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ELECTRICAL ENERGY GENERATION CONTROL IN RESTRUCTURED POWER SYSTEMS

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1. INTRODUCTION

Relevance of the Work

Power systems (PS) are currently in process of restructuring all over the world. The cornerstone of such restructuring is to secure an open generation and consumption entities access to power transmission system and implement market relations between entities in energy market. This work considers the benefits of separation generation, transmission and distribution as well as the consequences of alternative decisions in the areas of system operational control, reliability, financing, and legal control. All proposed and implemented alternatives must comply with the following requirements:

1. An open access to power transmission grids have to be ensured.
2. Ccompetition among the generation sources have to be created.
3. Choices for power consumers have to be offered.
4. The ways for politicians and monopolies to exercise illegitimate influence in the area of energy development have to be restricted.
4. The integrity and reliable functioning of power system technology have to be preserved.
5. To properly asses the true cost of separate processes of power production and transmission and their control.

The expected effect of power system restructuring is decreased end-user price of electrical energy taking into account its quality.

The cornerstone of energy system restructuring is the separation of production, transmission, distribution, and supply business areas of existing vertical monopolistic energy companies; refining of businesses of naturally monopolistic nature; liberalization of competitive businesses and legitimating of market relations; introducing market elements and ensuring transparency in monopolistic businesses.

One of the main business areas of electrical energy transmission which is essential to ensure functional reliability of a power system is the supply of system services and power system operational control services to market players, and the possibility of introducing market elements in the field of supply of ancillary and system services.

In restructured systems the way of operational control of an energy system changes. First of all, the power market requires the transparency and efficiency of provided system services, therefore the pricing of system services cannot be continued on a single basis of expenditures incurred by an operator of a transmission system. Each system service must be considered as a separate service subject to market laws, so that it would finally be possible to evaluate the efficiency of a transmission system operator in supplying and administrating of each service. Key system services include the following: frequency and active power control; voltage and reactive power control; supply of active power reserves; ensure transmission power (grid capacity) reserves; accident prevention; dispatch; automatic preventive control; power system restoration after blackout.

This list is by no means complete; however it is not feasible to detail further services due to the reason they are integrated into the dispatch service covering operational planning and control of power system, implementation and maintenance of information and dispatcher technology measures, etc.

Purpose and Objectives of this Work

The purpose of this work is to propose and study new ways of automatic generation control (AGC) and ways for accounting of this service; formulate key methodology principles of payment for system services; estimate costs of automatic generation control.

The objectives of this work are the following:

1. To investigate the effect of energy system restructuring towards the trends of control area and control block organization, automatic generation control structure, control processes, power supply reliability, and creation of a full-fledged power market where not only power but also control services as well are supplied on competitive basis.

2. To propose and study new ways for automatic generation control that are able to function in various implementation stages of power market, on conditions of various capabilities of power systems (different generation and loads structure, status of generation stations control systems, distribution of control resources, etc.).

3. To study the processes of automatic generation control in energy systems taking the following into account: the character of loads change determined by liberalized power market; requirements and actual potential for frequency and interchange power control; requirements for power quality and reliability of supply; consumers' potential of participating in the automatic generation control thus increasing the actual resources of control power.

4. To study and propose the ways for accounting of automatic power control services.

5. To formulate the key methodology principles of payment for services provided by separate partners participating the control process and estimate costs of automatic generation control.

This work analyses worldwide experience of automatic generation control in restructured systems and seeks for new ways of control best suitable for Lithuanian power system. It must be noted that Lithuanian power system (as well as Baltic PS) is unique from the perspective of its structure and environment thus requiring new original and unconventional solutions for its operational control within a restructured competitive environment. For the reason mentioned above, the studies are carried out taking into account the conditions of Lithuanian PS functioning as a part of a united energy system.

Scientific Novelty of the Work

For use for automatic generation control, the information evaluating the market dynamics is suggested, allowing reacting to and optimizing the processes of competitive market of power and ancillary services. The optimization of dynamic processes of competitive market ensures better utilization of control resources and efficiency.

This work presents new AGC ways (virtual and overlap control areas) allowing to develop and territorially expand the markets for ancillary AGC service, attract new suppliers (controllable loads) of this service, increase the amount of resources, and increase the functional reliability and quality of united power system.

An innovative model of secondary regulator with system operator is proposed for coordination of AGC service supply, which allows studying the ways to decrease the AGC impact to aggregate control systems while maintaining adequate control quality.

AGC service pricing principles and mathematical accounting model proposed herein allow developing and implementing the accounting and pricing system for this service.

Practical Value of this Work

In the process of electrical energy market development insufficient attention is often paid to ancillary services that are traditionally considered as monopolistic within the area controlled by the transmission system operator. This work shows that the end-user price of electrical power can be decreased by liberalizing the market of ancillary AGC services: enabling more efficient utilization of resources for those services without decreasing the reliability of power system operation.

The results of this work are to be used for the development of AGC service pricing system.

The service of control of frequency and interchange control is not provided within Lithuanian energy system due to technical deficiencies, but the development of AGC service market on the scale of united system is possible even now by employing AGC control ways of virtual and/or overlap area proposed herein. Such a market would allow the main producers to economically substantiate the implementation of control means and attraction of distributed resources such as controllable load.

Defensive Thesis of the Dissertation

The utilization of the new control area and control block organization, automatic generation control structure in the restructured energy systems make positive influence to the power supply reliability, and creation of a full-fledged power market where not only power but also control services as well are supplied on competitive basis.

The use of the information evaluating the market dynamics for the new models of automatic generation control, allow reacting and to optimize the processes of competitive market of power and ancillary services and ensures better utilization of control resources and efficiency.

The proposed ways for accounting of automatic power control services allow to create and introduce the accounting and pricing of this service.

Approval of this Work

The topic of this Thesis has been published in 14 scientific publications, of which 8 are editions recognized by Lithuanian Science Board for doctoral thesis.

The material presented herein has been presented at 9 scientific conferences:

1. Conference of Young Scientists of Lithuania "Electronics and Electrical Engineering". Vilnius. 2000.
2. KTU Conference "Technologies of Energy and Electric Engineering". Kaunas. 2000.

3. Conference of Young Scientists of Lithuania "Electronics and Electrical Engineering". Vilnius. 2001.
4. KTU Conference "Technologies of Energy and Electric Engineering". Kaunas. 2001.
5. RTU Conference "Power and Electrical Engineering". Riga. 2001.
6. KTU Conference "Technologies of Energy and Electric Engineering". Kaunas. 2002.
7. IFAC b’02 - 15th IFAC World Congress on Automatic Control. Barcelona. 2002.
8. EPE-PEMC-2004 - 11th International Power Electronics and Motion Control Conference. Riga. 2004.
9. EMD‘2004 – The XIV International Conference on Electromagnetic Disturbances. Vilnius. 2004.

The author of this Work has participated in preparation of the following normative documentation of the Republic of Lithuania, related to the topic of this Work: Grid Code approved by Order No.398 by the Minister of Economy of the Republic of Lithuania on 29-12-2001; Controls of Automatic Generation Control of Energy System of the Republic of Lithuania approved by Order No.322 by the Minister of Economy of the Republic of Lithuania on 12-09-2002.

Structure and Scope of this Work

This doctoral thesis consists of introduction, five chapters, main conclusions, and the table of references and publications by the author of this Work. Following the preface, the five chapters present the review of studies performed in the field; work methodology; the impact of power system restructuring on the structure of control areas; the results of study of control processes of restructured PS automatic generation control; system service pricing principles, and AGC accounting. The thesis consists of 127 pages, 112 figures, and 1 table; the table of references consists of 283 items.

2. STUDY REVIEW

Automatic generation control (AGC) is minimization of deviations of power system frequency and interchange power within the specified range and distributing the loads of generators participating in the control by performing primary control of generators and secondary control of control areas (CA) of which the united energy system (UES) consists. AGC maintains the power real-time balance between power consumption and production.

The functioning of automatic generation control is based on the reaction to area control error (ACE) resulting from the deviations of frequency and interchange power:

$$ACE_i = \Delta P_i + k_{si} \times \Delta f \qquad (1)$$

Where: ACE_i is area control error of i[th] area; ΔP_i – summary deviation of cross border interchange powers of i[th] control area; Δf – frequency deviation; k_{si} – factor specifying the degree of involvement of i[th] control area in frequency control.

During the functioning of AGC, the error close to zero is maintained in all areas.

Although the use of AGC is well established, the application within each specific electric energy system has its own unique features. New AGC may facilitate future decrease or stabilization of prices for power supplied to consumers.

The requirements posed to AGC systems on market conditions must be based on the following principles:

1. Transparent division of automatic control task among the market players.
2. Reliability and quality of service provision.
3. All market players including the distributed generation sources must be involved in PS control.
4. Setting the control cost.
5. Establishment of requirements for frequency sustention thus substantiating accepted frequency sustention norms.
6. Accuracy of measurements, frequency and reliability of parameters used in the control system.
7. Modern control technology of electrical equipment. The load imposed on the units by the central load management system must be limited.
8. AGC systems must be capable of compensating unplanned deviations of cross border interchange powers and time.

The following factors affecting control conceptions and new control purposes are presented:

1. Separated (liberated) services provided by PS entities (power plants and grids) are generation, transmission, distribution, and operational control.
2. It is necessary to reconsider and change the concept of a control area in order to satisfy newly emerging requirements and evaluating the penetration of independent generators, various forms of power trade, and competitive and environmental requirements.
3. In new control area concept it might be necessary to create a unit responsible for coordination and distribution of separated control services.
4. ACE that is currently used as a control criterion might be not the single base for CA generation control. There might be a need for new criteria for control performance applicable to all units (such as generation units, controllable loads) providing the control services.
5. To ensure reliable provision of services by responsible units, encouragement and penalties for the units must be introduced.
6. Only economy market drives are able to ensure the provision of generation services and readiness to meet the demands.
7. Retail power trade – the consumers will be able to choose energy producer.
8. Variety of services.

These issues mentioned above are the influencing factors arising during the power industry transition to more open market governed by supply and demand laws.

The review of frequency stability sustention in various united systems presented herein leads to the conclusion, that high requirements for frequency stability sustention are not a mandatory condition in the process of power market implementation. Nevertheless frequency stabilization compliant with high requirements for control quality (UCTE) has many benefits the most important of which are the economy and reliability of a united system. The main UCTE requirements and guidelines ensure the least cost for frequency control by using mutual equivalent mutual assistance that is properly (transparently) calculated. For that reason UCTE requirements facilitate fair competition in the area of system services in European power market. By following the principles (such as equality, transparency, subsidiarity, efficiency, unambiguousness and acceptance, supervision, and sanctions) of UCTE functioning on power market conditions, the operational control of separate power systems (control areas) is quite independent, and the processes may be discussed autonomously. However the variety of processes does increases, and it is necessary to clarify their new features.

In the process of power market development, the compatibility problems of development of power market and ancillary services emerge.

The ways of anticipatory static optimization for generation planning were used previously such as economic distribution with restrictions or optimum power distribution technique, which were based on estimated daily load schedules. To optimize the system functioning for a longer period, the increased efficiency may be obtained by employing competitive marked dynamics. It is usual for operating units as well as in the process of planning which units are to be started. The dynamic optimization technique has not been employed in large-scale electric energy systems due to great amount of data it requires. This technique may be improved by using minimum series models. Besides, the existing control systems are to be changed in evolutionary, not in revolutionary way.

The Authors' Input

Analysis of the referenced literature has proven that in the course of intensive development of the electricity market relations and during the restructuring of power companies enabling to more transparently satisfy the demands of electricity markets, the liberalization of ancillary services, including the automated generation control (AGC), is lacking sufficient attention, thus the Thesis is aimed to make a profound analysis of the impact of power system's restructuring on the organizational tendencies of control areas and control blocks, the structure of automated generation control, operational processes, the reliability of electricity supply and the development of viable electricity market where competition is established not only in the sphere of electricity supply but also in the automatic generation control services.

In the analyzed literature the ancillary services of automated generation control are limited by the traditional control areas or blocks, hence the possibilities to liberalize this service are not investigated. This Thesis proposes and analyses new methods of automated generation control which may be implemented at various development stages of electricity market and at different conditions of a power system (in terms of generation and load structure, status of generation units' control systems, allocation of regulation reserves, etc.).

The results of the research have confirmed that in the automated generation control systems of the already restructured power systems the automated generation control systems and the information assessing the market dynamics are not being used to a proper extent, new methods of automated generation control, which would enable to more efficiently use the management resources, are not being applied, and the principles of accounting and pricing of the AGC services are not sufficiently substantiated.

By using the new AGC methods proposed in the Thesis, the processes of automated generation control have been investigated with regard to the peculiarities of load changes dictated by the liberalized electricity market, the requirements of frequency and inter-system flow regulation and available tools, as well as by taking into consideration the requirements of electricity quality and the reliability of supply, consumers' possibilities to take part in the automated generation control thus increasing the available reserves of regulation capacity.

To assess the scopes of this new ancillary service, the method of accounting of the capacity regulation service has been examined and proposed in the Thesis. Besides, the main principles of the payment methodology for the services of individual partners participating in the system regulation have established, and the costs of automated generation control have been assessed.

3. WORK METHODOLOGY

The modeling and control structure offered and used herein provides a practical approach for the development of competitive supply-consumption market while maintaining reliability of system functioning.

Control structures compliant with operation criteria of certain level are allowed joint functioning with non-controlled systems. Such control flexibility is necessary for competitive electricity sector.

The proposed ways of modeling and control provides a possibility for a uniform formulation of generation control (management) objectives thus reacting to competitive transactions and preserving the system integrity for medium and long periods facing the changes of system input values caused by an open market. The proposed structure needs dynamic cost models related to generation control to be created. The efficiency of the entire system faced with competition and coordination exchange is studied, which is one of the foremost issues in determining the way the competitive markets indeed increase the efficiency of power system.

The proposed structure recognizes the value of incentives, identifies such incentives, and demonstrates the way those incentives shall join these two markets into a reliable free market.

The control mechanisms considered above allow to state that the control area may remain the main operational control unit of restructured power system. Only control algorithms can be transformed.

A restructured system may contain several generation, transmission and distribution companies drawing mutual contracts both within the controlled areas and across its boundaries. The structural control diagram is created by taking the transformed control error (CE) as a basis; for the ith area it is expressed as:

$$CE_i = ACE_i \times k_i + [\sum (k_{ji} \times \Delta DC_j) - \Delta GC_i]. \qquad (2)$$

Where:

$ACE_i = \Delta Pi + k_{si} * \Delta f$ (usual control error for the i^th^ area), k_i – the factor of involvement of the i^th^ generating company in the area error, k_{ji} – the factor of involvement of the i^th^ generating company in load monitoring of the j^th^ distributing company, ΔDC_j – load increase at the j^th^ distributing company, ΔGC_i – summary load monitoring power at the i^th^ generating company.

The study employs AGC system model created at Department of Electric Power Systems of Kaunas University of Technology. The purpose of modeling is to demonstrate features and properties of various AGC and explicate the possibilities for their use in various energy systems. Figure 1 shows the structural diagram of the model. The legend: S1, S2, S3 various energy systems; $L_{S1\text{-}S2}$, $L_{S2\text{-}S3}$, $L_{S1\text{-}S3}$ – generalized lines, connecting respective systems. Systems S1 and S3 comprise a control block (CB). It must be taken into account that a decentralized generation control is given the priority herein; therefore all processes are considered from the perspective of a single S1 system.

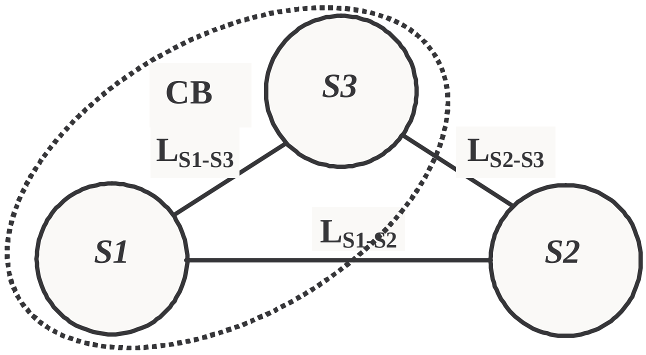


Fig. 1: Structural Diagram of United System Model

It is assumed that CB power amounts to 10% of S2 power. S2 stabilizes the frequency and CB – interchange power and can take part in frequency stabilization. The deviation change processes caused by load changes in any system are considered ($\Delta A = \pm 0{,}1$ p.u.). This condition (significant power deviation) does not completely correspond to reality, but the use of linear model provides the base for assumption that the process curves would quite adequately reflect process characteristics in case of small load deviations as well. During the modeling, the control algorithms were changed while the parameters of control units remained fixed.

The frequency stabilization method is possible to apply; therefore the control area error is calculated in this way:

$$ACE_{CR} = \Delta f \times k_{sCR}. \qquad (3)$$

This method may be applied either for a single control area (control block) of a united system or for an isolated system.

By applying the interchange power balance method, the control area error is calculated in this way:

$$ACE_{CR} = \Delta P_{CR}. \qquad (4)$$

If this method is applied, the secondary regulator stabilizes summary interchange of cross border powers and is not involved into the control of united system frequency. In that case the frequency must be stabilized by control areas applying cross border powers balance method with frequency correction, or a single control area applying frequency stabilization method.

Cross border power balance method with frequency correction is a method for cross border powers balance when the summary power exchange of cross border powers are stabilized if frequency deviations remain within set inactivity range, or these exchanges are corrected accordingly if frequency deviations exceed this range, thus joining the efforts to stabilize the united system frequency.

Linear models of separate PS components have been created using the published approach. MATLAB/SIMULINK software package has been used for modeling. The models have been appropriately simplified and separate links joined into larger blocks.

4. INFLUENCE OF RESTRUCTURING OF POWER SYSTEM TO THE STRUCTURE OF CONTROL AREAS

This chapter outlines the purpose of a control area, influence to the structure and size of a control area.

The processes of restructuring change the functions of control areas. The following factors manifest here: separation of transmission from trade; consumers' possibility to choose a remote power supplier; different conditions of power supply reliability assurance. A conventional control area is not able to ensure a proper solution to these new problems. It is absolutely necessary to modify the structure of control areas and apply new AGC methods. The stabilization of cross border summary power exchange might be no longer performed in restructured system taking into account remote partner contracts in the conditions of spot market. During the process of performing of bilateral or multilateral short-term contracts the intersystem power exchange become dynamic – they seldom are in steady state. Frequency control and load monitoring thus merge into a single functional task. Therefore it can be stated that the control area becomes a dynamic subsystem of a united PS.

It must be noted that PS communications system has undergone significant changes in the last years. Separate communication lines are being replaced by an open flexible communication network with automatic organization of reliable data transfer adapting to actual network conditions. This allows dynamically controlling frequency control and load monitoring regimes taking ancillary service supply contracts into account and without using preset parameters. A new possibility emerges to change the boundaries and structure of PS control areas in real-time according to the requirement of specific power trade contracts.

In restructured PS it might become necessary to remove certain control areas by consolidating them (merging together for joint activities in power market settings). There are various ways for CA consolidation: complete elimination of some control areas or establishment of a leading control areas assigned additional functions of coordinating the activities of several areas and responsibility for the whole group communications with external control areas. Figure 2 shows possible consolidation approaches.

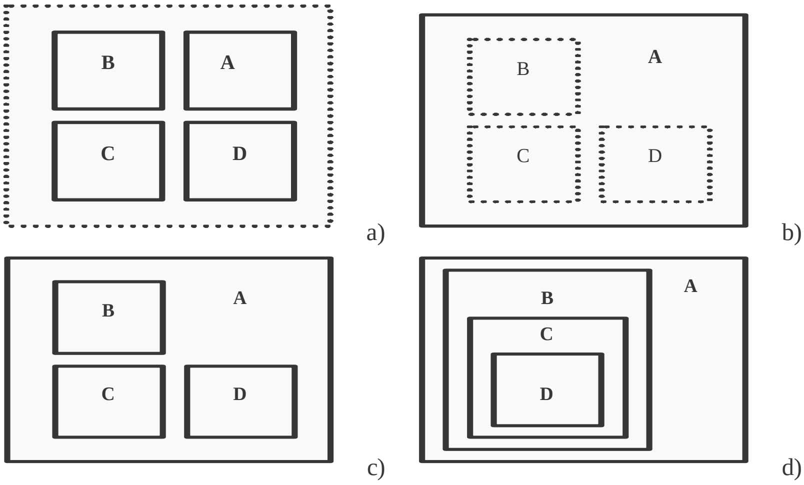
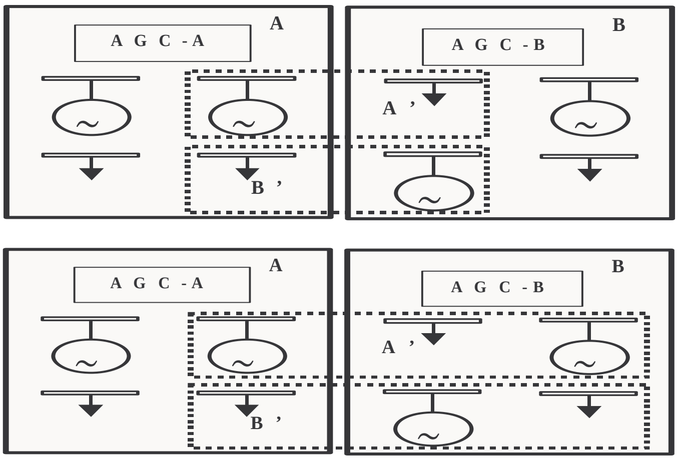


Fig. 2: Control Area Area Consolidation Approaches: a) Initial structure – 4 independent control areas (A, B, C, D) of a united PS; b) 4 independent areas are merged into a single one (A) by eliminating B, C, and D independent areas; c) A control area becomes a leading area with B, C, and D independent areas incorporated; d) Nested structure of inclusion of internal control areas (B., C., and D) into A control area.

Elimination approach to control area consolidation (Fig. 2b) might create better conditions for control resources optimizing (if there are no transmission limitations). A consolidated control area might provide new possibilities for ancillary service exchange among the internal CAs. However, the overlap automatic control approach is mandatory in a consolidated CA, which might create additional control problems in case of improper application. For that reason AGC approaches must be modified and extensive and reliable electronic communication network must be in place.

The approach of PS units' connection for joint performance can be modified by grouping together the consumers and the generators having drawn mutual bilateral contracts for power trade. Virtual control areas extending over several geographical (physical) areas and having no clear configuration might be organized for the fulfillment of such contracts. The grouping of generators and consumers is implemented as autonomous control of certain generators by monitoring load changes of assigned consumers. This is implemented by using automatic generation control systems of actual control areas and additional power telemetry of remote consumers. In principle many virtual control areas functioning simultaneously might be created in a united PS. Their automatic control may be autonomous and distributed. It is self-evident that this is the case of overlap control as actual and virtual control areas would be controlled simultaneously. It might have certain benefits such as possibility to better utilize regulating power reserves. Nevertheless in order to ensure the security of PS regimes it has to be a centralized coordination of virtual control areas activities (the number and scopes of bilateral contracts) within a certain area of a united PS. Figure 3 shows possible virtual control areas extending over two actual control areas (A and B).



a) b)

Fig. 3: Virtual Control Areas: a) A area generator supplies the power to B area consumer (A') and B area generator supplies the power to A area consumer (B'); b) A and B areas generators jointly supply the power to B area consumer (A') and B area generator supplies the power to A and B area consumers (B').

Figure 3 does not show all possible ways of establishment of virtual control areas, but illustrates the main approaches for their creation. It must be noted, that there might be other actual control areas not included into the virtual control areas in between of two actual control areas A and B. In other words, the actual control areas A and B might be not adjacent but remote in respect of each other.

It must be held in mind that cross border line summary power exchanges are no more stabilized, if virtual control areas are used. However it is also true that virtual control areas might be established inside of a consolidated control area (see Fig. 2c) while the last might communicate with other control areas and stabilize the cross border power balance in a conventional way.

There structural changes of control areas described above allow adapting to new operation conditions. These changes are not possible without the implementation of new control technologies (means of communication, digital equipment) and new control approaches.

Conclusions of Study of Power System Restructuring Trends:

1. In order to establish a power market in restructured PS it is advisable to have either sufficiently large conventional control areas or consolidated control areas.
2. Consolidated control areas provide more flexibility for adaptation to local conditions and better considerations of interests and institutional restrictions of different players of power market.
3. It is necessary to study the possibilities of automatic generation control systems of consolidated control areas and propose new ways of AGC service provision.
4. In conditions of power market, the stabilization of cross border active power exchange may be discontinued in united electric energy system thus expanding the possibilities for power market.

5. STUDY RESULTS OF AUTOMATIC GENERATION CONTROL PROCESSES OF RESTRUCTURED PS

The case of **bilateral contract implementation** is considered by applying the model described above, when the load emerging within one system (control area) is covered by buying the generation from another system (control area). Figures 4 to 7 show the process charts.

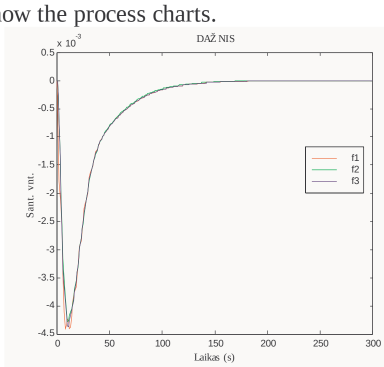


Fig. 4: Frequency variation curves in case of implementation of contract A1 – S2; p.u.

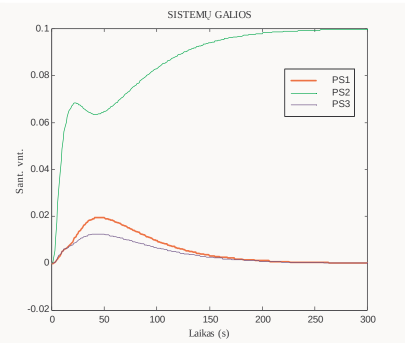


Fig. 5: Variation of powers in systems S1, S2, and S3 in case of implementation of contract A1 – S2; p.u.

Curves in Figure 4 show that the frequency changes are almost the same in all systems. The differences increase if connecting line resistances are larger. The frequency is restored approximately in 150 seconds after the load increase.

Figure 5 shows that the contract conditions are fulfilled in 300 seconds, i.e. system S2 increases its power to 0.1 p.u. (curve PS1). Systems S2 and S2 are not involved in load covering but they help regulate the frequency and powers (curves PS1 and PS2).

Without these systems in place, the quality indices (frequency deviations and process duration) would be worse.

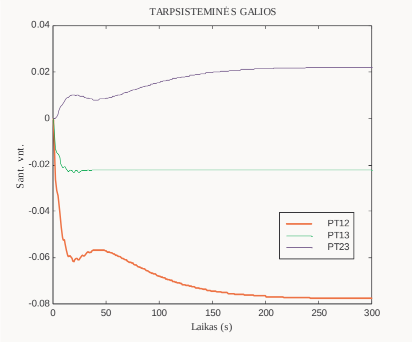


Fig.6: Variation of cross border exchange in Case of implementation of contract A1 – S2; p.u.

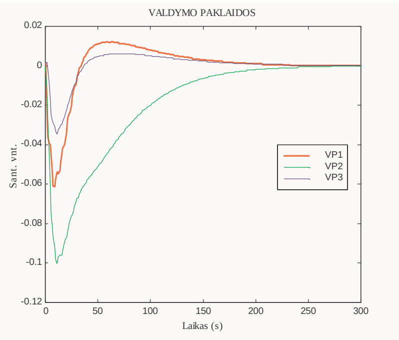


Fig. 7: Control error variation in case of implementation of contract A1 – S2; p.u.

Commercial power flows between the systems are contractual flows corresponding to the compensation of one system load with generation power bought in another system. These power flows may go in two directions at the same time, as power procurements might be bilateral. One might suggest that the actual power flows (PT12, PT13, and PT23) could be the difference resulting between these power flows; however Figure 6 shows they are not. Actually the transit power flows may go through all systems without affecting power balance of a control area. They depend on system structure and integrator coefficient of line model. In this particular case the actual power exchanges are calculated as follows:

$$P_{12} = PK1 * \left(\frac{\frac{1}{PT_{13}} + \frac{1}{PT_{23}}}{\frac{1}{PT_{12}} + \frac{1}{PT_{13}} + \frac{1}{PT_{23}}} \right), \qquad (5)$$

$$P_{13} = -P_{23} = PK1 * \left(\frac{\frac{1}{PT_{12}}}{\frac{1}{PT_{12}} + \frac{1}{PT_{13}} + \frac{1}{PT_{23}}} \right). \qquad (6)$$

Control error curves (Figure 7) reflect the variation of integral control indicator. It approaches zero as the process is complete. The biggest error deviation is observed in the control area where the generation power is changed (VP2). Second largest error is observed in the control area where the load increases (VP1) and the least error is in the third area (VP3).

A **multilateral contract of electrical energy procurement** is the contract when the generation power is procured both in the own and adjacent systems. The processes of their implementation do not depend on whether bilateral or single-buyer power market exists. Only the decision-making mechanisms are different. Figures 8 to 11 show the contract implementation processes.

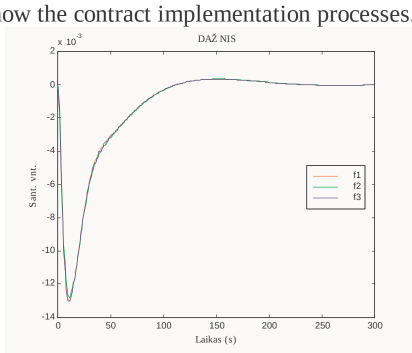


Fig. 8: Frequency variation processes in case of implementation of multilateral contract; p.u.

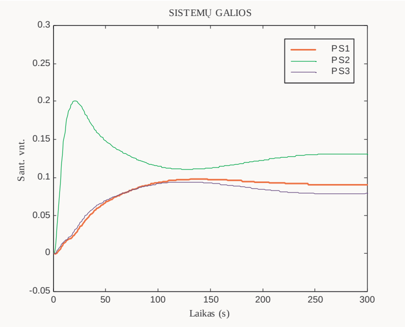


Fig. 9: System power variation processes in case of implementation of multilateral contract; p.u.

The nature of the processes remains the same (as compared with those shown on Figure 4), but the frequency deviation has correspondingly increased due to the triple increase of summary load.

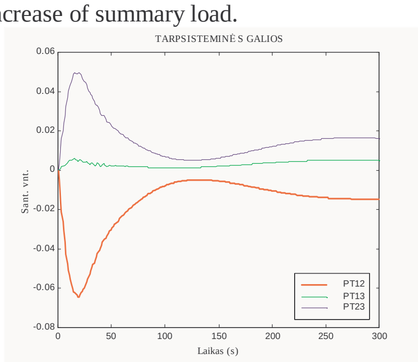


Fig. 10: Cross border power variation processes in case of implementation of multilateral contract; p.u.

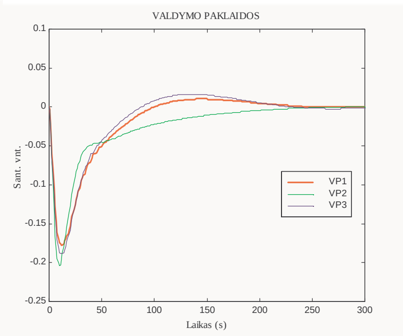
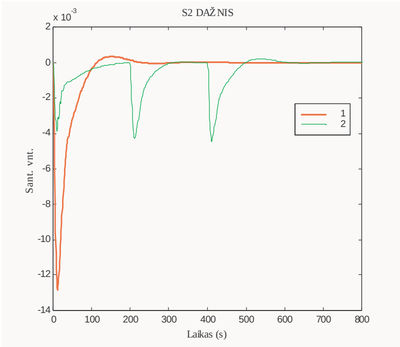


Fig. 11: Control error variation processes in case of implementation of multilateral contract; p.u.

The curves in Figures 8 to 11 show that multilateral contracts may be successfully implemented by applying the proposed automatic generation control model. However a control quality problem might arise. It can be estimated by control error curve indicators alone (Figure 11). Their maximum deviations exceed the power increase of the respective system. Besides, the control requires rapid changes of generation power (Figure 9) while the adequate resources might not be available.

One of the ways to resolve this problem is the use of **asynchronous contract implementation**. It is estimated that those power trade contracts are drawn for the period of one hour, therefore the latency of few minutes are tolerable. For that reason the separate parts of the contract might be gradually implement by introducing latency.



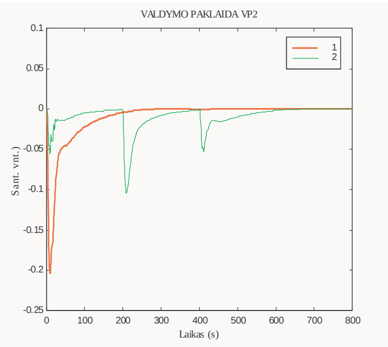


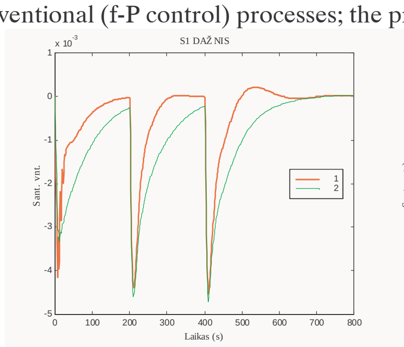
Fig. 12: Frequency variation curves of system S2: 1 – 1st method; 2 – 2nd method; p.u.

Fig. 13: Control error VP2 variation curves: 1 – 1st method; 2 – 2nd method; p.u.

The effect of asynchronous contract implementation can be the best explained by comparing process curves of both methods. Figure 12 shows frequency variation curves of system S2 (they are almost the same as those of S1 and S2).

Figure 12 and 13 show - 1st method is synchronous contract implementation, 2nd method – asynchronous contract implementation. Figure 12 shows that 2nd method significantly decreases frequency deviations; however, the process duration increases as well. In order to determine which indicator is more important, it is necessary to refer to specific conditions. Figure 13 shows the comparison of control errors. The examples described in Chapter 5 herein show the possibilities for multilateral power trade contract implementation and AGC process control. Adjusting contract implementation start for each specific case alone is sufficient for process quality optimization.

AGC systems of Baltic States shall operate in the **mode of interchange active power control** (**P control**) for a certain period of time. For that reason it is advisable to examine these control processes. Frequency control channels of AGC1 and ACG3 have been disconnected. Figures 14 and 15 show the comparison of resulting curves (P control processes) with the curves of conventional (f-P control) processes; the process changes are clearly visible.



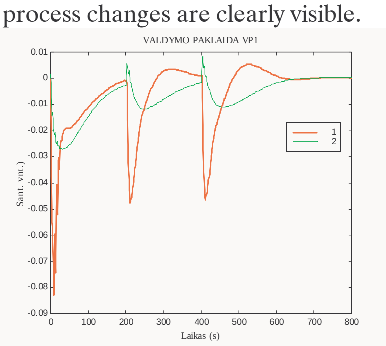


Fig. 14: Frequency variation of system S1(1:

Fig. 15: Variation of control error VP1

S1,S2,S3–f-P control. 2: S1,S3–P control., S2–f-P control); p.u.

(1:S1,S2,S3–f-P control. 2: S1,S3–P control, S2–f-P control.); p.u.

The final control outcome is fully the same in both cases of power control (P control) and frequency and power control (f-P control.). However the differences must also be noted. The decrease of control quality (a longer frequency restoration process) is evident. Deviations of control error VP1 (VP3) decrease as the system S1 (S3) does not respond to frequency changes. Deviations of control error VP2 remain almost the same as the system S2 bears the main frequency control load in both cases. During only cross border active power control by the systems S1 and S2, the system S2 bears greater control load and is entitled to greater compensation.

The examples below illustrate the **load control possibilities** and control process features.

In the process of implementation of contract A1-S2 it is reasonable to decrease the involvement of generators within the system S1, where the load is located, in the control process as they are not participants of the contract. Part of control load may be assigned to distributing company to compensate the load A1 of which the generation is procured in the system S2.

Figures 16 and 17 show the comparison of control processes with and without the programmed load control.

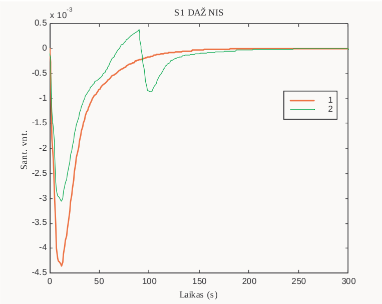


Fig. 16: Comparison of frequency variation: 1 – without load control; 2 – with load control; p.u.

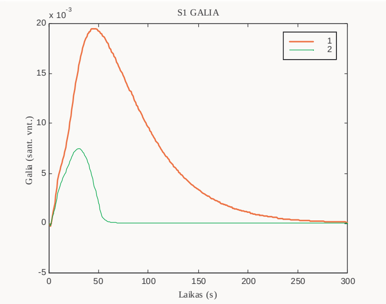


Fig. 17: Comparison of S1 power variation: 1 – without load control; 2 – with load control; p.u.

The curves in Figure 16 lead to conclusion that the integral frequency deviation decreases if load control is applied. The curves in Figure 17 show that the involvement of system S1 in the compensation of load A1 decreases approximately three times.

The presence of controllable loads is essential in cases when one of the systems (such as S1) has insufficient reserves of regulating power. In such case the decreased frequency remains in the united system after the control process is complete, therefore violating the main condition of united system joint functioning. In this case the generated power might be procured from adjacent systems but it might not be always available when necessary.

The resulting curves show that the main AGC system requirements for control processes are satisfied in that case. Connecting the disconnected loads is subject of decision by the system operator at certain later moment.

The above examples show that the presence of controllable loads in restructured PS is essential and their use is to be facilitated. They should be useful both for power supplying and consuming parties. This is a kind of automatic load shedding sequence when this equipment are able to function at considerably low frequency deviations and the power of connected consumers is quite low.

More complex model of four energy systems is further considered and its processes are examined. Figure 18 shows a simplified model of four energy systems. This model is used for examining Baltic PS working synchronically with much greater Russian PS – this shows the application of ideas described above.

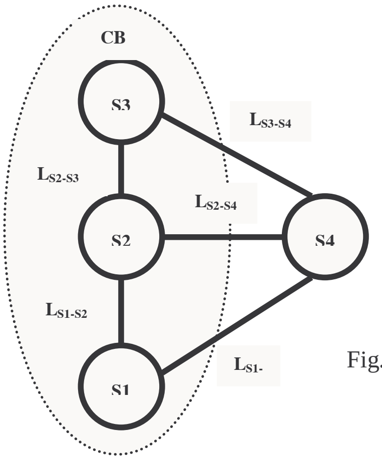


Fig. 18: Structural Diagram of United System Model

Different energy systems S1, S2, and S3 form a control block CB. It is assumed that CB (Baltic PS) power amounts to 30% of S4 (Russia) power. S2 stabilizes the frequency and CB – cross border power exchange (balance) and can take part in frequency stabilizing. The deviation change processes caused by load changes in any system are considered (ΔA = 0,1 p.u.). L_{S1-S2}, L_{S2-S3}, L_{S2-S4}, L_{S1-S4}, L_{S3-S4} – are generalized lines connecting respective systems. The processes are examined from the perspective of a single S1 system.

The diagram of automatic generation control model presented in the same way as that of three energy systems described in the previous chapter.

Figures 19 and 20 show curves representing the process of load increase in the system S1 (by 0.1 p.u.) while the systems S1 to S4 are self-regulated in a conventional way.

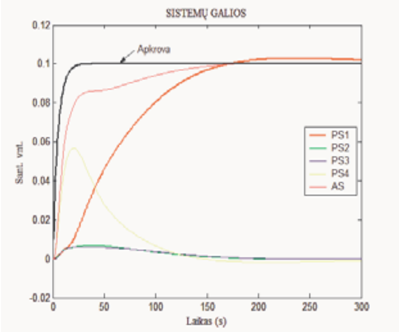


Fig. 19: Load of system S1 (Apkrova) and generation of S1 to S4; p.u.

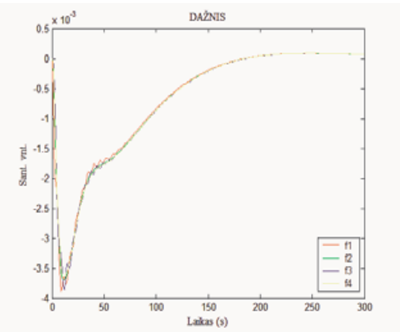


Figure 20: Frequency; p.u.

The AGC processes of **virtual control areas (VCA)** of four energy systems are examined. The errors of control areas (i and j) are calculated as follows:

$$ACE_{iVVR} = \Delta P_i + k_{si} \times \Delta f + (1 - k_{Ai}) \times \Delta A_i \, , \qquad (7)$$
$$ACE_{jVVR} = \Delta P_j + k_{si} \times \Delta f - (1 - k_{Ai}) \times \Delta A_i \, . \qquad (8)$$

In equation 7 and 8 the factor k_{si} ($0<k_{si}<1$) indicates, which part of the load in the i^{th} control area is regulated by the j^{th} area generators. The coefficient k_{Ai} is only necessary for study process modeling. Actually the load part $(1-k_{Ai})\times\Delta A_i$ is to be marked in the i^{th} control area and the results of measurement are to be submitted to secondary regulators of the i^{th} and j^{th} control areas, which can assign the generators (power plants) involved in VCA AGC. Figure 21 shows the process curves in case when the load change in the energy system S1 is compensated by the generation in the systems S1 and S2 (trade contract $P_{S1}=0.6P_{S1}+0.4P_{S2}$). Such a VCA can be designated as S1→S2.

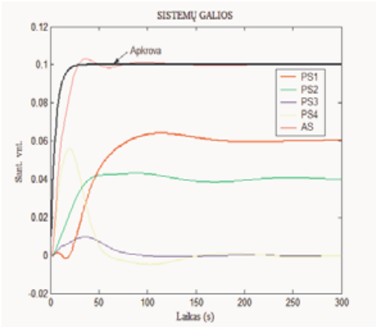


Fig. 21: Powers in S1, S2, S3 and S4; p.u.

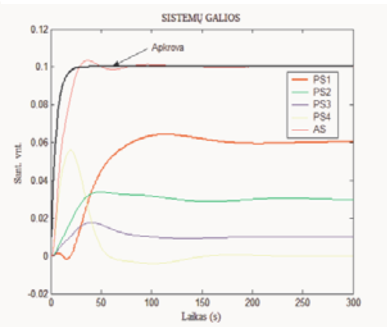


Fig. 22: System powers under VCA (S1→S2,S3); p.u.

Figure 21 shows that the load change (0.1 p.u.) in S1 has been regulated by S1 (0.06 p.u) and S2 (0.04 p.u.). It shows that S2 supplies the control for S1 and the VCR S1→S2 is active. This VCA covers the load in S1 by generator (generators) in S1 and S2 by means of AGC (secondary regulators of S1 and S2). Control area errors are expressed as follows:

$$ACE_{S1(S1\to S2)} = ACE_{S1} + 0.4 \times \Delta A_{S1}, \qquad (9)$$

$$ACE_{S2(S1\to S2)} = ACE_{S2} - 0.4 \times \Delta A_{S1}. \qquad (10)$$

The information transfer regarding the load change $(0.4 \times \Delta A_{S1})$ is essential for the functioning of this VCA. It must be noted that the systems S3 and S4 are involved in the control in the beginning of the process and their effect is directly proportional to the system size. The frequency curve remains exactly the same as in Figure 20.

Lets examine two more VCA cases: S1→S2,S3 and S2,S3→S1. Figures 22 and 23 show the curves of the process.

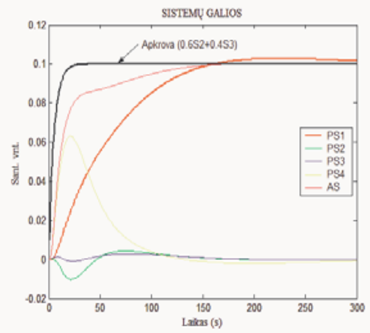


Fig. 23: System powers under VCA (S2,S3→S1); p.u.

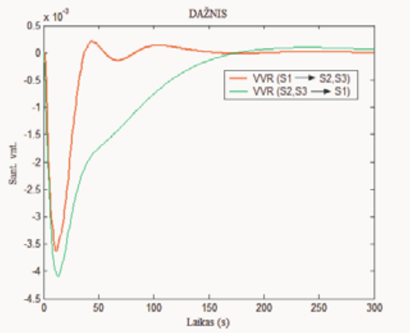


Fig. 24: Frequency variation comparison under different VCA; p.u.

Suppose that VCA S1→S2,S3 ($P_{A(S1)} = 0.1 = 0.6P_{S1} + 0.3P_{S2} + 0.1P_{S3}$) covers three conventional control areas (Fig. 22) with control areas errors expressed by Equations 11 to 13:

$$ACE_{S1(S1\to S2,S3)} = ACE_{S1} + 0.4 \times \Delta A_{S1}, \qquad (11)$$

$$ACE_{S2(S1\to S2,S3)} = ACE_{S2} - 0.3 \times \Delta A_{S1}, \qquad (12)$$

$$ACE_{S3(S1\to S2,S3)} = ACE_{S3} - 0.1 \times \Delta A_{S1}. \qquad (13)$$

The load change of VCA S2,S3→S1 in the systems S2 and S3 is regulated by the generator in the system S1 (Fig. 23): $P_{A(S2)} + P_{A(S3)} = P_{S1}$ ($P_{A(S2)} = 0.06$; $P_{A(S3)} = 0.04$; $P_A = 0.1$). Control area errors are expressed as follows:

$$ACE_{S1(S2,S3\to S1)} = ACE_{S1} - (\Delta A_{S2} + \Delta A_{S3}), \quad (14)$$

$$ACE_{S2(S2,S3\to S1)} = ACE_{S2} + \Delta A_{S2}, \quad (15)$$

$$ACE_{S3(S2,S3\to S1)} = ACE_{S3} + \Delta A_{S3}. \quad (16)$$

Figure 22 shows process curves calculated by Equations 11 to 13 and Figure 23 – those calculated by Equations 14 to 16. Positive sign of load change (ΔA) in Equations 11, 15, and 16 decreases the power of energy systems S1, S2, and S3; negative sign in Equations 12, 13, and 14 accordingly increases the power of these systems. The sum of decreased power is equal to the sum of increased power. These ways of VCA implementation provide new possibilities that may be realized in a united energy system.

Figure 24 compares the curves of frequency variation process.

The curves show that the quality of frequency control increases if the load is regulated by generators located in different control areas. In the case of first VCA (S1→S2,S3) the load is regulated by generators within three systems (S1, S2, S3); in the case of second VCA (S2,S3→S1) the load is regulated by the system S1. The higher quality of frequency control allows increasing the quality of cross border exchange, which means that CB is less dependant on S4.

Figures 2c and 2d show the structure of **overlap control area** (OCA). In case of a OCA a single system controls cross border lines ($L_{S2\text{-}S4}$, $L_{S1\text{-}S4}$, $L_{S3\text{-}S4}$) power exchange by its AGC regulator on behalf of the systems S1, S2, and S3. This system is the leading one in the block but it also must ensure sufficient regulating resources.

For the sake of the study an assumption is made that the energy system S2 is the leader of a OCA. In this case control area errors are expressed as follows:

$$ACE_{S1} = \Delta(P_{S1-S2} + P_{S1-S4}) + k_{sS1} \times \Delta f, \quad (17)$$

$$ACE_{S2} = \Delta(P_{S2-S1} + P_{S2-S3} + P_{S2-S4} + P_{S1-S4} + P_{S3-S4}) + k_{sS2} \times \Delta f, \quad (18)$$

$$ACE_{S3} = \Delta(P_{S3-S2} + P_{S3-S4}) + k_{sS3} \times \Delta f. \quad (19)$$

OCA allows improving AGC dynamics, quality of automatic control and ensuring control power reserves.

The dynamic process is different in conventional and overlap control areas. Figures 25 and 26 compare frequency and cross border exchange of both processes.

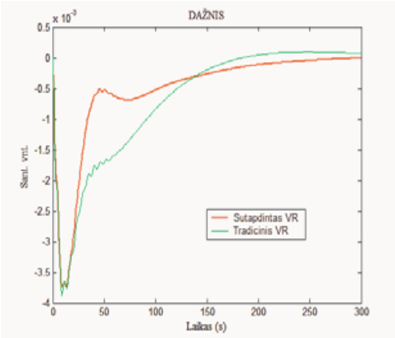


Fig. 25: Frequency comparison (- OCA, - traditional CA); p.u.

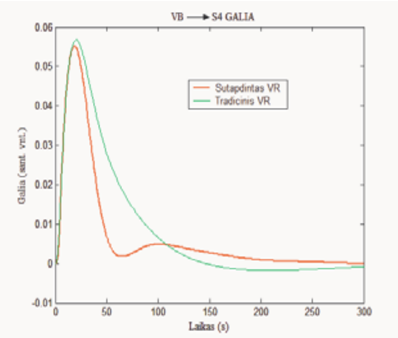


Fig. 26: Comparison of cross border power between CB and S4 (- OCA, - traditional CA); p.u.

It is evident that the frequency and cross border exchange settle faster if OCA is in place.

Main Conclusions of Process Modeling and Study:

1. It has been demonstrated that overlap AGC can be applied in control blocks, thus increasing control quality and reliability.
2. It has been determined that new AGC approaches (virtual and overlap) can be implemented by applying the approach of cross border active power control.
3. It has been demonstrated that controllable loads (disconnected and connected automatically or programmatically) must be in place in a restructured system to replace fast generation power reserve in certain cases.
4. It has been stated that other players of generation market are more or less involved in the implementation of bilateral power trade contracts as well. Bilateral contracts between partners located in different control areas (the approach of virtual control areas) replace the practice of cross border active power exchange stabilization.
5. It has been demonstrated that the proposed AGC approaches significantly increase the flexibility of automatic generation control and consequently the degree of their adaptation in the specific systems. In the beginning phase of power market implementation, an AGC system with incomplete function set might be employed such as the one functioning in the regime of cross border power control.
6. It has been demonstrated that in the process of implementation of power trade contracts the operator of a united system might not perform AGC automatic control functions – these may be performed in a distributed manner by secondary regulators (AGC systems) of separate systems; system operator is necessary for advance regime planning and coordinating of AGC system performance.
7. As power market and new AGC approaches are implemented, the amount of information transferred to AGC systems and the role of communication systems increases dramatically.

6. SYSTEM SERVICE PRICING PRINCIPLES AND AGC ACCOUNTING

Pricing structure for automatic control of frequency and active power should cover the following:

- Investments into regulating power reserves and primary control equipment.
- Operation costs and maintaining of active power reserves.
- Economy decrease due to uneven operation.
- Profit loss due to partial unit load.
- Other incurred costs.

Primary control costs must include the costs of production deviation from the schedule incurred during frequency deviations while primary regulators are active. There are different opinions on this issue expressed by various operators, which means that pricing approaches are also different. Some of them suppose that it is the regulating energy which price should be the same as previous hourly price of equivalent regulating energy; another opinion is that the price for this energy must equal to spot market price for that hour plus 10-15 percent.

The transmission system operators, as well as the providers of ancillary services are certain that the services of primary frequency and automatic power control must be priced; therefore it is necessary to align the approach for measuring of said services and provide continuous monitoring within any synchronous power system. The priority is given to the monitoring of this service in real-time, i.e. remote real-time measurements.

Economic penalties and rewards must be assigned according to the quality of service provision. Purely intangible conditioning such as public announcements of service provision results is not sufficient. The scale of such economic penalties and rewards must be quite large so that they would significantly exceed the costs saved by providing low-quality service.

The pricing for frequency and power automatic control is directly related to the accounting of provided service. The process modeling has shown that service accounting might be quite complex and technically difficult to implement. Without accounting in place, the price can only be estimated. However this would violate the principle of fair compensation. The simplest approach would be to charge for the service (such as active power reserve) according to is amount and provision duration. Nevertheless the provided services must comply with certain requirements (such as the duration for introducing the reserve, set dynamic characteristic, etc.). It is essential that the services are properly territorially distributed, i.e. distributed control used.

Such a situation allows the use of equivalent service exchange. It must be understood as the possibility for all power market players to contribute an according amount of these services and abandon financial settlements.

In this regard the following the power market implementation principles recommended by UCTE are critical:

1. Non-discrimination: equal market access rights should be granted together with a mandatory due based to "pollution tax" principle to cover the costs of system services.
2. Transparency: all market players are to recognize and understand rules and guidelines in force and ensure their observance.
3. Subsidiarity principle: the decisions must always be made on the lowest possible level of on the level closest to that where the effects of those decisions will manifest. Regulating must be applied only to the elements that cannot satisfactory function otherwise. The priority must be give to internal power system instruments whenever possible together with the application of cooperation principle (self-control). AGC system is based on this principle.
4. Efficiency: an UCTE principle stating that the necessary rules must be defined and applied in a non-bureaucratic way should be observed.
5. Unambiguity and acceptability: the rules in force cannot be understood in more than one way and must be understandable and acceptable to all market players.
6. Supervision: it is absolutely necessary to ensure the adherence to the basic rules. It is unconditionally recognized that the solidarity required by the operation and control of a united system cannot automatically spring into existence; the drive of market players to benefit on account of the others even for a short period must be taken into consideration.
7. Penalties: supervision and control are powerless if not accompanied by sanctions. A proper and legally valid penalty and reward system must be in place.

If those requirements are observed, the operational control of separate energy systems (control areas) is sufficiently independent, and the processes may be examined autonomously. In most cases reciprocal compensating for provided services may be applied.

Proper territorial distribution (dispersion) of ancillary services tends to increase reliability and decrease losses. The effect to controlled units is diminished.

To ensure **control service accounting,** control service indicators (dependence of interchange power on frequency deviations) shall be used indicating whether the system uses or provides control services.

The control service indicator can be established for two systems, i.e. control areas or control blocks (i and j) by using the following equations:

$$\Delta f_i = F_i(\Delta P_{ij}), \qquad (20)$$

$$\Delta f_j = F_j(\Delta P_{ji}). \qquad (21)$$

These equations contain values of modes of both systems (i and j): Δf_i, Δf_j – frequency deviations; ΔP_{ij}, ΔP_{ji} – interchange power deviations. The power deviation is positive if the power leaves the system (and negative if the power enters into the system). The system (control area) provides AGC services Δf_i and ΔP_{ij} , if the signs of Δf_j and ΔP_{ji} are different, i.e. $(sign(\Delta f_i \cdot \Delta P_{ij}) < 0)$, and consumes AGC services if the signs are the same $(sign(\Delta f_i \cdot \Delta P_{ij}) > 0)$. This service may be characterized by the control power of both systems (RG_i and RG_j) and expressed as follows:

$$RG_i = -\Delta P_{ij} \cdot (sign(\Delta f_i \cdot \Delta P_{ij}), \qquad (22)$$

$$RG_j = -\Delta P_{ij} \cdot (sign(\Delta f_j \cdot \Delta P_{ji}). \qquad (23)$$

The control power varies with time. The control area (i or j) provides control service if this power is positive and consumes it, if the power is negative. At any the same time moment the control powers of both systems have opposite signs. A continuous logging of control power is necessary for AGC service accounting. The amount of control service is equal to the integral value of an control power taken over a certain time period. This value might be either positive or negative. If the value of the integral (sum) is positive it means that the control area supplies the surplus of control service, if it is negative it means that the control service is consumed, and if it is equal to zero it means that the control service exchange between two systems is balanced. A transparent AGC service accounting and pricing is a critical condition in order to stimulate the provision of such services and the development of their resources.

It must be noted that the control power determined in this way also covers interchange power variations in cases when generation and consumption are not balanced within the control area or set frequency value is not restored. It happens if the principle of virtual or overlap area control principle is applied in case of power deficit.

Figure 29 shows the variation of control service indicators of systems S1, S2, and S3 when load increases in the system S1 (Figure 1 shows the structure) in case of conventional control approach (Fig. 27), and Figure 28 shows the processes of frequency and power control service exchange. They reflect the exchange of control services between these systems.

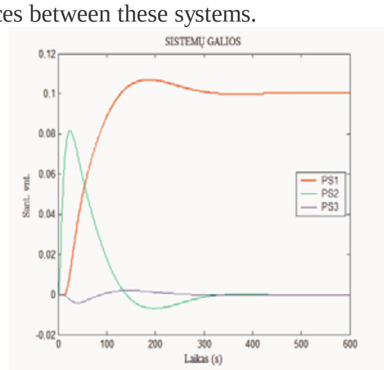


Fig. 27: Powers in systems S1, S2, and S3 in case of conventional control; p.u.

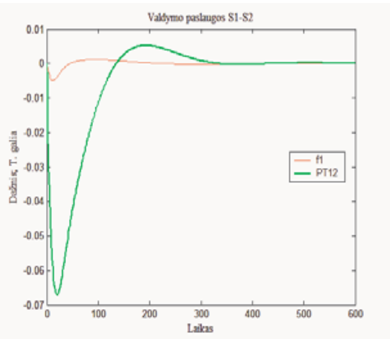


Fig. 28: Process of frequency and interchange power between S1 and S2 in case of conventional control; p.u.

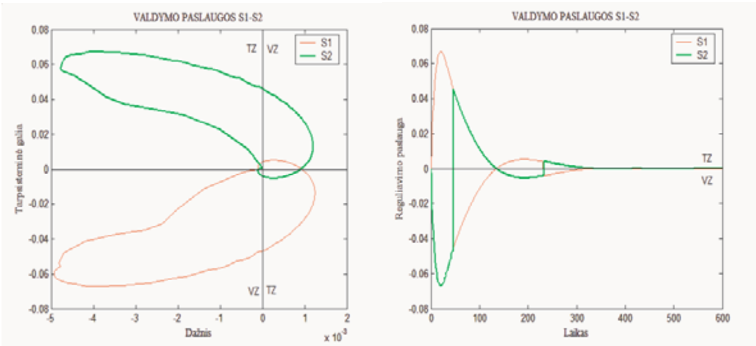


Figure 29: Processes of variation of control service indicators between S1 and S2 in case of conventional control

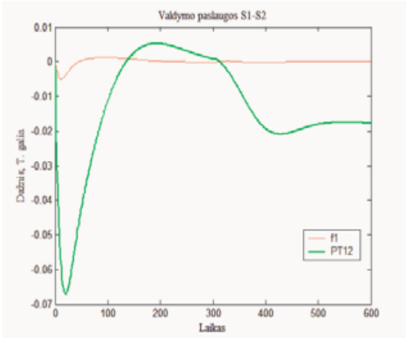


Fig. 30: Process of frequency and interchange power between S1 and S2 in case of VCA control; p.u.

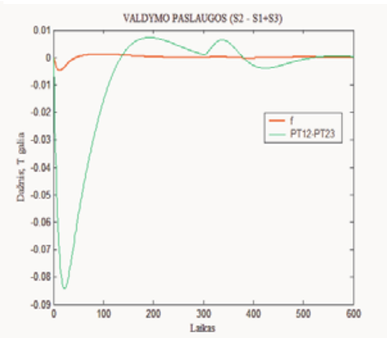


Fig. 31: Process of frequency and interchange power between CB and S2 in case of VCA control

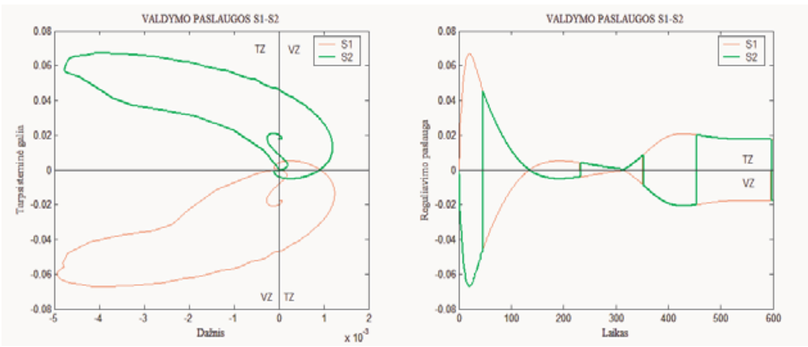


Figure 32: Processes of variation of control service indicators between S1 and S2 in case of VCA control

The left of Figures 29 shows the dependence of exchange power deviation from frequency deviation (the indicator variation hodograph). Figures 30 and 31 show the processes of AGC service exchange. They reflect the exchange of control services between systems. Figure 32 shows the variation of control service indicators of systems S1, S2, and S3 when load increases in the system S1 in case of VCA where a part of load increase (0.4 p.u.) is regulated by S3.

At any time moment the control service indicator may be either in the control service provision (TZ) or consumption (VZ). In the area of control service provision (TZ) the signs of power and frequency deviations are opposite; in the service consumption area (VZ) they match. Such a chart is useful for monitoring frequency control processes when it is important to determine the instantaneous status of control service provision. The right of the figures shows the variation of control indicators over time. These are transformed charts of cross border power variation where power signs are changed at certain moments. These charts show that after the load increases in CB (S1) it initially consumes control services provided by S2; after the load increases in the system S2 the service is provided by CB (S1, S3). In the process the services' signs change (service leaves VZ area and enters TZ area). The amount of services of different sign is not the same and it means that the exchange between the systems is not equivalent. It depends on selected control approach and system parameters.

Study Conclusions of System Service Pricing and AGC Accounting Possibilities

1. The possibility analysis of system service and AGC pricing and accounting leads to the conclusion that ancillary services may be separated as separate products of power market.
2. The main principles of AGC service pricing approach does not differs from similar principles of energy pricing principles valid in power market however the AGC service market must be separated from energy market due to different AGC administrating structure.
3. The possibility study of AGC service shows that irregardless of whether the approach of virtual or overlap control area is applied, the same AGC service accounting principle is suitable, and the amounts of AGC service provision can be determined by measurement and accounting tools.

7. MAIN CONCLUSIONS

1. The examination of trends of organizing control areas in restructured power systems has shown that with the liberalization of power market and relations among power market players the possibility appears for all market players to be involved in provision of ancillary services, therefore the development of a flexible structure of automatic generation control is necessary to make the application of various power market models possible.
2. The trend analysis of power market development has shown that it is feasible to abandon cross border interchange power stabilization in automatic generation

systems thus ensuring the implementation of short-time contracts among entities (generators and consumers) located in different control areas.

3. The studies completed lead to conclusion that AGC ancillary service market may be implemented by applying proposed distributed unconventional approaches by introducing automatic generation control of virtual and overlap control areas, that improves the reliability of power system operations and power quality and allows tapping into additional resources of distributed power reserves.
4. This work improves conventional models of automatic generation control system and modeling approach of automatic generation control processes that allows studying proposed approaches for automatic generation control by using the market dynamics assessment information.
5. The modeling shows that various studied approaches for automatic generation control increases the flexibility of AGC system application according to the technical status of market players and those approaches may be applied on various stages of power market implementation.
6. It has been demonstrated by AGC process modeling that it is feasible to implement automatically controllable loads (disconnection and connection) that increase regulated power reserves and partially replace controllable generation.
7. The studied approaches for AGC service control and accounting show that it is possible to account the amounts of exchange of these services among power systems being the basis for settlement of reciprocal compensation for such services. It is possible to exchange or trade control services with other systems by implementing proposed AGC approaches.
8. It is possible to start developing the payment methodology of AGC services provided by market players applying the proposed principles for automated generation control service cost estimation and pricing.

8. PUBLICATIONS BY THE AUTHOR DEALING WITH THE DISSERTATION

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About the Author

Ramūnas Bikulčius was born on November 2, 1965 in the town of Ignalina.

He graduated from Kaunas University of Technology in 1990 acquiring the certificate of electrical engineer. He started engineer job at the dispatch centre of Lietuvos Energija AB in 1990. From 1995 to 1997 – Assistant Director at Energetikos

Agentūra Public Company. From 1997 since now he works at the dispatch centre of Lietuvos Energija AB. A scientific study in the field of technology sciences, power and thermal engineering has been started at Department of Electric Power Systems of Kaunas University of Technology in 1999 and completed in 2004.

Reziumė

Darbo aktualumas

Šiuo metu visame pasaulyje vykdomos elektros energetikos sistemų (EES) restruktūrizacijos esmė – pasiekti atvirą generavimo ir vartojimo subjektų priėjimą prie elektros perdavimo sistemos ir rinkos santykių tarp energijos rinkos subjektų įdiegimas.

Viena iš pagrindinių elektros energijos perdavimo veiklos sričių, kuri ypatingai svarbi energetikos sistemos darbo patikimumui užtikrinti, yra sisteminių paslaugų ir operatyvinio energetikos sistemos valdymo paslaugų tiekimas elektros rinkos dalyviams bei rinkos elementų įvedimo galimybės papildomų ir sisteminių paslaugų tiekime.

Mokslinis naujumas

Automatiniam generacijos valdymui (AGV) pasiūlyta naudoti rinkos dinamiką įvertinančią informaciją, sudarančią galimybes reaguoti į konkurencinės elektros bei papildomų paslaugų rinkos procesus ir juos optimizuoti.

Pateikti nauji - virtualaus ir sutapdinto valdymo rajonų - AGV būdai, leidžiantys lygiagrečiai su elektros rinka vystyti ir teritoriškai plėsti AGV papildomos paslaugos rinkas.

AGV paslaugos teikimo koordinavimui pasiūlytas naujas sistemos operatoriaus antrinio reguliatoriaus modelis, kuris leidžia tirti AGV poveikio agregatų reguliavimo sistemoms mažinimo būdus, tuo pat metu palaikant tinkamą reguliavimo kokybę.

Pasiūlyti AGV paslaugos įkainojimo principai bei apskaitos matematinis modelis leidžiantis sukurti ir įdiegti šios paslaugos apskaitos bei kainodaros sistemą.

Tyrimų apžvalgoje atlikta pasaulyje vykdomų darbų, susijusių su rinkos diegimu pagalbinių paslaugų sferoje, analizė. Nustatyta, kad restruktūrizuotų EES AGV sistemose nepakankama apimtimi naudojama elektros rinkos dinamiką įvertinanti informacija, nepakankamas dėmesys skiriamas naujiems AGV būdams, įgalinantiems efektyviau išnaudoti valdymo resursus, ir nepakankamai pagrįsti AGV paslaugų apskaitos bei įkainojimo principai.

Darbo metodologijoje siūlomi nauji valdymo rajonų konsolidavimo būdai, pateikiama valdymo rajonų schema, kurios pagalba tiriamos konsoliduotų valdymo rajonų automatinio generacijos valdymo sistemų galimybės ir savybės, siūlomi nauji automatinio generacijos valdymo paslaugos teikimo būdai.

Restruktūrizuotų EES automatinio generacijos valdymo procesų tyrimo skyriuje pateikti tyrimo rezultatai, įgalinantys teigti, kad realizuojant elektros rinkos kontraktus, įvedant konkurencinę aplinką, galima padidinti automatinio generacijos valdymo paslaugų tiekimo galimybes, valdymo kokybę bei patikimumą.

Sisteminių paslaugų įkainojimo bei AGV apskaitos galimybių tyrimo skyriuje pateikta **s**isteminių paslaugų ir AGV įkainojimo analizė leidžia teigti, kad galima atskirti pagalbines paslaugas, kaip atskirus elektros energijos rinkos produktus, pagrindiniai AGV paslaugos apmokėjimo metodikos principai nesiskiria nuo elektros energijos rinkos už energiją apmokėjimo principų, tačiau esant skirtingai AGV administravimo struktūrai būtina AGV paslaugos rinką atskirti nuo elektros energijos rinkos.

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