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PHYSICAL AND TECHNICAL ENERGY PROBLEMS

TESTING OF THE PROTOTYPE FOR STATE ESTIMATION OF LARGE-SCALE POWER SYSTEMS

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The paper describes the algorithm for distributed state estimation (SE) and is focused on its testing and validation. For this purpose, different events in the modeled power system of the 330–750 kV electrical ring Latvia – Lithuania – Belarus – Smolensk – Moscow – St. Petersburg – Estonia – Latvia were considered. The methods for testing the Inter-TSO SE prototype and dynamic network monitoring & modeling are based on comparison of the available SCADA data about real events with those of SE calculation. In total, four operational states were studied, including initial, accident and two post-accident operational states.

Key words: *distributed and dynamic state estimation, SCADA, PMU, wide area monitoring.*

1. INTRODUCTION

Shortly after digital protection devices had been introduced, many experts predicted the soon-to-come end of digital fault recorders. However, their further development has provided completely new functions, whose application facilitates transparent management of communication and distribution systems as well as of power plants.

With application of the Phasor Measurement Unit (PMU) function at power plants as well as at high-voltage and ultra high-voltage switching stations, the absorbability of system has become much better. The main advantages of PMUs are time-synchronized measurements (unavailable with classical SCADA systems) and the time resolution of 20 ms *vs.* few seconds in SCADA systems.

Previously used systems – such as oscillographs and SCADA – did not ensure the necessary level of accuracy and synchronization. The new generation of devices like PMU provides the time-synchronized data of high accuracy and sampling rate which could be used for dynamic and distributed state estimation (SE).

In order to perform estimation of the type, a link between the system operator and the measuring devices is needed. This link is provided by the information technologies ensuring data representation, calculations and analysis. The objectives of such a technology could include the automatic and fast data input from PMU and the accident forecast. Future objectives of the SE prototype also comprise:

- Development of methods and algorithms for solving the SE problem based on Test Equations method [1] and new metering devices (PMU and smart power meters).
- Development of methods for dynamic SE to forecast and monitor the operating conditions on the basis of new systems and technologies (PMU, artificial intelligence (AI) methods, etc.).
- Development of distributed algorithms for solving the SE problem based on decomposition methods and PMU measurements.

2. TEST CASE FOR INTER-TSO STATE ESTIMATION

The Baltic 330–750 kV electrical ring comprising the nodes of five countries was chosen as the object of our test case. The ring is: Estonia – Latvia – Lithuania (Kaliningrad) – Belarus – Smolensk – Moscow – St. Petersburg – Estonia (Fig. 1).

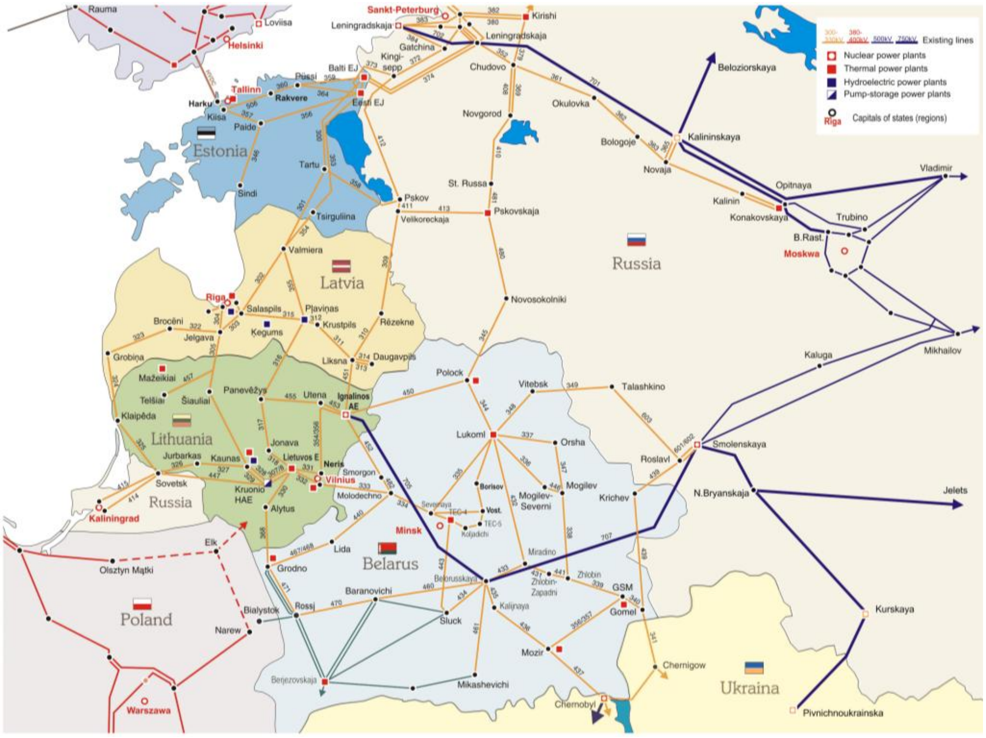

Fig. 1. The Baltic Electrical Ring.

The total length of Electrical Ring is about 2500 km [2]. Each intersystem connection has at least three parallel 330 kV transmission lines (TLs), except Smolensk – Belarus connection that has two 330 kV and one 750 kV TL and Moscow – St. Petersburg connection having one 330 kV TL and one 750 kV TL. The system consists of a large number of nodes and multiple power systems (PSs) of different countries, which is a great advantage for testing the algorithm. The model includes a large number of power plants (more than ten, total capacity

> 900 MW) which are connected to 330–750 kV network [3]. The following TSOs are involved in the operative and technological management of the electrical ring: Latvian, Lithuanian, of Kaliningrad, Minsk, Vitebsk, Mogilev, Gomel, Grodno, Smolensk, Moscow, Tver, Novgorod, Leningrad, Pskov as well as Estonian TSOs and those of united Belarus and Russian northwest PSs.

3. DATA SIMULATION

A large number of operational states were tested, and the calculated values were compared with the SCADA data provided by the Latvian TSO using *Mustang* software. The software has shown its efficiency in modeling the static and dynamic processes in large electric PSs. It includes the possibility to model the emergency automation, which is necessary in the cases of large-scale disconnection of generation units. The static operational state calculation was made using Newton–Rawson's method with improved borderline state convergence in accordance with Matveev's method. The linear algebraic equation system is solved in accordance with Gauss' method, which includes optimization of the sequence of excluding previously unknown variables [2].

For comparison with calculated data, the Latvian TSO prepared SCADA measurements. With *Mustang* software, several characteristic operational states were calculated, and an example was chosen with the biggest difference between the calculated values and the SCADA measuring results.

Figure 2 depicts the calculated values of power flows between the systems as of 26 April, 2010 and SCADA measured (red color). The difference between the SCADA and the simulated data was mostly 2–3%.

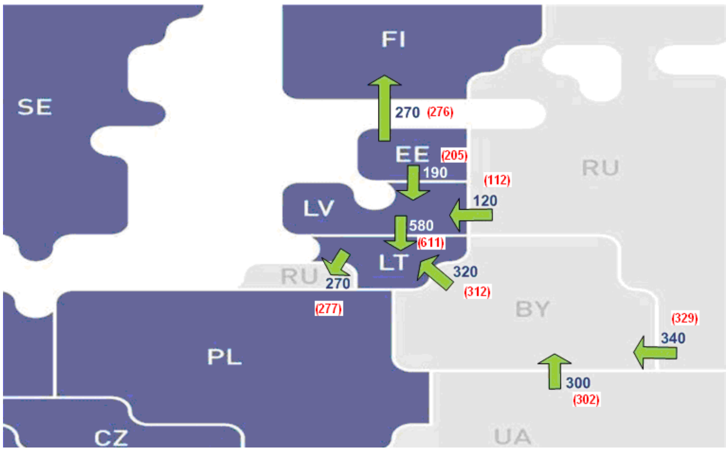

Fig. 2. Calculated values of power flows between the systems (26.04.2010) and SCADA measuring results (red color).

The difference between the calculated 330 kV voltage levels in the Baltic span of Electrical Ring is also not greater than 2% (see Fig. 3).

Figure 4 shows relative voltage monograms of a 330 kV network that correspond to 330 kV substation measurements (28 objects). Each name on the circle corresponds to a particular substation, and the Y-axis (from center to circumference) refers to the relative voltage angle. In this figure it is seen that the 330 kV voltage angle relative to the zero point of modeling scheme in the Baltic span also does not differ more than by 2%.

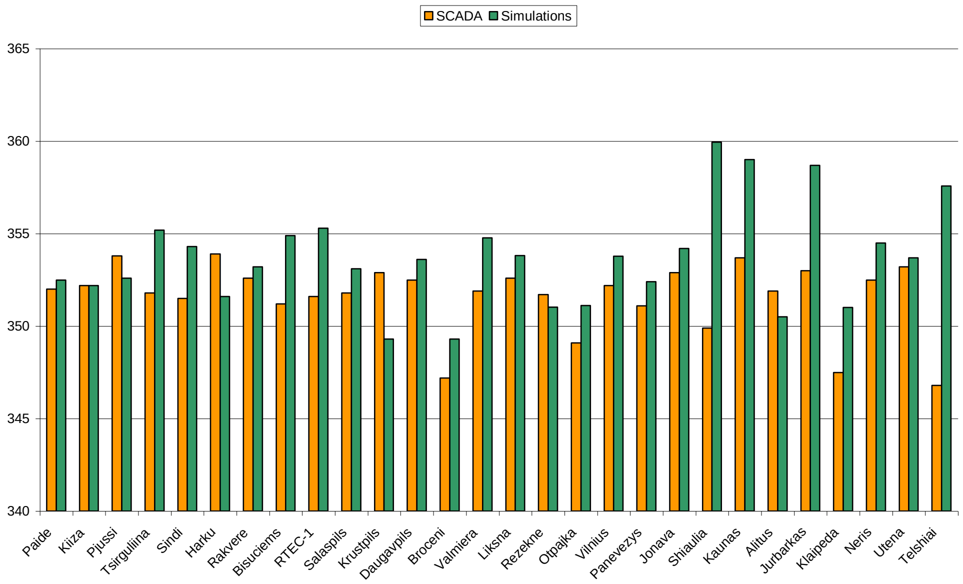

Fig. 3. Voltage levels in the Baltic state span of Electrical Ring.

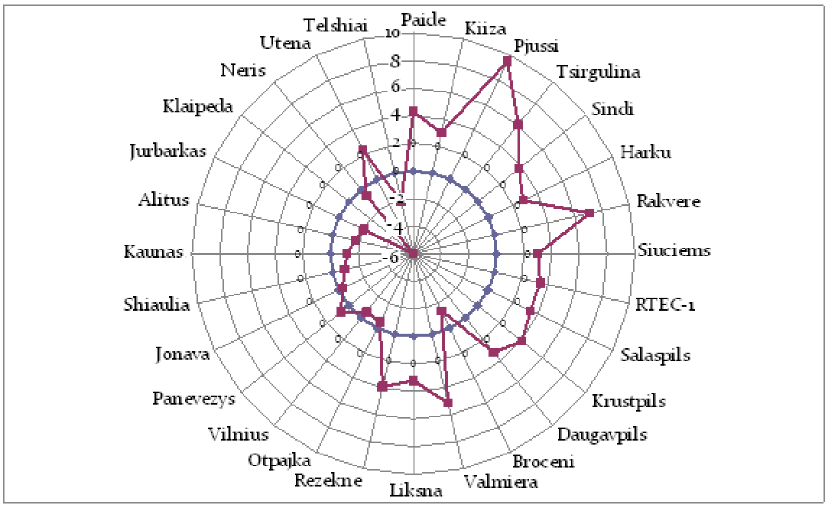

Fig. 4. Relative voltage angle monograms of 330 kV network.

From Figs. 2–4 it can be inferred that *Mustang* simulations are highly accurate, so the simulated data could be used for state estimation.

Next, the simulations of Baltic Electrical Ring parameters are provided. The results include operational states that will further be used for testing the SE algorithm.

Tables 1, 2 and Figs. 5–8 provide results of the 330 kV network simulation for three events (the third one also including four operational states).

For calculation of the voltage angles the Moscow Kalininskaya NPP substation was taken as reference (zero-angle).

The ranges of stable operation are 320–362 kV and 0–30 degrees for voltage levels and angles, respectively.

Event 1. The first event is the 400 MW loss in generation power at the Estonian power plant.

A 350 MW power flow passes through the DC link between Estonia and Finland in the direction to Estonia. The power flow distribution between 330 kV and 750 kV TLs in the electrical ring is illustrated in Table 1.

Voltage levels and angles are shown in Fig. 5 and Fig. 6, respectively, giving evidence that there is stably acceptable operating state after post-accident operation, as the voltage is in the 320–362 kV limits and the angles do not exceed 30 degrees [4].

The conditions in Electrical Ring before Event 1 were:

- Loads of the Baltic States PS system in a summer operational state.
- Out of operation (repair works):
    - 750 kV Smolenskaya NPP – Belarus TL (long-term disconnections do not relate to its technical condition);
    - 330 kV TLs: Sovetsk – Jurbakas, Utena – Panevezis, Ignalina NPP – Smorgon, Novosokolniki – Pskov CHP;
    - connected reserve TLs between the Ukraine and Belarus (Gomel – Chernigov and Mozir – Chernobyl NPP), aimed to partly compensate the 750 kV TL disconnected state.

The Estonian power station had a post-accident 400 MW generation power disconnection, with the total generation power decreased from 800 MW to 400 MW.

Table 1

Power flows (Event 1)

Connection name	P_{ij}*	P_{ij}* (initial op. state)
1. Centr – SevZap	357.61	549.38
2. EST – SevZap	0.77	–183.71
3. EST – Psk	9.91	–8.51
4. LAT – EST, Psk	–346.77	–305.44
5. LAT – LIET	614.43	573.58
6. LIET – BEL	–295.78	–336.21
7. LIET – Kgd	274.11	274.17
8. BEL – Psk	48.01	49.12
9. BEL – Smol	–283.34	–328.82
10. BEL – UA	–297.56	–297.49
11. EST – FIN	–350	270.00

* indices: *i* – starting node, *j* – end node.

Event 2. The second post-accident operating state arises after the power flow has changed its direction between Estonia and Finland – now 350 MW of power is flowing from Estonia to Finland.

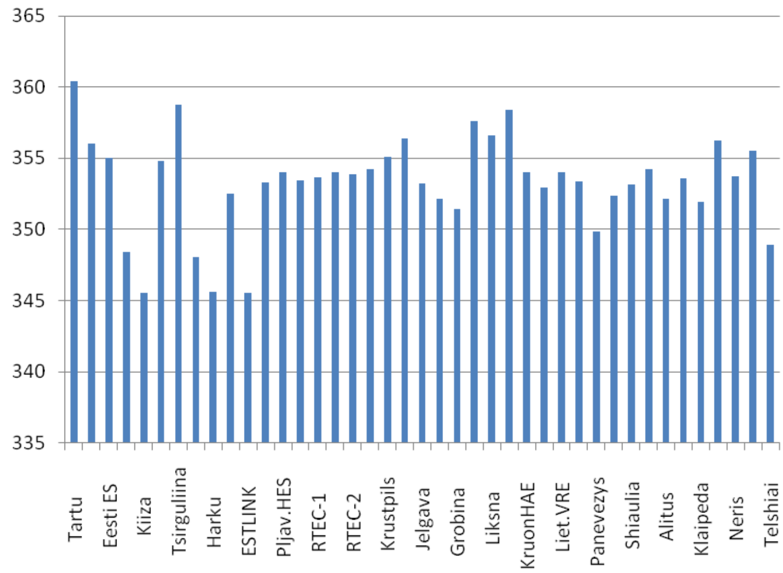

Fig. 5. Voltage levels (kV) in the 330 kV network
of Baltic power system (Event 1).

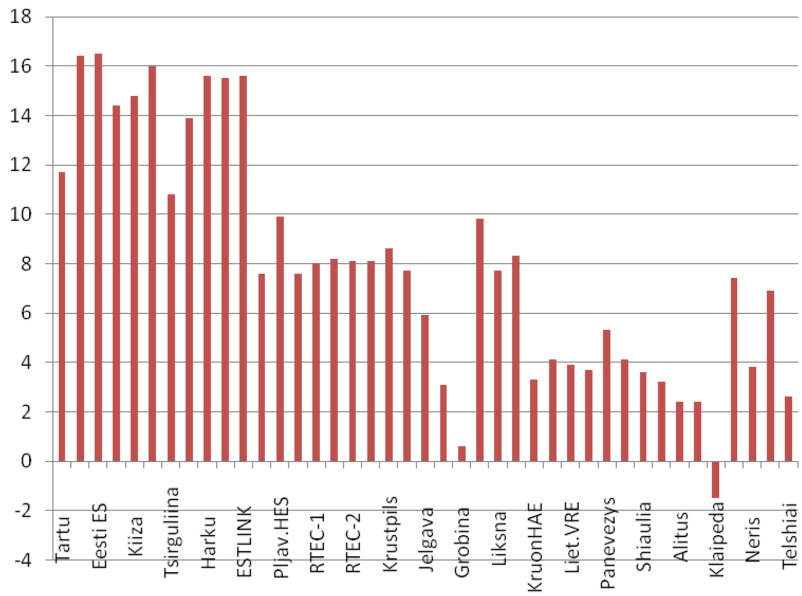

Fig. 6. Voltage angles (deg) in the 330 kV network
of Baltic power system (Event 1).

From Table 2 it is seen that about 84% of 700 MW power (±350 MW according to the direction of power flow in DC link) goes to the Centr – SevZap connection, increasing its power flow from 358 MW to 948 MW.

Figure 7 shows the voltage levels and Fig. 8 – the voltage angles with much higher negative values than in the first event. The absolute voltage angle values are 13–6° smaller.

The system conditions before Event 2 are the same as for Event 1.

Table 2

Power flows (Event 2)

Connection name	P_{ij}	P_{ij} (initial op. state)
1. Centr – SevZap	947.65	549.38
2. EST – SevZap	–568.61	–183.71
3. EST – Psk	–35.79	–8.51
4. LAT – EST, Psk	–219.60	–305.44
5. LAT – LIET	488.51	573.58
6. LIET – BEL	–420.61	–336.21
7. LIET – Kgd	274.29	274.17
8. BEL – Psk	51.40	49.12
9. BEL – Smol	–424.65	–328.82
10. BEL – UA	–297.33	–297.49
11. EST – FIN	350.00	270.00

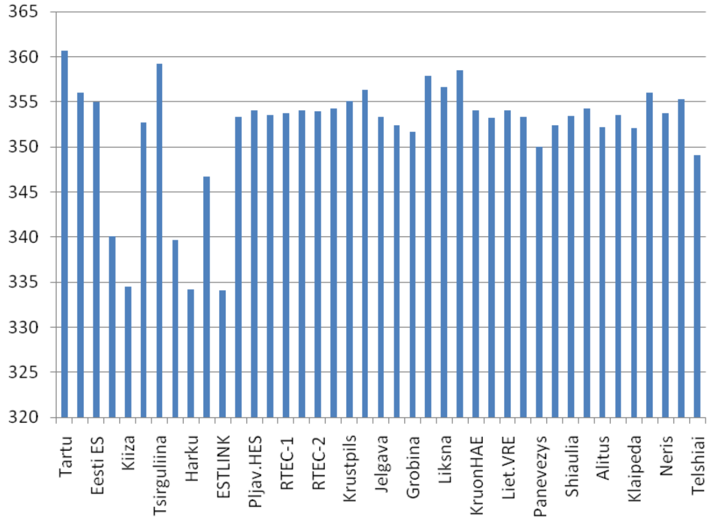

Fig. 7. Voltage levels (kV) in the 330 kV network of Baltic PS (Event 2).

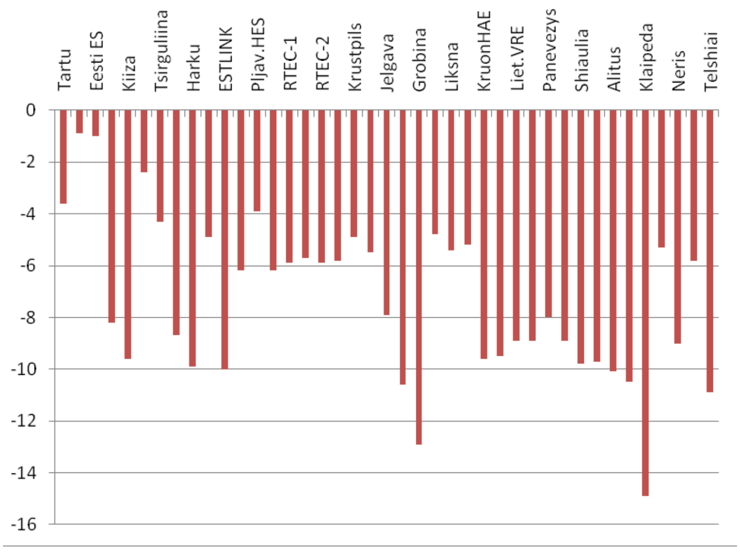

Fig. 8. Voltage angles (deg) in the 330 kV network of Baltic power system (Event 2).

5. TESTING THE PROPOSED ALGORITHM FOR DISTRIBUTED STATE ESTIMATION

The distributed SE algorithm was tested based on *Otsenka* software, using four operational states of Baltic Ring model. Operation state parameters are mainly SCADA data and partly *Mustang* simulation data.

For calculations, *Otsenka* software (developed at the Melentiev Energy Systems Institute) was applied [5, 6]. The software consists of four key modules:

1. A module for reading the information and construction of the calculation scheme for current.
2. A module for validation of measurements and telemetering signals on the basis of test equations.
3. A calculation module for estimation of the measured variables and state vector x.
4. A module for state calculation based on the estimates obtained.

The event (including three further sub-events) chosen for testing the SE efficiency is the Lukomla power plant disconnection. It is a real event that meets the requirements for test case events, including SCADA data provided by the Latvian TSO as input ones, comprising the major part of the network and having a large number of objects involved (power plants, electric lines and transformer sub-stations).

The working time of each module and the total calculation time were evaluated.

The testing comprises calculation of the parameters for four states (including normal operation) and comparison of the calculated and SCADA values. The operational states are described in Table 3.

Table 3

Operational states

Op. state 0	Normal operational state
Event 1	Disconnection of the Lukomla power plant (2100 MW) from the Belarus PS; lines from the power plant to the grid remain in operation.
Event 2	Disconnection of the Lukomla power plant (2100 MW) from the Belarus PS; lines from the power plant to grid are disconnected.
Event 3	Disconnection of the Lukomla (2100 MW) power plant from the Belarus PS; lines from the power plant are disconnected; Plav. HES (Latvia) raised generation by 600 MW

The mentioned events in the Baltic Ring were caused by the following factors:

- all turbo generators (8×300 MW) at the Lukomla power plant were dis-connected (Event 1);
- all outgoing 330 kV TLs (total seven) were disconnected after 1–1.5 min (Event 2);
- hydro-power plants on the Daugava river were launched with the total capacity of 600 MW after triggering the emergency automation at the Belarus substation (Event 3).

Power flows between the systems in the described operational states are shown in Table 4.

Table 4

Power flows in the operational states: initial and at three events

Syst. 1	Syst. 2	Initial op. state		Event 1		Event 2		Event 3	
		P_{ij}, MW	Q_{ij}, MVAr	P_{ij}, MW	Q_{ij}, MVAr	P_{ij}, MW	Q_{ij}, MVAr	P_{ij}, MW	Q_{ij}, MVAr
1*	2	772.2	–481.7	1651	–369.6	1853.2	–346.9	1414.3	–404.1
3	2	–460	–59.6	–866.5	117.5	–972.0	177.5	–737.2	54.9
3	4	–59	–32.9	–39.2	–38.3	–49.6	–36.6	–17.6	–39.7
5	3	–158	–116.2	–734	17.45	–893.4	62.7	–559.8	–36.4
5	6	–196	–45.8	374.7	–124.5	529.7	–133.6	796.5	–144.0
6	7	–701.5	–89.6	–128.5	–146.5	19.8	–10.6	282.6	–136.7
6	8	273.3	–106.9	272.57	–112.8	272.3	–115.9	272.2	–118.0
7	4	57.7	–59.1	–180.4	–0.72	–193.8	3.9	–145.3	–8.7
7	9	–835	–365	–2126.7	104.17	–1908.7	–141.1	–1663.5	–163.6
7	10	–297	72.8	–297.9	–37.6	–297.9	–54.5	–297.9	–32.1
3	11	270	150	270	150	270.0	150.1	270.0	150.1

* 1 – Centr, 2 – SevZap, 3 – Estonia, 4 – Pskovskaya, 5 – Latvia, 6 – Lithuania, 7 – Belarus, 8 – Kaliningradskaya, 9 – Smolenskaya, 10 – Ukraine, 11 – Finland.

6. RESULTS AND DISCUSSION

Comparison of all the events show that the power flow variations in the Belarus – Ukraine connection are insignificant; however, in some connections these are considerable, e.g. in the Belarus – Smolenskaya and Centr – SevZap connections.

The operational state of Event 3 remains stable, despite the inoperative 2400 MW generation capacity and seven 330 kV TLs in the Belarus PS. However, overloading of the network transformers in the northern and southern parts is impermissible, since this can cause damage to some elements and, as a result, a decrease in the capacity at a connection point and dynamic stability break at multiple connection points.

In order to complete the testing of SE efficiency, a comparison was performed for the calculated active power flows and the relevant SCADA data. Table 5 provides such a comparison for the modeled network and different operational states (the table is of introductory character, since in the complete form it would occupy too large volume).

Using *Mustang* software as a simulation tool in the SE prototype we have obtained results of high accuracy. The difference between SCADA and simulated voltages, angles and power flows is less than 3% in all cases.

Although the dynamic state estimation prototype is highly efficient, the model used was smaller as compared with that for distributed SE testing. Also, small angles in the results of calculations indicate the operational state with low power flow values, which means that the accuracy is not maximal though sufficient.

Table 5

Comparison of the calculated and real active power flows in the modeled network

Node 1	Node 2	Initial op. state		Op. state 1		Op. state 2		Op. state 3	
		Active flow, MW		Active flow, MW		Active flow, MW		Active flow, MW	
		Calc.	Real	Calc.	Real	Calc.	Real	Calc.	Real
Centr	KalinNPP	–2204	–2205	–995	–996	–877	–877	–1367	–1367
SmolNPP	Roslavlj	411	412	715	716	591	592	564	564
Vostochnaya	Juzhnaya	–476	–477	–455	–456	–499	–499	–462	–463

7. CONCLUSIONS

The results shown in Table 5 evidence that the calculated power flow values are very close to the real SCADA values in all operational states, which proves high accuracy of the proposed algorithm.

The application of Distributed State Estimation would enable the following:

- Minimization of information to be transferred between the control centers of subsystems operating in parallel and the coordination center.
- Decrease in the SE execution time for the full scheme.
- Simplification to the maximum extent of the coordination problem for individual subsystems, in some cases – elimination of iterative calculations for subsystems.
- Decrease in the non-uniformity of the schemes calculated for subsystems, thus providing a guaranteed convergence of the computational process.
- Improved efficiency of algorithms for Bad Data Detection [7] and better accuracy of SE results.

The Dynamic State Estimation algorithms allow for:

- forecast and estimation of the data at dynamic changes;
- compensation for loss of data with the help of pseudomeasurements;
- achievement of high accuracy;
- different calculation time depending on the scale of a (sub-)system.

The proposed monitoring and state estimation technologies would help in providing opportunities for TSOs, such as new communication channel, Dynamic State Estimation, investigation of accidents, and prevention of blackouts.

ACKNOWLEDGMENT

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LIELO ENERGOSISTĒMU STĀVOKĻA NOVĒRTĒŠANAS PROTOTIPA TESTĒŠANA

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K o p s a v i l k u m s

Rakstā tiek aprakstīti, testēti un novērtēti izkliedēta stāvokļa novērtēšanas algoritmi. Testēšanas nolūkos tika izmantoti dažādi 330–750 kV elektriskā loka Latvija – Lietuva – Baltkrievija – Smoļenska – Maskava – Pēterburga – Igaunija – Latvija modelēti scenāriji. Prototipa testēšanas metodoloģija balstīta uz pieejamo SCADA datu salīdzināšanu ar stāvokļa novērtēšanas prototipa aprēķina rezultātiem. Kopumā apskatīti sākotnējais, avārijas un divi pēcavārijas režīmi.

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