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FLEXIBLE AUTOMATIC GENERATION CONTROL IN THE CONDITIONS OF ELECTRICITY MARKET

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The purpose of this work is analysis of common principles of automatic generation control (AGC) operation in new conditions. The various ways are examined concerning implementation of AGC system in the conditions of electricity market. The main attention is devoted to the distributed AGC with flexible structure that is possible to realize on the base of modern control and communication systems. It is proposed the flexible structure of AGC that may be used during different stages of implementation of electricity market. Modeling and simulation were used for investigation of processes of distributed AGC. Proposed AGC control modes may be employed during introduction of electricity market in power systems of Baltic States. *Copyright © 2000 IFAC*

Keywords: Automatic Generation Control, Electric Power System, Modeling, Simulation, Electricity Market

1. INTRODUCTION

The restructuring of electric power systems is subject of extensive studies during last years. It means introduction of electricity market through open access to transmission networks, unbundling of services (generation, transmission, distribution and ancillary) and competition procurement. The main purpose of restructuring is reduction of prices for end users of electricity and a transparency of costing of different services. In the countries with transit economy and highly centralized power generation control (for example Baltic States) restructuring must be treated as mean for controllable growth of prices and risk reduction. The electricity market must send proper economic signals to all participants of electricity market and ensure fair competition. It must strengthen energetic security of state and help in avoiding excess investments.

Automatic generation control (AGC) is one of ancillary services of power market. AGC includes primary and secondary frequency control that balances power consumption and generation with load dispatch among the generators. The restructuring of power systems is new challenge for AGC. It is a guarantee of strict fulfilling of electricity trade contracts. The perfect AGC system may stimulate the new kinds of electricity trading. It must take into account institutional restrictions and different interests of market participants. The bilateral and multilateral electricity trade contracts may be used. This causes volatility of loads of generators and load flows in tie lines. It is observed when real time (spot) market is operating (Christie and Bose, 1996; Fink and van Son, 1998). AGC services must be accounted and remunerated. These requirements may be achieved by introducing principles of distributed AGC.

The purpose of this work is analysis of common principles of AGC operation in new conditions and foreseeing ways of development of this service. The main attention is devoted to structure of distributed AGC that improves flexibility of secondary frequency control. The operation of distributed AGC was investigated using modeling and simulation of processes.

2. AGC FUNCTIONS IN THE CONDITIONS OF ELECTRICITY MARKET

AGC functions and electricity market operation are investigated on the case of interconnected power system (Fig. 1) that has three systems (S1, S2, S3) and tie lines (L_{12}, L_{13}, L_{23}). Loads of separate consumers (L1, L2, L3) may be balanced by everybody generator (G1, G2, G3) of interconnection according electricity trade contract.

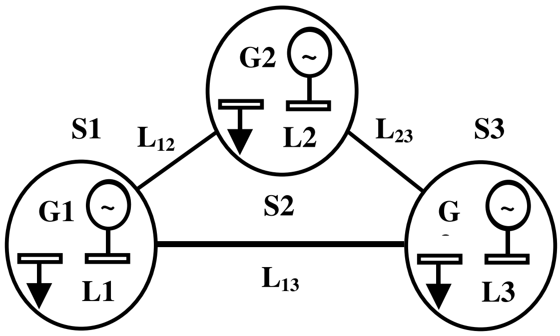

Fig.1. Structure of interconnection of power systems.

AGC system must keep power balance at every moment of time, stabilize frequency of interconnection and help in realizing electricity trade contracts of long term and short time (spot) market. Regulating power reserves there are necessary for performance of AGC functions. The generator must have advantage if it performs generation control. The secure operation of interconnection must be ensured avoiding power flow congestions in tie lines. It is possible to create centralized AGC system for this interconnection that controls electricity trade agreements.

AGC services accounting may be very complicated if centralized control is used. It is difficult to stimulate AGC services development in this case. The goal of this work is to show advantages of distributed and flexible AGC system in the conditions of electricity market.

3. OPERATION OF AGC IN THE CONDITIONS OF ELECTRICITY MARKET

At the present time distributed (decentralized) control is main method of automatic control of complex systems. Interconnected power system there is an example of complex systems. Distributed control of these systems is widely used. The examples of decentralized control there are relay protection, emergency automation, primary and secondary frequency control and etc. Automatic generation control must be properly distributed in the conditions of electricity market in order to ensure competitive trade of electric power and ancillary services. Territorial distribution of automatic control is guarantee for improving reliability of power system. Need for distributed control is stimulated by these reasons: possibility to realize different electricity and ancillary services trading contracts; creation of conditions for accounting of system services; improving security and reliability of interconnected power system; taking into account institutional limitations (power systems of different states). The reasons that encourage distributed control implementation there are achievements of new technologies during last years (Amin, 2000; Gross, *et al.*, 1999; Smathers and Akhill, 2001): creation of state-of-the-art computerized control systems; development of modern communication systems; creation of global positioning system (possibility to synchronize operation of remote automatic controllers); development of dispersed power resources (distributed generation, controllable loads); advances in control theory (agent based control, holonic control and etc.).

The distributed AGC system of interconnection is shown in figure 2. The power systems of interconnection (S1, S2, S3) are treated as control areas. AGC controllers of different systems have possibility operate on the base of three kinds of area control errors (*ACE*): tie lines net power and frequency deviation bias (1), tie lines net power deviation (2), and frequency deviation (3):

$$ACE_i = \Delta P_i + k_{si} \cdot \Delta f_i\,, \tag{1}$$

$$ACE_i = \Delta P_i, \tag{2}$$

$$ACE_i = \Delta f_i\,. \tag{3}$$

There are: ΔP_i, Δf_I – power flow and frequency deviation, k_{si} – frequency bias of control area. The minimization of *ACE* ensures stabilization of frequency and flows of net tie lines. The independent system operator (ISO) co-ordinates operation of AGC controllers allowing trade contacts which are acceptable in the sense of secure operation of interconnection. The regulating power reserves are obligatory for each control area (system).

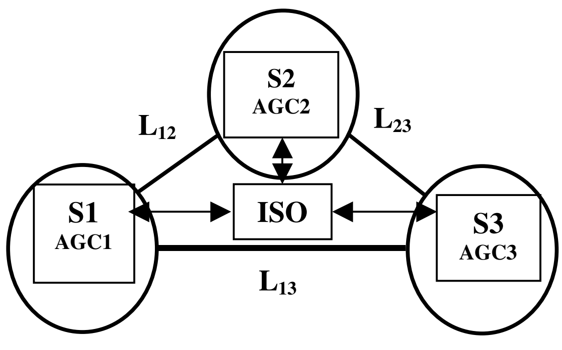

Fig. 2. Structure of AGC of interconnected power system.

This AGC system allows some kind of flexibility for taking into account real conditions of interconnection. There is possible to change borders of control areas or change mode of operation of different control areas. The example of use of different operation modes there may be: S1 & S2 – control according equation (2) and S3 – according (3). These possibilities of control are insufficient in conditions of electricity market.

4. NEW POSSIBILITIES CREATING FLEXIBLE STRUCTURE OF AGC

4.1 Virtual control area

AGC structure may be transformed in the conditions of electricity market. It is possible to use virtual control area (VCA) concept. VCA is comparatively new mode of AGC (Christie and Bose, 1996; Fink and van Son, 1998). At the beginning it was proposed for automatic realization of spot market electricity trade contracts. It means that load of one control area (i) is balanced by generator of another control area (j). AGC controllers of these control areas realize this contract. The controllers of two areas (i and j) minimize the modified control errors (CE_i and CE_j) and create virtual area for this contract ($L_i \rightarrow G_j$) that operates together with fixed control areas of different power systems:

$$CE_i = \Delta P_i + k_{si} \cdot \Delta f + (1\text{-}k_{Li}) \cdot \Delta L_i, \qquad (4)$$

$$CE_j = \Delta P_j + k_{sj} \cdot \Delta f - (1\text{-}k_{Li}) \cdot \Delta L_i. \qquad (5)$$

There are: ΔL_i, – consumer load change in systems i; k_{Li} – part of load deviation ΔL_i ($0 \leq k_{Li} \leq 1$) for which generation is bought in own system (control area) S_i; magnitude of $k_{Li} = 0$ if all generation for load balancing is bought in different system S_j and $k_{Li} = 1$ if generation is bought in own system S_i. Deviation of load flow among systems Si and Sj equals to $(1\text{-}k_{Li}) \cdot \Delta L_i$. The distribution of flows in lines depends on electricity networks laws. The losses in tie lines are included in ACE of control areas with changed power flows. They must be accounted and priced. These relations may be extended for several control areas forming many VCA operating simultaneously. It is possible to apply this method in systems (areas) with net tie line power deviation control according equation (2). If the control area (system) controls frequency according equation (3) it can't participate in creating virtual control area. The VCA principle may be used for exchange of regulating power reserves for secondary generation control. There is necessary wide-area measurement system for transferring values of k_{Li} and ΔL_i to corresponding AGC controllers. It must be noted that VCA control is putting on the network additional flows together with scheduled power flows that are controlled automatically. It means that possibilities of load exchange may be limited. For this reason the operation of VCA must be coordinated by independent system (transmission) operators (ISO). It is possible to change structure and number of VCA during every hour. Implementation of VCA principle needs of corresponding information transfer infrastructure.

4.2 Overlap control

Overlap control (OVL) is another way that may be used for automatic generation control. It is the mode of AGC when one of system controls the net tie line power of several control areas having own AGC controllers. The sufficient regulating power resources are necessary for system that performs OVL control. There is possible introduce OVL control for two control areas (for example, for S1 and S2) performing net power flow control. The control of systems S1 and S2 is performed on the base these equations for ACE:

$$ACE_1 = \Delta(P_{12} + P_{13}), \qquad (6)$$

$$ACE_2 = \Delta(P_{21} + P_{23} + P_{13}). \qquad (7)$$

In this case overlap control is performed by system S2 that have sufficient regulation power reserves. This kind of control may play different roles: improvement of quality of control (when dynamic parameters of system S2 are better of system S1) or supplying regulating power reserve for system S1 (when there is deficiency of regulating power).

4.3 Combination of various modes of control

The VCA and OVL control may enlarge possibilities of distributed AGC systems and help in implementing electricity market. There are another possibilities for distributed control by using grouping of separate systems of interconnection and applying various modes of control.

There is useful to group various modes of AGC for systems of small capacity (for example for power systems of Baltic States). The grouped system is shown in figure 3. The systems S1 and S2 are grouped as separate interconnection. It controls (stabilize) net power flows ($P_{13} + P_{23}$) among them and system S3. This system (S3) is responsible for frequency stabilization in bulk power system. The interconnection has own coordination body – independent operator (ISO12). It is possibility of cooperation among systems S1 and S2 (controllers AGC1 and AGC2) using different control principles: conventional control area, virtual control area, and overlap control. It is possible to change mode of control during operation. The change of borders of control area also may be used together with these operation modes. These possibilities require means for control services accounting that operates in real time. The AGC service quantity must be calculated for different power systems participating in ancillary service (automatic generation control) market. The accounting of these services is basis for AGC pricing.

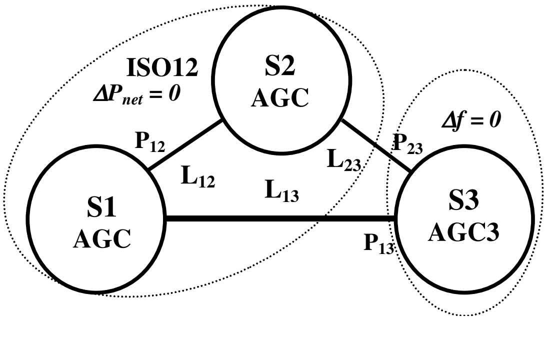

Fig. 3. Distribution of control functions in interconnected power system.

4.4 AGC service accounting

Automatic generation control service is necessary for execution of electricity trade contracts among consumers and generators. It requires participation of AGC controllers and regulating generators of neighboring systems. This participation has different volume and duration. This service must be accounted, priced and remunerated. Every system may consume or provide AGC service during the time of operation. The mutual compensation of services is a most desirable way for al systems of interconnection. In this case the obligatory rules and requirements (control performance criteria) are necessary for AGC systems and regulating reserves. The regulating help indicators may be used for accounting of AGC services (Maruejouls, *et al.* 2000).

The changes of regulation help indicator may be determined between two systems (*i* and *j*) of interconnection. It is possible to do on the basis of these equations:

$$\Delta f_i = F_i(\Delta P_{ij}), \tag{8}$$

$$\Delta f_j = Fj(\Delta P_{ji}). \tag{9}$$

There are magnitudes of operating conditions of both systems (*i* and *j*): Δf_i, Δf_j – frequency deviations and ΔP_{ij}, ΔP_{ji} – interchange flow deviations. The flow deviation is positive when flow is going out of system (negative when flow is going into system). System is supplying AGC service when signs of Δf_i and ΔP_{ij} (Δf_j and ΔP_{ji}) are different ($sign(\Delta f_i \cdot \Delta P_{ij}) < 0$)) and consuming AGC service when signs are the same ($sign(\Delta f_i \cdot \Delta P_{ij}) > 0$)). This help may be expressed as regulating power of both systems (P_{Ri} and P_{Rj}):

$$P_{Ri} = -\Delta P_{ij} \cdot (sign(\Delta f_i \cdot \Delta P_{ij}), \tag{10}$$

$$P_{Rj} = -\Delta P_{ij} \cdot (sign(\Delta f_j \cdot \Delta P_{ji}). \tag{11}$$

The regulating power is changing during the time. The system (*i* or *j*) is supplying regulating service when this power is positive and when power is negative – consuming regulating service. At the same moment these changes have opposite signs in different systems. The integral regulating power recordings there are necessary for AGC services accounting. The regulating service quantity is sum of regulating power during the integration period. It may be positive, negative or equal to zero. If sum is positive, system is providing excess of regulating service, if negative – system is consuming regulating service, and if equal to zero – there is balance of regulating services among systems (mutual compensation). When strict control rules are not established for whole interconnected power system, these recordings may be used for AGC services estimation. Transparent accounting and pricing of AGC services is necessary condition for stimulation of expansion of regulating power resources.

It is important to notice, that regulating power includes power exchange deviation, when consumption and generation is not balanced within borders of control area or frequency of interconnected system is not restored. This situation occurs when AGC operates in mode of virtual control area and overlap control in the case of power deficiency.

5. MODELING AND SIMULATION OF PROCESSES

The modeling and simulation of processes were used for verification of presented AGC modes and possibilities of real-time AGC services accounting. MATLAB program package was applied for simulation of processes according methods proposed by authors (Nargėlas, 2000). There is accepted that $P_{S1\&S2} \cong 0.1P_{S3}$. Load following processes were simulated. The response of AGC system was investigated to sudden load change ($\Delta P = 0.1$ *p. u.*) in different systems. This creates the possibility to disclose the main features of proposed ideas.

5.1 Simulation processes of virtual control area

The processes were simulated when load of system S1 (L1) is balanced by systems S1 and S2 according the trade contract: $P_{L1} \rightarrow 0.6P_{S1} + 0.4P_{S2}$. It means that load deviation (0.1 p.u.) in system S1 must be balanced by two systems: S1 (0.06 p.u.) and S2 (0.04 p.u.). It is the case power system S1 is buying regulating power in power system S2 (G2). It means that virtual control area (L1 → S2) is created beside of main control area (L1 → S1). This VCA is connecting load of system S1 (L1) with system S2. The results of simulation are in figures 4 and 5. The two cases of control were simulated: delayed (for 300 seconds) and simultaneous VC control. At the end of process power of systems S1 and S2 reaches required values in preset ratio. Curves of figure 4 shows processes of delayed virtual area control (VC) and figure 5 –simultaneous control of virtual and main areas (VC without delay).

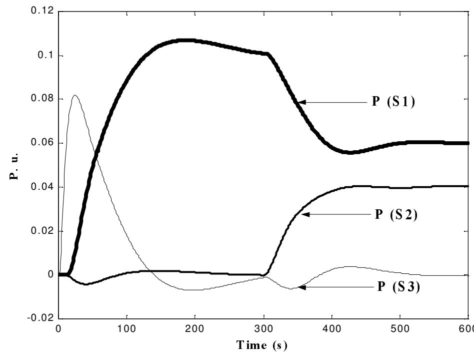

Fig. 4. Power control processes with VC delay.

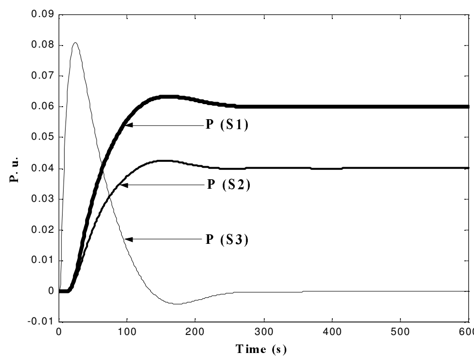

Fig. 5. Power control processes without VC delay.

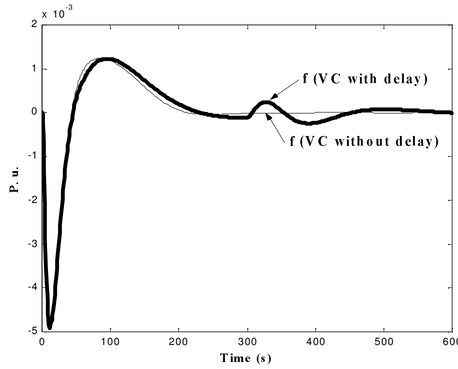

Fig. 6. Comparison of frequency control processes with different modes of VC.

Curves of figure 6 shows comparison of frequency control for both cases: with VC delay and without delay. For both cases frequency deviation is canceled at the end of control process. System S3 is participating in power balancing (frequency restoration) during short time. This participation it is necessary to account. At the end of control process net power balance $P_{12}+P_{23}$ is without changes. It means, that grouped systems S1 and S2 are regulating net power of tie lines (L_{13} & L_{23}), connecting them with system S3.

There must be noticed that control quality is better using simultaneous control, because power and frequency deviations are smaller. The required regulating power for system S1 is less in this case. It is substituted by regulating power of system S2. There is example of possibilities of regulating power (service) exchange among different systems of interconnection.

5.2 Simulation processes of overlap control

The results of overlap control simulation are shown in figure 7. The contract was investigated for covering load of own system (L1→S1). The load increase in system S1 (L1) was simulated when there is regulating power shortage ($\Delta P_{L1} = 0.1$ *p. u.* and $P_{G1} = 0.08$ *p. u.*). In this case regulating power generation shortage of system S1 (*0.02 p. u.*) is balanced automatically by system S2. Generators of system S3 are stabilizing frequency and supplying regulating service for both systems S1 and S2.

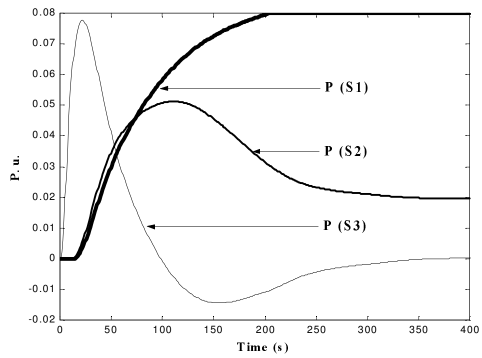

Fig. 7. Overlap control processes.

Presented examples of simulation of processes confirm possibility and advantages of distributed frequency and active power control in the conditions of electricity market. There is feasible implementation of flexible distributed automatic generation control system that changes own structure and mode of operation during the time. This may be useful during different stages of implementation of electricity market or when power systems of interconnection have different capabilities of AGC.

5.3 Simulation of processes of regulation power changes

The curves of processes (presented in figures 4, 5, 7) show participation of different systems in AGC services, but they are not suitable for services accounting. The curves of regulating power changes are necessary for this task.

The regulating power changes are presented in figure 8. The time period equals to 400 seconds. These changes are caused by the same load changes (0,1 p.u.) in different systems (S1and S3). Load increase in system S1 take place at moment t=0 s and in system S3 it occurs at moment t=200 s. The systems S1 and S2 operating in the mode of virtual control area ($P_{L1} \rightarrow 0.6P_{S1} + 0.4P_{S2}$) and the system S3 – in frequency control mode.

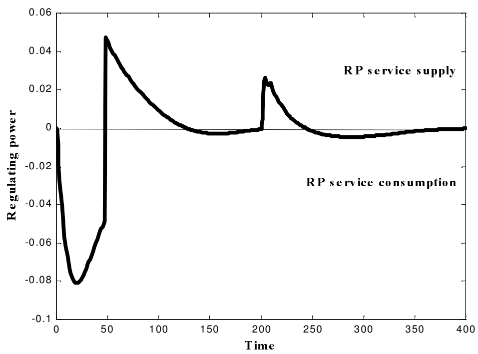

Fig. 8. Process of regulating power changes in systems S1 & S2.

Curve of figure 8 represents regulating service exchange among group of two systems (S1&S2) and system S3 (regulating power changes in system S3 have opposite direction). The sum of negative power (consumed energy) equals to 3,7166 units and this sum for positive power (supplied energy) equals to 1,929 units. The difference of powers is – 1,7876 units. It means that system S3 have provided this regulating power to systems S1 and S2 during period of investigation. The recorded difference of regulating power may be basis for AGC service remuneration. The curve of figure 8 also shows quality of automatic generation control. The shape of regulating power curve (sudden changes of direction) is indication of insufficient quality of control. The AGC control quality is better in system S3. The recording and pricing of regulating power creates base for stimulation of improvements of AGC system performance. It is possible to investigate characteristics of various modes of AGC operation. It is obvious that wide-area measurement system is necessary for implementation of this regulation service accounting method.

6. CONCLUSION

Presented investigation confirms possibility to create flexible distributed automatic generation control system that have advantages in the conditions of electricity market. The implementation of flexible AGC is possible on the base of modern control, communication, and wide-area measurement systems. Proposed AGC control modes may be applied during various stages of implementation of electricity market. The proposed ideas may be useful for introduction of electricity market in power systems of Baltic States. Investigation must be continued especially in the field of practical realization of proposed control modes and AGC services accounting and pricing.

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