Problems of frequency control in the power system with massive penetration of distributed generation

Vladimir Chuvychin, Antans Sauhats, Vadims Strelkovs

Abstract
The paper presents a study of the impact of increasing amount of distributed generation (DG) on control and management (operation) of transmission and distribution systems. Paper considers how DG penetration influences frequency control during normal and emergency operational conditions. Controllability of different types of DG associated with frequency control is considered. List of power system parameters influencing frequency control is presented. Case study is based on analysis of frequency control aspects for the Baltic States power system interconnection. Methodology for analysis of DG penetration aspect is based on determination of hosting capacity – maximal level of possible DG penetration that provides efficient frequency control. Numerical results of case studies are presented in paper.

Keywords: frequency control, distributed generation

Introduction

The balance between generation and load is one of the basic requirements of the operation of power systems. Different levels of control are in use to guarantee this balance: ranging from the primary frequency control at a timescale of seconds through the planning of power stations at a timescale of several years. The proportion of distributed generation (DG) on power systems has increased intensively [1].

The distribution generation units mostly are not equipped with control means, but for some specific DG configurations frequency and voltage control facilities can be introduced. As DG units are not equipped with frequency control (and are outside any long-term planning) their potential impact on power balancing will be obvious. Specific parameters of DG units' influencing behavior of frequency are considered.

Integration of DG with the distribution system will affect the power generation and may cause operational problems such as frequency deviations. Since distribution network has traditionally a rather inflexible design (e.g. a unidirectional power flow) and usually has a radial or loop design rather than meshed design, higher penetration levels with active power generators DG into system can cause problems.

Power system frequency control is analyzed for different types of DG, such as wind, solar, small hydro power plants and others. Recommendations for improvement of frequency control in presence of distributed energy sources are presented.

Impacts of different DG types are considered in paper. Different DG types have different impact to the frequency control due to the different technology and geographical location. For example, small CHP and solar plants are located close to the appropriate load. Wind power plants usually are not close to the load and it causes some operational problems.

The objectives of paper are not to solve all frequency control problems, associated with DG penetration. Short comparison of different frequency control practices, controllability of DG types and case study are presented. Case study illustrates possible practical dynamic of frequency and active power behavior during disturbance in the interconnected power system. Perhaps, transient dynamics for each particular power system will be different.

1. Frequency quality control requirements for different operational conditions

Under undisturbed conditions, the network frequency must be maintained within strict limits in order to ensure operation of control facilities in response to a disturbance. The various disturbances in a power system will cause frequency deviation in the network. Control facilities, which prevent frequency deviation and allow keeping it within strict limits, are primary, secondary and tertiary control [2, 3].

Primary control involves the action of turbine speed governors of generating units, which will respond during the frequency deviation from the frequency set point as a result of imbalance between generation and demand in the network. Its aim is to prevent deep power system frequency decline. With primary frequency control action, a change in system load will result in a steady-state frequency deviation, depending on the governor droop characteristic and frequency sensitivity of the load. All generating units will contribute to the overall change in generation, irrespective of the location of the load change. Restoration of system frequency to nominal value requires supplementary control action, which adjusts the load reference set point. As system load is continually changing, it is necessary to change the output of generators automatically. This is done by so called secondary control.

The function of secondary control in a given control area is as follows:

- the maintenance of scheduled power exchange program between the areas and all other interconnected zones;
- the secondary control reserve will only be activated in the control area where the imbalance appeared;
- the restoration of the synchronous system frequency to its set point value.

In some countries functions of secondary control are fulfilled by centralized control system – automatic generation control (AGC). The primary objectives of automatic generation control are to regulate frequency to the specified nominal value and to maintain the interchange power between control areas at the scheduled values [2, 4].

Tertiary control is any automatic or manual change in the output power's set points of generators, participating in secondary control, in order to guarantee the provision of an adequate secondary control reserve at the right time.

1.1. Normal operational conditions

During the normal operational conditions frequency quality control requirements are defined by adopted standards of power quality. Standard describes the minimal frequency quality requirements.

1.1.1. European standard EN 50160 requirements

For system with synchronous connection to an interconnected system shall be within a range of:

- 50 Hz ± 1% (i.e. 49.5 – 50.5 Hz) during 95 % of week,
- 50 Hz + 4%/-6% (i.e. 47 – 52 Hz) during 100 % of a week.

For systems with no synchronous connection to an interconnected system (islanding operation of a system) shall be within a range of:

- 50 Hz ± 2% (i.e. 49 – 51 Hz) during 95 % of a week,
- 50 Hz ± 15% (i.e. 42.5 – 57.5 Hz) during 100 % of a week.

Comment: Frequency quality requirements of EN 50160 standard are less strict than present mean performances of Transmission System operators.

1.1.2. UCTE frequency quality requirements:

UCTE frequency quality requirements were developed during the last decade and generalized in "Ground Rules concerning primary and secondary control of frequency and active power within the UCTE [3].

Three types of operational conditions are considered where the deviation between the instantaneous frequency and the set point frequency is:

- equal to or less than 50 mHz, operating conditions are considered as normal;
- greater than 50 mHz but less than 150 mHz, operating conditions are considered to be impaired, but with no major risk, provided that control facilities in the affected areas are ready for deployment;
- greater than 150 mHz, operating conditions are considered to be severely impaired, because there are significant risk of the malfunction of the interconnected network.

Even in case of a major frequency deviation, each control area will maintain its interconnections with adjoining areas, provided that the secure operation of its own system is not jeopardized.

1.2. Emergency operational conditions

In an extremely complex and highly integrated power system disturbances may be propagated over a vast area within a very short time period. Experience has shown that, in this type of situation, even a simple incident can degenerate extremely rapidly into large-scale blackouts. Imperfection of emergency automation control systems was the main reason of blackouts happened in 2002 and 2003.

Network operators need to apply any measures required to ensure that, so far as possible, the consequences of initial incidents will be contained within the frontiers of their respective area of operation. There are no common standards for preventing of deep frequency decline, caused by a large generating power deficiency. Under-frequency and over-frequency situations are treated in each power system differently. Usually manufacturers determine frequency-time zone limiting allowed decline of the power system frequency for each generating equipment.

2. Controllability of DG types associated with the frequency control

Low inertias, high reactance, small time constants and poor inherent damping characterize DG units. In most cases they are equipped with basic AVR's and are connected to distribution networks with protection operating times often in excess of the critical fault clearing time of generators [1]. DG units mostly are not equipped with frequency control as well. That's why the impact of DG on power systems should be investigated.

Frequency stability in electrical networks is essential for maintaining security of supply. It has been suggested that stability requirements may limit the level of penetration of DG in general and intermittent renewable energy in particular.

There is a wide range of types of DG – small hydro, solar, wind power plants; CHP; diesel engine, micro-turbine, fuel cell powered generation sources, for example. It is essential from the point of view of frequency regulation to divide the different types of DG into two main groups – the intermittent and non-intermittent ones. The most popular intermittent types are wind and solar power plants.

2.1. Wind power plants

Characteristics that define the different wind turbine technologies are:

- Fixed or variable blade angle.
- Fixed or variable generator speed.
- Induction or synchronous generator.
- Converter or no converter.
- Gearbox or no gearbox.

For most of mentioned wind power plants problem of controllability is determined by wind speed fluctuations.

Instant output power fluctuation is also very large. As an example practical data for Latvian wind park were presented in Fig.1. Fig.1 shows practical example of average daily output power for Latvian wind park - Vēju parks (with total installed capacity of 19.8 MW). Production pattern of "Vēju parks" is practically unpredictable. In some periods it's operating with nominal capacity, but in some with capacity less than 1 MW.

In order to avoid these problems, variable pitch angle turbines can be used, but even with a good control pitch angle scheme, the time constants of the mechanical systems are in the range of milliseconds and, if the wind speed varies rapidly, high power swings may still occur and affect the power system quality.

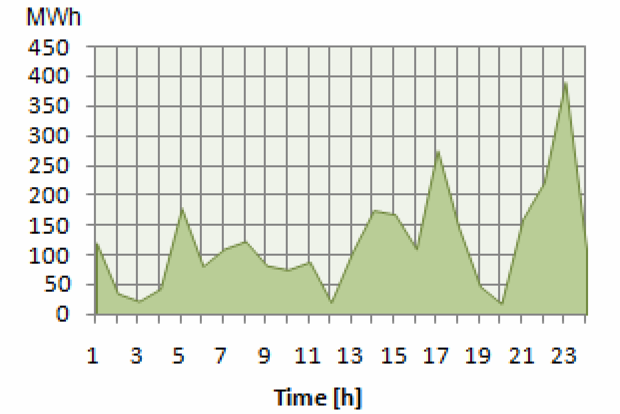

Fig.1 Average daily output power for Latvian wind park Vēju parks

Conclusions:

- No frequency control system is used in any type of wind power plant for grid-connected operation under normal and emergency conditions.
- The power output from wind power plants depends on variable wind energy thus burdening frequency and active power regulation for regulating power plants. Complicated and expensive converter systems should be used to reduce within the limits of possibility the output power deviations from wind power plants.
- Extra difficulties appear as a result of possible mismatch between wind power plant output and consumed power.
- There is a need in additional generation reserve, which would cover deviations in wind power plant output.

2.2. Solar power plants

Solar power plants should be 100 % reserved by conventional power plants as though the output power depends on the inconsistent solar irradiation. During the dark time (at night, late evening or morning) no power output from solar power plants is obtained.

2.3. Small hydro power plants (SHP)

There are two basic types of generators used in small-hydro plants, synchronous or induction generators. In SHP power plants up to 2-3 MW, induction generators are normally used if the grid conditions do not require the plant to operate on its own grid. For SHP-plants in the range of 3-10 MW, synchronous generators are normally used.

SHP mostly are not equipped with the frequency control, however it is possible to react on frequency changes and to help in active power and frequency regulation if generator is equipped with speed governor.

There are some seasonal periods when water inlet of the small rivers is minimal and, hence, participation in frequency control is limited.

3. List of power system parameters influencing frequency variation dynamics

Frequency variations in power system are electromechanical transient processes that can be described by so called "swing equation" [2]:

$$J\frac{d\omega}{dt} = T_{mech} - T_{elec} \qquad (1)$$

where:
J – combined moment of inertia of the generator and turbine [kg·m^2],
ω – angular velocity [rad/s],
t – time [sec],
T_{mech} – mechanical torque [N·m],
T_{elec} – electromagnetic torque [N·m].

Swing equation (1) can be written in many different forms. One of them is given below:

$$H\frac{d^2\delta}{dt^2} = P_{mech} - P_{max}\cdot\sin\delta - D\cdot\frac{d\delta}{dt} = \Delta P \qquad (2)$$

where:
ΔP – difference between the mechanical and electrical active power (the right side of the equation),
H – inertia constant [sec],
δ – rotor angle [rad],
P_{mech} – mechanical input power [p.u.],
P_{max} – maximal electrical output power [N·m],
D – load damping constant.

From equations (1) and (2) the basic parameters, which can influence frequency dynamic behavior can be seen:

- ΔP value represents the disturbance in the power system (load deviation).
- Moment of inertia J or corresponding time constant H. The higher these values are, the slower frequency changes during disturbance in power system. As though DG are characterized by small inertias, the penetration of them reduce average value of inertia of power system.
- Parameters of the speed governor that have an effect on mechanical input power P_{mech}. For example, for hydro power plant speed governor these parameters include permanent and droop coefficient S, time constant of electro-hydraulic servomechanism etc.
- Carrying capacity of transmission lines P_{max}. This parameter is dependent on the transmission line reactance, type and parameters of automatic voltage regulator (AVR), and usage of FACTS devices. Weak transmission lines (with relatively low carrying capacity) can delay the response of frequency regulators or emergency automatic, for example.
- Load damping constant D. Some loads contribute with positive damping. These contributions originate from the frequency dependency of the loads, but also their voltage dependency contributes.

Besides the parameters mentioned above, there are some other aspects that influence frequency dynamic behavior:

- Structure of power system.
- Types of power plants in power system.

The influence of different parameters will be shown in the chapter, describing the case study.

4. Case studies

4.1. Model of the Baltic States electric power system interconnection

High voltage power lines of 330 kV form the basic network of the Baltic interconnection. There are 58 high-voltage transmission lines of total length 4136.9 km and 32 substations equipped with 54 autotransformers of the 347/242 kV and 330/115 kV voltages with the total capacity of 8665.0 MVA. The electrical networks of Estonia, Latvia, Lithuania, as well as neighboring electrical networks of Russia and Belarus, form an electric Ring, consisting of 330 and 750 kV lines. The 750 kV network in the integrated power system is not closed. Regional transmission network of the Baltic interconnection consists primarily of 110 kV lines.

Dedicated approach for modeling the frequency behavior during normal operational condition, islanding situation and emergency situation was suggested.

4.2. Results of analysis of frequency control for normal operational condition

Let us consider the primary frequency control aspect for the power system with specific regulation parameters. Following parameters and conditions were assumed as for calculation example:

- S = 0.05 - governor's droop parameter,
- Δf_{max} = 0.2 Hz - maximal permissible frequency deviation from the rated value,
- D = 1.6 - load damping constant,
- f_{rated} = 50 Hz - rated frequency,
- P_{rated} = 100 % - generating unit's rated power.

The maximal load deviation value ΔP (hosting capacity) the primary frequency control is able to secure for considered case study is:

$$\Delta P = P_{rated} \cdot \left(\frac{\Delta f_{max}}{f_{rated} \cdot S} + \frac{\Delta f_{max} \cdot D}{f_{rated}} \right) = 8.6\,\% \qquad (3)$$

For considered case when DG penetration level is higher than 8.6 % from the installed capacity of those units, which participate in primary frequency control, the primary frequency control is not able to maintain power system frequency within permissible range.

In the worst-case scenario equivalent wind power plant is 8.6 % of total installed power and its output power decreases to 0. The influence of power system and control parameters to dynamics of transients during load deviation is illustrated in Fig. 2, 3, and 4. The case study is considered for different values of H, D and governor droop.

The influence to frequency deviation of load damping factor D and governor droop S is significant. The methodology of determination of frequency control efficiency is based on the concept of hosting capacity. For each relevant operational issue one or more performance indicators will be defined as well as a limit for what frequency control is acceptable. The value of the performance indicator will be calculated as a function of the DG penetration level. The hosting capacity is obtained as the penetration level for which the performance index exceeds its limit.

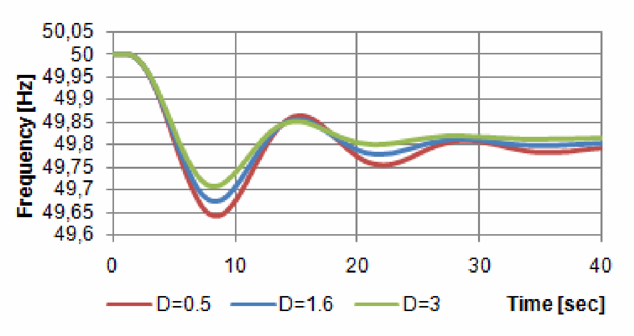

Fig.2 The influence of load damping factor D. D=0.5, D=1.6, and D=3

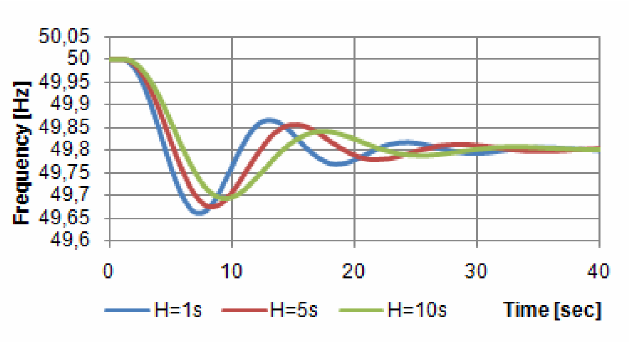

Fig.3 The influence of inertia constant H. H=1s, H=5s, and H=10s

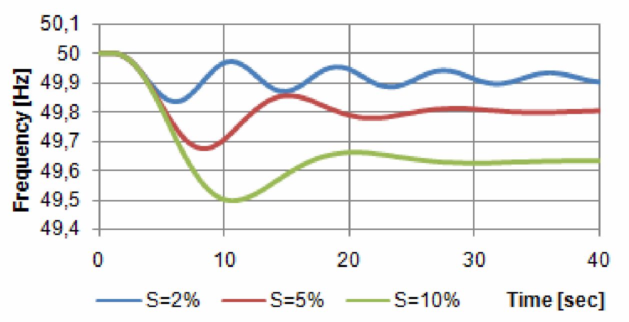

Fig.4 The influence of governor droop S. S=2%, S=5%, and S=10%

Fig.5 illustrates results of the case study for the Baltic States interconnecting determining limits of possible DG penetration for different power system indicators. Maximal level of wind power plant penetration exists between 4.2 % up to 21.2 % for different power system parameters.

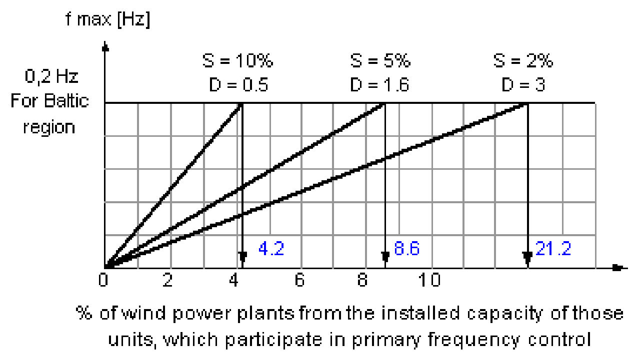

Fig.5 Hosting capacity region of wind power plants, if the active power reserves for primary frequency control are increased proportionally to the penetration level of wind power plants

4.3. Results of analysis of frequency control for emergency operational condition

This chapter presents results of analysis of load shedding operational effectiveness for different UFLS parameters during disconnection of large value of generation.

The quality of frequency control in the power system depends on the chosen control principle and parameters of execution unit (under-frequency relay). The main objectives of the UFLS are to prevent decline of the system frequency below allowed frequency-time zone by disconnection without time delay or with small delay part of the load on under-frequency.

Mathematical model was developed for numerical analysis of UFLS operation based on Matlab and Simulink software package. The model of UFLS system applied for the Baltic interconnection was created. Functional UFLS unit simulates load shedding operational logic and includes frequency setting and ability to simulate load disconnection intensity dP/df. Comparison of operational principles with different UFLS parameters can be feasible assuming disconnection of a load by multiple steps uniformly distributed in selected frequency range with predetermined disconnection intensity dP/df and tripping time of under-frequency.

Fig. 6 presents results of emergency condition's simulation for operation of existing UFLS system for different levels of DG penetration in relation to traditional power plants (TPP). For considered case 30 % of power deficiency is assumed. Increase of DG level for considered case cause dangerous over-frequency situation. For such case new adaptive UFLS system should be developed.

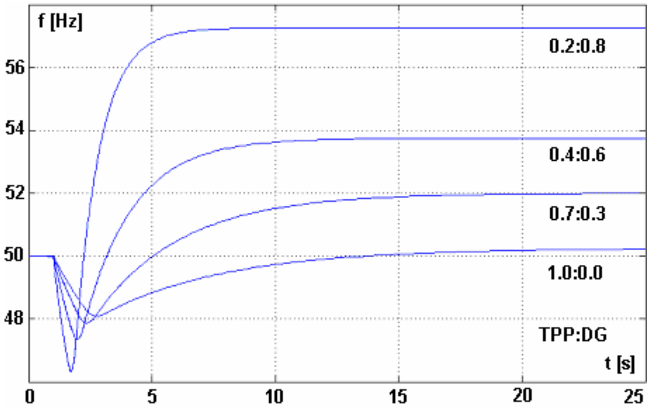

Fig.6 Results of emergency condition's simulation for operation of existing UFLS system for different levels of DG penetration

Recommendations and conclusions

1. No frequency control systems are used in most intermittent types of DG for grid-connected operation under normal and emergency conditions. Hence, penetration of DG causes necessity to have additional generation reserves for conventional power generators, which would cover deviations in wind and solar power plant output.

2. The power output from wind and solar power plants depend on inconsistent natural resources, thus burdening frequency and active power control for regulating power plants. In comparison with the wind power plant, fluctuations of output power for solar plant are smoother.

3. The possible solution of mentioned above problem is to use additional battery or other type of energy storage to filter fluctuations of energy deviations.

4. Most of non-intermittent types of DG do not depend on intermittent natural resources and can have enough fuel on site or accumulate it, in case of small hydro power plants, to maintain a constant output power. However, most of such DG are not equipped with frequency control systems.

5. Problem of DG participation in frequency control has more economical aspects due to necessity to estimate economical efficiency of installation of governors.

6. Normally for integrated power system with the large generating reserves the decisive hosting capacity index is not frequency deviation but the amplitude of intersystem power oscillations. This index should be calculated for each case study separately.

References

[1] McDONALD, J. R., DUDGEON, G. J. W., EDWARDS, F. E., and LEITHEAD, W. E. (2000): The Dynamics of Distributed generation in Distribution Systems. In: Proceedings of the IEEE PES SM2000.

[2] KUNDUR, P. (1994): Power System Stability and Control. McGraw-Hill, Inc., 1176 pp.

[3] UCTE (1998). Ground rules concerning primary and secondary control of frequency and active power within the UCPTE.

[4] SHOULTS, R. R., IBARRA, J. A. J. (1993): Multi-area Adaptive LFC Developed for a Comprehensive AGC Simulator. In: IEEE Transactions on Power Systems, Vol. 8, No. 2.

Vladimir Chuvychin, professor, Dr.habil.sc.ing

Riga Technical University
Faculty of Electrical and Power Engineering
Kronvalda bulv. 1
LV-1010, Riga, Latvia
E-mail: chuvychin@eef.rtu.lv

Antans Sauhats, professor, Dr.habil.sc.ing

Riga Technical University
Faculty of Electrical and Power Engineering
Kronvalda bulv. 1
LV-1010, Riga, Latvia
E-mail: sauhatas@eef.rtu.lv

Vadims Strelkovs, Dr.sc.ing

Riga Technical University
Faculty of Electrical and Power Engineering
Kronvalda bulv. 1
LV-1010, Riga, Latvia
E-mail: vadims.strelkovs@latvenergo.lv