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Dalius Šulga

ACTIVE AND REACTIVE POWER CONTROL IN RESTRUCTURED ELECTRICAL ENERGY SYSTEM

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Scientific supervisor:

Assoc. Prof. Dr. Enrikas Vilimantas NEVARDAUSKAS (Kaunas University of Technology, Technological Sciences, Power and Thermal Engineering, 06T).

Council of Power and Thermal Engineering trend:

Prof. Dr. Rimantas Pranas DEKSNYS (Kaunas University of Technology, Technological Sciences, Power and Thermal Engineering, 06T) – **chairman**;

Prof. Dr. Habil. Vaclovas MIŠKINIS (Lithuanian Energy Institute, Technological Sciences, Power and Thermal Engineering, 06T);

Prof. Dr. Albertas NARGĖLAS (Kaunas University of Technology, Technological Sciences, Power and Thermal Engineering, 06T);

Prof. Dr. Habil. Algimantas Juozas POŠKA (Vilnius Gediminas Technical University, Technological Sciences, Electronics and Electrical Engineering, 01T);

Prof. Dr. Habil. Antans SAUHATS (Rigas Technical Univercity, Technological Sciences, Power and Thermal Engineering, 06T).

Official opponents:

Assoc. Prof. Dr. Anzelmas BAČAUSKAS (Kaunas University of Technology, Technological Sciences, Power and Thermal Engineering, 06T);

Prof. Dr. Habil. Mati VALDMA (Tallinn University of Technology, Technological Sciences, Power and Thermal Engineering, 06T).

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Address: K. Donelaičio g. 73, LT-44029 Kaunas, Lithuania.
Phone: (8~37) 300042, fax: (8~37) 324144, e-mail mok.skyrius@ktu.lt

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Dalius Šulga

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Mokslinis vadovas:

Doc. dr. Enrikas Vilimantas NEVARDAUSKAS (Kauno technologijos universitetas, technologijos mokslai, energetika ir termoinžinerija, 06T).

Energetikos ir termoinžinierijos mokslo krypties taryba:

Prof. dr. Rimantas Pranas DEKSNYS, (Kauno technologijos universitetas, technologijos mokslai, energetika ir termoinžinerija, 06T) - **pirmininkas**;

Prof. habil. dr. Vaclovas MIŠKINIS (Lietuvos energetikos institutas, technologijos mokslai, energetika ir termoinžinerija, 06T);

Prof. dr. Albertas NARGĖLAS (Kauno technologijos universitetas, technologijos mokslai, energetika ir termoinžinerija, 06T);

Prof. habil. dr. Algimantas Juozas Poška (Vilniaus Gedimino technikos universitetas, technologijos mokslai, elektros ir elektronikos inžinerija, 01T);

Prof. habil. dr. Antans SAUHATS (Rygos technikos universitetas, technologijos mokslai, energetika ir termoinžinerija, 06T).

Oficialieji oponentai:

Doc. dr. Anzelmas BAČAUSKAS (Kauno technologijos universitetas, technologijos mokslai, energetika ir termoinžinerija, 06T);

Prof. habil. dr. Mati VALDMA (Talino technologijos universitetas, technologijos mokslai, energetika ir termoinžinerija, 06T).

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Adresas: K. Donelaičio g. 73, LT-44029 Kaunas, Lietuva,
Tel. (8~37) 300042, faksas (8~37) 324144, mok.skyrius@ktu.lt

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1. INTRODUCTION

Relevance of the Work

In the process of energy system reorganizing in various countries the primary aim is to separate the activities of electrical energy production, transfer, and distribution. By dividing one or separate companies into separate companies performing independent businesses it is possible to avoid mutual sponsorship of activities and provide conditions for transparency of activities. Another aim of activity separation is to create conditions for emergence of market relations in this field. The following topics are widely considered while market relations take hold in electrical energy field: the efficiency of power generation, transfer, and distribution, reliability before and after the emergence of market relations, and the consequences of market relations. One of essential purposes of restructuring is to create competition between the generating sources while maintaining the integrity and reliable functioning of electrical energy system (EES). However, recent large-scale accidents in European and American energy systems leaving entire large regions without power caused a revision of system control principles and used tools in order to improve system control and increase the reliability of power system functioning in market conditions.

Market relations being implemented in energy systems change the conventional system control principles and applied algorithms. Energy system control acquires other value and importance in market conditions. Energy system control factors affect market players and commercial agreements drawn by them. Under market relations in energy system, the market players create the daily schedule of power energy balance based entirely on economic factors. The assurance of energy system reliability and anticipation of emerging restrictions becomes extremely complex and crucial task of a transmission system operator (TSO) in market conditions. In market conditions TSO performs any actions solely upon necessity; therefore the accident risk increases. The anticipation and prevention of potential accident situations become an important and mission -critical job for a system operator because any accident in electrical energy systems causes tremendous financial losses for market players and other consumers and producers. After market relations are introduced into the power system, the transmission system operator has very little time to anticipate and eliminate potential risks and failures. The efforts are made to allow the market players making transactions as close to real-time moment as possible. This aggravates the system operator's work and performed functions. Only by using good technical tools and applying proper and effective algorithms the system operator is able to anticipate possible problems or system bottlenecks and make right and effective decisions. "Bottlenecks" are such points in the power grid where the voltage, current, or other parameters first reach maximum or minimum value after a certain event in the energy system such as disconnection of a line, circuit breaker, or generating source.

State estimation may be used as an effective tool for optimal power system control even in complex situations. By applying the state estimation it becomes possible to process and assess received information in quick and efficient manner. An essential application of this problem is the determination of wrong or inaccurate measurements. However to enable real-time usage of state estimation calculations the power system must be modeled in a way allowing real-time calculations of various power system modes with the condition that the calculated modes correspond to the actual modes as closely as possible. After having studied the accidents that happened in energy systems, many power system specialists, committees, and experts have noted that the state estimation being in place and the creation of power system model so that the calculated modes would correspond to the actual modes as closely as possible are the essential factors that might be an efficient support for the system operator at the critical moments.

To make the power grid state estimation possible to apply in Lithuanian power system it is necessary to create the power system model that could be used for real-time modeling of system status, determination of bottlenecks, and selection of optimal actions for accident prevention. In the process of creation of power grid model it is necessary to consider and evaluate the information available in real-time and determine which system part is to be included into the model. Sometimes in the process of creation of power grid model it may appear that the information available in real-time is not sufficient to create the power system model.

Task of the Work

The main objective of the Thesis is to work out the methodology aimed to develop a closely integrated electricity network model to be used for real time calculations, and afterwards, based on this methodology, to develop a model of a closely integrated electricity network, which would be applicable in real time calculations of active and reactive power.

Based on the analysis of calculation methods used by the state estimation software, on the analysis of calculation algorithms and with regard to the peculiarities and impact of market relations, the Thesis is targeted to identify potential improvements in the state estimation software as well as the development tendencies in the electricity network's state estimation. Subsequent upon the analysis of application possibilities of the electricity network state estimation as well as the operation of the state estimation software, the Thesis is aimed to identify the potential of further improvement in this area, which would enable to upgrade the state estimation software by its better adaptation to contemporary requirements.

The Thesis is aimed to find methods for decreasing the number of calculated operation regimes by using the worked out module of electricity network state estimation by identifying potentially dangerous failures in the power system (ensuring of n-1 criterion in real time).

To reach the main purpose of this Work means to complete a number of the following smaller tasks:

- To analyze methods and approaches for real-time calculation of power modes.
- To create a method for real-time calculations to establish the power grid model.
- To perform power mode calculations and analyze resulting modes to establish Lithuanian power system model best suitable for real-time calculation of modes.
- To examine the effect of various possible factors to Lithuanian power system model.
- To study the influence of balancing node to system modes and application possibilities of distributed balancing node.
- To determine the directions and trends for further improvement and development of power grid state estimation.
- To analyze the reliability and accident-susceptibility of separate elements of power system transmission grid.

- To create the list of essential failures to be modeled according to the reliability evaluation of separate elements of power system and their affect to the modes.

Scientific Novelty of the Work

In the Thesis the methodology has been worked out based on which it is possible to develop a model of a closely integrated power system applicable in real time calculations. It contains a set of more detailed and comprehensive issues which have to be researched in order to develop a model of closely integrated power system. The development of a model of electricity network which would be suitable for real time calculations in closely integrated systems was not profoundly investigated and examined yet, because such systems are not very numerous.

The Thesis contains a survey and analysis of technologies and calculations used for the power system’s state estimation, as well as the analysis of the drawbacks of the presently used state estimation modules, their features which require improvement with regard to the established market relations and their impact on the power systems’ management. Resultant of the analysed state estimation module, applied methods and calculation algorithms, the improved algorithm of state estimation and tools enabling to achieve better calculation results of state estimation have been proposed in the Thesis.

Besides, the impact of a distributed balancing node on the calculation results, the benefits obtained by using the distributed balancing node as well as additional new estimation possibilities arising from the use of the distributed balancing node have been assessed in the Thesis.

Real time application of n-1 criterion in the closely integrated systems is rather complicated due to numerous power system components. Besides, when a Transmission System Operator, involved in a real time operation, is provided with a very big quantity of various calculated operation regimes, it is very difficult for him to evaluate these calculations, to select potentially most critical cases and to project actions enabling to avoid faulty operation or failure. Hence, based on the analysis of impact of individual network components on its reliability and system operation regimes, a new method was worked out in the Thesis enabling to decrease the number of calculated regimes. The list of potential failures requiring calculations has been compiled by taking into consideration the analysis of reliability of specific system components, the analysis of fault statistics, impact of individual system components on network operation regimes. To assess the impact of specific system components on the power system’s operation regimes, the principles of systemic analysis methodology have been used in the Thesis.

Practical Value of the Work

The prepared model of Lithuanian energy system for real-time mode calculation is very useful for the implementation of real-time power mode calculation in Lithuania, as the first precondition for real-time mode calculation and the calculations of power grid state estimation is the creation of an energy system model. The created and studied power grid model has been implemented and tested at National Dispatcher Centre of Lietuvos Energija AB, within the real-time system of automated dispatch control.

The application of prepared and tested creation approach of tightly integrated energy system model for real-time mode calculation allows creating the models of other tightly integrated energy systems for real-time calculations of active and reactive power modes. This Work shows that the modes of more extended model of the power grid not necessarily ensures better correspondence to the modes of the model of entire power grid in tightly integrated energy systems. An action sequence for power grid model implementation has been determined and presented that allows successful implementation of a power grid model for state estimation.

The implemented power grid model for real-time mode calculation in the automated dispatch control system allows the application of other grid analysis problems for real-time anticipation of possible accidents and control optimization thus significantly increasing the reliability of power system control and functionality.

The completed analysis of reliability and accident rate of separate transmission grid elements allows making a smaller list of possible grid failures, selecting only the failures that are critical and have the most severe impact on the system functioning, and eliminating the failures that are insignificant or have low impact on the grid functioning. Such an approach significantly accelerates the calculations of possible failures and allows more efficient use of the possibilities of this problem without dumping unnecessary redundant information on the system operators.

The completed analysis of state estimation and other grid analysis problems allows better preparation for the implementation of state estimation and other grid analysis problems, selection of better and most modern calculation approaches, and application suggestions regarding the improvement of state estimation.

Defensive Propositions of the Dissertation

The methodology of development of the closely integrated power systems model can be efficiently used in developing real time calculation models for other closely integrated and less integrated power systems.

The state estimation module is a compulsory tool in the power system dispatch centres because of the impact of market relations, increasing integration of the power systems, growing interdependence among interconnected power systems.

An additional portion of primary information in the state estimation module will enable to improve the quality and accuracy of the calculation results of electricity network’s state estimation.

In big and closely integrated power systems it is necessary to look for possibilities to reduce the number of potential failures to be calculated in real time in order to save technical resources and to avoid overburdening of dispatchers with information.

The number of calculated failures may be significantly reduced by using the statistical information about faulty operation of the system components and their impact on the operation regimes.

Approval of the Work

The material presented herein has been presented at 10 scientific conferences

The topic of this Thesis has been published in 6 scientific publications.

Doctoral Dissertation Structure

This Thesis consists of preface, five chapters, main conclusions, and the table of references. The Thesis consists of 96 pages, 40 figures, 22 tables. The table of references consists of 91 items.

2. STUDY REVIEW

This part examines the impact of reorganization and the emergence of market relations on active and reactive power flow control in the energy systems and the change of relations in the process of energy systems reorganization. Recent events in electrical energy systems resulting in "blackout" of large segments of developed power system have shown that it is crucial to ensure the power supply reliability and security in market conditions. This part also examines the main conclusions and results of other researches completed in this field.

The control of a reorganized energy system essentially being a cluster of independent companies undergoes significant changes in market conditions. All generators could be directly used for system control previously, but market conditions allow their use only under relevant agreements. Besides, the relations among separate companies become clearly defined and precise, as it has been agreed in a bilateral contract. The operation of the entire power system is also changing, as many companies springing from a single company have different of even opposite goals in the operating energy system. The management of companies functioning in market conditions is much more complex. However upon the completion of the process of reorganization of a vertically integrated company and introduction of market relations among the companies the relations among them become more prominent and the services acquire specific values and costs, which is difficult to achieve in a vertically integrated company.

The making of control decisions changes first in the power market. Previously the control information was accumulated and the decisions were made in a single location, but in conditions of restructured energy systems the information is accumulated and the decisions are made practically at each energy company. In order to avoid confusion and ensure the reliable functioning of an energy system, the task of the transmission system operator (TSO) is to take care of general energy system issues and ensure the reliable and stable general functioning of the entire energy system.

It has become much more difficult for TSO to attend to these tasks after the introduction of market conditions. The stages of alignment with market operator (MO) and other companies have emerged. It takes more time. The freedom and liberality for creation of daily operation schedules and energy system control decreases due to market relations. Due to the reason of market players involvement in the process of creation of daily operation schedules it is not always possible to examine the daily schedules in an exhaustive and detailed manner and make them safer from the perspective of system functioning. The efforts are made to create the most favorable conditions for the market players to perform trade as close to real-time hour as possible. As a consequence the system operator must function in settings practically leaving no time for extensive checks of future system operating modes according to the daily operation schedule created by the market players. The power grid state estimation is referred to as an efficient tool facilitating the energy system control in such complex settings. After the completion of consequence and cause analysis of the accidents having occurred in modern energy systems (in the United Kingdom, France, Finland, Denmark, and Sweden), the conclusions refer to completely different accident scenarios if only the state estimation were applied and not only own electrical energy system but parts of adjacent electrical energy systems had been properly modeled as well.

This part also outlined the developments and trends of power grid state estimation and other grid analysis problems. After the introduction of more reliable calculation algorithm for the state estimation, various analyses for both real-time and non-real-time operation were rapidly created. The approaches suggested by F. Schweppe enabling the isolation of wrong measurements and the separation of measurement noise are referred to as the basis for power grid state estimation. Various technology problems of grid analysis that are nowadays applied can be categorized as follows: 1) mode monitoring, control, and state estimation; 2) generation supervision and frequency control; 3) active power flow balancing; 4) forming and control of power and flows reserves; 5) system stability check; 6) mode balancing according to the reactive power; 7) grid voltage adjustment; 8) voltage mode stability check; 9) calculation of power and energy losses; 10) transmission grid power flow optimization; 11) optimal distribution of generator loads; 12) load forecast and operation plan creation; 13) system operating reliability calculation. All these problems directly depend on state estimation that is fundamental to all further calculations and analyses.

The electrical energy system functioning within large-scale energy systems has additional benefits in ensuring a stable and reliable functioning of energy system but it presents a challenge for the operation of state estimation and other problems as the operation within a large-scale energy system requires the modeling of a significant its part thus resulting in thousand of nodes and hundreds of thousands of various measurements in the model. The researches have been performed and grid analysis problems successfully implemented mostly in isolated energy systems with a small number of intersystem power transmission lines. The peculiarities of creation of similar power grid models for tightly integrated energy systems have not been researched.

The introduction of the state estimation approach must be associated with the introduction of least squares approach; it has undergone quite rapid development and improvements since its introduction. The least squares approach has been invented by Gauss and further developed by Kalman modern forms. Gauss characterized the simple layout of least squares approach as the starting point for innumerable and exciting researches. It has been proved afterwards by determining that Kalman filter might be considered as an efficient solution for least squares calculation. Gauss stated that the probability density function peak is determined by maximizing the logarithm of this function. In that way the maximum probability method has been derived that has been invented by R. A. Fisher in 1912 and thoroughly investigated since then. It is interesting to note that Gauss has rejected the maximum probability approach but reduces the difference between the functions of calculation and observation functions and reworked the least squares approach independently from the theory of probability. However the problem of least squares approach has been determined by maximizing the logarithm of independent and normally scattered residual errors. Further improvement of estimation theory is related to the introduction of Kalman filter. R. A. Fisher has suggested the maximum probability estimation, and Kolmogorov in 1941 and Winner in 1942 made further progress with the approach of linear minimum mean square estimation. Gauss reached a conclusion that linear equations must be suitable for solving the state estimation problem in case of precise state assumptions. Nevertheless there are quite a number of differences between the problem examined by Gauss and that examined by Winner and Kolmogorov. First of all, the assumption of constant signal value is not permissible. The signal might be different at each n value, but statistically it may be designated as autocorrelation and cross-correlation functions of measurement data and signal. Secondly, the probability version of least squares approach has been chosen as a quality index instead of proving that the calculation is the most probable.

If the power system regimes are close to their limit values within the entire power system or its part there is a rapidly rising probability that the calculations will not converge, i.e. no result will be obtained. System mode calculations at boundary system parameters strongly depend on the way of power system modeling.

It is essential to define grid analysis purposes, desired potential and functionality before creating the power transmission grid model for real-time calculations. It has great impact on power grid model preparation.

In the process of selection of system model to be used for real-time calculation of system modes, an engineering study is first of all performed to determine the significance of impacts by various events on the system modes. The engineering studies consider the loads and their characteristics, the affect of and difference among separate days, the affect of climatic conditions, and system control features. However it has been established in many cases that the entire power system grid does not necessarily must be reflected and modeled. A simplified power grid model is created in that way allowing much faster calculations and results. In the process of power grid engineering studies additional tasks might be as well defined such as determining the points of unstable balance that reflect system stability and transient stability in most cases. These scenarios are recorded and re-calculated for checking purposes after the simplified power grid model has been obtained. The engineering studies having been complete, it is recommended to determine the power grid parts having low impact on the modes of power grid part in the process of creation and prepare several possible power grid modules that are further recommended to study by applying engineering studies and mode calculation programs. The last stage is the according implementation and production testing of the model using actual data. In case of unsatisfactory or even wrong calculation results the analysis of initial results is to be performed after which the entire process of power grid model creation is repeated according to the results obtained.

Besides the classical calculations the dynamic system estimation may be applied in some case as a new state estimation approach. Real-time state estimation is a complex task due to continuous variations of system state and separate grid parameters. Dynamic state estimation helps estimating the separate grid parameters or grid part. It is usually used if critical grid measurements are lost or separate grid parts become unobservable due to the lack of data. Nonetheless the most important input into the creation of grid model is made by engineering solution, and the successful state estimation largely depends on the selected grid model.

3. DETERMINATION OF THE POWER NETWORK MODEL CREATION METHOD

This chapter examines the approaches used for power grid state estimation, various possible calculations, modeling possibilities for power grid elements; the approach for creation of model of tightly integrated energy system power grid is selected according to power grid model creation approaches described in previous chapter.

The initial power grid state estimation used the statistic information analysis approach. The system topology being known, the received telemetry information was statistically processed by analyzing and comparing the averages of received information with those of previously received information. Kalman filter was used in most of initial state estimation. To improve the results of state estimation it was proposed that all used information should be considered as inaccurate, with certain statistical error or inaccuracy present. It also covers the static information about the power grid such as resistances, capacities, inductivities, and positions of switching units. The grid analysis problem most often consists of two functional modules – grid configuration determination and power grid state estimation modules. One of the main purposes of grid configuration module is to make up the model of nodes and their connecting lines from bus section diagram according to the states of switching units. This chapter describes the stages of the functioning of this model and performed calculations.

Without state estimation in place the dispatches must rely only on incoming telemetry information. In such case it is his task to estimate this information. If there are large amounts of such information, the dispatcher will have no practical way to estimate and check incoming information. Besides, this problem is able to eliminate and identify telemetry information "jams" that sometimes occur while collecting the information from different sources. The application of state estimation allows not only identifying such cases but also replacing the wrong information with calculated correct information. Yet to ensure the correct operation of this problem and avoid misleading by incorrect calculations of the dispatcher or any other person applying this problem it is critical to make the right choice of the power grid model and perform correct modeling.

This chapter analyzes and describes the development of grid configurator, state estimation, observability analysis, calculations used in the modules to remove wrong data, performed functions, and applied methods and methods, approaches and trends of calculation applied nowadays.

One of critical choices in the application of state estimation is whether an external or surrounding power system is to be estimated. The state estimation may be performed by applying one pass or two-pass technique. In case of two-pass state estimation the operational state of observable part of the grid solely based on received real-time telemetry information. The state of internal part of the grid is estimated first, and the stat of external part of the grid is estimated during the next stage. A solution for each unobservable power grid island is found in the second stage of estimation. The solution is set in the way so that the grid states would be compatible or the same at the intersection of observable and unobservable grid parts.

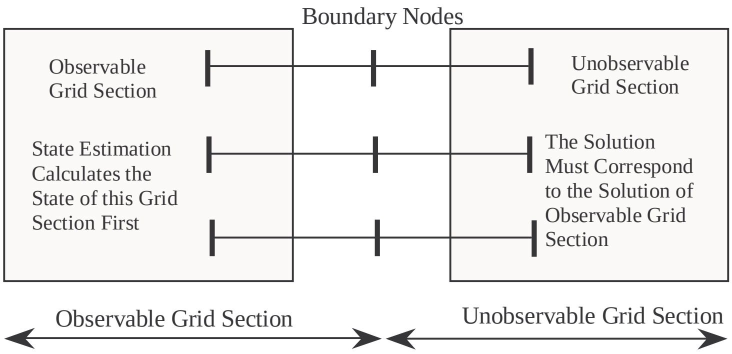


Fig. 1: Observable and Unobservable Grid Sections

One of the first steps in the process of state estimation is the establishment of observable grid regions according to the obtained amount of telemetry from various grid locations. The grid region is considered observable if there is sufficient telemetry of good quality for the grid state estimation. Topology, digital, or hybrid approaches may be used for the estimation of grid observability.

One of main functions of state estimation is the identification and elimination of wrong or low-quality telemetry. The simple heuristic, successful greatest normal remainder, combinatory search, binary tree, and Taboo search methods and algorithms are used for the estimation and inter-compatibility of great amounts of incorrect data and their interconnection with correct measurements. The principle of gradual elimination of incorrect measurements is used to identify and eliminate incorrect measurements. This chapter describes these calculation methods and their features.

The equations used for state estimation calculations are linearized. At each non-linear iteration the equation is linearized at current solution point.

$$\Delta \underline{Z} = H \cdot \Delta \underline{x} + \underline{e} \qquad (1)$$

H is partial derivative of Z matrix with respect to x vector. The size of H matrix is mxn, and each F row contains only a few non-zero elements. If the row of H matrix correspond to line flow measurement, then the row contains only two non-zero values located on the columns corresponding to the flow at the beginning and the end of the line respectively. If the row of the element of H matrix corresponds to the value of flow through the node, then the row contains only one non-zero element on the column corresponding to the adjuncts of the respective node. If the row of H matrix corresponds to the value of voltage measurement, then this row contains only one non-zero element on the column corresponding to the voltage value of the respective node. This approach undoubtedly has certain benefits as it is critical to avoid complex calculations in real-time that should consume much time and other resources.

The classical weighted least square estimation theory first proposed by Schweppe is usually applied in modern state estimation modules. The method researches have shown that the best mathematical estimation of a power system is obtained by using the measurement set and minimizing the following expression:

$$J(x) = 0.5\left[Z - h(x)\right]^t R^{-1}\left[Z - h(x)\right] \qquad (2)$$

Where:

J – weighted least square values
x – state vector (voltage values and phase angles)
Z – measurement vector
h – system model relating the status vector with the measurement set
R – error discrepancy matrix

The first method that might be applied to solve equation 2 is normal equations. This method is based on the assumption that x is the minimum of J matrix. It can be linearized by applying Newton iteration calculus technique $h\left(\hat{x}^{j+1}\right)$.

Other equations are further solved by iteration method:

$$C\left(\hat{x}^{j}\right)\Delta\hat{x}^{j+1} = H\left(\hat{x}^{j}\right)^{T} R^{-1}\left[z - h\left(\hat{x}^{j}\right)\right] \qquad (3)$$

$$\hat{x}^{j+1} = \hat{x}^{j} + \Delta\hat{x}^{j+1}$$

Where:

$$C\left(\hat{x}^{j}\right) = H\left(\hat{x}^{j}\right)^{T} R^{-1} H\left(\hat{x}^{j}\right) \tag{4}$$

Other method to solve the least square problem is based on the use of transformation. This method is based on the assumption that there exists an orthogonal transformation of a matrix that can be expressed by the following equation:

$$T\tilde{H}\left(\hat{x}^{j}\right) = \begin{bmatrix} U \\ 0 \end{bmatrix} \tag{5}$$

U is determined by solving $\tilde{H}\left(\hat{x}^{j}\right)$by Givens rotation. These problem-solving methods are most often applied in state estimation and are generally considered among the best methods producing the results of calculation.

The power flow distribution module usually has several classical calculation algorithms that can be used for choice. Both flow distribution calculation algorithms (Newton-Rapson and Fast decoupled) produce the same results in all cases of system topology, and the main difference between them is the calculation speed. Nonetheless in order to obtain the calculation result for power system with a large number of connections (for instance the resistance/conductivity of connections might be low) it might be necessary to use Newton-Rapson calculation method.

$$\begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta\Theta \\ (\Delta V)/V \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{6}$$

Where:

ΔP – active power deviation vector

ΔQ – reactive power deviation vector

$\Delta\Theta$ – deviations of angular vectors of node voltage phases

$(\Delta V)/V$ – node voltage value deviations

Table 1: Mathematical approaches applied in power flow distribution

Mathematical approach	Description
Matrix analysis	For calculation of linearized equations in iteration schemes
Digital calculation method	The iteration technique is set for the calculation, the information on convergence, uniqueness, etc. is provided
Dispersed matrix method	Effectively solves extremely large systems

The nature of flow distribution problem is non-linear. The solution can be expressed as follows:

$$x = A^{-1}b \tag{7}$$

Where A is n×n matrix, x and b are the vectors of state and initial values of n row. Unfortunately the solution of this equation is always extremely complex. There always exists such a combination of demand and the values of initial variables where no solution exists. Yet even if a solution exists there might be more than one solution. Fast-decoupled algorithm for calculating the power flow distribution is determined by analyzing the calculation technique and ignoring certain sections of the matrices. Fast decoupling calculation methods usually requires more iterations that Newton-Rapson method but the iteration calculation is significantly faster. The detailed description of calculation methods is provided in this chapter.

To properly estimate the security and optimality of a power grid it is essential to represent the adjacent grids in a proper and sufficient manner. If the adjacent grids were represented with sufficient details but not enough their data and measurements existed, the status estimation model could function incorrectly and produce incorrect results. The more redundant information exists, the higher the probability for higher quality of calculation results of state estimation. In the process of state estimation the measurement redundancy is usually not high (<2 times or <100% for internal grids and <1.2 times or <20% for external grids). The measurement redundancy necessary for state estimation must be no less than 1.1 or no less than 10%. In case of tightly integrated power systems a higher amount of redundant information is recommended – no less than 20%.

The analysis of the calculation methods used by grid analysis problems, features, requirements for power grid model, and power grid creation approaches described in previous chapter having been complete, the method for creating a power grid model is prepared. It has been notified that a power grid model for tightly integrated energy system may be prepared in the same stages, paying closer attention to the study and analysis of several possible power grid models that have been prepared. In the first stage the size of an internal power grid and the voltages of covered grids are defined. This is determined by the problem application purposes. The next step is to study the sections of the external power grid and determine which of them have low impact on the modes of internal power grid. The load flow calculation program is used during this study. Several possible power grid models are further prepared and thoroughly examined. The correspondence of prepared several possible power grid model modes to the modes of the entire power grid is examined. The sufficiency analysis of real-time information is performed as well. A single power grid model to be modeled on the dispatcher control system is selected according to the real-time sufficiency analysis and the correspondence of power grid model modes to the entire power grid model modes. During the last stage the power grid model implemented in the dispatcher control system is planned to use for calculations and anticipate further possible steps for the improvement of calculation accuracy according to the obtained results.

4. CREATION OF THE MODEL AND ADAPTATION TO THE REAL TIME INFORMATION

This chapter describes the creation of the power grid model for Lithuanian energy system according to the stages set out in previous chapter.

Before determining the power grid model, it is necessary to first formulate goals and objectives to be reached by the application of the power grid module as this might cause changes in the possible power grid module.

Table 2: Power Grid Model Application Goals and Issues to Be Solved

Possible Goals	Issues to Be Solved
1. To check the information obtained on certain section of the internal grid (not the entire grid). 2. To check all information on a section of the internal grid. 3. Losses calculation and minimizing. 4. Calculation of corona losses. 5. Voltage and reactive power control. 6. Optimum redistribution of active power. 7. Identification of potential failures. 8. Liquidation of potential failures. 9. Power flow exchange control. 10. Service provision to other operators.	1. Identification and definition of internal grid boundaries. 2. Identification of a section of the internal grid. 3. Identification of the external grid influencing the desired objectives of the internal grid. 4. Identification of grid elements to be modeled and their locations. 5. Determination of detailing level for the power grid. 6. Division of the internal and external grids into regions. 7. Determination of detailing level for the generating sources. 8. Identification of initial information sources. 9. Selection of balancing node/nodes.

The operators of transmission and distribution grids are separated in the most of electrical energy systems; therefore the size of the power grid model must correspond to the tasks performed by each of the operators. In the process of creation of the power grid model it is necessary to take into consideration the boundary between the transmission and distribution grids, locations of large consumers, the boundary effect, and the operator functions. An exhaustive analysis and evaluation of performed functions and purposes has led to the conclusion that 330 kV and 110 kV Lithuanian grid is to be modeled.

A power transmission line may be represented by π-model with a serial conductivity $g_l + jb_l$ and two shunt circuits $jb_c / 2$.

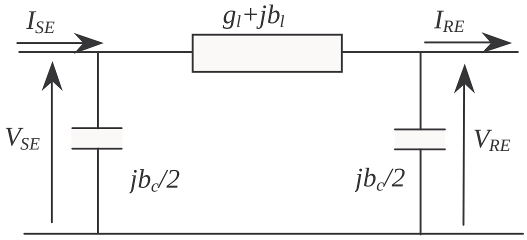


Fig. 2: π-model of Line

The power at the line start S_{SE} is expressed as follows:

$$\overline{S_{SE}} = P_{SE} + jQ_{SE} = \overline{V}_{SE}\,\overline{I^*_{SE}} = \overline{V_{SE}}\left[(g_l + lb_l)\left(\overline{V}_{SE} - \overline{V}_{RE}\right) + j\frac{b_c}{2}\overline{V}_{SE}\right]^* =$$
$$= \left[V_{SE}^2 g_l - V_{SE}V_{RE}\left(g_l\cos\Theta_{SR} + b_l\sin\Theta_{SR}\right)\right] +$$
$$+ j\left[-V_{SE}^2\left(b_l + \frac{b_c}{2}\right) + V_{SE}V_{RE}\left(b_l\cos\Theta_{SR} - g_l\sin\Theta_{SR}\right)\right] \qquad (8)$$

Differential variation of active power losses is expressed as follows:

$$\Delta P_{loss}^{line} = 2g_l\{[V_{SE}V_{RE}\sin(\Theta_{SE} - \Theta_{RE})](\Delta\Theta_{SE} - \Delta\Theta_{RE}) +$$
$$+ [V_{SE} - V_{RE}\cos(\Theta_{SE} - \Theta_{RE})]\Delta V_{SE} +$$
$$+ [V_{RE} - V_{SE}\cos(\Theta_{SE} - \Theta_{RE})]\Delta V_{RE}\} \qquad (9)$$

The power at the transformer start can be analogically expressed:

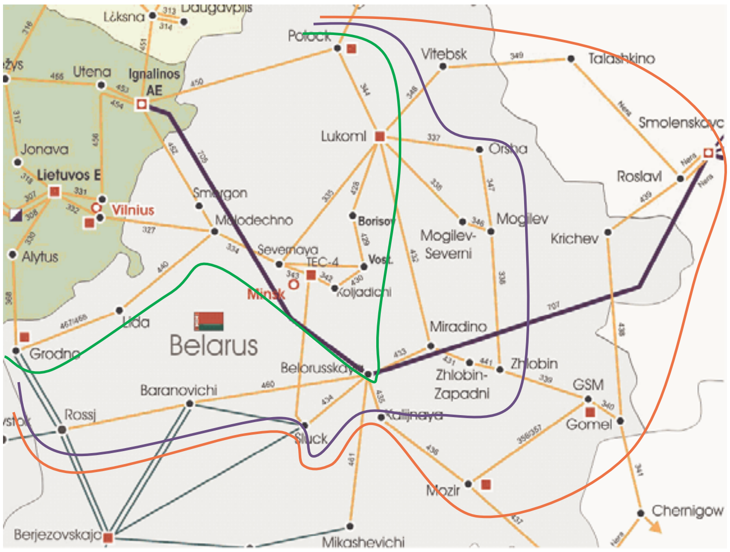
$$\overline{S}_{SE} = \left[\left(1 - \frac{1}{t_r}\right)b_l V_{SE}V_{RE}\sin\Theta_{SR} - b_l V_{SE}V_{RE}\sin\Theta_{SR}\right] +$$
$$+ j\{b_l\left(1 - \frac{1}{t_r}\right)\left[V_{SE}^2\left(1 + \frac{1}{t_r}\right) - V_{SE}V_{RE}\cos\Theta_{SR}\right] +$$
$$+ b_l V_{SE}V_{RE}\cos\Theta_{SR} - b_l V_{SE}^2\} \qquad (10)$$

Lithuanian and Latvian energy systems are very strongly developed according to the principle of regional development so the number of transmission lines between these energy systems is equal to or even greater than the number of internal lines. The analysis of the influence of separate parts of the entire power grid to 330 kV and 110 kV Lithuanian grid has led to the conclusion that Estonian and Russian power grid has minimum impact on the modes of Lithuanian internal grid. Therefore in the process of creation of the model Lithuanian transmission grid the power grid simplification may be performed at the location of Estonian and Russian power grids.

The experimental study approach shall be applied for the study of Lithuanian power grid model including the use of static load flow calculation programs, as the calculation technique employed by these programs is similar to real-time technique. Matlab, PSS/E, Mustang and other relevant calculation programs may be used for calculation of static (settled) modes. PSS/E and Mustang calculation programs have been used in this Work.

Lithuanian power transmission grid is tightly integrated with the adjacent power systems. High-level integration with the adjacent power systems and quite intensive existing transits hinder the creation of power grid model as the impact of adjacent energy systems is much higher in many cases, so the grids of the adjacent energy systems must be more thoroughly analyzed as well as the modes resulting after the disconnection of either internal grid elements or the adjacent power grid elements. The total capacity of Lithuanian transmission grid exceeds the maximum country demand several times.

According to the analysis of various modes three power grid models have been established that differ in the modeling of the Belarusian energy system part.



— - 1 simplified scheme

— - 2 simplified scheme

— - 3 simplified scheme

Fig. 3: Power Grid Models

The prepared models of simplified scheme have been compared with the model of the entire ring scheme by calculating various modes. Figures 4 to 6 show that 1st simplified scheme mode quite well corresponds to the entire ring mode. The resulting differences are low – to 30 MW. 2nd simplified scheme mode incorporating Belarusian energy system extended by a higher degree corresponds less to the entire ring modes. The resulting differences in four lines are from 50 MW to 100 MW in this case. 3rd simplified scheme model also shows an excellent correspondence to the entire ring modes. The deviations resulting from the mode comparison of this model with the entire ring model are very low – only to 20 MW.

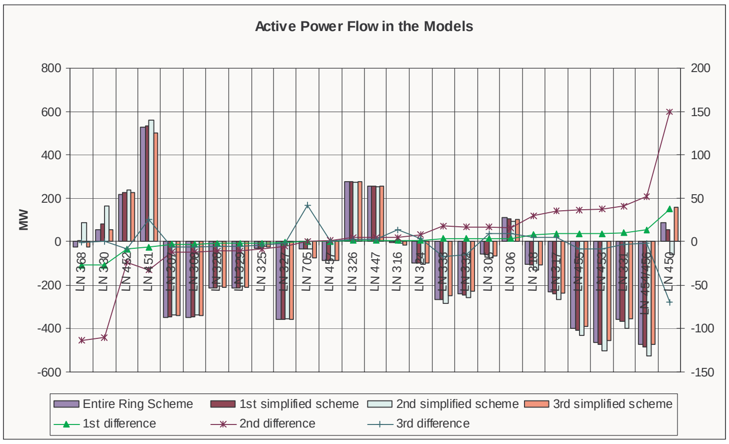


Fig. 4: Active Power Flow in the Model of Entire Ring Scheme and Simplified Schemes

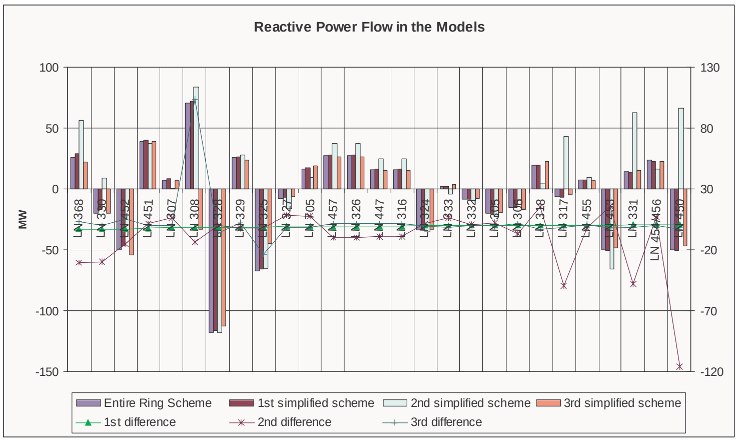


Fig. 5: Reactive Power Flow in the Model of Entire Ring Scheme and Simplified Schemes

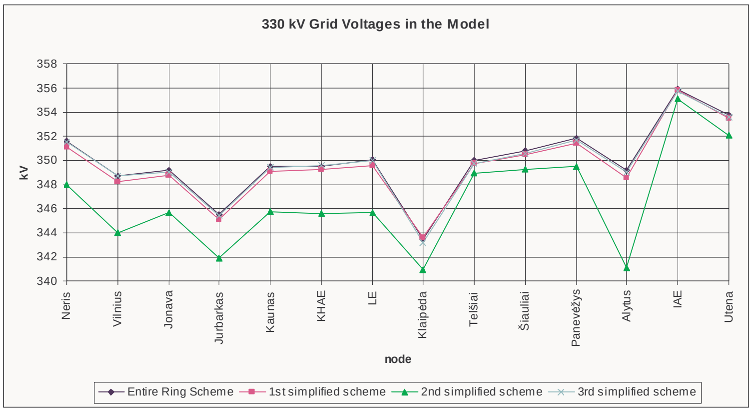


Fig. 6: 330 kV Grid Voltages in the Model of Entire Ring Scheme and Simplified Schemes

The real-time information analysis has shown that the existing modern commercial accounting system may be efficiently employed as additional data source for state estimation.

Table 3: Information Amounts in Dispatch Control System and Real-Time Data Provided by Automated Commercial Accounting System at Kaunas Region of Transmission Grid

	Number of Measurements	Entities
SCADA	156	17
ACAS	190	57 (All entities)
Total No. of measurements	346	
Total No. of required measurements	549	57

The real-time information received from the automated commercial accounting system complements the information obtained in the dispatch control system (SCADA). The amount of this additional information is quite significant, and without this information and Automated Commercial Accounting System (ACAS) in place the evaluation of 110 kV grid state would be virtually impossible. It has been also noticed that the real-time data on the adjacent energy systems is one of the most significant information shortages hindering the efficient application of state estimation.

● - Fully observable node, all necessary information present

○ - Partially observable node, part of information present, only a small amount of information missing

● - Unobservable node, only a small amount of information present

• - Unobservable node, no information present

Fig. 7: Real-Time Information on Latvian Grid

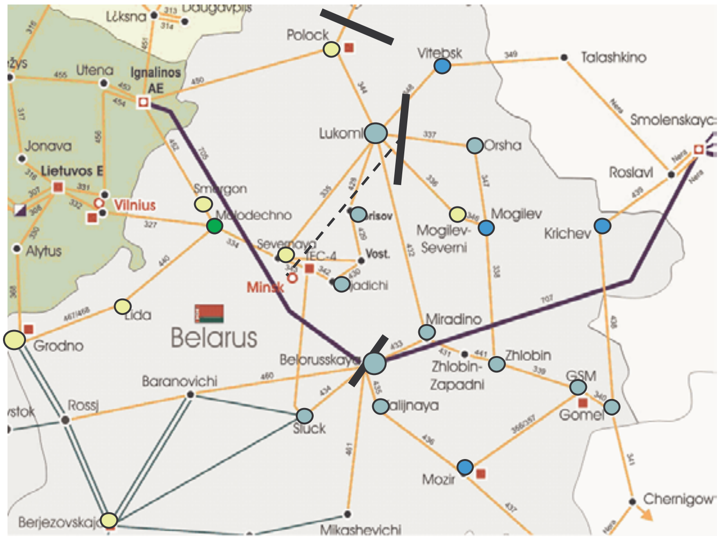


Fig. 8: Real-Time Information on Belarusian Grid

After the evaluation of existing real-time information on the power grid, the conclusion has been made that only modeling of 1st simplified scheme is currently possible. After more real-time information on Belarusian grid is received, it will be feasible to extend the model to the scope of 3rd simplified scheme.

In the process of balancing node selection the condition was assumed that it should be a node with a generating source and having a large number of lines connecting to the power system. The impact analysis of the location of the balancing node to power modes and losses has shown that the best location to assign as the balancing node is Lithuanian Power Plant (LPP) or Kruonis Hydro Pump Storage Power Plant (KHPSPP).

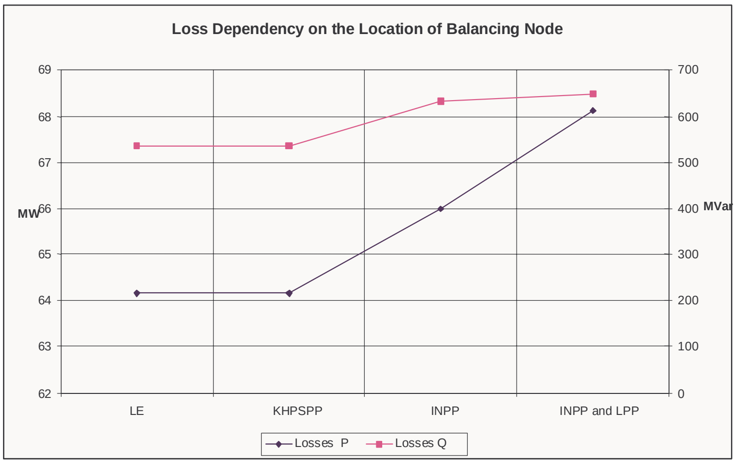


Fig. 9: The Dependency of Lithuanian Transmission Grid Losses on Balancing Node Location

The power grid model created according to 1st simplified scheme has been modeled on dispatch control system of GE Harris XA/21 dispatch centre of Lithuanian TSO. Initial state estimation calculations were unsuccessful due to the information inaccuracy. The cause analysis had shown that the reason was the absence of the information on switching unit locations. After a manual input of switching unit locations the calculations have successfully converged and produced results that corresponded to the estimated results.

5. RELIABILITY ANALYSIS AND PREVENTION OF THE FAILURES

This chapter analyses tools and ways to identify potential power grid failures, anticipate their consequences, and take accident prevention measures. This chapter also provides suggestions regarding the possibilities for further improvement of state estimation according to the impact of market relations on active and reactive power mode control.

After the real-time calculations for state estimation are complete and the power system mode is prepared, the unexpected event analysis problem might help analyzing resultant modes in case of one or another event according to the event list made in advance. The events may be the following: disconnection or connection of switching units, generation increase or decrease, disconnection of generating sources. Lithuanian electrical energy system is tightly integrated with the adjacent electrical energy systems so the calculation of all possible n-1 modes would be quite complicated and hardly possible. This chapter specifies that it is not necessary to calculate all possible n-1 disconnections; instead only the most critical, significant, or dangerous modes could be selected and calculated. Other not so dangerous failures can be missed, as their consequences would be no more harmful than the consequences of the most dangerous failures.

This chapter analyzes various criteria for the selection of the most dangerous failures. The analysis has shown that it is virtually no possibility to apply the statistical information on the electrical energy amounts having not been supplied to determine the danger level of the failure. Instead the possibility has been identify for the evaluation of statistical information on grid element disconnection, by assigning higher priority to older, les reliable and more often disconnecting grid elements. The statistical analysis of disconnections may by efficiently applied for the calculations of unscheduled events by isolating 110 kV power transmission lines according to the statistical data on disconnections.

To calculate and efficiently apply the real-time calculation and analysis problem of all possible failures it is necessary (as possible) to eliminate non-dangerous possible failures that cause no serious accidents of damage, analyze potential disconnections of critical system elements by applying the disconnection analysis, assign priorities to separate events or include them into the list of events to be calculated in case they are not in the list yet.

MAIN CONCLUSIONS

1. The power system’s state estimation is a compulsory tool to be used by the system operator under the market conditions and speedily growing volumes of information.
2. Resultant of the analysis of the calculation methods used in the power system’s state estimation and based on the experience of other countries, the methodology for the development of a closely integrated electricity network has been worked out serving as a background for establishment of three possible models of Lithuanian power system to be used in real time calculations.
3. Resultant of the analysis of 3 possible models of Lithuanian power system it has been determined that one of them is suitable for modeling with regard to the available scope of real time teleinformation.
4. In compiling the model of a closely integrated power system to be used in real time calculations, the biggest impact has been made by a scope of available real time data about a relevant power system. Insufficient data have forced to significantly simplify the modeling of neighboring power systems and to use for modeling the first simplified model.
5. The developed real time calculation model of Lithuanian power system is of a minimum scope, which, however, is sufficient and suitable for calculation of regimes in the transmission grid. The calculated flows in the developed model

of the power system and in the model of an entire interconnected ring differ only by some 20-30 MW, 5-7%.

6. The developed model of Lithuanian power system has been implemented and tested in the dispatch centre. By using the testing results of the power system model in an automated dispatch control system an action plan has been drawn aimed to improve the operation of this state estimation tool.
7. Real time information obtained from an automated metering system has significantly supplemented the volumes of missing information regarding the 110 kV electricity network (by nearly 30%). This enabled to improve the quality of results of electricity network state estimation and to carry out the state estimation of the entire 330-110kV grid by manually entering the data of 110kV TS commutation apparatus.
8. Based on the completed assessment of power system models, the potential for further expansion of the model by upgrading the operation of state estimation and network analysis modules has been identified. The differences between the regimes calculated by this model and the model of the entire interconnected ring would equal only 10 - 20 MW, 3-5% and would be close to the regimes of the entire ring. The expansion of the module is mainly delayed because of insufficient real time supervision in the neighboring power systems.
9. The analysis of various options for selection of balancing nodes in Lithuanian energy system has shown that from the perspective of the concordance of losses/modes to the actual losses/modes the best location for the balancing node would be the nodes of Lithuanian Power Plant of Kruonis HPSPP.
10. Resultant of the assessment of network analysis and state estimation modules, further improvements in the state estimation modules have been proposed with an aim to promote its speed of operation, accuracy and to expand the application possibilities of obtained results.
11. By using the statistical information about network failures and by compiling the list of most important and most influential faults it is possible to decrease the number of potentially dangerous regimes, to save the computer system resources and to avoid overburdening of dispatchers with excessive information.

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INFORMATION ABOUT THE AUTHOR

Dalius Šulga was born on December 30, 1971 in Vilnius. He graduated from the secondary school in 1990 and in the same year he becomes a student of Vilnius Gediminas Technical University. He completed with commendation automatisation specialty Electronics Faculty in 1994 and obtained Bachelor degree. Two years later in 1996 he completed Electronic and Electrotechnics speciality and obtained Master of Science degree. Dalius Šulga started work in Lietuvos energija AB, the National Dispatch Centre as an engineer in 1994. From 1996 – Deputy Head of National Dispatch Centre. From 2002 – Director of Energy development department in Lietuvos energija AB. A scientific study in the field of technology sciences, power and thermal engineering has been started at Department of Electric Power Systems of Kaunas University of Technology in 1999 and completed in 2004.

REZIUMĖ

Pagrindinis darbo tikslas yra sudaryti labai integruoto elektros tinklo modelį, tinkantį aktyviosios ir reaktyviosios galių skaičiavimams realiame laike rinkos sąlygomis. Elektros tinklo modelio sudarymui skaičiavimams realiame laike reikalinga išanalizuoti naudojamus skaičiavimo metodus, principus, susipažinti ir išanalizuoti elektros tinklo modelio sudarymo metodus. Elektros tinklo modelis skaičiavimams realiame laike turi būti sudaromas atsižvelgiant į turimos informacijos realiame laike apimtis. Sudarytą elektros tinklo modelį reikalinga ištirti, siekiant nustatyti sumodeliuoto tinklo režimų atitikimą realiems režimams. Tiriant sudaryto elektros tinklo modelio režimų atitikimą realiems reikalinga palyginti įvairius režimus tarpusavyje. Atlikus režimų analizę nustatyta Lietuvos elektros tinklo dalis, kurią galima sumodeliuoti ir išbandyti realioje veikiančioje dispečerinio valdymo informacinėje sistemoje. Lietuvos energetikos sistemos ypatumas yra tas, kad ji yra labai integruota su šalia esančiomis elektros energetikos sistemomis bei per Lietuvos energetikos sistemą prateka daug ir įvairių tranzitinių srautų. Tai apsunkina Lietuvos energetikos sistemos modelio sukūrimą skaičiavimams realiame laike. Elektros tinklo modelio sudarymas skaičiavimams realiame laike labai integruotoms elektros sistemoms nėra labai ištirtas ir išnagrinėtas, kadangi tokių labai integruotų energetikos sistemų yra labai nedaug.

Išanalizavus elektros tinklo būklės įvertinimo naudojimo galimybes bei būklės įvertinimo programų veikimą, rinkos sąlygų keliamus reikalavimus elektros sistemos valdymui šiame darbe pateikiami siūlymai, kurie leidžia patobulinti būklės įvertinimo programas, geriau jas pritaikyti prie šiandien keliamų reikalavimų. Darbe paruoštas labai integruotos elektros sistemos aktyviosios ir reaktyviosios galių režimų skaičiavimo realiame laike modelio sudarymo metodas. Remiantis šiuo metodu paruoštas Lietuvos energetikos sistemos modelis, tinkamas realaus laiko režimams skaičiuoti, apimantis dalį Latvijos, Baltarusijos ir Rusijos energetikos sistemų.

Labai integruotoms energetikos sistemoms sudėtinga taikyti n-1 kriterijų realiame laike dėl labai didelio elektros tinklo elemento kiekio. Be to, gavus labai didelį kiekį paskaičiuotų skirtingų režimų perdavimo sistemos operatoriui, dirbančiam realiame laike, labai sudėtinga tuos įvertinti, atrinkti blogiausius galimus atvejus ir numatyti veiksmus, kurių pagalba būtų galima išvengti galimos avarijos ar sutrikimo. Darbe nustatytas metodas, išanalizavus elektros tinklo atskirų elementų įtaką patikimumui, tinklo režimams, atsižvelgiant į atskirų elektros tinklo elementų patikimumo analizę, avaringumo analizę, įvertinant atskirų elementų įtaką elektros tinklo režimams leidžiantis sumažinti skaičiuojamų skirtingų režimų kiekį. Atlikta atskirų perdavimo tinklo elementų patikimumo ir avaringumo analizė leidžia sudaryti mažesnį galimų tinklo sutrikimų sąrašą, išrinkti tik svarbiausius ir labiausiai sistemos darbą įtakojančius sutrikimus, eliminuojant nereikšmingus ar nelabai įtakojančius tinklo darbą sutrikimus. Tokiu būdu galima labai pagreitinti galimų sutrikimų nustatymo skaičiavimus bei efektyviau panaudoti šio uždavinio galimybes, neapkrauti sistemos operatorių nereikalinga pertekline informacija.

Sukurtas ir ištirtas elektros tinklo modelis įdiegtas ir išbandytas AB „Lietuvos energija“ nacionaliniame dispečeriniame centre automatizuoto dispečerinio valdymo realaus laiko sistemoje. Įdiegtas elektros tinklo modelis automatizuoto dispečerinio valdymo sistemoje režimų skaičiavimams realiame laike leidžia panaudoti kitus tinko analizės uždavinius galimų avarijų realiame laike nustatymui, valdymo optimizavimui ir tuo žymiai padidinti elektros sistemos valdymo bei funkcionavimo patikimumą.

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Išleido leidykla „Technologija“, K.Donelaičio g. 73, 44029 Kaunas
Spausdino leidyklos „Technologija“ spaustuvė, Studentų g. 54, 51424 Kaunas