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POWER FLOW MODELING, SAMPLING AND ASSESSMENT FOR INTERCONNECTED POWER SYSTEMS

Summary of the Doctoral Thesis

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Timurs Kuzņecovs ……………………………. (signature)

Date: 11 September 2017

The Doctoral Thesis has been written in English. It contains an introduction, five chapters, conclusions, and list of references with 195 sources. It has been illustrated by 8 tables and 13 figures. The volume of the present Doctoral Thesis is 112 pages.

CONTENTS

TOPICALITY OF THE THESIS

Power engineering is one of the main fields of science and industry. In many ways, the extent of using various sources of energy determines the level of economic development of any country. Electric power systems (EPSs) meet the society's need for electricity and heat. Present-day EPSs are sophisticated complexes of interrelated power facilities with a large number of highly developed regime control automation devices. An EPS can be considered a multi-section and multi-circuit control object, the condition of which is subject to continuous (and, in the general case, stochastic) changes under the influence of external factors as well as continuous goal-oriented changes in the parameters controlling the components of the power system itself. The complexity and changeability of the object are such that for a number of tasks it is not possible to make a sufficiently complete mathematical description of it. This is particularly true for operational control tasks, when it is necessary to take into consideration the changes in the condition of the controlled facility in the tempo of a process. Therefore, operational and information complexes (SCADA), which represent developed systems of teleinformation collection, transmission and processing by means of information technology, play an important role in present-day EPSs. Successful use of SCADA requires continuous improvement of the technical level and increased use of telemechanic devices and information technology. Issues related to the reliability of receiving and the checking of plausibility of teleinformation are becoming decisive for the functioning of SCADA itself and, insofar as it has been implemented, for the performance of a number of important functions of the EPS within the interconnected power system.

The analysis of EPSs, like the analysis of mechanical systems, includes investigation of equilibrium conditions. In order to determine the equilibrium conditions of mechanical systems, systems of equations are composed and solved, the equations are based on the equality of the internal and external forces acting upon the system under consideration. The classes of tasks and the mathematical apparatus used in EPS calculations can be divided as follows:

Calculations of steady states

Steady-state regimes can be described by Ohm's and Kirchhoff's laws and, based on these, systems of equations of bus voltages or circuit currents. The mathematical apparatus is based, as a rule, on solving systems of linear and non-linear algebraic equations. Here, such EPS regime parameters are evaluated as voltages in the buses of the calculation model, currents and power flows via power transmission lines, reactive powers of power supplies, transformation ratios, etc.

Analysis of transient processes

An EPS is a system of the dynamic type, which is characterised by continuous changes of state (changes in the load value, the mix of energized generators, switches, transformers, etc.). Moreover, all these physical quantities (voltages, currents) change over time, striving towards a new steady value. As the system leaves the state of equilibrium, transient processes of various nature, strength and duration emerge, which have to be investigated in order to make a good-quality evaluation of the electric regime and to find the maximum permissible (in terms of stability) deviations of the controlled electric quantities in the normal regime.

The analysis of system movement is performed by means of the mathematical apparatus of the theory of differential equations. The analysis of transient processes in an EPS is more complicated than for mechanical systems since in the case of an EPS, not only the changes of mechanical quantities need to be considered (speed, acceleration, momenta of turbogenerators, hydrogenerators, engines, etc.) but also the changes of electrical quantities (currents, voltages, power). However, the existing similarities not only provide a better understanding of transient processes in EPSs but also help to synthesise (select) the differential equations.

Forecasting and optimisation of the regimes and the tasks of designing the development of EPSs

The essence of the EPS operation task is that the equipment has to be maintained in an operable condition and the consumers have to be reliably supplied with electricity. These functions have to be fulfilled with the lowest possible expenditure of material, labour, financial and energy resources. Here, the tasks of forecasting and optimal distribution of the total load of the EPS among generating sets operating in parallel; minimising losses of power and energy in the electrical networks; and forecasting the development of the EPS and optimum distribution of investment are solved.

In the forecasting of loads, the basic mathematical apparatus consists in statistical analysis with elements of the approximation theory; in optimisation – mathematical programming.

Optimal control of the regimes of the EPS

As mentioned above, one of the main tasks of EPS operation is control of regimes. It is not sufficient to only observe the processes taking place in EPSs. They also have to be actively directed via such a trajectory as to preclude catastrophic consequences that might result from loss of control. Moreover, the interference has to be performed purposefully in accordance with a certain set of control tactics or a control strategy. The logic depends on the goals of the control. For example, one set of tactics is used for eliminating short circuit; a different one should be used for increasing the stability of generators during transient processes, and the third one – for making the parameters of the electrical regime enter the area of permissible values, etc. With this purpose, various means of automatic and automated control are developed and implemented at EPSs.

The basic mathematical apparatus of this class of tasks consists in the theories of optimal automatic and automated control of complex EPSs.

The reliability of EPSs

The effectiveness of any technical system, including electric power systems, is usually considered in terms of three basic properties: safety, reliability and economic efficiency. An EPS consists of an extremely large number of elements, the failure of one of which may, but must not, lead to a chain reaction of failures with unpredictable consequences. For example, loss of tightness in an air circuit-breaker may lead to failure during elimination of short circuit, which in turn actuates the circuit-breaker failure protection, as a result of which the other circuit-breakers related to the faulty busbar system switch off. This, in turn, may result in loss of static or dynamic stability, etc.

The basic mathematical apparatus of this class of tasks consists in the probability theory, the theory of mathematical statistics and the theory of reliability of technical systems.

The information support of EPSs.

Any control of a system requires information regarding the regime parameters, the condition of the elements, etc. In power engineering, we encounter systems, the behaviour of which is determined by many thousands of variables, which are subject to the influence of random and determined factors. All the regime parameters can be monitored only by means of relay-based protection and system-level automation devices, which, in turn, serve as initial information for the dispatcher, who controls that part of the interconnected power system.

In the case of partial uncertainty and incomplete observability of parameters, it is necessary not to just lead the regime of the system but also to effectively manage its functioning and development. Measurement and data transmission errors should also be taken into account. The problem of data transmission, filtering, evaluation and utilisation arises.

The basic mathematical apparatus of this class of tasks consists in the information theory and the EPS states evaluation theory.

All the above-mentioned tasks need to be solved not only on a global scale but also as applied to the power systems of the Baltic States, which already in and of itself determines the topicality of improving the methodology for solving them. The restructuring conducted in the field of power engineering and the setting of an electricity market in the territory of the Baltic States have only added to this topicality. From this perspective, the investigations and research conducted within the present Thesis that is aimed at the improvement of the software used in power systems are to be considered timely and topical.

THE HYPOTHESIS, AIMS AND TASKS OF THE THESIS

Process of modeling in the case of interconnected power system can be implemented using the decomposition and equivalence of power system model, which creates an opportunity to solve power flow calculation tasks under conditions of incomplete information.

The main aim of the present Thesis is to increase the efficiency of the operational control of the regimes of the power systems in the Baltic States within the interconnected power system, considering the characteristics of the functioning of the electricity market. The following tasks have been accomplished to achieve the aim:

1. An analysis of the information flows arriving at the operators of the transmission and distribution networks has been performed.
2. Insufficiency of information to be exchanged among the operators of transmission networks has been found out, leading to a decrease in the reliability and economic efficiency of the control of power systems.
3. The nature of the changes of active power balances in the power systems over a 24-hour period has been investigated, as well as the power flows via the power networks of the transmission system operator and the distribution system operator.
4. The permissibility of calculating the regimes of power systems according to a pre-set scenario has been shown.
5. Substantiation has been proposed for the methodology of simplifying the task to be solved, based on the compilation of an equivalent calculation model of the external power network.
6. Substantiation has been proposed for using a shared calculation model for a group of transmission system operators.
7. A methodology has been developed for minimising the amount of routine work for plant engineers of power systems from the moment of receiving data till the moment when appropriate control decisions are made on the basis of the results of the regime calculation.

RESEARCH METHODS AND TOOLS

1. Test circuit IEEE 118 Bus Test Case (Rich Christie, University of Washington).
2. Software MUSTANG for calculating steady-state and transient electromechanical regimes (Vladimir Ivanov, Viktor Rimarev).
3. Software: Drawshe, RDIGS, PE123, Sinica (AST); PSS®E (Siemens PTI); Notepad2 (Florian Balmer).
4. The methods for solving systems of linear algebraic equations.
5. The methods for solving systems of non-linear algebraic equations.
6. The method of deformation of equations for non-linear algebraic equations to ensure convergence of the Newton-Raphson method in the vicinity of the boundary of the stability area.
7. The methods for solving systems of Park-Gorev differential equations.

SCIENTIFIC NOVELTY OF THE THESIS

1. It has been shown that improvement of software influences the process of creating a model of the power system, which is intended to be used for solving a certain regime task.
2. *MUSTANG* software has been developed further, expanding its data acquisition and processing functionality as well as its possibilities in the simulation and analysis of calculation results.
3. A principle for creating subsystems in the form of a "tree of folders" has been substantiated, ensuring novel possibilities for the operation of software. This provides a new structure with advantages as compared with the possibilities offered by the currently generally accepted principles of rigidly tying the elements of the calculation model to a hierarchic structure of power systems.
4. The advantages of the new approach to the creating of controllable cross-sections and to the introduction of current and power restrictions for the branches of the calculation model have been shown.
5. It has been proved that a branch of the calculation model needs to have more than two logical states for the power system model to function effectively within the dispatcher training simulator (DTS).
6. An algorithm has been developed for automated obtaining a power system with the set results of the controlled parameters.
7. A simplified method for evaluating frequency at the monitored buses of the network has been developed for the needs of the DTS of the Latvian transmission system operator, using software intended for calculating steady-state regime.
8. The concept of an equipotential grid model has been introduced and the way for obtaining such a diagram has been indicated.
9. A methodology has been proposed for using an equipotential grid model to analyse the influence of emergencies in the external network on the part of the interconnected power system under consideration. This methodology can be regarded as the development of the methods based on the determination of the distribution factors PTDF and LODF. Using this methodology makes it possible to increase the reliability of the evaluation of potential emergency situations in real time.

PRACTICAL SIGNIFICANCE OF THE THESIS

1. Methods have been proposed for fine-tuning the calculations of steady-state regimes of the power system for operational planning in the following directions:
   a) Hourly calculations of the active power flows in the BRELL ring network for the following 24-hour period;
   b) Hourly calculations of the possibility of additional supply of electricity for the 24-hour period following the operation of the Nord Pool Spot market;
   c) The first stage of the hourly calculations of electric power losses in the network of the Latvian transmission system operator for the set number of days ahead.
2. Using the "tree of directories" and the developed methodology for obtaining a regime with the set results of the controlled parameters considerably increases the efficiency of the engineer's work and makes the calculations conducted by the engineer more demonstrative as MUSTANG program interacts with other programs, for example, Microsoft Excel, in the command interpreter mode.
3. Using the results of the present Thesis in the creation of a DTS system for a dispatcher of the Latvian TSO has made it possible to conduct training in the restoration of power supply to consumers after a complete blackout of the power system.

4. A methodology has been proposed for creating an equipotential grid model, which can be algorithmically implemented in most programs used for steady-state regime calculations. Calculation of emergencies $N - i$ by using an equipotential model may be of practical interest for those transmission system operators within ENTSO-E who are not provided with detailed operational information regarding the operating modes of neighbouring power systems.

THE AUTHOR'S PERSONAL CONTRIBUTION TO THE RESEARCH CONDUCTED

1. The concept of creating a "tree of directories" has been substantiated, as well as a methodology for obtaining a regime with the set results of the controlled parameters, which expands the functionality of the present-day software for calculating the regimes of power systems.
2. The interpretation of the logical conditions of the branches of the power system calculation model has been improved, which makes it possible to use a unified approach to modeling, both in the calculations of planned regimes and in the creation of a model for DTS simulation.
3. A methodology for creating an equipotential grid model has been proposed and approbated in order to analyse the influence of emergencies in the external network on the part of the interconnected power system under consideration.
4. The idea to create a DTS in the Latvian TSO has been proposed and implemented.
5. A methodology for simplified evaluation of frequency at controlled buses for the needs of DTS has been proposed and practically implemented.
6. The algorithm for obtaining a regime with the set results of the controlled parameters for the power systems of the Baltic States has been tested.
7. The methodologies for conducting calculations of steady-state regimes developed and proposed by the author have found practical application in the operational planning of the regimes of the AST electrical networks.

APPROBATION OF THE RESEARCH RESULTS

The issues discussed in the Thesis have been presented at international conferences of various levels:
1. Mahņitko, A., Lomane, T., Kuzņecovs, T., Rimarevs, V. Program Set MUSTANG Use in the Dispatch Control for the United EPS Regimes. In: Proceedings of 9th International Conference CPS'2010, Slovakia, High Tatras, Štrebské Pleso, May 18–20, 2010. Bratislava: Faculty of Electrical Engineering and Information Technology of Slovak University of Technology in Bratislava, 2010, pp. 1–7.
2. Mahņitko, A., Lomane, T., Gerhards, J., Rimarevs, V., Kuzņecovs, T. The Planning of the Intersystem Connections Regimes on the Base of the Program Set MUSTANG. In: Proceedings of the XI International Scientific Conference "Problems of Present-Day Electrotechnics" (PPE–2010), Ukraine, Kiev, June 1–3, 2010. Kiev: National Scientific Academy of Ukraine, 2010, pp. 1–1.
3. Mahņitko, A., Lomane, T., Kuzņecovs, T., Rimarevs, V. Simulation, Synthesis and Estimation of Modes for the United Power System. In: Elektroenergetika: 6th International Scientific Symposium, Slovakia, High Tatras-Stara Lesna, September 21–23, 2011. Košice: Technical University of Košice, 2011, pp. 323–328.
4. Kuzņecovs, T., Mahņitko, A., Lomane, T., Rimarevs, V., Dambis, A. Dispatcher Training Simulator for TSO from Power Flow Calculations. In: Electrical and Control Technologies: Proceedings of the 8th International Conference on Electrical and

Control Technologies (ECT–2013), Lithuania, Kaunas, May 2–3, 2013. Kaunas: Kaunas University of Technology, 2013, pp. 158–161. ISSN 1822-5934.

5. Kuzņecovs, T., Mahņitko, A., Lomane, T., Rimarevs, V., Dambis, A. Frequency Definition if the Steady-State Regimes Calculation Program is Used in Dispatcher Training Simulator. In: Electrical and Control Technologies: Proceedings of the 9th International Conference on Electrical and Control Technologies (ECT–2014), Lithuania, Kaunas, May 8–9, 2014. Kaunas: Kaunas University of Technology, 2014, pp. 100–103. ISSN 1822-5934.

Besides, almost all of the discussed methodologies have been successfully implemented in *MUSTANG* program.

PUBLICATIONS

1. Mahnitko, A., Lomane, T., Kuznetsov, T., Rymarev, V. Program Set Mustang Use in the Dispatch Control for the United EPS Regimes. In: 9th Intern. Conference CPS'2010 (CONTROL OF POWER SYSTEMS '10), Slovakia, High Tatras, Štrebské Pleso, May 18–20, 2010. Bratislava: Faculty of Electrical Engineering and Information Technology of Slovak University of Technology in Bratislava, 2010, pp. 1–7.

2. Махнитко, А. Е., Ломан, Т. В., Герхард, Я. Г., Рымарев, В. В., Кузнецов, Т. В. Планирование режимов межсистемных связей на базе программного комплекса MUSTANG. In: Proceedings of the XI International Scientific Conference "Problems of Present-Day Electrotechnics" (PPE–2010), Ukraine, Kiev, June 1–3, 2010. Kiev: National Scientific Academy of Ukraine, 2010, pp. 1–1.

3. Махнитко, А. Е., Ломан, Т. В., Рымарев, В. В., Кузнецов, Т. В. Моделирование, синтез и оценка режимов межсистемных связей объединенных энергосистем. In: Электричество, Москва, 2011, N 5, с. 8–16. ISSN 0013-5380.

4. Mahnitko, A., Lomane, T., Kuznetsov, T., Rymarev, V. Simulation, Synthesis and Estimation of Modes for the United Power System. In: Elektroenergetika: 6th International Scientific Symposium, Slovakia, High Tatras-Stara Lesna, September 21–23, 2011. Košice: Technical University of Košice, 2011, pp. 323–328.

5. Kuzņecovs, T., Mahņitko, A., Lomane, T., Rimarevs, V., Varfolomeeva, R. Research of the Reactive Power Compensation Influence to Losses in Electrical Networks. In: Electrical and Control Technologies: Proceedings of the 7th International Conference on Electrical and Control Technologies (ECT–2012), Lithuania, Kaunas, May 3–4, 2012. Kaunas: Kaunas University of Technology, 2012, pp. 239–244. ISSN 1822-5934.

6. Kuzņecovs, T., Mahņitko, A., Lomane, T., Rimarevs, V., Dambis, A. Dispatcher Training Simulator for TSO from Power Flow Calculations. In: Electrical and Control Technologies: Proceedings of the 8th International Conference on Electrical and Control Technologies (ECT–2013), Lithuania, Kaunas, May 2–3, 2013. Kaunas: Kaunas University of Technology, 2013, pp. 158–161. ISSN 1822-5934.

7. Mahņitko, A., Loman, T., Kuzņecovs, T., Rimarevs, V., Dambis, A. Transfer capacities and reliability. In: Elektroenergetika: 7th International Scientific Symposium, Slovakia, High Tatras-Stara Lesna, September 18–20, 2013. Košice: Technical University of Košice, 2013, pp. 555–558.

8. Kuzņecovs, T., Mahņitko, A., Lomane, T., Rimarevs, V., Dambis, A. Frequency Definition if the Steady-State Regimes Calculation Program is Used in Dispatcher Training Simulator. In: Electrical and Control Technologies: Proceedings of the 9th International Conference on Electrical and Control Technologies (ECT–2014), Lithuania, Kaunas, May 8–9, 2014. Kaunas: Kaunas University of Technology, 2014, pp. 100–103. ISSN 1822-5934.

9. Kuzņecovs, T., Mahņitko, A., Sauhats, A., Oboskalov, V. Power Flow Studies for Assessment the Security of Steady States in Zone Inside the Large Interconnected Power System. In: Elsevier B.V. Procedia Computer Science ICTE 2016, December 2016, Riga, Latvia, p.8, ISSN 1877-0509.

THE STRUCTURE AND VOLUME OF THE DOCTORAL THESIS

The Doctoral Thesis consists of an introduction, five chapters, conclusions, bibliography with 195 reference sources, and appendices. The volume of the Thesis is 112 pages; it contains 8 tables and 13 figures.

The introduction contains substantiation of the topicality of the subject, defines the aim and tasks of the Thesis, as well as formulates scientific novelty. The personal contribution of the author is described and conferences and publications are listed.

The first chapter discusses and analyses the role of interconnected power systems in the electric energy sector. (The electrical energy consumption in the world energy sector is currently approximately two times less in comparison with oil consumption and by twenty percent more than gas consumption in the world.)

The second chapter describes the power-flow calculations as a tool for power system studies, because some of the tasks of design, planning and operation of the power system are associated with calculations of the steady state power flow on mathematical models of power systems.

The third chapter reviews the power-flow modeling of interconnected power systems. The sizes of models, the information for the model and the interaction with the power-flow calculation program are reviewed for a typical power-flow calculation program. The power-flow calculation method and the interesting practical implementations are also described based on MUSTANG program.

The fourth chapter covers the advanced usage of the power-flow calculation program for training dispatchers of the transmission system operator in Latvian TSO (AST). The problem of determination of the frequency of alternating current in the controlled buses by means of power-flow calculation program was solved with sufficient accuracy for simulator training dispatchers.

The fifth chapter is dedicated to the power-flow calculations based on a balanced equipotential grid model. The approach proposed in this chapter allows calculating the effect of possible outages in external grid on power system regime in the case of minimum information available.

1. THE ROLE OF THE INTERCONNECTED POWER SYSTEMS IN THE WORLD ENERGY SECTOR

Energy sector is one of the key and complex branches of economy in any state in the world [1]. The standard of living of people is determined by the electricity consumption level per capita and depends on the level of primary energy production [5]. The availability of energy resources and development of systems for production, transmission and distribution of energy have great influence on the energy industry.

Electric power systems form part of the energy sector, in which processes of production, transmission and distribution of electricity take place. Electrical grids play a supportive role in the energy sector. Their task is to bring electrical power from power plants to installations of electricity consumers.

The development in the world electricity sector was extensive until the 1970s. It was based on power unit high rated power. Power for a single unit has exceeded 1000 MW. Power was distributed over longer distances; therefore, power lines on higher rated voltage were developed.

The electricity sector aims to ensure high-reliability electricity at minimum cost [14]. The interconnected power systems [6] provide reliable and high-quality transmission of electric power from generators to the market participants and operators to the distribution networks at the interstate scale today. Power grid operators (PGOs) are a basis for the interconnected power systems in most cases. PGOs ensure coordination of planning processes, power system design, and control complex interconnected systems. 17 PGOs with a maximum load exceeding 30 GW are members of the international group for operators of very large power systems GO15. Information on the PGOs as of the year 2013 is collected in Table 1.1. It can be concluded from Table 1.1 that PGOs serve more than half of the world's population and transmit four fifths of all electricity produced for people. One fifth of the generated energy passes through other transmission network operators (TSOs), one of which is Latvian TSO Augstsprieguma Tīkls (AST). If one were to compare AST with SGCC – the largest PGO in the world, the AST is about 400–500 times less. This does not prevent AST from transferring electric power inside the interconnected power system securely and efficiently. However, countries in which there is a PGO, define the world policy in the area of energy efficiency and promote new technologies in energy-intensive industries. These countries determine the electricity industry development in the world.

The challenge of any TSO is to ensure robust and reliable transmission of electric power to a consumer. Most TSOs are working in interconnected power systems. Therefore, power plants, as well as consumers participating in the balance of TSO can be located far outside the TSO operating zone and even outside the AC grid of joint synchronous operating area. Consequently, the regimes of TSO have an impact on the operation of other TSOs. At the same time, the size of the AC grid in a synchronous operating area can significantly exceed the dimensions of an operating zone of a single TSO. In order to determine the impact of the entire electric grid on the operation modes of TSO, the processes in an external network should be taken into account. Such an integrated approach is more difficult due to insufficient data for modeling outside the network and due to a large number of system components. A large number of system components in a calculation program require automation when entering data for the calculations and obtaining a result. Aggregation of information can help simplify the process of entering data, as well as make the process of analysing the calculation results more visible. It is rather impossible to obtain outstanding accuracy of the calculation results, without having sufficient data for the simulation. However, the present research shows that a relatively small amount of data may be sufficient for a qualitative accounting impact of the external network on the regimes of TSO operation.

Table 1.1

Data on Power Grid Operators (maximum demand above 20 GW)

GO15	Power Grid Operator	Country	IPEEC	Max, GW	Customers, ×10^6
1	SGCC	China	Yes	544	1100
2	PJM	the USA	Yes	164	60
3	SO UPS	Russia	Yes	157	144
4	PGCIL	India	Yes	135	1200
5	CSG	China	Yes	129	240
6	RTE	France	Yes	100	65
7	MISO	the USA	Yes	98	39
8	GCCIA	Saudi Arabia	none	93	47
9	ONS	Brazil	Yes	77	189
10	KPX	South Korea	Yes	76	50
none	ERCOT	the USA	Yes	67	23
11	Tepco	Japan	Yes	64	45
12	National Grid	the UK	Yes	61	62
13	Terna	Italy	Yes	57	60
none	SPP	the USA	Yes	54	16
none	California ISO	the USA	Yes	45	30
14	REE	Spain	As EU	44	46
none	Tavanir	Iran	none	43	76
none	CFE	Mexico	Yes	38	115
none	TEIAS	Turkey	none	38	75
none	Hydro Quebec	Canada	Yes	38	8
15	Eskom	South Africa	Yes	37	50
16	AEMO	Australia	Yes	35	19
none	KEPCO	Japan	Yes	32	13
none	Taipower	Taiwan	none	32	23
none	Amprion	Germany	Yes	30	27
17	Elia Group	Belgium	As EU	29	30
none	NPC Ukrenergo	Ukraine	none	29	45
none	SVK	Sweden	As EU	26	9
none	PSE	Poland	As EU	26	38
none	Statnett	Norway	none	26	5
none	TenneT	NL,DE	As EU	22	36
none	PLN Java-Bali	Indonesia	none	21	145
	Total (unmatched)			2467	4130
	World (unmatched)	Estimated		3060	7162

Data for 2013 obtained from [190] and from the PGO homepages.

2. THE USE OF STEADY-STATE POWER FLOW CALCULATIONS OF INTERCONNECTED POWER SYSTEMS FOR TASKS IN THE ELECTRIC POWER INDUSTRY

Power-Flow Calculations as a Tool for the Power System Study

The power system operation can be defined as a complex continuous process. Different tasks in terms of importance, scope and complexity should be solved to ensure safe and stable operation of the power system as soon as they appear or better before they appear. Most of the problems in the power system operation cannot be solved efficiently without the use of modern computer technology [13]. Some tasks of design, planning and operation of the power system are associated with calculations of the steady-state power flow on mathematical models of power systems [11]. Calculations of electric power systems at the mathematical models allow the researcher to be aware of grid reaction on the possible changes in the future with sufficient accuracy.

It can be seen in Table 2.1, where the calculations of steady-state power flow are used, and what types of calculations include the model of power system grid.

The challenges of improving the quality of calculations in load flow studies for the problem of power system planning in the short term is the subject of the Doctoral Thesis. Load flow studies can also be extended and used for the purpose of simulator for operator training. This problem is also the subject of study within the framework of the Doctoral Thesis. Brief descriptions of all studies on power system models provided in Table 2.1 help distinguish the place for power-flow calculations among the studies on power system models.

Table 2.1

Power System Problems and Load Flow Calculations

Load flow calculations are optional in problems solution	Load flow calculations are obligatory in problems solution	
Statistical data and trends analysis	Fault analysis	
Comparison of variants base on multi-criteria analysis	Power system stability analysis	
	Power system planning	
Projects of power system components	Operator training	
Power equipment testing, production and construction	Supervisory control and data acquisition	
	Energy quality assessment	
Logistics and workflow optimization	Reliability of power system components	
Power market auction price calculations	*Studies on power system models:* [1]	
Power measurements and accounting	1.	*Load flow studies*
Demand forecast	2.	*Short-circuit studies*
IT, computer networks, Cyber security	3.	*Steady-State and Transient stability*
Power system optimization	4.	*Motor-starting studies*
Analysis of social, environment and economic impact of power systems	5.	*Switching transient studies*
	6.	*Protective device coordination studies*
Staff training	7.	*Harmonic analysis studies*
Equipment decommission	8.	*Reliability studies*
Client interfaces	9.	*Ground mat studies*
Data exchange	10.	*DC auxiliary power system studies*

[1] according to [195].

Power-flow calculations or load flow studies determine the voltage, current, active and reactive power in a power system [7]. A number of operating procedures, for example, contingency conditions, such as transmission line outage or loss of generator, can be analysed based on power-flow calculations [39]. This is the main tool for power system planning. The results of power-flow calculations are the starting points for short-circuit studies, steady-state [62], [162] and transient stability studies [3], [51], [160]. Modern power-flow calculations are performed on very large models of interconnected power system [119].

As can be seen from the information above, power-flow calculations are a useful tool for the power system study. Although the model of a single element is basic, calculations are not so simple since an engineer typically has an exceptionally large number of elements in the load flow study.

Information for Power-Flow Calculations in the Case of Interconnected Power Systems

There are two types of data for studies with power system models. The equipment model is the backbone of any calculation. The information can be defined as static data. The information about the equipment connection to the grid, equipment loading, voltage levels, power flows and network injections is needed in order to set the conditions for the load flow study. The information can be defined as a set of data variables. Some of variables serve as the data inputs for study. Other variables represent the calculation results. This information can be used for validation purposes or as the target values for calculation.

The analysis of historical information allows the engineer to simulate a certain expected state of grid in the future. The interconnected power system gives undeniable advantages in improving reliability of electricity, power quality and cost-effectiveness of the operation of the system as a whole and of its individual parts. However, the problem of receiving the variable data from other parts of the grid currently is not resolved fully [122], [137]. As a result, models of different transmission operators within one and the same interconnected power system are significantly different from each other. In spite of these differences, the power-flow calculations of electric power systems are successfully applied to the maintenance of voltage quality and reduce energy losses in the network, as well as calculations are used in the planning of electric power systems for the immediate future and in the long term.

The Use of Power-Flow Calculations for Planning Operations of Interconnected Power Systems

Energy consumption is affected by daily, weekly, seasonal periodic changes. Irregular fluctuations caused by common influence random events overlap with periodic changes. The more power in the system, the less the relative total impact of random factors. It follows that the total power consumption of the electric power system is more predictable and consistent than the load of individual consumers. The challenge of modern electricity markets is to ensure correspondence of power production to the power consumption on each planned time interval, taking into account the limited transmission capacity via the network [68], [76]. The duration of planned intervals may vary, but usually it is equal to one hour or less. Power flow distributions on each planning interval differ from each other.

The transmission capacity of the network from the point of view of the electricity market is fundamentally different from the maximum allowable active power flow on overhead power lines. It is important for the market to set the maximum limits, how much electricity during each planned interval could be transmitted from one bidding area to another [81], [91]. TSO is setting the numerical values of these limits for the market. The problem is that TSO should set the limits to the market before the market has been finalised. The market provides the total energy balance and is not worrying about power flows inside the electric power system. In this way, the TSO should define the limits, when the generating schedules of power plants are not yet known. Therefore, the margin is needed in order to keep the network reliable [94], [136]. The

flow determined by power markets differs from the active power flows via overhead power lines. Therefore, during normal market operation, the network can be overloaded in some places and vice versa, the critical lines can be underloaded while the network transmission capacity is fully used.

The TSO task is to ensure the power transfer from generators to consumers at its control area in the interconnected power system. In order to know the loading of network elements expected on the following day, power flow calculations are required. The scheduled values of power plant generation and scheduled electrical loads are used as a source of data in this case. It is recommended to use the "the planning backward" in operational planning, i.e., to perform the planning of regime, which already passed, for example, yesterday on the basis of the fact of scheduled data. If the planning values for the past day significantly differ from the corresponding data from the meters, the model is not ready for planning tasks. Analysis of differences will show what kind of data is not enough and how the engineers should improve the technology in order to achieve the result with acceptable accuracy. The planning regime for tomorrow will be less accurate than the planning regime for yesterday, but good planning accuracy can be achieved even in the case of the interconnected power system. Coordination of the planning operations and the mutual exchange of data for planning regimes between the TSO are essential for the good planning process. Power flow calculations in operational planning are carried out in several stages, when new information becomes available. The most accurate calculations are carried out at the last stage, and the results of the operation of the market are used as a starting point. Thus, the TSO can know the potential problems in the transmission network for the next operational day based on schedules.

The Description of IEEE 118 Bus Power System Static Test Case

The IEEE 118 Bus Test Case represents a portion of the American Electric Power System (in the Midwestern US) as of December, 1961. The data were manually entered from a copy of a copy of a copy, etc., of the AEP 118 Bus Test System document dated December, 1962 and "made available to the electric utility industry as a standard test case". It was entered in PECO PSAP format and later in IEEE Common Data Format by Rich Christie at the University of Washington, Seattle, Washington, USA in 1993 [192]. The power-flow data for the model were typed manually and very likely can be used for testing the knowledge of the university students. In order to obtain a regime that is close to the solution that is indicated in IEEE CDF format, it is necessary to use data from files of both formats as well as the graphical representation of the power system diagram.
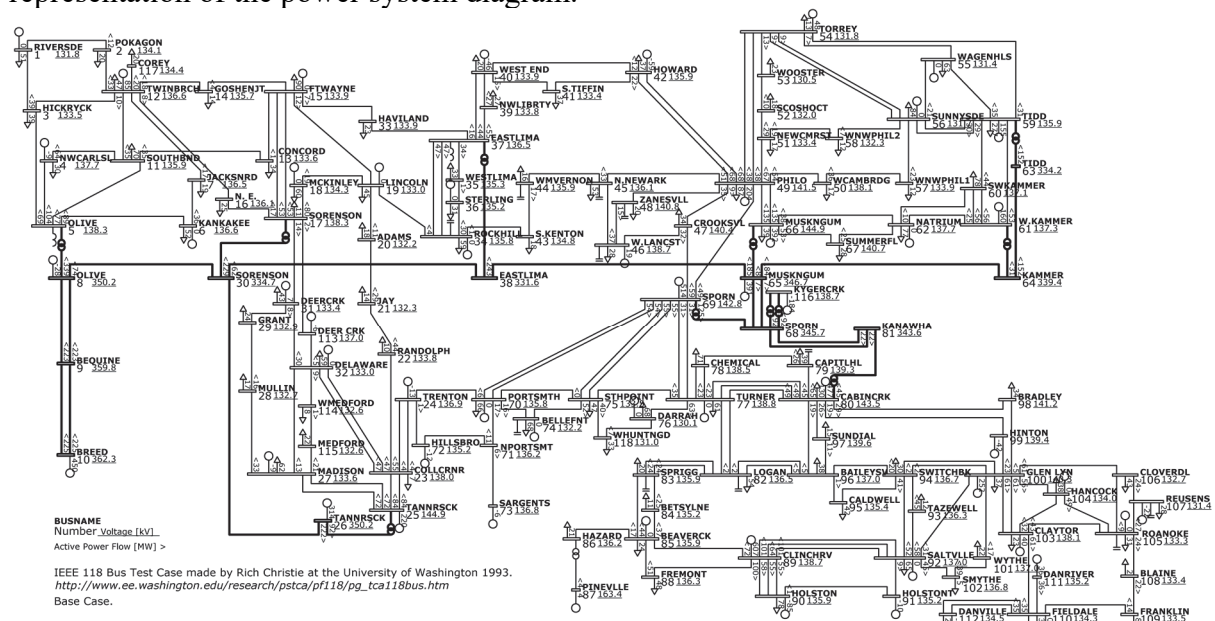

Fig. 2.1. The single-line diagram with power flow of the IEEE 118 Bus Test Case.

16

The single-line diagram with initial power flow of the test case is shown in Fig. 2.1. The test case includes 118 buses, 200 power transmission lines, 12 transformers, 19 power plants of various power, 18 synchronous compensators, 12 shunt reactors, 2 capacitor banks, 15 aggregated motive loads and 91 buses with static load. The total power of the power system is approximately 4375 MW. The power system is modelled on the transmission network level, using three voltage classes. 11 buses belong to the highest voltage class – 345 kV. In the calculation model, there is also one bus with a rated voltage of 161 kV. The other 106 buses of the network, which concentrate the whole static load, are represented with a rated voltage of 138 kV. The voltage in the swing bus SPORN (bus number 69) is 142.83 kV in absolute value. The voltage angle of the swing bus is 29.95 degrees.

3. MODELING REGIMES OF INTERCONNECTED POWER SYSTEMS

The Mathematical Modeling as a Scientific Method

Mathematical modeling has found its application in all areas of modern science and technology. The essence of the methodology consists in the replacement of object studied on its "image", which is known as a mathematical model, and further study of model using the computation and logical algorithms that can be implemented in the form of a computer program. Mathematical modeling may be considered a study method, which combines many merits of theoretical and experimental methods of knowledge [111], [184]. The work using the "image" of an object, phenomenon or process provides a researcher with the opportunity to quickly, safely, without large financial costs to investigate the object behaviour under any hypothetical situations. At the same time, computational experiments on mathematical models allow making use of the great potential of contemporary computing technology and modern computing methods for a detailed and in-depth study of modeling object.

The process of establishing a mathematical model consists of several stages. The physical properties of an object that determine its characteristics from the point of view of study process or phenomenon should be explored at the first stage. Physical regularities describing the phenomenon or process may be formulated on the basis of observations and experiment. As a result, the most important properties of an object can be described mathematically. The mathematical formulation of a problem is not copy of the real object, yet projection of an object into the space of the studied phenomena. Consequently, mathematical formulation reflects only the properties of a real object that are important in the study of certain type of problems.

The algorithm of solutions of the equations describing the mathematical model on the computer is developed at the second stage. Computational algorithms should be effective in terms of calculation process on a computer and in terms of execution time of a problem.

The algorithm is "translated" to the language understandable by a computer at the third stage, as well as the computer interface should be provided in order to connect a computer program with the user. A computer program that is intended for mathematical modeling may be described as "an electronic equivalent" of the studied object and a set of instruments for measurements or, in other words, cheap and safe equipment for the computational experiments.

If the computational experiment shows that the model requires refinement, the whole process of mathematical modeling is repeated at a new level. As a result, the model specifies, and part of environment is converted to objects of the system. It should be noted that also the return process can take place in modeling, in which an overly detailed model is becoming more sensitive to errors when determining the initial conditions. Simpler mathematical models could provide more reliable results in this case.

The Size of Modeling Objects in the Power System Study Depends on the Scale of Power System

Electrical network is conditionally constant part of an electrical system, which links substation of power plants with switchgears of consumers. The structure of existing electrical networks depends on the geographical location of generation and consumption centres. Most networks of power consumers and small power plants are connected to the distribution networks at low and middle voltage. The distribution grids and industrial energy consumers, as well as power plants are connected to the transmission network at a high voltage. The transmission networks are also connected to one another at the extra high and high voltage, forming the transmission grid of interconnected power system. The frequency of the alternating current is common for all feeders inside the interconnected system.

The scale of model and requirements for the level of detail for models formulated as an object of the study should be visible in the specified format. The scale of model has a tendency to increase and a level of detail of model tends to decrease with an increase in total rated power of consumers connected to the simulated network. Many independent models and many connected models can exist as the elements in the modeling space inside the interconnected power system while the originals affect each other less or more. If models notably affect each other, the association can improve the quality of calculations.

The larger the scale of the network, the less the relative power of single power units, the more diversity under normal and emergency regimes, the initial information also contains more uncertainty. Energy consumer can simulate all power system components in the internal study area in detail and accurately, while the rest of interconnected power system can be represented in the form equivalent [42]. Here, the voltage at connection busbar is most important outside the study area. TSOs are used to model a grid at a large scale focused on power flows via the branches. Power flows depend on the total loads and generation in power plants. Therefore, the influence of individual electrical installations is taken into account approximately. Thus, in the case of interconnected power system more electrical components will be included in the network model and fewer detailed models of individual power system elements can be used in the calculations.

Measurements, Signals and Data from Electricity Meters as the Source for Calculations

The measurements and the signals from the interconnected power system are the main source of information for TSO dispatchers [172]. The modern dispatcher can have detailed information to control objects, which are within his operating area. Measurements and signals coming via data links from substations show the current situation in the power grid. Data from electrical energy counters complement the telemetry information with integral estimations.

Unfortunately, the information on the regimes of neighbour electric power systems comes in a much smaller amount and the information on the other parties working in parallel virtually is not available. The exchange with the ready parts of calculation models on the basis of actual data, in which each TSO simulates power flow regime within its operating area, seems to be most promising at the moment. Parts of the models for calculations, prepared for the exchange, should be synchronised in time. If each TSO in the interconnected power system maintains the quality of its power flow model at a high level, it can be useful for assembling the qualitative model for calculations of electrical regimes throughout the interconnected power system based on actual data. The common grid model of the interconnected power system should be available to all participants in data provision. It should be noted that the complexity of the task creation of the common grid model for the interconnected power system based on the actual data in real time is determined not only by data availability, but also by the level of detail of model. The problem of building a detailed model of the grid based on actual data in real time is still awaiting an appropriate solution in the future.

Some Features of Modeling of Electrical Regimes for Interconnected Power Systems

Regimes of interconnected power systems are calculated on the mathematical models using computer programs [26]. Mathematical models for power flow calculations in electric power systems will be made inside the calculation program based on initial data about power system. Using the same initial data about a power system, for each method of calculation its special mathematical model will be constructed [37], [158], [166]. Nevertheless, the results of the steady-state power flow calculation obtained using different calculation programs at the same initial data about power system with the same source of data are almost identical. Therefore, the results of the calculations to a greater extent do not depend either on a specific calculation program or the calculation method [37], but depend on initial data about the power system [23]. The initial data about the power system is not universal in the general case, since it is used by each program in its own way. Models are built from the individual elements, and structure of elements may be quite complex.

As an example let us look at the elements that comprise the model in MUSTANG program [20]. Construction methods of the models for the calculation of power flows in the interconnected power system in other programs differ in some details, but are fundamentally similar. Model for power-flow calculations consists of buses and branches:

Bus – a network point, in which the model elements could be connected to each other. The original of bus can be part of substation, the busbar section, place of branch line connection to overhead line, the internal point of multi-winding transformer, the place of connection of the current transformer, etc.

Branch – the model of equipment which conducts the electrical current and connects the two buses. Physically the original of branch can be the transmission line segment, transformer, circuit breaker, disconnector, etc.
Three-phase network is modelled in one linear representation. Voltages between two phases could be defined and calculated at the buses. The impedances for branches, and also currents via branches should be calculated for one phase.

Active and reactive powers at the buses are defined as the sums for all three phases. The full power S is equal to line voltage U multiplied by the phase current $\underline{I}$ and multiplied by the square root of three. The assumption on the equal parameters of all three phases is used in the model for power flow calculation. Thus, the power flow model is the positive sequence model. The load flows for non-symmetrical studies are possible to calculate with the addition of the negative and zero symmetrical components to this power flow model [175]. Hereinafter in the Thesis only symmetric regimes of power systems will be considered and the named measurement units will be used. If the voltages at buses are defined in kV, the power flows and injections are defined in MW and Mvar, and resistance – in Ohms, the currents will be obtained in kA. In order to avoid the large number sets in the initial data, the active and reactive admittances were set in μS. A positive sign for the reactive impedance and for the reactive admittance, as well as for reactive power load corresponds to inductance. The capacitance is set as the negative value reactive impedance. The positive power flow direction via the branch is from the bus toward the line, for load and shunt from the bus to the load. For the generator, the positive power flow direction is from the generator to the bus. The total power of all generators, loads and shunts connected to a single bus is called by injection. The positive power flow direction for injection is the same as for the load.
Figure 3.1 shows the models of the main system components: bus i and branch k from i to j.

The bus model in MUSTANG program includes one generator, one load and one shunt simultaneously as a standard. Zero value in this case means the absence of component. Since the buses with no branches will be eliminated from the case during the power flow calculation, at least one branch should connect each bus to the other bus. The minimal power system in MUSTANG is two buses and one (even offline) branch. The number of buses and the number of branches from one bus are not restricted.

The module of initial bus voltage and also bus type are important bus characteristics. Bus type determines which parameters are used as initial data, and what results should be calculated by the program. Bus in MUSTANG could be one of three types: the generator bus, or the load bus, or the infinite power bus.

The initial active power of the generator at the generator bus does not change during the calculation. The initial voltage at bus is supported as a conditionally constant value. The calculated voltage at the generator bus is equal to the initial voltage, if the reactive power produced by the generator is within the specified limits. If the generator has produced a maximum reactive power for keeping the voltage, it is fixed at the maximum limit, and the calculated voltage at the generator bus is decreased. If the generator has produced a minimum reactive power for keeping the voltage, it is fixed at the minimum limit, and the calculated voltage at the generator bus is rising.
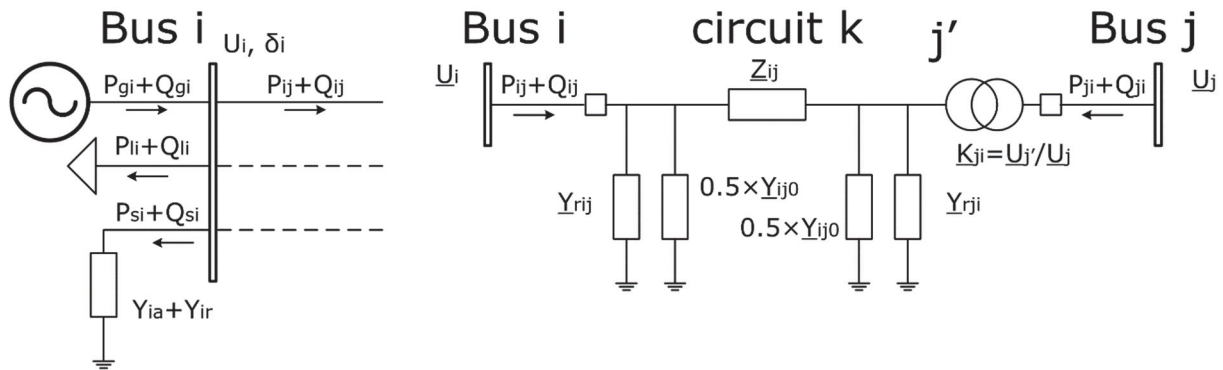

Fig. 3.1. Bus & Branch oriented power system component model.

P – active power, MW; Q – reactive power, Mvar; $\underline{Z} = R + jX$ complex impedance, Ω; $\underline{Y} = G + jB$ complex admittance, µS; $\underline{U} = Ue^{i\delta}$ – complex voltage, kV.

Both the active and the reactive power load for the generator do not change during the calculation for the load bus. The load bus in the calculation has the same behaviour as the generator bus with the maximum reactive power limit equal to the minimum reactive power limit, i.e., the reactive power for voltage control is null.

The values of voltage module and voltage angle are set and do not change during the calculation for the infinite power bus. Constant module of voltage is provided by a change in generated reactive power at bus in the unlimited range. In order to ensure the initial voltage angle the active power generated at bus also changes without restrictions. In this way, bus type determines how the generator that is connected to the grid at this bus should be taken into account in the calculation.

Two buses are considered electrically connected, if there is at least one path of the energized branches connected in series. Any group of electrically connected buses should have at least one infinite power bus. There can be tens of thousands of electrically disconnected groups of buses in the model, but, usually, all of the components are electrically connected. There are possible other types of buses in theory, but right now they cannot be set in MUSTANG.

The data types of buses are identified in MUSTANG program by digital codes for ease of operation, as described in Table 3.1. The bus may also be turned on and off logically.

The generators usually correspond to separate synchronous machines or power plants connected to the bus. Sometimes large engines are modelled by the generator, for example, synchronous machines of pump storage power plants, and also devices for controlled reactive power compensation. The generator differs from the load because the initial active power generation does not change if the voltage changes.

Load is usually the power flow to consumers and, in general, depends on the calculated module of voltage at the bus. The active and reactive components of load at bus could be defined according to the static load characteristics from voltage, which could be described by formulas 3.1 and 3.2. The normal voltage at bus is the voltage magnitude at which the load, defined with static voltage characteristic, is measured. The active and the reactive power of load at the bus do not change during the calculation in case, if static characteristics were not defined, or were defined as independent from voltage magnitude.

$$P_{li} = P_{li0}(a_0 + a_1 U_i/U_{inorm} + a_2 U^2_i/U^2_{inorm}). \tag{3.1}$$
$$Q_{li} = Q_{li0}(b_0 + b_1 U_i/U_{inorm} + b_2 U^2_i/U^2_{inorm}). \tag{3.2}$$

P_{li} (MW) and Q_{li} (Mvar) are active and reactive load components at normal bus i voltage U_{inorm} (kV). Note that U_{inorm} differs from rated voltage at bus i; a_0, a_1, a_2 – polynomial coefficients for second-degree P_{li} polynomial in bus i voltage; b_0, b_1, b_2 – polynomial coefficients for second-degree Q_{li} polynomial in bus i voltage.

Shunt at the bus normally corresponds to the static device with constant admittance. The loads of buses eliminated from the study case also tend to be represented as the shunts in the equivalent parts of power system. When voltage changes the admittance of shunt does not change.

Table 3.1

Bus Type Codes Available in MUSTANG Program

Code ($U\delta PQ$)	U, kV	Angle, °	P, MW	Q, Mvar	Usage
1100	Fixed	Fixed	Variable	Variable	Infinite bus
1010	Fixed	Variable	Fixed	Variable	Generator
0022	Variable	Variable	Fixed	Fixed minimal	Generator at minimal Q limit
0044	Variable	Variable	Fixed	Fixed maximal	Generator at maximal Q limit
0011	Variable	Variable	Fixed	Fixed	Load

A branch is described by series impedance, shunt admittance and complex transformation coefficient. All the branches in MUSTANG program are simulated as Pi-form equivalent circuit. Reactive admittance corresponds to the charging capacitance of line. It simulates the impact of charging power on the currents at the ends of line measured on the substations. If the line has a non-adjustable shunt reactor, it can be simulated by the corresponding positive susceptance at the end of branch. Active admittance components of branches correspond to losses on the corona in overhead power transmission lines and also correspond to power losses in transformers or in shunt reactors in open-circuit.

The magnetising admittance of two-winding transformers is simulated on the i site in many programs. Such a transformer model could be reproduced on MUSTANG universal branch model by specifying the magnetising admittance at the j site of branch. In order to model a multi-winding transformer in MUSTANG, each coil should be simulated separately. The additional dummy bus is needed for a common internal point for each transformer according to star equivalent circuit. Alternatively, the transformer could be modelled as polygon equivalent circuit without a mid-point.

Branch in the model is identified by the bus numbers at start and end, as well as by the unique circuit number. The unique circuit number should be defined for each branch, if between the two buses several branches are defined because the absence of circuit number means null.

The null identifier means "for all" and therefore branch could not be identified in the case of some branches. The model of branch can be enabled or disabled from any end, as well as under voltage or no voltage. This feature of the program theoretically gives eight possible logical states of branches. Not all of them can be used in practice, but this possibility allows the engineer to simulate switches and disconnectors [53] in the model without the use of logical switching elements. Table 3.2 shows the logical statuses for the branch model.

Table 3.2

Logical Statuses for the Branch Model

Status	Abbreviation: "on" from bus i & "on" from bus j & alive Logical states: 0 = no, 1 = yes		
(ijU)	Short description	Operator see	Program see
000	Branch is offline.	Off	Off
001	Branch is offline, but Alive. (not used)	…	…
010	Branch is disconnected from bus i. Cold.	Travel	Off
011	Branch is disconnected from bus i. Alive.	Travel	Open End
100	Branch is disconnected from bus j. Cold.	Travel	Off
101	Branch is disconnected from bus j. Alive.	Travel	Open End
110	Branch is connected. Cold.	ON	Off
111	Branch is connected. Alive.	ON	ON

Based on the data for buses and branches in the power flow case, MUSTANG program builds the mathematical model of the power system, which is presented in detail in [182], [183]. Form of a mathematical model, as well as methods for solving the equations of steady-state regimes differ and depend on the calculation program. The algorithms and models that are commonly used in the power flow calculation programs are discussed in [4], [7], [8], [158].

Methods of Reporting the Information Generalized on the Power System Model

Contemporary power flow calculation programs use grouping of individual buses in the subsystems. The traditional subsystems are formed based on the information that is given as the attributes of bus in the calculation model. The bus comes in several types of subsystems (substation, zone, district, area), which are usually formed by the geographical principle. Each bus is included exactly once in each type of subsystems. This ensures strict grouping of buses inside the subsystems. This robust mechanism of formation of the subsystems was created a long time ago, while the relatively small network models were used in practical calculations.

The principle of aggregation of groups of buses and branches applied inside MUSTANG program is a more promising approach in the subsystem creation. Subsystem in this case is not determined at the buses of the network model, and is set in a tree of directory folders, which is stored in a separate file. The folder, in general, contains the recorded identifiers of model buses and subfolders belonging to this subsystem. Each bus can be included in each of the folders no more than once. Folders are formed arbitrarily, on the basis of the tree of directories, so grouping of buses to the subsystems is not limited. The subsystem also includes the branches that connect the buses inside the folder by default. If one of the buses belonging to the branch is not included in this folder, the branch is considered the tie line for this folder. If not further specified, what must be included in the loss, the loss in tie lines refers to the folder with the active power inflow via the line. In order to be able to define a more complex division of subsystems such as "the owner", a user has the opportunity to directly set what percentage

of loss of the branch belongs to this folder. The information is given in other additional files. Thus, it is possible not only to create the subsystem in which there are buses and branches emanating from them, but the subsystem in which there are either only buses or only some parts of the branches. The advantage of this approach to the grouping of buses is that groups may be formed dynamically as creating new folders and deleting the existing ones virtually pose no effect on other groups. Using additional files leads to the fact that the model "does not know" about the existence of groups. Therefore, changes in the tree of directories do not affect the model. Obviously, in the folder the bus numbers can also be recorded that do not exist in the model. This means that the folder tree tends to be mobile. In various variants of the network model, the same tree of directories can be used with some redundancy. Redundancy elimination function allows the user to remove the non-existent elements from the tree of folders. In this case it is easy to monitor the appearance of new buses in an unfamiliar network model. If the user renumbers the buses, the numbers in the tree of directories will be changed by the program automatically. On the other hand, this approach is not so strict and therefore in the formation of grouping mistakes of the subsystems are possible. Fortunately it is not a big problem for the user. In Fig. 3.2 an example of the formation of the subsystems based on traditional concepts of "area" and "zone" is shown on the left and a similar example using the tree of directories is shown on the right.

Here 12 buses are divided into two areas and three zones. The buses are marked as big balls in Fig. 3.2. The buses 1, 4, 6, 8, 9, 10, 12 are included in area 1. Other buses are included in area 2. The buses 3, 6, 9, 12 are included in zone 3. The buses 10, 11 are included in zone 2. Other buses are included in zone 1. The figure on the left for each of the buses provides the mandatory information about one area and one zone. The figure on the right shows the subsystems as concentric polygons on vertices of which points mark the belonging of buses to this folder. The bus is placed into the directory, if the point is at the intersection of the segment connecting the bus with a common centre of polygons with the vertex of the polygon. The number of concentric polygons may be any natural number. Each bus may be recorded in any folder no more than once.
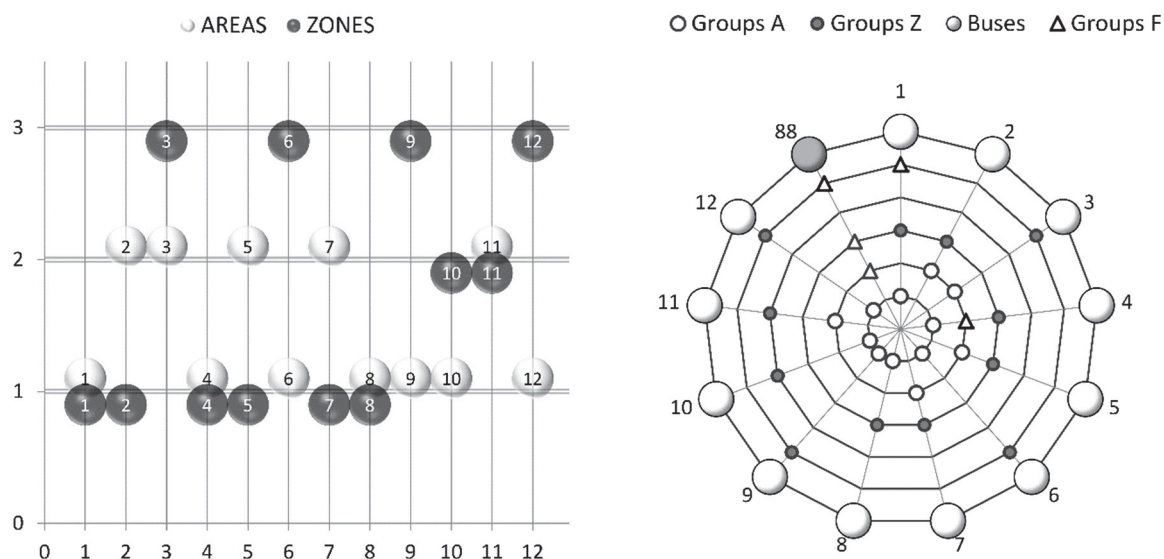
Fig. 3.2. The difference between conventional method and MUSTANG technique for subsystem creation based on 12 bus model with two areas and three zones.

The tree of directories in MUSTANG is the extra intermediate interface between data tables and engineer. It allows creating the generalised tables in the program that can be used not only for the study of the results of the calculation, but also for editing the data. The tree of directories greatly enhances the capabilities of the tabular, as well as the graphical representation of information. It should be noted that similar opportunities give the user also

the traditional mechanism for the formation of groups. However, the tree of directories provides an additional opportunity for the advanced dynamic formation of groups automatically by the calculation program. This possibility cannot be easily done, if the traditional mechanism of formation of subsystems is used.

Fig. 3.3. The simplified representation of single-line diagram for 345 kV network of the IEEE 118 Bus Test Case.

The engineer may be interested not only in data generalisation into subsystems because the information about the total flow capacity for groups of branches of the power system model is important too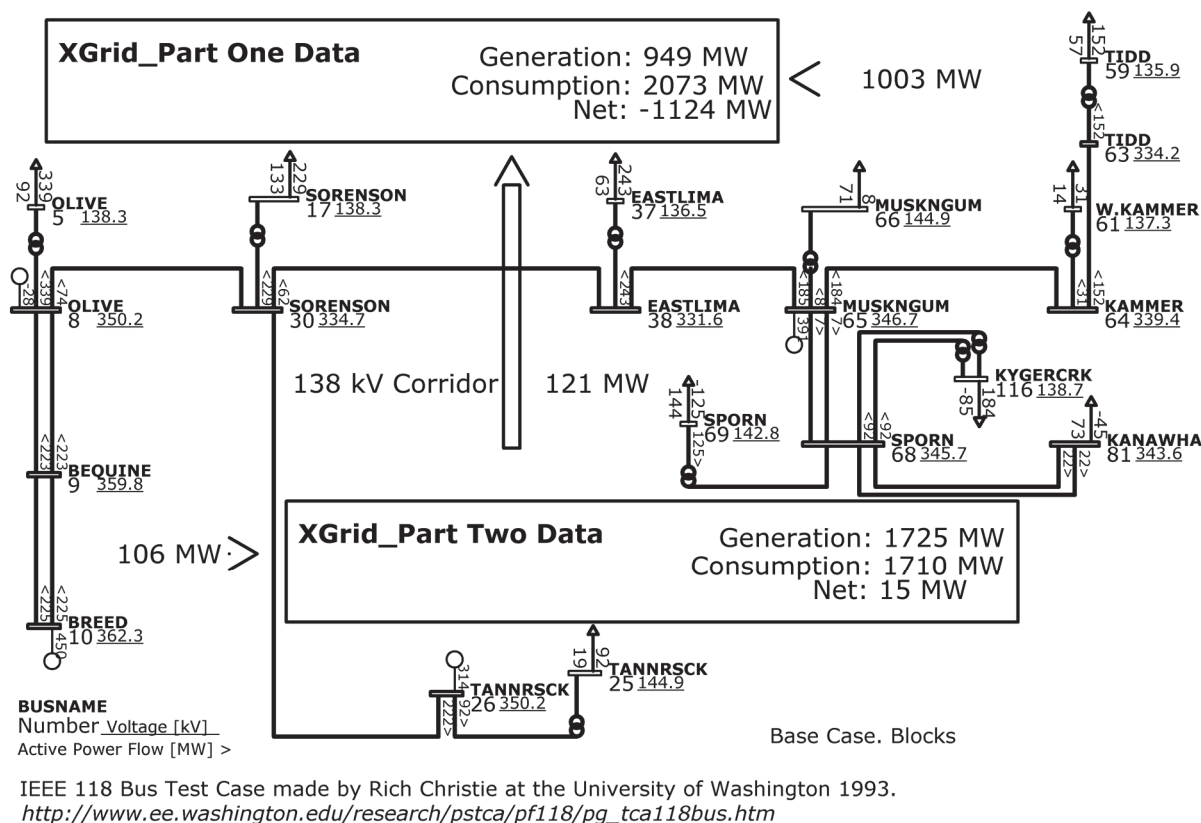. Generalised branches are the groups of branches with pre-defined positive directions for active power flows. In a real power system, they are called area interconnections, cross-sections or line corridors. Generalised branches in MUSTANG program may be formed in a similar way, but instead of the folder name there is the name of the used cross-section. Obviously, these groups can also be used to control the total power flow in any bus subsystem.

The single-line diagram of the IEEE 118 Bus Test Case is shown in Fig. 2.1. As can be seen in Fig. 2.1, the diagram is difficult to read. Consequently, in order to readably show the regimes of present-day interconnected power systems with tens of thousands of buses, most of buses and branches of the calculation model should not be drawn on single drawing.

Let us try to diminish the number of elements in the drawing and find out how this affects the clarity of the test diagram. We leave the whole 345 kV network unchanged and group the network of the lower voltages into two subsystems as follows: the buses located above the horizontal line formed by the power transmission lines from the 345 kV substation EASTLIMA (bus number 38) belong to the first subsystem and the other buses – to the second subsystem. It can be found that the subsystems are directly connected to each other by a group of five lines of 138 kV, which in turn for the clarity can be drawn in aggregated representation like the cross-section. The result is shown in Fig. 3.3. As can be seen in Fig. 3.3, the diagram has become less detailed. At the same time, a power-flow regime for the test case becomes clearer from the perspective of the 345 kV network.

Conceptually, a new approach to the creation of subsystems based on the "folder tree" for the power-flow calculation program has already been implemented in MUSTANG program. This allows the engineer to save time while solving many practical tasks. The idea of additional files is quite productive because it does not complicate the structure of the data model. This idea is not only simpler, but it puts fewer restrictions from the user's position.

The Load Flow Calculation on Power System Model for Obtaining the Predefined Calculation Results

One method of reducing the input data preparation efforts for power flow calculations in the interconnected power system can be the process of adjustment the initial data for obtaining a given calculation result. For example, the regime with a certain active power flow via intersystem connection is required for the further analysis. It is a quite usual task, but its difficulty lies in the fact that the power flows at lines are obtained as a result of power flow calculation. Therefore, changes in the input data are required in order to obtain the desired values of regime parameters, which will be known only after the calculation. Obtaining the power flow based on the set of calculation results requires feedback, so the process of obtaining the targeted power flow tends to be the iterative process. Each of iterations includes the control of the calculation results, the change of the initial data in the model to the desired path and the calculation of the power flow. The process of selection of the initial data to achieve the desired calculation result takes a long time, if the engineer changes the data manually via program interface. Many simple tasks become hard to solve when calculating at a fairly detailed model of interconnected power system without the use of automation.

To obtain the predefined result in MUSTANG program, the algorithm of changes of the initial data is based on the chord method [178], [179]. The result of power flow calculation or the controlled parameter is an implicit function of the group of initial data or control parameter determined by the equations of mathematical model of the power system. At each step of the iterative process, the algorithm performs a linearized function. The algorithm checks the controlled parameter on correspondence to the target value. If the module of deviation of controlled parameter from the target value is outside the limit of precision, the first tentative step to change the control action and the expected value in the expected direction should be made, and power flow on the power system model will be calculated in order to determine a new value of the controlled parameter. For instance, we can use the results of sensitivity analysis for the first step [31], [92], [95]. Next iteration will be repeated and, if accuracy is not reached, the control parameter will increment by value defined by the parameters of the two previous steps. The algorithm operates in parallel and allows obtaining several specified controlled parameters simultaneously. The algorithm also operates sequentially, i.e., allows obtaining groups of values of controlled parameters using various control actions in several stages. A new stage begins when the previous step is completed successfully. Details of controlled parameters and control parameters, as well as data on the expected impact of the control parameters on the controlled parameters are specified in the supplementary file. The sequence of steps how to change the initial data to obtain the desired result is given in this file too. The values of the controlled parameters are set dynamically. Thus, the user can set the calculation results as the input to the power flow calculation program. If it is set how to obtain these results, the program on a simple or quite complex algorithm can set the results of power flow calculation defined by the user via changing the corresponding initial data. In the case of an unsuccessful process, the program can sometimes bring the initial power flow case closer to the power flow, which was set by the user. The active and reactive power flows via branches or via cross-sections; either net interchanges or power consumptions of subsystems, the calculated voltage of buses and currents along the branches could be taken as the controlled parameters. Control parameters are the active and reactive power of generators, loads and shunts or the corresponding total parameters of subsystems.

As an example, let us try to modify the initial regime, which is shown in Figs. 2.2 and 3.3, into a regime with flows of active power equal to 100.0 MW ± 0.1 MW – from the 345 kV network to the 138 kV network via each 345/138 kV autotransformer. The total active power flow from the 345 kV network to the 138 kV network will diminish by 9 MW. Levelling of the transmitted power will be ensured due to changes in the generation active power of the selected power plants.

Table 3.3

The Controlled and Control Parameters at Iteration Steps 0, 6, 12, 18

| | $y = F(x)$ | | | | $y_{i0} + \Delta y_{i0} = y_{i18}$, $x_{i0} + \Delta x_{i0} = x_{i18}$ | | | | | | | |
i	y_i Branch P_{ij}, MW	x_i Bus P_{gen}, MW	y_{i0}	x_{i0}	Δy_{i0}	Δx_{i0}	y_{i6}	x_{i6}	y_{i12}	x_{i12}	y_{i18}	x_{i18}
1	KAMMER-W.KAMMER(64-61)	W.KAMMER(61)	30.5	160.0	69.5	–125.8	100.3	32.6	100.0	34.5	100.0	34.2
2	SPORN-SPORN(68-69)	MUSKNGUM(65)	–125.4	391.0	225.2	13.7	109.1	402.4	100.7	403.9	99.7	404.7
3	KANAWHA-CABINCRK(81-80)	CLINCHRV(89)	–44.8	607.0	144.7	–212.5	96.5	403.5	97.3	399.3	99.9	394.5
4	MUSKNGUM-MUSKNGUM(65-66)	MUSKNGUM(66)	8.4	392.0	91.6	–273.5	91.1	135.2	100.9	117.3	100.0	118.5
5	SPORN-KYGERCRK (68-116 2)	KYGERCRK(116)	92.1	–184.0	7.9	–15.8	100.0	–199.8	100.0	–199.8	100.0	–199.8
6	SPORN-KYGERCRK (68-116 1)	KYGERCRK(116)	92.1	–184.0	7.9	–15.8	100.0	–199.8	100.0	–199.8	100.0	–199.8
7	TANNRSCK-TANNRSCK(26-25)	TANNRSCK(25)	91.6	220.0	8.3	0.4	97.0	226.8	99.7	221.1	100.0	220.4
8	OLIVE-OLIVE(8-5)	NWCARLSL(4)	339.1	–9.0	–239.1	363.9	100.9	353.5	100.0	354.9	100.0	354.9
9	EASTLIMA-EASTLIMA(38-37)	WEST END(40)	243.5	–46.0	–143.5	327.0	101.0	278.3	100.2	280.8	100.0	281.0
10	SORENSON-SORENSON(30-17)	DEERCRK(31)	229.3	7.0	–129.3	405.3	99.4	414.7	100.1	411.6	100.0	412.3
11	TIDD-TIDD(63-59)	TIDD(59)	151.7	155.0	–51.7	97.2	101.8	247.5	100.1	252.1	100.0	252.2

The difficulty of this task consists in the fact that one of the autotransformers in the substation SPORN (bus numbers 68, 69) is directly linked to a swing bus. The generation power of the swing bus depends on the power of all the other generators. Therefore, if the power of any of the generators changes, the active power of the swing bus will compensate for these changes. Consequently, if the deviations of the current regime from the specified regime are large, then the active power flow via the autotransformer in the substation SPORN will have a large forced component. In this case, the method of chords does not guarantee bringing the regime closer to the specified calculation result. In order to improve the convergence of the automated process of obtaining the specified result, it is necessary to diminish the sensitivity of the algorithm to the accuracy of reaching the value of the parameter of active power via the autotransformer SPORN (bus numbers 68, 69) and increase the value of the permissible deviation of the resultant active power flow to ±0.5 MW.

The specified pre-definite calculation result was obtained in eighteen iterations; each was a steady-state regime calculation with new values of control parameters. The program automatically ended the calculation since after the eighteenth iteration all the controlled parameters reached their values with deviations within the specified accuracy range. Table 3.3 provides the controlled and control parameters, their initial values, the deviations of the resultant values of the parameters from the initial values and the values of the parameters after

the sixth, the twelfth, and the eighteenth iteration. Figure 3.4 provides an observable representation of the process, in which the controlled parameters enter the specified solution plane. Figure 3.5 shows the obtained solution in a single-line diagram.

Delta from the 100MW target flat
[MW] 250

KAMMER-W.KAMMER(64-61)
SPORN-SPORN(68-69)
KANAWHA-CABINCRK(81-80)
MUSKNGUM-MUSKNGUM(65-66)
SPORN-KYGERCRK(68-116 2)
SPORN-KYGERCRK(68-116 1)
TANNRSCK-TANNRSCK(26-25)
OLIVE-OLIVE(8-5)
EASTLIMA-EASTLIMA(38-37)
SORENSON-SORENSON(30-17)
TIDD-TIDD(63-59)

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
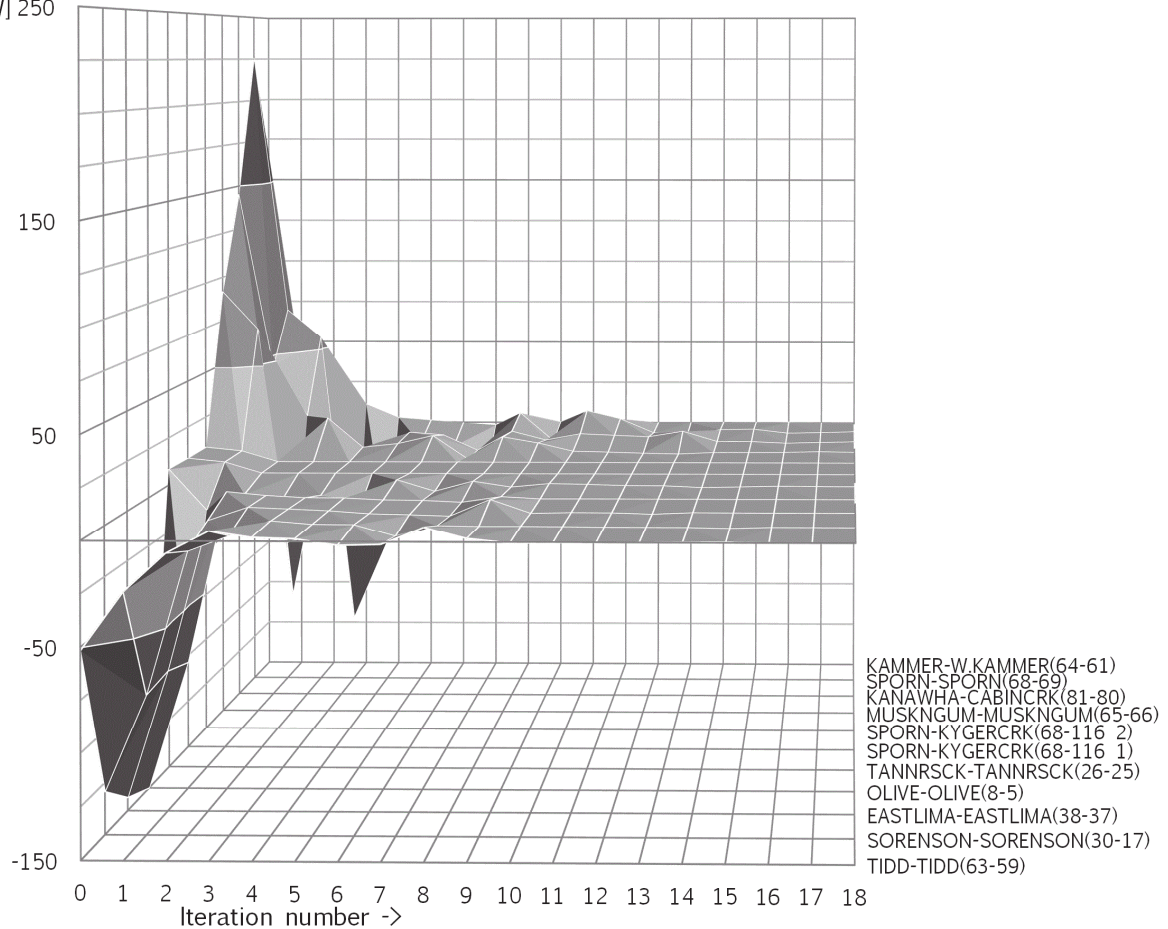Iteration number ->

Fig. 3.4. The deviations of the values of the controlled parameters from the target values as the function of iteration number.

The obtaining of the desired result is guaranteed with a given degree of accuracy in the case of the successful iterative process on selection of the initial data for a given result, so additional verification of the obtained values is not required in this case. On the other hand, the unsuccessful iterative process of power flow change can only be used in certain cases. The problem of determining the critical regime with the static stability limit [57] for power transfer via the group of parallel transmission lines between the two power systems can be mentioned as an example of use of unsuccessful iterative process. In order to solve this task, the original power flow regime should be selected so that the interconnection lines were loaded more heavily than the rest of the interconnected power system.

Let us assume that the trajectory for obtaining the target result is chosen so that the generators in one part of grid are loaded by active power until the predefined value of intersystem flow is reached; consequently, other generators of the power system will be unloaded. In this case the expected active power flow on the intersystem lines will grow and may exceed the maximum possible value on static stability criterion. If the regime with the specified value of intersystem active power flow is reachable, the program will get it. If the predefined value is not feasible, then the regime will be not possible to reach. The program will receive a regime, which will be restricted by the static stability limit in this case.

Automatic process of selection the initial data for obtaining a given result is an important feature that is explicitly or implicitly used in most industrial power flow calculation programs.

The characteristic feature of the implementation of the functions in MUSTANG program is that the power flow calculation algorithm is not changed to achieve the result. Thus, the method ensures high reliability of results. The disadvantage of this method is that it requires tens of consecutive power flow calculations in order to achieve the result in some cases. It should be noted that the calculations are carried out automatically, and it drastically reduces the total time of the regime preparation on the mathematical model of the power system for further use, while minimising engineering work. Automatic selection function of initial data for a given result, generally speaking, could also be applied if the result were given in implicit form. As an example, there is a problem of minimising the losses in the power system when changing the active power generators of some power plants. The value of minimum losses is not known in advance. At the same time, the used algorithm is designed to find a certain value. Consequently, the desired result has to change dynamically and a criterion of success of the iterative process has to be modified. At this stage of the program development, the task of selection of initial data by the desired result is still waiting for solution, if the result is given in implicit form.
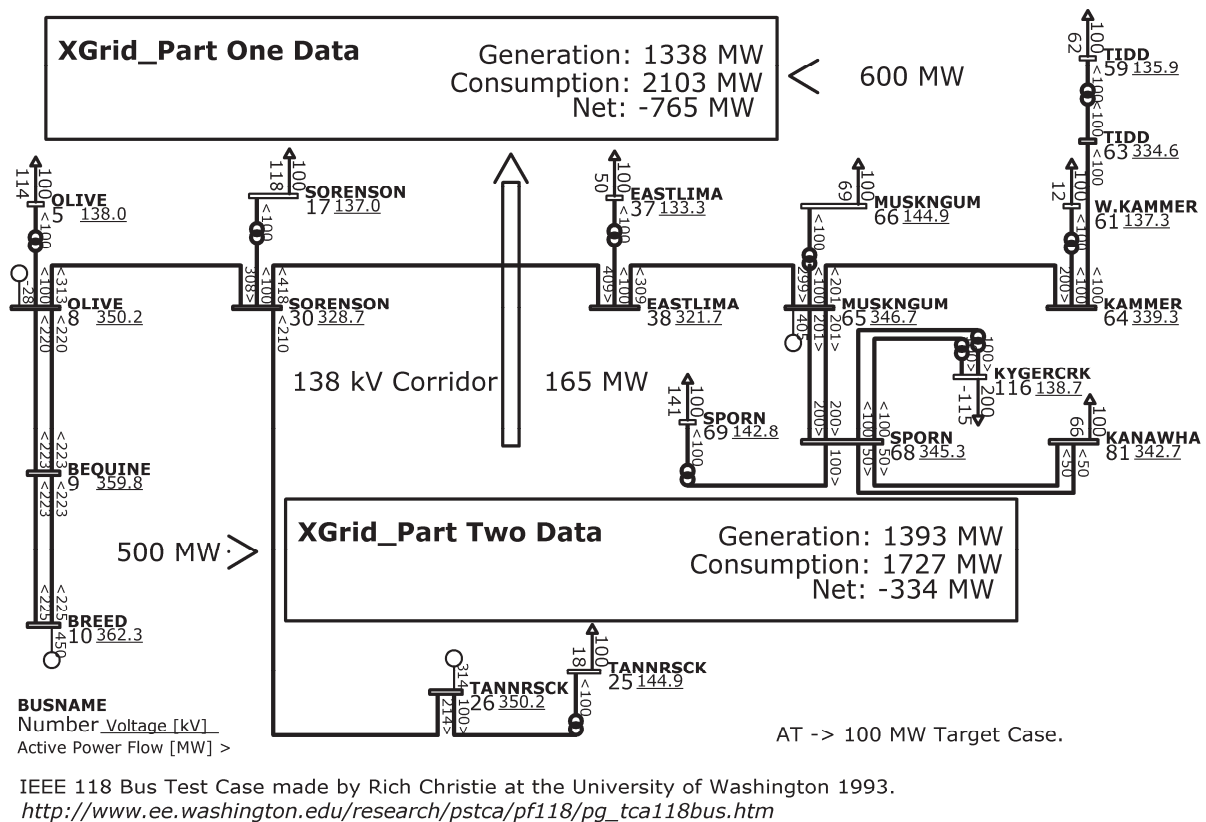
XGrid_Part One Data
Generation: 1338 MW
Consumption: 2103 MW
Net: -765 MW
< 600 MW

OLIVE 5 138.0
SORENSON 17 137.0
EASTLIMA 37 133.3
MUSKNGUM 66 144.9
TIDD 59 135.9
TIDD 63 334.6
W.KAMMER 61 137.3

OLIVE 8 350.2
SORENSON 30 328.7
EASTLIMA 38 321.7
MUSKNGUM 65 346.7
KAMMER 64 339.3

138 kV Corridor   165 MW

KYGERCRK 116 138.7

SPORN 69 142.8
SPORN 68 345.3
KANAWHA 81 342.7

BEQUINE 9 359.8

XGrid_Part Two Data
Generation: 1393 MW
Consumption: 1727 MW
Net: -334 MW

500 MW >

BREED 10 362.3

TANNRSCK 26 350.2
TANNRSCK 25 144.9

BUSNAME
Number Voltage [kV]
Active Power Flow [MW] >

AT -> 100 MW Target Case.

IEEE 118 Bus Test Case made by Rich Christie at the University of Washington 1993.
http://www.ee.washington.edu/research/pstca/pf118/pg_tca118bus.htm

Fig. 3.5. Target regime with flows of active power equal to 100.0 MW ± 0.1 MW via each 345/138 kV autotransformer.

The Influence of Methods Organising the Process of Power Flow Calculations for Multi-Variant Tasks on the Overall Speed of Result Acquisition

When solving tasks such as operational planning of the regimes in the interconnected power system, determining the best options for the development of the power system, analysing the impact of the emergency equipment failures on the parameters of regime in the power system, the engineer has to perform multi-variant power flow calculations on the same power system model. At present, almost all of these problems are solved sequentially, i.e., each variant of regime is calculated separately, and then it can be compared with other options. At the same time, the modern development of computer technology allows the user to create sufficiently

large power system models and gives the opportunity to solve many relevant variants of calculations simultaneously within the same power system model as isolated independent parts. In fact, the parallel execution of calculations requires more RAM, but if the computer resources for the task are not limited, the engineer may be interested in the question that will give a faster result for multi-variant problem, the sequential calculation of all the options or the method of parallel calculation of all the variants simultaneously. The answer to this question depends on the method [34], [35], [37], [113] of calculation and also depends on the power flow calculation program because some power flow calculation programs are optimised algorithmically for sequential calculations [46], [49] and a few programs are optimised algorithmically for parallel calculations [82], [142]. The Newton-Raphson method in combination with the Gauss method of solving a system of linear equations, which are used in MUSTANG program, can be considered the most widespread methods in power flow calculation programs.

The computational experiment was made in order to study this problem. The calculations of steady regimes on MUSTANG program were carried out on a computer with Windows 7 32-bit Operating System with Intel® Core™ 2 Quad CPU Q9450 2.67 GHz with usable 3.48 GB RAM 500 GB 7200 RPM HDD. The program uses only one CPU process for calculations. The IEEE 118 bus system model which can be freely downloaded from Internet webpages [192], [193] has been taken as a sample power system model for power flow analysis. The model has been solved with a flat start for three iterations.

In order to determine the time of the calculation of the power flow, the macro module was written in Microsoft Excel VBA that had to create the file with the task for MUSTANG on hard disk, then the file had to be renamed into the input file for the calculation program and from that moment the time count would begin. MUSTANG program had to execute sequentially the chain of power flow calculations by the Newton-Raphson method with flat start. When calculations ended, the program had to produce the output file with size of 9 bytes of the report, which had to be read by macro module. Once the report file was detected on the disc, the countdown had to be stopped. Three to five attempts were made to determine the average time of calculation. The computational experiment had to be started from the original model. For further steps the volume of the model had to be increased four times by twice doubling of the model data and all the computing process had to be repeated for a new model. The biggest power system model for this experiment contained 4096 independent islands for 118 buses and 212 branches each.

The results of the computational experiment are given in Table 3.4.

As Table 3.4 shows, the impact of the model size of power system on the overall speed of the computing process is well approximated by an exponential function with the exponential factor of 1.075. The total time of the parallel calculation of many variants is always greater than the total time of successive calculations of the same variants. In the case of the four variants, the slowdown will be about 9 %, in the case of 30 variants the process will slow down by about 29 %. Thus, the parallel calculations of many options within a single power system model can only be applied in the case of small network models when the total calculation time is not the main factor. Serial calculation of many options in every respect seems to be the best solution as compared to the parallel calculation.
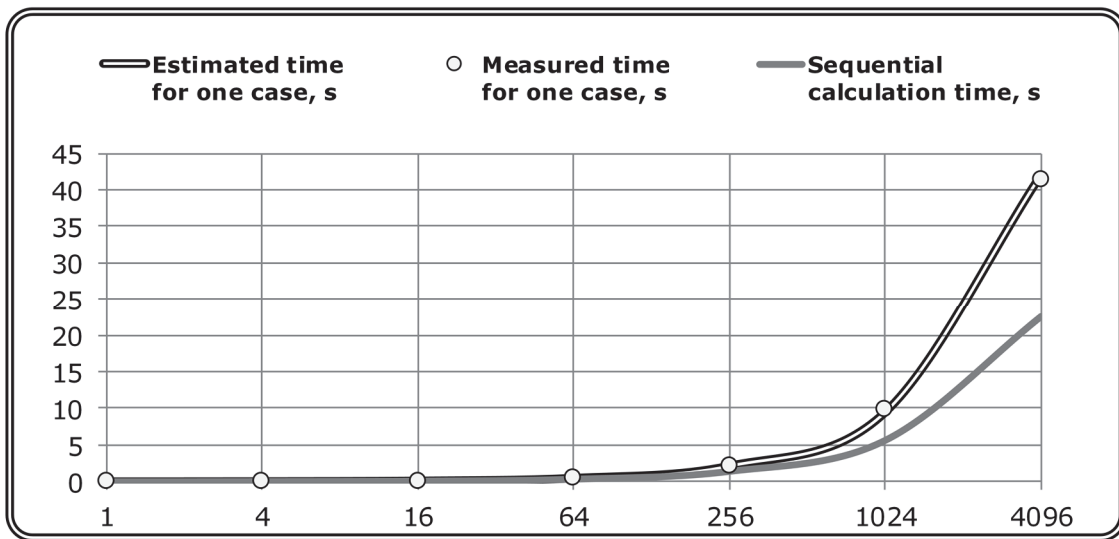
It should be noted that in the computer systems that employ multi-threaded processors, time saving can be achieved by applying a serial-parallel method of organisation of the power flow calculation process for multi-variant tasks. On the same computer, the real task was carried out by four copies of MUSTANG programs simultaneously. Then each copy consistently fulfilled quarter of all calculations for multi-variant task. After this procedure, the same number of computations was performed by two copies of the program and also was performed by one copy of the program. Total time of the job included not only the calculation but also multiple read and write information on a single hard disk. Working with the disk, in the case of a single

copy of the program amounted to approximately 20 % of time and did not change when running multiple copies. If we take the time to perform calculations of one copy of the program as a base, then with two copies of the program, the calculations were carried out about 1.7 times faster. In case with four copies of the program, the calculations were made about 2.5 times faster. If we compare the execution time of calculations for two and four copies of the program, the process with the four copies was made about 1.4 times faster.

Table 3.4

Parallel Calculations of Variants in Multivariant Calculations Tasks

IEEE118·n in parallel	Buses	Branches	Measured time for one case t/i, s	Chain of calculations i	Estimated time for one case $T \cdot n = (n \cdot t_1)^{1.075}$, s	Relative error, %
1	118	212	0.0055	10000	0.0055	0.00 %
4	472	848	0.024	10000	0.024	0.00 %
16	1888	3392	0.105	1000	0.108	−2.78 %
64	7552	13568	0.456	1000	0.481	−5.20 %
256	30208	54272	2.186	100	2.134	2.44 %
1024	120832	217088	9.759	100	9.472	3.03 %
4096	483328	868352	41.487	100	42.039	−1.31 %

Based on these results, we can see that multi-processor win in productivity will decrease at higher computer loading. Therefore, increasing the number of streams used for parallel computing n times does not allow the resultant to increase in productivity n times, despite the fact that the calculations themselves indeed are accelerated about n times. However, if even the acceleration of the implementation of calculations is 40 %, this is a very good indicator and can be recommended for use in practical applications. All of the above-mentioned considerations relate to the calculation programs, if they use only one CPU process for computation. If the program is already based on multi-processor computer systems, win in productivity will not be so effective in this case.

4. THE USE OF THE POWER FLOW CALCULATION PROGRAM FOR TRAINING DISPATCHERS OF THE TRANSMISSION SYSTEM OPERATOR

The Data Exchange for the DTS and Handling of the Information across Different Data Spaces

If the other programs can use the load flow calculation on a mathematical model of power system as the implicit function, the programs can solve other problems beyond the load flow study. Hence, the scope of use of the program for power flow calculations can be significantly extended without changing the program itself. It is clear that if one program controls the other program, the table editor and a GUI program, which was made for the engineer, are not needed. The controlled program can be operated in the black box mode. Moreover, most of operations, which used the hard drive during normal operation of the program, can be made in the computer's memory. Therefore, only the resulting values of monitored parameters can be recorded to hard disk. The productivity result in this mode will be significantly higher. The practical example of the use of the power flow calculation program is the experience of its operation in the dispatcher training simulator (DTS/OTS) AST.

The world has a lot of experience in the creation of DTS/OTS systems [54], [108], [106], [112], [120], [123], which differ both by the type of calculation program and by the location relative to the SCADA system. Simple DTS systems [60] tend to use the power flow calculation programs. More complex DTS mostly use the calculation programs for electromechanical transient stability [120]. The calculations of electromechanical transients are used where the sampling period of the incoming information is equal to a fraction of a second, which is typical, for instance, for the power plant operator. Dispatcher of power transmission system does not receive the data so often. Therefore, the dispatcher can see only the consequences of the fault, for example, the fact of disconnection of power lines. Usage of power flow calculation program for dispatcher training in power transmission system seems to be more practical in terms of implementation solution. DTS systems usually work inside the SCADA systems. This typical approach has obvious advantages and hidden disadvantages. The process of creating DTS in SCADA system can be described as complex and time consuming, but the main problem lies in the restricted mobility of DTS, if it runs inside the SCADA system. TSOs are interested in the fact that DTS are less dependent on the SCADA system. These DTS systems also exist in the world. For example, well-known ARISTO DTS system developed with the participation of Swenska Kraftnät (Swedish TSO) does not depend on the main SCADA system. The task for AST is to provide a reasonable accuracy in power system simulation for DTS with the minimum complexity of the DTS system itself.

SCADA XA21 system from General Electric allows developing and integrating the customer's own programs to the main SCADA system in order to increase the SCADA abilities and meet each customer's requirements. This very positive feature made it possible to develop many useful programs in AST. One of the programs developed by M. Korshunov is able to get the original displays from the SCADA system and show the real time data, or historical data, or formatted text data for SCADA users in a local network (LAN) outside the SCADA system. This program, let us name it as the display-emulator, also has a built-in command interpreter that can read the measurement and the signals from batch files to the displays. Moreover, the program records the actions for the change in the measurement values and for the changes in the position of signals produced by man via displays into other batch files. Thus, the program can simulate the control of remote object by the dispatcher. During the program operation, the solution was found by the author of the research. If the actions performed on the displays can be transferred to the power flow calculation program in order to calculate the new regime and return the results to the displays, it turns out that the engineer can control the power system model and see how his actions affect the regime of the modelled power system. For the

implementation and further development of this idea, the computer program was developed. This program is responsible for interaction of the emulator program with the power flow calculation program, as well as for additional control of the power flow calculation program in order to reflect the changes in the power system regime, which occur independently of the dispatcher. Let us name this computer program the program-manager.

The program-manager has the three main functions. The first one is the reading and the writing of batch files in formats of program-emulator and of the power flow calculation program (it tends to work in black box mode for DTS) in accordance with the cross-reference table (X-reference). The second function is calculation of various quantities in "real time". The third function is sending the changes in the control parameters of power system regime to a black box and to the program-emulator. Changes in the control parameters can occur on a predetermined schedule, or on the program-emulator command, or in accordance with the internal clock of program-manager, or on command of program-manager, simulating emergency changes on the results of the calculations of the quantities in "real time", or on command from the outside world, if the command syntax is recognised by program-recipient. Let us explain how it works in more detail.

The space of mathematical model of the power system, which is operated by the power flow calculation program in black-box mode, significantly differs from the projection of a real power system on the SCADA system. The data space of the SCADA system at every given time is a set of values of different physical nature, which we call points, with indication of the quality of its measurement for each value. For the data acquisition convenience, the multiplicity of points can be divided into various classes, such as the analogue points, the status points, the accumulator points, etc. Nevertheless, all points are values of something. Each point is restricted in advance by a certain range for it. The resulting values of the monitored parameters, derived by the black-box program every time, form a set of points too. However, it can be found that there is the corresponding point from the SCADA data space for many of the resulting values of power flow calculation. X-reference table is used to determine the relationship of the elements of the model data space with the SCADA data space.

Let us assume that a – the n-dimensional column vector from the model space of "black box" program and b – the corresponding n-dimensional column vector from the SCADA data space. Then the coordinate system transforms can be done according to (4.1) and (4.2).

$$b = Da; \tag{4.1}$$
$$a = D^{-1}b; \tag{4.2}$$

where D is $n \times n$ diagonal matrix with all d_{ii} elements, which are predetermined constant rational numbers in our case.

This mapping allows setting the corresponding value in "black box" program model or in SCADA data space, if only one of the two relevant values of variable is given. The d_{ii} coefficients are needed in order to bring different values into the same scale. For example, the phase voltage is measured in the SCADA system and the linear voltage is calculated in the "black box" program; therefore, $b_i = 0.69336127435a_i$.

The cross-reference tables are used in the majority of SCADA systems, but they do not allow obtaining integral values or the sum of several measured values of real power system. To do this operation, the calculation in real time (RTC) module is used by SCADA, which is applied also inside the program-manager. Typically, each y value calculated in the RTC module has its own function from the measured data. It can be expressed as (4.3).

$$y = F(y_{t=0}, y_{t=dt}, x_1, \ldots, x_n, t/dt), \tag{4.3}$$

where $y_{t=0}, y_{t=dt}$ – the initial and final value of y;

$x_1,…, x_n$ – other values and constants; t/dt – the relative time on the basis of the calculation execution time dt.

Each RTC function has its own lifetime from null for simple formula to infinity for continuous functions. The execution of function starts on the start trigger of calculation, which is associated with some change in the data, and continues till dt, or stops by the trigger for the end of the calculation. The y value is changing by a specific law on the interval of lifetime. Calculations are carried out for an expanded plurality of elements of the SCADA points. This means that the special intermediate points, which are not transferred to the emulator program, can be among the elements. For instance, the points of load schedules, which are set in the program-manager, can be transferred to a black box according to the internal clock of the program. The schedules of generations, consumptions and states of the network elements in the DTS AST are set for a 24-hour period with a minute step.

Figure 4.1 shows the simplified model of the data exchange between the program-emulator and the black box program during the organisation of the mutual interaction by the program-manager. The values in the batch file format of black box are indicated by black arrows, the values in the batch file format of the emulator-program are marked by tintless arrows. All three programs, as well as the user programs participate in the data exchange. The DTS system in the AST is working according to Fig. 4.1.
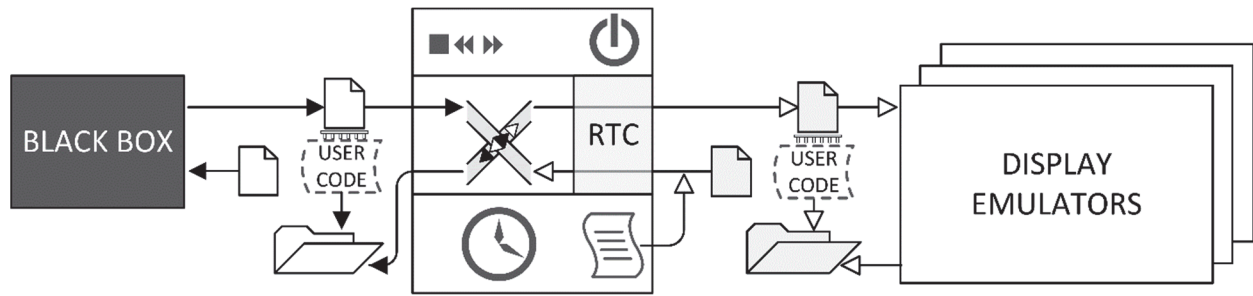

Fig. 4.1. The data exchange and handling loop in DTS AST (outline drawing).

The frequency of the data update could be set in the program-manager. In the case of AST, it is typically two seconds. The model of interconnected power system currently has more than 4000 buses, many of which are the whole substations; many are only the busbar sections. Given the nature of the modeling of branches in MUSTANG program, this type of model can be called by the natural combined model because both bus-branch and node-breaker models [19], [139] have been constructed based on the same modeling approach in MUSTANG.

Problem of metering of frequency at substations in the simulation of large disturbances, blackouts and during the system restoration appeared after several practical dispatcher trainings, i.e., the program for the power-flow calculation in steady-state normally does not simulate the frequency of the power system. One of the objectives of the Thesis has been to solve the problem of estimating the frequency of points inside the interconnected power system for DTS AST. The proposed solution of this problem is given in the next section.

Determining the Frequency of Alternating Current at the Controlled Buses in DTS by Using the Advanced Features of Power-Flow Calculation Program

There are different approaches to predict the power system frequency response after faults: dynamic calculation [107], [159], [161], [162], statistical approach [73] using filters [140] or neural nets [55], [149] or special programs [109], and steady-state power flow calculation. A power system model for calculating a steady-state power flow has to comprise at least one swing bus, which is usually of the $U\delta$ type. If the total generation at the buses does not correspond to the total consumption of the power system, the whole imbalance concentrates in the swing buses. Still a swing bus is a mathematical abstraction. In a real-life power system,

generation always corresponds to consumption. To make swing buses not distort the distribution of power flows in the part of the interconnected power system under discussion, there are ways that are used to compensate for the influence of the swing buses on the regime. The first way is to displace the swing bus outside the region under consideration. According to the second way, the total imbalance is distributed among a group of *PU* buses (distributed slack). Here, the alternating current frequency regulation by the power plant generators in the power system is approximately reflected. The variable frequency can also be included in power flow algorithm [67] directly. None of these methods provide us with a description of the AC frequency changing process under the influence of emergency imbalances, but they only give the result of the power flow distribution after the completion of the frequency-changing process.

Within the black box program, an algorithm for automatically detecting islands is in place; the term "island" is attributed to groups of buses joined by energized branches if there are no swing buses among them. These groups are entered into dynamically created folders within the directory tree. Further, for each island a new swing bus is dynamically appointed in the largest *PU* bus of the group. If no *PU* type buses remain in the group, the whole island is extinguished and the generation capacity of the buses becomes zero. Considering the above-mentioned peculiarity of the modeling of logical states of branches, in the black box program it is possible to subsequently introduce the utilisation equipment of the island, retaining the network configuration that has been in place before the outage. However, this algorithm changes the capacity of the largest power plant of the island and does not determine the frequency in the singled-out region.

Let us suppose that the nominal alternating current frequency is maintained in an interconnected power system. How will the system react to a sudden trip of one generator if no changes occur in the load mix of the system and none of the capacities of the remaining generators change? The trip of the generator will lead to a gradual decrease of the rotation frequency of all the generators and most electric motors of the power system. Initially, the frequency will be inhibited by the inertia of the rotating masses [148], but as the kinetic energy reserve is depleted, the system will arrive at a new state of equilibrium – a steady-state regime with diminished frequency. The electric capacity of the remaining generators will change little since, firstly, the turbines of power plants have a more robust mechanical characteristic as compared to the common load, secondly, electric motors have a lower electromechanical time constant as compared to generators, and thus they react to a frequency decrease faster. Consequently, to determine frequency in DTS, it can be assumed that the imbalance caused by the disconnection of the generator will diminish the total load of the interconnected power system, which will afterwards be restored due to changes in the generation amount of the power plants. If the algorithm for automatic detection of islands is changed in such a way that the program maintains the specified capacity of the $U\delta$ type bus due to the changes in the initial loads of the island in the model of the interconnected power system, then the ratio of the calculated initial load and the specified initial load of any of the buses of the model may become an indicator of the frequency change tendency in that bus. It is also obvious that if the values calculated by (4.4) are different for two buses of the network model, these buses belong to different islands.

$$K_{fi} = P_{\text{load\_0\_calc}\_i} / P_{\text{load\_0\_fnom}\_i}, \tag{4.4}$$

where, $P_{\text{load\_0\_calc}\_i}$ – the current base load at bus i (obtained after the last calculation); $P_{\text{load\_0\_fnom}\_i}$ – the initial base load at bus i (set before the last calculation); K_{fi} – the factor of relative local active power change due to the frequency deviation.

In fact, the black box program can solve power-flow problem without infinite buses specified by the user. The program is supporting a given active power generation by changing the initial loads across each interconnected subsystem in this case. K_{fi} is always equal to one, if

the load is absent at the bus or if the load is connected to the infinite bus specified by the user. In order to get K_{fi}, the load with some positive active power should be set at the controlled bus.

The black box program ensures calculation of the steady-state regime of the power system. It is assumed that the duration of the regime is not limited. Alternating current frequency is a parameter that is changeable over time. Therefore, in order to determine the frequency value, it is necessary to know the value of time. Of all the programs that make up the DTS of the Latvian TSO operator, only the manager-program has the time variable. Besides, the manager-program can use frequency as the argument of an RTC function. In the author's opinion, determining alternating current frequency in a bus by means of the functions of the manager-program is a logical solution.

Let us designate the frequency which the alternating current frequency in a bus approaches if there is no reaction to the perturbation, as F_{1i} ; in such case, F_{1i} can be calculated as follows (4.5):

$$F_{1i} = F_{\text{nom}} \cdot |K_{fi}|^{\gamma}, \tag{4.5}$$

where F_{nom} – the rated frequency [Hz] and γ – the exponential factor that shows how load depends on frequency.

In order to determine the current value of frequency in bus i F_{2i} on the basis of F_{1i} and the current value of frequency in the previous step F_{2i0}, an RTC function with an unlimited performance time of the form (4.6) was input into the manager-program according to [164]:

$$F_{2i} = F_{1i} + (F_{2i0} - F_{1i})e^{-dt/T_f}, \tag{4.6}$$

where dt – time from the last formula calculation, s, and T_f – time constant for frequency change, s.

The exponential factor in formula (4.6) is convenient when performing practical calculations in the DTS system since it functions over the whole frequency range. At the first approximation T_f can be assumed to be constant and equal to about 4 s to 8 s. However, T_f should depend on K_{fi}. According to [163], frequency decreases faster than rises in most practical cases. This is due to large synchronous machines in comparison with typical load of relatively large mechanical inertia constants. On the other hand, the black box program should have completed at least two cycles of calculation during T_f so that it would be possible to simulate the processes associated with the frequency change with the required sampling. Note that T_f and γ should be common for all buses in the model that can work synchronously.

The obtained current values of alternating current F_2 at the buses according to (4.6) and, directly, K_f could also be used as input signals for system-level automation models, for example, Under Frequency Load Shedding [18], [22], [24], [171], Automatic Generation Control [173], etc. Still the simulation of fast-acting automation devices of the power system cannot be precise in DTS systems on the basis of programs for calculating steady-state regimes and is possible only by some simplified and generalised characteristics. It has to be noted that such simplified simulation practically does not affect the realism of DTS systems for the transmission grid operators. Practice shows that the proposed methodology for evaluating the frequency of buses makes the process of system restoration after a complete blackout sufficiently realistic from the point of view of the dispatcher.

5. EVALUATION OF ACTIVE POWER INCREMENTS BASED ON A BALANCED EQUIPOTENTIAL GRID MODEL

The Analysis of the Influence of the Simplification of the Calculation Model on the Simulation Quality

The transmission system operator, under normal circumstances, works inside the interconnected power system and controls the regime of a small part of a large system. The size

of the external part of interconnected power system generally exceeds the size of the internal operational area of a single TSO. In fact, the main data volume about the parameters of the power system comes from the internal operational area. The external area of the interconnected power system tends to be less observable [50], [133]. The operator of the transmission system, in general, cannot ignore the impact of other participants working in parallel [96]. Hence, the calculated model of the power system should include the external part of the network.

The analysis of the current regimes of the power system is made difficult for TSOs by the fact that TSOs do not have detailed operational information about other power systems of the interconnected power system. Therefore, one small TSO cannot maintain a detailed model of the interconnected power system. This task is usually addressed using one of the two methods. According to the first method, the external part of the network is to be substituted by an electrical equivalent: Ward [25], [88], [141], [147] (Norton) [17] Equivalent Circuits, Dimo REI (Radial Equivalent Injections) method [131], [174] or other techniques [85], [118], [126], [128], [130], [134], [144], [150], [180]. This method is more frequently chosen in the case of minimum amount of operational information about the external network. As the external network is substituted by an equivalent [41], the TSO can analyse only the regimes of its own power system. The second method consists in the scaling of an external network that is represented to a full extent. For the both modeling methods, a problem is posed by the impossibility to monitor the quality of the regime of the external network. The disadvantage of equivalent models is that it is impossible to find out how disconnections of lines in the external part of the network influence the regime in the area under investigation.

Balanced Equipotential Grid Model as the Open Circuit Method
for Simplification of the Calculation Model

In order to ensure the power system reliability, TSO should be ready for any single fault in the power system every time. As the contemporary interconnected power system has strong boundaries, fault in the neighbouring power system may affect the TSO regime greatly. TSO should be able to analyse not only faults inside the control area, but also faults in the bulk transmission system outside the control area. It is necessary to study the potential problems or contingencies before the real event occurs. The contingency analysis is the real field of study of the power flow regime in the power system for many years [86], [87], [90], [99], [110], [114], [116], [121], [127], [143].

The present study proposes one more method for the external network in the analysis of the regimes of a power system. This method simplifies the model data rather than the calculation model itself. The simplification of the calculation model, or DC Power Flow [36], needs faster results and was analysed in [70] and [97]. The simplification of calculation sequence [84] and contingency selection based on ranking [93], [100], [117], [125], [129] also give faster results with a typical calculation model. Sometimes better results can be obtained without simplification [124]. The proposed method can be used both independently and as a supplement to the above-mentioned methods. According to this method, changes in the external part of the network are specified at the scale of 1 : 1, which will be called perturbations. Afterwards, a special model is used to calculate the changes that may occur in the remaining part of the network in the case of the specified disturbances. The calculated changes are added to the corresponding values of the controlled parameters of the regime. The initial regime of the special calculation model does not change as the regime of the interconnected power system changes. In this way, the lack of information about the external network in the course of the analysis of the current regimes is compensated. The method yields well to automation and this makes it suitable for using in the simplified analysis of incidents in the internal network of the TSO.

The analysis of possible emergencies on the basis of the estimated actual regime can warn the dispatcher about a potential problem, but is not intended to provide practical assistance

to the dispatcher during the elimination of accidents. For this reason, the accidents in the power system are eliminated by dispatchers in manual mode without the help of computer programs. Application of automation system allows accelerating the process of liquidation of failures greatly, thereby improving the reliability of electricity supply to consumers. However, reliable identification of the control actions is required for any automation.

The proposed method for analysing possible emergency situations without state estimation is simpler and at the same time more reliable. The simplicity of the method consists in the fact that the initial regime for analysis depends only on the topology of the network [75], [98]. The numerical values of the regime parameters can be assumed directly on the basis of the telemetric information and the numerical values of the perturbations can be obtained, for example, by forecasting. The reliability of obtaining the calculation results is ensured by the fact that the method allows scaling emergency perturbations. The acceptable accuracy degree of the method makes it possible to automate the process of distributing active power generation in the case of emergency. The automation of the process of eliminating emergency situations in the power system facilitates the work of the dispatcher.

The method does not require the use of an estimated regime as the initial regime. Instead, it is proposed to use a regime with zero flows of active and reactive power in each of the branches of the calculation model of the power system. $N-i$ emergency changes are superimposed on the initial mode (here i – a freely chosen natural number) simultaneously. The generator to be disconnected is replaced by one equivalent load in the connection bus, of equal size to the generated active and reactive power before the emergency. In the same way, with an opposite sign, simulation of a generator's switching on or a load's switching off is done. The power transmission line to be disconnected in the model is disconnected and replaced by two equivalent loads in connection buses: a negative one is equal to minus the initial power flow at the transmitting end of the line, and a positive one is equal to minus the initial power flow at the receiving end of the line. The task of involving a power transmission line is not solved in this way because the transient process is important rather than the steady-state value of current or power.

As $N-i$ emergency changes are superimposed onto an equipotential grid, the model's regime departs from equilibrium. Calculation of the regime is performed, resulting in a set consisting of the deviations of the regime's parameters from the initial values. As the initial values, the measured values of power, current or voltage can be assumed. The calculated values of the regime parameters received for the equipotential grid as well as the emergency injections applied to the elements are added to the initial values. For example, the active power flow in a branch is added to the actually measured value of power via the monitored power transmission line. If this is a branch that is to be disconnected, the sum of the measured value and the applied emergency injection will be equal to zero. As a result, we obtain the values of the regime controlled parameters that are to be expected after emergencies $N-i$. In this way, calculation according to the equipotential grid provides an evaluation of the influence of emergency $N-i$ on all the elements of the network model.

An assumption has been made for analysing potential emergency situations: changes in the regime of a power system in the case of emergency depend only on the changes of the initial injections determined by the faulty elements of the system into the buses of the calculation model as well as on the initial configuration of the network. Such an assumption presupposes that the superposition principle [29], [43], [66] is in force in the power system. For a non-linear system this is, strictly speaking, not true.

A balanced equipotential grid is needed to obtain an initial regime for further calculations. Such an initial model can be constructed from the model of an interconnected power system where the backbone electrical network is represented to the fullest extent possible. The power system regime for obtaining the equipotential grid may be whatsoever. Equipotential grids already find application in some regime calculation tasks, yet investigations of this kind of circuits have not been encountered in research literature. The process of creating

equipotential grids, notwithstanding its simplicity, is not obvious. Since any computational experiment has to be reproducible to other researchers, the author of the Doctoral Thesis will now provide the algorithm for creating a balanced equipotential grid model step by step. The sequence of a balanced equipotential grid model creation is shown in Fig. 5.1.

The first step implies that all sources of reactive power are used to maintain the voltage at the network across the model, that is, all generators, except the infinite bus or $U\delta$-bus are transferred from the *PU* control mode into *PQ* mode. The correction of available range for reactive power control should also be made by shifting the upper and lower limits of the actual reactive power generated by the compensation device in the initial case.

In the second step, all the network injections are excluded from the model. The power generations and loads, shunts at buses, charging of lines and magnetising admittances of transformers should be deleted at all the buses and branches in the model.

In the third step, all the ratios of transformer tap changers are normalised. This means that all the rotations of angles for voltage phases should be set to zero, and the modules of transformation coefficients should be set to be relatively equal to each other. The ratios of tap changers for transformers feeding the radial networks do not affect the distribution of power flows in the case of equipotential grid model. However, to minimise errors it is proposed to take all the coefficients equal to one in per unit systems. Then in the named units the transformation ratios will be equal to the relation of voltages, i.e., nominal voltage at high side divided by nominal voltage at low side of grids connected with the transformer.
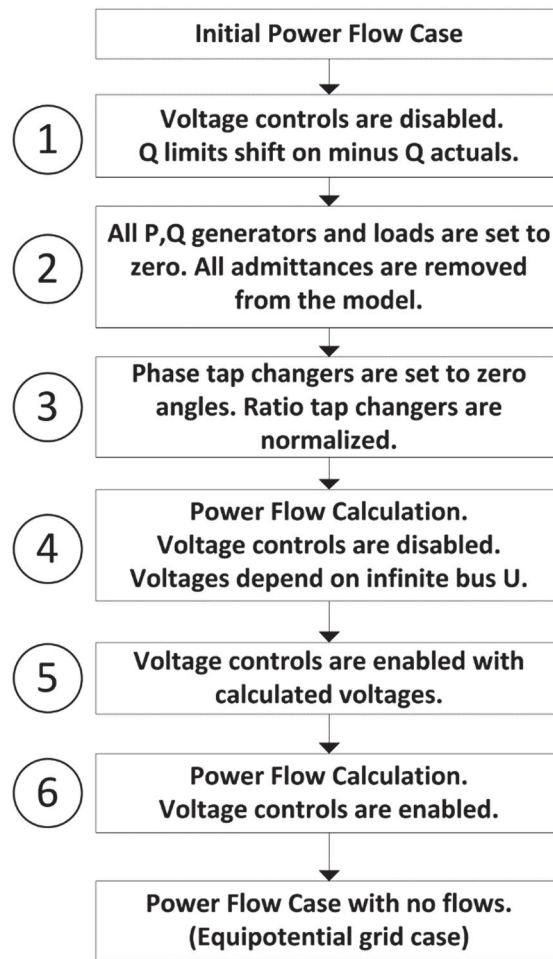

Fig. 5.1. Equipotential grid model creation step by step.

In the fourth step, the controlling power-flow calculation on the model is made. If all the transformations on the model have been performed correctly, the infinite bus, regardless of the initial voltage, there would be zero generating both active and reactive power. In addition, the voltage at all buses of each class of voltage should be equal to each other, and the active and reactive power in all branches of the model would become infinitesimals. The power-flows for any branches may not be exactly equal to zero, if, for example, the ratios of transformer tap changers are irrational. Nevertheless, we can always provide that the power flows for all branches of the model become infinitesimals.

In the fifth step, all the generators and other reactive power compensation devices, which are able to maintain the voltage at the buses, are reverted to the *PU* mode. Generators as well as reactive power compensation devices should continuously maintain those voltages, which have been obtained in the fourth step. Generators and reactive power compensation devices are necessary in order to bring the reaction to emergency disturbance on the equipotential model to the appropriate response on disturbance, if it is simulated on the original model. The passive model without the units in *PU* mode cannot provide support to the voltage required for the active power transmission over long distances. The active power of each generator should be zero. The reactive power range of each generator should be such that the zero generation of reactive should be within the range, i.e., the minimum limit of reactive power should be negative, and the maximum limit of reactive power should be positive.

In the sixth step, the final power-flow calculation on the model is made. If the voltages of generators are supported as it have been solved in the fourth step of transformation process, all injections at the buses and the power flows through the branches will remain zero in the re-calculated power-flow in this case. Thus, the balanced equipotential grid model is created and ready to work.
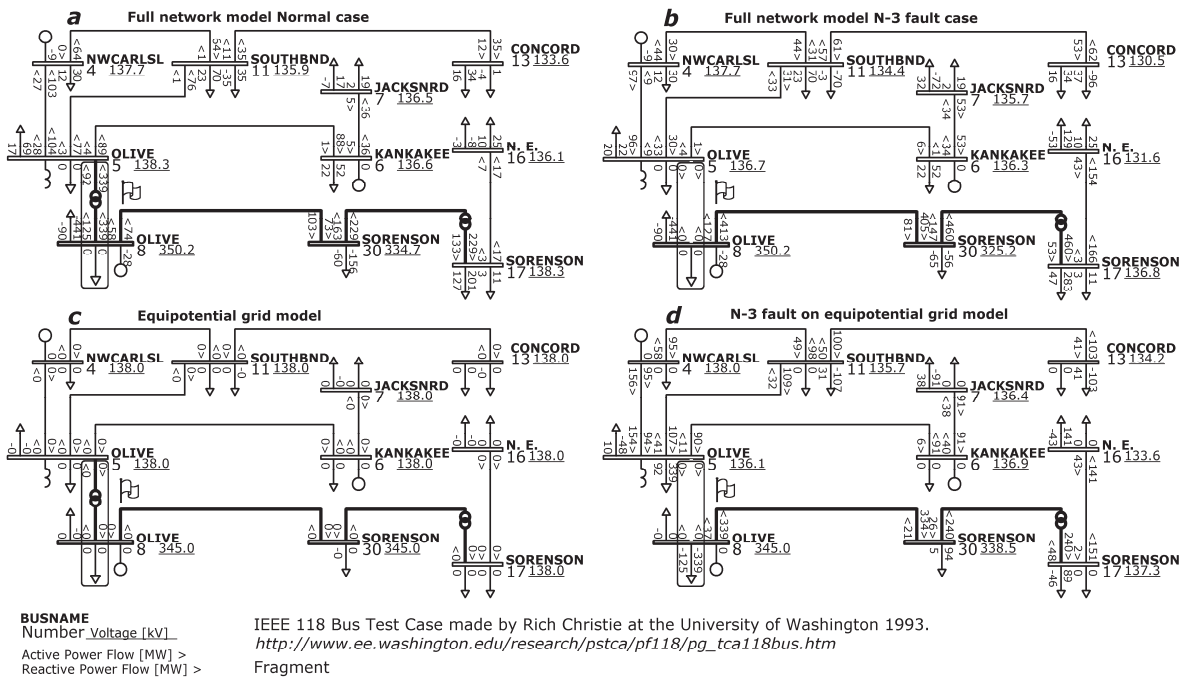
Fig. 5.2. $N - i$ fault study on full model vs superposition study on equipotential grid model.

The equipotential grid model has the following important properties:
- Power flows through the branches do not change when you change the network configuration.
- Voltages at buses remain unchanged as long as the buses are not disconnected from the grid.

For the qualitative result of calculation, it is necessary to know the status of all power transmission lines, transformers and circuit breakers that may affect the operation of the power

system under study. In the analysis of possible emergency situations, it is desirable to have information on the actual or perceived loading of transmission lines and generators, which can be disabled as a result of the fault, as well as the volume of active power reserves and their placement that can be activated in order to eliminate the consequences of the accident. If such information is not available, line loading or generation can be taken like the permanent maximum allowable value or like the planned value or any expected value at a certain interval. Figure 5.2 demonstrates the scheme of the method.

Each part of Fig. 5.2 represents a fragment of the calculation model. Three simultaneous faults of grid elements were modelled. One transformer at substation Olive (bus numbers 8 and 5) is shown with flag on the fragment. The two disconnected 345 kV lines from substation Muskingum (bus number 65) to Kammer (bus number 64) and to Eastlima (bus number 38) are outside the fragment and are not shown in Fig. 5.2. On the left, the initial regimes "a" and "c" are depicted. On the right, the regimes "b" and "d" after the emergency $N-3$ are shown. The calculations in the first row have been made for a full model "a" and "b" and in the second row, for an equipotential grid model "c" and "d". It can be seen that the calculation result for a full model "b" right-hand top can be obtained by adding to the initial regime "a" the deviations of the corresponding parameters obtained by simulating emergency for a balanced equipotential grid model "d" right-hand bottom. For example, the expected active power flow via the 138 kV line from JACKSNRD (bus number 7) to KANKAEE (bus number 6) $P_{1\_76} = -36+91 = 55$ MW (53 MW in the original case). In the practical analysis of the gravity of the emergency (based on the current estimated regime), usually the deviations of the regime parameters from the initial parameters are calculated, i.e., $dP_{1\_76} = 53 - (-36) = 89$ MW. When performing calculations for the equipotential grid model, the values of the active power flow deviations are obtained as a result of regime calculations and no additional calculations are required in this case.

The method has additional errors as compared to a calculation based on a current regime according to the full calculation model of the interconnected power system. Still, in terms of accuracy, the method is halfway between calculation on the basis of a full model and calculation on the basis of PTDF/LODF [80], (Power Transfer Distribution Factors / Line Outage Distribution Factors), which is used in calculations of emergency regimes [83]. It should be noted that this is a good indicator in favour of further research in this area.

Calculation of Emergency $N-3$ in an Equipotential Grid Model and Comparison with the Calculation Results for a Full Grid Model

Figure 5.3 shows the calculation of the initial regime on an equipotential grid model for the test case. In such a diagram, let us calculate the regimes entailing the disconnection of the autotransformer of substation Olive and two 345 kV overhead transmission lines from substation Muskingum to Eastlima and to Kammer for winter and for summer cases and compare them with the corresponding C0 regimes from Table 5.2, which were calculated according to full diagrams for checking the equivalent models.

In order to calculate Winter Case $N-3$ contingency, it is necessary to simulate the following perturbation on an equipotential model:
- AT Olive and two 345 kV overhead lines from substation Muskingum to Eastlima and to Kammer are disconnected;
- 339.11 MW + 91.94 Mvar load is added at bus 5 Olive, 182.73 MW + 66.5 Mvar load is added at bus 64 Kammer, 181.69 MW + 57.5 Mvar load is added at bus 38 Eastlima (load side);
- 339.11 MW + 124.77 Mvar load is deducted at bus 8 Olive, 368.64 MW + 31.72 Mvar load is deducted at bus 65 Muskingum (generation side).

After the calculation, Delta Grid (DG) winter case is obtained. The sum of all the loads is –4.22 MW + 59.45 Mvar for the winter DG case.

In order to calculate Summer Case $N-3$ contingency, let us simulate the following perturbation according to the equipotential grid model:

- AT Olive and two 345 kV overhead lines from substation Muskingum to Eastlima and to Kammer are disconnected;
- 218.91 MW + 100.03 Mvar load is added at bus 5 Olive, 141.54 MW – 47.99 Mvar load is added at bus 65 Muskingum (load side);
- 218.91 MW + 115.43 Mvar load is deducted at bus 8 Olive, 113.05 MW – 89.86 Mvar load is deducted at bus 38 Eastlima, 30.02 MW – 80.76 Mvar load is deducted at bus 64 Kammer (generation side).
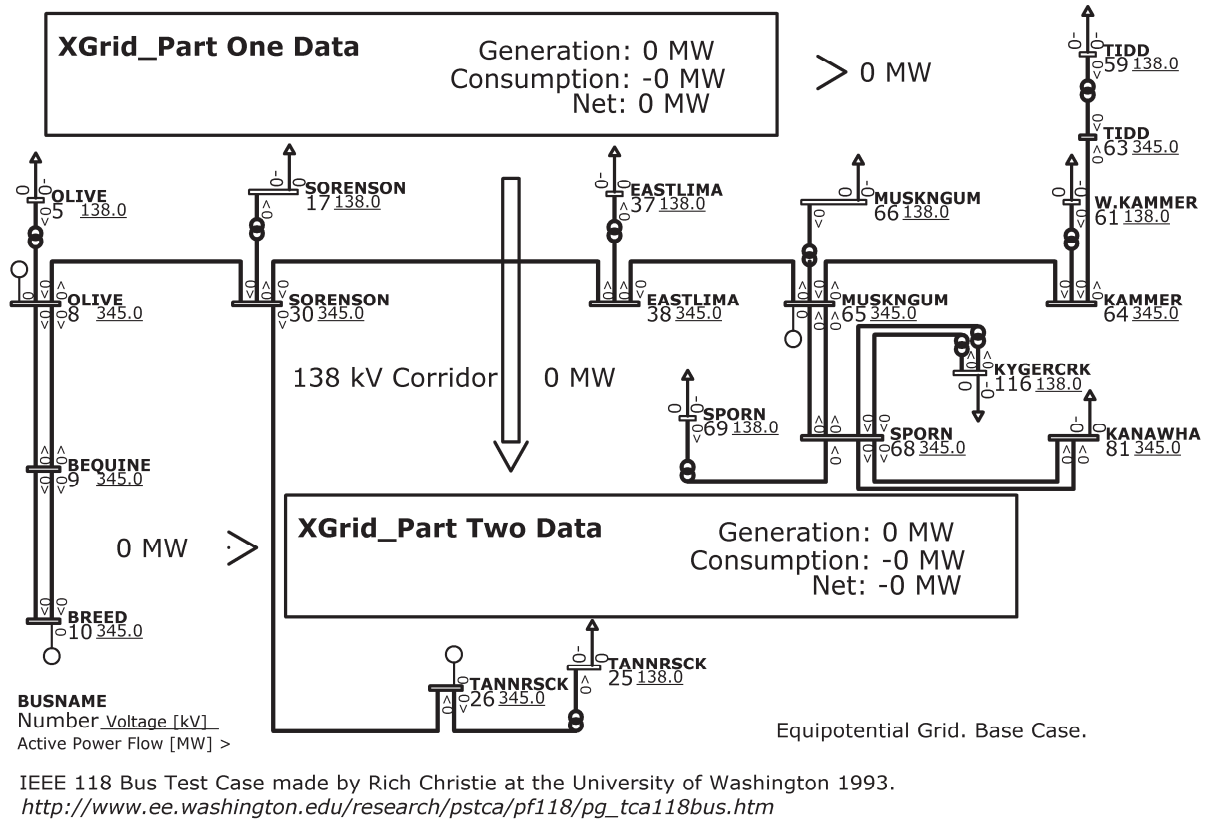
Fig. 5.3. The initial regime on an equipotential grid model for the test case.

After the calculation, Delta Grid (DG) summer case is obtained. The sum of all loads is –1.53 MW + 107.24 Mvar for the summer DG case.

Both winter DG case and summer DG case were scaled in order to investigate the effect of the scaling of the applied perturbations. During scaling, all the injections are diminished ten times and the values of the results obtained from the equipotential regime are afterwards multiplied by 10. In this way, Delta Grid Scaled (DGS) winter and summer cases are obtained. A comparison of a small part of the calculation results is shown in Table 5.2, where DC0 – after fault and pre-fault differences in Full Models, EG – Equipotential Grid, DGC – Difference between Delta Grid Model and Full Model in case of $N-3$ grid faults described above in this chapter.

A graphical comparison of all the bus voltages for the winter case is demonstrated in Fig. 5.4. The difference between a full model and an equipotential grid model in case of $N-3$ grid faults is not so big in relation to deviations caused by grid faults. This can also be seen if we analyse the active power flow differences. A graphical comparison of all the branch active power flows for the winter case is shown in Fig. 5.5

An analysis of the results shows that the initial regime of the interconnected power system influences the changes in the active power flows via the power transmission lines mainly

by how the elements to be disconnected are loaded before emergency. Thus, by using an equipotential grid model, approximately knowing the loading of the network elements under investigation and knowing the configuration of the backbone electrical network, it is possible to make a proper evaluation of how the disconnection of network elements or start-up of generators in the external part of the interconnected power system may influence the active power flows in the internal controlled part. In order to evaluate the possible change of active power flow via a cross-section, it is necessary to consider the initial loading of the emergency-disconnected lines in that cross-section. An example can be provided by the cross-section 345 kV – XGrid_P1, with emergency disconnection of 345/138 kV transformer at substation Olive.

Table 5.2

A Comparison of the Essential Calculation Results for Winter and Summer Cases

Case Title			Winter Case $N-3$					Summer Case $N-3$				
Parameter	Unit	EG	C0	DC0	DG	DGS	DGC	C0	DC0	DG	DGS	DGC
Generation P, Q												
Total by Power Plants	MW	0.0	4375.	136.0	93.6	3.2	−42.4	2500.	21.7	25.7	1.1	4.0
Total by Power Plants	Mvar	0.0	514.2	257.1	116.7	8.2	−140.	−1361	105.8	108.6	76.9	3
Generated by SPORN(69)	MW	0.0	509.2	136.0	93.6	3.2	−42.4	567.4	21.7	25.7	1.1	4.0
Generated by SPORN(69)	Mvar	0.0	−123.	−9.8	−33.6	−26.5	−23.9	329.1	1.5	7.9	12.0	6.4
Corridors P, Q												
345 kV - XGrid_P1	MW	0.0	1003.	−74.9	255.9	221.4	330.8	328.4	17.3	248.8	239.6	231.5
345 kV - XGrid_P1	Mvar	0.0	528.0	69.7	81.5	121.3	11.9	521.1	−19.8	−30.7	−19.3	−10.9
345 kV - XGrid_P2	MW	0.0	105.5	179.5	165.0	124.0	−14.5	785.1	−6.3	−5.9	−18.3	0.4
345 kV - XGrid_P2	Mvar	0.0	151.8	−247	−121	−137	126	88.6	−277	−166	−167	111
XGrid_P2-XGrid_P1	MW	0.0	121.4	−6.6	−7.6	−9.3	−0.9	−190.	9.3	5.0	4.4	−4.3
XGrid_P2-XGrid_P1	Mvar	0.0	−78.6	11.4	−21.2	−48.9	−32.6	25.9	23.4	2.0	−5.4	−21.5
EHV 345 kV Grid U												
SORENSON(30)	kV	345.0	334.7	−9.6	−6.5	−2.2	3.1	335.3	−6.1	−3.6	−2.2	2.5
EASTLIMA(38)	kV	345.0	331.6	−13.4	−12.4	−6.6	1.1	333.5	−11.5	−8.7	−7.6	2.9
TIDD(63)	kV	345.0	334.2	−2.2	−2.6	−2.5	−0.5	335.6	−3.2	−3.2	−3.2	0.0
KAMMER(64)	kV	345.0	339.4	−4.1	−4.4	−4.2	−0.4	340.4	−5.0	−5.0	−4.9	0.0
SPORN(68)	kV	345.0	345.7	0.0	−0.1	−0.1	0.0	343.6	0.2	0.0	0.0	−0.2
KANAWHA(81)	kV	345.0	343.6	−0.1	−0.2	−0.2	−0.1	342.5	0.1	0.1	0.1	0.0
No changes for Substations OLIVE(8), BEQUINE(9), BREED(10), TANNRSCK(26), MUSKNGUM(65)												
HV 138 kV Grid U												
OLIVE(5)	kV	138.0	138.3	−1.6	−1.9	−1.5	−0.4	138.3	−1.3	−1.4	−1.3	−0.1
SORENSON(17)	kV	138.0	138.3	−1.5	−0.7	0.5	0.8	138.9	−0.6	0.0	0.4	0.6
EASTLIMA(37)	kV	138.0	136.5	−3.1	−3.0	−0.6	0.1	137.3	−1.4	−0.5	−0.3	0.9
No changes for Substations TANNRSCK(25), TIDD(59), W.KAMMER(61), MUSKNGUM(66), SPORN(69), CABINCRK(80), KYGERCRK(116)												
EHV 345 kV Lines P, Q												
TANNRSCK(26)>SORENSON 30	MW	0.0	222.4	9.1	14.4	5.8	5.3	195.4	−45.5	−38.1	−41.4	7.4
MUSKNGUM(65)>EASTLIMA38	MW	0.0	184.9					−112.				
MUSKNGUM(65)>KAMMER(64)	MW	0.0	183.7					−29.9				
KAMMER(64)>TIDD(63)	MW	0.0	152.2	−62.4	−63.4	−64.8	−1.1	31.8	7.7	8.2	7.7	0.5
OLIVE(8)>SORENSON(30)	MW	0.0	73.5	339.1	339.1	339.1	0.0	206.6	218.9	218.9	218.9	0
SORENSON(30)>EASTLIMA(38)	MW	0.0	62.0	109.0	108.3	123.4	−0.8	254.7	−10.7	−9.5	−4.2	1.2
KANAWHA(81)>SPORN(68) 1	MW	0.0	22.4	−13.5	−14.4	−15.3	−0.9	102.4	8.2	7.7	7.5	−0.5
KANAWHA(81)>SPORN(68) 2	MW	0.0	22.4	−13.5	−14.4	−15.3	−0.9	102.4	8.2	7.7	7.5	−0.5
MUSKNGUM(65)>SPORN(68) 1	MW	0.0	7.0	39.4	48.0	63.6	8.6	336.7	−33.2	−34.4	−30.4	−1.2
MUSKNGUM(65)>SPORN(68) 2	MW	0.0	7.0	39.4	48.0	63.6	8.6	336.7	−33.2	−34.4	−30.4	−1.2

Table 5.2 continued

Case Title			Winter Case $N-3$					Summer Case $N-3$				
Parameter	Unit	EG	C0	DC0	DG	DGS	DGC	C0	DC0	DG	DGS	DGC
TANNRSCK(26)>SORENSON 30	Mvar	0.0	6.2	33.7	20.5	6.8	–13.2	1.9	18.3	16.4	11.4	–1.8
MUSKNGUM(65)>EASTLIMA38	Mvar	0.0	–8.3					3.4				
MUSKNGUM(65)>KAMMER(64)	Mvar	0.0	40.1					44.6				
KAMMER(64)>TIDD(63)	Mvar	0.0	52.5	–23.4	–19.7	–19.8	3.7	55.1	–26.0	–25.9	–25.9	0.1
OLIVE(8)>SORENSON(30)	Mvar	0.0	58.4	68.3	37.4	–13.5	–30.9	52.8	51.8	14.2	–4.7	–37.6
SORENSON(30)>EASTLIMA(38)	Mvar	0.0	–8.0	18.7	24.9	13.7	6.3	–13.6	28.4	27.7	29.3	–0.7
KANAWHA(81)>SPORN(68) 1	Mvar	0.0	–36.5	0.6	0.7	0.8	0.1	–34.5	–1.1	–0.4	–0.4	0.7
KANAWHA(81)>SPORN(68) 2	Mvar	0.0	–36.5	0.6	0.7	0.8	0.1	–34.5	–1.1	–0.4	–0.4	0.7
MUSKNGUM(65)>SPORN(68) 1	Mvar	0.0	–7.0	–2.7	–3.0	–4.5	–0.3	1.6	–2.6	2.8	2.2	5.3
MUSKNGUM(65)>SPORN(68) 2	Mvar	0.0	–7.0	–2.7	–3.0	–4.5	–0.3	1.6	–2.6	2.8	2.2	5.3
No changes for Lines BREED(10)>BEQUINE(9)1, BREED(10)>BEQUINE(9)2, BEQUINE(9)>OLIVE(8) 1, BEQUINE(9)>OLIVE(8) 2												
AT 345/138 kV P, Q												
OLIVE(8)>OLIVE(5)	MW	0.0	339.1					218.9				
EASTLIMA(38)>(37)	MW	0.0	243.5	–74.0	–74.0	–58.3	0.0	138.5	102.5	103.5	108.9	1.1
SORENSON(30)>(17)	MW	0.0	229.3	231.0	240.2	221.0	9.2	142.1	178.9	188.1	181.5	9.2
TIDD(63)>(59)	MW	0.0	151.7	–62.1	–63.5	–64.9	–1.5	31.7	7.7	8.2	7.7	0.5
SPORN(68)>(116) 1	MW	0.0	92.1	0.0	0.0	0.0	0.0	49.8	0.0	0.0	0.0	0.0
SPORN(68)>(116) 2	MW	0.0	92.1	0.0	0.0	0.0	0.0	49.8	0.0	0.0	0.0	0.0
TANNRSCK(26)>(25)	MW	0.0	91.6	–9.1	–14.4	–5.8	–5.3	118.6	45.5	38.1	41.4	–7.4
KAMMER(64)>(61)	MW	0.0	30.5	–120	–119	–118	1	–61.8	22.3	21.8	22.3	–1
MUSKNGUM(65)>(66)	MW	0.0	8.4	289.8	272.6	241.4	–17.2	–141.	–75.2	–72.7	–80.8	2.4
KANAWHA(81)>(80)	MW	0.0	–44.8	27.0	28.8	30.6	1.8	–205.	–16.4	–15.4	–15.0	0.9
SPORN(68)>(69)	MW	0.0	–125.	51.8	67.1	96.6	15.4	771.6	–49.0	–53.5	–45.7	–4.5
OLIVE(8)>OLIVE(5)	Mvar	0.0	124.8					115.4				
EASTLIMA(38)>(37)	Mvar	0.0	86.6	–57.5	–39.5	–44.6	18.0	78.8	–62.4	–62.6	–60.7	–0.2
SORENSON(30)>(17)	Mvar	0.0	162.9	–16.4	–26.2	–26.3	–9.8	150.9	–22.4	–22.8	–25.2	–0.4
TIDD(63)>(59)	Mvar	0.0	67.5	–20.2	–20.6	–19.9	–0.4	74.7	–26.0	–26.1	–25.9	0.0
SPORN(68)>(116) 1	Mvar	0.0	–49.7	–1.5	–3.1	–3.5	–1.6	–120.	7.9	1.6	1.6	–6.3
SPORN(68)>(116) 2	Mvar	0.0	–49.7	–1.5	–3.1	–3.5	–1.6	–120.	7.9	1.6	1.6	–6.3
TANNRSCK(26)>(25)	Mvar	0.0	21.6	–0.3	0.0	0.0	0.3	22.6	2.2	0.3	0.0	–2.0
KAMMER(64)>(61)	Mvar	0.0	14.0	–43.1	–46.8	–46.7	–3.7	25.7	–54.8	–54.8	–54.9	–0.1
MUSKNGUM(65)>(66)	Mvar	0.0	72.2	14.6	12.0	0.9	–2.6	75.5	4.4	0.9	0.1	–3.6
KANAWHA(81)>(80)	Mvar	0.0	72.9	–1.3	–1.4	–1.6	–0.1	69.1	2.2	0.8	0.7	–1.5
SPORN(68)>(69)	Mvar	0.0	156.6	–2.1	0.0	–0.7	2.1	237.8	–10.9	0.9	0.4	11.7

Since the voltages at the substations and the reactive power flows in the network are of local nature, the calculation of the influence of deviations on the voltages in the network will be approximate; moreover, it will be made with some underestimation of the gravity of the emergencies. The scaling of the perturbations introduces an additional error to the evaluation. Therefore, it is recommended that it should be used only in the cases when the regime does not converge at the specified perturbations. This technique considerably increases the reliability of the method. In the example presented, it can be seen that the scaling of the perturbation at the scale of 1 : 10 gives a solution that is almost identical to the one that would have been provided by the calculation of the possible active power flows according to LODF, which is quite a good result.

The calculation according to an equipotential grid model cannot be more accurate than the calculation according to a full model with a flow distribution that is ideally close to the real-life regime of the interconnected power system. At the same time, such a calculation is essentially simpler and more reliable in terms of obtaining the solution.

The method can be compared with the study by X-rays as all the important details appear, but more subtle features of the regime are not visible. The method can provide a fairly objective assessment of the severity of the accident. However, in order to make definitive conclusions on determining the severity of the accident, further research is needed.
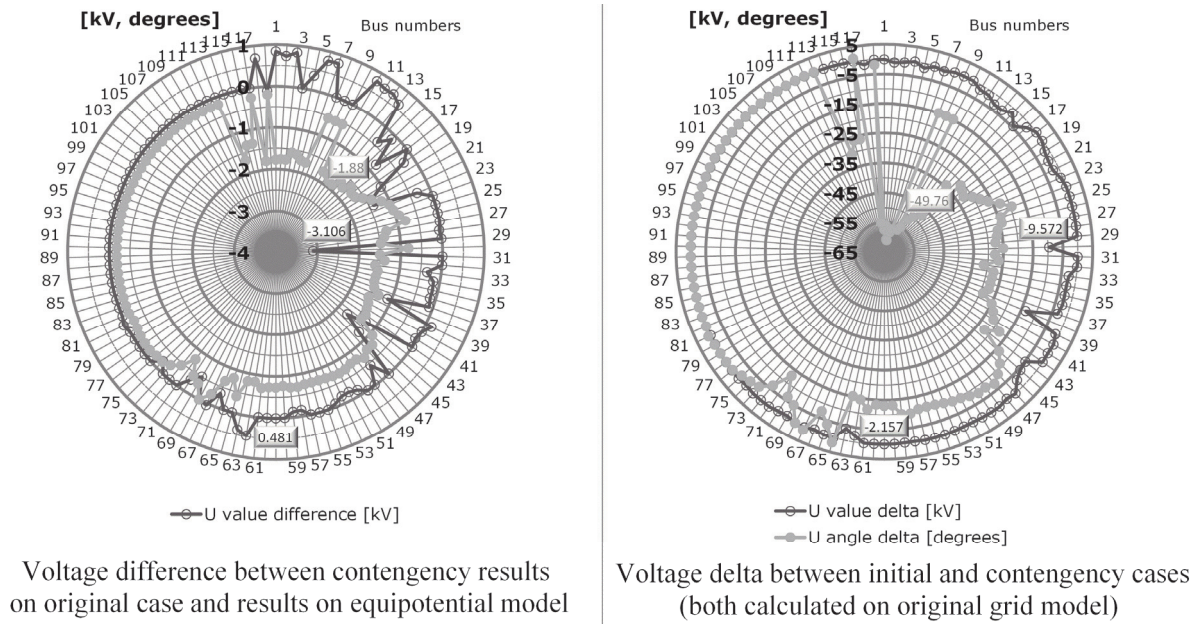
Voltage difference between contengency results on original case and results on equipotential model

Voltage delta between initial and contengency cases (both calculated on original grid model)

Fig. 5.4. Voltage difference between the original and equipotential models for Winter Case $N-3$.

Active power flow difference between contengency results on original case and results on equipotential model

Active power flow delta between initial and contengency cases (both calculated on original grid model)

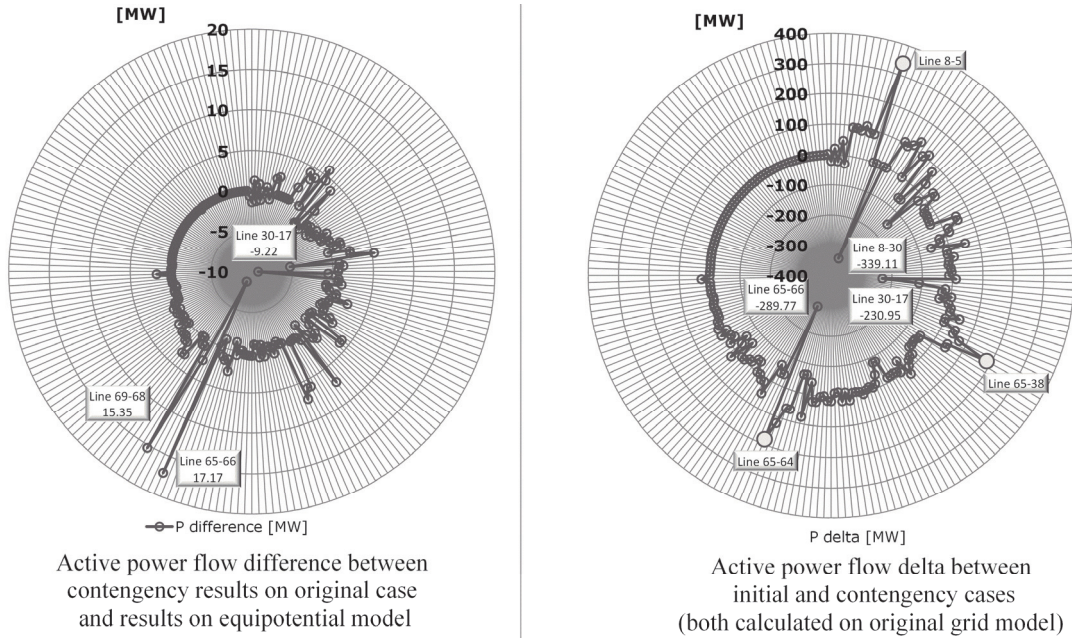Fig. 5.5. Active power flow difference between the original and equipotential models for Winter Case $N-3$.

CONCLUSIONS

1. As the global community is solving the task of achieving economically effective, reliable and renewable power supply, this leads to a more distributed, more interconnected and more flexible power system as compared to the present one.
2. To control the mode of individual power systems, power plants and power networks within the present-day interconnected power systems, both decentralised and hierarchical structures have been created, which are able to organise the control of a large system based on forecasts of the condition of the system and on calculations of electrical regimes.
3. Simulation has been performed by using complicated software, compliant with technical limitations, which ensures evaluation of stability, reliability, efficiency, and energy losses.
4. In the case of considering a large system, the modeling problem acquires an extremely complex form, since it is non-linear, stochastic, multi-objective and should be solved by taking into account a huge number of decision variables, restrictions, uncertainties and processes that will occur in the distant future.
5. The mathematical description of a large power system contains a vast number (millions) or differential and algebraic equations. Due to the achievements of present-day mathematics and information technology, simulation can be performed even for the largest systems without essential restrictions related to the number of equations and calculation time consumption.
6. As the dimensions of a system increase, the greatest difficulties in modeling are presented by:
   - collection and input of input information;
   - depiction of the simulation results.
7. In Latvia, the power system is operated on the basis of MUSTANG software. The program has been synthesised and developed over a period of 30 years and remains competitive against the best foreign software products.
8. Efforts to simplify the collection and input of information lead to the use of simplified power system models, which make it necessary to search for a compromise between complexity and accuracy. The compromise solution can be adopted upon comparing the results of using the complex model and the simplified one.
9. Hypothesis of decomposition and equivalence methodology for the grid model intended for analysing the influence of emergencies $N - i$ in the external network on the investigated part of the interconnected power system considerably simplifies calculations and particularly their preparation. The methodology can be regarded as the development of methods based on the determination of the PTDF and LODF distribution factors. Its use allows increasing the reliability of the evaluation of possible emergency situations in real time.
10. Calculations of steady-state regimes of the power system have been performed for operational planning of the following functions:
    - hourly calculation of the active power flows in the BRELL ring network for the following 24 hours;
    - hourly calculation of the possibility of additional electricity deliveries for 24 hours following the Nord Pool Spot market coming into action ;
    - the first stage of the hourly calculation of the electric power losses in the network of the Latvian transmission system operator for the specified number of days ahead.

    This can be significantly accelerated by using the developed methodology, which is based on common software blocks for performing calculations intended for various purposes.

11. Using a "tree of directories" and the developed methodology for obtaining a regime with partly specified results of the controlled parameters considerably increases the effectiveness of the engineer's work and makes the calculations performed by them more demonstrative in the interaction of MUSTANG software with other programs, for example, Microsoft Excel, in the command interpreter mode.

12. Using the results of the present Thesis for the creation of a DTS system for the dispatcher of the Latvian transmission system operator has provided an opportunity for consumers to train in the field of electric power restoration after a complete blackout of the system.

13. The methodology of creating an equipotential grid model can be algorithmically implemented in most programs intended for calculating steady-state regimes. Calculation of emergencies $N - i$ according to an equipotential grid model may be of practical interest to those TSOs within ENTSO-E who are not provided with detailed operational information regarding the operating regime of neighbouring power systems.

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