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SYNTHESIS AND ANALYSIS OF POWER SYSTEM SMART AUTOMATION

Summary of Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
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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.

Roman Petrichenko ....(signature)

Date ....

The doctoral thesis is written in Latvian language, it contains introduction, 4 chapters, conclusions, recommendations and list of references. Total number is 182 pages, which include 32 figures, 4 tables, 14 appendixes. The list of references includes 122 literature sources.

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1. General description of the work

1.1. Topicality of the work

Problems of economical efficiency, reliability, impact to environment for energy production and consuming systems became very topical in the connection with dynamic development and complication of electric power systems, growth of cities, and development of new infrastructures. Even short interruption of energy supply is very dangerous for such systems. Large blackouts, happened in some countries, caused great damages and even victims. There is a tendency in increase of energy production expenses. In some countries there is still drawback of electrical energy. Increase the efficiency of electrical energy production and distribution lead to the change in electric power system structure and use of market approach [1]. However there are contradictions between reliability, impact to environment and efficiency.

Indeed there should be large expenses for different types of reserves, maintenance of emergency automation, increase of transmission line capacities and creation of renewable energy sources. Problems of economical efficiency, reliability, impact to environment should be solved for continuously variable conditions. Let us use abbreviation for electric power system efficiency criterion – EEC. It is obvious that the change of electric power system's functioning conditions includes wide time diapason. This diapason is from milliseconds for wave processes to years for introduction of the new generating facilities. Depending on the electric power system functioning conditions EEC value determination is variable. For fast acting processes human-operator is not able to take rational control decision. Control process should be automatic. For slow processes is possible to perform complex calculations and modeling. For considered doctoral thesis fast operational processes are considered when decision for control should be performed by automation devices. Large technical and economical effect is provided during smart grid methodology application for power system control [2]. Synthesis and analysis of smart grid application for control system is presented in doctoral thesis.

The use of market conditions for electric power system operational control results in contradictions in strivings for controversial EEC. For example, trend to increase an economical efficiency can result in recommendation to increase permissible overload of transformer, transmission line and other power equipment. This will minimize reserves for providing of static, dynamic and thermal operational conditions or recommends to use only fossil fuel that will maximize influence of energy production to environment.

Nowadays control of power system causes necessity to fulfill multi criteria optimization tasks. There are at list four goals for control:

1. Increase of economical efficiency;
2. Increase of reliability level;
3. Minimization the influence to environment;
4. Improvement of sustainability.

For realization of mentioned aims many investigations and devices were performed. Significant contributions were made by Latvian scientists: Jānis Bubenko, Veniamin Fabrikant, Jēkabs Kuzmins, Jānis and Voldemars Putniņi, Jānis Gerhards, Zigurds Krišāns, Jēkabs Barkāns, Antans Sauhats, Vladimirs Čuvičins, Anatolijs Mahnitko, Kārlis Briņkis, Vilnis Krēsliņš. Complexity of power engineering problems and limited technical resources were the reason that many scientific investigations in 20 century were limited with simplified optimization approach. Usually one or two parameters were considered as optimization goals, but others were considered as limiting conditions. In considered doctoral thesis all goals are considered as criterion functions. This is very topical approach. So called Smart Grid technology approach can be used as solution for development of a new power system control methods and systems. Part of this approach is considered in doctoral thesis as investigation objective [3, 4].

1.2. Objectives and tasks of the thesis

Increase of energy supply efficiency and reliability value will minimize emissions and improve sustainability. For achievement of specified objectives mentioned below tasks were fulfilled in doctoral thesis:

1. Analytical survey of Smart Grid technology application was done [1, 2, 5, 6].
2. The new centralized automatic underfrequency load shedding algorithm and model was developed. Smart Grid technology was used for new algorithm and model.
3. A new frequency control method was developed. Coalition of the large number generating facilities was provided for this method. Possibility to get additional profit was proven. The Shapley method was used for this purpose.
4. For calculation of Shapley vectors specialized programme was synthesized and verified (Matlab/Simulink environment).
5. For verification of the new frequency control method simulations of operational conditions for 3 and 5 generating districts were done. Additional profit was calculated for electric power system with parameters similar to the Latvian power system parameters.
6. Hydro generators' stability analysis was performed and specialized programme was synthesized for selection of power system stabilizers parameters.
7. Emergency underfrequency condition was analyzed for large interconnection with different underfrequency load shedding systems.

1.3. Scientific novelty of doctoral thesis

1. Completely new underfrequency load shedding automation algorithm and layout was justified. The efficiency of algorithm implementation was proved for underfrequency emergency liquidation.
2. Completely new power system frequency control method was synthesized. Method is based on application of the new (for such tasks) mathematical approach (cooperative game theory and Shapley vector) and Smart Grid technology.
3. The models of underfrequency load shedding automation and centralized generation reserves were synthesized. Models were realized using Matlab/Simulink environment. Models and programme efficiency was verified.
4. Application of Smart Grid technology for electric power system frequency control automation allows to increase automation's efficiency. Besides there is possibility to receive additional profit and to increase reliability level.
5. For hydro generators' stability analysis models and their realization algorithms were synthesized and verified.

1.4. Methodology of research

1. Matlab/Simulink programme complex is used.
2. Differential equations and their solution methods are used for modeling of electric power system units in Matlab/Simulink environment.
3. Cooperative game theories were used especially Shapley vector approach.

1.5. Practical value of doctoral thesis

1. Suggested frequency control method can be used for analysis of competitiveness improvement of Latvenergo and private Latvian electric power plants and as result – there will be hundreds thousands euro of economical efficiency.
2. In spite of that for realization of suggested underfrequency load shedding automation there is need in additional expenses and in development of coordination with the neighbor countries, realization of automation is possible taking into consideration development of communication channels and Smart Grid technology application in the power systems.
3. Results of simulation of emergency underfrequency conditions are used as part of the international European project ICOEUR, devoted to analysis of possibility for joint operation of European and Russian electric power companies.
4. The modern underfrequency load shedding automation can be executed partially (proved by calculations). Such possibility is very important for modernization of automation.
5. Developed methodology for selection of Keguma HPP power system stabilizer's parameters can be used for improvement of generator's stability level.

1.6. Main aspects of research to defend

It is proven in thesis that application of Smart Grid technology can create:

1. New electric power system frequency control method which, because of creation of generating companies' coalition and Smart Grid technology application, ensure effective generation control and additional economical effect.
2. New underfrequency load shedding automation for prevention of frequency emergency situation which is equipped with fast acting communication channels and smart metering system and is able to interrupt emergency situation development and to liquidate the consequences.
3. Analysis of behavior for a large joint power system from the point of view efficiency of the frequency automation was performed. Availability of the problem was proven and possible solution methods were presented.
4. To synthesize models and prove possibility to optimize HPP stabilizer's setting methodology for improvement of stability value.

1.7. Personal contribution of author to performed research

Fundamentals of defended thesis are ideas developed under supervision of professors Vladimir Čuvičins and Antans Sauhats. Doctoral thesis can be considered as continuation the research activity of professors.

Verification of ideas, simulation of the processes in electrical power systems, development of the models and necessary programming approaches, numerical experiments and their analysis, recommendations for application – all is personal contribution of author.

1.8. Approbation of doctoral thesis

1.8.1. The results obtained in the frames of development of the thesis were reported and discussed at **9 international conferences:**

1. The 6th International Conference on Electrical and Control Technologies – ECT2011, "The Influence of Excitation System's Parameters to the Power System Stability", Kaunas, Lithuania, 5.04-6.04.2011.
2. The 10th International Conference on Environment on Electrical Engineering (EEEIC2011), "Optimization of Excitation System Parameters for Kegums Hydro Power Plant of Latvia", Rome, Italy, 8.05-11.05.2011.
3. The 7th International Conference on Electrical and Control Technologies – ECT2012, „Application of Smart Grid Technologies in Emergency Automation", Kaunas, Lithuania, 3.05-4.05.2012.
4. The 3rd International Symposium on Power Electronics for Distributed Generation System, „Smart Load Shedding System", Aalborg, Denmark, 25.06-28.06.2012.
5. 10th International Scientific Conference "Control of Power Systems 2012 (CPS2012), „Development of Smart Underfrequency Load Shedding System", High Tatras, Slovakia, 15.05-17.05.2012.
6. 12th International conference on Environment and Electrical Engineering, "Coexistence of different load shedding algorithms in interconnected power system", Wroclaw, Poland, 5.05-8.05.2013.
7. PowerTech2013 conference, „Underfrequency Load Shedding in Large Interconnection", Grenoble, France, 16.06-20.06.2013.
8. PowerTech2013 conference, „Spinning Reserve Allocation Using Game Theory", Grenoble, France, 16.06-20.06.2013.
9. The 2014 International Conference on Power Systems, Energy, Environment (PSEE'14), "Problems of fast frequency variation control in interconnected power systems", Interlaken, Switzerland, February 22-24, 2014.

1.8.2 During two conferences (12th International conference on Environment and Electrical Engineering and 10th International Scientific Conference "Control of Power Systems 2012") two reports "Development of Smart Underfrequency Load Shedding System" and "Coexistence of different load shedding algorithms in interconnected power system" were considered as the best papers and awarded by corresponding prizes.
1.8.3 Suggested frequency control and underfrequency load shedding methodology were discussed with "Latvenergo" and „Siltumelektroprojekts" leading experts.
1.8.4. The results obtained in the frames of development of the thesis are included in **14 publications** in international proceedings:

1. N.Gurovs, **R.Petričenko,** „Sinhronā ģeneratora stabilitātes paaugstināšana ar ierosmes sprieguma regulēšanas metodi", RTU zinātniskie raksti. 4. sēr., Enerģētika un elektrotehnika. - 26. sēj., 76-80 lpp. (*EBSCO, ProQuest, Versita, VINITI*).
2. V.Chuvychin, N. Gurov, **R. Petrichenko**, "Optimization of Excitation System Parameters for Kegums Hydro Power Plant of Latvia", The 10th International Conference on Environment on Electrical Engineering (EEEIC), 8-11 May 2011, Rome, Italy. (*IEEE Xplore*, *Elsevier's EI Compendex, IET's Inspec, SCOPUS, Thomson Reuters' Web of Science).*
3. V. Chuvychin, **R. Petrichenko**, "Application of Smart Grid Technologies in Emergency Automation", The 7th International Conference on Electrical and Control Technologies 3-4 May 2012, Kaunas, Lithuania, p.135-138 (*indeksēts ISSN 1822-5934*).
4. V. Chuvychin, **R. Petrichenko**, "Smart Load Shedding System", The 3rd International Symposium on Power Electronics for Distributed Generation System, 25 - 28 June 2012, Aalborg, Denmark, p.64-71 (ISBN 978-1-4673-2022-1, *IEEE Xplorer and EI Compendex*).

5. V.Chuvychin, N. Gurov, **R. Petrichenko**, A. Dambis "The Influence of Excitation System's Parameters to the Power System Stability", "Journal of Energy and Power Engineering" ISSN 1934-8975, USA, vol.6, Nr.7., July 2012 p. 1146-1152 (*EBSCO, CSA, CEPS, OCLC, SummonSerials Solutions*).
6. V. Chuvychin, **R. Petrichenko**, "Development of Smart Underfrequency Load Shedding System", "Journal of Electrical Engineering", Slovakia, VOL. 64, NO. 2, 2013, p.123-127 (*ISSN 1335-3632*, *Thomson-Reuters SCIE, Scopus Elsevier, INSPEC, IET and ADS Harvard, last impact factor 0.278*).
7. **R. Petrichenko**, V. Chuvychin, A. Sauhats, "Coexistence of different load shedding algorithms in interconnected power system", 12^{th} International conference on Environment and Electrical Engineering, 5-8 May, 2013, Wroclaw, Poland (ISBN 978-1-4673-3058-9, *IEEE Xplorer).*
8. A. Sauhats, V. Chuvychin, V. Strelkovs, **R. Petrichenko**, E. Antonov, "Underfrequency Load Shedding in Large Interconnection", PowerTech2013 conference, Grenoble, France, 16-20 June 2013 (*IEEE Xplorer).*
9. **R. Petrichenko**, A. Sauhats, V. Chuvychin, "Spinning Reserve Allocation Using Game Theory", PowerTech2013 conference, Grenoble, France, 16-20 June 2013 (*IEEE Xplorer).*
10. **R. Petrichenko**, M. Kolcun, M. Novak, „The application of the combined method for selection of optimal excitation parameters", The 7^{th} International Scientific Symposium on Electrical Power Engineering, Košice, Slovak Republic, 18-20 September, 2013.
11. M. Novak, **R. Petrichenko**, I. Zicmane, "Modeling of excitation system influence to transient stability of power system using PSLF", The 7^{th} International Scientific Symposium on Electrical Power Engineering, Košice, Slovak Republic, 18-20 September, 2013.
12. **R. Petrichenko**, A.Sauhats, V. Chuvychin, "Spinning reserve allocation using shapely method", Riga Technical University 54th International Scientific Conference on Power and Electrical Engineering, 14-16 October, 2013 (*EBSCO, ProQuest, Versita, VINITI*).
13. V. Chuvychin, A. Sauhats, **R. Petrichenko**, G. Bochkarjova, "Problems of fast frequency variation control in interconnected power systems", The 2014 International Conference on Power Systems, Energy, Environment (PSEE'14), Interlaken, Switzerland, 22-24 February, 2014(SCOPUS, EBSCO, Scholar Google etc).
14. A. Sauhats, E. Kucajevs, D. Antonovs and **R. Petrichenko.** Monitoring, Control and Protection of Interconnected Power Systems, Chapter 14 "Dynamic Security Assessment and Risk Estimation", Springer-Verlag Berlin Heidelberg, 2014.

1.9. The structure and content of doctoral thesis

Doctoral thesis is prepared for defense as a set of publications. The set of publications consist of 16 scientific publications, which are segregated to four groups:

1. The **first group** is devoted to the syntheses of smart underfrequency emergency automation.
2. In the **second group** publications are devoted to underfrequency load shedding system during emergency situation in the large interconnections.
3. In the **third group** publications are devoted to analysis of power system generator stabilizator's settings selection.
4. The **fours group** publications are devoted to analysis of spinning reserve allocation developing generators' coalition.

2. Development of smart underfrequency load shedding system

2.1. Introduction

During emergency situation in the power system caused by generating power deficiency frequency decline takes place. Dynamics of underfrequency during the deficiency of generation in the power system can have very different character. It depends on the value of disturbance, response of emergency automation, governor system and reasons of emergency situation [7-9].

Existing underfrequency load shedding automation (UFLS) has drawbacks, which limit adaptability of emergency automation to a change of underfrequency situation in a power system. UFLS tripping frequency settings are selected for some specific emergency situation, which is considered more probable for specific power system. It is not possible to foresee all situations that can occur in the power system. UFLS operation will be effective only for mentioned calculated emergency cases. Problem of value of a load to be shed is also very topical. Redundant tripped load can create overfrequency situation, which sometimes is more dangerous than underfrequency [10-12].

There is a need in creation more sophisticated and adaptive underfrequency load shedding system. Problem is very topical especially taking into consideration creation of intersystem transmissions. Many papers described attempts to develop adaptive load shedding systems using frequency and rate-of-change of frequency. The drawback of traditional and some new developments is that value of shedded load sometimes does not coincide with the value of active power deficiency. As consequence of this imbalance overfrequency of frequency hovering situations can occurs.

With the rapid development of information technology is possible to receive and process a big amount of information during minimum time.

Application of the new information technology allows to develop smart underfrequency load shedding system.

2.2. Application of smart grid (meters) approach to the emergency automation system

The aim of this chapter is illustration of integration of smart grid technology into emergency automation and investigation of control process of such automation. Fig. 1.1. shows the simplified diagram of the power system. As can be seen from the Fig. 1.1., the power system consists of five power districts. Each power district generates and consumes a certain value of active power. Power districts are connected via transmission lines.

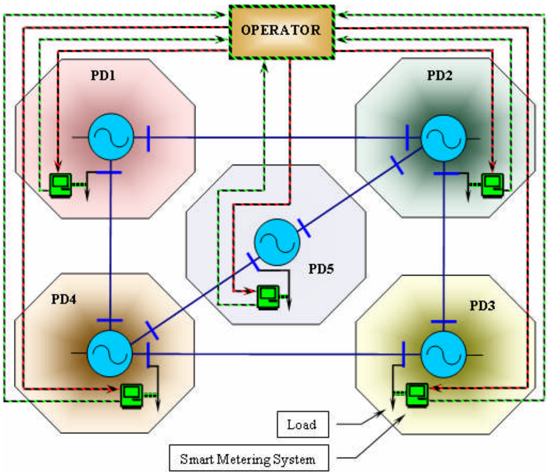

Fig.1.1. Simplified diagram of interconnected power districts with smart metering system technology

Each district is equipped with interactive measuring device (smart meter) [3]. Measuring device interactivity means receiving of information about the active power consumption and generation as well as full load control (load shedding and restoration).

In Fig. 1.1 measuring devices are connected to a central control unit "Operator", hence, interactive information system between districts' load and emergency automation is made.

Each power district is equipped with a power deficiency calculation block. Let us consider appearance of deficiency value and its determination:

Electric power manufactured by generators P_G during the normal operational condition always is equal to a load power P_{Load}.

$$P_G = P_{Load} \tag{1}$$

When deficiency appears in the power system (for example due to disconnection of part of generating power) imbalance takes place between generated and consumed powers:

$$\Delta P = P_G - P_{Load} \tag{2}$$

Rotor swing equation can be used for calculation of deficiency:

$$\frac{T_J}{f_{nom}} \cdot \frac{df}{dt} = P_G - P_{Load} = \Delta P \tag{3}$$

Equation (3) can be transformed [11]:

$$\Delta P = T_J \cdot \frac{df}{dt} + \frac{\Delta f}{k_{gov}} + \Delta f \cdot k_{load} \tag{4}$$

where $\Delta f = \dfrac{2 \cdot \pi \cdot f - 2 \cdot \pi \cdot f_0}{2 \cdot \pi \cdot f_0}$

T_J – rotor's inertia constant; P_G – electric power of generator; P_{Load} – electric power of the load; k_{gov} – governor speed droop; k_{load} – load-damping constant; f – frequency.

In such a way information center "Operator" receives the full information about the current condition of the active power consumption in each power district, about the location and value of arisen deficiency.

Automation's operational process (let's call it smart underfrequency load shedding system - SUFLS) can be presented by few calculation cycles:

A. Determination of deficiency value;
B. Memorization of deficiency value and its location;
C. Calculation of number of substations to compensate deficiency;
D. Calculation of optimal variant for disconnection of load.

2.3. Case study

To compare results of UFLS and SUFLS automation operation the mathematical model has been constructed using Matlab Simulink software. Behavior of frequency during different emergency situations is presented. Parameters of power system are shown in the Table 1.1 (Experiment A, B) [13, 14].

Experiment A.

The governor speed droop at all stations is equal 10%. As emergency situation power instant deficiency ΔP = 1.4 (p. u.) at the third power district at the time moment t = 0.0 (sec) was simulated. Transmission lines have a concrete maximal admittance of transmitted active power (see Table 1.1).

Fig. 1.2 illustrates frequency behavior at emergency situation.

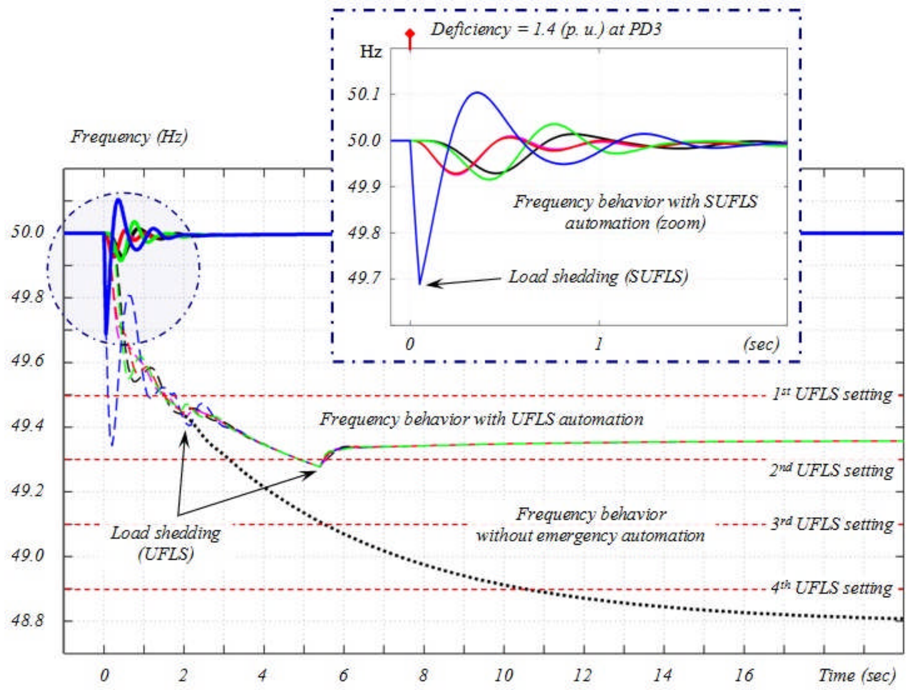

Fig.1.2. Frequency behavior for different types of load shedding automation

Comparison of UFLS system and SUFLS system shows advantage of new suggested automation system. During operation of UFLS system frequency hovering takes place at the level of 49.36 Hz. During operation of SUFLS system short decline of frequency to 49.69 Hz level is observed. It should be noted that the precision of the SUFLS automation depends on the discreteness of the disconnected load at each power district. Speed of load shedding depends on the type of circuit breakers. In this paper, assumed that gas-insulated circuit breakers, with operating time t~0.05 (sec) are used.

Experiment B.

The operation of proposed automation has been also tested at cascade emergency situation. Cascade emergency situation is more dangerous and happens very often. Power system parameters are shown in the Table 1.1 (Experiment A, B). As emergency situation power instant deficiency at the fifth and the third power district at time t=0 (sec) and t=160 (sec) was simulated. The assumed active power deficiency value is 2.0 (p. u.) and 1.4 (p. u.) respectively. Fig. 3 shows the behavior of the power system's frequency using the existing emergency automation UFLS and the proposed emergency automation SUFLS.
The red dashed horizontal lines show automation UFLS settings. Frequency values of the 1st, 2nd, 3rd and 4th UFLS automation's settings respectively are 49.5, 49.3, 49.1, 48.9 Hz. When frequency crosses UFLS automation settings load shedding takes place. Let's consider frequency behavior when traditional UFLS is operating.
As seen from Fig.3, when the first deficiency occurs at t=0 (sec), three steps of the load shedding were activated. During this operation the frequency drops to 49.12 Hz and hovers at this level. Then frequency restoration is simulated (using traditional UFLS2 automation). After restoration frequency hovering at level 49.89 Hz takes place.

Table 1.1. Network condition

Experiment A, B					
Power district	***Generation [p. u.]***	***Load [p. u.]***	***Not available load [p. u.]***	***Available load [p. u.]***	***Maximal admittance of transmission-line [p. u.]***
PD1	$P_{G1} = 1.0$	$P_{Load\ 1} = 1.5$	$P_{NotAvLoad1} = 0.00$	$P_{AvLoad1} = 1.50$	$P_{max1-2} = 0.71$
PD2	$P_{G2} = 1.0$	$P_{Load\ 2} = 1.0$	$P_{NotAvLoad2} = 0.00$	$P_{AvLoad2} = 1.00$	$P_{max2-5} = 1.25$
PD3	$P_{G3} = 1.5$	$P_{Load\ 3} = 1.5$	$P_{NotAvLoad3} = 0.00$	$P_{AvLoad3} = 1.50$	$P_{max2-3} = 0.97$
PD4	$P_{G1} = 1.5$	$P_{Load\ 1} = 0.5$	$P_{NotAvLoad1} = 0.00$	$P_{AvLoad1} = 0.50$	$P_{max3-4} = 0.97$
PD5	$P_{G1} = 2.0$	$P_{Load\ 1} = 2.5$	$P_{NotAvLoad1} = 0.00$	$P_{AvLoad1} = 2.50$	$P_{max4-1} = 0.97$, $P_{max4-5} = 1.25$

When the second emergency situation occurs at t=160 (sec), three already disconnected steps cannot be used for load shedding. As shown in the Fig. 1.3, only 4th step of UFLS is activated. In case of SUFLS operation the deep drop of frequency isn't observed. SUFLS automation chooses the optimal variant of disconnected load at the first and the second occurrences of active power deficiency. As result of SUFLS operation, frequency does not drop below 49.56 Hz (at the first occurrence of deficiency). Accuracy of SUFLS automation operations is better than the traditional ones.

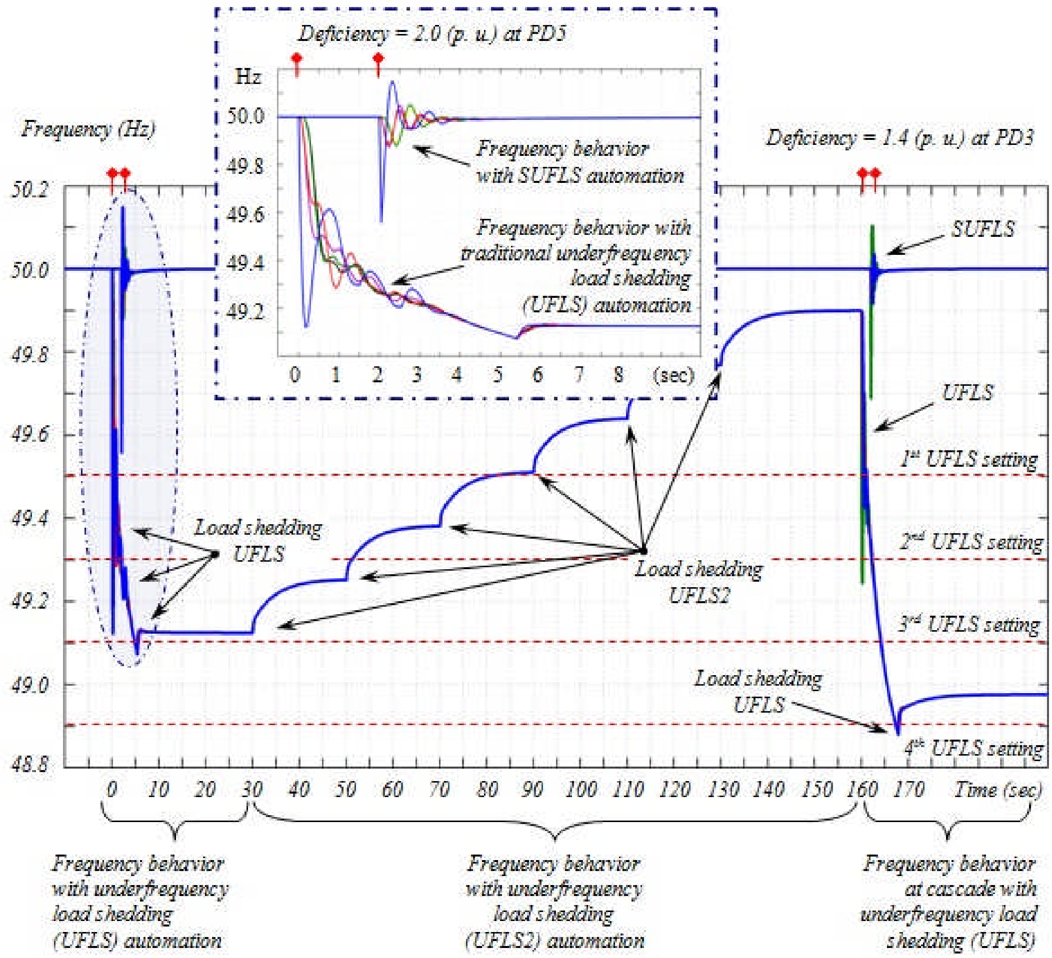

Fig.1 .3.. Frequency behavior at cascade type of emergency situation

2.4. Conclusions

- The drawback of traditional UFLS is that value of shedded load sometimes does not coincide with the value of active power deficiency. As consequence of this imbalance overfrequency or frequency hovering situation can occur.
- New method of load shedding is suggested. Simulations for analysis for frequency behavior were conducted for existing and new load shedding system.
- The advantages of SUFLS automation are: suggested load shedding system is more effective emergency automation system than traditional underfrequency load shedding system; new emergency automation allows to prevent deep frequency drop during generated deficiency condition; for large united power system suggested frequency control algorithm can be implemented for different power system districts separately.
- Shedded load restoration algorithm is described. As well as simulation of restoration for frequency behavior's analysis was observed.

3. Underfrequency load shedding systems in large interconnections

3.1. Introduction

During the last years many international projects were devoted to the problem of interconnection of the large transmission networks in Europe [15]. Such system has been built from the national transmission grids that were progressively interconnected for the main purpose

One example of a large transmission network is possible interconnection of ENTSO-E system with the system of the Baltic States and IPS/UPS system of Russia.

There are many problems that complicate such interconnection:

- Different philosophy of frequency and active power control can cause oscillations of power transmitted through the intersystem tie line.
- Methods of frequency control for normal and emergency operational conditions in different systems are different.
- During emergency situations probability of out-of-step condition is raised. In some cases islanding take place not obligatory at intersystem tie line.

A very important task for operators of large scale interconnected power systems is the analysis of methods and tools for assessing the stability of large transmission systems. The different parameters of underfrequency load shedding system in each united power system can cause nonselective load shedding and hence, underfrequency or overfrequency emergency situations.

This chapter presents result of analysis of frequency behavior for power system interconnection with different types of UFLS automation.

3.2. Main parameters of underfrequency load shedding system

Fig. 2.1. presents an example of a frequency variation during operation of the frequency actuated load shedding system [16, 17]. The point $f < f_{nom}$ corresponds to the moment of active power deficiency appearance in the power system. From this moment the frequency drop starts.

When the power system frequency reaches the level of a first load shedding setting f_{set1}, the first part of the load is disconnected. The next part of the load will be disconnected when frequency reaches second load shedding setting f_{set2}.

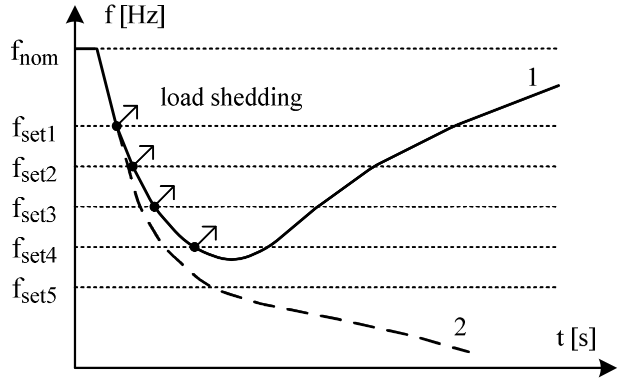

Fig.2 .1. Power system frequency variations during the UFLS operation

With each next load shedding step rate-of-change of frequency decline is cut down and after a certain moment the increase of frequency takes place. Such logics of the load shedding operation apply to most of the power system utilities.

The joint power system of the former USSR has more advanced frequency actuated load shedding automation which is described in the paper. The first system is the fast-acting automatic load shedding system with different frequency settings called UFLS-I. The aim of this system is to prevent deep frequency drop.

The second system is an automatic load shedding system with one frequency tripping setting for all steps and different tripping time delay called UFLS-II. The aim of UFLS-II is to restore the frequency to a level close to the rated frequency value.

3.3. The goal of analysis of frequency behavior during emergency situation in the power system

A very important task for operators of large scale interconnected power systems is the analysis of methods and tools for assessing of stability the transmission system. Paper shows results of an analysis of frequency behavior during emergency situation in united power systems of ENTSO-E and IPS/UPS (see Fig. 2.2).

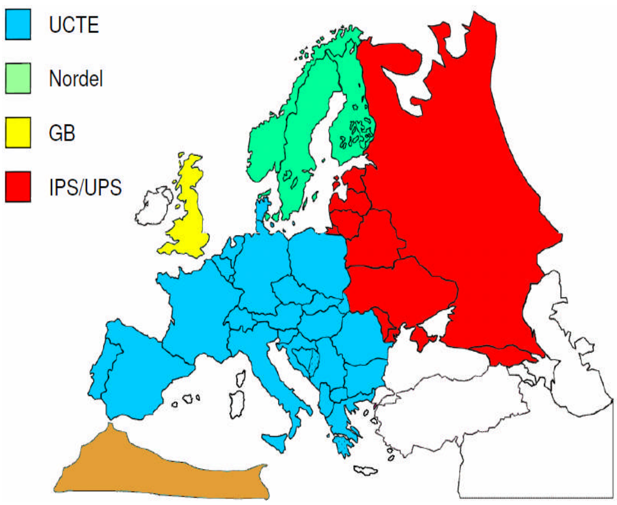

Fig. 2.2. Synchronous areas in Europe

The different parameters of underfrequency load shedding automation in each united power system can cause nonselective load shedding and hence, underfrequency of overfrequency emergency situations.

The model of first category under-frequency load shedding was created which is presented in Fig. 2.3.

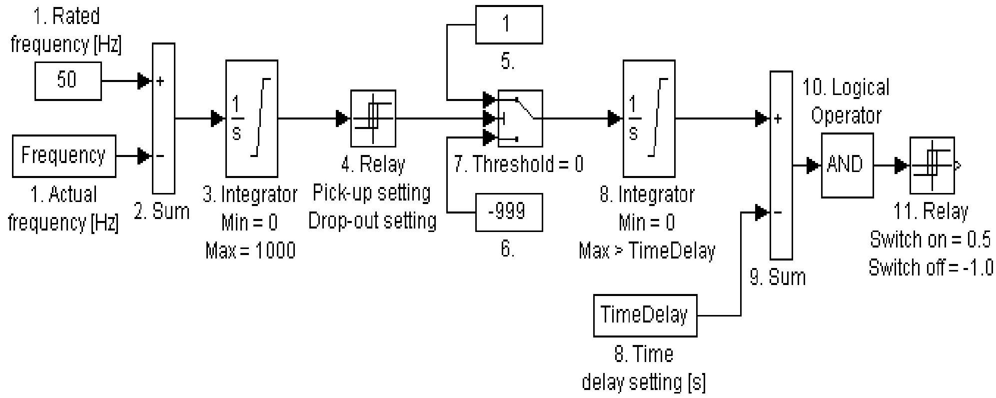

Fig. 2.3. The structure of UFLS-I model for one step

The goal of the analysis is to find operational conditions which can cause emergency situations.

3.4. Analysis of frequency behavior for different algorithms of UFLS

As it was mentioned above, the main objectives of the UFLS is to prevent decline of the system frequency. This chapter presents results of analysis of under-frequency load shedding operational effectiveness for different emergency situations caused by loss of part of the generation. The specific structure of the load shedding automations for ENTSO-E and IPS/UPS power systems will be presented in the paper. For this purpose appropriate model was developed for simulation of frequency behavior.

In different countries parameters of load shedding algorithm are different. For developing an algorithm of the load shedding system the below mentioned problems should be taken into consideration:

- Selection of upper frequency setting level.
- Selection of intervals between nearest frequency settings.
- Maximal capacity of a load connected to the load shedding system should be determined. This problem is solved specifically for each power system.
- Selection of the number of necessary steps for the load shedding.
- Selection of the tripping time for a load shedding automatic relay.

A. Analysis of frequency behavior in the ENTSO-E and the Baltic States system during operation of underfrequency load shedding

This chapter describes frequency behavior when both systems are interconnected with the strong tie lines.

In Fig. 2.4 the frequency behavior is shown with a deficiency of active power equal to 5 % and 10 % of the total generation for the ENTSO-E power system. The frequency does not restore to its nominal value after the under-frequency load shedding operation because the total disconnected load by the steps of UFLS is twice smaller as the deficiency of active power in both cases.

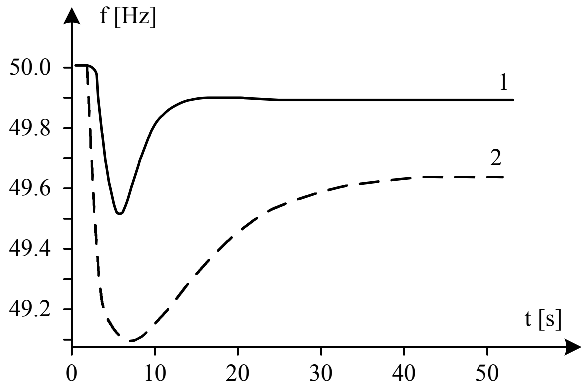

Fig. 2.4. Frequency behavior for 5% (1), 10% (2) of active power deficiency

Thus for the second case two tripping steps (49.5 and 49.3 Hz) where initiated with 5% of disconnected load. Load-damping was assumed to be constant and equal to 2. This parameter provides smooth restoration of the frequency up to the level of 49.6 Hz.

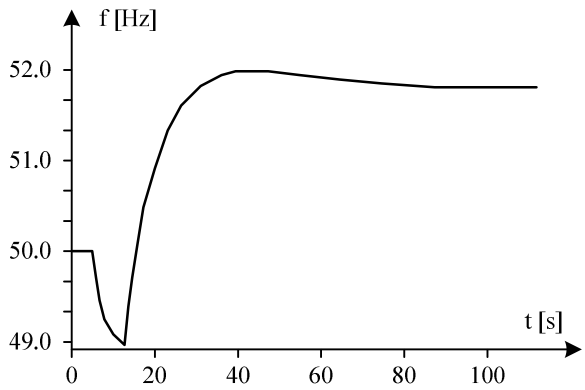

Fig. 2.5. Frequency behavior for 10.8% of active power deficiency

Fig. 2.5 presents results of calculation of emergency situation caused by loss of 10.8% of generation (P_{def} = 10.8%).The overfrequency situation after UFLS operation happens because the total disconnected load of the steps of UFLS is two times as large as the deficiency of active power in the network. Three steps of UFLS (49.5, 49.3 and 49.0 Hz) disconnect 20% of the load. An overfrequency situation was discovered which is very dangerous for the power system. This simulation proves that probability of nonselective operation of UFLS is possible.

Very often underfrequency situation in the power system has so called iterative (cascade type) character when after first loss of generation a second generating source can be lost.

The frequency behavior at a load deficiency of 20% and an iterative deficiency of the active power of 6.7% is shown in Fig.2.6. During cascaded event the stabilization of frequency can occur at a dangerously low level without being noticed by UFLS. In some professional publications this situation is called as "frequency hovering". It can happen if the active power disconnected by UFLS is not sufficient to return frequency back to permissible range. In the considered case the frequency stays at 48.9 Hz.

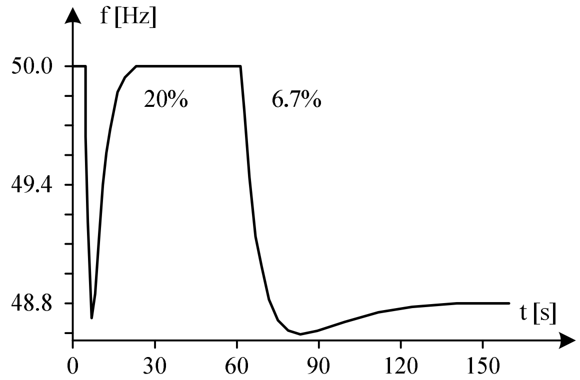

Fig. 2.6. Frequency behavior for 26.7% of active power deficiency

B. Frequency behavior in the united power system of the Baltic States and ENTSO-E during operation of UFLS with power deficiency at the Baltic State side or at ENTSO-E side

This chapter describes frequency behavior when both systems are interconnected with the strong tie lines. The frequency behavior was analyzed for different emergency underfrequency situation in the united power system of the Baltic States and ENTSO-E when deficiency of power is at the ENTSO-E side. During the united power system operation when the deficiency of active power by its value exceeds the value of the load shed by the steps of UFLS of one of the systems, the frequency restores close to its nominal value and stays in the area of the normal admissible range. Frequency hovering is possible at the iterative accident.

For all considered cases the disconnected load is mostly located in the deficient part of united system. Fig. 2.7 illustrates frequency behavior for the case when power deficiency is at the ENTSO-E side.

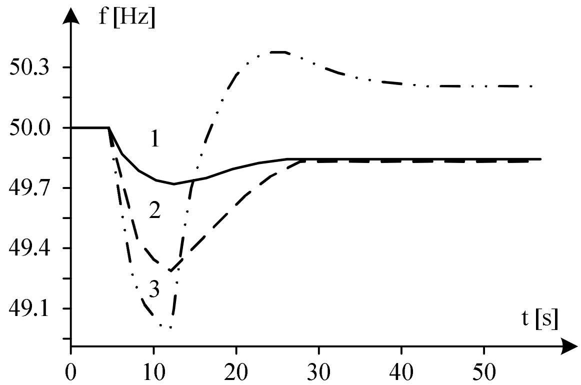

Fig. 2.7. Frequency behavior for 5% (1), 10% (2) and 15% (3) of active power deficiency

When deficiency of power is at the Baltic States side for some considered cases disconnected load is located in the normal, but not deficient part of interconnection. This is due to the different philosophy of underfrequency load shedding automation.

C. Analysis of frequency behavior in the power system of the Baltic States during operation of UFLS.

This chapter presents results of analysis of operational effectiveness of underfrequency load shedding for different emergency situations using the combined model of UFLS applied for the Baltic States power system.

UFLS-II category is used for frequency restoration after UFLS-I operation. While restoring the frequency with the help of UFLS-I and UFLS-II at the same time trying to disconnect as few loads as possible the combination of these two algorithms' operation is used.

The number of combined UFLS steps and their thresholds settings were accepted as an example of one of the Baltic country (Latvia). This model of UFLS has 74 steps and 11 thresholds with total disconnected load of 66.9%.

In Fig. 2.8 the frequency behavior at the deficiency of 5% of active power (1) is shown. For such a small value of power deficiency the frequency decline was stopped by the governor's operation.

At the deficiency of 7.5% (2) one step of UFLS-I have operated but the disconnected power is 2.5 times smaller than the deficiency value, hence, the frequency restores close to its nominal value, but stays in the rate of the marginal permissible range.

In the case when the deficiency of the power in the network is equal to 8.9% (3) one step of the UFLS-I and two steps of UFLS-II were operated.

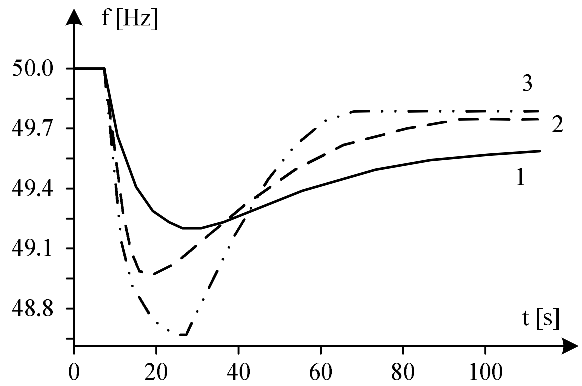

Fig.2.8. Frequency behavior for 5% (1), 7.5% (2) and 8.9% of active power deficiency at the Baltic States

Investigations show that the application of combined UFLS-I and UFLS-II exclude overfrequency and underfrequency situation in the power system. This is an advantage of the load shedding system in the Baltic States' network.

At the iterative accident the frequency restores close to its nominal value and stays in the area of the normal admissible range. Application of UFLS-II model allows providing such proper operation.

More than 20 different variants of deficiency were considered. For all considered cases the maximal deviation of frequency after its restoration is in the range of -0.22 Hz to +0.023 Hz.

The frequency behavior at a deficiency in the power system of 20% and at the iterative accidents with deficiency of 6.7% (1) and 7.5% (2) is shown in the Fig.2. 9.

At the iterative accident the frequency restores close to its nominal value and stays in the area of normal admissible range because of the operation of combined model of UFLS. At the iterative deficiency the steps of UFLS-II combined with UFLS-I are operating.

The overfrequency or underfrequency situations are impossible using the combined model of UFLS.

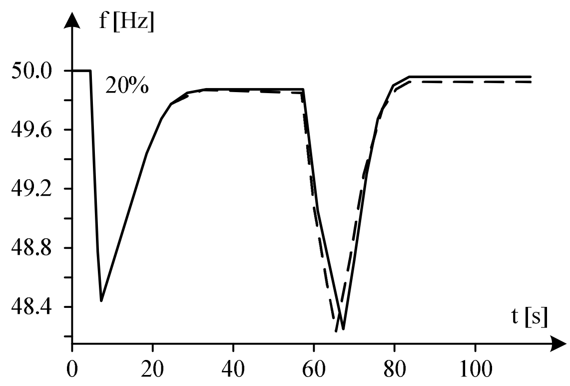

Fig.2.9. Frequency behavior for 26.7% (1) and 27.5% (2) of active power deficiency

D. Simulation of joint power system operation via weak intersystem tie.

Initial period of interconnected operation of power systems usually is characterized by relatively weak intersystem ties.

Fig. 2.10 illustrates the case of 14% of active power deficiency that leads to asynchronous operation of both systems with different UFLS types due to a weak intersystem tie.

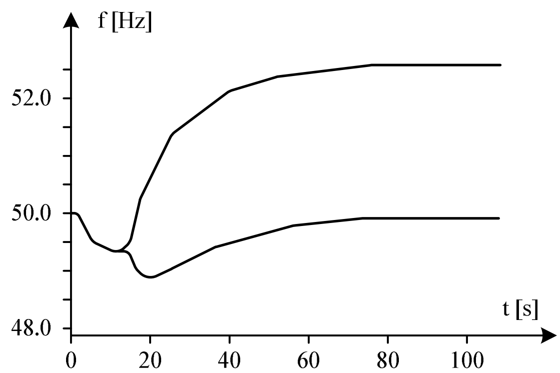

Fig.2.10. Frequency vs. time transient for the third simulation case (both systems operate with different frequencies)

One system continues to operate with a frequency close to the rated frequency and the other experiences a frequency increase towards 54 Hz.

3.5. Conclusions

Author developed the method and models for analysis of frequency behavior for different values of deficiency in the power system. Two cases were considered – when deficiency is divisible and not divisible to the value of the load disconnected by the UFLS automation.

Suggested approach allows discovering possible over-frequency situation as well as hovering situation for cases when the deficiency is not divisible to the value of the load disconnected by the UFLS automation. To prevent the power system from dangerous over-frequency situations specific automation algorithms should be used.

Frequency control problems were discovered using example for different underfrequency emergency situations in the united power system of the Baltic States and ENTSO-E when deficiency of power is at the Baltic side as well as at ENTSO-E side.

During emergency situations caused by deficiency in the interconnected power system underfrequency load shedding automation is activated in all interconnections. The frequency restores and stays in the area of the normal admissible range in all cases of single emergency underfrequency situations considered. For some considered cases disconnected load mostly is located in the normal, but not deficient part of the united system due to the different philosophy of UFLS automation operational. The overfrequency or underfrequency situations are impossible using the combined model of UFLS.

4. The influence of excitation system's parameters to the power system stability

4.1. Introduction

The quality as well as reliability of electrical energy transmitted to consumers is one of the main parameters for successful operation of the power system. The problem of power oscillation damping in the power system is solved using power system stabilizer (PSS) as additional voltage regulation loops. Power system stabilizer can be considered as smart automation system. A lot of works has been dedicated to this problem [18-20]. Kegums hydro power plant (HPP) is one HPP creating cascade of the three HPP at the Daugava River. Modernization of equipment in the Latvian power system takes place during the last decades. Excitation system of the Kegums HPP is an old fashioned АРВ-СД excitation system with different stabilization parameters. Few other power plants are with modernized excitation systems. Hence, parameters of excitation system of the Kegums HPP are no more optimal. Chapter deals with analysis of parameters of excitation system of Kegums HPP. Optimal parameters allow to improve power oscillation damping. Possible adaptive approach for more effective oscillation damping is suggested. Three possible excitation systems were considered. The first model is simplified which gives possibility to analyze excitation process. Second model is more complicated AIR-SDP1 system. The third regulator is based on determination of power deficiency approach.

4.2. Methodology of stability analysis

For simulation of excitation system dynamics *Matlab Simulink* software was used. Excitation system model was developed which allows analyzing stability of transients during disturbances near to the Keguma HPP. Fig. 3.1 presents simplified diagram of excitation system [21-23].

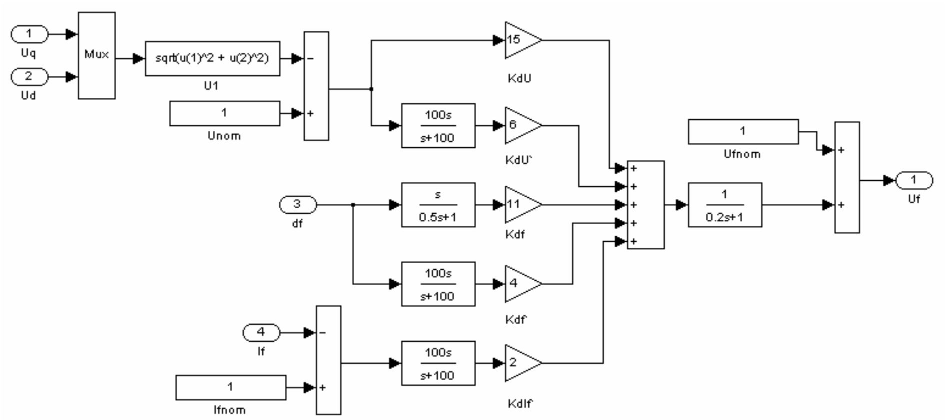

Fig. 3.1. Simplified diagram of excitation system

Fig. 3.2 represents voltage U_G, active power P_G and load angle δ at the Keguma HPP buses during three phases short circuit with duration of 0.1 sec.

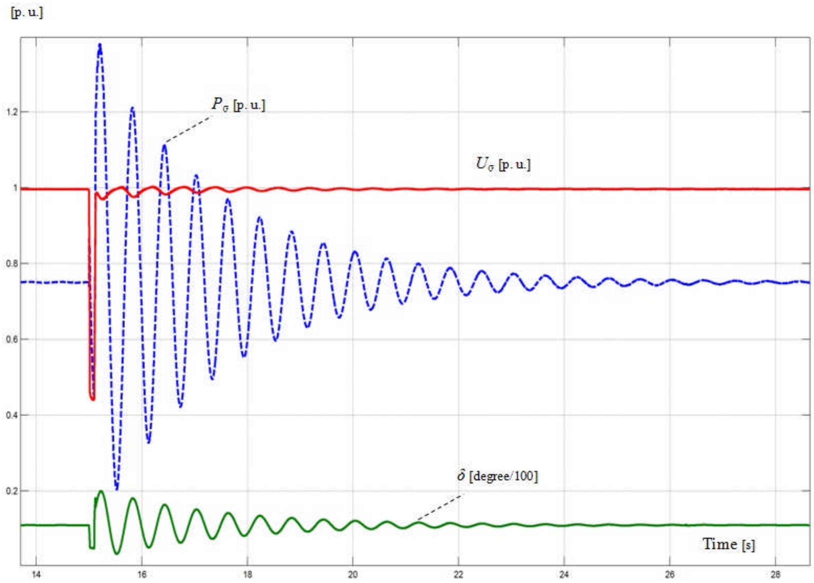

Fig. 3.2. Voltage U_G, active power P_G and load angle δ at the Keguma HPP buses during three phase's short circuit

4.3. Description of Keguma HPP excitation system

The construction of Kegums HPP was finished in 1979. Since that time three generators of 64 MW capacities are in service. Generator voltage is 13.8 kV. Excitation system is АРВ-СДП1 type developed in the former USSR [24].

Transfer function of excitation system:

$$U_{reg}(p)=\left(\Delta U(p)\left(K_U+pK_{U'}\right)+\Delta f(p)\left(\frac{pK_{\Delta f}}{Tp+1}+pK_{f'}\right)\right.$$

$$\left.+\Delta I_f(p)pK_{I_f}\right)\cdot\frac{K}{T_y p+1} \qquad (1)$$

where $T=0.5s$, $T_y=0.2s$, $K=1$.

Fig. 3.3 presents block diagram of АРВ-СДП1 excitation system.

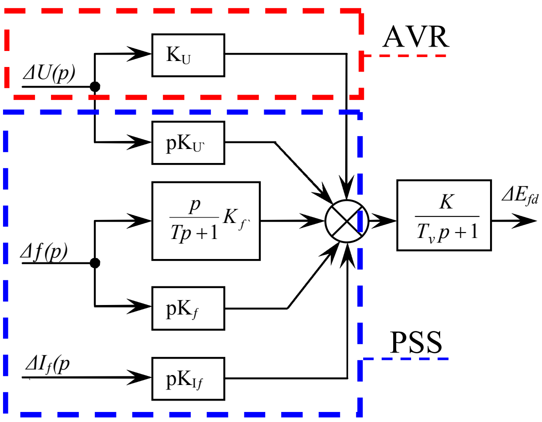

Fig. 3.3. Block diagram of АРВ-СДП1 excitation system

4.4. Influence of PSS parameters to dynamic of control process

Simplified "machine-system" diagram (Kegums HPP and System) is presented in Fig. 3.4.

Generator is equipped with standard governor and automatic voltage regulator and connected to infinite bus through three-phase transformer and transmission line. Simulation model was developed using Matlab Simulink simulation software.

Model is equipped with block, simulating short circuit event. It simulates three-phase to ground short circuit. This type of short circuit selected as the heaviest case to study transient process.

The dynamic of power system transient investigated for three phase to ground for different duration of short circuit simulation. In this case duration of short circuit is 0.3 seconds. Increase the duration causes out-of-step condition. Maximal short circuit duration depends on the load value in the power system [25]. For considered case load is represented by HPP auxiliaries. Increase of the load will increase maximal duration of the short circuit, but it will not influence optimization process of excitation system.

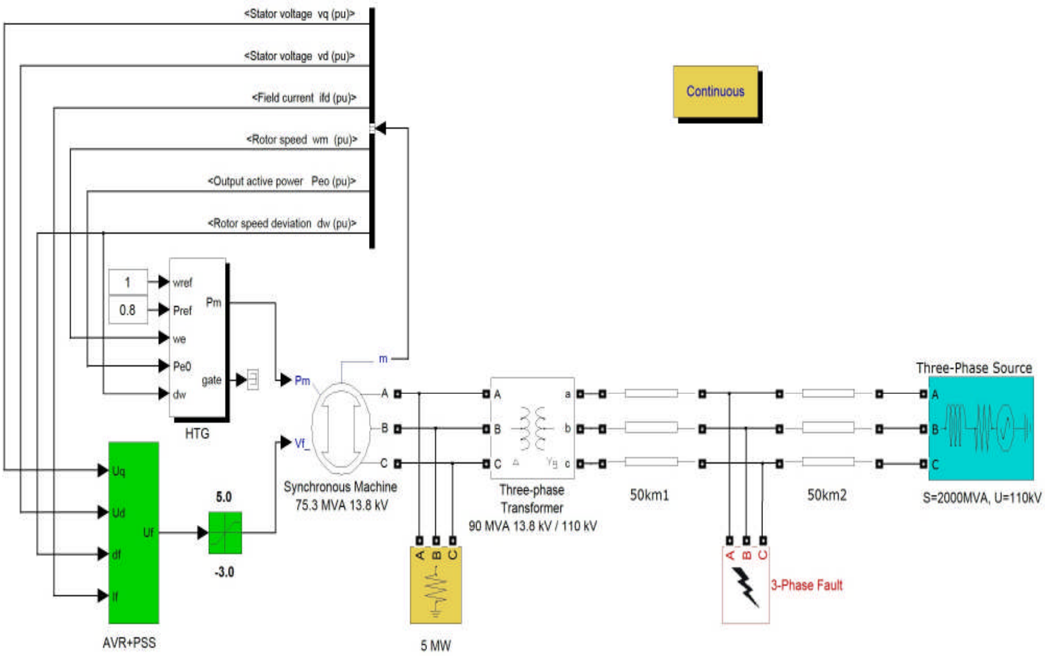

Fig. 3.4. Simplified model of Keguma HPP

4.5. Optimization of excitation system

The following equation as optimization criterion is suggested [19]:

$$A = \alpha_1 \int_0^t \left| P_G(t) - P_{ref}(t) \right| dt + \alpha_2 \int_0^t \left| V_G(t) - V_{ref}(t) \right| dt + + \alpha_3 \int_0^t \left| f_G(t) - f_{ref}(t) \right| dt \quad (2)$$

where P_G denotes the active power, P_{ref} is its desired value; V_G and V_{ref} are the terminal voltage and its desired value, f_G denotes the frequency, f_{ref} is desired value.

The values of quantities used in equation (active power, voltage and frequency) are different. So deviation of one parameter will always exceed others. For unbiased estimation of optimization system it is possible to divide multi-objective equation into few simple equations and analyze each taken separately. Comparison of simple equations can develop recommendations for optimization of the system. Optimization criteria can be:

$$A_1 = \int_0^t \left| P_G(t) - P_{ref}(t) \right| dt \rightarrow min \qquad (3)$$

$$A_2 = \int_0^t \left| V_G(t) - V_{ref}(t) \right| dt \rightarrow min \qquad (4)$$

$$A_3 = \int_0^t \left| f_G(t) - f_{ref}(t) \right| dt \rightarrow min \qquad (5)$$

From the transfer function (1) it is seen that for different coefficients character of control is different.

Table 3.1 illustrates combination of coefficients used for the study of optimization the excitation system. Fig. 3.5 illustrates optimization results for excitation system when optimization criteria are A2. When criteria A1 and A3 are selected the most optimal variant is for parameters of variant 6 and criterion A2 gives best result with parameters of variant 10. There is need in selection priority of variant for coefficients P, f and U or to select compromise version.

Table 3.1**.** Variants of coefficients used for the study of optimization the excitation system of Kegums HPP

Nr	**ΔU**	**ΔU'**	**Δf**	**Δf'**	**ΔI'f**
1	15	6	11	4	2
2	25	8.5	11	4	2
3	15	8.5	14.4	4	2
4	50	6	11	5.5	2
5	25	6	14.4	5.5	2
6	15	6	11	4	3
7	50	8.5	11	4	3
8	15	8.5	14.4	4	3
9	25	8.5	14.4	4	3
10	15	8.5	11	5.5	3
11	50	6	14.4	5.5	3
12	50	8.5	14.4	5.5	3

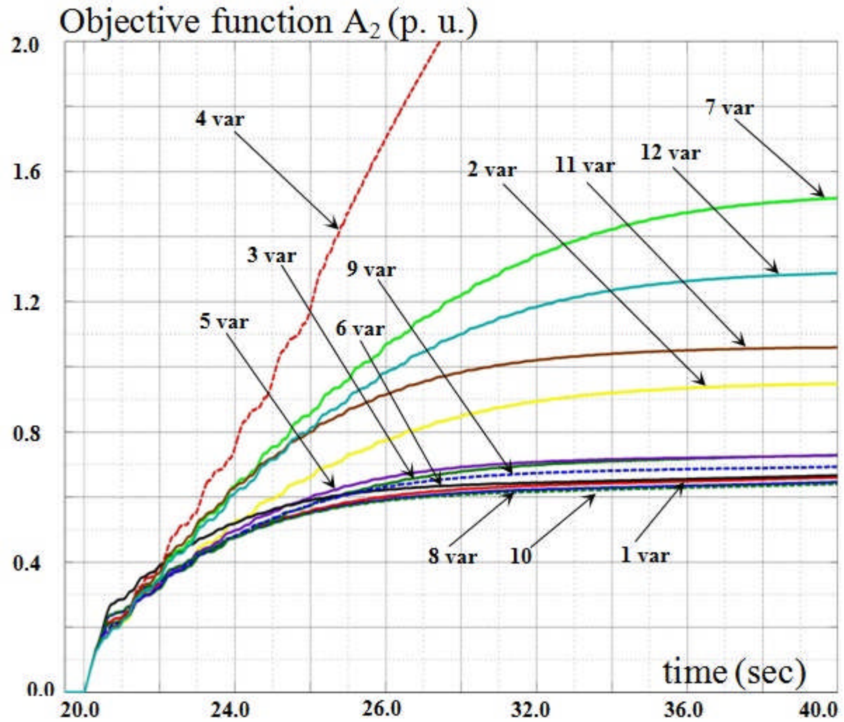

Fig. 3.5. Variations of objective function A2 for different variants of coefficients during short circuit

Simulation of dynamic of excitation system for objective functions A1 and A3 were also fulfilled [26, 27].

Fig. 3.6 and 3.7 illustrate results of parameters' optimization.

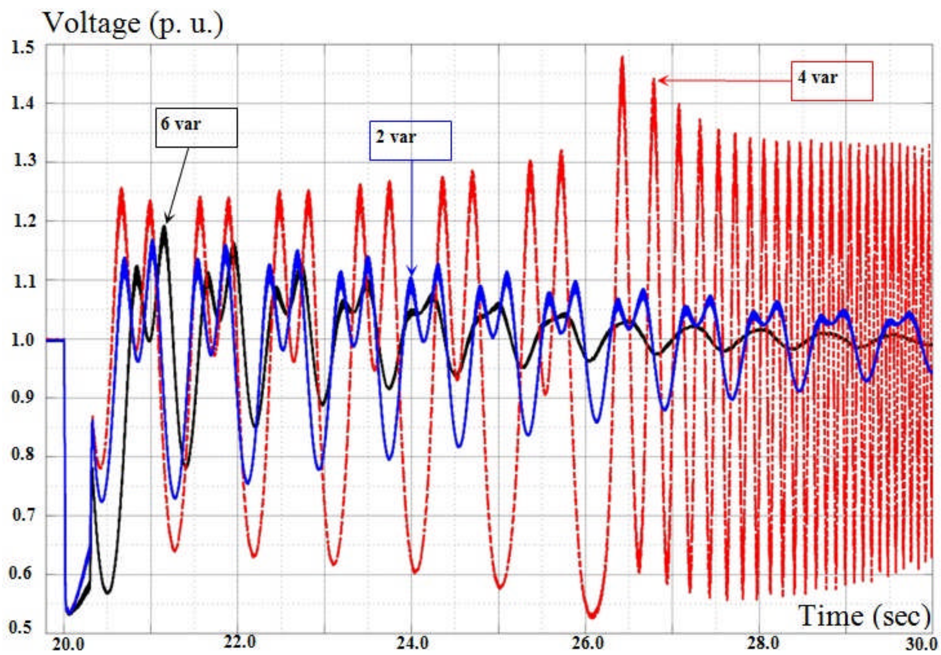

Fig. 3.6. Variation of Kegums HPP generator's voltage depending on combination of control coefficients

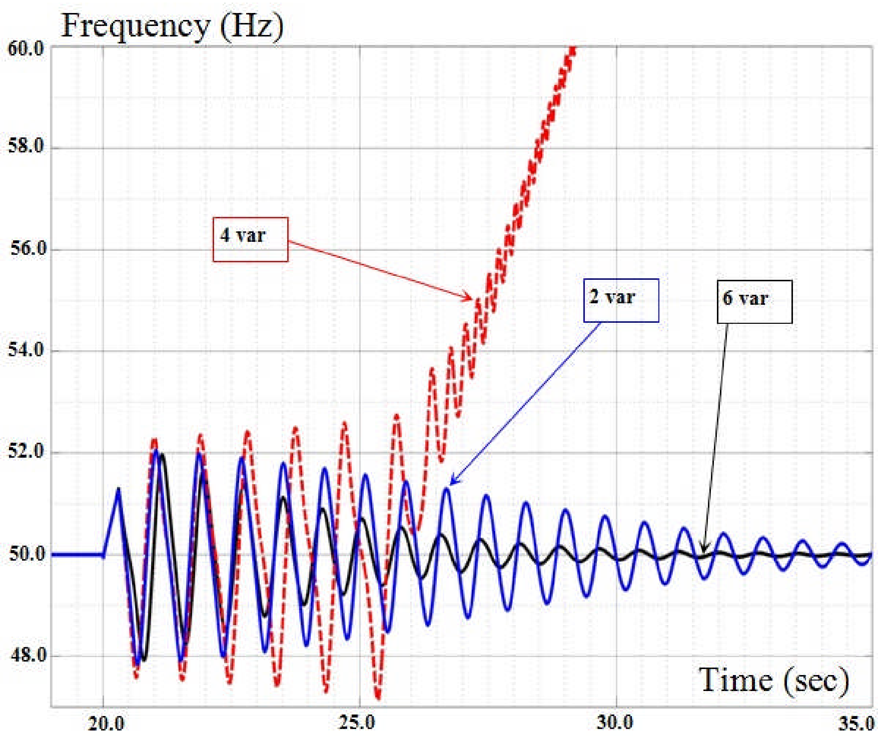

Fig. 3.7. Variation of Kegums HPP generator's frequency depending on combination of control coefficients

Transient processes for voltage and frequency variations are shown for different optimization parameters. Application the coefficients of variant 4 will cause out-of-step condition. The best damping case is observed for application of variant 6.

4.6. Adaptive approach for control of excitation system

The next step of research was verification of optimal parameters' selection when influence of a neighbor power plant is investigated. The design diagram of the Latvian power supply system represents the mathematical model which is constructed with PSS/E software.

The excitation system presented in Fig. 3.4, was integrated into simulation model of the Latvian power system.

Fig. 3.8. represents investigated network of the Latvian power system. For practical analysis of dynamic behavior during disturbances in the power system each plant is represented by an equivalent generator.

Optimization criteria search was determined at three-phase to ground short circuit, with duration 0.3 seconds.

Variations of objective function A2 for different variants of coefficients are illustrated in Fig. 3.9. Fig. 3.9 shows that parameters of variant 3 are the most optimal. Two worst parameters of transient process are for variants 6 and 11.

Results of voltage investigation on the bus of the Kegums HPP's synchronous generator during transient process (Fig. 3.10), shows that at parameters of variant 6 there is a significant voltage drop.

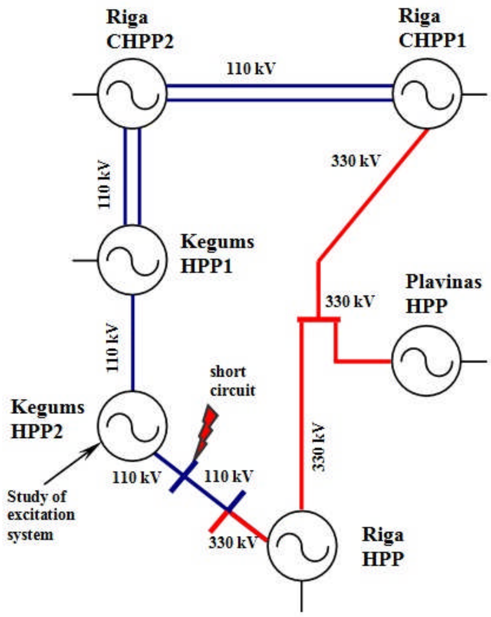

Fig. 3.8. Simplified diagram of interconnected power plants

For parameters of variant 11 at the moment of voltage recovery visible overshoot (voltage raise) take place. In turn, comparing voltage raise at parameters of variants 3 and 11, it is possible to reduce overshoot by 5%.

Using objective function A1 parameters of variant 10 are most optimal, but the worst is 11 variant.

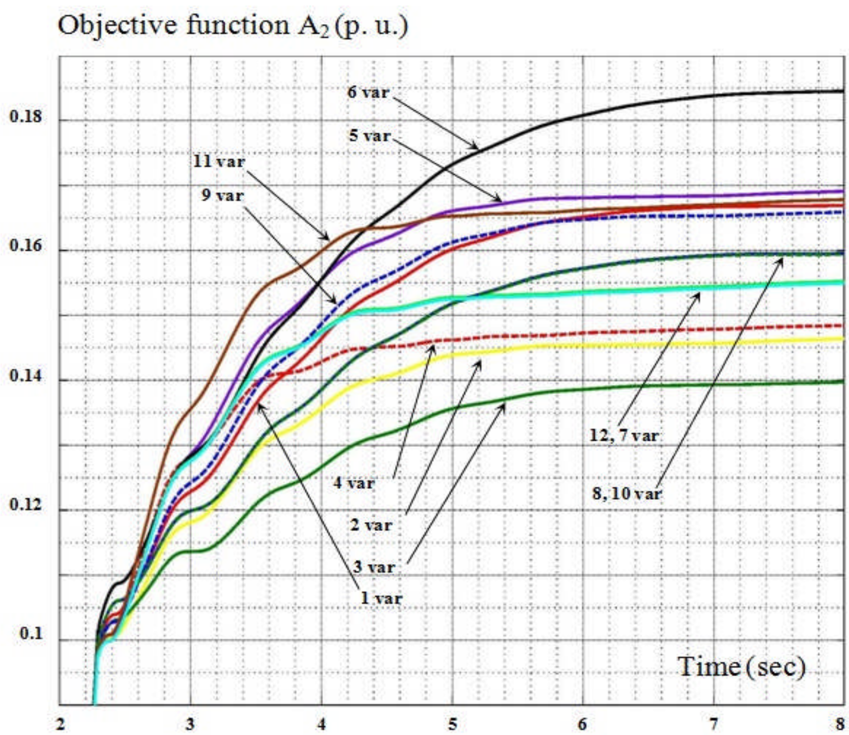

Fig. 3.9. Variations of objective function A2 for different variants of coefficients during short circuit

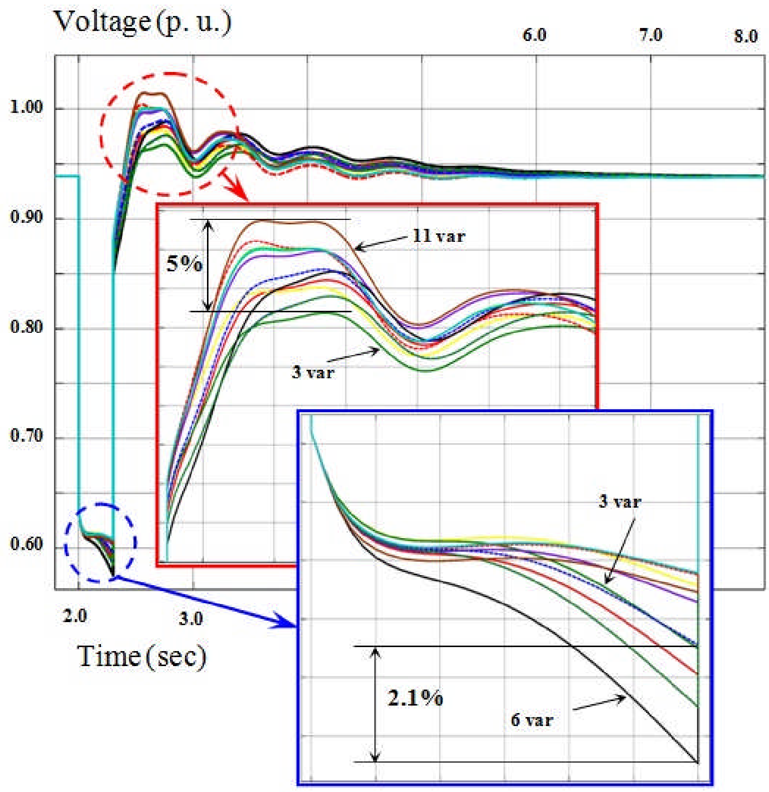

Fig. 3.10. Variation of Kegums HPP generator's voltage depending on combination of control coefficients

4.7. Conclusions

1. Influence of PSS parameters to dynamic of control process was investigated.
2. Optimal parameters for Kegums HPP were selected using objective functions.
The investigations done using simplified scheme show those criteria (3), (4), (5) are possible to improve synchronous generator's output parameters' damping and in some cases can prevent out-of-step condition.
3. Influence of neighbor operating power plants' parameters was considered from the point of view stability of excitation control. Influence of neighbor power plant's parameters is significant. The results of investigations which are done using simulation model of the Latvian power supply system, show that optimization of Kegums HPP excitation system's parameters can increase stability and efficiency. Possibility of damping increasing of synchronous generator's output parameters is illustrated in the paper. For example, active power's amplitude's reducing on 14.7 % and on 27.0 % in the first period.

5. Spinning reserve allocation using game theory

5.1. Introduction

Balance control between produced and consumed power is one of the important tasks of the power systems normal operation. Instantaneous changes of load, generation units and transmission line disconnections arise network unbalance condition [18].

Auxiliary services necessary for frequency and the active power flows regulation fulfill significant functions of any power system operation [28, 29].

Power plants, belonging to different owners, can participate in the frequency control process. In this case each owner tends to maximize profit. The largest total profit can be obtained by the coordinated operation of all power plants. The problem of valid sharing of benefit between the members of coalition arises in this case. This is the main approach which is described in paper.

The choice of the active power primary reserve value depends on the total generated active power in network. Selection of the primary reserve value is corrected once a year [18, 30].

According to the directives of UCTE in interconnected power systems (IPS), which include some participants, the value of primary reserve is calculated for each power system (participant). After that, each participant of power pool chooses its own power plants for the primary frequency control.

In case when the system frequency is stable primary reserve is not activated. The price for this service is quite high, and companies are competing for the right to participate in the process of primary frequency regulation. Besides the providing the quality of frequency control there is another additional problem of expenses minimization.

It should be noted that the large-scale use of renewable and distributed energy sources increases the probability of power import-export level deviation from planned state. These deviations determine the trend of power spinning reserve growth.

In this paper the principle of the optimal primary reserves allocation (with the goal of energy cost minimization) for power system primary frequency regulation participants is considered.

Optimal primary reserves allocation must be based on determination of common profit for participants. The profit sharing approach must be based on application of the cooperative game theory methods [31]. Several papers suggest application of the Shapley distribution method to solve cost and/or profit allocation problems between participants [32, 33]. This paper explores cooperative game approach toward frequency regulation task which can improve the existing frequency control methods and as result the efficiency of power systems [28, 30, 34].

5.2. Statement of a problem

The operation of several power companies, which simplified scheme is presented in Fig. 4.1, is observed. Let us suppose that each company contains several power plants, which are operating in market conditions. The supporting of generated and consumed energy balance at the nominal frequency and costs minimization are the general targets of cooperation of energy companies [35].

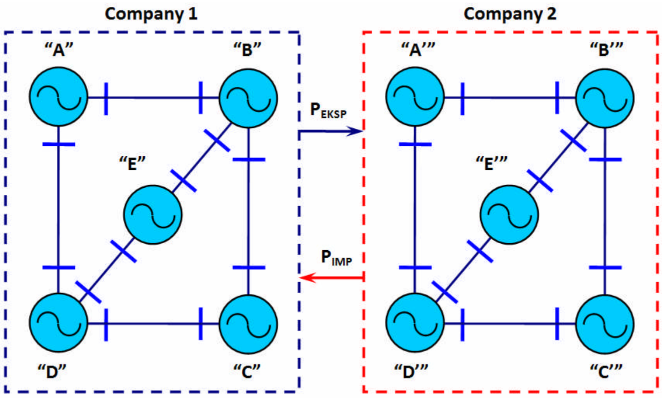

Fig 4.1. Simplified diagram of interconnected power system

Let's suppose, that generated and consumed power balance is done, as well as operating power plants configuration and power value are determined, as a result of energy consumption's prediction and power energy market at each time moment *t* of planed time period *T*.

Occurring power imbalance, frequency deviation from the nominal value takes place. This power deficiency must be taken over by high-speed automatic governors.

Energy power import-export planned value changes as a result of compensation of unplanned imbalance. The redistribution of power flows takes place.

For correction of the stable deviations of power generation-consumption level the short-term market mechanism is used. After bids new settings for power supply companies are specified.

There are different ways to provide power reserve of parallel operating IPS. One of the most common is the method based on distribution of the total required reserve of IPS proportionally to planned power capacity of each power system [28, 30].

Mentioned case and method of improvement is considered below, as well as a solution of the problem of optimal primary reserve allocation for IPS (at specific conditions, which occur at time moment t_i) is offered.

A. Possible approaches for determination of distribution of spinning reserve in IPS.

Assume power system which consists of five power plants. Let us consider two possible approaches for spin reserve distribution:

1 - Five plants operate independently, supporting specified part (reserve) of the planned power (classical approach);

2 – All five plants strive to most profitable operation and costs minimization.

Let's suppose, that five power plants are operating - S_1, S_2, S_3, S_4, S_5. The capacities of each plant are - P_1, P_2, P_3, P_4, P_5. Production cost values - C_1, C_2, C_3, C_4, C_5. Each plant provides a reserve - p_1, p_2, p_3, p_4, p_5, with production costs c_1, c_2, c_3, c_4, c_5.

The resulting costs E_{RS} are:

$$E_{RS} = \sum_{i=1}^{5} (P_i \cdot C_i + p_i \cdot c_i) \cdot \Delta t, \qquad (1)$$

Assume, that generators must provide a planned power P_Σ of interconnected power system, as well as possible random deviations of power p_Σ for all i of $C_i < C_{i+1}$ and $c_i < c_{i+1}$. Suppose that density of power deviations $f_{ij}(p_{ij})$ is known for each time moment *t*.

The goal is to provide balance of powers:

$$\sum_{i=1}^{5} P_i + p_i = P_\Sigma + p_\Sigma, \tag{2}$$

at a time t with minimal E_{RS} in the interval Δt.

Selecting generators' powers P_i and reserves p_i it is necessary to take into account many technical limitations, which depend on: thermal and electrical loads of consumers, operational condition of thermal and electrical network, water levels in reservoir of hydro power plants.

To provide these limitations the fulfillment of conditions (3) is required:

$$\{P_{ij}, p_{ij}\} \ni A, \tag{3}$$

where A is the domain of the allowed states of the power system. The task for selection of spinning reserve can be formulated as:

$$\{P_{ij}^*, p_{ij}^*\} = arg\,min \sum_{j=1}^{N} (\sum_{i=1}^{n} P_{ij} \cdot C_{ij} + E_{ij}(c_R)) \cdot \Delta t, \tag{4}$$

with condition fulfillment of (2) and (3), where

$$E_{ij}(c_R) = \int_{0}^{p_{ij\,max}} p_{ij} \cdot c_{ij} \cdot f_{ij}(p_{ij}) dp_{ij}, \tag{5}$$

$E_{ij}(c_R)$ - mathematical expectation of the spinning reserve expenses i-th power plant at j-th time interval of Δt.

P_{ij}^* *u* p_{ij}^* - optimal capacity of considered plants (providing the minimum cost).

Let's assume that:

1. Probability of applied reserve is low. Hence, equation (4) can be simplified by deleting the integral from the equation;
2. Let's assume that optimization process and results of plants' capacities P and production costs C are known.

B. Technical implementation of the optimal spinning reserve control's problem.

Besides observed relatively complex mathematical problem for searching of optimal values of P_{ij}^* *u* p_{ij}^*, for the practical realization of optimization problem there is a need for application of information and organization technologies, which provide regulation of settings for special generators. The simplified diagram of the power reserve's control of IPS generators is shown in Fig.4.2.

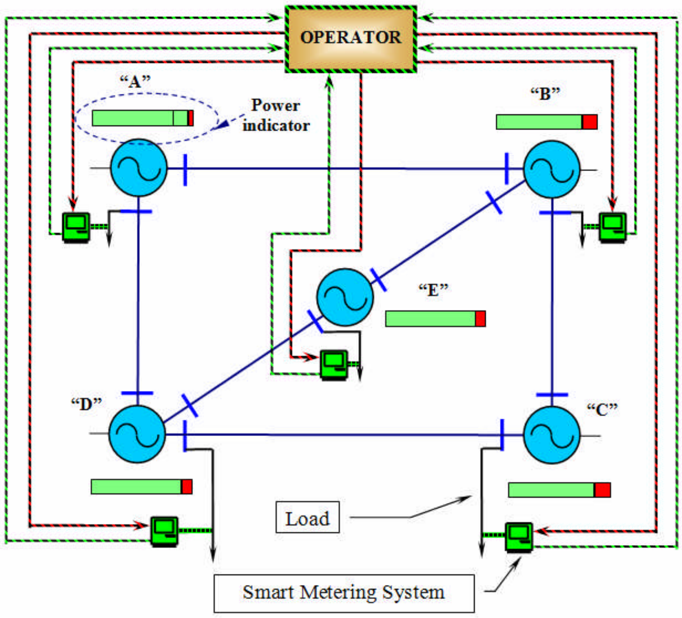

Fig. 4.2. Simplified diagram of interconnected power plants involved in primary frequency control

Using received information and models of the power plants or their combination it is possible to set and solve problems of optimal control [34].

Assuming that the before mentioned problems have been solved by known methods let's focus on the problem of obtaining and distribution the additional profit.

5.3. Proposed Allocation Method of Primary Reserve

The aim of this method is calculation of the most beneficial distribution of the primary reserve among the power plants (power districts) which are involved in the primary frequency control. Let's consider operation of the proposed method using example of the power system which is shown in Fig.4.2.

Fig. 4.2 shows indicators with main parameters of power plant operation conditions. Fig. 4.3 shows zoomed in picture of power indicator.

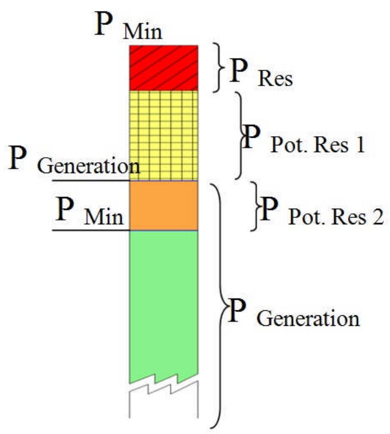

Fig. 4.3. The structure of parameters of power indicators

The next parameters of power plant are shown in Fig.4.3:

- maximal possible generation (P_{Max});
- the value of primary reserve (P_{Res});
- generated active power ($P_{generation}$);
- minimal generation level (P_{Min}) (technical limitation);
- potentially possible reserve 1 ($P_{Pot.Res\,1}$);
- potentially possible reserve 2 ($P_{Pot.Res\,2}$).

Let's describe some parameters. P_{Min} parameter is a technical limitation. It means minimal value of possible generation. Value P_{Min} depends on technical conditions or on economical reasons. There is possibility to set this value.

$P_{Pot.Res\,1}$ and $P_{Pot.Res}$ parameters are parts of potentially possible reserve:

$$P_{Pot.Res} = P_{Pot.Res\,1} + P_{Pot.Res\,2} \ . \tag{6}$$

In turn:

$$P_{Pot.Res\,1} = P_{Max} - P_{Res} - P_{generation} \ , \tag{7}$$

$$P_{Pot.Res\,2} = P_{generation} - P_{Min} \ . \tag{8}$$

Considering power balance in IPS for assumption that $P_{Pot.\,Res\,1} = 0$, $P_{Pot.\,Res} = P_{Pot.\,Res\,2}$.

To receive information, as well as to provide full control of power plant's primary reserve, the interactive information system SM - smart metering has to be applied [34]. SM system transmits the technical and economic data to the control center.

The technical information includes mentioned above parameters, such as $P_{generation}$, P_{Max}, P_{Min},. Economic information includes current production costs of electricity for each power plant and the current selling price of generated active energy.

Redistribution of network primary power reserve must be done by information and control center "operator". Taking into account complexity of processes, "operator" has to be realized by IT technologies. Let's describe steps of information and control center's algorithm:

a) algorithm ranks all players (power districts) by value of profitability, from the least to the most profitable (as example see Table 4.1, 2nd column);

b) algorithm solves all possible combinations of the primary reserve allocation among the players and calculates the most profitable variant. During analysis of variants the initial data for creation coalition of players can be received.

c) algorithm calculates the sharing of benefit among the players;

d) "operator" generates control signals to change the settings of the primary reserve control equipment for each players.

5.4. Benefit Sharing Approach

The mentioned above algorithm's point c) is most interesting, because benefit sharing is one of the main power market issues. In the case of the coalition formed by two players, profit sharing is equally distributed between the players (50%/50%).

However, in the case of three, four or five players' coalition, the problem of equitable profit sharing appears. So, if the optimal variant is a coalition of more than two players, profit sharing is done by using the Shapley vector [31].

Let's suppose that the *i-th* player gets benefit equal to the average value of this player contributions to all coalitions:

$$\phi_i(v) = \sum_{S \subset N} \frac{(|S|-1)!(n-|S|)!}{n!} (v(S) - v(S \setminus \{i\})) \tag{9}$$

The number $v(S)-v(S \setminus \{i\})$ is the contribution of i player when he is joining the coalition $S \setminus \{i\}$, but the weight factor

$$\frac{(|S|-1)!(n-|S|)!}{n!}$$

can be interpreted as the probability of the coalition $S \setminus \{i\}$ forming.

Shapley's value of cooperative game is a vector:

$$\phi(v) \overset{def}{=} (\phi_1(v),......,\phi_n(v))^T \tag{10}$$

5.5. Case Study

To describe the current state of the primary frequency regulation let's take the simplified example of the power system which consists of five power plants. Each power plant is involved in control and has ability of maintaining the primary reserve. As it was mentioned, the value of the primary reserve remains unchanged for at least one year [28, 30].

There can be two cases of spinning reserve application:

Power reserve can be used with low value of probability;

Power reserve can be used with high value of probability.

Here low value of probability of power reserve application, which is more profitable from the point of view of benefit sharing approach, is observed. It must be noted, that case "a" of the spinning reserve application responds to real operation of interconnected power system [35, 36].

Now let's consider operation of proposed automation using a specific example. Suppose that initial capacities of power plants are known, as well as prices, reserves, etc. Frequency control reserve is stated by system operator equal to 4% of maximal generated power P_{Max}. The initial parameters required for calculations are shown in the Table 4.1.

The power system operates in normal condition, when the generated and consumed active powers are equal (initial situation): $P_{generated} = P_{Load} = 6.2$ (p. u.).

TABLE 4.1. PARAMETERS OF PLAYERS BEFORE OPTIMIZATION

Player	$C_{Cost\ Price}$ (p. u.)	P_{Max} (p. u.)	P_{Min} (p. u.)	P_{Res} (%)	$P_{Pot.\ Res.}$ (%)	$P_{Generation}$ (%)
"A"	0.9	1.500	1.410	4.00	0.67	94.66
"B"	0.8	1.400	1.334	4.00	0.43	95.57
"C"	0.7	1.300	1.238	4.00	0.15	95.38
"D"	0.6	1.200	1.132	4.00	1.67	96.00
"E"	0.5	1.100	1.046	4.00	0.36	95.45
Σ		6.5		4.00		95.38
Initial situation						

$C_{cost\ price}$ – production cost value of produced power, (p. u.).

Let's assume that the selling price of electricity is equal to 1.1 (p.u.). Algorithm calculates profitability of all possible combinations of players. In our case, using the basic parameters listed in Table 1 and using equations (9) and (10), the algorithm calculates (Fig. 4.4 situation 1) that the best variant would be a coalition of all players ("*A+B+C+D+E*") with a total net profit equal to 0.0076 (p.u.).

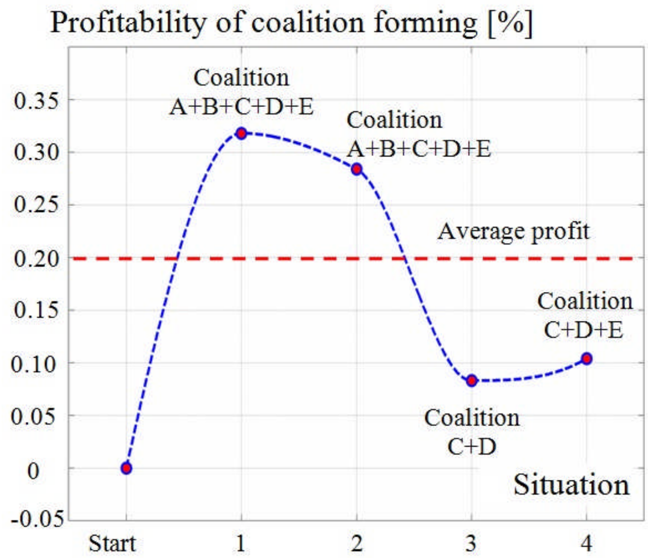

Fig. 4.4. Players' profitability in different situations

As a result of proposed optimization, the primary reserve control function is redistributed from more effective power station to a less one (with a higher production cost). The total value of the primary reserve isn't changed.

The maximum additional profit arises in case when the primary reserve was not activated in specific time interval. Using equations (9) and (10), it is possible to calculate the sharing of profit among the players. The results of the sharing are presented in Table 4.2.

TABLE 4.2. PROFITABILITY IN DIFFERENT SITUATIONS AND RESULTS OF PROFIT'S SHARING

Number of situation	1	2	3	4
Additional profit of coalition' (p. u.) / Benefit of player (%)	0.0076	0.0068	0.0020	0.0025
"A"	35.74	31.37	0.00	0.00
"B"	10.61	12.60	0.00	0.00
"C"	5.26	18.63	50.00	46.66
"D"	18.86	23.28	50.00	36.66
"E"	29.52	14.12	0.00	16.66

Such parameters, as selling price of electricity, $C_{Cost\ Price}$, P_{Max}, remain unchanged. It should be noted, that after each optimization process initial value of IPS's spinning reserve wasn't changed.

Using results of simulation, the following curves were built:

1) Fig. 4.4 shows the profitability of optimal coalitions creating accordingly to independent operation of players during different situations. Each point of optimization shows coalition forming (or no any operation).

2) Fig. 4.5 shows the changes of IPS' generated power at others situations.

3) Fig. 4.6 shows the changes of players' generated power at others situations. In other words, curves can be used as control signals to change the settings of power plants (players) governors.

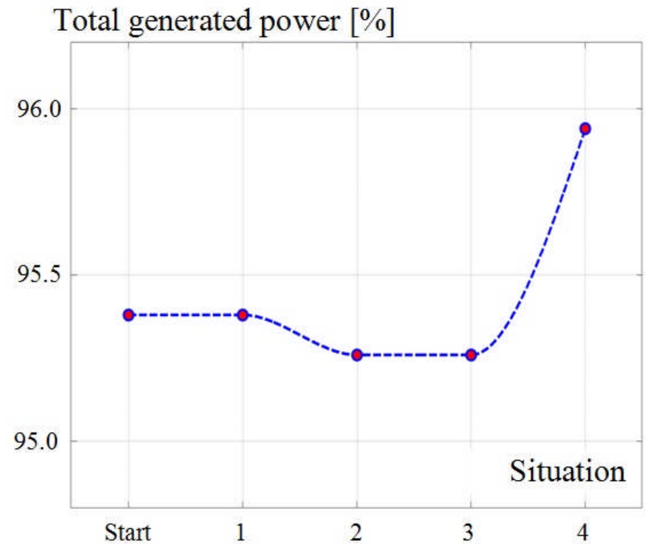

Fig. 4.5. Total generated power of IPS in different situations

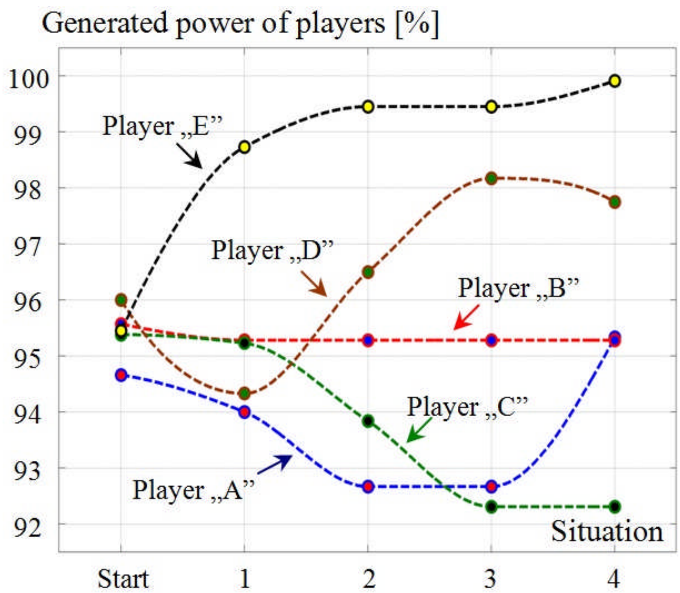

Fig. 4.6. Players' generated power in different situations

5.6. Conclusions

- Optimal distribution of the primary reserve can be based on cooperative game theory method.
- Proposed algorithm, which takes into account technical limitations and economic aspects of the primary frequency control participants, has to be used.
- Results of practical calculation of additional profit prove feasibility of application of game theory method for optimal distribution of frequency control reserves.
- The mathematical model of the power system with proposed calculation algorithm can be performed using computer program Matlab Simulink [27].

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