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Evaluation of Latvian Power System Static Stability According to a New Development Strategy until 2025

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Abstract: The current stage of world energy development is characterized by the creation of powerful, territorially unified energy systems under free market conditions as well as renewable energy integration. Such transactions challenge networks' configurations and their operating modes. Electric power system (EPS) static stability could be considered one of the primary targets in this regard. The aim of this study was to evaluate the undergoing and expected modernization of the Latvian EPS in terms of static stability in a regional scale-based case study. In order to define static stability, a method based on a bus admittance matrix was proposed. A simplified Latvian EPS model was developed and assessed for the following three modes: past (2017), current (2020), and planned (2025), taking into account the Baltic States' planned development scenarios including large wind farm integration. The evaluation of computation results provided an opportunity to visually inspect changes in the EPS' sensitive elements such as lines and nodes. As a result, positive changes were observed (decrease of several weak points) for the planned mode (2025) as compared to the past mode (2017) under the considered modernization scenario. The detailed analysis and results are presented in the article.

Keywords: power system modeling; power system interconnection; renewable energy sources; static stability analysis; sensitivity; sustainable development; wind energy integration

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1. Introduction

Electric power systems are complex objects of dispatching and management, requiring compliance with restrictions related to the reliability, safety, quality, and economy of their operating modes. These requirements must be fulfilled by all participants that make up the technological basis of the electricity market. Such concern is essential for an expansion of existing power systems and the modernization process for future, built-up, large energy systems, moving toward their unification in terms of operation and regulations/legalization within certain regions. Thus, the development of market relations in the power industry drives the necessity of the evaluation of network operation modes, considering their multifactor analysis, and forecasting, leading to market relations becoming a key element in ensuring the smooth functioning of the electricity market as well as the integration of renewable energy resources (RES). Ensuring the reliability of the evaluated modes must be considered one of the priority tasks of operational dispatch management.

Currently, the European Union (EU) is updating its energy policy to facilitate the transition to clean energy and improve energy security. Because Baltic region countries (including the Republic of Latvia) are members of the EU, they must gradually approach their energy and economic policies more similarly to the EU. For example, some reforms are mentioned in [1]. For instance, the EU strategy focuses on the support and protection of investments in the energy sector including RES consideration and energy efficiency patterns and contributes to the secure transit of energy supplies [2]. In this way, the aforementioned energy transition must be evaluated and adapted on the regional level in terms of different aspects including vulnerability (stability studies must be conducted in this regard). The implementation of shared objectives and policies must be accelerated and achieved. For instance, the projects of common interest (PCIs) serve as tools aimed to link the EPSs of the EU countries. A detailed list can be found in [3]. Despite a positive tendency toward achieving set targets, some geopolitical issues still exist. For example, the Nord Stream 2 pipeline project, the twin pipeline of around 1230 km that stretches through the Baltic Sea from Russia to Germany [4], is considered to be having a great impact leading to the reduction of Europe's energy security as well as promoting certain consequences for regional integration in energy security. A study of Southeast Europe's energy transition in terms of energy security, sustainability, resilience, and vulnerability is presented in [5].

In accordance with the agreement between the leaders of the Baltic region, Polish and Baltic transmission system operators (TSOs), a formal procedure for expanding the continental European energy network has been started that includes the Baltic States, which will be managed by ENTSO-E (European Network of Transmission System Operators) [6,7].

Considering the priorities of the EU energy strategy [8] and the impacts of the expected reforms including Latvian energy development guidelines [9], let us highlight the primary targets including:

- Increasing energy efficiency;
- Developing the electricity market;
- Increasing the reliability of the power supply;
- Using and integrating RES. For instance, there is a possibility of increasing wind energy share from the existing 8% to 20% when considering the technical and economic factors of the Republic of Latvia, thus increasing the competitiveness of energy prices;
- Preserve the environment while producing, transmitting, and distributing different types of energy.

To address the above-highlighted targets, one important considerations must be devoted to power system stability issues. Stability analysis of any power system leads to defining its performance and weakness indicators in terms of current and planned operation modes. In that turn, it justifies following up on the feasibility of established strategies, regulations, and planned implementation measures for adaptation to the examined power network.

As it is known, the stable operation of a power network depends on its capacity for continuous provision of the generated and consumed power balance as well as the required quality level of electric power. In the past, the stability of proposed systems has been estimated by extrapolating the experience obtained from existing systems and using the rule-of-thumb method. In the future, however, more precise computation methods for predicting and evaluating stability will be required [10] that consider the prospects of growth of the share of renewables.

Usually, a list of the most "dangerous" systems is obtained by simulation of single or joint failures, using a complete or simplified mathematical model of the EPS based on expert judgements and heuristics. For instance, the vulnerability of the EPS may be estimated on the basis of complex systems' general theory [11]. Using this approach, in compliance with the overload level (by comparison with other lines), only one weak point (or branch) of the network, the losing of which brings about a relative decrease in the operation and general efficiency of the whole network for a 34-node diagram, will be determined. Moreover, different optimization techniques have been applied to access power system vulnerability; for instance, a genetic algorithm presented in [12] defined critical system components, a dynamic vulnerability assessment described in [13] used the coherency concept and a fuzzy clustering algorithm considering large power networks, and a nonsequential Monte Carlo approach was applied for power system analysis with protection failure, shown in [14].

Another approach [15] provided a formalized technique for analysis of cascade-developing emergency processes, which allowed obtaining a fairly adequate depiction of the actual events, states, and processes in the EPS that appeared in the cascade development of the accident but did not allow analyzing emergency situations before they occurred. A lot of other studies have been devoted to cascading failure and blackouts analysis; for example, using fault chain theory in power transmission networks [16], a cascading failure graph-based model taking into account continuous transmission line temperature impact [17], a PageRank-based rapid screening method for large-scale power grids [18], a stochastic model under uncertain events (renewable generation and load variation) [19], using new metrics such as the critical moment for a DC power flow model and transient stability analysis [20], and a cascading failure model presented in [21], which included both the structural vulnerability and the state vulnerability of a power network.

A further study [22] aimed to identify weak points and allowed finding the critical (weak) sections (by static stability), based on simplified models. The disadvantage of this approach was the difficulty of analysis and systematization of the results of numerous calculations. Some other research works are related to the same issue; for instance, the geodesic vulnerability approach in [23] explains how to identify power network critical buses, and an adjacent graph is used in [24] to indicate branch importance and at the same time, define fault adjacent relationships between branches. Moreover, to assess the stable operation of a power system, a whole range of different software packages have been designed, both market available and research-focused, which can be used to model a variety of operating modes of power systems.

All the above-mentioned factors highlight the importance of stability analysis for power system operation modes.

This paper aimed to evaluate the Latvian power network in terms of static stability issues for three operation modes by considering their models as follows: past (before modernization, according to system infrastructure in 2017), current (after some modernization was implemented and in particular, the "Kurzeme Ring" project's second and third stages, wherein newly constructed 110 kV and 330 kV transmission lines expanded the existing transmission network, laid out in 2020), and planned (the expected modernization includes new interconnections of transmission lines and the construction of new large wind parks according to the established plan by 2030 [25], when the expected break of continental Europe from the energy ring of BRELL (Belarus, Russia, Estonia, Latvia, and Lithuania) will be fully realized.

An overview of Latvian energy system specifications is presented in Section 2. Next follows the theoretical background of the proposed approach in Section 3. The obtained results and analysis are given in Section 4. A brief discussion of highlights is in Section 5. The final section, Section 6, draws the conclusions.

2. An Overview of Latvian Energy System Specifics

Latvia (officially the Republic of Latvia) is a sovereign state in the Baltic region of Northern Europe. Since the restoration of independence (1990), Latvia has been referred to as one of the Baltic States. It is bordered by Estonia in the northern region, Lithuania in the southern; to the east is Russia, Belarus is to the southeast, and it shares a maritime border with Sweden to the west. Latvia has about 1,900,000 inhabitants and a territory of 64,589 km^2. The country has a temperate seasonal climate.

The Latvian transmission power system historically developed as a deficit power system and then developed the transmission system to a greater extent, paying less attention to the construction of new generating capacities because there was a constant opportunity to buy necessary volumes of electricity from neighboring power systems. Currently, the Latvian transmission power system operates in a single energy ring with the energy systems of Belarus, Lithuania, Russia, and Estonia (BRELL). However, in view of the existing economic and political situation, all three Baltic States (BALTSO) are expected to exit BRELL, joining the Union for the Coordination of Transmission of Electricity (UCTE) (Figure 1) [26].

Figure 1. Preliminary operation scheme for the Baltic countries' system (BALTSO) in an isolated model [26].

Latvia depends on the import of primary energy resources. Without fossil resources, Latvia is highly dependent on oil and gas imports. Hydropower and gas provide almost all the domestic supply of electricity and in recent years have been supplemented by wind energy and energy derived from biomass. Self-sufficiency in energy supply has reached 40% and therefore, both the security of supply and the liberalization of the energy market are vital. Historically, Latvia has been strong in the renewable energy sector due to its high percentage of hydropower use (Table 1). More than a third of total energy consumption in Latvia comes from RESs, and Latvia ranks second in terms of renewable energy consumption among EU countries, but mainly, its strength is related to the significant role of water energy resources (60% of total electricity production; 92% of electricity derived from renewable sources is produced in hydroelectric power stations) and a large amount of biomass (Figure 2) [27].

Table 1. Baltic States' net generation capacity in 2020, MW [28].

Power Plant (PP)	Net Generation Capacity, MW	Energy Source
LITHUANIA		
Fossil fuel PP	1139	
Lithuania PP	570	Natural gas
Kaunas combined heat and power plant (CHP)	102	Natural gas
Vilnius CHP	160	Natural gas
Panevėžys CHP	33	Natural gas
Industrial PPs	274	Natural gas
Kruonis hydroelectric pumped storage power plant (HPSPP)	1125	
RES	1205	
Kaunas hydro power plants (HPPs)	99	Hydro
Small HPPs	40	Hydro
Wind	750	Wind
Solar	80	Solar
Bio	236	Including 37 MW waste
TOTAL	3469	
LATVIA		
Fossil fuel PP	1144	
Riga CHPs	989	Natural gas
Other CHPs	155	Natural gas
RES	2050	
Daugava HPPs	1589	Hydro/Run-of-River
Small HPPs	28	Hydro
Wind PPs	310	Wind
Solar	3	Solar
Biomass and Biogas PPs	170	Bio
TOTAL	3244	
ESTONIA		
Fossil fuel PP	2185	Thermal (oil shale, natural gas etc.)
RES	1046	
HPPs	8	Hydro
Wind PPs, Solar	925	Wind, solar, etc.
Bio	95	Biomass, biogas
Bio	19	Waste
TOTAL	3232	

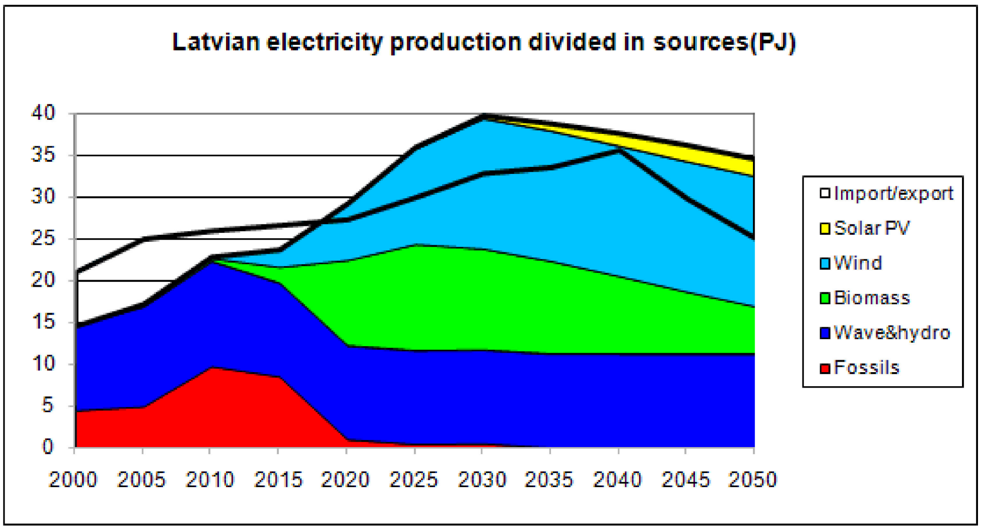


Figure 2. Development of electricity production and sources following Vision 2050 [27].

The most significant local energy resources used are fuelwood and hydro energy (the Daugava Hydroelectric Power Plant (HPP) cascade). Solid fuel, oil products, and electricity are imported from several countries and supply regions, but there is only one supplier for natural gas—Russia.

Overview of the Baltic States' electricity generation, consumption, and average Nord Pool electricity exchange prices in 2020 are given in Figure 3 and Table 2. As shown, in Latvia, variable hydro resources influence the amount of electricity produced by the Daugava HPP cascade. Because Latvian power plants are not capable of producing the required amount of electricity throughout the whole year, a shortage in electricity supply (or sale of surplus produced electricity in full-water periods of the year) is realized using interconnections.

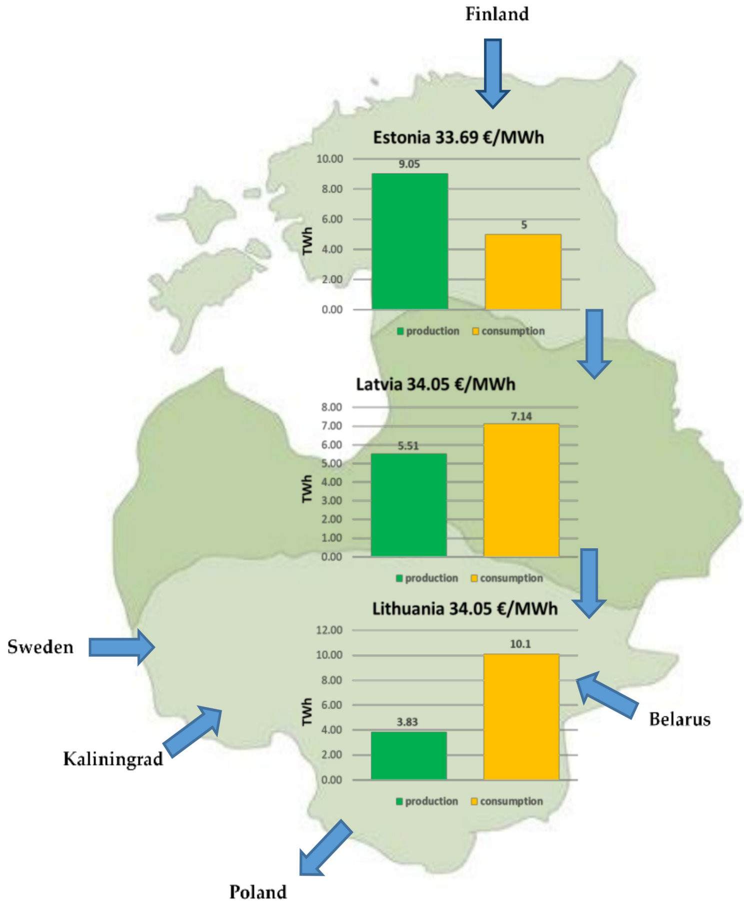


Figure 3. Baltic States' electricity generation and consumption in 2020 [29–32].

According to Nord Pool information in 2020, Sweden (via NordBalt cable) exported to Lithuania 4,559,426 MWh and to Poland (through the Lit–Pol Link), 458,046 MWh, while Finland exported to Estonia 6,438,480 MWh. Additionally, 3,949,672 MWh were supplied from third-party countries (Belarus and Kaliningrad (Russia)) through Nord Pool Lithuanian and Latvian trade areas. As result, the total consumption of electricity was 7,135,520 MWh in 2020, 2.2% lower than consumption in 2019 [29].

Using local generation, Latvia covered its electricity consumption by 77%. In 2020, primary energy consumption was 5.4 Mtoe, but final energy consumption was 4.5 Mtoe (Table 3) [33].

Table 2. Electricity generation and import/export, consumption indicators in Latvia, 2020 [29].

Indicator	Electricity in 2019, MWh	Electricity in 2020, MWh	Relative Changes, %
Daugava Hydro	2,036,063	2,514,338	23.5
Thermal	2,822,835	1,739,352	−38.4
Wind	152,489	175,084	14.8
Cogeneration (up to 10 MW)	383,821	308,543	−19.6
Biomass (up to 10 MW)	399,627	391,788	−2.0
Biogas (up to 10 MW)	322,780	309,070	−4.2
Small Hydro (up to 10 MW)	59,829	69,671	16.4
Solar	1534	2039	33.0
Production (Total)	6,178,978	5,509,885	−10.8
Electricity import to Latvian electricity grid	4,610,761	4,173,365	−9.5
Export from Latvian electricity grid	3,492,683	2,547,730	−27.1
Net exchange SALDO	1,118,078 (deficit)	1,625,635 (deficit)	45.4
Latvian electricity consumption	7,297,056	7,135,520	−2.2
Consumption share covered by local generation	84.70%	77.2%	−7.46
Import from 3rd countries to the Baltic States	7,823,174	3,949,672	−50
Import from EU countries to the Baltic states	7,913,798	11,455,952	45

Table 3. Absolute level of energy consumption in 2020 (Mtoe) in EU countries [33].

EU Member State	Primary Energy Consumption, Mtoe	Final Energy Consumption, Mtoe
Austria	31.5	25.1
Belgium	43.7	32.5
Bulgaria	16.9	8.6
Croatia	10.7	7.0
Cyprus	2.2	1.9
Czechia	44.3	25.3
Denmark	17.5	15.2
Estonia	6.5	2.8
Finland	35.9	26.7
France *	226.4	137.9
Germany	276.6	194.3
Greece	24.7	18.4
Hungary	26.6	18.2
Ireland	13.9	11.7
Italy	158.0	124.0
Latvia	5.4	4.5
Lithuania	6.5	4.3
Luxemburg	4.5	4.2
Malta	0.8	0.6
Netherlands	60.7	52.2
Poland	96.4	71.6
Portugal	22.5	17.4
Romania	43.0	30.3
Slovakia	16.4	9.2
Slovenia	7.1	5.1
Spain	123.4	87.2
Sweden	43.4	30.3
United Kingdom	177.6	129.2
Sum of indicative targets EU28	1543.1	1095.8
EU target 2020	1483	1086

* Adjusted with an estimate for international aviation energy consumption of 6.5 Mtoe.

3. Theoretical Background of the Proposed Approach

Computation methods used for practical purposes require experimental verification. To be able to assess rapidly the performability, efficiency, and reliability of new equipment and new devices; test new theories and methods; and evaluate the assumptions and premises of already existing methods, it is necessary to have the ability to test experiments in the system, allowing for simulating many modes and reproducing any accidents as well as observing and identifying their consequences. In the real power system, the possibilities of conducting experiments are very limited. All observations of "naturally occurring" accidents or in rare cases, accidents "specially produced" in systems, must be processed and presented in criterial dependencies with the application of data from a single (in essence, unique) experiment to a number of (class) similar systems and conditions. However, the difficulty and fundamentally limited possibilities of obtaining such results lead to the need to create an experimental system. It is obvious that only a model system can be used as such, in connection with the various analogue and computing devices finding extensive use in the electric power industry.

The construction of reliable mathematical models of power systems provides the possibility of controlling the electric power system (EPS) regime based on a single approach of structural analysis, simultaneously associated with the widest possible set of regime indicators and electrical system characteristics.

Application of this approach allows solving the actual management tasks related to:

- Determination of the admissibility of adding new loads to the existing power system and the need to modernize the energy system to meet current electricity demand;
- Identification of power system weak connections with regimes closest to the stability limit;
- Visibility of marked nodes where installation of active mode control devices is rational, leading to increased reliability and economy in the transmission of electricity.

The technological processes of electricity production and transmission are connected with many other processes in industry, transport, and other life sectors. Therefore, the implementation of economic development plans in Latvia should provide the possibility for construction of new electric power facilities, including high-voltage interconnections. Currently, JSC Augstspriegumu Tikls is implementing several projects: for instance, the third 330 kV interconnection between Estonia and Latvia, the 330 kV transmission line between Riga TEC-2 and Riga HES, and synchronization of the Baltic States with continental Europe, as shown in Figure 4.

Furthermore, when addressing issues related to the safety of the energy supply, safety aspects should be carefully evaluated, both nationally and regionally, to ensure a flexible and secure energy supply on a national scale.

Analysis of the regime characteristics of existing overhead power lines with a nominal voltage of 330 kV requires specification of the limiting regimes. Thus, the carrying capacity is not determined by all indicators characterizing the stable operation of power transmission lines. Reserve coefficients of static stability in some cross sections are lower than normatively permissible. Regulatory properties of the receiving power system are not fully considered. In these conditions, let us consider the influence of various factors affecting the ultimate power transmission modes and the possibility of improving carrying capacity.

For certain values of both the regime and system parameters, the limiting regimes in the cross sections can be estimated based on a criterion analysis. In the first approximation, the limiting regimes, obviously, are determined by the carrying capacity under the stability conditions of the normal preset operating modes. When calculating modes, steady-state calculation methods are used. To do this, one can use the node potential method or other iterative calculation methods.

The uniqueness of the solution of the steady-state electric network with successive weighting of the regime, as it is known, characterizes the steady-state regime. The deterioration of convergence characterizes the presence of "heavy" regimes. The violation of convergence determines the approach to the limiting regimes for both aperiodic stability and other constraints. The limit of regime existence is close to the limit in aperiodic stability.

Consecutive weighting of the regime, as a rule, must begin with the "weak" ties in this cross section. Next, it is necessary to determine the limit regime for other ties in this cross section. The following situations are possible: First, a solution can exist, but the regime is aperiodically unstable, or secondly, the state of the power system cannot be limited in stability.

The EPS sensitivity issue in steady-state regimes was first studied in relation with the analysis of errors' influence in initial data. From the EPS modeling point of view, errors' influence in initial data on the results of an accurate model is quite relevant to the effects of the real disturbances in the values of the regime parameters. Thus, the errors' study in results is interesting when considering the problem of weak points. For instance, in [34], attention was drawn to role of the Jacobian matrix condition number in estimating the calculation results error, showing that the main reason for poor conditionality was the branches' resistance difference in the electric network.

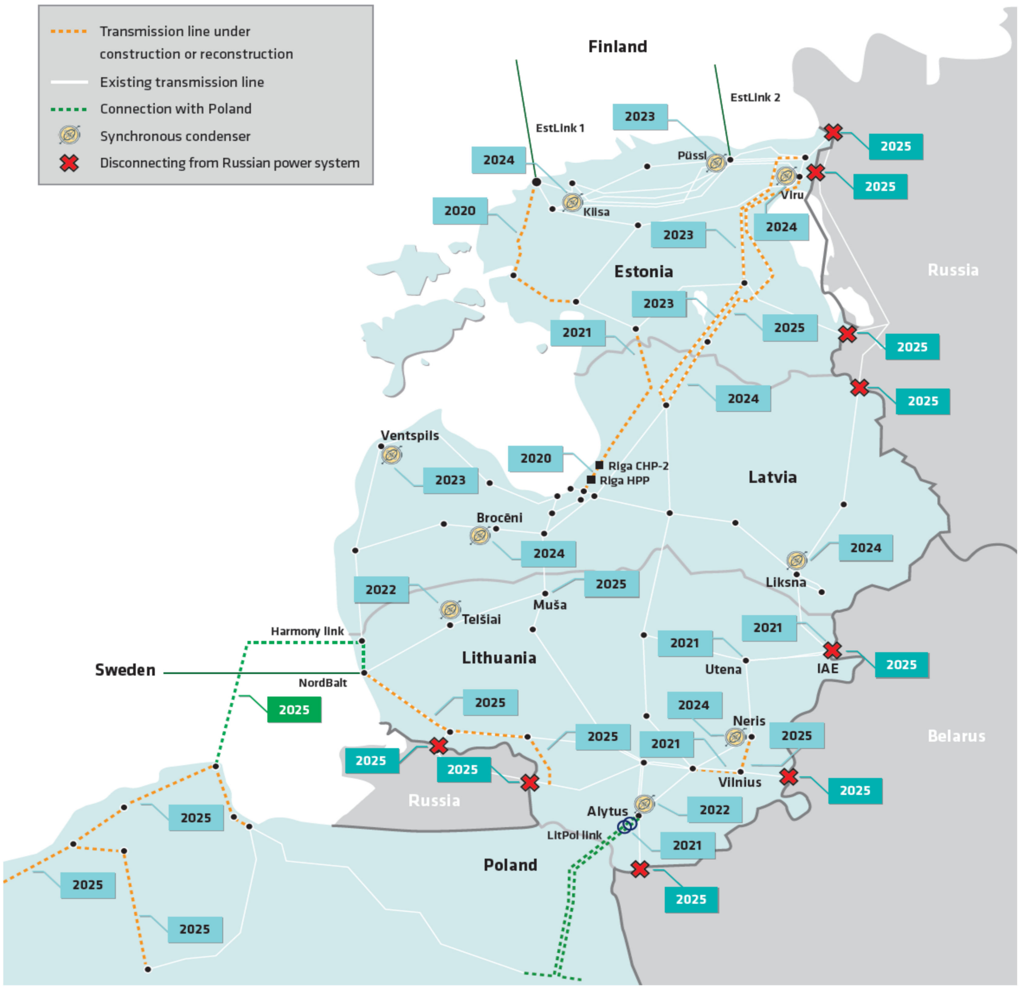


Figure 4. Development of power transmission networks in the Baltic region up to 2025 [35].

The disadvantage of most approaches is vast numerous calculations. At the same time, the main difficulty is related not so much to the modeling of situations and the execution of calculations, but rather to the analysis and systematization of the obtained results. In addition, it should be noted that the calculation of the roots is very simple for the characteristic equations of the first and second degrees. There are general expressions for the roots of equations of the third and fourth degrees, but these expressions are cumbersome and useless. As for the equations of higher orders, it is generally not possible to write a general expression for them. Therefore, a direct solution of the characteristic equation has not been widely used thus far in stability calculations.

The calculation based on the bus admittance matrix and Jacobian matrix provides a more accurate calculation of small eigenvalues in comparison with competing algorithms. To determine sensitivity based on the Jacobian matrix and the bus admittance matrix, a smaller number of operations are required, while sensitivity analysis under normal modes requires less resources, providing the accuracy of the results of computations. The advantage of using the Jacobian inverse matrix is that it is not necessary to solve a system of linear equations in this case. However, the use of the Jacobian matrix has advantages, which will be considered further.

Sensitive elements are those elements of the electrical network in which a given (single) disturbance of the primary parameter causes the greatest change (reaction) of the secondary parameter. At the same time, the definition of sensitivity (sensority) is the degree of regime parameters' reactions to a single disturbance, which can be determined taking into account numerical experiments or indirect indicators, specifically by the following proposed indicators connected with the singular values and eigenvalues of sensitivity matrices. As a result, operational parameters and elements of the EPS that are related to them, with sensitivity that is significantly higher than the sensitivity of others, are called sensory [36].

The most interesting question in the research of EPS vulnerability is the localization of the diagram's branches, changes in the parameters of which influence sensitivity.

In mathematics, in particular functional analysis, the singular value decomposition of the matrix A allows one to calculate the singular numbers of a given matrix as well as the left and right singular vectors of the matrix A when the left singular vectors of the matrix A are the eigenvectors of the matrix AA^T, but the right singular vectors of the matrix A are the eigenvectors of the matrix A^TA. The following expression (1) presents that the arithmetic values of the square roots of the common eigenvalues λ of real matrices A^TA and AA^T are called matrix singular values A:

$$\sigma_i(A) = \sqrt{\lambda_i(A^TA)} = \sqrt{\lambda_i(AA^T)}, \tag{1}$$

if $i = 1, \ldots, k$, and an indicator of the sensitivity increase is a reduction of the minimum singular value σ1 of the Jacobian matrix. Because the matrices A^TA and AA^T are symmetric and not negatively defined, all $\sigma_i \geq 0$, where $i = 1, \ldots, n$ [36,37].

Therefore, to assess the impact of the diagram parameters and operational parameters on the sensitivity of its elements, the matrix derived from the Jacobian matrix by conductance of branches *yij* of the analyzed diagram was studied.

The presence and placement of sensors and weak points was determined using numerical and analytical methods for studying the scheme of the EPS and its parameters of singular analysis with the Jacobian matrix formulated in Equation (2) and the bus admittance matrix given in Equation (3):

$$J = W \sum V^T = \sum_{i=1}^{k} w_i \sigma_i v_i^T, \tag{2}$$

$$Y = W_Y \sum_Y V_Y^T = \sum_{i=1}^{k} w_{Yi} \sigma_{Yi} v_{Yi}^T, \tag{3}$$

where $\sum = diag(\sigma_1, \sigma_2, \ldots, \sigma_k)$ and $\sum_Y = diag(\sigma_{Y1}, \sigma_{Y2}, \ldots, \sigma_{Yk})$ were diagonal matrices of singular values; W, V and W_Y, V_Y were orthogonal matrices of size $k \times k$; their i-th columns were respectively the i-th left and the i-th right singular vectors of the corresponding matrices; and the conditions $w_i^T w_i = v_i^T v_i = 1$, $w_i^T w_j = v_i^T v_j = 0$ were valid for them if $i \neq j$ [36,37].

Based on singular analysis, the following indicators $\chi_{J\sigma}$ and $\chi_{Y\sigma}$ were used as generalized indicators to identify weak branches [36,37]:

$$\chi_{J\sigma} = \frac{\partial \sigma_1}{\partial y_{ij}} = w_{1\delta}^T \left(\frac{\partial^2 P}{\partial \delta \partial y_{ij}} \right) v_{1\delta} + w_{1\delta}^T \left(\frac{\partial^2 P}{\partial U \partial y_{ij}} \right) v_{1U} + w_{1U}^T \left(\frac{\partial^2 Q}{\partial \delta \partial y_{ij}} \right) v_{1\delta} + w_{1U}^T \left(\frac{\partial^2 Q}{\partial U \partial y_{ij}} \right) v_{1U}, \tag{4}$$

$$\chi_{Y\sigma} = (w_{Yp1} - w_{Yq1}) \times (v_{Yp1} - v_{q1}) \tag{5}$$

where $\partial^2 P/\partial\delta\partial y_{ij}$, $\partial^2 P/\partial U\partial y_{ij}$, $\partial^2 Q/\partial\delta\partial y_{ij}$, $\partial^2 Q/\partial U\partial y_{ij}$—were derivatives of Jacobian matrix by the conductance of branches, y_{ij}, w_1, v_1 were the first left and the first right singular vectors of the Jacobian matrix; and w_{Y1}, v_1 were the first left and the first right singular vectors of the nodal conductance matrix.

The algorithm for the calculation of steady-state parameters of the EPS is shown in the flowchart in Figure 5. Appendix A shows detailed description of the computational procedure.

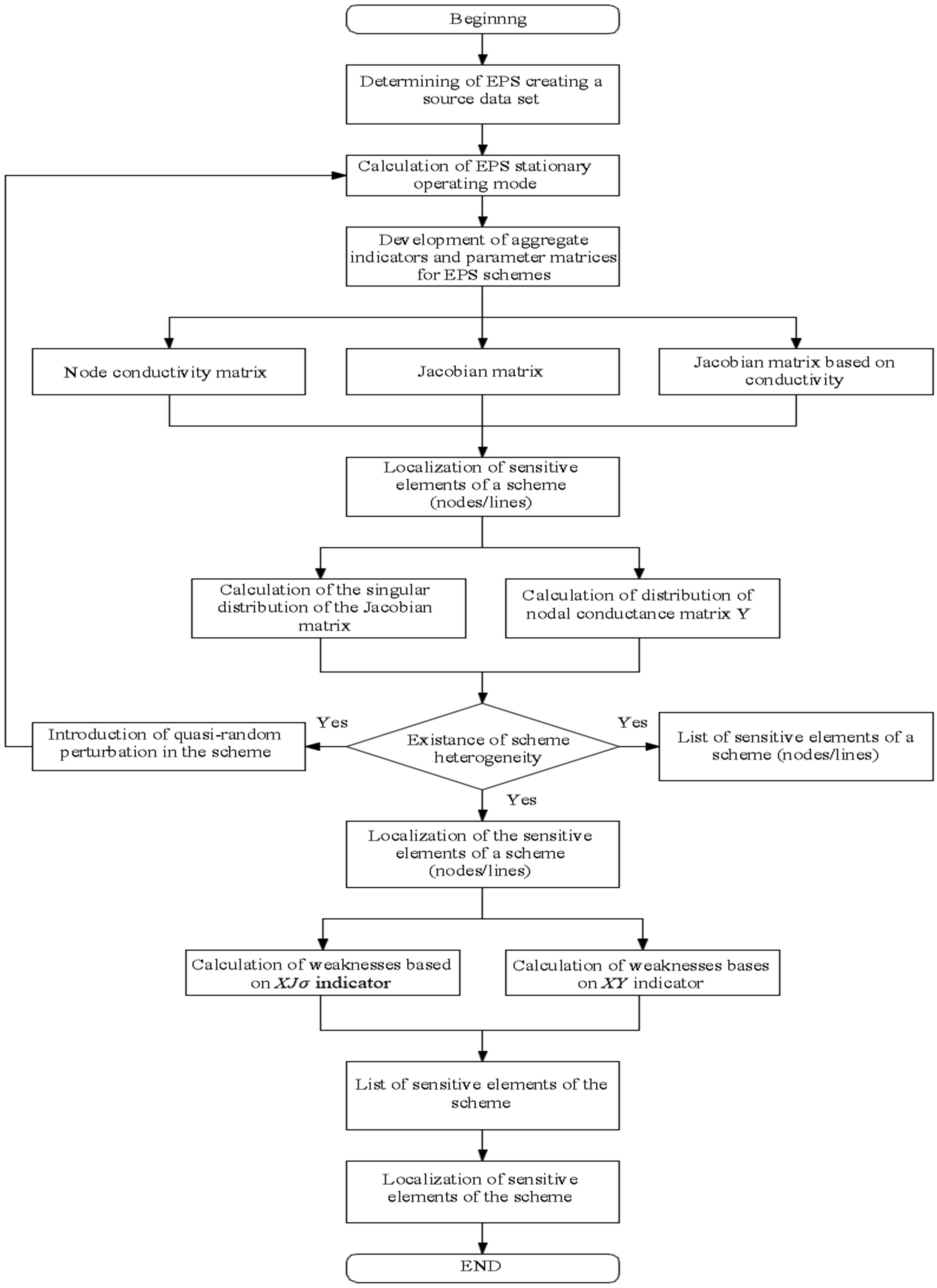


Figure 5. Flowchart of the algorithm for the calculation of steady-state parameters of the EPS [38].

It should be noted that the considered approach to the analysis of the power system was very convenient for using. It made it easy to identify the weak points of the EPS and to predict the balance/imbalance of the power system in conditions of shortage and excesses of electricity as well as to take measures to achieve a normal balanced regime. To compare sensitivity estimation obtained using the singular analysis of the Jacobian matrix and the singular analysis of the nodal conductance matrix, we concluded that almost the same nodes and branches were sensitive to the deviation of the voltage modules. The distinction in results may have been explained by the fact that the sensitivity of some elements of EPS were more dependent on system parameters and others on regime parameters [38].

The greatest interest from the point of view of the research of the vulnerability of the EPS was the localization of the branches of the network, the change in the parameters of which maximized the sensitivity. The indicator of increasing sensitivity was the decrease of the minimum singular value $\varsigma 1$ of the Jacobian matrix. Therefore, to evaluate the influence of the parameters of the network scheme and the parameters of the regime on the sensitivity of its elements, the derivative matrix of the Jacobian matrix, with respect to the conductivities of the branches of the analyzed network, was studied.

4. The Obtained Results and Analysis

It should be noted that many scientific articles and monographs are devoted to the problem of calculating the stationary modes of an EPS [15,39–45]. IEEE test schemes [46–51] are often used for testing, comparing, and demonstrating methods for solving problems of analysis and modeling the static modes of various power systems. In this paper, the authors use the EPS model, which approximates real conditions, partially reflecting the situation in the EPS of the Baltic States [11,52–57].

Research of the Latvian power system was carried out based on three model schemes obtained for the past mode (2017) presented in Figure 6, the current mode (2020), and the planned mode (2025) including development scenarios (Figures 7 and 8) considering the share of the growth prospects of renewable power generating capacity and the disconnection of continental Europe from the BRELL. The Latvian power system has interconnection lines with Estonian, Lithuanian, and Russian networks and is a part of the Nord Pool Spot market. The transmission power system of Latvia operates in two voltage classes: 110 kV and 330 kV.

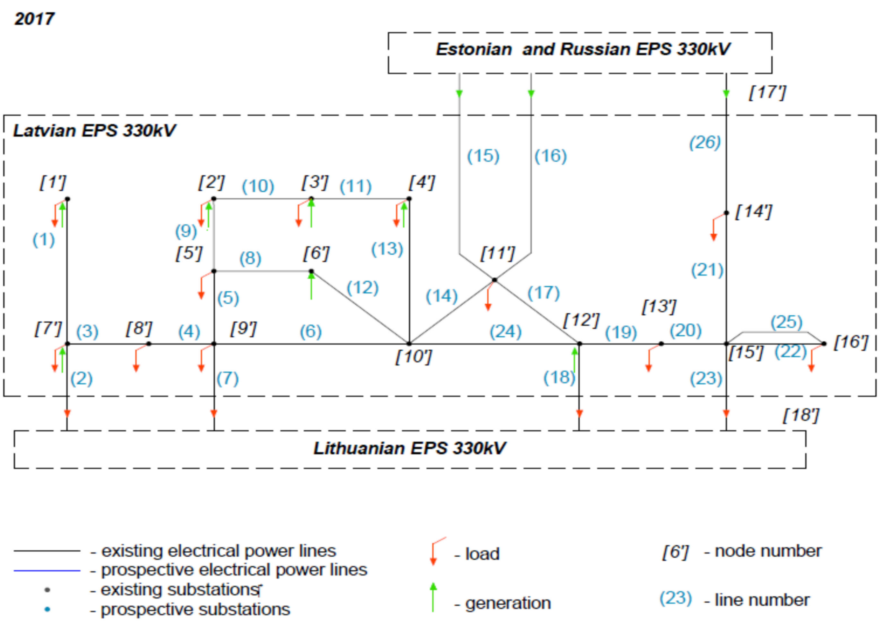


Figure 6. The examined 330 kV power network diagram—past mode (2017).

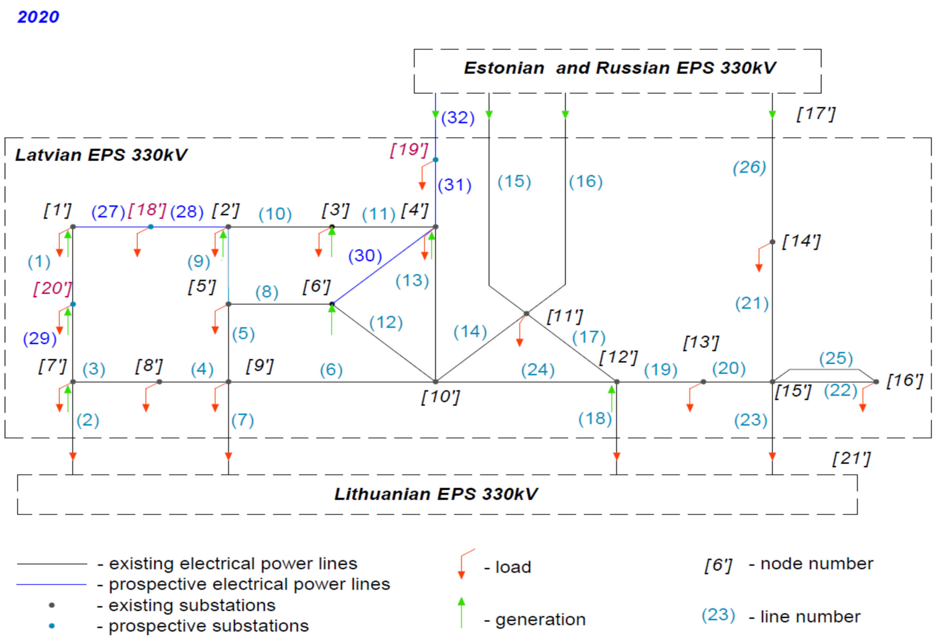


Figure 7. The examined 330 kV power network diagram—current mode (2020).

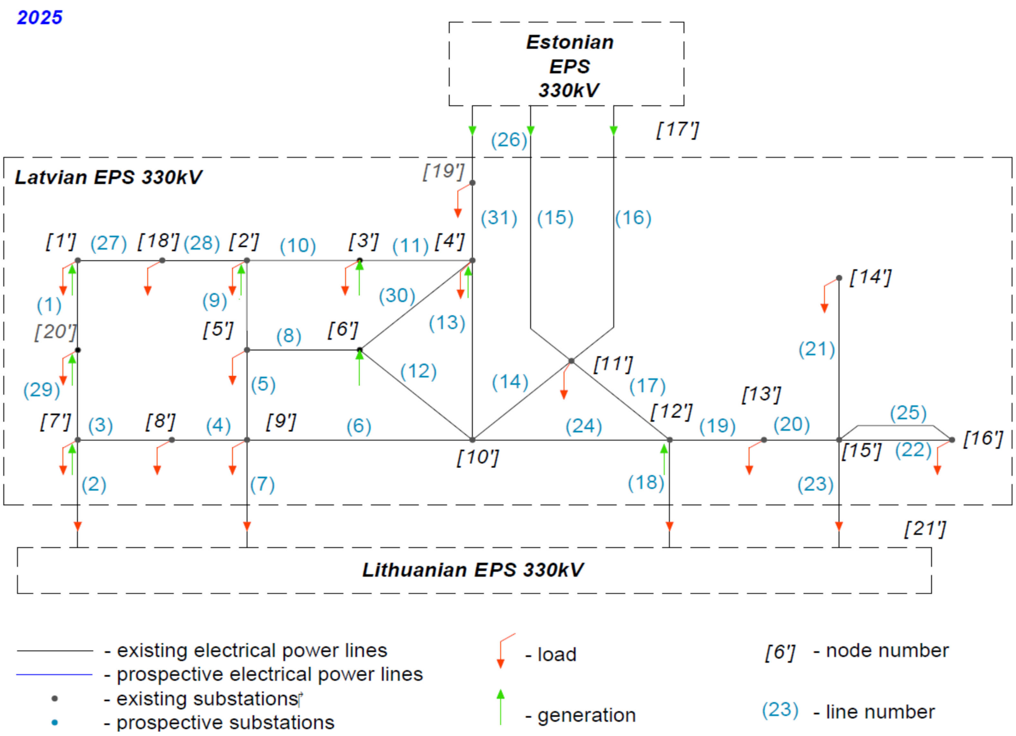


Figure 8. The examined 330 kV power network diagram—planned mode (2025).

The normal balanced mode of operation of the studied EPS model was considered the initial one. The mathematical model included the parameters of the stationary mode of the EPS (voltage class, loads, and generation) and network parameters (the combination of internal and external communication for power transmission, branch resistances).

The Nord Pool statistical data from 2017 have been taken for initial computations that are given in Table 4. At the same time, a 2% increase in consumption and generation was taken into account, considering forecasts until 2025. In addition, the expected redistribution between energy types over the examined period, until 2025, was considered [25].

Table 4. Models of power generation nodes.

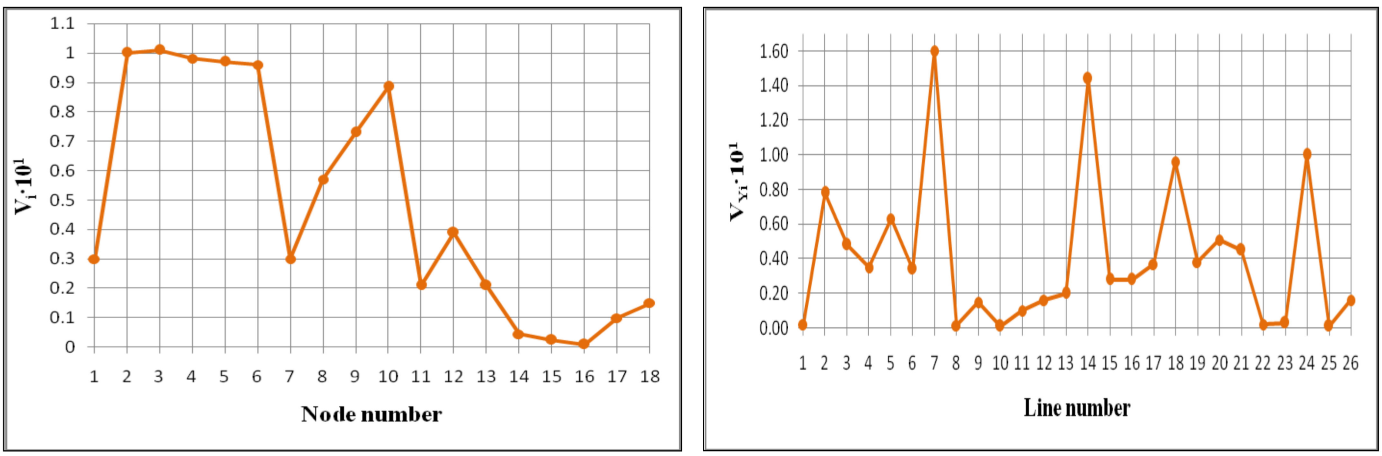
Node Name	Past Mode—2017		Current Mode—2020		Planned Mode—2025	
	Node No.	Generation, MW	Node No.	Generation, MW	Node No.	Generation, MW
Ventspils (wind farm)	1′	4	1′	45	1′	49
CHP-Imanta (Riga)	2′	13	2′	3	2′	3
CHP-1 (Riga)	3′	46	3′	9	3′	10
CHP-2 (Riga)	4′	270	4′	55	4′	61
Bishiciems (Riga)	5′	0	5′	0	5′	0
HPP (Riga)	6′	96	6′	112	6′	123
Grobina	7′	8	7′	178	7′	197
Broceni	8′	0	8′	0	8′	0
Viskali	9′	0	9′	0	9′	0
Salaspils (Riga)	10′	0	10′	0	10′	0
Valmiera	11′	0	11′	0	11′	0
Plavinas HPP	12′	192	12′	223	12′	246
Krustpils	13′	0	13′	0	13′	0
Rezekne	14′	0	14′	0	14′	0
Liksna	15′	0	15′	0	15′	0
Daugavpils	16′	0	16′	0	16′	0
Russian and Estonian EPS	17′	600	17′	634	17′ [1]	700
Tume	-	-	18′	0	18′	0
Salacgriva (Aloja)	-	-	19′	0	19′	0
Wind farm	-	-	20′	45	20′	49
Lithuanian EPS	21′	0	21′	0	21′	0

[1] Estonian EPS only.

For computations, certain software was used as a calculation tool, including ETAP [58], REGUS [59], and Mathcad [60].

For example, if about 46% of all generated energy was accounted for by heat power stations (HPP) in 2015, 52% by thermal power plants (TPP), and only 2% by wind power stations (WPS) [9], then for 2025, the following distribution was considered: HPP—50%, WPS—40%, and TPP—10%.

Using the methods of singular analysis of the Jacobian matrix and the bus admittance matrix, for the scheme shown in Figure 6 (2017), the maximal components of the right singular vector corresponding to the minimal singular value of the Jacobian matrix were identified as voltage sensing nodes 2′, 3′, 4′, 5′, 6′, 10′ (Figure 9a). Having sensitivity in terms of loss of voltage were branches 2, 7, 14, 18, 24, (Figure 9b).



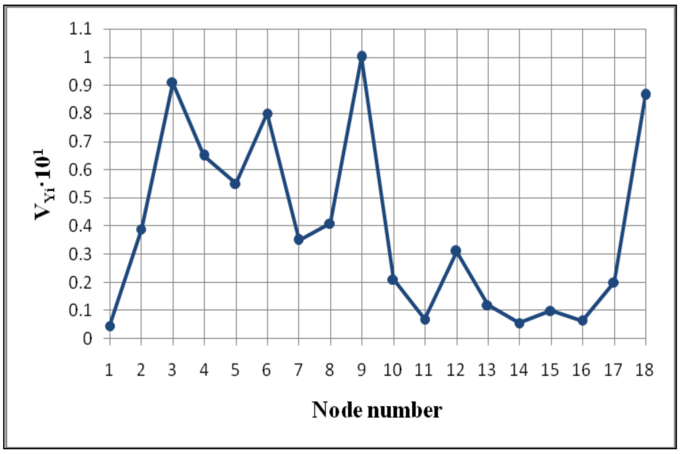
(**a**) (**b**)

Figure 9. Computation results of branch sensitivity of the examined power network (2017) based on singular analysis of the Jacobian matrix: (**a**) node sensitivity for bus voltages; (**b**) branch sensitivity by voltage loss.

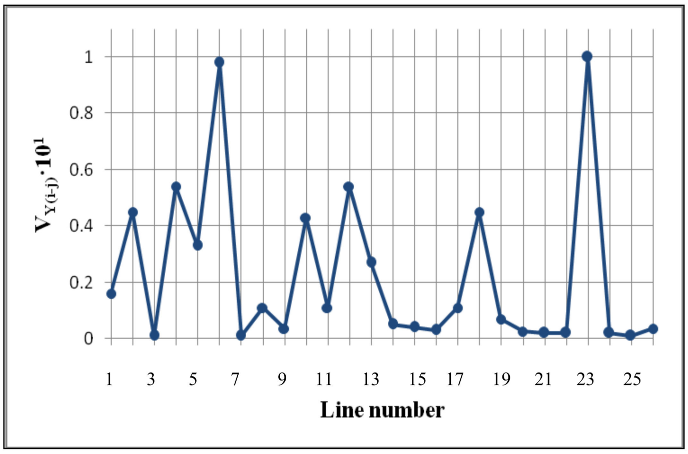
Nodes and branches having the maximal calculated values of the components of the first right singular vector V1 of the matrix Y, showing sensitivity for voltage, were identified nodes 2′, 3′, 4′, 5′, 6′, 9′, 18′ (Figure 9a).

Difference estimates corresponding to the nodes at the ends of the branches of the components of the first right singular vector σ_{min} of the matrix made it possible to identify the branches sensory to the loss of voltage: 2, 4, 6, 10, 12, 18, 23 (Figure 9b).

Evaluation of the computation results of the sensitivities obtained using the singular analysis of the Jacobian matrix (Figure 9) and the singular analysis of the bus admittance matrix (Figure 10) showed that practically the same nodes and branches had sensitivity in terms of deviation of voltage modules.



(**a**)



(**b**)

Figure 10. Computation results of branch sensitivity of the examined power network (2017) based on singular analysis of the bus admittance matrix: (**a**) node sensitivity for bus voltages; (**b**) branch sensitivity by voltage loss.

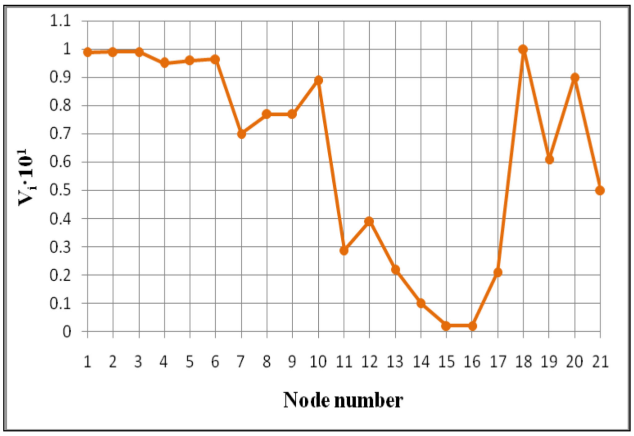
Analysis of the obtained results allowed us to establish that branches 2′ and 18′, whose components were maximal, were weak.

The difference in results was explained by the fact that the sensitivity of some elements of the EPS depended only on the topological parameters of the network, while others on the regime parameters as well.

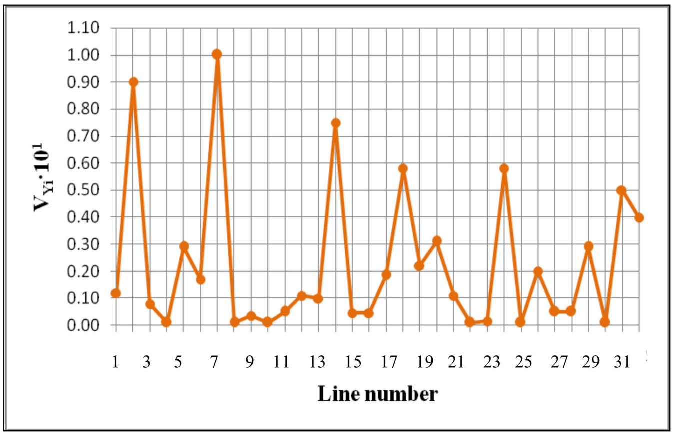
Using the methodologies "Singular analysis of the Jacobian matrix" and "Singular analysis of the bus admittance matrix", the calculations for the schemes of 2020 (Figure 7) and 2025 (Figure 8) were provided. Obtained results are presented in Table 5.

Table 5. Summary of computational results of the branch and node sensitivity of the examined power network.

Applied Method	Past Mode—2017		Current Mode—2020		Planned Mode—2025	
	Node No.	Branch No.	Node No.	Branch No.	Node No.	Branch No.
Singular analysis of the Jacobian matrix	3′, 4′, 5′, 6′, 9′, 18′	2, 4, 6, 10, 12, 18, 23	1′, 2′, 4′, 5′, 6′, 10′, 18′, 20′	2, 7, 14, 18, 24	1′, 2′, 3′, 4′, 5′, 6′, 9′, 10′, 18′	2, 7, 14, 18, 24
Note:	Figure 9a	Figure 9b	Figure 11a	Figure 11b	Figure 13a	Figure 13b
Singular analysis of the bus admittance matrix	3′, 6′, 9′, 18′	6, 23	1′, 7′, 20′	2, 3	1′, 7′, 20′	2, 3
Note:	Figure 10a	Figure 10b	Figure 12a	Figure 12b	Figure 14a	Figure 14b

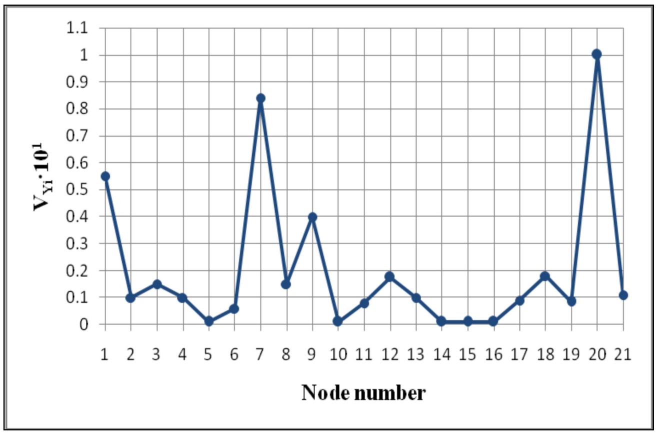


(**a**)

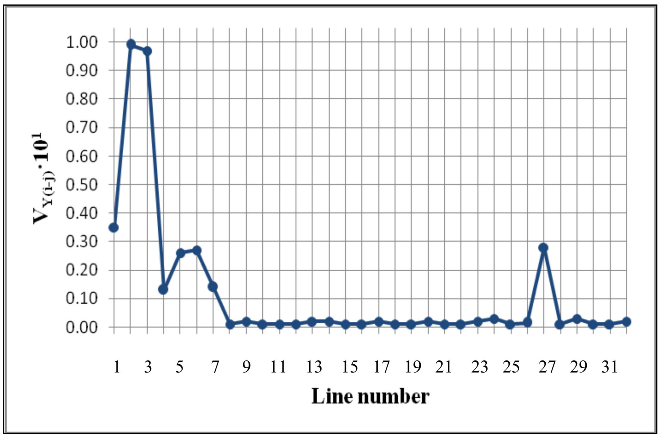


(**b**)

Figure 11. Computation results of branch sensitivity of the examined power network (2020) based on singular analysis of the Jacobian matrix: (**a**) node sensitivity for bus voltages; (**b**) branch sensitivity by voltage loss.

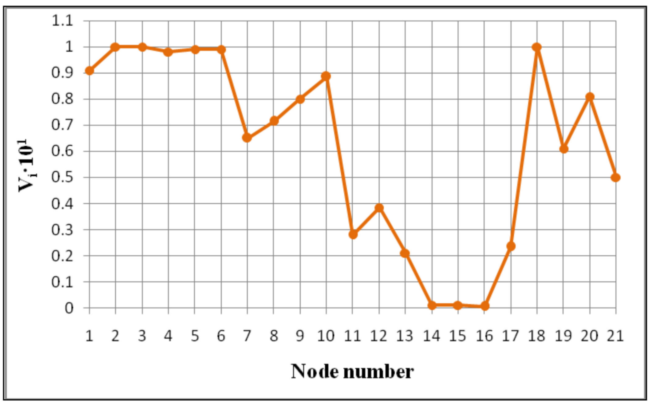


(**a**)

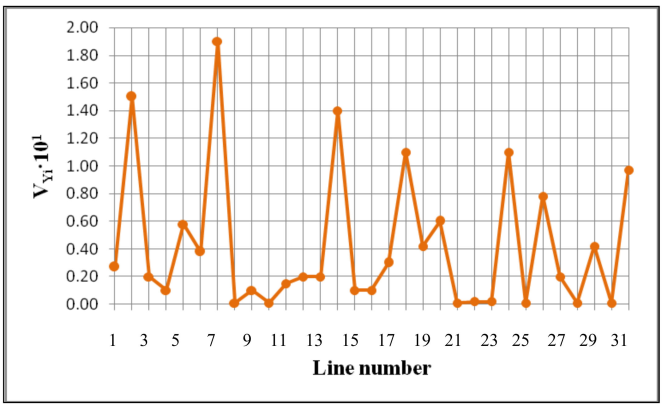


(**b**)

Figure 12. Computation results of branch sensitivity of the examined power network (2020) based on singular analysis of the bus admittance matrix: (**a**) node sensitivity for bus voltages; (**b**) branch sensitivity by voltage loss.

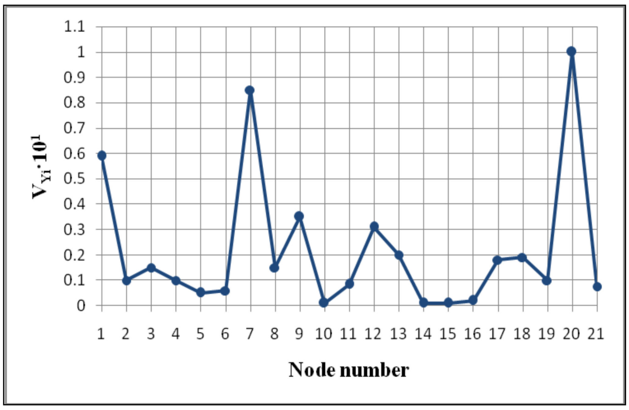


(**a**)

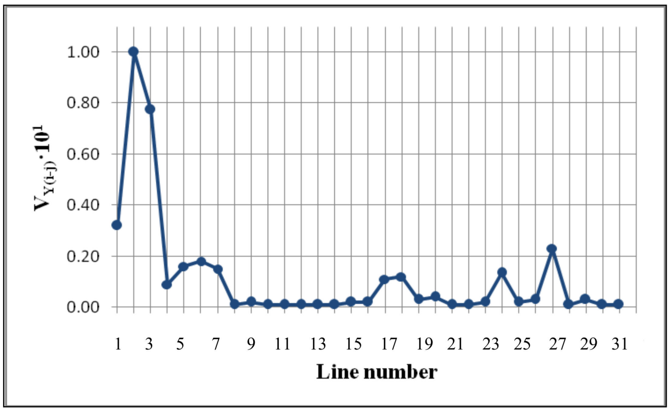


(**b**)

Figure 13. Computation results of branch sensitivity of the examined power network (2025) based on singular analysis of the Jacobian matrix: (**a**) node sensitivity for bus voltages; (**b**) branch sensitivity by voltage loss.



(**a**)



(**b**)

Figure 14. Computation results of branch sensitivity of the examined power network (2025) based on singular analysis of the bus admittance matrix: (**a**) node sensitivity for bus voltages; (**b**) branch sensitivity by voltage loss.

As followed by the computation results (Figures 9–14) as well as the results of Table 5, the received results of weak point localization for different development and modernization stages of the Latvian EPS model as well as vulnerability assessment in the design phase allowed us to provide activities associated with the construction of full-strength networks, thereby pre-emptively eliminating dangerous or unwanted situations, and in the operational phase, to develop protective measures minimizing damage to the power system and the country's economy through possible emergencies.

Summarizing the obtained results of the examined network in terms of the sensors and weak points, the following was observed:

- For past mode—2017 (Figure 6), it could be stated that nodes 3′ (CHP-1 (Riga)), 4′ (CHP-2 (Riga)), 5′ (Bishiciems (Riga)), and 6′ (HPP (Riga), and branches 2 and 18 were sensory in terms of voltage (Figure 15);
- For current mode—2020 (Figure 7), sensory nodes were 1′ and 10′ and 20′, and branch 2 was sensory (Figure 16).
- For planned mode—2025 (Figure 8), sensory nodes were 1′ and 20′, and branch 2 was sensory (Figure 17).

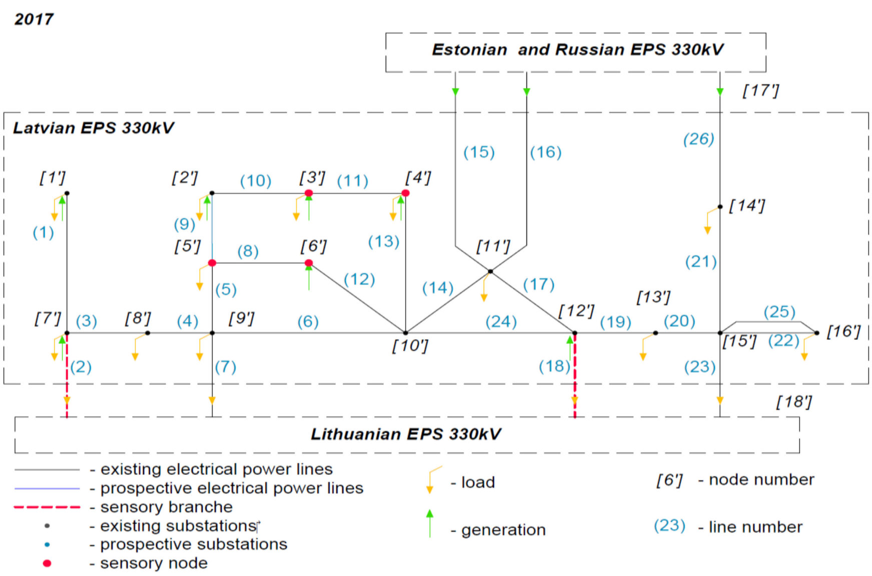


Figure 15. The examined 330 kV power network diagram with identified weak branches and nodes—past mode (2017).

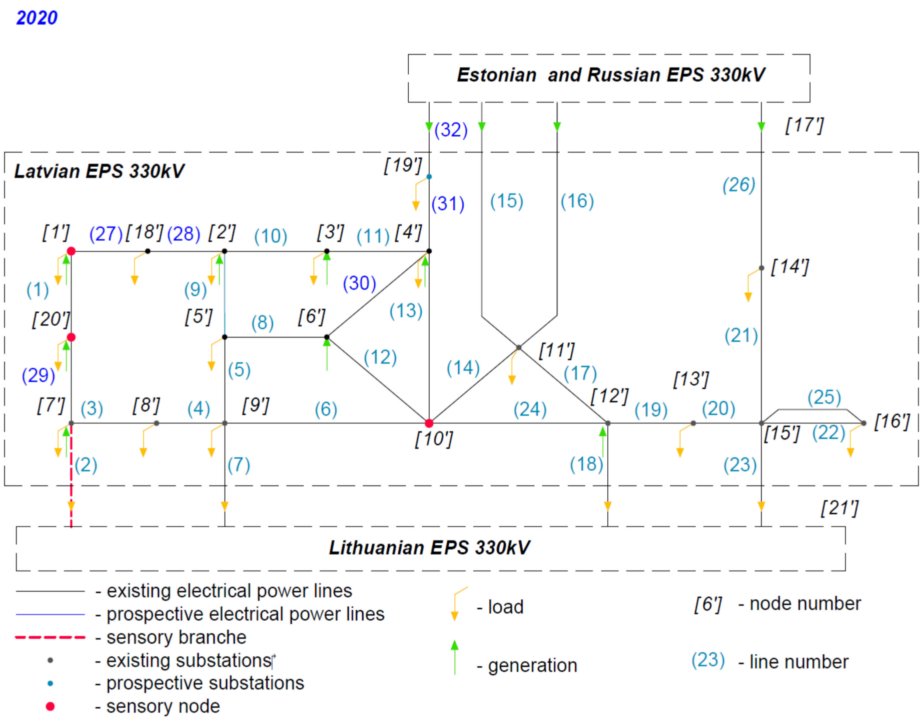


Figure 16. The examined 330 kV power network diagram with identified weak branches and nodes—current mode (2020).

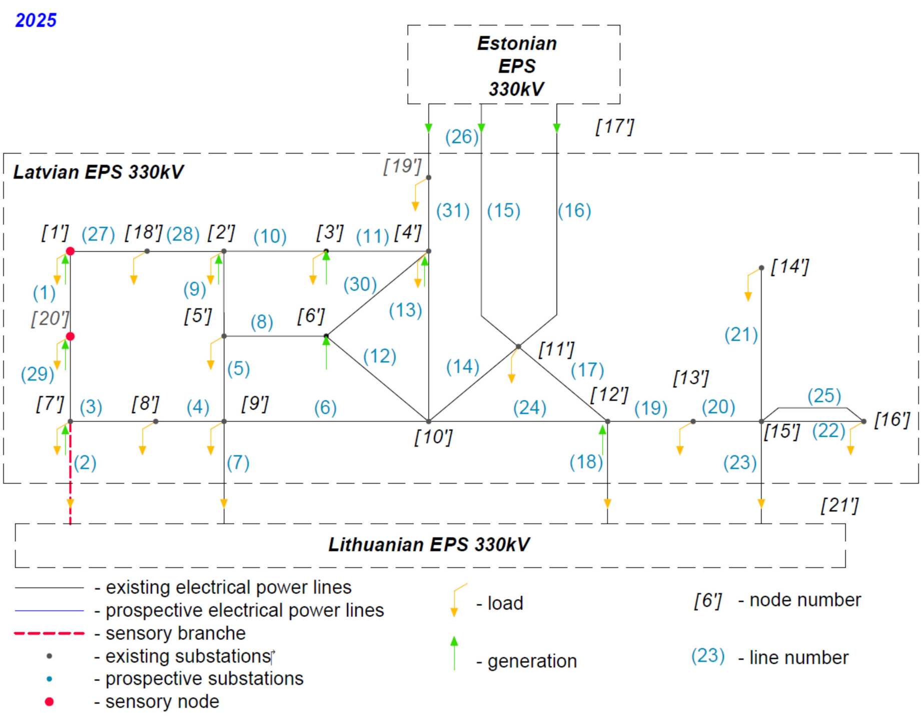


Figure 17. The examined 330 kV power network diagram weak branches and nodes—planned mode (2025).

5. Discussion

The formation of focused directions for power industry development can be carried out based on an investigation of both the stationary and transient states of the EPS, including a study of the static stability. The complicity, structure, impacting factors, and possible state of the EPS must be considered. The initial task was set up for the EPS' requirements as well as the equipment and control systems.

The most important phase in the EPS vulnerability analysis was the examination of the generation impact scenarios leading to the development of an EPS crash. When a power system has a relatively small number of elements, impact scenarios can be created manually by listing different variants. However, the elements' number increases rapidly due to EPS expansion, leading to network configuration changes.

As a result, the proposed method provided the possibility of investigating and discovering the most vulnerable parts of the power system that caused EPS crashes by searching so-called sensitive points (nodes, lines) without performing statistical tests and counting a huge number of external exposure scenarios.

The computations considered the following parameters:

- EPS stationary mode parameters such as voltage magnitude and angle, power, load, and generation at nodes;
- Network parameters such as the internal and external communication sets for power transmission and branch resistance.

In order to ensure convergence (balance between generation and consumption) of the EPS operational mode, both the balance node and reactive power were set arbitrarily under the examined model and assumed to be close to the real operating conditions of the EPS' models. The computations of the respective modes were approximate as well, and thus the estimation of active and reactive power flows could not be considered with high reliability.

The task of analyzing EPS heterogeneities included use of the matrices based on generalized values of EPS elements and data about the applied points of perturbations for searching and localizing examined EPS weak points. The generalized values were expressed via parameters of the nodal conductance matrix and the Jacobi matrix of equations in a steady-state mode serving as the main data sources about the EPS' sensitivity and heterogeneity. Sensitive points and their locations were defined using numerical and analytical methods considering the power network's scheme and parameters.

Due to the limited scope of this work, computations were performed for only one mode, aiming to demonstrate the effectiveness of the proposed approach rather than a detailed study of the behavioral properties of the system or namely, parameters of the EPS' stationary mode and network.

This study included evaluation of three modes of the Latvian EPS model, in particular the past (2017), current (2020), and planned (2025), by analyzing and comparing obtained computation results based on the proposed method. The performance of the Latvian EPS revealed positive results under realized and planned modernization scenarios, leading to an increase in the stability of the power system by eliminating some of the existing weak points. The examined EPS models were close to real-world conditions and partially reflected the situation of the Baltic States' EPSs (taking into account development strategy) without claiming detailed similarity to the latter.

The obtained results of EPS vulnerability localization allowed us to provide measures aimed at constructing an equally stable power network and thus preventing dangerous or undesirable situations as well as developing protective measures to minimize EPS damage during its operational phase from possible external exposures.

Currently, the authors are working on data library creation devoted to collecting information about operating modes that are the most typical for a particular time of year, considering climatic conditions (including long-term forecast of their changes), time of day, market requirements, etc. in order to increase the reliability of the performed computations.

6. Conclusions

Latvian EPS configuration has been experiencing great changes because of modernization processes (new interconnections of transmission lines, construction of large new wind parks), leading to a need for evaluation of the Latvian power system's static stability for both current and planned modes. For this purpose, the detection methods of the weakest network parameters in relation to external impacts must be applied, highlighting the identification of such nodes as a priority task. In this way, the nodes' sensitivity will increase, contributing to the occurrence of their significant violations in the deviation and content of higher harmonic voltage components.

This article demonstrated an application of analytical techniques for node conductance matrix Y and Jacobian matrix J of power system equations of the steady-state mode. Such an application resulted in the development of an original instrument for identification of the sensitivities and vulnerabilities of a heterogenous power system.

Scientific novelty lies in finding the "hidden values" in aforementioned matrixes and enhancing the potential of their usage for the purposes of power system research. The possibility and efficiency of these methods' applications, leading to the ability to solve analysis problems and control modes by considering voltage limits at buses, are what justifies a wide range of applications: The proposed approach allows detecting the most vulnerable parameters of the power system such as voltage drop and external impacts (sensors) as well as their relationships with EPS parameters. The availability of data of sensor locations provides the possibility of determining and controlling nodes, in which the biggest oscillations of operational parameters are observed due to disturbances in the system. As result, EPS behavioral properties are improved.

The model of the Latvian EPS for the periods of 2017, 2020, and 2025 has been analyzed in terms of an effect on the nodes' sensitivity degree (sensory "leaf" nodes) based on a weighting scheme of the reactive load power. By identifying weaknesses, predicting balance/imbalance of the power system under deficits and surpluses of electricity will force taking further measures to achieve a balanced system regime.

Simulations of the developed Latvian EPS model have been performed considering new interconnection lines and an increased share of WPS energy; thus, to keep the system balanced, a part of the reacting power has been increased.

Comparison of the past mode (2017) and the planned mode (2025) showed positive changes in the revealed weak places/nodes of the Latvian power network. To conclude, the computation results of the planned and ongoing modernization of the Latvian EPS predict an obvious decrease of several weak spots.

It is worth mentioning that the existence of weak spots is inherent in any power supply system, but their sensitivity can be reduced. As the obtained computation results showed, weak point localization as well as vulnerability evaluation of the Latvian EPS in the design stage allows for defining further measures to increase system static stability.

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Appendix A

This appendix presents the computation example that clarifies how the proposed mathematical model was applied to define EPS sensitivity elements, evaluation of the EPS model based on the current mode—2020. The method (with nodal conductance matrices and Jacobi matrices) and the process of identifying these sensitive points are presented below.

The following steps were performed (for details, kindly see Figures A1–A6 below):

1. Set up the initial data of the considered power network in a steady state;
2. Calculate the main parameters' values of the examined EPS' sensitive elements;
3. Build the matrix of own and mutual node conductance;
4. Localize the EPS' sensitive points using singular decomposition of the Jacobian matrix and obtain results;
5. Localize the EPS' sensitive points using singular decomposition of the node admittance matrix and obtain results;
6. Analyze the obtained results and evaluate the EPS' stability.

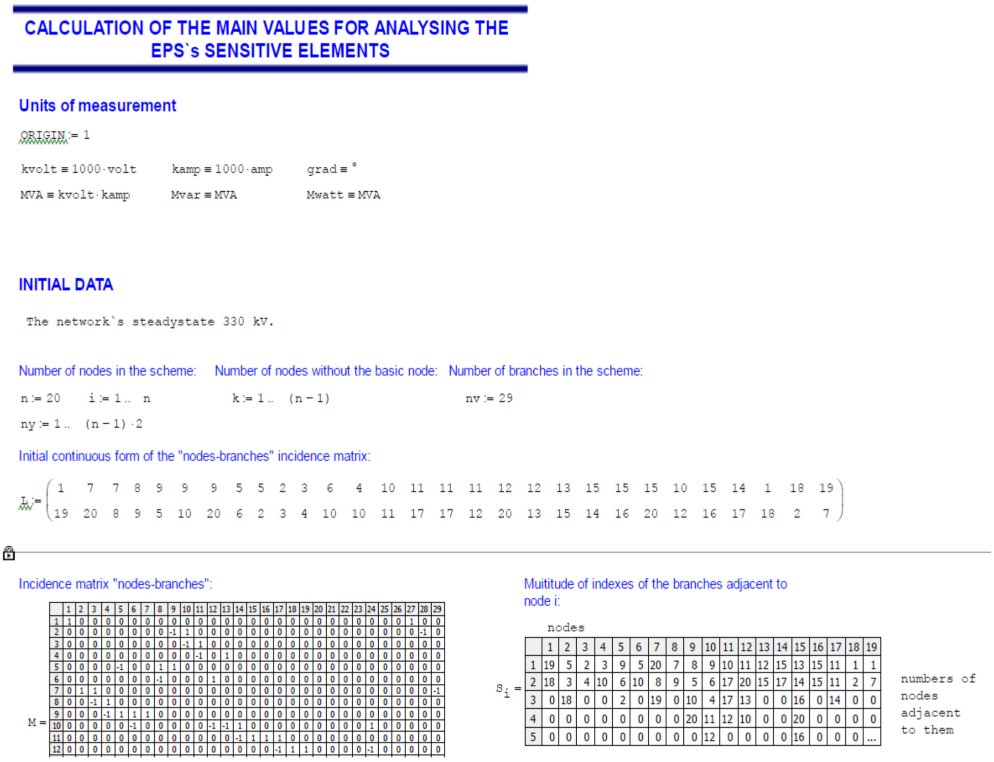


Figure A1. Visualization of Step 1.

13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	1	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	1	1	0	1	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	-1	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	-1	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	0
19	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
20	0	-1	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	-1	0	0	0	0	0	0

Resistances and conductances of the branches

```
l_km := (57  120  89  77  46  53  90  15  15  14  12  17  14  105  132  60  110  127  60  73  83  13  50  66  12  156  130  65  60 )
k_tr := (1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1  1 )

R_l := for  i ∈ 1 .. 29
         | RR1,i ← l_km1,i · k_tr1,i · 0.08  if k_tr1,i = 9
         | RR1,i ← l_km1,i · k_tr1,i · 0.07  if k_tr1,i = 1
         | RR
```

R_l =

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
1	3.99	8.4	6.23	5.39	3.22	3.71	6.3	1.05	1.05	0.98	0.84	1.19	0.98	7.35	9.24	4.2	7.7	8.89	4.2	5.11	5.81	0.91	3.5	4.62	0.84	10.92	9.1	4.55	4.2

```
X_l := for  i ∈ 1 .. 29
         | RR1,i ← l_km1,i · k_tr1,i · 0.42  if k_tr1,i = 9
         | RR1,i ← l_km1,i · k_tr1,i · 0.33  if k_tr1,i = 1
         | RR
```

X_l =

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	18.81	39.6	29.37	25.41	15.18	17.49	29.7	4.95	4.95	4.62	3.96	5.61	4.62	34.65	43.56	19.8	36.3	41.91	19.8	24.09	27.39	4.29	16.5	21.78	3.96	...

Branch resistance:

$R_v := R\_l^T \cdot ohm \qquad X_v := X\_l^T \cdot ohm$

Capacity conductance of the branches i-j (shunts):

$Y_{iijc} := (0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0)^T\ 10^{-6} \cdot siemens$

Conduccance of the shunts connected in the node i:

$Y_{sh} := (0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0)^T\ siemens$

$Z_v(R_v, X_v) := R_v - X_v j$

$Z_v(R_v, X_v) =$

	1
1	3.99-18.81j
2	8.4-39.6j
3	6.23-29.37j
4	5.39-25.41j
5	3.22-15.18j
6	3.71-17.49j
7	...

$\cdot ohm$

$last(R_v) = 29$

$last(X_v) = 29$

$last(Y_{iijc}) = 29$

$last(Y_{sh}) = 29$

Load and generation powers

$P_{Hi} := (27\ 151\ 151\ 151\ 151\ 0\ 53\ 9\ 45\ 0\ 18\ 0\ 18\ 27\ 0\ 62\ 0\ 18\ 0\ 414)^T \cdot Mwatt \qquad last(P_{Hi}) = 20$

$Q_{Hi} := (0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0)^T \cdot Mvar \qquad last(Q_{Hi}) = 20$

$P_{Gi} := (45\ 3\ 9\ 55\ 0\ 112\ 178\ 0\ 0\ 0\ 0\ 223\ 0\ 0\ 0\ 0\ 634\ 0\ 45\ 0)^T \cdot Mwatt \qquad last(P_{Gi}) = 20$

$Q_{Gi} := (0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0)^T \cdot Mvar \qquad last(Q_{Gi}) = 20$

Nodal voltage module and phase

Nominal nodal voltage phase and module:

$U_y := (347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347\ 347)^T \cdot kvolt$

$\delta_y := (0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0)^T\ grad$

$last(U_y) = 20$

$last(\delta_y) = 20$

Figure A2. Visualization of Step 2.

Voltage module and phase in the steady state:

$$xU_y := \begin{pmatrix} 346.83 \\ 344.27 \\ 344.26 \\ 344.6 \\ 344.57 \\ 345.09 \\ 347.63 \\ 346.35 \\ 345.41 \\ 345.3 \\ 349.3 \\ 347.71 \\ 347.22 \\ 348.04 \\ 346.95 \\ 346.87 \\ 352.58 \\ 344.94 \\ 347.48 \\ 347 \end{pmatrix} \cdot \mathrm{kvolt} \qquad \mathrm{last}(xU_y) = 20$$

$$x\delta_y := \begin{pmatrix} -1.38 \\ -0.02 \\ -0.08 \\ -0.4 \\ -0.23 \\ -0.73 \\ -1.55 \\ -0.89 \\ -0.43 \\ -0.99 \\ -5.37 \\ -2.71 \\ -1.98 \\ -3.48 \\ -1.3 \\ -1.24 \\ -8.16 \\ -0.35 \\ -1.67 \\ 0 \end{pmatrix} \mathrm{grad} \qquad \mathrm{last}(x\delta_y) = 20$$

BUILDING THE MATRIX OF OWN AND MUTUAL NODAL CONDUCTANCES

$Y(R_v, X_v) =$ (·siemens)

	1	2	3	4	5
1	0.0155+0.0732j	0	0	0	0
2	0	0.0944+0.4451j	-0.0439-0.2071j	0	-0.041-0.1933j
3	0	-0.0439-0.2071j	0.0952+0.4488j	-0.0513-0.2417j	0
4	0	0	-0.0513-0.2417j	0.0952+0.4488j	0
5	0	-0.041-0.1933j	0	0	0.0954+0.4497j
6	0	0	0	0	-0.041-0.1933j
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	...

Figure A3. Visualization of Step 3.

LOCALIZATION OF THE EPS`s SENSITIVE POINTS USING SINGULAR VALUE DECOMPOSITION OF THE JACOBIAN MATRIX

Rectangular system of coordinates:

$$J := \begin{pmatrix} \frac{dWp}{dUa} & \frac{dWp}{dUr} \\ \frac{dWq}{dUa} & \frac{dWq}{dUr} \end{pmatrix}$$

Polar system of coordinates:

$$J := \begin{pmatrix} \frac{dWp}{dU} & \frac{dWp}{d\delta} \\ \frac{dWq}{dU} & \frac{dWq}{d\delta} \end{pmatrix}$$

Analysis Jacobian matrices

$MJ^{-1} =$

	1	2	3	4	5	6	7	8	9	10
1	-0.0231	-0.0061	-0.0056	-0.0051	-0.0054	-0.005	-0.0098	-0.007	-0.0045	-0.0045
2	-0.0061	-0.01	-0.009	-0.008	-0.0085	-0.0077	-0.0038	-0.0049	-0.0058	-0.0069
3	-0.0055	-0.009	-0.0102	-0.0088	-0.0079	-0.0075	-0.0035	-0.0047	-0.0057	-0.0071
4	-0.005	-0.008	-0.0088	-0.0094	-0.0074	-0.0073	-0.0033	-0.0045	-0.0055	-0.0073
5	-0.0054	-0.0085	-0.0079	-0.0074	-0.0093	-0.0081	-0.0036	-0.0049	-0.0061	...

$MJ =$

	1	2	3	4	5	6	7	8	9	10
1	-5.4063	0	0	0	0	0	0	0	0	0
2	0	-32.4925	15.1239	0	14.1126	0	0	0	0	0
3	0	15.1235	-32.7687	17.6344	0	0	0	0	0	0
4	0	0	17.6519	-32.8337	0	0	0	0	0	15.1104
5	0	14.1249	0	0	-32.8763	14.1105	0	0	4.6032	...

Figure A4. Visualization of Step 4.

ANALYSIS OF SINGULAR VALUE DECOMPOTISION OF THE FULL JAKOBIAN MATRIX

Singular value decomposition of the Jacobian matrix:

$J_{svd}(MJ) =$

	1	2	3	4	5
1	$3.2222\cdot10^{-10}$	-0.0006	0.0015	-0.0007	$4.6544\cdot10^{-6}$
2	$6.4013\cdot10^{-7}$	-0.3782	0.508	-0.2313	0.001
3	$-1.9779\cdot10^{-6}$	0.4715	-0.0177	0.5259	-0.0005
4	$7.9568\cdot10^{-6}$	-0.4874	-0.4191	-0.2049	-0.0007
5	$-1.3311\cdot10^{-6}$	0.3111	-0.5501	-0.3412	0.0001
6	$5.9479\cdot10^{-6}$	-0.2666	0.0954	0.5204	-0.001
7	$1.0636\cdot10^{-9}$	-0.0001	0.0001	0.0004	$-9.4145\cdot10^{-7}$
8	$-4.4332\cdot10^{-8}$	0.0031	-0.0013	-0.0069	0
9	$1.6527\cdot10^{-6}$	-0.0639	0.0206	0.1022	-0.0002
10	-0	0.4252	0.4552	-0.4299	0.0009
11	-0	-0.0172	-0.026	0.0262	-0.0012
12	0.0008	-0.0257	-0.0378	0.0379	0.0073
13	-0.0214	0.0016	0.0033	-0.0035	...

i-th left singular vectors of the Jacobian matrix

$W(MJ) =$

	1	2	3	4	5
1	$3.2222\cdot10^{-10}$	-0.0006	0.0015	-0.0007	$4.6544\cdot10^{-6}$
2	$6.4013\cdot10^{-7}$	-0.3782	0.508	-0.2313	0.001
3	$-1.9779\cdot10^{-6}$	0.4715	-0.0177	0.5259	-0.0005
4	$7.9568\cdot10^{-6}$	-0.4874	-0.4191	-0.2049	-0.0007
5	$-1.3311\cdot10^{-6}$	0.3111	-0.5501	-0.3412	0.0001
6	$5.9479\cdot10^{-6}$	-0.2666	0.0954	0.5204	-0.001
7	$1.0636\cdot10^{-9}$	-0.0001	0.0001	0.0004	$-9.4145\cdot10^{-7}$
8	$-4.4332\cdot10^{-8}$	0.0031	-0.0013	-0.0069	0
9	$1.6527\cdot10^{-6}$	-0.0639	0.0206	0.1022	-0.0002
10	-0	0.4252	0.4552	-0.4299	0.0009
11	-0	-0.0172	-0.026	0.0262	-0.0012
12	0.0008	-0.0257	-0.0378	0.0379	0.0073
13	-0.0214	0.0016	0.0033	-0.0035	...

Diagonal matrix of singular values of the Jakobian matrix:

$\Sigma(MJ) =$

	1	2	3
1	180407.8135	0	0
2	0	104825.3293	0
3	0	0	80623.3279
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	...

Vector of singular values:

$\sigma(MJ)\cdot10^{0} =$

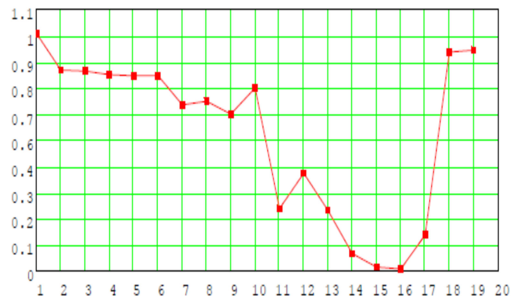
	1
1	180407.8135
2	104825.3293
3	80623.3279
4	76854.1288
5	65089.148
6	34300.4128
7	31638.4599
8	28425.1142
9	21787.4159
10	20603.8003
11	20399.0776
12	13244.0726
13	...

i-th right singular vectors of the Jacobian matrix:

$V(MJ) =$

	1	2	3	4	5
1	0	$-4.4679\cdot10^{-10}$	$8.5783\cdot10^{-10}$	$-4.1454\cdot10^{-10}$	$2.0221\cdot10^{-12}$
2	$-2.2481\cdot10^{-13}$	$1.0776\cdot10^{-7}$	$-1.4922\cdot10^{-7}$	$1.7447\cdot10^{-8}$	$-1.6914\cdot10^{-10}$
3	$1.2389\cdot10^{-12}$	$-1.9399\cdot10^{-7}$	$-9.5384\cdot10^{-8}$	$-1.807\cdot10^{-7}$	$-5.8428\cdot10^{-11}$
4	$-1.2\cdot10^{-11}$	$4.274\cdot10^{-7}$	$5.8454\cdot10^{-7}$	$2.8104\cdot10^{-8}$	$1.0258\cdot10^{-9}$
5	$9.9637\cdot10^{-13}$	$-1.9201\cdot10^{-7}$	$3.5968\cdot10^{-7}$	$3.8769\cdot10^{-7}$	$-4.6403\cdot10^{-10}$
6	$-8.665\cdot10^{-12}$	$2.5294\cdot10^{-7}$	$2.6058\cdot10^{-9}$	$-7.3689\cdot10^{-7}$	$1.5024\cdot10^{-9}$
7	0	$-3.6213\cdot10^{-11}$	$-3.6033\cdot10^{-12}$	$1.1475\cdot10^{-11}$	$1.082\cdot10^{-13}$
8	$7.0471\cdot10^{-15}$	$-4.9158\cdot10^{-11}$	$-1.6616\cdot10^{-9}$	$6.7346\cdot10^{-10}$	$-3.8356\cdot10^{-12}$
9	$-2.3736\cdot10^{-12}$	$3.2974\cdot10^{-8}$	$1.8759\cdot10^{-8}$	$-8.0541\cdot10^{-8}$	$8.8893\cdot10^{-11}$
10	$7.5198\cdot10^{-11}$	$-7.7712\cdot10^{-7}$	$-1.1993\cdot10^{-6}$	$1.2595\cdot10^{-6}$	$-1.7047\cdot10^{-9}$
11	$2.3482\cdot10^{-11}$	$1.5575\cdot10^{-8}$	$6.6642\cdot10^{-8}$	$-7.9144\cdot10^{-8}$	$7.682\cdot10^{-9}$
12	$2.2166\cdot10^{-10}$	$-4.5863\cdot10^{-9}$	$1.1985\cdot10^{-8}$	$-1.9743\cdot10^{-8}$	$-1.0815\cdot10^{-8}$
13	$-4.3212\cdot10^{-9}$	$-1.2192\cdot10^{-10}$	$-1.1641\cdot10^{-9}$	$1.4449\cdot10^{-9}$	...

Values of the components of the first right V singular vector corresponding to nodal voltage modules (maximal components correspond to nodes sensitive to voltage loss):



Values of differences related to nodal voltage modules of the ith and jth component of the right singular vector of the full Jakobian matrix (branches sensitive to voltage loss):

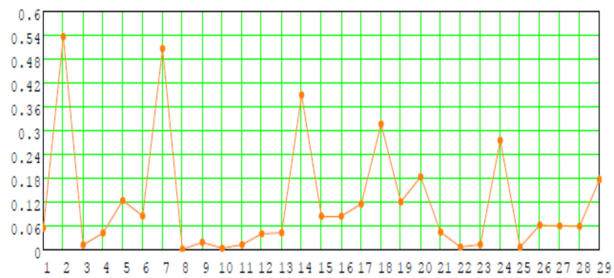


Figure A5. Visualization of Step 4 continued—results.

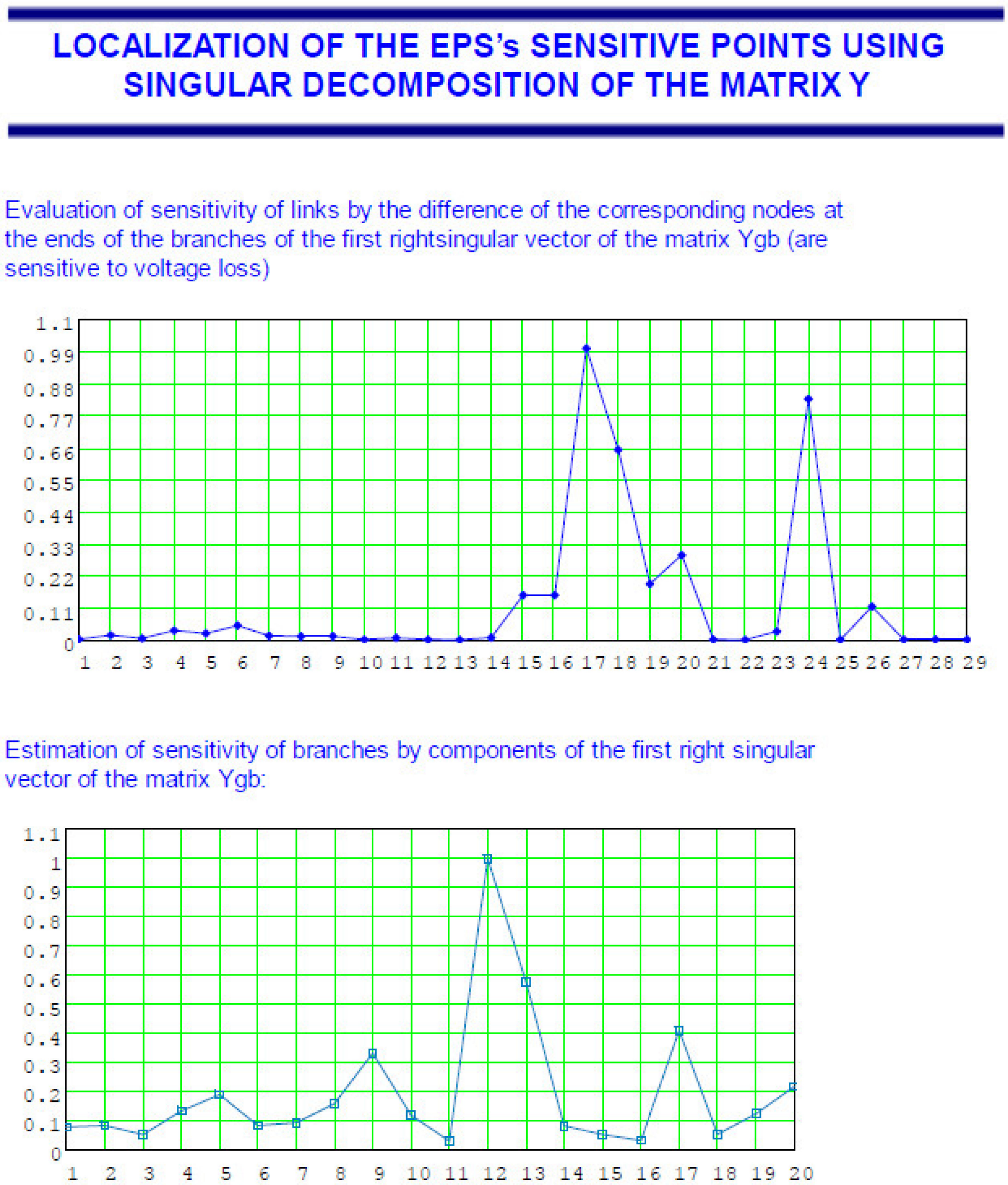


Figure A6. Visualization of Step 5.

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