation).

The system for monitoring of power system state includes devices intended to measure the required parameters and tools for their processing as well as systems for their storage and mapping. Until recently the measurements employed in the EPS state estimation were mainly the measurements received from SCADA (Supervisory Control And Data Acquisition) system. The SCADA systems are designed to receive and process information at a rate of once per second. At the same time there are delays in information delivery of several tens of seconds. In order to improve the reliability of information the state estimation methods are applied, which make it possible to filter random measurement errors, i.e. estimate them and calculate non-measured state variables. The disadvantages of SCADA systems in terms of energy problems are insufficient volume and low accuracy of measurements.

State estimation (SE) of modern large scale power systems that contain thousands of nodes and ties of different voltage levels encounters the problems that concern inhomogeneity of the studied systems, large volume, irregularity, incompleteness and inaccuracy of information obtained from the measuring systems. This leads to bad conditionality of the problem solved, to slow convergence of the computational process and considerable distortion of state estimation and, as a result, to make a wrong decision in generation of control actions [2].

Besides, SCADA systems do not provide absolute synchronization of data because measurements are scanned successively. Non-simultaneous arrival of measurements is particularly noticeable when calculating subsystems that operate in parallel and have their own systems for acquisition and transfer of information. The state variables calculated on the basis of such data lag behind the current state of EPS. Analysis and formation of control actions on the basis of delayed data is a reason for delayed response of control system to EPS behavior which results in overestimated

requirements for static and dynamic stability margins, and decreases the overall efficiency of automated and automatic control systems.

An essentially higher level of observability and controllability in EPS can be achieved owing to the WAMS (Wide-Area Measurement Systems) technology. Creation of the wide area systems of synchronized data with PMUs as basic measurement devices [3], enables power systems to both operate accurately and improve essentially the results of power system state estimation [4].

The synchronized PMU data received from WAMS (voltage and current measurements and their derivatives), distributed data processing on the basis of modern network technologies and decomposition methods of state estimation problem make it possible to essentially enhance the efficiency of computational procedure of state estimation for EPS with a multi-layer hierarchical structure.

Along with the improvement of algorithms for EPS state estimation and the increase of their speed, an important role in creating a system for monitoring the current state of EPS is also played by the algorithms of dynamic state estimation of EPS [5] and automatic short-term forecasting of state variables [6], that are developed for the purposes of operation and emergency control of EPS but have not been paid sufficient attention to until now.

Due to the absence of short-term forecasting systems the analysis and generation of control actions are made on the basis of obsolete data with a delay from several tens of milliseconds to several tens of seconds. With the time required for response and decision making by dispatcher the real delay equals minutes, while monitoring and control problems require some advance estimation of system state (“to control is to foresee”).

In this paper the problems of distributed state estimation and forecasting the parameters of expected operating conditions are considered for development of power monitoring system.

2 DISTRIBUTED STATE ESTIMATION

Distributed processing of information for decomposition of state estimation problems is an efficient method of solving problems for monitoring and forecasting operating conditions and for operation and emergency control. This approach to state estimation is offered in the articles by the Russian scientists [7], [8] and scientists from other countries [9-11] etc.

The basic algorithms of SE problem decomposition are based on division of the calculated scheme into subsystems by either boundary nodes or boundary branches [2]. Decomposition of the calculated scheme by boundary branches is used more often.

The results obtained during the studies are:

A hierarchical algorithm has been developed for state estimation. It employs the structural decomposition of problem, i.e. division of the studied system into subsystems, and the functional decomposition which is made in accordance with the problems solved while estimating power system state: bad data detection, state estimation proper on the basis of squared and non-squared criteria.

The functional decomposition of the SE problem makes it possible to coordinate interaction among subproblems solved at different levels; organize a flexible choice of a method for solving one or another state estimation subproblem for every subsystem; integrate the artificial intelligence and numerical methods of problem solving; accelerate processing of measurements and, hence, decrease the time of state estimation for the entire system.

Distributed SE includes the following main procedures:

- 1) decomposition of the entire calculated scheme into subsystems (local areas),
- 2) state estimation for each local area on the basis of available local area measurements,
- 3) solution of the coordination problem, i.e. calculation of the boundary variables and check of the boundary conditions. If the conditions are not met, the subsystems are recalculated with new values of boundary variables,
- 4) aggregation of calculation results for individual subsystems and transfer of aggregated data to the Control Center.

3 USE OF PMUs FOR DISTRIBUTED STATE ESTIMATION

For decomposition of power system SE problem it is necessary to maintain accurate values of voltage magnitudes and phases at boundary nodes of subsystems for iteration-free solution of

coordination problem. Placement of PMUs at boundary nodes makes it possible to considerably simplify the procedure of coordinating solutions for individual subsystems. A simple but not an optimal solution is placement of PMUs at all boundary nodes. Based on the measurements to be received from the PMUs the voltage magnitude and phase at a neighbor node can be calculated using the electrical circuit equations. We also use the so called “calculated” PMUs because the accuracy of their measurements virtually equals the accuracy of measurements received from the physical PMUs [2]. With an optimal combination of physical and “calculated” PMUs at all boundary nodes of subsystems it is possible to determine voltage magnitudes and phases required to coordinate the solutions obtained for individual subsystems.

Installation of PMUs at boundary nodes allows one to fix boundary variables U and δ on the values measured with high accuracy.

When decomposition of the calculated scheme into subsystems is made by boundary branches a physical PMU is installed at one of the nodes of boundary branch, and a “calculated” PMU can be placed at the other end of the branch. In this case:

- the combination of measurements from physical and "calculated" PMUs at an incident node ensures that boundary conditions in boundary branches are met,
- since PMU installed at a node allows one to obtain or calculate the measurements (pseudo-measurements) of power flows in all the branches going from the node the boundary conditions (the relationships for power flows from the i -th subsystem to the j -th subsystem) will also be fulfilled.

In this case SE of separate subsystems can be calculated independently from each other, the iterative calculations on subsystems are not required.

For coordination of voltage phase angles received from local areas only one node with PMU measurement of phase angle is enough in each subsystem. Such node is appointed for subsystems as reference node. PMU measurements coordinate the SE results obtained for separate subsystems. Traditionally reference node with a zero angle is set in one arbitrarily chosen subsystem. In reality, however, a zero value of angle at reference node does not correspond to the PMU measured angles at other nodes. Therefore, it is necessary to install PMU at reference node or to appoint the node with PMU as reference one.

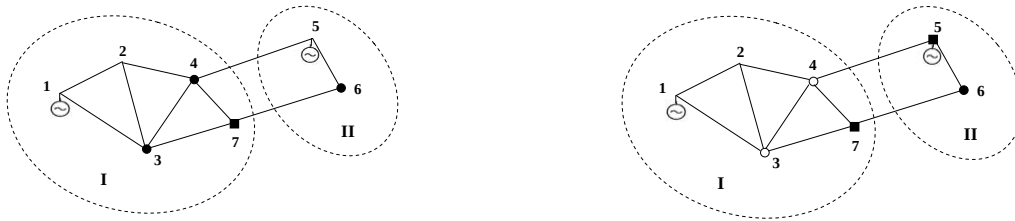


Fig. 1: Decomposition of the network by boundary branches

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|---|--|
| <p>a) Physical PMU is at node 7, "calculated" PMUs are at nodes 3, 4 (Subsystem 1) and node 6 (Subsystem 2)</p> | <p>b) Physical PMU is at node 7, "calculated" PMUs are at nodes 3,4 (Subsystem 1); Physical PMU is at node 5, "calculated" PMU – at node 6 (Subsystem 2)</p> |
|---|--|

When the calculated scheme is decomposed into subsystems by boundary branches a node at one end of the boundary branch in which PMU is installed can be chosen as a reference node. In spite of the fact that the “calculated” PMU with exact voltage phasor can be obtained for an incident node of the boundary branch it is undesirable to use this very node as a reference node of the second subsystem. The matter is that in case of a gross error in the phase angle measurement, the value of phase angle at reference node of two subsystems (Fig. 1,a) is distorted at once. In [12] the authors suggest avoiding the installation of PMUs at nodes that belong to coherent groups, since all of them will give the correlated information in emergency conditions. A more appropriate approach is installation of physical PMUs at reference nodes of each subsystem (Fig. 1,b).

Case study. In order to test the efficiency of the suggested PMU placement algorithm for decomposition of state estimation the calculations were made for a real scheme consisting of 146 nodes (Fig. 2).

The entire scheme consists of five subsystems which contain 20, 28, 41, 28 and 29 nodes including 4, 6, 9, 8 and 8 boundary nodes, respectively. Placement of PMUs at these boundary nodes was modeled.

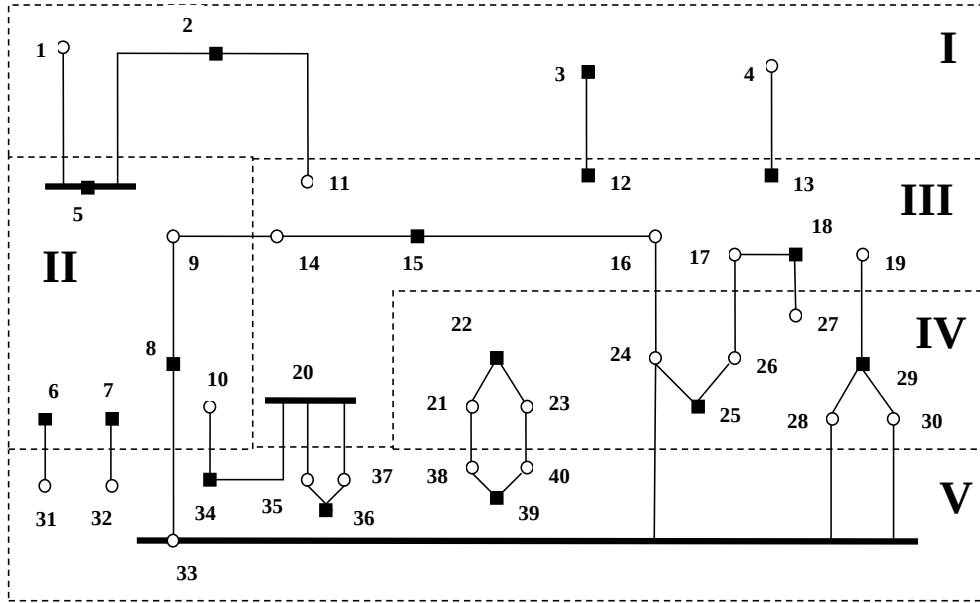


Fig. 2: PMU placement for coordination of SE problem (black boxes - physical PMUs, circles - "calculated" PMUs)

The efficiency of the algorithm for distributed SE was assessed by comparing the results of calculations made for subsystem II to the results of calculation made for the entire scheme.

The criteria considered were:

1. Agreement between the estimates of state vector (U, δ) at boundary nodes and standard values

Node with PMU	Full scheme		Subsystem II	
	U, kV	δ , degree	U, kV	δ , degree
2	359.634	-2.264	359.563	-2.253
5	357.011	-1.993	357.0	-1.993
6	353.445	-0.389	353.4	-0.389
7	352.527	-3.745	352.5	-3.745
8	357.159	-2.447	357.2	-2.447
34	351.412	-8.572	351.4	-8.572

Table 1: Calculation of estimates at boundary nodes with PMU

Node without PMU	Full scheme		Subsystem II	
	U, kV	δ , degree	U, kV	δ , degree
1	358.531	-1.923	358.448	-1.931
10	351.248	-7.521	351.135	-7.525
31	352.821	-3.603	352.708	-3.593
32	352.485	-5.195	352.466	-5.188
33	357.064	-2.121	357.086	-2.127

Table 2: Calculation of estimates at boundary nodes on the other end of intertie branch

Judging from minimal discrepancies in results the state is fulfilled accurately.

2. Agreement between the estimates of power flows at the ends of corresponding branches adjacent to boundary nodes and standard values

Branch	Full scheme				Subsystem II			
	P_{ij}	Q_{ij}	$\hat{P}_{ij}$	$\hat{Q}_{ji}$	P_{ij}	Q_{ij}	$\hat{P}_{ij}$	$\hat{Q}_{ji}$
5-2	11	-53	12	-53	11	-53	11	-52
5-1	-11	-40	-11	-41	-11	-40	-10	-40
6-31	169	-45	166	-44	168	-45	168	-45
7-32	155	-35	156	-36	155	-35	155	-35
8-33	-44	-3	-42	-3	-44	-3	-43	-3
34-10	-57	-13	-56	-12	-57	-13	-57	-12

Table 3: Calculation of estimates in boundary branches (P-MW,Q-MVAR)

3. Average mean of weighted square root of deviation of estimates from measurements for:

$$\text{magnitudes of nodal voltages } U_i \quad \Delta_U = \frac{\sum_{i=1}^{n_U} (\hat{U}_i - \bar{U}_i)^2 / \sigma_i^2}{n_U};$$

$$\text{active power flow } P_{ij} \quad \Delta_P = \frac{\sum_{i=1}^{n_P} (\hat{P}_i - \bar{P}_i)^2 / \sigma_i^2}{n_P};$$

$$\text{reactive power flow } Q_{ij} \quad \Delta_Q = \frac{\sum_{i=1}^{n_Q} (\hat{Q}_i - \bar{Q}_i)^2 / \sigma_i^2}{n_Q}.$$

Objective function	Full scheme		Subsystem II	
	Without PMU	With PMU	Without PMU	With PMU
φ_Σ	559.7	4.11	38.3	2.94
φ_P	167.7	2.14	15.1	0.467
φ_Q	279.5	1.56	17.0	0.38
φ_U	111.8	0.416	6.11	2.09

Table 4: Value of the objective function of full scheme and subsystem II

4. Total calculation time for entire scheme and for the most provided with telemetry subsystem

No. of module	Full scheme		Subsystem II	
	Without PMUs	With PMUs	Without PMUs	With PMUs
1	0.30	0.30	0.11	0.07
2	0.12	0.11	0.11	0.05
3	0.41	0.33	0.33	0.16
4	0.16	0.19	0.06	0.3
Total time	0.99	0.93	0.61	0.58

Table 5: Calculation time entire scheme and for the most provided with telemetry subsystem (Work of modules of software “Otsenka”).

The use of PMU measurements allows one to obtain complete agreement between the calculation results and standard values in the first iteration.

4 FORECASTING OF THE EPS OPERATING CONDITIONS

Forecasting of all state vector components some time ahead makes it possible to forecast the values of all state variables. Forecasting of state vector components is considered as dynamic state estimation if there are no new measurements.

The technique for forecasting all state vector components was checked for the scheme shown in Fig.2.

Creation of a database. In order to solve the stated problem we create a virtual database of measurement snapshots. Each snapshot is created in the following way: at a certain load value the steady state is calculated. Then the errors are generated by random number generator and superimposed on measured state variables. The values of measurements are calculated according to the expression:

$$y_{simul} = y_{ss} + x_{rand} \sqrt{\sigma^2},$$

where σ^2 – a variance of measurement errors, $x_{rand} \rightarrow N(0,1)$, y_{ss} – a steady state variable. Calculated measurement values are called a snapshot and are initial information for solving the problem of dynamic state estimation.

Fig. 3 presents the forecast values of voltage magnitude and phase measurement.

Variances of measurement errors are $\sigma_U^2 = 1.7kV^2$, $\sigma_\delta^2 = 0.01rad^2$, $\sigma_P^2 = 25MW^2$, $\sigma_{Pij}^2 = 25MW^2$, $\sigma_Q^2 = 100MVAR^2$, $\sigma_{Qij}^2 = 100MVAR^2$.

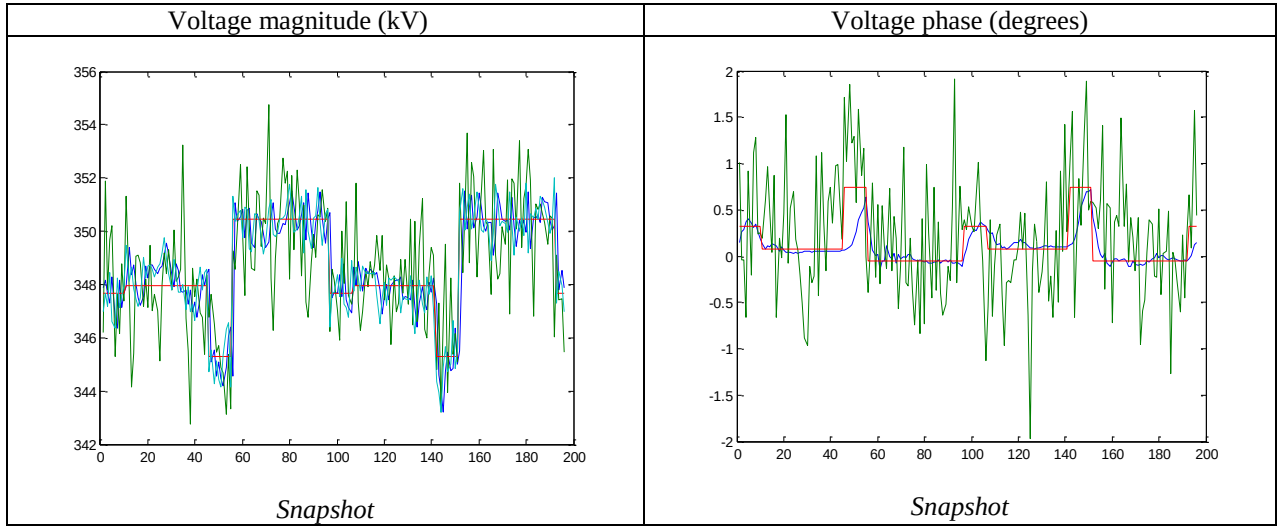


Fig. 3: Forecasting the state vector component

Table 6 (column 2) presents average errors in forecasting that were calculated in 200 snapshots in accordance with:

$$err = \frac{1}{k} \sum_{i=1}^k (|\tilde{x}| - |\hat{x}|),$$

where $\bar{x}$ – the measurement of state vector component, $\hat{x}$ – the estimate, $\tilde{x}$ – the forecast, k – the number of snapshots. Table 6 (column 3) presents average errors in forecasting in %.

Component	Average errors in forecast	
	(kV, degrees)	%
U	0.83	0.24
δ	0.004	0.26

Table 6: Average errors in forecasting state vector components

Analysis of Fig. 3 and table 6 shows that under the considered conditions the forecast is made with high accuracy.

5 CONCLUSION

1. Currently there is a need for development of a system for wide area monitoring and forecasting of the EPS current state and control. The problems of distributed static and dynamic state estimation are the basic problems to be solved within the system in question.
2. The use of synchronized highly accurate phasor measurements provided by PMUs makes it possible to solve certain problems arising in the SE problem decomposition:
 - 1) PMU placement at boundary nodes considerably simplifies the procedure of coordinating solutions for individual subsystems and does not require iterative calculations by subsystem;
 - 2) setting the nodes with PMU as slack nodes of subsystems provides coordination of voltage phase angles in subsystem calculations;
 - 3) measurements from PMUs placed in the vicinity of boundary nodes enhance essentially the efficiency of bad data detection in boundary regions and improve the accuracy of obtained estimates.
3. Dynamic state estimation with application of the Kalman filter can be used to forecast all the EPS state variables for a short period of time. Regular tuning of the filter improves the forecast quality.

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