RIGA TECHNICAL UNIVERSITY
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PROBLEMS AND SOLUTIONS OF STABILISATION OF ELECTRIC POWER SYSTEMS DYNAMICAL PROCESSES

Summary of doctoral thesis

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CONFIRMATION STATEMENT

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

Santa Kiene …………………………….(signature)

Date …………………………………….

Doctoral thesis is written in Latvian language, containing introduction, 7 chapters, conclusions and recommendations, bibliography, and 2 appendices. The total volume of thesis is 163 pages of computer typesetting, which contains 74 figures and 8 tables. The bibliography listed 105 sources of literature.

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CONTENTS

IMPORTANCE OF THE ISSUE

Topicality of the problem is the improvement of power supply reliability and power quality by elaboration of new methods for control of normal and emergency operational conditions of power system.

Formation of large interconnected power systems is an essential part of the world's globalization process. Integration of electrical power systems involves considerable technical-economic advantages. However, interconnection of power systems appears also in a number of fundamental problems, such as unlocal reaction nature of power system to the disturbances, power systems become more complex, appears a high diversity of power system operating conditions and emergency disturbances, which provides a huge number of different emergency situations, etc.

As power systems evolve and become more complex a special urgency acquires the reliability, as well as the control quality problem of interconnected power systems. Nowadays, construction of new power transmission lines is difficult due to the environmental and other constraints, but power companies face a continuous increase in power consumption and the liberalization of the market, so power systems are operated near stability limits. Loading of power transmission lines then reaches the limits of its maximum transfer capacity; therefore power systems are much more sensitive to the different disturbances of operational conditions. A congested power system is a high probability of a cascading emergencies risk. One consequence of the event with a cascading effect can be spread to large areas of power system causing significant economic losses, as demonstrated by the large system blackouts in the U.S., Canada and Europe.

All of the above factors increase the importance of accurate organization of power system control. Insufficient controllability of power systems limits the effective solution of this problem, mainly, during emergency conditions associated with reduced fundamental capabilities of emergency control automation. Hence, there is the need for development of control systems by elaborating new, more complete control principles and new control tools.

AIM AND TASKS OF THE THESIS

The aim of this doctoral thesis is the improvement of power system stability. To achieve the placed goal the following tasks are solved:

1. Analysis of balance type and the calculated active power deficiency (surplus) type generator rotor dynamic equation.
2. Development of mathematical models for obtaining numerical results of a power system functioning in time.
3. Elaboration of algorithm for application of control actions to provide an optimal control of normal operational conditions of power system.
4. Elaboration of algorithm for application of control actions to provide an optimal control of emergency operational conditions of power system.

METHODOLOGY OF RESEARCH

1. Tasks of doctoral thesis are mainly solved in MATLAB® software and its visual simulation addition SIMULINK®. In some cases also PSCAD® software is used.

2. Various mathematical models are designed and used for research – the traditional sources of generation, power transmission lines, etc., as well as the automatic devices with new operating principle.

SCIENTIFIC IMPORTANCE OF DOCTORAL THESIS

1. New methodology and mathematical models are elaborated, which can be used for various simulations of power system dynamical processes.
2. Analysis of dynamic equation is given to determine the actual active power deficiency (surplus) in power system.
3. Algorithm for determination of control doses is developed for control of normal operational conditions, as well as for emergency control after large disturbances, in both cases providing high control accuracy.
4. Algorithm for optimal control of power system emergency operational conditions is developed, which improves the operating efficiency of automation for prevention of stability disturbances.

PRACTICAL VALUE OF DOCTORAL THESIS

1. Proposed new methodology can be used for determination of faster and more precise control actions in comparison with current methods. Also it adjusts better to the emergency process.
2. Established research methodology and mathematical models can be used in a variety of practical goals, such as analysis of ongoing emergency situations in power system.
3. Created mathematical models are universal – they can be used for calculation of operational conditions in various power system simulation software.

APPROBATION OF DOCTORAL THESIS

1. „Power System Stability Maintenance Problems during Frequency Control," RTU 47th International Scientific Conference, Riga, Latvia, 2006, October 12 – 14.
2. „Stability Problems of Power System Control During Emergency, Caused by the Active Power Deficiency," ECT 2007, 2nd International Conference on Electrical and Control Technologies, Kaunas, Lithuania, May 3 – 4, 2007.
3. „Frequency Control and Determination of Controlling Actions to Enhance Stability of Power System," 4th Scientific Symposium „Elektroenergetika-2007", Stara Lesna, Slovakia, September 19 – 21, 2007.
4. „Method for the Determination of Controlling Actions to Enhance Power System Stability," RTU 49th International Scientific Conference, Riga, Latvia, 2008, October 13 – 15.
5. „Application of Actual Power Deficiency Value on Load Shedding," ECT 2009, 4th International Conference on Electrical and Control Technologies, Kaunas, Lithuania, May 7 – 8, 2009.
6. „Application of New Emergency Control Principle in Power Systems," 2009 IEEE Bucharest PowerTech Conference, Bucharest, Romania, 29 June – 2 July, 2009.

PUBLICATIONS

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1. Chuvychin, V., Gurov, N., Kiene, S. Power System Stability Maintenance Problems during Frequency Control. Scientific proceedings of Riga Technical University, Power and Electrical Engineering, 4th series. Riga: RTU, 2006, Vol.17, pp.52-58.
2. Chuvychin, V., Gurov, N., Kiene, S. Stability Problems of Power System Control During Emergency, Caused by the Active Power Deficiency. Scientific proceedings of the 2nd International Conference on Electrical and Control Technologies of Kaunas University of Technology, Kaunas, Lithuania, May 3 – 4, 2007, pp.98-101.
3. Chuvychin, V., Gurov, N., Kiene, S. Frequency Control and Determination of Controlling Actions to Enhance Stability of Power System. Proceedings of 4th Scientific Symposium „Elektroenergetika-2007", Stara Lesna, Slovakia, September 19 – 21, 2007, pp.709-712.
4. Chuvychin, V., Gurov, N., Kiene, S. Method for the Determination of Controlling Actions to Enhance Power System Stability. Scientific proceedings of Riga Technical University, Power and Electrical Engineering, 4th series. Riga: RTU, 2008, Vol.23, pp.31-36.
5. Chuvychin, V., Gurov, N., Kiene, S. Application of Actual Power Deficiency Value on Load Shedding. Scientific proceedings of the 4th International Conference on Electrical and Control Technologies of Kaunas University of Technology, Kaunas, Lithuania, May 7 – 8, 2009, pp.298- 301.
6. Chuvychin, V., Gurov, N., Kiene, S. Application of New Emergency Control Principle in Power Systems. Proceedings CD of the IEEE Bucharest PowerTech Conference, Bucharest, Romania, 29 June – 2 July, 2009, 6 p.

STRUCTURE AND CONTENTS OF DOCTORAL THESIS

Thesis is written in Latvian, it contains an introduction, seven chapters, conclusions and recommendations, list of references and two appendixes. The total volume of thesis is 163 pages of computer typesetting, which contains 74 figures and 8 tables. The bibliography listed 105 sources of literature.

1. DYNAMICAL PROCESSES AND STABILITY OF LARGE POWER SYSTEM INTERCONNECTIONS

This chapter is devoted to the general overview of the large power system interconnections around the world and benefits and problems of its interconnections. Concept of physical nature of power system dynamical processes and evaluation of stability criteria are provided.

Reliable work of power system is largely dependent on its stability, which is associated with the ability of whole generating units in the system to rotate synchronously, irrespective of the different system disturbances. Due to the increasing power consumption and the importance of electricity supply reliability for industry and society in general power systems are expanded by connecting power systems of several countries to work synchronously through the power transmission lines. Thus, stability of interconnected power systems is of increasing importance [1].

Historically there are formed large power system interconnections such as UCTE, NORDEL, IPS/UPS, the North American connections, which combine transmission system operators (TSOs) of one or more countries for joint cooperation in order to coordinate power system conditions of parallel operation, to maintain grid stability and to provide electricity trading possibilities.

The tendency to create as far as possible larger power systems appears in almost all countries since the interconnection of power systems presents significant technical and economic advantages compared with individual power plants supplying its electricity to local consumers [1]. The main advantages of power system interconnections are:

- increase of capacity installed for single unit improving its technical characteristics and reducing specific costs of electricity output, as well as reducing the turbine specific metal input and specific fuel consumption;
- reduction of total peak load of interconnected power system, consequently reduction of its total installed capacity;
- reduction of necessary total reserve capacity;
- increase of economy of operational conditions for different types of power plants, providing fuel efficiency and consequently reducing the cost of electricity;
- electricity trading possibilities;
- relieving of power system operation during maintenance and emergencies.

Nevertheless, despite the considerable advantages of power interconnections, a number of fundamental problems also appear [1]. Main problems of power interconnections, which cause difficulties in maintaining power system stability, are the following:

- power system merges power consumers in a large area, which together with a high degree of concentration of power generation leads to the need for power transmission from a fairly remote sources to consumers. Also appears unlocal power system response nature to the operational condition disturbances;
- power systems become more complex, appears a high diversity of power system operational conditions and emergency disturbances, which provides a huge number of different emergency situations, i.e., the conditions of emergency processes to be identified and to whom minimal possible control actions need to be found to ensure power system stability;
- power systems are penetrated with control, automation and regulation systems, therefore requiring them more responsible tasks the refusal cost of these systems, as well as the role of their proper organization increase.

The most severe emergencies of interconnected power systems reflect their control problems. So, for example, 2003 is characterized with five blackouts of power systems – North America (August 14), London (August 28), Scandinavia (September 23), Italy (September 28) and Chile (November 7), where large number of electricity consumers within large areas were left without electricity for several hours. Also many other emergencies with significant adverse consequences have occurred in the world - in Athens, 2003, in Moscow, 2005, etc. Recently happened incident in Europe took place on November 4, 2006, when after cascading trip of numerous 380 kV and 220 kV transmission lines the UCTE system were split into three isolated islands – West, Northeast and Southeast. More than 15 million consumers remained without electricity.

Power systems consist of thousands of generators, transformers, hundreds of thousands kilometres of power lines and millions of consumers. All grid elements function as a single system. Primary function of the power system is a reliable supply of consumers with continuous electricity with certain quality. The quality of accomplishment of primary function characterizes the term power system reliability, which requires that the power system must be in normal steady state operation with invariable and certain quality operational parameters (electric power, voltage, current, vector shift angle of machine electromotive force, frequency, etc.). However, operational conditions of power system are subjected to a large number of disturbances, some of which may occur continuously, for example, the change of consumers, some rarely, but with a potentially high danger – switching on and off generators, power lines, transformers, high-power substations (load nodes), as well as short-circuits, equipment damages, isolation overlap and rupture, improper operation of various equipment and facilities, human erroneous actions, etc. Any power disturbances cause the dynamic processes in the power system determining the transition of its initial operational condition to another. System behaviour during this period is called the system dynamics. As for any dynamical system the main factor for reliable operation of power system is its stability. Stability is defined as the ability of power system to restore the balance of operational condition after arisen disturbance, while maintaining the majority of the condition parameters within acceptable limits so that the whole system remains intact.

Development of new power system interconnections, technology and equipment, as well as planning of heavier power operational conditions has led to different forms of system stability – rotor angle stability, frequency stability and voltage stability. Furthermore, the rotor angle and voltage stability depending on the size of the disturbance can be divided into the steady state (small disturbances) and transient (large disturbances) stability.

The main task to provide stability of interconnected power systems is the rotor angle stability or maintenance of synchronism of all the rotating machines, which is relevant to providing of relative angles between the vectors of synchronous machines' electromotive forces within acceptable limits during emergency process until a new steady state operational condition takes place and which theoretically can be evaluated with a certain steady state and transient stability criteria [2].

Recently occurred severe power system blackouts indicate that the realization of potential possibilities to improve power system reliability and stability must focus special attention on development of effective control systems and emergency control tools.

2. CONTROL OF INTERCONNECTED POWER SYSTEMS

This chapter is devoted to the survey of main control tasks provided in interconnected power systems separately dealing with normal control and emergency control of operational conditions. In general emergency control tools applied in power systems and their operating principles are considered.

Control organization of large interconnected power systems is a complex scientific and technical problem. The main task of power system is reliable, economical and qualitative consumers' supply of electricity, realization of which is impossible without application of control automation tools and systems. For power system reliability continuous automatic monitoring and control of power system operational condition is needed in order to prevent disturbances of power system stability [3].

Power system control objectives are following:

- continuous maintenance of balance between generated and consumed power. As electrical energy can not been accumulated in sufficient quantities, there is the need for fast available and controllable reserve capacity;

– providing of stated level of power supply reliability and quality (voltage and frequency values must be within tight, strictly-defined limits);
– ensuring of minimal cost and minimal environmental impact.

Power system control tasks depend on a particular power system state, which in turn is defined with the nature of power system operational condition and transient process. There can be defined five states in power system, as shown in Fig. 2.1. There are developed and implemented control tasks under each state to ensure effective control action in each state.

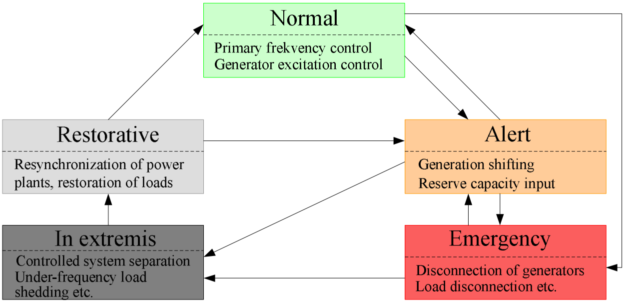


Fig. 2.1. Classification of power system operating states

A prerequisite for power system reliability is normal operating state. Any other state decreases system reliability and is considered to be adverse, therefore improvement of power system stability requires effective control of its operational condition in normal and emergency states, to which the given thesis is devoted.

Power system frequency and active power control

One of the most important power system quality indices is frequency, and the main control task of normal power system state is frequency control.

System frequency must be kept within the strictly defined limits [4]. There are different theoretical approaches for frequency control in power systems across the world. It is regulated by geographical, technical and economical characteristics of each country. Typical frequency control structure of UCTE performs three levels of control called primary, secondary and tertiary frequency control. In interconnected power systems all three levels of control are used. In smaller isolated power systems secondary control may not exist as such. Realization of different frequency control levels may vary depending on the types of generation sources, size of power system, economic considerations and tradition of particular power system.

This doctoral thesis in detail deals only with the primary frequency control, which aims to restore the balance between generated and consumed power at certain frequency level after different disturbances.

Rotation frequency and active power of generator in general depends on the input of energy carrier amount into turbine during unit of time, thus, the frequency is controlled by the governors of generator rotation speed [4].

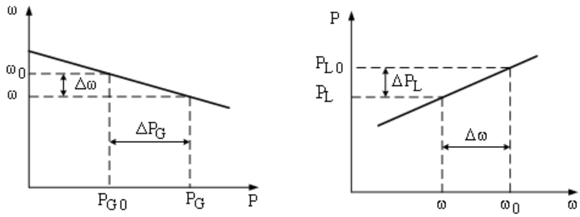
Primary frequency control is the proportional type high-speed control drawn up by the time of 0-30 s after the balance of generation and load power is disturbed, and is executed in accordance with the static characteristics of generator rotor speed governors, as shown in Fig. 2.2. (a).

In IPS/UPS system primary frequency control practically is not used, because the system frequency is determined by the interconnection, in which frequency control is performed by specially assigned power plants. Such type of control is called floating control, where system frequency theoretically remains constant at any load changes. In this case, unit capacity must be 8 to 10% of total system capacity. However, world practice shows that each interconnected power system should participate in frequency control.

Therefore, in order to distribute the load between parallel operating units there are assigned static characteristics to speed governors designated to primary control, which is characterized with droop factor R. Droop factor measures the degree of turbine change and consequently the change of generator's output power ΔP_G after the change of system frequency on value Δf :

$$R = \frac{\Delta f}{f_0} \cdot \frac{P_{G0}}{\Delta P_G}, \qquad (2.1)$$

where ΔP_G - change of generated power [MW], P_{G0} - rated power of generator [MW], f_0 - nominal system frequency [Hz], $\Delta f = f - f_0$ - change of frequency [Hz], f - actual system frequency [Hz].



(a) (b)

Fig. 2.2. Static characteristics of: (a) generating unit, (b) load

Droop factor of hydropower plants can usually change around the range of 0-10%. Droop factor of thermal power plants (especially a large capacity) is unchangeable (around 4-6%).

System frequency deviation will cause not only the change in generating capacity, but also change in load, since the power system has a range of consumers, whose active power depends on frequency in the first, second and even the third order. Load power dependence on frequency variations in the power system is called the load damping effect, and is characterized by a static load curve, as shown in Fig. 2.2. (b). Slope of static load curve is defined by load damping factor D, which describes the change of active load power ΔP_L of various consumers after the change of frequency on value Δf :

$$D = \frac{\Delta P_L}{P_{L0}} \cdot \frac{f_0}{\Delta f}, \qquad (2.2)$$

where ΔP_L - load power change [MW], P_{L0} - load capacity at rated frequency [MW].

Load damping factor value may change significantly during the day due to both the dependence on change of consumers' contents and voltage dependence on frequency change. Most typical value of load damping factor for different loads and power systems is approx. 2. Generally, this value fluctuates in relatively small range.

Hence, in case of primary control with a static characteristic the balance of active power is restored at a frequency that differs from nominal. Frequency level after disturbance of power balance is defined by the contribution of governors involved in primary control, which depends on the droop factor of rotor speed governors and the reserve capacity of primary control, as well as on the load damping factor.

In order to restore the frequency to its nominal level, as well as to restore deviated power flows between interconnections to their planned values the secondary frequency control is applied, which is slow-acting proportionally-integral-type control executed by the central governor.

This method of level type control of frequency and active power can take several tens of minutes, which negatively refers to the quality of transient process of power system operational condition. There is a need for advanced frequency control system to improve the quality of the transient process.

Emergency control

Larger disturbances of power system operational condition can lead to faster transient processes of state parameters, which in turn can cause power system emergencies. Emergencies, which take place in power system with wide disconnections of power consumers, are quite rare, but they cause a large negative impact on many social activities. Therefore, control of emergency operational conditions in power systems is of particular importance.

Emergency control for the listed types of power system stability is required to ensure the following tasks:

- prevention of disturbance of stability of power system parallel operation, i.e., the maintenance of relative angle between the electromotive force vectors of synchronous machines within acceptable limits;
- termination of out-of-step condition in power system, if the prevention of stability disturbances is not successful;
- prevention of frequency, voltage and current values exceeding the feasible limits.

In interconnected power systems automatic emergency control is mainly focused on the accomplishment of the first task, since the out-of-step condition, unacceptable frequency, voltage and current deviations in most cases appear either after power system stability disturbance or at post-emergency conditions, which are close to the stability limits. Therefore, prevention of stability disturbance in most cases provides the rest of the tasks.

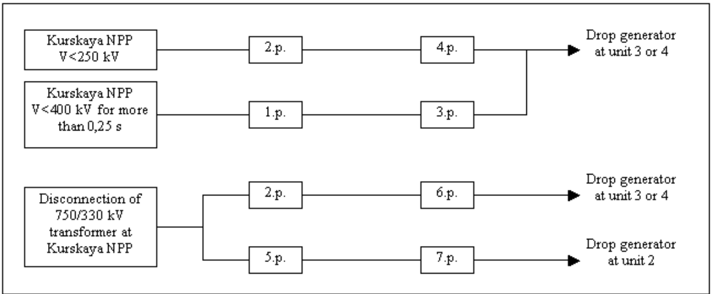
Realization of emergency control is provided by the emergency automation equipment. In large North American and Western European power systems emergency automation is defined as a Special Protection Schemes (SPS) or Remedial Action Schemes (RAS).

Special protection schemes are designed to detect the fast deviations of power system parameters from the permissible levels, which can cause severe power system emergencies, and to provide certain types of dosed control actions to remove detected parameter deviations [2], [3], [5].

Now there are various types of SPS used in the world. SPS according to their given task can be a generator disconnection, load disconnection, under-frequency load shedding, system separation, turbine valve control, out-of-step prevention, generator dynamic braking, etc. One type of SPS can fulfil several functions depending on the situation in the power system, such as, for example, Stability Disturbance Prevention Automation (SDPA) applied in IPS/UPS system, which aims to restore the active power balance after an emergency disturbances by reducing generated power output in power system part with excess capacity and shedding load in power system part with power shortage.

Emergency control can be classified into two categories: pre-defined and real-time emergency control. Now basically there is only pre-defined emergency control in the world, which operates in accordance with previously calculated emergency situations in power system. For the basis of calculations the most severe emergencies are considered, which require maximal control actions. Generally adopted computing resources are static models, physical models, analog and digital computing equipment of AC power network.

From the point of view of emergency condition detection the SPS can be divided into two groups: SPS with detection of emergency condition by element status and SPS with detection of emergency condition by the change of controlled parameters. In the first case the SPS are designed to respond to specific event combinations, such as logical unit of Kurskaya NPP unloading automation in Russian power system as shown in Fig. 2.3. Another type of SPS is based on the measurements of electrical parameters and operates at a certain limiting criteria, such as under-frequency load shedding.



Starting factor	Total generation of units 1-2:	Total generation of the NPP	Control action
	1.p. – more than 800 MW	3.p. – more than 2500 MW	
	2.p. – more than 1100 MW	4.p. – more than 2850 MW	
		750/330 kV trans former load:	
	Generation of unit 2:	6.p. – more than 500 MW to 330 kV bus	
	5.p. – more than 700 MW	7.p. – more than 300 MW to 750 kV bus	

Fig. 2.3. Sample branches of Kurskaya NPP unloading logic unit

One of the main operating criteria of SPS is the accuracy requirement or proper selection of amount of control action. Operating settings, as well as determination of necessary amount of control actions of existing emergency automation are based on the calculations previously made for different power system operational conditions and emergency situations [2], [3], [5], [6].

In case of logical units the maximum amount of each control tool is determined as the largest of all estimated emergency situations. For example, the amount of generation disconnection necessary to provide in the k-th node of power system is defined as follows:

$$P_{GA.k} = \max\{P_{GA.kj}\}, \qquad (2.3)$$

where $P_{GA.kj}$ - a necessary amount of generation disconnection in k-th node at the j-th estimated emergency situation.

The maximum amount of unloading ΔP_{unload}^{max} to be provided by the SPS after disconnection of certain power transmission line in electrical cross-section is defined as the difference between the maximum permissible transmission capacity of the original scheme and the capacity subjected to normative static stability margin (8%) at post-emergency scheme:

$$\Delta P_{unload}^{max} = k_{U\uparrow} \cdot \left(P_{pre/e.m.p} - P_{post/e.8\%}\right), \tag{2.4}$$

where indices “pre/e.m.p” and “post/e.8%” refers to the maximum permissible pre-emergency condition and post-emergency condition with allowable 8% margin accordingly, $k_{U\uparrow}$ - the factor that respects the possibility of transmission capacity increase in different variations of operational conditions, $k_{U\uparrow} = 1 \div 1.5$. Similarly the maximum amount of unloading to be provided by SPS after a powerful generator or power unit disconnection can be determined.

In order to realize more accurate emergency control the rate of change of frequency is used in practice and publications mostly for determination of necessary active power amount, which is basically used only in under-frequency load shedding (UFLS) automation. For example, the required amount of the control action at the initial moment of disturbance, used for UFLS:

$$\left.\frac{df}{dt}\right|_{t=0} = -\frac{\Delta P_G \cdot f_0}{P_{L0} \cdot \left[\tau_{TG} \cdot \left(P_{L0} - \Delta P_G\right) + \tau_L\right]}, \tag{2.5}$$

where the minus sign points to the frequency decrease; ΔP_G - deficiency of generated power [pu], P_{L0} - steady state load power before the disturbance [pu] f_0 - steady state frequency value before the disturbance [Hz], τ_{TG} - mechanical inertia time constant of turbine and generator [s], τ_L - mechanical inertia time constant of load (engines and mechanisms) [s].

Somehow it is possible to predict all probable emergency situations based on a defective equipment disconnection from the power network: transmission power line, busbars, transformers, generators, etc., but it is practically impossible to predict emergencies related to equipment or facility failures leading to cascading disconnection of equipments with a time delay or incorrect tripping of unforeseen equipment from the power network.

As power systems become more complex the diversity of their operational conditions and emergency situations increase, which can not be fully taken into account estimating selection of appropriate operating settings and control actions of emergency automation.

Insufficient amount of required control action of emergency automation, as well as its excess can lead to the development of emergency. In addition, emergency disturbance occurred in one location of power system in short time interval spreads out to other locations of power system, therefore the amount of necessary control action changes that is not considered in the current emergency automation [2], [3], [5].

Consequently, emergency control with the method of pre-determined emergency situations can be inefficient, therefore there are carried out researches of new methods for emergency control in the world based on the real-time emergency control techniques.

Emergency control in real time is based on the measurements of power system parameters in real time detecting the system stability disturbances, implementing appropriate control actions, and following the system behaviour and making appropriate adjustments, if necessary. Real time emergency control is a desirable supplement to a pre-determined control. In publications offered algorithms for real-time emergency control are based on the use of latest technologies, such as Wide Area Monitoring Systems (WAMS), application of which is currently at a research and experimental level and wider implementation requires significant investments.

3. ALGORITHM FOR THE DETERMINATION OF ADAPTIVE CONTROL ACTION

This chapter describes the proposed algorithm for determination of emergency control action, which is an actual active power deficiency or surplus occurred during emergency in power system, as well as there are elaborated the principles that perform the dosing of this control action and application in automation of frequency control and emergency control.

Considering the drawbacks of emergency control described in previous chapters a need for development of adaptive automation arises, which would determine necessary control action during all transient process adapting to the ongoing emergency process and accordingly adjusting the amount of control action.

Algorithm for active power deficiency (surplus) determination

Determination of active power deficiency (surplus) value is based on the use of well-known dynamic equation for single generator equivalent power system with concentrated electrical load on its busbars in the following way [4], [6]:

$$\frac{T_J}{\omega_0} \cdot \frac{d\omega}{dt} = P_G - P_L , \tag{3.1}$$

where T_J - rotor mechanical inertia time constant [s], ω_0 - nominal rotor angular frequency [rad], ω - actual rotor angular frequency [rad], P_G , P_L - turbine produced power at generator busbars and load electrical power at generator busbars accordingly [pu].

Equation $d\omega/dt = 0$ is a sufficient condition for steady state determination characterized by the balance of generated and consumed power $P_G = P_L$. Value of $d\omega/dt$ can be used for preventing of fast decline in frequency by shedding load until $d\omega/dt$ becomes zero. However, the equation $P_G = P_{sl}$ can set at any angular frequency value different from nominal. Therefore frequency restoration to its rated value is an important task of power system control. For solving this task the elements of equation (3.1) are expanded to include their frequency dependent functions [1] - [6].

Doctoral thesis presents expanded description of the dynamic equation including self-regulation effect of turbine, coefficients of frequency-dependent parts of load, as well as separately generator and load mechanical inertia time constants. But practically simplified methodology for active power deficiency (surplus) determination is used as described below.

As described in Chapter 2, frequency deviation will change power output of generator on value ΔP_G in accordance with the unit's static characteristic. As a result, the actual value of generated power from equation (3.1) can be expressed as sum of its value at the rated frequency P_{G0} and the amount of power changed by speed governor ΔP_G :

$$P_G = P_{G0} + \Delta P_G \,, \tag{3.2}$$

where the value ΔP_G from (2.1) expressed in per units:

$$\Delta P_{G*} = -\frac{\Delta f_*}{R} \,, \tag{3.3}$$

and $\Delta f_* = (f - f_0)/f_0$.

Expression (3.3) describes operation of speed governor in simplified form not including differential equations describing operation of governor elements.

The actual value of load power can be expressed as sum of its value at rated frequency P_{L0} and the amount of load changed by load damping effect ΔP_L :

$$P_L = P_{L0} + \Delta P_L \,, \tag{3.4}$$

where the value ΔP_L from (2.2) expressed in per units:

$$\Delta P_{L*} = \Delta f_* \cdot D \,. \tag{3.5}$$

Further the mathematical description is provided without the per unit designation "*".

Mechanical inertia time constant T_J is numerically equal to the time required for unit to set turning from peace state to nominal rotation frequency in affect of nominal torque. It consists of mechanical inertia time constants of generator T_{JG} and load T_{JL} . Load of engines and driven mechanisms define constant T_{JL} , which can vary during the day, therefore determination of the load effect on the total power system mechanical inertia time constant is more complex than for generators, mechanical inertia time constants T_{JG} of which can be easily identified from their certificate data. Due to simplifications the analysis of power system ongoing processes is made not taking into account the mechanical inertia time constant of load ($T_{JL} = 0$) as it is in average one order lower than the mechanical inertia time constant of generator ($T_J = T_{JG}$).

Including the initial frequency independent disturbance value ΔP rotor motion equation in per units can be written taking into account the active load power change due to load damping effect, as well as active generated power change due to operation of turbine speed governors:

$$T_J \cdot \frac{df}{dt} = \left(-\frac{\Delta f}{R}\right) - (\Delta f \cdot D) + \Delta P \,. \qquad (3.6)$$

Consequently, the value of active power unbalance occurred due to emergency in power system can be determined as follows:

$$\Delta P = T_J \cdot \frac{df}{dt} + \frac{\Delta f}{R} + \Delta f \cdot D \,. \qquad (3.7)$$

As seen from (3.7), if active power deficiency appears in power system, then value ΔP is negative, if surplus, then – positive. Value of active power unbalance ΔP will be equal to zero only at the nominal frequency ($\Delta f = 0$).

Expression (3.7) is the basic equation for determination of active power deficiency (surplus) in per units in single generator power system. Analogue dynamic equations and algorithms for determination of active power deficiency (surplus) can be written for all power plants of interconnected power system taking into account the parameters of each power plant (generator), and determine the deficiency (surplus) of the whole power system.

Summarizing all the above, the simplified algorithm for the determination of active power deficiency (surplus) is developed for single generator with local load. The power deficiency (surplus) determination algorithm is shown in Fig. 3.1.

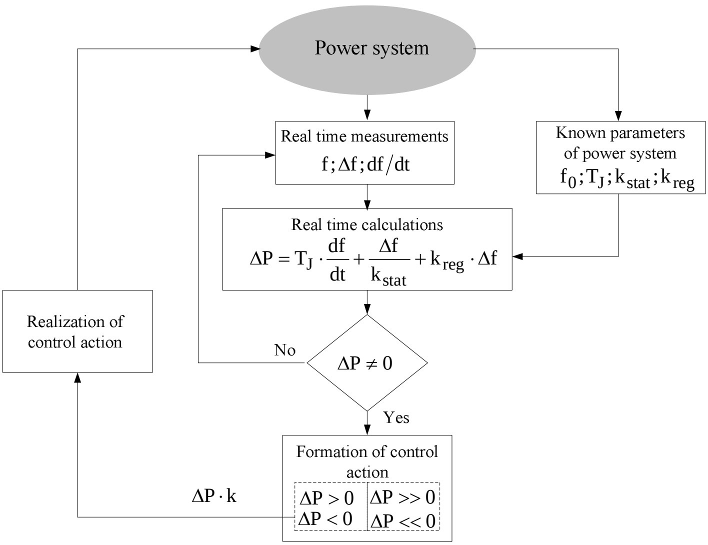


Fig. 3.1. Active power deficiency (surplus) determination algorithm

All parameters used in algorithm of Fig. 3.1. can be defined: f_0 - generally known power quality index; T_J - from equipment technical certificates; R - from the settings of automation devices; D - from experimental data or assumptions.

In the formation block of control actions (Fig. 3.1.) the necessary control action to power system is determined depending on the size and sign of power unbalance value. It may be an increase in generation ($\Delta P < 0$), reduction of generation ($\Delta P > 0$), as well as the generation disconnection ($\Delta P >> 0$) or load shedding ($\Delta P << 0$). In any case the control action shown in Fig. 3.1. is represented as the calculated active power deficiency or surplus value multiplied by a certain factor k.

Developed principle reflects several key factors:

- in order to analyse power system emergency conditions a new approach to the description of its dynamic equation is applied, which taking into account the process dynamics can determine whether the power system is deficient, surplus or is in free movement towards the nominal frequency;
- impacting power system with the calculated active power deficiency (surplus) value allows restoring frequency to its rated value;
- considered control principle allows restoring frequency during emergency not only to its rated value, but also to any other assigned value. This is actual in cases of necessity to resynchronize separated power systems;
- using proposed control method an emergency automation can be developed, which during emergency determines the precise size of control action to the power system and adapts to emergency process making appropriate adjustments to the amount of control action.

Dosing method of control action

In order to reduce the impact of inaccurate parameters and to improve the accuracy of emergency control there is a need to split the control action into several parts (doses) – after the first control action frequency will move towards its nominal value, and the calculation inaccuracy will gradually decrease, therefore each subsequent action will be more accurate.

The matter of proposed splitting or dosing method is in fact, that the active power deficiency (surplus) described with the algorithm above is eliminated by impacting on increase/decrease of power system generation or load disconnection with settings, numerical value of which is calculated by law of geometric progression decrease with the progression denominator less than unity. Taking into account all equipment total operating time the time interval between the operations of settings may be taken in range from 0.2 s to 0.5 s.

Control action to the power system is realized by the following algorithm:

1. The first amount of control action is determined as the amount of initial estimated power deficiency (surplus) ΔP multiplied by the proportionality factor k, which defines the part of deficiency (surplus) to be eliminated with the first setting, or further called control impulse:

$$P_{im1} = \Delta P \cdot k = \Delta P \cdot (1-k)^0 \cdot k \ . \tag{3.8}$$

   Value of k is constant during whole control process, and in order to increase the accuracy of control (to minimize the impact of inaccurately estimated active power deficiency (surplus)) is assumed less than unity: $k \approx 0.7 \div 0.9$.

2. Amount of each next control impulse is calculated as the remain power deficiency (surplus) value multiplied by a coefficient k:

$$\begin{cases} P_{im\,2} = \Delta P \cdot (1-k)^1 \cdot k, \\ P_{im\,3} = \Delta P \cdot (1-k)^2 \cdot k, \\ \dots\dots\dots\dots\dots\dots\dots\dots, \\ P_{im\,n} = \Delta P \cdot (1-k)^{n-1} \cdot k. \end{cases} \tag{3.9}$$

Control action to the power system with the first control impulse constituting the largest amount of action slows down the transient process. This, in turn, allows operating next control impulses before the power system stability disturbance takes place and reducing the control inaccuracy. Control inaccuracy (choice of coefficient k <1) prevents the possibility of frequency overcorrection [3].

Significant advantage of the proposed active power deficiency (surplus) determination method is the gradual decreasing of possible calculation inaccuracy when frequency is moving closer to its nominal value.

Application of active power deficiency value in under-frequency load shedding automation

Since the doctoral thesis proposes method based on a quiet accurate calculation of active power deficiency in real time determining the necessary amount of load to be shed, then this information can be used in under-frequency load shedding automation. Therefore the principle of the application of calculated active power deficiency value in under-frequency load shedding automation is developed.

When active power deficiency value reaches a certain magnitude of automation activation setting P_{set} ($\Delta P \geq P_{set}$), a number of n should be delivered to the shedding, which corresponds to the load settings interruptible simultaneously and is defined as the calculated active power deficiency value divided by the amount of load connected to one setting:

$$n = \frac{\Delta P}{\Delta P_{UFLS\,i}} . \tag{3.10}$$

Activation setting value P_{set} of automation is to be chosen equal to the amount of load connected to one setting of automation ΔP_{UFLSi} ($P_{set} = \Delta P_{UFLSi}$).

Simultaneous disconnection of automation settings provides high-speed of shedding. Remaining amount of division in expression (3.10) makes the amount of untripped load power after operation of automation, which may be referred to as automation operational error. Automation operational error depends on the selected parameters, but in any case it does not exceed the amount of load connected to one setting of automation ΔP_{UFLSi} .

Activation setting value P_{set}, at which automation should initiate load shedding, is to be determined separately for each power system or power region depending on its size, specifications and available amount of reserve capacity. In order to improve the efficiency of emergency control process the activation setting value should be selected to initiate load shedding when active power deficiency exceeds the amount of available primary reserve capacity. Such a selection is justified by improvement of both the high-speed of shedding and quality of frequency, as well as by disposing of available primary capacity reserves, therefore avoiding of redundant disconnection of consumers.

Operating time of settings and steps between the settings depend on the operating time of active power deficiency determination device, as well as on the frequency measurement devices, accuracy and operating speed of relays.

The main advantages offered by the operation principle of suggested unloading automation compared to the conventional UFLS are:

- quite accurate information on the amount of interruptible load to restore the frequency to its set level;
- elimination of the largest amount of calculated active power deficiency by the first action slowing down the transient process;
- avoidance of redundant consumers shedding and subsequent frequency overcorrection;
- local operation without the use of communication links and information from electrically remote sites, hence the ability to operate after power system separation.

Wherewith, developed principle for application of active power deficiency value in load shedding automation improves the efficiency of load shedding operation [4].

Application of active power deficiency (surplus) value in power system stability disturbance prevention automation

Preceding sections offered the automation, which eliminates the active power deficiency or surplus, but very often interconnected power system can face the emergencies causing only temporary unbalance of active power, which is compensated by changes of power flow in power transmission lines.

To prevent the possible exceeding of maximum transfer capacity P_{max} of power transmission line after any disturbance SPS should realize the disconnection of load/generation in respective power region, but to provide the operating efficiency of automation it is essential to know the amount of control action. For this purpose the principle for application of active power deficiency (surplus) value in Stability Disturbance Prevention Automation (SDPA) is developed, where in addition to calculation of active power unbalance value ΔP the actual capacity of transmission line P_{line} is controlled. The principle for the simplest scheme "generator – power transmission line – infinite bus" is as follows:

1. Active power unbalance value ΔP in the considered power plant is calculated continuously, where negative value means the deficiency ($-\Delta P$), positive – surplus ($+\Delta P$) in accordance with the proposed algorithm.
2. Actual transmission line capacity P_{line} is measured continuously, for calculations assuming that positive is node outflow capacity ($+P_{line}$) and negative – node inflow capacity ($-P_{line}$).
3. Allowable transfer capacity of power transmission line P_{max} is set to SDPA.
4. SDPA controls if the following conditions are fulfilled:
   a) if $\Delta P + P_{line} \geq P_{max}$, then calculated SDPA control action is:

$$\Delta P_{SDPA} = \Delta P + P_{line} - P_{max} \cdot \sin \delta_{p.em} , \qquad (3.11)$$

where $\delta_{p.em}$ - preferred power angle in post-emergency condition set to SDPA. Angle selection can be based on the reliability criteria of considered power system.

b) if $\Delta P + P_{line} \le (-P_{max})$, then calculated SDPA action is:

$$\Delta P_{SDPA} = \Delta P + P_{line} + P_{max} \cdot \sin \delta_{p.em} . \tag{3.12}$$

From the foregoing, in case of positive SDPA action the command to generation reduction (disconnection of generators or its dynamic braking, turbine unloading) is to be transmitted, while in case of negative SDPA action – to load disconnection. In both cases, feasible action ΔP_{STNA} provides unloading of power transmission line up to the preferable angle $\delta_{p.em}$ at post-emergency condition.

An important aspect is considered by choosing the active power deficiency (surplus) value as the activation parameter of automation – active power deficiency (surplus) may vary by step thus enabling to foresee possible power surge on a power transmission line after particular disturbance.

Method can be extended also to a couple power systems operating in parallel taking into account the operation of SDPA in both power regions. In this case, during an emergency SDPA will determine equal control actions only with opposite signs. In case of interconnection of multiple power systems an active power flow across all the connecting power transmission lines has to be considered, therefore the general expression is written describing the control action of SDPA for k-th power region for n regions within interconnection:

$$\begin{cases} \Delta P_k + P_{line\,k-i} \ge P_{max\,k-i}, \Delta P_{STNAk} = \Delta P_k + P_{line\,k-i} - P_{max\,k-i} \cdot \sin \delta_{p.em}; \\ \Delta P_k + P_{line\,k-i} \le (-P_{max\,k-i}), \Delta P_{STNAk} = \Delta P_k + P_{line\,k-i} + P_{max\,k-i} \cdot \sin \delta_{p.em}, \end{cases} \tag{3.13}$$

where i = 1...n.

In case of multiple power systems calculation of SDPA control actions will be affected by the distribution character of active power deficiency (surplus) to other power regions and power flow changes in power transmission tie lines. Consequently, the estimated SDPA control actions to load disconnection and simultaneous generation reduction in opposite power regions can be different thus causing power unbalance in power system at post emergency. Therefore, simultaneously with the estimation of SDPA control action in one power region the same amount of control action with opposite sign should be provided automatically to the power region located at the opposing side of risky power transmission tie line.

Elaborated principle of application of active power deficiency (surplus) value in stability disturbance prevention automation increases the efficiency of its operation by calculating the necessary type and amount of control action to unload the risky power transmission line up to a certain limit and maintaining the relative angle between two power systems within acceptable limits at nominal frequency.

4. DEVELOPMENT OF MATHEMATICAL MODELS NECESSARY FOR ANALYSIS OF DYNAMICAL PROCESSES

This chapter examines principles used in doctoral thesis for modelling of power systems and description of mathematical models for analysis of power system dynamical processes. Using the theoretical principles described in Chapter 3 new mathematical models are developed for the practical determination and application of adaptive control actions in power system control.

Research of control systems is based on the replacement of elements in real system with elements described by mathematical transfer functions, in which the output signal depending on the changes of input signal varies according to a certain regularity of the element parameters, i.e., differential equations of elements.

In this thesis the analysis of dynamical processes has been carried out using the most common characterization of each element by the block of transfer function accordingly to this element descriptive differential equation in the form of operators, and introducing the Laplace Operator $p = d/dt$ in order to replace the differential equation with the algebraic equation functioning in the environment of operator p.

Basic principles of large power system modelling are used for research [1].

For research basically mathematical models are used characterizing power system ongoing dynamical processes, realizing them in MATLAB software. Using transfer functions models of the simplified thermal power plant and power transmission line are created, which basically are used for development of variety power system structures, as well as UFLS model applied in Baltic interconnected power system is developed. In the same way series of new mathematical models are developed for the analysis of proposed principle – model of active power deficiency (surplus) calculating device, model of control action dosing device, model for automatic load shedding realization, and SDPA model shown in Fig. 4.1.

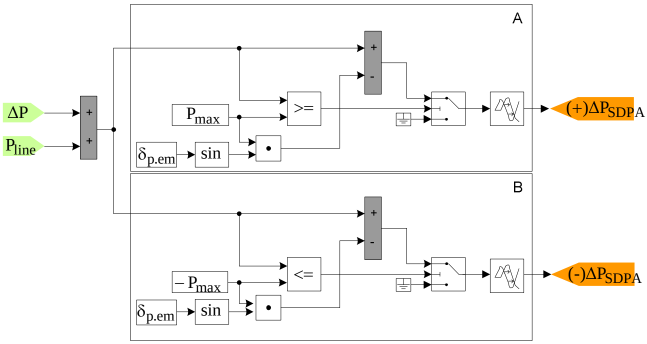


Fig. 4.1. Proposed model of SDPA

Created models provide the possibility of their practical application in different power system simulation software (PSCAD, PSS™ E, EUROSTAG etc.).

Some cases for realization of power system control tasks, for example, in interconnected Baltic power system are simulated on mathematical models developed in PSCAD software, taking also into account the operation of excitation governors.

5. APPLICATION OF ADAPTIVE CONTROL ACTION DURING FREQUENCY AND ACTIVE POWER CONTROL

This chapter describes the automatic control in normal operational conditions of power system performing frequency and active power regulation.

Control processes are examined in case of conventional primary frequency control subsystems applied in power systems, as well as applying the proposed methods of active power deficiency (surplus) calculation and adaptive control action dosing with the objective to improve the quality of control and stability of power system. Examples of concentrated power system [1], [2], and parallel operation of two power systems [3], as well as interconnected power system of complex structure are observed.

Complex power system model analysed in the thesis, which consists of five equivalent thermal power plants (PP1 - PP5) with connected electrical load to each plant is shown in Fig. 5.1.

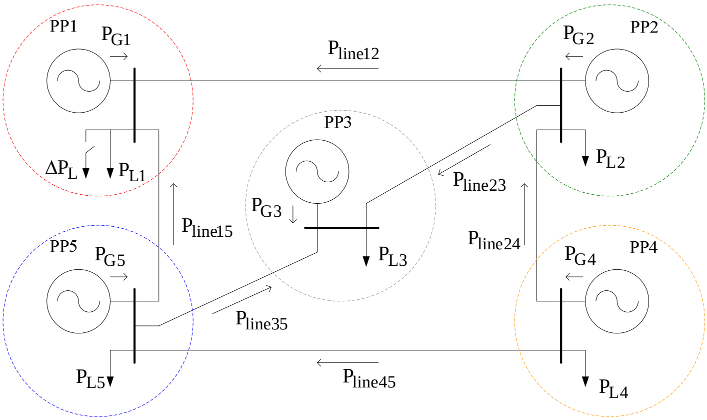


Fig. 5.1. Scheme of complex structure power system

In scheme of complex structure power system, which consists of a large number of power plants connected to each other via power transmission tie lines after the load power increase on one or more busbars of generators the dynamics of frequency deviation for each generator will differ, which is defined by many factors.

Distribution character of active power deficiency in all power regions after load power step up at 0.5 pu in PP1 in case of primary control with droop $R = 10\%$ of all governors is shown in Fig. 5.2. Character of frequency dynamics in case of adaptive control application for all power plants of power system is shown in Fig. 5.3. Character of adaptive control action dynamics estimated during control process is shown in Fig. 5.4.

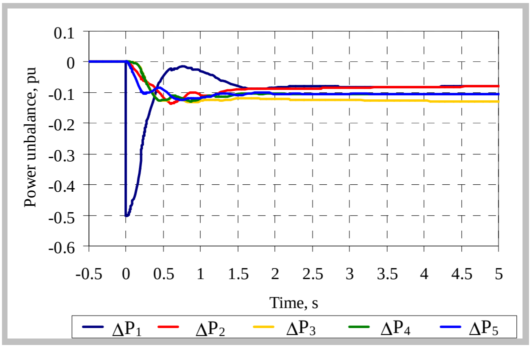


Fig. 5.2. Active power deficiency dynamics in case of primary control at all power regions

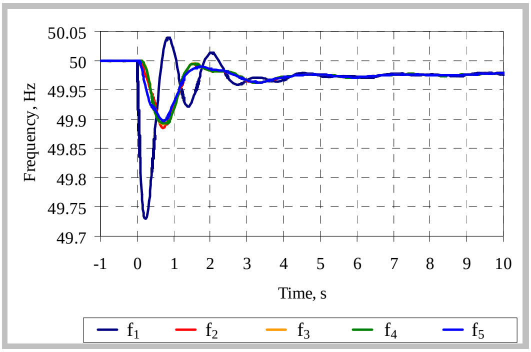


Fig. 5.3. Frequency dynamics in case of adaptive control actions applied at all power plants

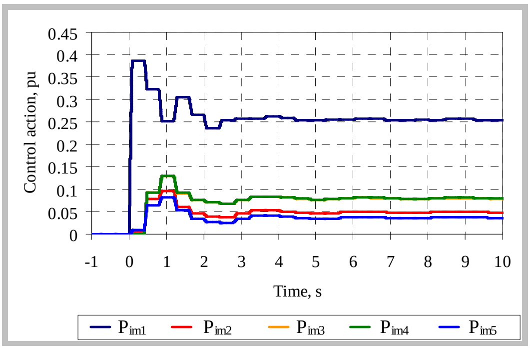


Fig. 5.4. Dynamics of adaptive control action applied at all power plants

Calculations of frequency control for different power system examples showed that:

– frequency after the operation of primary speed governors is not restored to its rated value, and the balance of active power sets at frequency below nominal. There is a need for secondary frequency control, which prolongs the control process deteriorating its quality;

- frequency control with the application of adaptive control actions can simultaneously perform primary and secondary control functions restoring both the active power balance and the nominal frequency. In addition, there is higher accuracy of frequency control, significantly lower frequency restoration time;
- difference between types of power system frequency control defines the different process dynamics. Frequency control system with method of adaptive control action dosing is more stable, frequency control quality – better;
- distribution character of active power deficiency indicates the location of emergency and the necessary control actions for each power plant in such way pointing to the necessary principle of control – to perform control action momentarily, thus preventing total deficiency (surplus) near the emergency location and without the involvement of other power plants in the control process, or to perform control after a while at all power plants simultaneously removing deficiency (surplus) portion distributed to every power plant;
- most beneficial option to perform an adaptive control is to provide control actions at all power plants. Especially important it is in case of few power plants, since the contribution of each power plant then is greater, as well as the term of large interconnections about the necessary reduction of reserve capacity in every individual power system is fulfilled;
- with the different rate of dosing of control actions various character of control process is obtained;
- proposed frequency control method efficiently functions during normal operational conditions of power system.

6. APPLICATION OF ADAPTIVE CONTROL ACTION DURING EMERGENCY CONTROL

The aim of this chapter is to examine the possibility of increasing power system stability during emergency situations with the application of proposed active power deficiency (surplus) in emergency automation. Emergency control is analyzed by carrying two tasks of providing stability – maintenance of power system frequency stability and stability of parallel operation.

Maintenance of frequency stability

Application of adaptive control actions in maintaining the frequency stability is viewed in scheme of concentrated power system with single generator, as well as in scheme of multi-machine concentrated power system, taking into account also the impact of voltage and reactive power variations. Principal electrical scheme of multi-machine power system created in PSCAD software with system parameters are shown in Fig. 6.1. [4].

Frequency dynamics for three emergency situations with different active power deficiency amounts considering the operation of existing UFLS is shown in Fig. 6.2. (a). Frequency dynamics for considered emergency situations considering the operation of load shedding automation with suggested principle is shown in Fig. 6.2. (b).

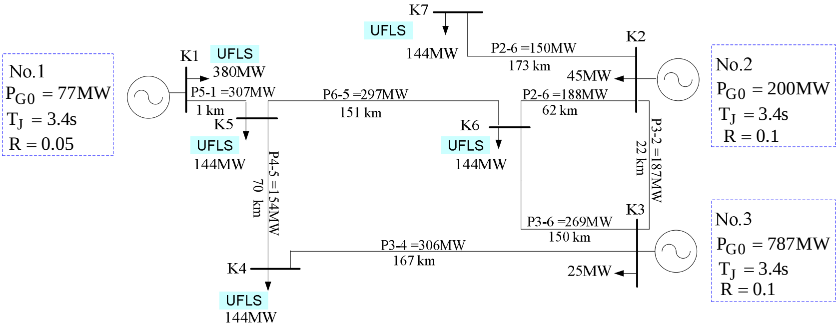
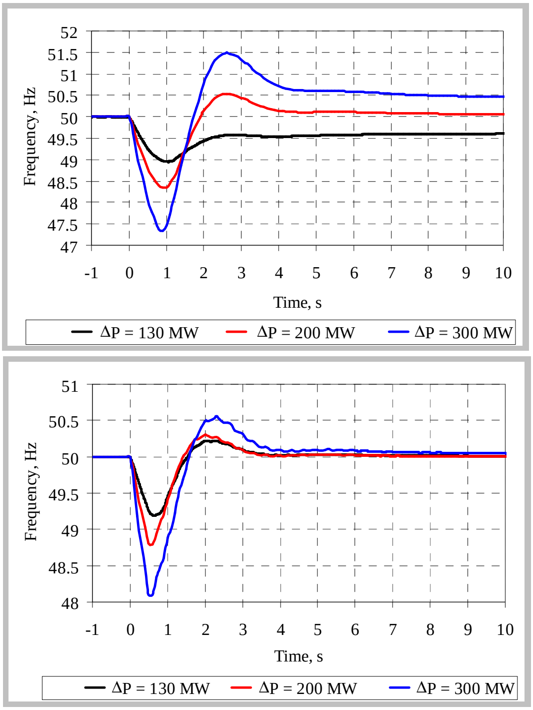


Fig. 6.1. Power system model for analysis of automatic load shedding operation



(a)

(b)

Fig. 6.2. Frequency dynamics: (a) considering operation of existing UFLS, (b) considering operation of proposed load shedding automation

Performed calculations allow concluding that:

– considered operation of automatic load shedding provides the task of frequency stability maintenance in both the concentrated single generator power system and multi-machine power system with distributed load;

– operation of new automatic load shedding more efficiently prevents decline of frequency, faster and more accurately restores frequency within acceptable limits, and eliminates frequency overcorrection in post-emergency condition;
– considered example of multi-machine power system presents centralized type of load shedding operation by summarizing all of the estimated active power deficiencies on each power plant and simultaneously applying the determined control action to each power substation provided for load shedding realization. It is useful to consider also a decentralized type of load shedding operation, assigning separate regions to each power plant for corresponding deficiency unloading.

Maintenance of power system parallel operation

Analysis of SDPA operation provided for accomplishment of the task of power system parallel operation maintenance, the operational principle's theoretical layout of which is suggested in Chapter 3, is observed during emergency conditions in two parallel connected power system scheme, in three machines scheme [5], and in multi-machine annular scheme [6]. For all examples the most characteristic emergency disturbance is examined, which is the tripping of power transmission line.

Principle electrical scheme of several interconnected power regions analyzed in thesis and representing a simplified equivalent of Baltic interconnected power system operating in parallel with the Russian and Belarusian power systems forming the so-called electrical ring, as shown in Fig. 6.3. [6].

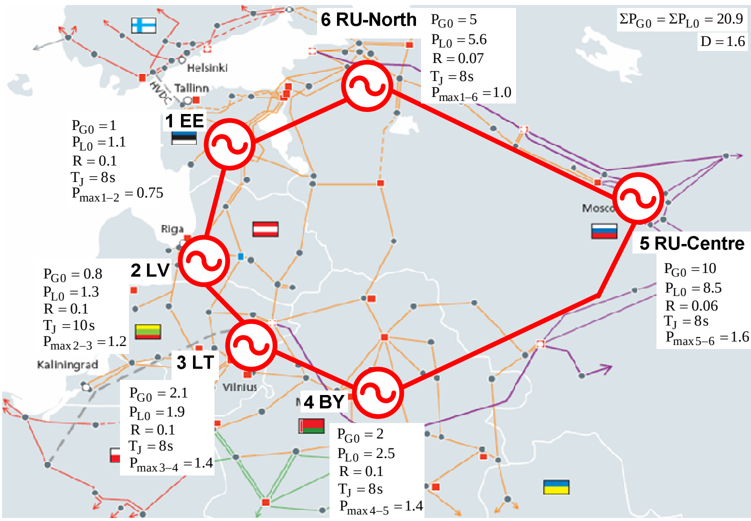


Fig. 6.3. Equivalent model of Baltic, Russian, and Belarusian interconnected power system

Disconnection of the loaded electrical cross-section between power systems of Russia Centre and North (Fig. 6.3.) will cause the out-of-step condition in the electrical cross-section between power systems of Russia Centre and Belorussia, since the considered cross-section is already heavily loaded at normal operational condition. Currently in such situation the emergency complexes in Baltic, Russian and Belarusian power system will react. In case of failure preventing out-of-step condition power system will be separated by disconnecting ties of risky cross-section. However, as the main task of this thesis is to maintain the parallel operation of power systems, then there the method of SDPA control action application is analyzed to maintain the synchronous operation of electrical ring.

Applying control actions of SDPA at each power region the stability of parallel operation of interconnection is maintained after considered emergency disturbance, as illustrated by the power unbalance distribution character in power system shown in Fig. 6.4. (a). Calculated and applied SDPA values of adaptive control actions at unloadable power regions are shown in Fig. 6.4. (b).

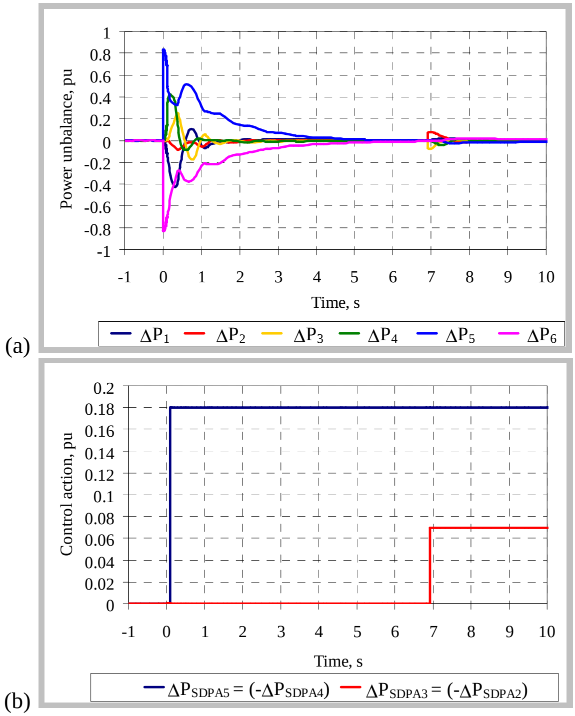


Fig. 6.4. Distribution character of active power unbalance value considering SDPA operation (a) and estimated SDPA control actions to the generation/load disconnection (b)

From the performed calculations it can be concluded that:

– after an emergency disturbance active power balance distributes along the interconnected power system by a certain law. Application of active power deficiency (surplus) calculating devices at each power system allows defining power unbalance at any time moment, thus providing information about emergency process and necessary control action;
– provision of each power system or region with SDPA performing the real time measurements of active power unbalance and power flow of power transmission

line allows determining the minimal necessary amount and type of control actions to maintain parallel operation of interconnection;

- application of proposed method for determination of adaptive control action significantly improves the reliability and adjusts the operation of automation for cascade type emergency situations, as well as allows avoiding of redundant consumers disconnection and operation of out-of-step prevention automation;
- SDPA calculations are performed in real time, and creation of SDPA does not require information on the power system topology, initial operational conditions, state of elements, and previously determined transient stability ranges;
- simultaneous and equal control actions of SDPA realized at the opposite sides of power system tie line provides a fast stabilization of transient process, eliminates frequency deviations at post-emergency state. It is an effective tool for the transient process stabilization and maintenance of parallel operation stability.

7. TESTING OF APPLICATION OF ADAPTIVE CONTROL ACTION METHOD IN THE BALTIC INTERCONNECTED POWER SYSTEM MODEL

This chapter gives the analysis of the application of method proposed in doctoral thesis for determination of adaptive control actions to emergency control in the Baltic interconnected power system model.

It should be noted that the main purpose of this chapter is not a precise simulation of isolated operation of Baltic power system, but to verify the possibility of the proposed principle to function in example of complex and real power system.

Fig. 7.1. Baltic 330 kV separated power transmission network

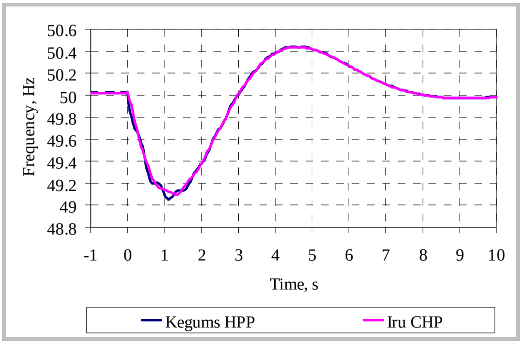
Mathematical model of interconnected power system of Baltic States is developed for examining dynamical processes in PSCAD software on the basis of experimental data of region separation in 2003. Baltic 330 kV power transmission network scheme during the separation experiment in 2003 is shown in Fig. 7.1.

For the simplification purposes of power system model each power plant is simulated as an equivalent generator, the rated output power of which corresponds to the total output power of power plant during the separation experiment in 2003.

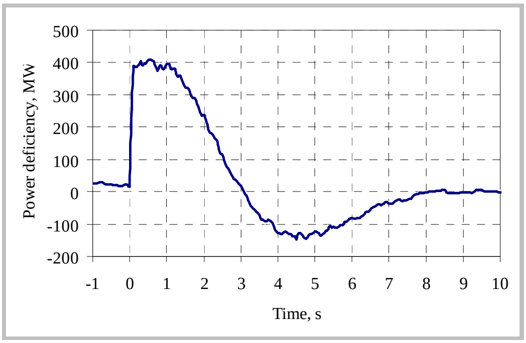
In all power plants the primary speed governors are simulated. Each power plant is equipped with the proposed active power deficiency (surplus) calculating device. Disconnection of generated power in Plavinas HPP is simulated as an emergency disturbance.

If the power governors of each power plant would be affected by the value corresponding to active power deficiency of this power system calculated in real time, then taking into account available capacity of spinning reserves the nominal frequency in the system will be restored automatically. In thesis it is assumed that spinning reserve capacity is sufficient.

Frequency dynamics in case of such control is shown in Fig. 7.2. (a). The corresponding active power deficiency dynamics considering operation of power governors with calculated deficiency value is shown in Fig. 7.2. (b). Elimination of deficiency with the new deficiency calculating governor prevents deep drop in frequency – the minimum value of frequency is less than 49 Hz, and about in 8 seconds the frequency is restored to its nominal value. It should be noted that in case of primary frequency control the minimum value of frequency reaches 48.9 Hz and the deviation remains around 49.4 Hz level.



(a)



(b)

Fig. 7.2. Frequency dynamics at Kegums HPP and Iru CHP busbars after disconnection of Plavinas HPP (a) and corresponding dynamics of total active power deficiency (b) considering the operation of power deficiency governors

Frequency overcorrection value could be reduced by optimizing the time constants of active power deficiency governor – a time of signal calculation period and impulse impact.

Similar calculations are made taking into account the operation of new power deficiency calculating governors along with centralized type of load shedding automation, as well as new power deficiency calculating governors along with decentralized type of load shedding automation.

The results showed that:

- control of power plant's generated power by the proposed active power deficiency (surplus) determination algorithm operates also in the complex power system with different types and characteristics of power plants;
- operation of proposed active power deficiency governors allows using capacity reserves of some power plants reducing the amount of disconnected consumers;
- proposed centralized type of load shedding automation successfully eliminates the active power deficiency occurred in power system, it is fast-acting and efficient;
- proposed decentralized type load shedding automation successfully operates in separate regions of power system by eliminating active power deficiency only in location of its occurrence and near;
- decentralized type of load shedding automation is a successful solution for maintenance of allowable frequency level after power system emergency separation into isolated power regions;
- both centralized and decentralized type of load shedding automation not only prevents a fast decrease in frequency, but also restores it to nominal value or close;
- emergency control system with active power deficiency (surplus) application is adaptive, which allows operating simultaneously different kind of automation with different types of control actions (generator/load disconnection, etc.);
- optimal operation of emergency automation with the application of active power deficiency (surplus) would significantly increase the efficiency of emergency control in the Baltic interconnected power system also in its isolated operation;
- operation of generator excitation governors at each power station does not affect the determination and elimination process of active power deficiency (surplus), as well as the voltage on the buses of power plants and substations remains within acceptable level during emergency control with application of active power deficiency (surplus) values.

8. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

1. Along with power system interconnection a great variety of operational conditions and emergency situations appears, thereby control of operational conditions becomes more complex. In turn, tasks of control accuracy and proper organization become more responsible along with the increasing significance of electricity supply reliability.
2. Major blackouts happened in interconnected power systems basically were related to the disturbances of active generated and consumed power balance causing unacceptable frequency deviations, which, in turn, is one of the key indicators of electricity supply quality in power system. Thus, it is necessary to know the exact size of balance disturbance, resp., appeared active power deficiency (surplus) in real time.
3. Existing control of normal operational conditions providing frequency and active power control in power system respond to the disturbances of power balance indirectly, it is slow-acting and not fully automated.
4. Existing emergency automation providing the change of generation or load in the power system basically operates with a pre-determined algorithm; it can not adapt to all possible emergency situations and is not adaptive to a process of definite emergency situation. Development of efficient automatic emergency control system and adaptive emergency automation is necessary.

5. Method for determination of adaptive control actions is proposed in thesis, which is based on the application of active power deficiency or surplus value calculated in real-time in normal and emergency operational conditions’ control automation. Dosing method is elaborated for application of calculated active power deficiency (surplus) value in frequency and power control automation, emergency load shedding automation, and stability disturbance prevention automation. Practical realization of the proposed algorithm is possible on microprocessor-based components.
6. Research methodology and mathematical models are developed for calculation of various power system operational conditions and analysis of the proposed method.
7. Simplified examples of mathematical models are given in thesis for different structure power systems, mainly with dominant thermal power plants. There is a need to improve models with more precise mathematical descriptions, with different types of power plants and governors considering also the operation of various existing automation and relay protection devices.
8. Proposed method was approbated using examples of practical application analysing operation of single concentrated power system, simple structure of interconnected power systems, more complex structure of multi-machine interconnected power systems, and detailed Baltic power system. Results obtained during development of thesis showed the efficiency and advantages of proposed method application.
9. Basic operational principles of the proposed method in power system examples were analyzed at a constant or stably maintained voltage (in case of Baltic power system example). Possible impact of voltage and reactive power changes to the proposed control principle should be analyzed additionally.
10. Proposed method can be extended considering also voltage dependent functions of power system elements in the algorithm of adaptive control action determination.
11. Proposed active power deficiency (surplus) dosing method can be improved using some additional optimization procedures to determine more efficiently the intensity of control impulse, to reduce the possible control errors, as well as to considering operating time of switches and equipment.
12. Emergency load shedding automation with decentralized type of operating principle is offered determining and implementing control actions only in emergency originating region. It would be necessary to deepen the study of the proposed principle by optimizing the organization of load shedding automation operation and selection of necessary parameters within each region.
13. Simple disturbances are analyzed, mainly, associated with emergency disconnection of a grid element, but it would be necessary to evaluate the operation of proposed method also in case of short circuits close to power plant, as well as to extend the study of cascading emergency situations.
14. Emergency control with the proposed method is evaluated on certain assumptions and simplifications. Further development of method requires more in-depth study of its organization and application for using of certain emergency tools, for example, development of algorithms for selection of switchable generators and load, selection of parameters for generator dynamic braking, turbine power output limitation, etc.
15. While the essential advantage of active power deficiency (surplus) determination method is gradually decreasing of errors caused by inaccurately selected parameters, yet there should be also considered the impact of calculating device failure on control of operational condition and necessary organization of control redundancy, as well as coordination with other types of automation operating in power system.

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