ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2011. No. 10(116)
ELEKTRONIKA IR ELEKTROTECHNIKA

ELECTRICAL ENGINEERING
T 190
ELEKTROS INŽINERIJA

Peculiarities of Frequency Transients in Isolated Baltic Power System

M. Azubalis, A. Bandza, A. Jonaitis
Department of Electric Power Systems, Kaunas University of Technology,
Studentų str. 48, 51367 Kaunas, Lithuania, phone: +370 37 300287, e-mail: mindaugas.azubalis@ktu.lt

crossref http://dx.doi.org/10.5755/j01.eee.116.10.870

Introduction

Synchronous operation of Baltic and Continental Europe transmission systems is a strategic objective as a step towards the full integration of the Baltic electricity market into the European Union common electricity market. The power system intended to interconnect with Continental Europe power systems must meet particular requirements. One of these requirements is the ability of the power system to operate autonomously at different seasonal conditions. Isolated Baltic power system is considered as a small power system with large power generating units. In such systems, it is hard to maintain the sufficient primary, secondary and tertiary power reserves that are necessary for frequency stability and frequency transients within safe margins. The system should operate with the smallest available loads of large power generating units at different operating conditions in order to ensure that power reserves are sufficient. For the assessment of the adequacy conditions [1, 2], it is necessary to investigate power balancing capabilities to meet the frequency control requirements in case of significant change of load and hardly predictable generation variation of the renewable energy sources.

Peculiarities of the small power system operation conditions depend on composition and characteristics of generating units. Generating units of different types, e.g. thermal, hydro, nuclear, wind generators etc., have different designed possibilities of flexible operation. The second important criterion is the installed unity capacity of these generators. The most extreme conditions may occur in a small power system with large capacity generating units at low loads. Significant oscillations and deviations of operating parameters may be excited at every emergency situation. Loss of high capacity generating unit causes large frequency deviations. Frequency restoration as well as voltage control in the power grid becomes a very complicated task.

In the paper, frequency transients and stability conditions of isolated Baltic power system are analysed. Autonomously operating Baltic power system is considered as a small power system with large generating units and relatively low loads [3]. According to the development scenario of Baltic power system, new generators of large unit capacities will be installed till 2020. The analysis is based on different seasonal forecasted load and generation conditions of 2020.

Estimation of power reserves in power system

The initial frequency transients caused by disconnection of generating units mainly depend on the level of primary power reserve and response characteristics of operating generating units. In a small power system with large generating units, primary reserve may be insufficient to cover the generation loss. In this case, the frequency may decrease below the permissible temporary value, load shedding would be activated to recover frequency up to the required minimal quasi-steady value [4]. As the consequence of such scenario, some of loads would remain switched off. If primary power reserve is insufficient, the quasi-steady frequency deviation will exceed the permissible value.

There are three cases depending on dynamic properties of the power system and the load shedding levels:

- Load shedding is not activated;
- Load shedding is activated and load is reconnected after frequency restoration;
- Load shedding is activated and load is not reconnected due to low frequency level.

The loss of generating power ΔP must be covered by the primary response power $\Delta P^{\mathrm{I}}_{\mathrm{G}}$ of operating generating units and reduced load power $\Delta P_{\mathrm{load},f}$ of frequency dependent loads

$$\Delta P = \Delta P_{\mathrm{G}}^{\mathrm{I}} + \Delta P_{\mathrm{load},f}. \tag{1}$$

The sufficient primary power reserve when load shedding is not activated is equal to

$$\Delta P_{\mathrm{G}}^{\mathrm{I}} = \Delta P - \Delta P_{\mathrm{load},f} = \Delta P - \Delta f_{\mathrm{qs}} \cdot \lambda_{\mathrm{load}}; \tag{2}$$

here Δf_{qs} is the deviation of quasi-steady frequency; λ_{load} is the slope of load static frequency characteristic.

The necessary total rated capacity required for participation in primary control when load shedding is not activated may be evaluated according to

$$P^{\text{I}}_{\text{GN}\Sigma} = \left(\Delta P - \Delta f_{\text{qs}} \cdot \lambda_{\text{load}}\right) \cdot \frac{s_{\text{G}*}}{\Delta f_{\text{qs}} / f_{\text{N}}}; \tag{3}$$

here $s_{\text{G}*}$ is the total droop of generating units' speed governors in per units; f_{N} is the rated frequency.

Assuming that the amount of shed load $\Delta P_{\text{load sh.}}$ is known and neglecting the dead zone of primary control, the necessary primary reserve $\Delta P^{\text{I}}_{\text{G}}$ and the total rated capacity of generating units participating in the primary control $P^{\text{I}}_{\text{GN}\Sigma}$ may be determined according to:

$$\Delta P^{\text{I}}_{\text{G}} = \Delta P - \Delta P_{\text{load sh.}} - \lambda_{\text{load}*} \cdot \frac{\Delta f_{\text{qs}}}{f_0}\left(P_{\text{load}\Sigma} - \Delta P_{\text{load sh}}\right), \tag{4}$$

$$P^{\text{I}}_{\text{GN}\Sigma} = \left(\Delta P - \Delta P_{\text{load sh.}}\right) \cdot \frac{100 \cdot s_{\text{G}*}}{2 \cdot \Delta f_{\text{qs}}} - \lambda_{\text{load}*} s_{\text{G}*}\left(P_{\text{load}\Sigma} - \Delta P_{\text{load sh.}}\right); \tag{5}$$

here $\lambda_{\text{load}*}$ is the slope of load static frequency characteristic in per units; $P_{\text{load}\Sigma}$ is the total load power.

If the relative value of power reserve $P_{\text{res}*}$ corresponding to the generating units participating in primary control is known, the total necessary rated capacity participating in primary control and covering the total power loss equals to

$$P^{\text{I}}_{\text{GN}\Sigma} = \frac{\Delta P}{P_{\text{res}*}} - s_{\text{G}*} \cdot \lambda_{\text{load}*} \cdot P_{\text{load}\Sigma}. \tag{6}$$

Generally, the primary power reserve of generating units is approximately equal to 5 % of the rated capacity, i.e. $P_{\text{res}*}$ equals to 0.05. The slope of load static frequency characteristic $\lambda_{\text{load}*}$ equals to 1.0 and the droop of generating units $s_{\text{G}*}$ equals to 0.05. Since the frequency regulating effect of load is much less than the regulating effect of generating units, the primary power control mainly depends on the characteristics of generating units.

In order to ensure that frequency stability is not disturbed, the levels of primary, secondary and tertiary power reserves must be sufficient. Power reserves should limit frequency deviation after the accident. The operating power of the largest generator in synchronous zone should not exceed the level of the primary power reserve. The primary reserve must be activated in a couple seconds and must be available in less than 30 seconds [1].

The secondary power reserve in power system is dedicated to restore frequency and to replace the primary power reserve, as well as for compensation of unpredictable load and renewable sources power variation. The secondary power reserve must restore frequency and power flow exchange in less than 15 minutes [1]. The tertiary power reserve is dedicated to restore exhausted secondary reserve and to cover the deficiency of secondary reserve if the secondary reserve is not sufficient for the primary reserve restoration.

Characteristics of turbine speed governors

While the overall power system stability conditions after disturbances are affected by behaviour of generators, excitation systems, automatic voltage regulators, turbine speed governors and loads [5], the frequency transients mainly depend on the characteristics and response of turbine speed governors. Different types of the generating units are equipped with different primary movers with different speed governing characteristics. According to the response and behavior to the frequency transients, the turbines may be classified into few groups: steam turbines, gas turbines, turbines of the combined cycle power stations (steam or gas turbines mounted on one or separate shafts) and hydro turbines. In the primary power control, only thermal units of condensing power plants, units of gas turbines and gas units of combined cycle power plants participate. Due to high water inertia, units of the hydro power stations only partly participate in the primary power control.

Gas turbines have a good dynamics and reaction to the frequency deviation is very fast (curve 1 in Fig. 1). In combined cycle power plants, only gas turbines participate in the primary power control. The response of steam turbines in combined cycle power plants is very slow and these turbines do not participate in fast power control (curve 7 in Fig. 1).

Depending on the implemented algorithm of power control, steam turbines and their speed governors may operate in different modes: constant pressure, constant power and coordinated mode [6, 7]. Most of small combined heat and power plants operate with constant pressure and does not fully participate in frequency control (curve 4 in Fig. 1). If a thermal power plant operates in constant power mode, the power of these generating units is controlled manually (curve 3 in Fig. 1). While the initial response of such unit to the frequency deviation is better than the first one, behavior of this speed governor is also insufficient to participate in the primary power control at full range. The coordinated mode is the combination of turbine leading and turbine following regimes (curve 2 in Fig. 1). During the operation in this regime the compromise between quick response and boiler safety is determined. Most of the steam turbines are taking part in primary frequency control though just governors of coordinated regime operate at full range.

Inertia of water flow through hydro turbine may cause continuous oscillations of turbine power during transient processes when governor droop is low. In order to avoid these oscillations, the temporary droop is added during transients. Also, the temporary droop decreases response and reaction speed of the governor. It is considered that the primary reserve is partially activated during the first 30 s of the transient. The frequency response of typical hydro power plants and pumped storage power plants is presented in curves 5 and 6 in Fig. 1. At the 30th s, only half of steady-state power is reached for hydro units. Frequency response of pumped storage power plant is slower due to larger water inertia.

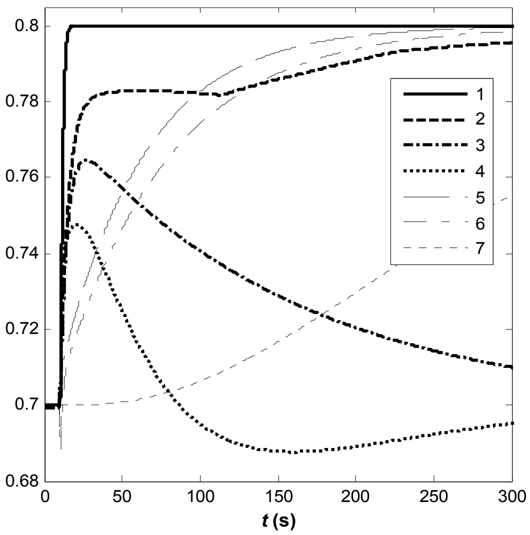

Fig. 1. Responses of generating units' speed governors to frequency deviation of 0.5 %: 1 – gas turbine; 2 – steam turbine of thermal power plant coordinated power control; 3 – steam turbine of thermal power plant with manually controlled power; 4 – steam turbine of thermal power plant with turbine following power control; 5 – hydro turbine of hydro power plant; 6 – hydro turbine of pumped storage power plant; 7 – steam turbine of combined cycle power plant

Analysis of frequency transients in isolated Baltic power system

The analyzed isolated Baltic Power System (PS) consists of Estonian PS, Latvian PS, Lithuanian PS and Kaliningrad PS. The typical operation conditions of summer low load, winter peak load and spring melt-water period peak load are simulated. The research is mainly focused on the operating conditions in the year 2020. In continuous weekly operation, the total load varies from 60 % at weekend to 100 % at workday. The operating power plants must cover this range. The composition of the generating units is selected so that the same generators cover the load during continuous operation and satisfy the requirements of power reserve. The summary of total rated capacities and loadings of generating units used in analysis is presented in Table 1. The largest capacities in the studied cases are the new nuclear power plant and the new thermal unit in Lithuanian power plant. The loading of the nuclear power plant should be reduced regarding the primary power reserve limit.

The design accident of the research is the fault at the high voltage switchgear terminal near the appropriate power station and the consequent disconnection of generating unit. During the fault, frequency increases and after the tripping of the generator, frequency rapidly decreases to the minimal value.

Usually, the power system operates at maximum load conditions during the winter time. The largest frequency deviation occurs when the largest power generator is tripped during the fault. During winter peak load of 2020, the largest possible generating power loss was evaluated as the nuclear power plant generator operating with the power of 362 MW and therefore approximately equal to the primary power reserve. The lowest frequency value may reach 49.58 Hz and settle in the range of 49.80–49.83 Hz.

Table 1. Total rated capacities (in MW) and loadings (in brackets, in p.u.) of generating units at different conditions

	Winter peak load	**Summer low load**	**Spring melt-water period**
Nuclear PP	1300 (0.28)	1300 (0.22)	1300 (0.20)
Thermal PP	6970 (0.55–0.76)	4730 (0.54–0.79)	3590 (0.54–0.74)
Hydro PP	1700 (0.058–0.64)	1410 (0.069–0.57)	2720 (0.52–0.73)

In summer low load period, the disconnection of maximum power corresponding to the primary power reserve may cause frequency decrease to 49.55 Hz and in spring melting-water period, to 49.57 Hz (Fig. 2). The quasi-steady value of frequency may exceed 49.8 Hz due to the response of hydro and small combined heat and power plants that are not accounted when evaluating the primary power reserve. The speed of frequency restoration depends on the total inertia of generating units. In summer conditions, only minimum of generating units is in operation, thus frequency restoration is slower. During the melt-water period in spring, all the attempts are pulled to complete exploitation of hydro power plants, thus reducing output power of thermal power plants while keeping the number of operating units similar to winter conditions. The increased number of operating hydro generating units increases the speed of frequency restoration to quasi-steady value. The disconnected power corresponding to the primary power reserve as well as minimum and steady-state frequency values after the fault in Baltic PS are presented in Table 2.

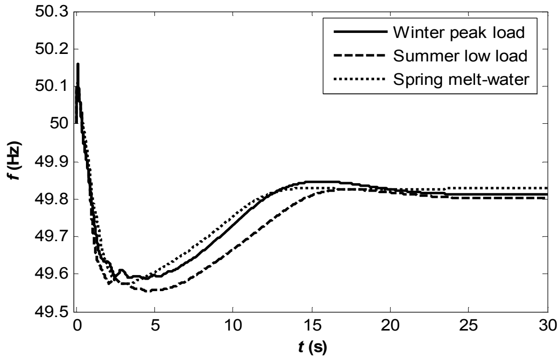

Fig. 2. Frequency transients after disconnection of generating unit corresponding to the primary power reserve

Table 2. The maximum and minimum frequency values during the fault in Baltic PS, Hz

Operation conditions	**Disconnected power, MW**	**Minimal frequency, Hz**	**Steady-state frequency, Hz**
Winter	362	49.58	49.84
Melt-water spring	264	49.57	49.83
Summer	287	49.55	49.80

During low load conditions, the pumped storage power plant (PSPP) operates in pump mode. The research covers a modelling of tripping of Kruonis PSPP pump units as well. The most severe situation emerges after the simultaneous trip of two pump units at spring melt-water period when thermal power plants operate at minimum load. The tripping of two or one pumps may cause the increase of frequency to 50.50 Hz and 50.21 Hz (Fig. 3). The frequency increase may be limited by implementing emergency control automation which trips hydro generating units immediately after the fault. Also, the frequency stability conditions were analysed for the case when the largest unit capacity of generating unit is disconnected. It is considered that the largest unit capacity equals to 450 MW and corresponds to the capacity of the new generating unit in Lithuanian power plant. The frequency decrease is very significant in such cases (Table 3). Only in winter conditions, load shedding would not be activated. If the generating unit of 1300 MW is disconnected, the frequency stability would be disturbed.

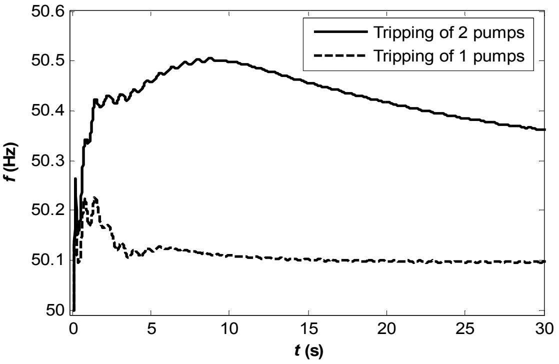

Fig. 3. Frequency transients after disconnection of pumps of pumped storage power plant

Table 3. The minimal values of frequency after the tripping of generating unit of 450 MW output

Operating conditions	Minimal frequency, Hz
Winter	49.51
Melt-water spring	48.60
Summer	48.67

Conclusions

Frequency transients caused by loss of generating units after the short circuit fault in isolated Baltic power system in 2020 were analysed. If the loss of generation equals to the primary power reserve, the minimal frequency during transient process may reach 49.55–49.58 Hz depending on operation conditions. The quasi steady-state value of the frequency will be within the permissible range. If the generating unit with output power corresponding to the maximum unit capacity is tripped, the load shedding would operate. Tripping of pumped storage power plant's generating units operating in pump mode may cause increase of frequency up to 50.50 Hz. In such case, it is suggested to implement the emergency automation which disconnects hydro generating units.

References

1. **ENTSO–E. Operational Handbook. Policy 1. Load–Frequency Control and Performance.** Online: https://www.entsoe.eu/resources/publications/system–operations/operation–handbook/.
2. **ENTSO–E. UCTE System Adequacy Forecast 2009–2020.** Online: https://www.entsoe.eu/resources/publications/former–associations/ucte/system–adequacy/.
3. **Chuvychin V., Strelkovs V.** Frequency and Active Power Control in Islanded Power Systems Based on the Magnitude of the Disturbance Estimation // IEEE Bucharest Power Tech Conference. – Bucharest, Romania, 2009. – P. 1–6.
4. **Sauhats A., Chuvychin V., Antonovs E., Zicmane I., Strelkovs V.** Interconnection of Power Systems with Different Under–Frequency Load Shedding Schemes // 10th International Conference on Environment and Electrical Engineering (EEEIC), 2011. – P. 1–4.
5. **Jonaitis A., Daunoras J.** Identification of Dynamic Model of Synchronous Generator High Frequency Excitation System // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 1(107). – P. 25–28.
6. **Kundur P.** Power System Stability and Control. – New York: McGraw–Hill, 1993. – 1176 p.
7. **Pereira L., Kosterev D., Davies D., Patterson S.** New Thermal Governor Model Selection and Validation in the WECC // IEEE Transactions on Power Systems, 2004. – Vol. 19. – No. 1. – P. 517–523.

Received 2011 06 20
Accepted after revision 2011 09 06

M. Azubalis, A. Bandza, A. Jonaitis. Peculiarities of Frequency Transients in Isolated Baltic Power System // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 10(116). – P. 11–14.

Analysis of peculiarities of frequency stability and transient processes in isolated Baltic power system is presented. Significant variation of loads and large capacities of operating generating units are common for this system. The method of evaluation of primary power reserve is described. Characteristics and responses to frequency deviation of generating units' turbine speed governors are presented. Possibilities of frequency control are described. Frequency transients caused by disturbances are simulated for different specific seasonal operating conditions of Baltic power system: winter peak load, summer low load and spring melt-water season. The design conditions are composed according to forecasted load of 2020. The composition of operating generators is formed considering to the recommended adequacy methodic of ENTSO-E. Ill. 3, bibl. 7, tabl. 3 (in English; abstracts in English and Lithuanian).

M. Ažubalis, A. Bandza, A. Jonaitis. Dažnio kitimo ypatumai izoliuotoje Baltijos elektros energetikos sistemoje // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 10(116). – P. 11–14.

Analizuojami dažnio stabilumo ir pereinamųjų procesų ypatumai izoliuotoje Baltijos elektros energetikos sistemoje. Šiai sistemai būdingas didelis apkrovų kitimas ir didelės galios generatoriai. Aprašyta pirminio galios rezervo įvertinimo metodika. Pateikiamos generatorinių agregatų turbinų greičio reguliatorių charakteristikos bei reakcijos į dažnio pokytį ir apžvelgiamos dažnio reguliavimo galimybės. Sumodeliuota, kaip keičiasi dažnis įvykus avarijoms Baltijos elektros energetikos sistemoje būdingomis sezoninėmis sąlygomis: esant žiemos didžiausioms ir vasaros mažiausioms apkrovoms bei pavasario polaidžiui. Skaičiuojamieji režimai sudaryti pagal prognozuojamas 2020 metų apkrovas, o veikiančių generatorių sudėtis sudaryta atsižvelgiant į ENSO-E rekomenduojamą adekvatumo metodiką. Il. 3, bibl. 7, lent. 3 (anglų kalba; santraukos anglų ir lietuvių k.).