RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
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Sergey KOVALENKO
The Doctoral student of Post-graduate program „Power Engineering”

Power System Static Stability Assessment Methods, Criteria and Algorithms

Summary of Doctoral Thesis

Scientific supervisor
Dr. sc. ing., professor
I. ZICMANE

Scientific advisor
Dr. sc. ing.
G. GEORGIEV

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OFFICIAL OPPONENTS

Professor, *Dr. habl. sc. ing.* **Antans Sauhats**
Riga Technical University, EEF

Dr. sc. ing. **Aleksandr Lvov**
Electrical engineer of Operational planning division, AS „Augstsprieguma tīkls"

Dr. sc. ing. **Arturas Klementavicius**
Lithuanian Institute of Power Engineering, leading researcher

CONFIRMATION STATEMENT

Hereby I confirm that I have worked out the present doctoral thesis, which is submitted for consideration at Riga Technical University for achieving *Dr. sc. ing.* degree. This doctoral thesis is not submitted to any other university for achieving scientific degree.

Sergejs Kovaļenko .... (signature)
Date ....

The doctoral thesis is written in English, it has an introduction, 5 chapters, conclusion and a list of literature. The doctoral thesis consists of 141 pages, 47 figures, 29 tables. The list of literature includes 98 references.

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TOPICALITY OF THE SUBJECT OF DOCTORAL THESIS

The steady state stability of power systems has been and continues to be of major concern in system operation. Modern electrical power systems have grown to a large complexity due to increasing of interconnections, installation of large generating units, and extra-high voltage tie-lines etc. Steady state stability refers to the ability of the power system to regain synchronism after small and slow disturbance, such as gradual power changes.

Economic and operational factors make power systems to utilize utmost percentage of their transmission capacity and consequently operate close to stability limit with small margins. In such environment voltage instability is emerged as a major threat for power system security. At present most of electric utilities use the fast response excitation systems, faster relays and stabilizing devices to improve the system security margin. Power systems have become increasingly concerned world-wide with voltage stability and collapse problems. A number of major voltage collapse phenomena have been experienced by utilities resulted in widespread blackouts. In spite of dynamic nature of voltage instability, static approaches are used for its analysis based on the fact that the system dynamics influencing voltage stability are usually slow.

Again, fault may occur at various locations of a power system network such as near the generator middle of the transmission line, and near the infinite bus etc. Steady state stability problems use a very simple generator model which treats the generator as a constant voltage source. The solution technique of steady state stability problems is to examine the stability of the system under incremental variations about an equilibrium point. The methods of linear analysis can be used to determine whether the system will remain in synchronism following small changes from the operating point or not. It is convenient to assume that the disturbances causing the changes disappear. The motion of the system is free; stability is assured if the system returns to its original state. Such a behavior can be determined in a linear system by examining the characteristic equation the system.

In all stability studies, the principle objective is to determine whether or not the rotors of the machines being perturbed return to constant speed operation. Obviously this means that the rotor speeds must depart at least temporarily from synchronous speed. In the past three decades, power system stabilizers (PSSs) have been extensively used to increase the system damping for low frequency oscillations. Worldwide the power utilities are currently implementing PSSs as effective excitation controllers to improve the system stability under various faults conditions.

Fig. 1.1 BEMIP [55]

On June 17, 2009, eight Baltic Sea Member States (Denmark, Germany, Estonia, Latvia, Lithuania, Poland, Finland, and Sweden) signed a Memorandum of Understanding on the Baltic Energy Market Interconnection Plan. The BEMIP is the result of nine months' work at the initiative of the European Commission (EC) to look at concrete measures to connect Lithuania, Latvia and Estonia better to wider EU energy networks (Fig. 1.1).

The necessity of development assessment of the Latvian Western region transmission network is required by a number of considerations, the most important of which is the safety of power supply. The next few years are provided significant changes for the generating capacity connected to the transmission network of this region, as well as the creation of connections of new intermediate systems (Fig. 1.2). It is expected to construct the Kurzeme KES and wind farms on the west coast, as well as it is planned to build new intermediate system connections from the Baltics to Sweden and Finland. These changes make it necessary to check the carrying capacity adequacy of the transmission network and determine doable technical measures [34].

The market economy dictates the terms of unification of the energy systems of the countries that leads to a change in number of interconnections, the increase of the transmitted power, and therefore, it is necessary to reconfigure the networks and, consequently, the recalculation of their normal modes, as well as the project assessment of static stability is required. Stability is an important constraint in power system operation and control. Power system stability is understood as the ability to regain an equilibrium state after being subjected to a physical disturbance. Principal among methods of static stability analysis is the determination of system stability on the consideration of eigenvalues in steady state condition. This provides appropriate strategy to have a quick decision on the system's steady state behavior.

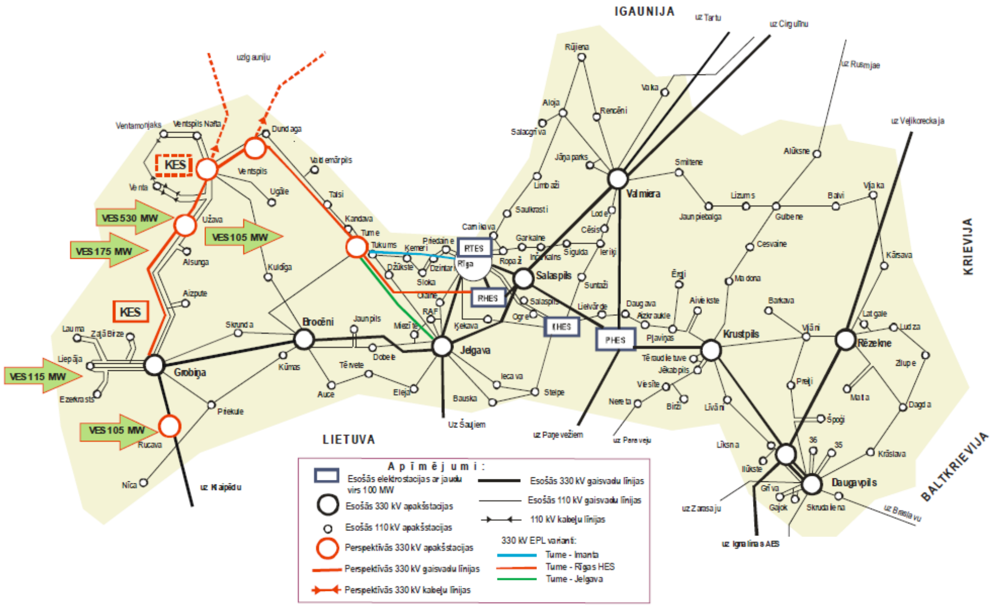

Fig. 1.2 The long-term energy development scheme of Latvia until 2018

Power system stability has been recognized as an important problem for secure system operation since the 1920s. Many major blackouts caused by power system instability have illustrated the importance of this phenomenon. Historically, transient instability has been the dominant stability problem on most systems, and has been the focus of much of the industry's attention concerning system stability. As power systems have evolved through continuing growth in interconnections, use of new technologies and controls, and the increased operation in highly stressed conditions, different forms of system instability have emerged. For example, voltage stability, frequency stability and interarea oscillations have become greater concerns than in the past. This has created a need to review the definition and classification of power system stability. A clear understanding of different types of instability and how they are interrelated is essential for the satisfactory design and operation of power systems [33].

The check of stability has the highest value when examining the systems of automatic control, which the majority of industrial objects and transport are equipped with [36].

Airplanes most of the time fly controlled by automatic devices – autopilots. Ships in sea are managed by automatic steersmen, stability characteristics of technological processes are supported by automatic controllers at most plants. For example, the stability theory is widely applied in aviation as well for safely operation of the engines of the helicopter. There are numerous applications of Unmanned Aerial Vehicles (UAVs) in defense and civil areas for monitoring, remote sensing, surveillance, dangerous environment etc. Quadrotor helicopter is an emerging rotor craft concept for UAV that consist of four rotors, with two pair of counter rotating, fixed pitch blades located at the four corners of the aircraft. A quadrotor is a dynamic vehicle with four input forces, six output coordinators, highly coupled and unstable dynamics (Fig. 1.3.). The stability theory (the theory of Lyapunov) is used to stabilize this system [43].

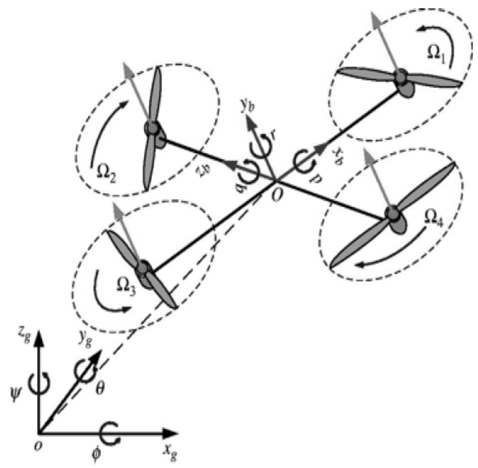

Fig. 1.3 Scheme of quadrotor helicopter [43]

Variables $x1$; $x2$; ... xn, as a rule are the deviations of the process characteristics from the desired value in control systems. If a mathematical model of the automatic control system is a system of differential equations with unstable solutions, these deviations will increase rapidly and normal system operation will be impossible. Therefore, even in the course of design is checked whether the projected system will be stable or not in all design and organizational organizations. Only the system, which accordingly to checking calculation is stable, can be implemented in „metal". Let's assume that unstable control system was recognized as the stable one due to a mistake in calculation. It is unpleasant, but not dangerous. The system instability will be revealed immediately during the tests due to rapidly increasing deviations of real flow of the controlled process from the desired one, so the system will be written off as throw-outs with appropriate write-off of losses. The more dangerous is the mistake related to maintaining stability under variations of parameters [36].

Thus, the theory of stability is the fundamental one in many fields of science and it is widely used for reliable and high-quality operation of various engineering systems.

AIMS AND OBJECTIVES OF THE THESIS

Aim - raising the level the static stability of power systems.

Objectives of this thesis are:

1. Inspection of the current methods of the static stability assessment of EPS.
2. The search for a fundamentally new algorithm of the static stability assessment.
3. The study of the classical approach to analyze the static stability with the help of CP and the introduction of new ideas for it application for small EPS.
4. The development of the static stability assessment criterion for large EPS on the basis of the modified method of rotation.
5. The development of the graphical module of an algorithm for a computer program of the static stability assessment. This algorithm has to visualize changes of the electrical network configuration.

METHODS AND TOOLS OF THE RESEARCH

The results of the paper were obtained by applying the following computer programs and methods:

1. The theory of differential equations, matrix algebra and the graph theory;
2. The EPS modeling in the environment of MATHCAD, EUROSTAG, ETAP;
3. The CP analysis using computer programs MAPLE and MATHCAD;
4. The result processing and graphical representation – MS EXCEL, MATHCAD.

NOVELTY OF THE DOCTORAL THESIS AND BASIC RESULTS

The scientific innovation is characterized by the following aspects:

1. The fundament concerning creation of a unified criterion for the static stability assessment is laid, which conditionally can be divided into two directions:

1.1 for the analysis of small EPS – use of CP and the modified Newton’s method, a graphical localization of the roots;

1.2 For the analysis of large EPS – use of the modified method of rotation and decomposition method because of which data related to each subsystem structure is confidential and remains closed for the owner of other system.

2. The graphical module of an algorithm for a unified computer program to assess the static stability of EPS was worked out.

PRACTICAL IMPORTANCE OF DOCTORAL THESIS

The market economy dictates the terms of unification of the energy systems of the countries that leads to a change in number of interconnections, the increase of the transmitted power, and therefore, it is necessary to reconfigure the networks and, consequently, the recalculation of their normal modes, as well as the project assessment of static stability is required. Thus, the results of this paper can serve as a basis for further research in the field of static stability of complex EPS, as well as for creating a module for the specialized computer program for the static stability assessment.

APPROBATION OF THE DOCTORAL THESIS

The results were reported and discussed at 10 international conferences:

1. G. Georgiev, I. Zicmane, **S. Kovalenko**, E. Antonovs. AN ALGORITHM OF AUTOMATIC PLOTTING OF ELECTRICITY SUPPLY NETWORK CIRCUIT. The 5th International Conference "ELECTRICAL AND CONTROL TECHNOLOGIES ECT – 2010", 2010, 6–7 May, Kaunas, Lithuania, ISSN 1822-5934
2. Г. Д. Георгиев, И. А. Зицмане, Э. С. Антонов, **С. А. Коваленко**. СОЗДАНИЕ МОДЕЛИ ДЛЯ ПРАКТИЧЕСКОГО РЕШЕНИЯ ПРОБЛЕМЫ РАЦИОНАЛЬНОЙ КОМПЕНСАЦИИ В СЕТЯХ ВЫСОКОГО И СРЕДНЕГО НАПРЯЖЕНИЯ. XI Международная Научно-техническая конференция. „ПРОБЛЕМЫ СОВРЕМЕННОЙ ЭЛЕКТРОТЕХНИКИ-2010", 2010, 31 May – 4 June, Kyiv, Ukraine.
3. G. Georgiev, I. Zicmane, **S. Kovalenko**, E. Antonovs. ВИЗУАЛИЗАЦИЯ ТОПОЛОГИИ ЭЛЕКТРИЧЕСКИХ СЕТЕЙ С ПОМОЩЬЮ ВОЛНОВОГО АЛГОРИТМА ЛИ. „THE INTERNATIONAL ENERGY FORUM 2010", 2010, 23–26 June, Varna, Bulgaria.
4. G. Georgiev, I. Zicmane, **S. Kovalenko**, E. Antonov. THE PRINCIPLE OF CREATING A GRAPHICAL EDITOR FOR AUTOMATIZATION PROCESS TRACING ELECTRICAL CIRCUITS. The 51st Annual International Scientific Conference of Riga Technical University, 2010, 14 October, Riga, Latvia, ISBN 978-9934-10-054-3

5. G. Georgiev, I. Zicmane, E. Antonov, **S. Kovalenko**. EXPRESS ESTIMATION OF INFLUENCE OF COMPENSATORY REACTIVE POWER ON THE ACTIVE LOSSES IN THE HIGH VOLTAGE NETWORKS. International Scientific and Technical Conference “Electrical Power Engineering 2010”, 2010, 14–16 October, Varna, Bulgaria, ISBN 978-954-20-0497-4

6. G. Georgiev, I. Zicmane, E. Antonov, **S. Kovalenko**. AN AGGREGATE ANALYTICAL LOAD MODEL WITH VOLTAGE DEPENDANT CHARACTERISTICS. The 6th International Conference on Electrical and Control Technologies ECT-2011., 2011, 5–6 May, Kaunas, Lithuania, ISSN 1822-5934

7. G. Georgiev, I. Zicmane, **S. Kovalenko**. HIGH ORDER CHARACTERISTIC POLYNOMIAL ROOTS’ LOCATION ANALYSIS (ИССЛЕДОВАНИЕ РАСПОЛОЖЕНИЯ КОРНЕЙ ХАРАКТЕРИСТИЧЕСКОГО ПОЛИНОМА ВЫСОКОЙ СТЕПЕНИ). ELEKTROENERGETIKA 2011 The Sixth International Scientific Symposium on Electrical Power Engineering., 2011, 21–23 September, High Tatras, Slovakia, ISBN 978-80-553-0724-4

8. G. Georgiev, I. Zicmane, **S. Kovalenko**. STATIC STABILITY ANALYSIS OF ELECTRICAL POWER SYSTEMS BY MEANS OF ROOT LOCATION OF A CHARACTERISTIC POLYNOMIAL. The International Scientific Conference ELECTRIC POWER ENGINEERING 2012., 2012, 23–25 May, Brno, Czech, ISBN 978-80-214-4514-7

9. G. Georgiev, I. Zicmane, **S. Kovalenko**. A STUDY OF THE CHANGE IN ASSESSING THE STABILITY OF THE INTERCONNECTED SYSTEM WHEN CONNECTING A LINK (LINE) BETWEEN ITS TWO SUBSYSTEMS 12. International Conference on Environment and Electrical Engineering., 2013, 5–8 May, Wroclaw, Poland, ISBN 978-1-4673-3058-9

10. G. Georgiev, I. Zicmane, **S. Kovalenko**. NEW APPROACHES OF STATIC STABILITY RESEARCH OF UNIFIED ELECTRIC POWER SYSTEMS. POWERTECH 2013, 2013, 16–20 June, Grenoble, France, ISBN978146735595

PUBLICATIONS

<u>The work materials were published in 15 international editions:</u>

1. G. Georgiev, I. Zicmane, **S. Kovalenko**, E. Antonovs. AN ALGORITHM OF AUTOMATIC PLOTTING OF ELECTRICITY SUPPLY NETWORK CIRCUIT. The

5th International Conference “ELECTRICAL AND CONTROL TECHNOLOGIES ECT – 2010”, 2010, 6–7 May, Kaunas, Lithuania, ISSN 1822-5934

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8. In scientific journal: G. Georgiev, I. Zicmane, E. Antonovs, **S. Kovalenko**. OPERATIONAL REDUCTION OF ACTIVE LOSSES IN HIGH-VOLTAGE NETWORKS VIA REACTIVE POWERS. Scientific Proceedings Of Riga Technical University, Power And Electrical Engineering, 4th series. Riga: RTU, 2011, serial 4, vol. 28, ISSN 1407-7345

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13. G. Georgiev, I. Zicmane, **S. Kovalenko**. A STUDY OF THE CHANGE IN ASSESSING THE STABILITY OF THE INTERCONNECTED SYSTEM WHEN CONNECTING A LINK (LINE) BETWEEN ITS TWO SUBSYSTEMS. 12. International Conference on Environment and Electrical Engineering., 2013, 5–8 May, Wroclaw, Poland, ISBN 978-1-4673-3058-9
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STRUCTURE AND SIZE OF THE THESIS

The doctoral thesis is written in English, it has an introduction, 5 chapters, conclusion and a list of literature. The doctoral thesis consists of 141 pages, 47 figures, 29 tables. The list of literature includes 98 references.

1. HIGHLIGHTS OF THE STATIC STABILITY ANALYSIS OF THE COMPLEX ELECTRICAL POWER SYSTEMS (EPS)

Ensuring the stability of power systems is one of the important tasks of its engineering and operation. Thus, violation of the stability of the parallel operation of generators can lead to disruption of power supply of a large number of the electric power consumers and even to a complete collapse of the power system. In its turn, the EPS union and its power growth make the issue of the stability ensuring of the most urgency.

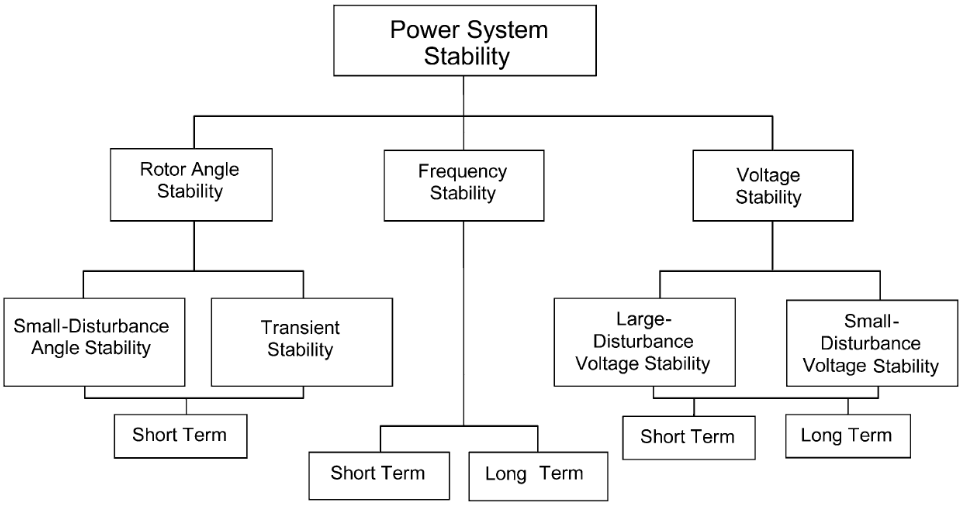


Fig. 1.4 Classification of power system stability [33]

The EPS stability evaluation is complex and includes many aspects, in connection with that you have to separate this task into three main components (Fig. 1.4):

1. The stability calculation for *short-term planning mode*, the basis of which is the results obtained in a long-term planning. This is primarily the experimental, prognostic and calculation data which allow making the equivalent circuit of a minimum amount for a sufficiently accurate presentation of the load qualities, regulator devices and automatic devices. The stability calculation for a short-term planning is expected to carry out to validate the permissibility of repair application and determinate the required mode changes and automation settings, as well as clarifying the stability restrictions within the mode optimization [3, 24, 35, 37, 38].

2. The stability calculations of power systems in the *operational management* enable to determine the required mode changes and anti-damage automation for solving the emergency applications and clarify the stability restrictions for operational optimization mode. In this

case, the automatic data entry is required and too little time is given for the problem solving because of which special methods and algorithms are required. The stability problem solving for the automatic management is aimed to increase the anti-damage automation adaptability, i. e. to save the staff from its responsible, complex and frequent setting operation changes [3, 24, 35, 37, 38].

3. The stability evaluation of the power systems at the *engineering stage* of its development which is a continuous process in time. It is important not only equipping with automatic regulators of the introduced new facilities, but also possible changes in the network topology with reconstructions of old and/or building of new electric mains [3, 24, 35, 37, 38].

Conclusion on Chapter 1

1. The market economy dictates the unification conditions of energy systems of the countries that lead to a change in the number of interconnections, increasing of the transmitted power in relation to what it is necessary to reconfigure the networks.
2. The market economy requires a planned assessment of the static stability.
3. Since the time of Lyapunov to the present days the theory concerning the solution stability of differential equations has developed significantly and it has been widely used in the power industry (the automatic control, the static stability analysis of complex EPS).

2. REVIEW OF MODERN APPROACHES USED FOR THE STATIC STABILITY ANALYSIS OF THE COMPLEX EPS

First of all it should be noted that in general the development of information computing technologies left an imprint and caused a revision of classical approaches to the research of the static stability. The characteristic polynomial (CP) was widely used at the earliest stage of the development of automatic control and introduction of automatic devices, but in case when difficulties arose while finding its roots, the algebraic or frequency stability criteria were employed (criteria of Routh, Hurwitz, Mikhailov, Nyquist etc.). Two disadvantages of this approach appeared with the subsequent increase of the problem dimension:

1. The increasing difficulty in obtaining a characteristic equation on the basis of initial operating description, even if it is set in a normal form of the matrix of coefficients, as it is required to find its determinant with still unknown operator;
2. The increasing difficulty in applying the stability criteria, because quite laborious calculations were in must.

The development of computer technologies has not led to essential progress in this way as this approach is difficult to formalize and effectively algorithmizate. Moreover, the calculation of the coefficients of the characteristic equation led to the accumulation of a large computational error, which, in its turn, has often led to incorrect eigenvalues (EV) and contrary to meaning results of stability. Now the most interesting was finding of eigenvalues by more direct ways – speed and memory of computing devices allowed acquiring the eigenvalues directly from the matrix of coefficients under a relatively simple algorithmization, including also the original construction of the matrix in a normal form. Let's remind that the system of linear differential equations is in normal form when it involves derivatives of the first order only. In case when there are a higher-order derivatives, the system can be easily normalized by introducing new equations and extra variables instead of derivatives of the higher orders (for instance, instead of X'' it should be written Y' and added one more equation to the system: X' = Y, taking into account the introducing of a new variable Y).

The modern association of EPS demanded the further increase of the problem dimension with the presence of powerful computing environment. The decision itself is not a problem anymore, but the efforts of researchers were directed towards operating speed (efficiency) and adequacy of the realized computer models. In this sense it is possible to highlight 6 independent directions (approaches) of researching the EPS static stability [3, 5, 21, 26, 46]:

Modern trends and approaches in the investigation of static stability of EPS:

1. New aspects of D-fragmentation

2. Solving problems of analysis of static stability of power system on the basis of artificial neuron networks (ANN)

3. Methods for computing the Gramians and use of them for the stability analysis of large linear systems

4. The pseudo-spectral analysis of the static stability of the large-scale EPS
5. Express method of the EPS stability evaluation
6. The signum function method

Conclusion on Chapter 2

1. Despite the vast variety of the described approaches, a set of methods of the static stability analysis of EPS, given in the algebra-differential form is substantially small. It includes spectral methods (the generalized problem methods of eigenvalues) and iterative methods (methods based on various iterative procedures). All these methods, despite the modern computer technologies are quite bulky. Consequently, there is an urgent need for a completely new express method of evaluation of the static stability of EPS.
2. With all the variety of modern computer software in the field of power industry, none of the above mentioned programs have the isolated module that would evaluate exactly the static stability of EPS. Only the combined use of programs can provide a good result that in point of fact is irrational. Thus, the issue of creation a new program to assess the static stability of EPS remains topical, based on a new algorithm.

3. SYNTHESIS OF A NEW ALGORITHM FOR EVALUATION OF ROOTS OF THE CHARACTERISTIC POLYNOMIAL (CP)

Summarizing the above mentioned in the Chapter 1 of this paper, it should be noted that there are two major directions in the static stability research field of electric systems:

1) Construction and research of the characteristic equation of the system as a polynomial of the n-th degree with real coefficients a_i (i = 0,1,...,n) and a_n>0:

$$a_n z^n + a_{n-1} z^{n-1} + a_{n-2} z^{n-2} + \ldots + a_1 z_1 + a_0 = 0, \qquad (3.1)$$

where z_i – a number of roots n, taking into account its multiplicity. If among them there are complex variables, the latter always follow in the conjugate pairs since the coefficients of the characteristic polynomial (CP) are real numbers. It is enough that all the polynomial roots are in the left half-plane of the complex field in order to derive the preservation of stability, but the very fact of the stability preservation does not depend on its specific values which affect the character of already known damped oscillations – aperiodic or oscillatory [13, 14, 15, 37]. According to the necessary, but not sufficient stability condition, the CP coefficients should always be positive values: if at least one of the coefficients is a negative number, then the system is unstable because the presence of positive coefficients does not allow obtaining the real roots in the right half-plane, consequently, the aperiodic stability disturbance cannot occur. However, the conjugate roots with positive real part may locate from the right of the imaginary axis, which in its turn will lead to the oscillatory violation of stability.

The criteria of Hurwitz, Routh, Nyquist-Mikhailov etc. are widely known, they indicate sufficient conditions for the stability preservation, focused on a hand-counting method which is *a complex task for large-scale schemes, but its formalization for program implementation is quite laborious* [14, 15, 16, 39].

2) Construction and obtaining of the eigenvalues of the coefficient matrix of the system of linear differential equations presented in a normal form.

It is possible to turn from the initial description to the normal way of writing of the differential equations, *lowering the order of the derivatives, by introducing new unknown functions.* However, recently more and more application of static stability is researched with the help of *eigenvalues* due to rapid development of computational tools. It is possible *to build the CP proceeding directly from the system description thanks to the computer technology*, *without taking it to a normal form, which in its turn may lead to the revision and full development of methods related to the CP root research.*

Today, there are a variety of algorithms and software tools for finding the eigenvalues (table 4.1), the basic one of those is *the rotation method*, the main idea of which is: the eigenvalues agree closely with the CP roots and consequently, in the case of the stability preservation among them should not be eigenvalues from the right half-plane. Unfortunately, the existing theoretical methods for the transition from the matrix to the characteristic equation and back have not found wide practical application due to laboriousness of the matrix determinant of a high order [14, 15, 16, 39].

In what follows, we take as a basis analysis of the roots of the characteristic equation (3.1) with a complex variable in a polar form $z = Re^{j\varphi}$ after its expansion into the real *y1* and imaginary *y2* parts:

$$y1 = R^n a_n cos(n\varphi) + \ ... \ + \ Ra_1 cos\varphi + a_0 = 0; \tag{3.2}$$

$$y2 = R^n a_n sin(n\varphi) + \ ... \ + \ Ra_1 sin\varphi \ = 0, \tag{3.3}$$

where the unknowns are n of modules R_i and its phases φ_i, satisfying the system (3.2, 3.3).

The selection of suitable initial conditions for the Newton's iterative process (3.5) was carried out with the help of a gradient minimization positively towards the definite function of residuals (inaccuracies):

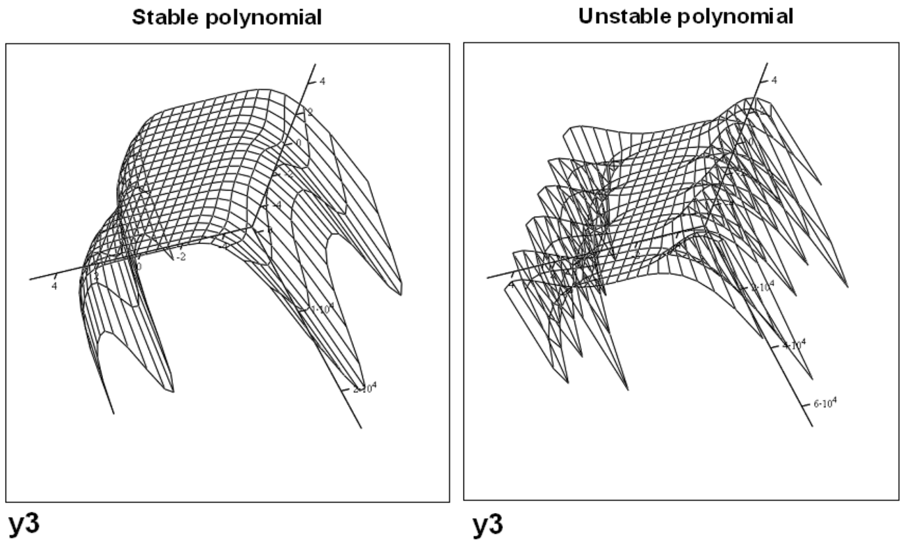
$$y3(R, \varphi)= y1(R, \varphi)^2 + y2(R, \varphi)^2 \tag{3.4}$$

$$\begin{vmatrix} \varphi' \\ R' \end{vmatrix} = \begin{vmatrix} \varphi \\ R \end{vmatrix} - \begin{vmatrix} \dfrac{\partial y1}{\partial \varphi} & \dfrac{\partial y1}{\partial R} \\ \dfrac{\partial y2}{\partial \varphi} & \dfrac{\partial y2}{\partial R} \end{vmatrix}^{-1} \times \begin{vmatrix} y1 \\ y2 \end{vmatrix} \tag{3.5}$$

It was necessary to research the function *y3(R, φ)* antigradient in the first quadrant within a quite small area from the origin of coordinates in direction towards the first quadrant. The function reduction (3.4) shows that it is possible to find the required root in this area, i.e. you can specify initial approximations for the iterative process with great accuracy by moving the initial point in the direction of antigradient [14, 15, 16, 39].

On Fig. 3.1 are presented contours for different values of an absolute term and - radius of the functions *y1(R, φ), y2(R, φ), y3(R, φ)*, as well as the function antigradient *y3(R, φ)* for the polynomial of the form $Y(z) = z^3 + z^2 + z + a_0$. Thus, increasing the absolute term within the area of the origin of coordinates, antigradient $-\nabla\ y3(R, \varphi)$ reduces. When $R = 0$, $\varphi = 90°$–
$\nabla\ y3(R, \varphi) = 0$. When the radius values are $R>0$, antigradient increases.

According to the obtained results we can conclude that in case of the stable polynomial the function *y3(R, φ)* contours are smooth curves, slightly vertically curved, at that, the more unstable the polynomial is, the more strongly pronounced form of perturbations acquires the contour form (Fig. 3.2) [14, 15, 16, 39].



$$y3(R, \varphi) = y1(R, \varphi)^2 + y2(R, \varphi)^2$$

$$a_3 z^3 + a_2 z^2 + a_1 z^1 + a_0$$

$$a_0 = 0 \longrightarrow a_0 = 100$$

Fig. 3.1 Stable and unstable surfaces of the auxiliary function *y3(R, φ)* for a polynomial of the form $Y(z) = z^3 + z^2 + z + a_0$

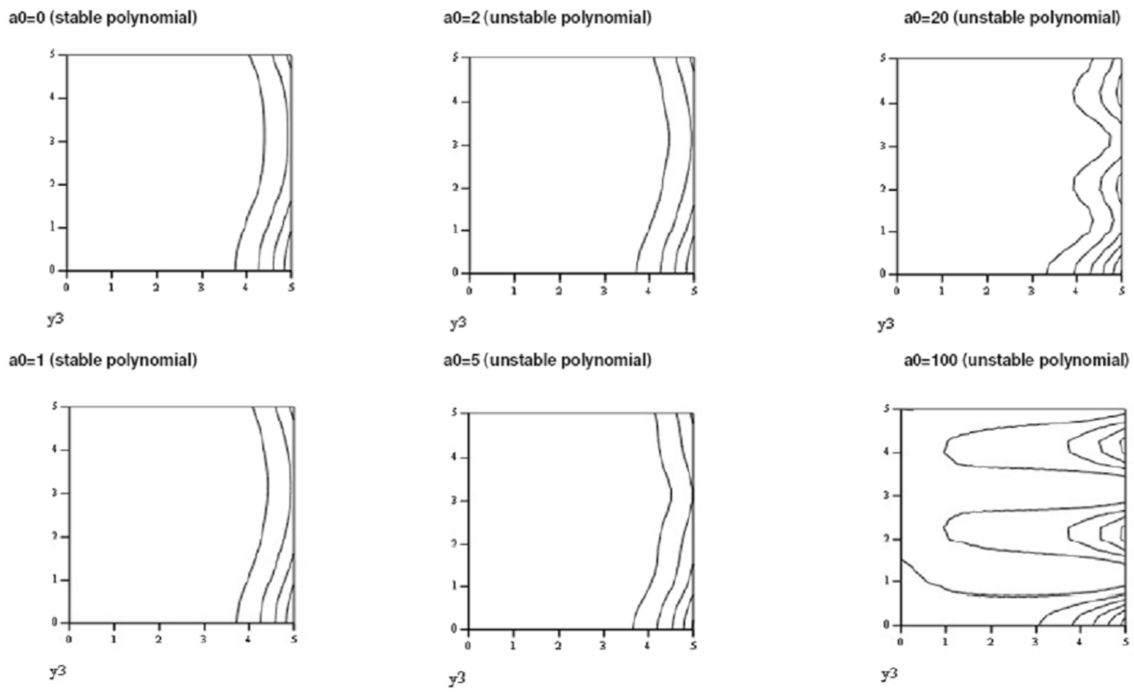


Fig. 3.2 The function *y3(R, φ)* contours for a polynomial of the form $Y(z) = z^3 + z^2 + z + a_0$ for different values of the absolute term

On the basis of the above mentioned will provide *the idea of generalized algorithm for evaluating the static stability of complex power systems.* The algorithm is sequential and it consists of the following basic steps (Fig. 3.3):

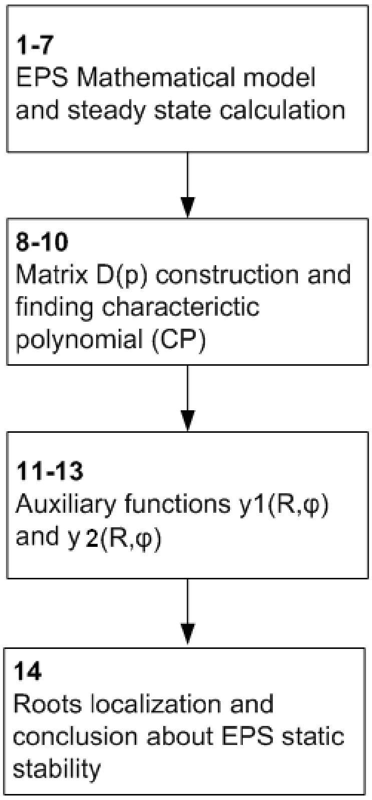


Fig. 3.3 Generalized algorithm of EPS static stability calculation

1. *Entering the topology and the power system data* - parameters of generators, transformers, loads, lines etc.;
2. *Bringing the power system parameters* to a single voltage class or transition to a system of relative values;
3. *Calculation of the steady-state network regime*;
4. *Calculation of the stator circuit regime of generators* to determine the complex values of electromotive force on the basis of voltages of station nodes found in p. 3.
5. *Exclusion of load nodes* of the system applying the Jordan method in order to obtain the generalized complex conductivities between the generator branches;
6. *Compilation of expressions for calculation of node capacity*;
7. *Accounting of regulators in the mathematical model*;
8. *Finding the partial derivatives* by angles and values of the electromotive force;

9. *Constructing of the matrix D*(*p*) *(3.5)*, consisting of 4 submatrices:

$$D_0(p) = \begin{vmatrix} \Delta_{ik} T_{Jk} p^2 + C_{ik} & B_{ik} \\ E_{ik} & D_{ik} \end{vmatrix} \tag{3.5}$$

$$C_{ik} = \frac{\partial P_i}{\partial \delta_k}; \; B_{ik} = \frac{\partial P_i}{\partial E_k};$$

$$E_{ik} = \tau_{doi} p \frac{\partial E'_{qi}}{\partial \delta_k} + \frac{\partial E_{qi}}{\partial \delta_k} - \sum_j \frac{\partial \Pi_{qi}}{\partial \delta_k} W_{\Pi_{ij}}(p);$$

$$D_{ik} = \tau_{doi} p \frac{\partial E'_{qi}}{\partial E_k} + \frac{\partial E_{qi}}{\partial E_k} - \sum_j \frac{\partial \Pi_{qi}}{\partial E_k} W_{\Pi_{ij}}(p),$$

where T_{Jk} – a diagonal matrix of constant inertia (with the size of *NxN*);

C, B, E, D – quadratic matrices of the size *NxN*;

P_i, – electromagnetic power of *i*-th machine;

E_i, E_k – EMF of synchronous machines;

τ_{doi} – time constant of time winding;

E_{qi}, E'_{qi}, E_{qei} – the synchronous, transient and forced EMF;

$W_{\Pi_{ij}}(p)$ – the transfer function of excitation regulator, which includes records of transient processes in the automatic excitation regulator (time constant τ_p) and in the exciter (time constant τ_e) of the *i*-th synchronous machine for the *j*-th regulation parameter Π_{ij}. The summation for the *j*-th regulation parameters Π_{ij} is required in those most common cases when the regulation is carried out by several regime parameters (for instance, current and voltage, frequency and voltage etc.);

Δ_{ik} – symbol of Kronecker. When *i* = *k* $\Delta_{ik} = 1. Пpu \; i \neq k \; \Delta_{ik} = 0$;

10. *Drafting of the characteristic polynomial* and finding a determinant of the matrix *D*(*p*);

11. *Recording of the characteristic polynomial (3.1) as a system of equations (3.2) and (3.3)*

12. *Choice of initial conditions φ0 and R0 = Rc/2 ;*

13. *Finding the roots of φi and Ri by the iterative method of Newton (3.5)* for each set of initial conditions.

14. *Conclusion on the conservation/violation of the static stability:* in the case when not all roots φi are outside of the range [–90 ÷90] deg., the iterative process of Newton diverges that indicates the stability violation.

Based on the foregoing, we conclude the possibility of establishing a unified program for evaluation of the static stability for training purposes. The idea is to create two-block modules. *The first block – training.* The basic algorithm – obtaining the CP and studying of its roots by the example of small EPS (up to 10 nodes). *The second block – computation* for a large-scale systems. The basis – analysis of the matrix coefficients *D(p)*, i. e. the analysis by partial derivatives (the modified method of rotation – Chapter 4). Also, in this program could be a graphical module – more simplified, suitable especially for students and educational purposes [46, 52, 53, 54].

Conclusion of Chapter 3

1. It has been shown how the conjugate roots of CP with positive coefficients may appear in the right half-plane. It was suggested to observe the polynomial division to the real *y1* and imaginary *y2* parts with the transition to a polar form of a complex argument and identifying the conditions for this purpose, under which both parts are simultaneously zeroized. Due to the graphical output it is easy to define upper and lower limits of the root modules in the right half-plane, depending on an absolute term.

2. A new graphical method (locus) of localization of roots in the right half-plane by motion by the contour of a central circle within a sector $0°÷90°$ and return on ordinate up to origin of coordinates was offered. A sufficient stability condition – symmetric alternation of zeros of functions *y1* and *y2*. It is required a relatively small number of points to construct the locus.

3. A simple method of calculation of roots in the first quadrant in accordance with the Newton's method was offered, based on the derivatives of the functions *y1* and *y2* in phase and module.

4. Any iterative methods (3.5) need sufficiently good initial approximations. The question of appointment of initial approximations required more detailed study. Per se, the proposed algorithm is a general plan for the static stability evaluation of large-scale power systems.

Difficulties arise when finding its polynomial (p. 10.) as it involves a large number of computations, which is difficult to realize even with the use of modern computer technology.

5. There is an additional problem – the need to identify the sensitivity of the polynomial roots, i. e. assessment of its changes for some small perturbations of the coefficients.

6. An important positive aspect of the proposed algorithm is the presence of p.11: the matrix in this block always has the dimensions of *2x2*, regardless of the size of the power system! It should be noted, in the raw this idea may be applied for the stability analysis of not too large (partially equivalent) power systems, the necessity to use not the polynomial of p. 10, but the matrix $D(p)$ itself (p. 11.) arises in order to calculate the power systems of a larger dimension.

7. The auxiliary function *y3*, its antigradient and contours were introduced, that at deeper study can serve as a more accurate selection of the initial conditions in the iterative process (6).

8. The use of a graphical image makes it easy to determine the upper and lower limits of the root modules located in the right half-plane and depending on the value of an absolute term. A sufficient condition for preserving the static stability of the power system is the symmetric alternation of zeros of the functions *y1* and *y2*.

9. The idea of creation of a graphical module for a unified program for the static stability analysis was offered, which could be used for training purposes. The algorithm we have discussed, independent of its certain share of heuristics gives more than acceptable results and its characteristics are superior to those of other algorithms we have tested. The outcome coordinates of *X* and *Y* can be easily transposed to a graphics editor for the further plotting of the obtained computation results.

10. The plotting of the electricity supply circuit can be done with multi-color layers determined by the layers of tension – first for the 400 kV circuit, then for 330 kV, taking as fixed the nodes from the preceding layers, and so forth.

4. THE MODIFIED METHOD OF ROTATION FOR THE STATIC STABILITY ANALYSIS OF THE EPS

The static stability assessment of large power systems is related with some formidable tasks that must be solved on the EPS scheme models of large-scale dimensions, implemented in software packages. In this regard, a number of questions appear:

1) How to determine the part of a large system that can be logically separated and simulated independently, but to get a fairly accurate result for evaluating the static stability of its synchronous generators?
2) How much detailed is it necessary to describe the oscillating electromechanical process, i. e. is it possible to do without taking into account the electromagnetic processes in the rotor and stator of a synchronous machine and if so, in what kind of machines?

Obviously, that the problem solution is related to the problem statement: i.e. what type of the stability should be researched. For example, it is only about the aperiodic stability violation, it is possible to only consider the accounting of electromechanical equations of the rotor motion while constructing a model.
3) What is the solution sensitivity depending on the accuracy of source data?

Probably, even small inaccuracies in accounting (selection) of electrical or mechanical parameters of network, such as moments of inertia of generator shafts with prime engines, will lead to the opposite in meaning conclusion and real statically stable system while modeling will be unstable.
4) How to take into account non-linear loads, set by its static characteristics (SLC) and whether to exclude such load nodes in the transition to an equivalent network model consisting only of generator units?

This problem was successfully solved in the general case [18, 19, 20] for the random non-linear SLC of active P and reactive powers of Q depending on the voltage U in the form:

$$P = P_0 \, (U/U_0)^{\alpha} \, ; \qquad Q = Q_0 \, (U/U_0)^{\beta}, \qquad (4.1)$$

where P_0, Q_0 and U_0 - basic parameters of the steady-state regime.
5) Which method of the static stability assessment should be applied to minimize the accumulation of computational error?

Examine the system consisting of two subsystems, connected by a single bond (line):

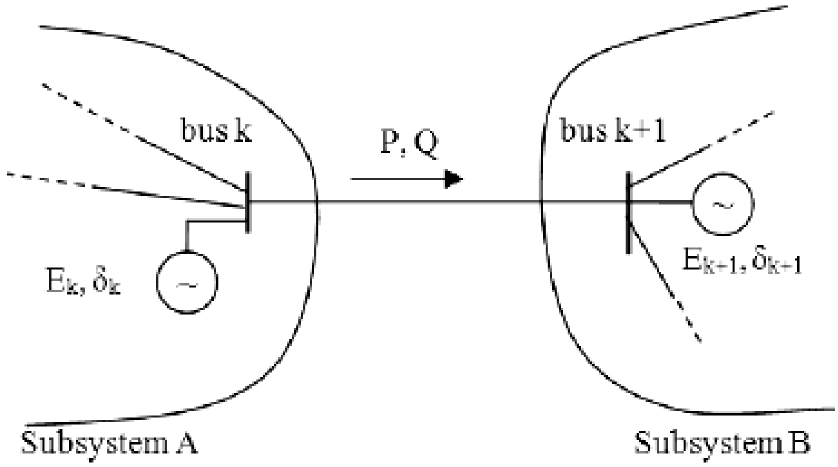


Fig. 4.1 The electrical system consisting of two interconnected subsystems

Imagine that the models of two subsystems consist of two synchronous generators and equivalent lines between them and assume, that for all of them are already known the eigenvalues in the isolated state, but preserving the internal steady-state regimes achieved by the addition of equivalent load and generation at nodes *k* and *k+1*, respectively (Fig. 4.2):

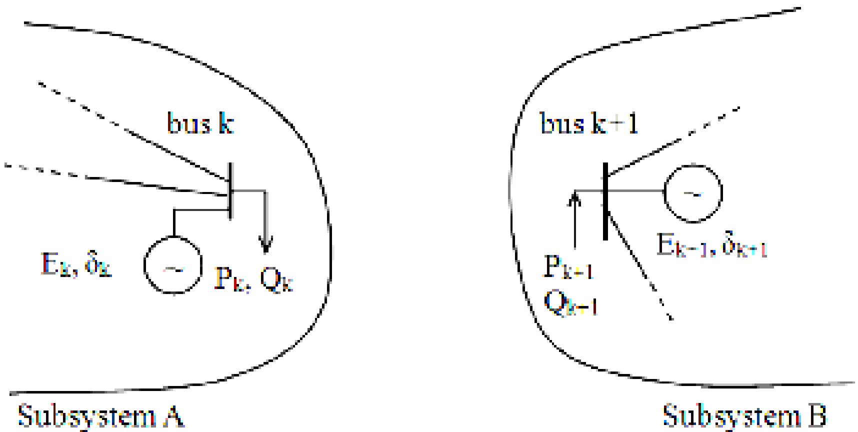


Fig. 4.2 The electrical system consisting of two isolated subsystems

In this case the matrix of coefficients will consist of two mutually diagonal blocks (Fig. 4.3 a):

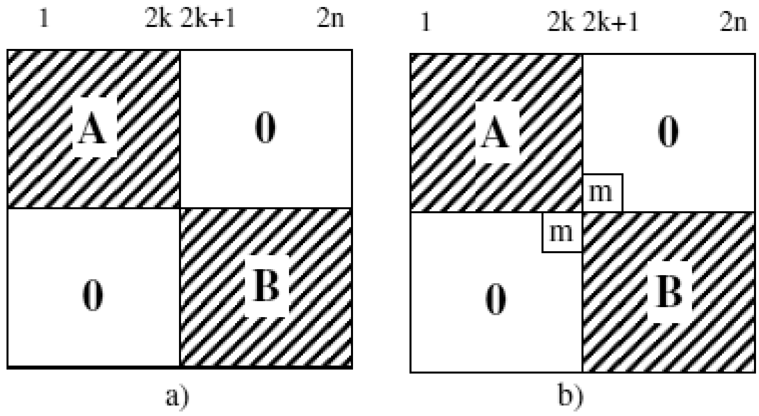


Fig. 4.3 The structure of the matrix of coefficients: a) for two isolated subsystems; b) after combining the subsystems, where m – added elements

We mark the eigenvalues of a block A (Fig. 4.3 a), corresponding to the subsystem A with $\lambda_1, \lambda_2, ..., \lambda_{2k}$, but the eigenvalues of a block B, corresponding to the subsystem B with $\lambda_{2k+1}, \lambda_{2k+2}, ..., \lambda_{2n.}$ Obviously, that the obtaining of its can be made separately for each block according to any of the known methods because this matrix has a natural block decomposition.

When combining the subsystems A and B (Fig. 4.1), this matrix will be complemented by two elements and its structure acquires the form displayed on the Fig. 4.3 b. These elements are partial derivatives of the true power overflow P of a flowline at the corners $\partial P/\partial\delta_k$ and $\partial P/\delta_{k+1}$ respectively. Thus, suppose that the original description consists only of electromechanical equations given in the operator form:

$$T_i p\omega_i + P_{di}\omega + \sum_{j=1}^{n}\frac{\partial P_{ij}}{\partial \delta_j} = 0, \qquad j \neq i \tag{4.2}$$

$$\omega_i - p\,\delta_i = 0\,, \tag{4.3}$$

where T_{Ji} – iterative time constant of the rotor of the i-th machine;
ω_i – its angular velocity;
P_{di} – damping coefficient.

The record is given in relative units, at that for the convenience of ordering columns of the lock A is in the order of ω_1. δ_1, ω_2, δ_2,..., but then in the block B is in order of δ_{k+1}, ω_{k+1}, δ_{k+2}, ..., ω_{k+2}, ..., ω_{2n} [18, 19, 20].

Table. 4.1 Selection the task-solving algorithm of eigenvalues

Name of the algorithm	**Used for**	**Result**	**Recommended for finding their own eigenvalues**			**Notes**
			The largest or smallest	**All <=6**	**All >=6**	
Determinant (iteration)	General matrix	Eigenvalues		*		Requires to find the roots of a general form
Iteration (iteration)	General matrix	Eigenvalues and eigenvectors	*	*	*	Provides the best accuracy for the largest and smallest eigenvalues
The Jacobi method (transformation)	Symmetric matrices	Diagonal form of the matrix		*	*	Theoretically requires an infinite number of steps
The Givens method (transformation)	Symmetric matrices	Tridiagonal form of the matrix		*	*	Requires knowledge of the simple polynomial roots
	Unsym-metrical matrices	The Hessenberg form		*	*	Requires the use of additional method
The Householder method (transformation)	Symmetric matrices	Tridiagonal form of the matrix		*	*	Requires knowledge of the simple polynomial roots
	Unsym-metrical matrices	The Hessenberg form		*	*	Requires the use of additional method
The LR method (transformation)	General matrix	Quasidiagonal form of the matrix		*	*	Sometimes unstable
The QR method (transformation)	General matrix	The same		*	*	The best method which possesses the greatest generality

The selection of a suitable algorithm for solving a problem of eigenvalues (EV) is determined by the type of eigenvalues, by the matrix type and a number of desired eigenvalues. The more complex the task, the lower is a number of algorithms to choose from. Table 4.1 makes the choice easier. Usually, the computer mathematical packages include subprograms, where all these algorithms or some of them are used. One of the most effective ways to use the existing mathematical software is the simultaneous use of two subprograms that allows combining the best qualities of them. For example, if you have the general form of a matrix, you can reduce it with the help of the Householder method to Hessenberg form, but later to find the eigenvalues with the help of the algorithm *QR*. At the same time both speed provided the Householder method and universality of the algorithm *QR* [18, 19, 20, 45, 50, 51].

Conclusion of Chapter 4

1. The decomposition algorithm fpr stability assessment is suggested in case when two subsystems are interconnected for transmission of power (trade). It is based on internal stability assessments for each subsystem before merging, taking into account the boundary link parameters and its regime.
2. The modification of the method of rotation was proposed to implement the algorithm used to find the matrix eigenvalues.
3. The data on the structure of each subsystem preserves its privacy and remain closed for the owner of other subsystem due to the proposed algorithm.
4. The algorithm has natural parallelism. The required operations may occur in each subsystem simultaneously and independently of each other.
5. The proposed approach can be used to deal with cases of more complex connectivity of subsystems.

5. COMPLEX POWER SYSTEM STATIC STABILITY ANALYSIS

Chapter 5 consists of three estimations:

1. The three machine system`s static stability is estimated by localization of the roots of the characteristic polynomial (Fig. 5.1.) Auxiliary function *y3* shows that the system is stable (Fig. 5.2, Fig. 5.3.)

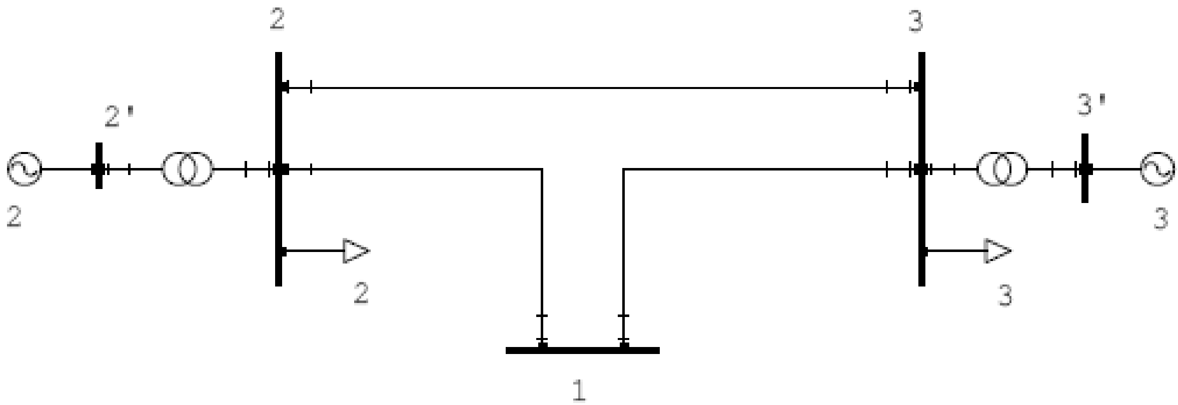


Fig. 5.1 A scheme consisting of two generators and BIP

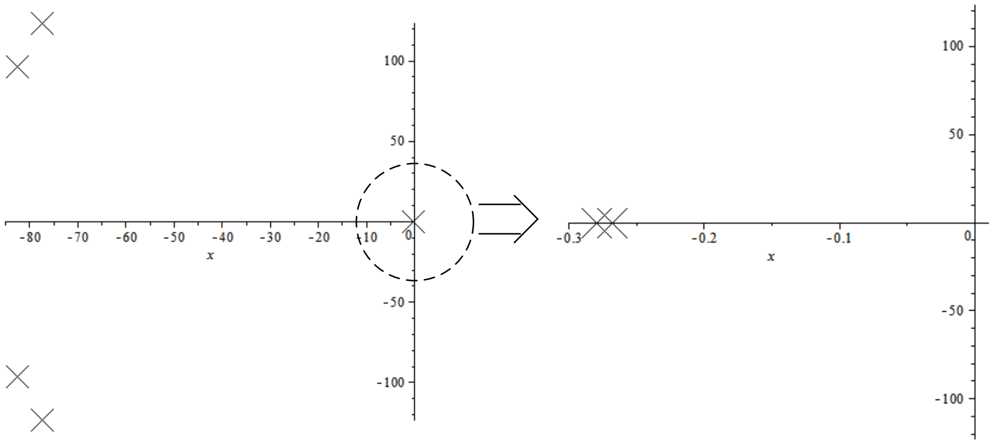


Fig. 5.2 Location of the CP roots in a complex plane

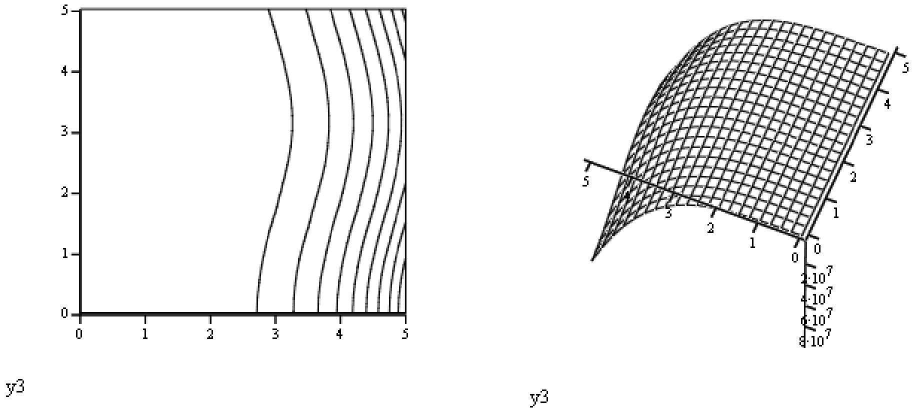


Fig. 5.3 Contour lines and surface of the function *y3* for the polynomial *D* (*p*)

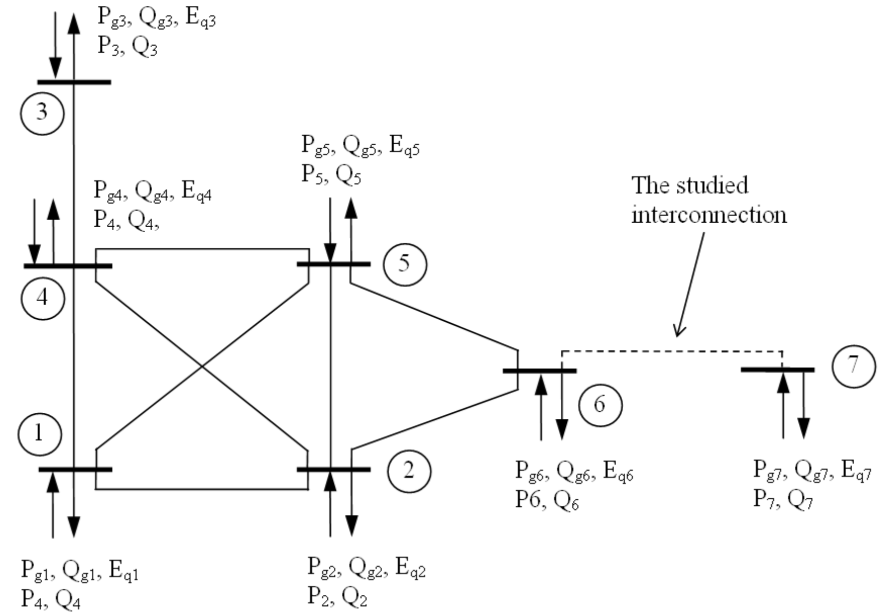


Fig. 5.4 Equivalent circuit of approximate electrical system with the set node active (P_{gi}) and reactive (Q_{gi}) generating capacities of turbo generators, the calculated electromotive force for the generator stators (E_{qi}) and loads (P_2, Q_2). The line 6-7 is connected to this system

2. The effect of impact of the transit line (connecting the generator) on static stability of power system (Fig. 5.4.) was studied, using the modified method of rotation.
3. Static stability of the Latvian power system was estimated, showing that the system is stable (Fig. 5.5, Fig. 5.6.)

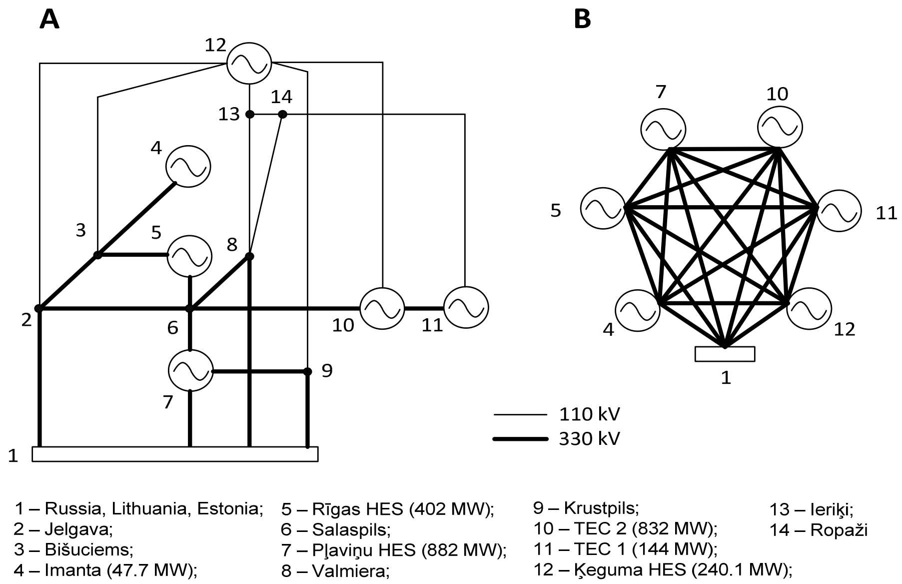


Fig. 5.5 A. Latvian power system and its main stations and substations;

B. Simplified scheme after the application of Jordan's method

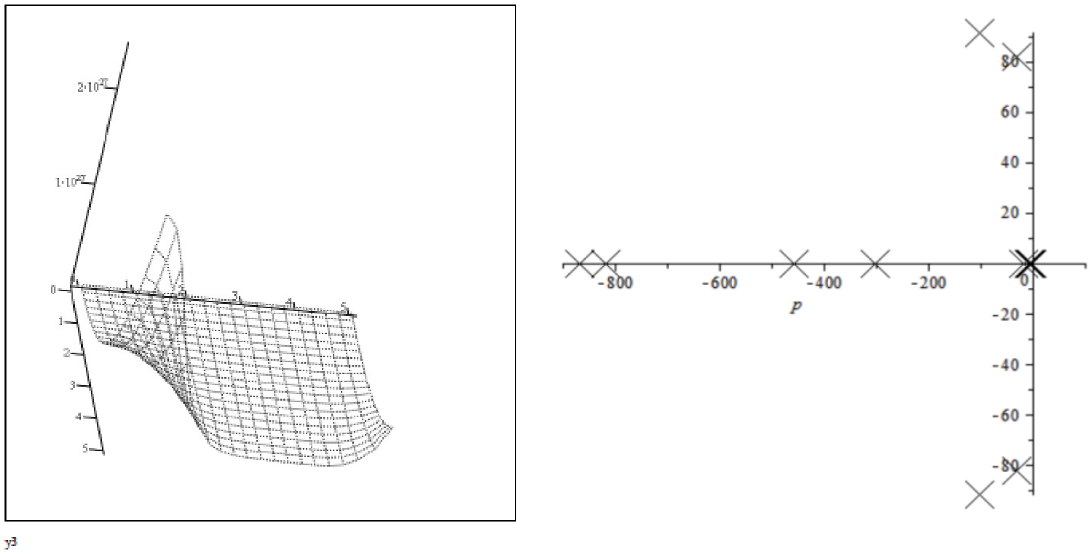


Fig. 5.6 Latvian power system's eigenvalues and surface of the auxiliary function *y3 (R,φ)*

Conclusion of Chapter 5

The analysis of the static stability of complex EPS would be best to carry out choosing three machine subsystems out of the entire system, but later for each of them with the help of the classical method by means of the CP analysis to evaluate the static stability. The advantage of the proposed auxiliary functions of the CP is **easy to implement localization of its roots on the complex plane.** In case you need to find the roots itself, you can do it with the help of auxiliary functions *y1* and *y2*. Besides, the static stability can be identified by the shape of contour lines of the auxiliary function *y3*.

It should be noted that there are no special difficulties to find the roots for the CPs of the three machine subsystem of the sixth degree. Then by transforming the matrix with the help of Givens method and sequentially adding generators (or gradually combining the 3-machine subsystems) it is quite simply to find the EV of the already augmented matrix, as well as to make a conclusion how the static stability would change after the combining, i.e. to carry out the analysis of the large-scale EPS. The main advantage of the technique is a much simpler form of the equation record to study the static stability in comparison with the model of the whole system.

Practically this method of calculation of complex EPS gives the opportunity to know which generators should be calculated and which of them not yet **at the level of the analysis of subsystems.** For example, if it is required to set a controller of the n-th station and determine its amplification **coefficient**, it would be enough to simulate only a small contiguous part of a system. It is possible to determine which stations can be excluded from the analysis because they cannot affect the evaluation of the static stability of the system in general in accordance with the proposed method in the process of Givens rotation without the last row and in the process of comparing the diagonal elements (those that have not changed), but later in the process of combining the subsystems by the last row. Also, this approach has important practical meaning because for the perturbations with the purpose to test the controller's settings in real situations it is sufficient to functionally isolate a small part of the system that is much easier and with minimal risk can be organized and implemented in respect to a dispatcher without affecting the operation of the rest system. The proposed approach is valid for a detailed calculation of electromagnetic transients that leads only to an increase in dimension of still small matrices of subsystems. This method has been illustrated on a small example.

The further directions of research can be identified on the basis of the research work:

1. Finding a **practical convergence criteria at the iterative process of finding the roots** of the functions *y1* and *y2* as signs of instability of the CP.

2. Development of a method to choice **convenient** initial approximations for R and γ that ensure convergence to determine the roots located in the left half plane.

3. Mathematical basing of the contour line shape of the function *y3* **(degree of evenness of a contour line as the stability criterion of the CP).**

4. **Computer implementation of the new criteria found with convenient interactive visualization of the system quality to be researched for the static stability.**

CONCLUSION AND FINDINGS

This doctoral thesis researched the static stability of electric power systems (EPS).

The market economy dictates the unification conditions of energy systems of the countries that lead to a change in the number of interconnections, increasing of the transmitted power in relation to what it is necessary to reconfigure the networks. The market economy requires a planned assessment of the static stability.

The stability theory from Lyapunov times up to nowadays was examined (use of gramians, the matrix signum function etc.). Despite the vast variety of the described approaches, a set of methods of the static stability analysis of EPS, given in the algebra-differential form is substantially small. All these methods, despite the modern computer technologies are quite bulky. Consequently, there is an urgent need for a completely new express method of evaluation of the static stability of EPS.

Comparing five software we concluded that the unified program for static stability analysis of EPS should be developed.

The static stability research can be divided into two directions assuming that there are *large-scale EPS* and *small dimension EPS*:

1. *The classical approach* using the CP for small EPS. The detailed calculation of unregulated three machine system was carried out – was analyzed the stability. It was proposed:

1.1 Separating the CP into two auxiliary functions *y1*, *y2;*

1.2 The method of graphical localization of the roots in the 1st quadrant;

1.3 The introduction of the auxiliary function *y3* to specify initial conditions of the iteration (use of the function *y3* antigradient);

1.4 Analysis of the function *y3* contours (waviness, curvature);

1.5 The idea of a graphical module to create a program for static stability analysis.

The advantage of the proposed auxiliary functions of the CP is *easy to implement localization of its roots on the complex plane.* In case you need to find the roots itself, you can do it with the help of auxiliary functions *y1* and *y2*. Besides, the static stability can be identified by the shape of contour lines of the auxiliary function *y3*.

Also Latvian power system static stability is calculated with method of CP roots localization.

2. *Alternative approach* to use the modified method of rotation for finding the eigenvalues and for further analysis of static stability:

2.1 The modified method of rotation;

2.2 Decomposition algorithm.

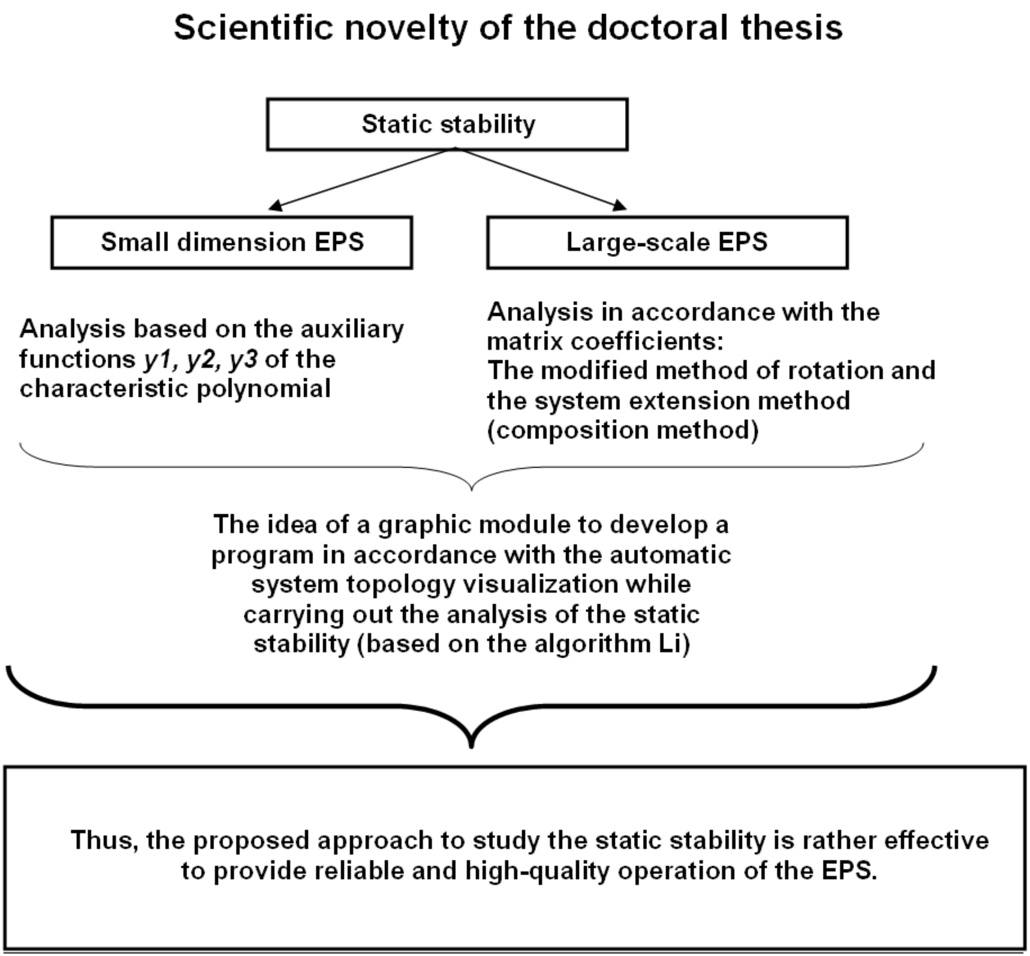
The decomposition algorithm for stability assessment is suggested in case when two subsystems are interconnected for transmission of power (trade). It is based on internal stability assessments for each subsystem before merging, taking into account the boundary link parameters and its regime. The modification of the method of rotation was proposed to implement the algorithm used to find the matrix eigenvalues. The data on the structure of each subsystem preserves its privacy and remain closed for the owner of other subsystem due to the proposed algorithm.The algorithm has natural parallelism. The required operations may occur in each subsystem simultaneously and independently of each other. The proposed approach can be used to deal with cases of more complex connectivity of subsystems.

Therefore, considerable work to study the static stability of EPS was carried out within the paper. The question is very topical for market economy and technical reequipment of electrical networks, its modernization and development (Table 6.).

Further ways of study

1. Finding a practical convergence criteria at the iterative process of finding the roots of the functions *y1* nd *y2* as signs of instability of the CP.
2. Development of a method to choice convenient initial approximations for *R* and *γ* that ensure convergence to determine the roots located in the left half plane.
3. Mathematical basing of the contour line shape of the function *y3* (degree of evenness of a contour line as the stability criterion of the CP).
4. Computer implementation of the new criteria found with convenient interactive visualization of the system quality to be researched for the static stability.
5. Calculation the static stability of the Baltic states in accordance with methods proposed in this doctoral thesis

Table 6. Scientific novelty of this doctoral thesis.



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