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STATE ESTIMATION OF POWER SYSTEM MODE PARAMETERS BY TELEMETRY AND SYNCHRONIZED PHASOR MEASUREMENTS

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Abstract. *Real time hardware and software systems are operated at centers of a power system operation. The key unit of these systems is the state estimation block since, based on the results of mode parameters derived from this block, parameters that are more comprehensive can be calculated. These parameters are considered for system stability and reliability. Currently, not only telemetry but also synchronized phasor measurements can be used for a state estimation. Therefore, the development of state estimation methods is the relevant task. The proposed method allows improving the estimation accuracy and the quality of decisions, related to system stability and reliability. The method is based on mathematical frameworks of the Gauss-Newton method and extended Kalman filter, when telemetry and synchronized phasor measurements arrays are used simultaneously. It is confirmed, that the given method increases an accuracy of the voltage and active power flow estimation at steady state and post-accident modes, in contrast to the standard state estimation method. The developed algorithm enables the implementation of this method into the state estimation block of real time hardware and software systems. The upcoming trends for the development of state estimation methods in the event of dynamic processes in power system areas are also formed.*

Keywords: state estimation, Gauss-Newton method, extended Kalman filter, telemetry, synchronized phasor measurements.

1. Introduction

Automated dispatch management systems, for instance, Centralized Emergency Control Systems (CECSs), System Integrity Protection Schemes control modes operate in high voltage power systems based on state estimation (SE) results [1-4]. To obtain SE results, telemetry of mode parameters is often used. It has major sample spacing, and the parameters are asynchronous in time. Moreover, telemetry does not involve such parameters as voltage and current vectors. These factors reduce the accuracy of solutions to technological tasks, particularly, when calculating power flows before electrical switching operations, identifying maximum and emergency allowed power flows, and making an expert analysis of emergency states, which requires a proximity control of a current mode.

Wide-Area Measurement Systems (WAMSs) are embedded at power system facilities [5, 6]. Synchronized phasor measurements (SPMs) of mode parameters, received from WAMSs, are timed by Global Positioning System (GPS), updated before 50 cycles per second. SPMs include measurements of direct voltage and current vectors. The high update rate ensures control of sudden changes in a power system structure and its mode; records of voltage and current vectors improve the Jacobian and computing process stability; high accuracy of SPMs increases SE results veracity [7–9]. Figure 1 illustrates telemetry and SPMs acquisition and transition.

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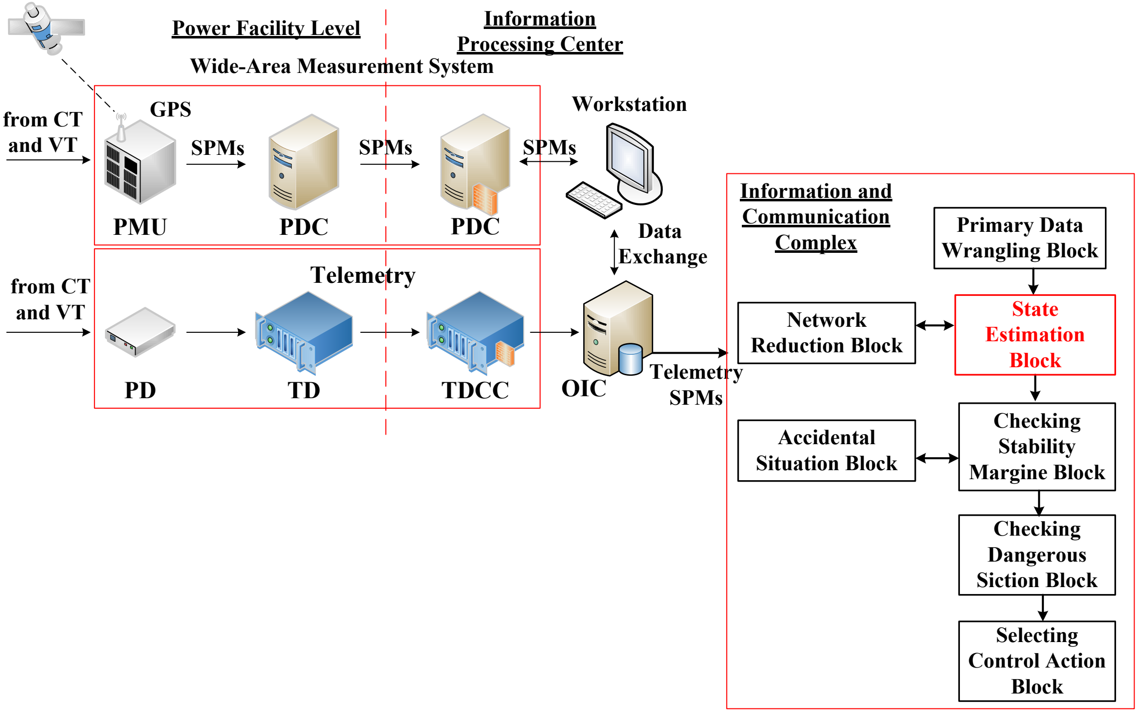

Fig.1. Scheme of telemetry and SPMs acquisition and transition

In the telemetry system, a primary detector (PD) does not guarantee that telemetry is bound to Coordinated Universal Time. As a result, telemetry is asynchronously transferred to a telemetry device (TD), then to a telemetry device of a control center (TDCC) and an Operative information complex (OIC). Time irregularity of the parameters recording falsifies SE results.

WAMSs involve two types of facilities: phasor measurement systems (PMUs) and phasor data concentrators (PDCs). PMUs record mode parameters, received from voltage (VT) and current (CT) transformers, and provide label binding to SPMs by GPS. PDCs receive SPMs from PMUs, save them and process SPMs consistency. After that, SPMs are transmitted to the Information Processing Center (IPC) via the communication network. Subsequently, telemetry and SPMs arrive at the OIC and they are transmitted to the Information and Communication Complex (ICC). According to figure 1, ICC software includes some blocks, where the SE block is the primary unit, as an accidental situation simulation and checking stability margin are performed on the basis of the mode, estimated in the SE block.

Significantly, WAMSs are installed only at 220 kV and above power system facilities. Therefore, SPMs and telemetry can be consistently used for obtaining more precise SE results. Combining SPMs and telemetry enables to develop SE methods [10-12].

Currently, in the modern automated dispatch management systems the SE is achieved by the standard static method, when telemetry is only used as the data, for the reason that this method is not adapted for SPMs [13].

It is reported in [14-21], that dynamic SE methods demonstrate greater accuracy at steady state conditions than the standard static SE method. However, authors stated, that the accuracy of dynamic SE methods is spiraled downward, when sudden changes in a power system are occurred, but no solutions have been proposed [15, 20].

All in all, despite the development of SE methods, the issue of the adequate combining static and dynamic SE methods for the improvement of the SE quality has not yet been come to a decision.

In this paper, the SE method combining sophisticated static and dynamic SE methods in line with the Gauss-Newton mathematical method and extended Kalman filter (EKF) is proposed and tested. This method provides high-quality SE results at various power structures and modes. This is crucial for identifying technological tasks in real-time.

2. Theory of the Method

The SE method is based on the following principles:

1. SE operates in polar coordinates to consider voltage and current angles;
2. It is offered to calculate SPMs weight factors with the formula, which gives a reliable repeatability of an iterative process.

Generally, the static SE method is formalized by the Newton or the Gauss-Newton methods [12, 13]. The Gauss-Newton method is used to solve nonlinear systems of equations and it differs from the Newton method in that the Jacobian is used for approximation instead of the Hessian matrix. Hence, the iterative process time is decreased for the calculation of large-scale systems of equations, such as power system mode equations. For that reason, the Gauss-Newton method is the most relevant for SE. This fact is especially important for automated dispatch management systems. It should be noted that, the Gauss-Newton method is already implemented in the algorithm of the State Estimation Block (fig.1). For that reason, it remains only to modify these method and algorithm for the simultaneous using telemetry and SPMs with economically justifiable expenses.

Dynamic SE methods rest on Kalman filters: *EKF*, *Unscented Kalman Filter (UKF*) and others [12, 15-20]. UKF ensures higher accuracy than *EKF, if a mathematical model is* non-linear. This is due to the fact that at UKF nonlinear predictive functions are plotted by sigma-points, while a model can be linearized in each iteration by the Jacobian at EKF.

However, it is required to define additional model parameters for UKF. Indeed, it is impossible to predetermine additional model parameters in advance for all schemes and modes, therefore, EKF is preferred.

If a scheme and a mode are rapidly changed, then in the proposed method a state estimation is provided by the static SE method during the specified time Δt to configure an amplification matrix. Further, the matrix is applied as initial data for SE by the dynamic SE method.

2.1 Transition to the polar coordinate system and development of the mathematical framework for SPMs

The mathematical statement of SE task comes down to identification of the state vector $\boldsymbol{u}$, with 2N-1 dimension, where N is the number of nodes. In the current SE blocks the state vector components are longitudinal and transversal components of the node voltages: E_1, V_1; E_2, V_2;…, $E_{N\text{-}1}$, $V_{N\text{-}1}$; E_N, V_N.

Every measured mode parameter r_i =1…M, where M is the number of measurements, is an explicit function from voltage $r_i(U)$, and the analytical form of this function corresponds to Ohm's law and Kirchhoff's law. The calculation results of the mode parameters $r_i(U)$ and r_i are inconsistent with each other, due to measurement errors, resulting from imperfection of measuring equipment and irregularity of mode parameters measurements. The proximity measure of calculated and measured parameters can be identified by means of the formula (1):

$$\boldsymbol{r} = \boldsymbol{r}(U) \pm \boldsymbol{f}(U), \tag{1}$$

where $\boldsymbol{r} = \{U_i, P_i, Q_i, P_{ij}, Q_{ij}\}$ is a mode parameters vector; $\boldsymbol{r}^T(U) = \{U_i, P_i(U), Q_i(U), P_{ij}(U), Q_{ij}(U)\}$ is a vector-function, defining mode parameters with node voltages; $\boldsymbol{f}^T(U) = [r_1(U) - r_1; r_2(U) - r_2; \ldots; r_m(U) - r_m]$ is a vector of measurement errors; P_{ij}, Q_{ij} are active and reactive power flows from node i to node j; T is an attribute of the conjugation.

Absolute magnitudes and angles of node voltages U_1,δ_1; U_2,δ_2;…,$U_{N\text{-}1},\delta_{N\text{-}1}$; U_N, δ_N are implemented to the state vector $\boldsymbol{u}$ for SPMs accounting purposes. This approach significantly enhances the Jacobian condition, accelerates a convergence of a computation process and reduces SE time.

At nodes, where SPMs are measured, voltage and angle measurements are given as $U_i = U_i^{SPM}$ and $\delta_i = \delta_i^{SPM}$, and, at nodes, where telemetry is measured, as $U_i = U_i^{telemetry}$ and δ_i=0 respectively. If a voltage measurement is not available at a node, it is necessary to assume that $U_i^k = U_i^{nominal\ voltage}$ and δ_i=0.

The vector and the vector-function of mode parameters are expanded for SPMs accounting purposes (2), (3):

$$\boldsymbol{r} = \left\{U_i, \delta_i, P_i, Q_i, I_{ij}, \sigma_{ij}, P_{ij}, Q_{ij}\right\}, \tag{2}$$

$$\boldsymbol{r}(U)=\left\{U_i,\delta_i,P_i(U),Q_i(U),P_{ij}(U),Q_{ij}(U),I_{ij}(U),\sigma_{ij}(U)\right\}, \tag{3}$$

where U_i, δ_i are the voltage absolute magnitude and angle at the node i; $I_{ij}=\sqrt{\left(C_{ij}^2+D_{ij}^2\right)}$ and $\sigma_{ij}=\text{arctg}\left(D_{ij}\div C_{ij}\right)$ are the current absolute magnitude and angle in the ij connection; $P_{ij}=C_{ij}\cdot\sqrt{3}\cdot U_i$ and $Q_{ij}=D_{ij}\cdot\sqrt{3}\cdot U_i$ are the active and reactive power flows in the ij connection; $P_i=\sqrt{3}\cdot U_i\cdot\sum_{j\in N}^{N}C_{ij}$ and $Q_i=\sqrt{3}\cdot U_i\cdot\sum_{j\in N}^{N}D_{ij}$ are injections of active and reactive powers at the node i, if $C_{ij}=U_i\cdot(g_{ii}+g_{ij})-U_j(g_{ij}\cdot\cos\delta_{ij}-b_{ij}\cdot\sin\delta_{ij})$ and $D_{ij}=U_i\cdot(b_{ii}+b_{ij})-U_j(g_{ij}\cdot\sin\delta_{ij}+b_{ij}\cdot\cos\delta_{ij})$, where g_{ii}, b_{ii} are active and reactive self-conductivity of the node i; g_{ij}, b_{ij} are active and reactive conductivities of the ij connection; $\delta_{ij}=\delta_i - \delta_j$ is the voltage reciprocal phase shift between nodes i and j; δ_i, δ_j are the voltage angle at nodes i and j. The Jacobian is also expanded for:

current absolute magnitude and angle (4):

$$\frac{\partial I_{ij}}{\partial U_i},\frac{\partial I_{ij}}{\partial U_j},\frac{\partial I_{ij}}{\partial \delta_i},\frac{\partial I_{ij}}{\partial \delta_j},\frac{\partial \sigma_{ij}}{\partial U_i},\frac{\partial \sigma_{ij}}{\partial U_j},\frac{\partial \sigma_{ij}}{\partial \delta_i},\frac{\partial \sigma_{ij}}{\partial \delta_j}, \tag{4}$$

active and reactive power flows (5):

$$\frac{\partial P_{ij}}{\partial U_i},\frac{\partial P_{ij}}{\partial U_j},\frac{\partial P_{ij}}{\partial \delta_i},\frac{\partial P_{ij}}{\partial \delta_j},\frac{\partial Q_{ij}}{\partial U_i},\frac{\partial Q_{ij}}{\partial U_j},\frac{\partial Q_{ij}}{\partial \delta_i},\frac{\partial Q_{ij}}{\partial \delta_j}, \tag{5}$$

injections of active and reactive powers (6):

$$\frac{\partial P_{i}}{\partial U_i},\frac{\partial P_{i}}{\partial U_j},\frac{\partial P_{i}}{\partial \delta_i},\frac{\partial P_{i}}{\partial \delta_j},\frac{\partial Q_{i}}{\partial U_i},\frac{\partial Q_{i}}{\partial U_j},\frac{\partial Q_{i}}{\partial \delta_i},\frac{\partial Q_{i}}{\partial \delta_j}, \tag{6}$$

Accordingly, the transition from the rectangular coordinate system to the polar coordinate system with SPMs is provided.

2.2 Calculation of SPMs weight factor

In the SE block the weight factor matrix recognizes the importance and quality of a measured mode parameter in reference to the other mode parameters. It is complicated by user's configurations resulting in frequent failure of an iterative process. Therefore, the formula (7) is suggested

$$c_{ij}=\frac{1}{\sum_{i=1}^{M}j_{ij}^2}, \tag{7}$$

where j_{ij} is the Jacobian component.

This approach guarantees a monotonous reduction of the weighted sum of the voltage square imbalance.

2.3 Algorithm of the method

The algorithm flow-chart of the proposed SE method is presented in figure 2, where k_{max} is the limit number of iterations; ε is the reasonable error of the voltage vector estimation, calculated as the difference of estimated voltage values at power system nodes on k and k+1 iterations, representative of an iteration convergence; t is the time interval, when a measurement array is formed; t_1 is the calculation time; t_0 is the time, when the last hard change of a topology and a mode is recorded. Diagonal entries of the covariance matrix of the process noise $\boldsymbol{Q}$ equal the measurement variance σ^2: σ=0.02 for telemetry and σ=0.005 for SPMs [20].

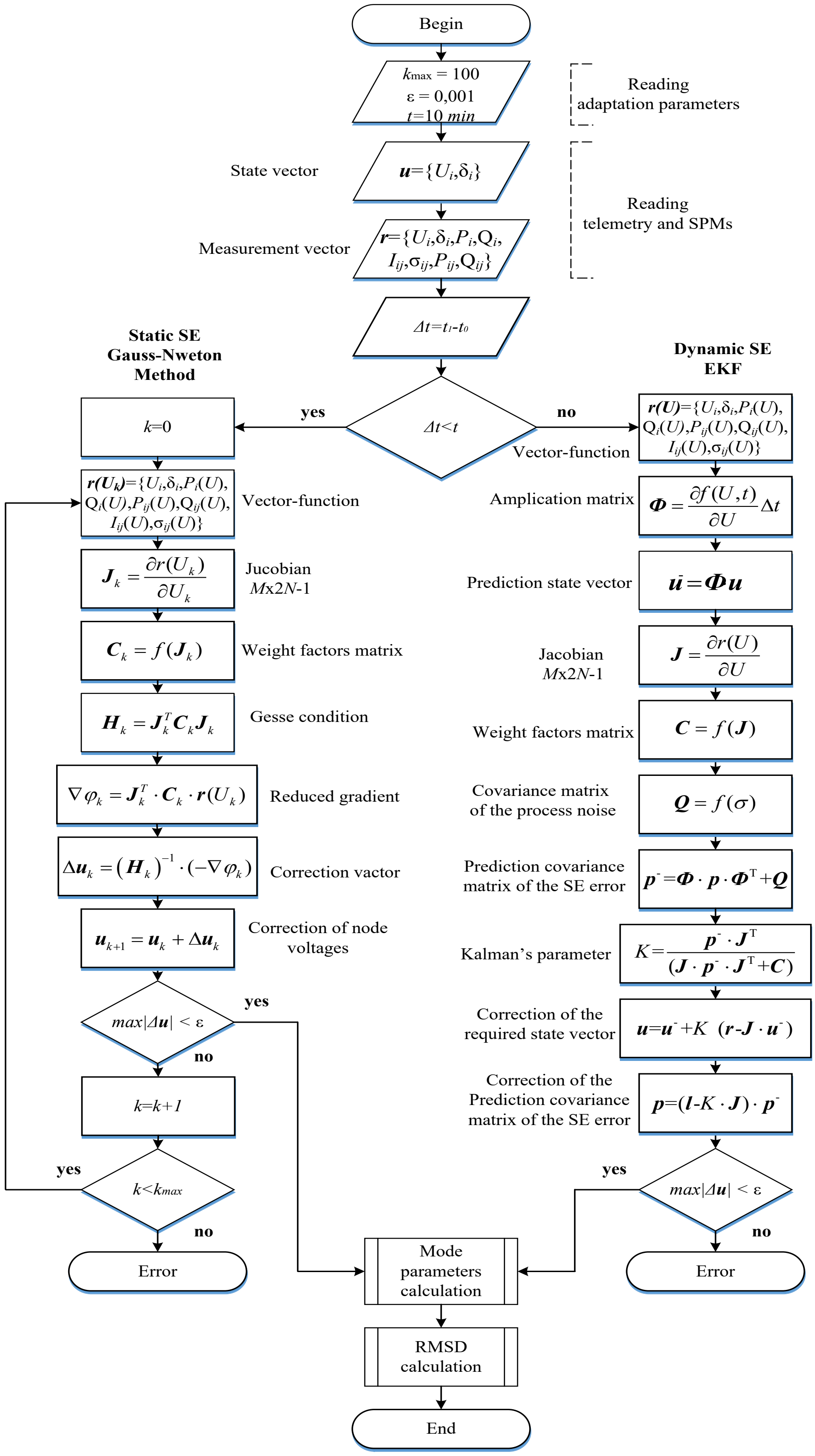

Fig.2. The algorithm flow-chart.

A root-mean-square deviation (RMSD) of mode parameters from a reference parameter is calculated by formula (8):

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(r_i - \overline{r})^2}{n-1}}, \tag{8}$$

where r_i is a mode parameter value; $\overline{r}$ is the mean mode parameter value in a data selection; n is the number of values in a data selection.

3. Practical approbation and results

Figure 3 shows the part of the equivalent topology of 500 kV Siberian united electrical grid. This model is implemented to the automated dispatch management system. The following legends are assumed: a State Regional Power Plant (SRPP), a Hydro Power Plant (HPP), and a Power Substation (PS). The telemetry and SPMs are collected from OIC.

PMUs are located on connections: SRPP-1 – PS-4, SRPP-2 – HPP-2, PS-14 – HPP-2, PS-14 – PS-15, HPP-3 – PS-19, PS-20 – PS-19, PS-20 – PS-21, PS-18 – PS-20, PS-21 – PS-18, PS-21 – PS-20, PS-21 – HPP-4, PS-21 – HPP-5, PS-21 – PS-22. They are marked with a grey circle.

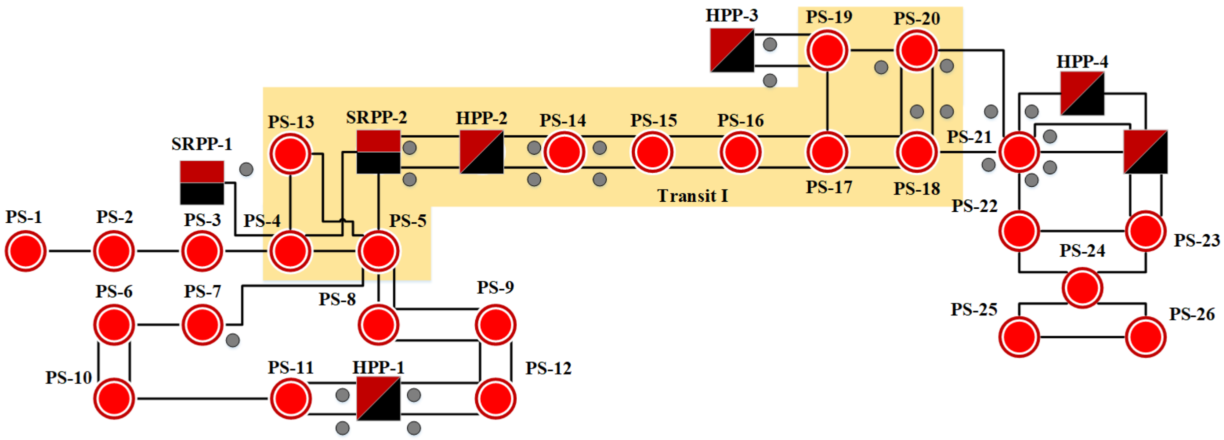

Fig.3. Equivalent topology of 500 kV united power system electrical grid.

Steady state and post-accident modes are studied. The post-accident mode is aligned with the shutdown of 500 kV power line PS-19 – PS-17 by a relay protection. SE is completed by the standard static SE method by telemetry and the suggested method by telemetry and SPMs. According to the nodes of Transit I, figures 4 – 7 demonstrate the RMSD sharing for an active power and voltage measured and estimated values from control values, obtained in the steady state and post-accident modes.

The active power RMSD mean value equals 1.62 MW for measured values, for estimated values by the standard static SE method by telemetry is 1.51 MW and for estimated values by the suggested method by telemetry and SPMs equals 0.86 MW. The voltage RMSD mean value equals 1.91 kV for measured values, for estimated values by standard static SE method by telemetry is 1.32 kV and 1.15 kV for estimated values by suggested method by telemetry and SPMs.

The active power RMSD mean value equals 3.68 MW for measured values, for estimated values by standard static SE method by telemetry is 3.15 MW and 2.11 MW for estimated values by suggested method by telemetry and SPMs. The voltage RMSD mean value equals 3.65 kV for measured values, for estimated values by standard static SE method by telemetry is 2.12 kV and 2.07 kV for estimated values by suggested method by telemetry and SPMs. In the mode, when PS-19 – PS-17 power line is shutdown, active power flows are rerouted between PS-20 – PS-19, PS-18 – PS-20, PS-17 – PS-18 power lines. In this case, the SE accuracy is notably higher for the nearby nodes, where the structure of a power system and the mode are changed.

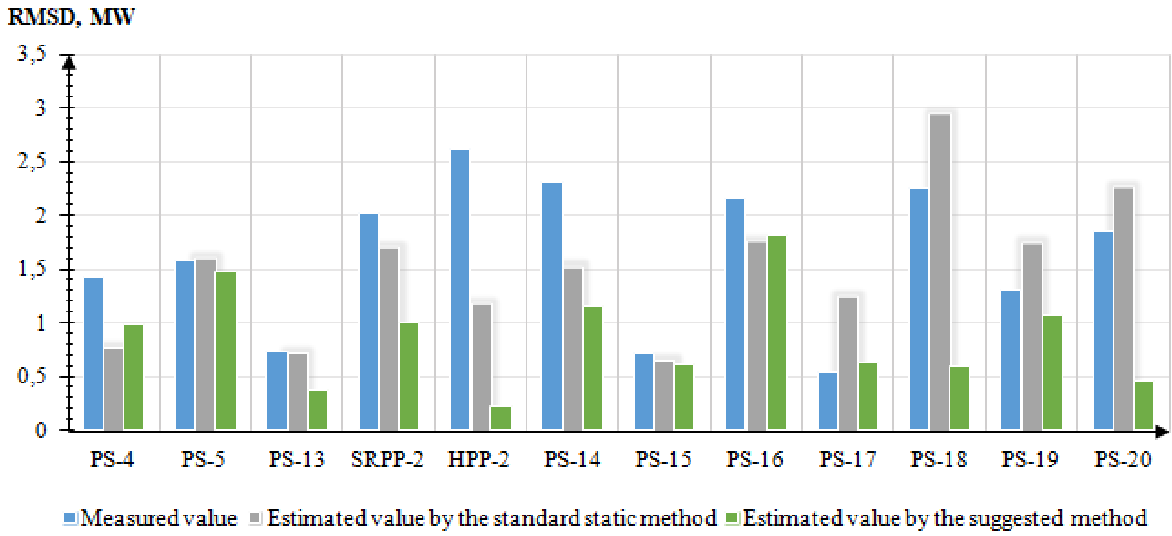

Fig.4. Active power RMSD sharing at the steady state mode

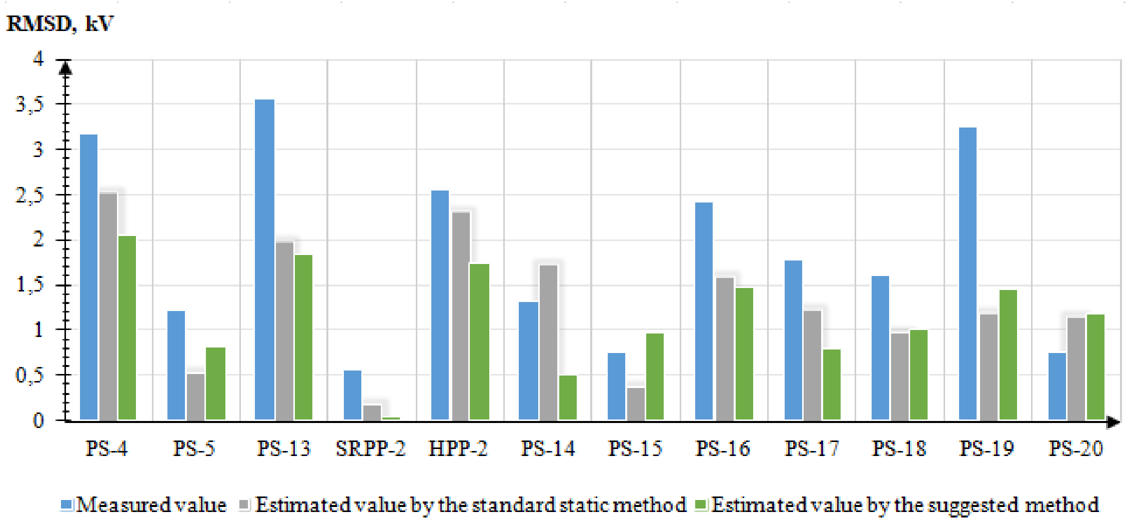

Fig.5. The voltage RMSD sharing in the steady state mode

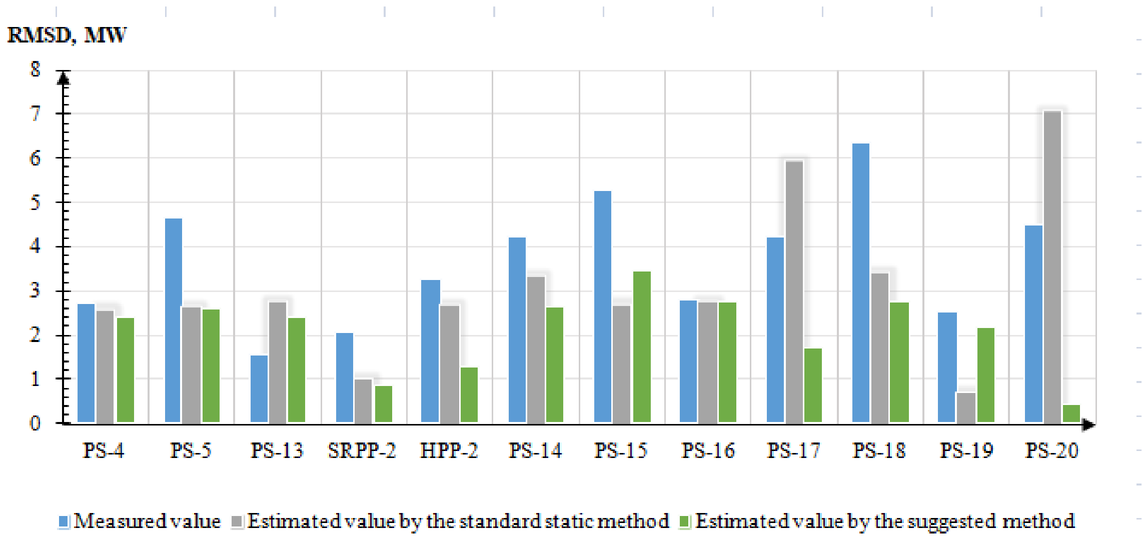

Fig.6. The active power RMSD sharing in the post-accident mode

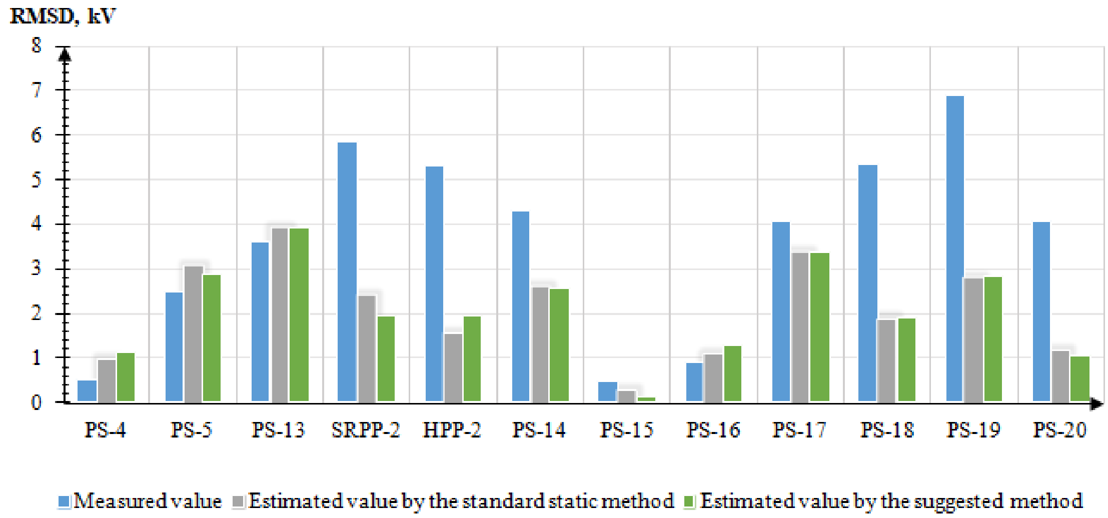

Fig.7. The voltage RMSD sharing in the post-accident mode

The high efficiency of the proposed method for nodes with SPMs is associated with the correct prediction of mode parameters based on measurements in previous time. Meanwhile, the predictive accuracy is lower for nodes with telemetry due to low data rate.

4. Conclusion

1. The SE method is formulated and tested by the high voltage power system. This method is based on the sophisticated Gauss-Newton method and the extended Kalman filter, when telemetry and synchronized phasor measurements are used in combination. The suggested method allows evaluating mode parameters with greater accuracy than a standard static SE method. It is to be noted that:

– SE operates in polar coordinates considering voltage and current angles (formulas 2 – 6), therefore, the Jacobian condition and calculation process convergence are improved.

– Even though the unscented Kalman filter has a desirable accuracy, it requires identifying additional parameters, which are initially indeterminable for all complexes of the system structures and modes. For that reason, the extended Kalman filter has been chosen for dynamic SE.

– Formula (7), which ensures convergence of the iterative process, is offered for calculating weight coefficients of a measured parameter relative to other parameters.

2. It should be noted that the suggested method improves the accuracy of active power flow estimation by 1.76 times for the steady state mode and by 1.5 times for the post-accident mode, while, voltage estimation accuracy shows a 1.2 increase for the steady state mode. These results enable the solution of technological tasks in power engineering with greater accuracy.

3. To implement this method in real-time software packages of the ICC state estimation block, an algorithm (fig.2) is developed. This algorithm includes the command option to receive data from OIC and WAMS.

4. The authors emphasize the importance of codify the theory of continuous and discrete linear Kalman filters, quasilinear filters, generalized nonlinear Kalman filters and continuous and discrete suboptimal nonlinear Pugachev filters to improve the dynamic component of the SE method [22].

5. The additional researches represented that the proposed method permits to calculate maximum allowed active power flows and control action volumes at controlled sections with greater accuracy. The mode parameters, estimated by the suggested method, is applied for calculations of maximum allowed active power flows and control action volumes at controlled sections of 14-bus IEEE electrical grid and 220 kV real power system. The obtained results show that in the steady stay mode, maximum allowed active power flows outnumber by 12 MW against the previously defined number and in the post-emergency mode it is more by 40 MW. It indicates that the total capacity of controlled sections is not used to the end. Whereas, control action volumes in the steady stay mode is more by 2 MW and 13 MW in the post-emergency mode. The use of underestimated control action volumes can not support the stability and reliability in a power system.

Conflict of interest statement
The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

CRediT author statement
Batseva, N.L.: Conceptualization, Writing - Review & Editing; **Foos, J.A.:** Validation, Investigation, Software.
The final manuscript was read and approved by all authors.

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