

THESIS ON POWER ENGINEERING,  
ELECTRICAL ENGINEERING, MINING ENGINEERING D40

**Variations of Power Demand and Wind Power  
Generation and Their Influence to the  
Operation of Power Systems**

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Declaration:

Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for a doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree.

Kalle Kilk .....

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ENERGEETIKA. ELEKTROTEHNIKA. MÄENDUS D40

**Elektritarbimise ja tuulegeneraatorite  
võimsuse muutused ja nende mõju  
elektrisüsteemi talitlusele**

KALLE KILK



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## **ABBREVIATIONS AND UNITS**

AC	Alternating Current
AGC	Automatic Generation Control
ATC	Available Transfer Capacity
BALTSO	Organization of Baltic Transmission System Operators
BRELL	Organization of Byelorussian, Russian, Estonian, Latvian and Lithuanian Transmission System Operators
CCGT	Combined Cycle Gas Turbine
CFBC	Circulating Fluidized Bed Combustion
CHP	Combined Heat and Power
CO <sub>2</sub>	Carbon Dioxide
DC	Direct Current
DEPP	Diesel Engine Power Plant
DISCO	Distribution Company
ENTSO-E	Organization of European Transmission System Operators
EU	European Union
FERC	Federal Energy Regulatory Commission
FOR	Forced Outage Rate
GENCO	Generation Company
GT	Gas Turbine
GW	Gigawatt
GWh	Gigawatt hour
HVDC	High Voltage Direct Current
HPP	Hydro Power Plant
IPS/UPS	Unified Power system of Independent Power Systems
ISO	Independent System Operator
kV	kilovolt
kW	kilowatt
LOLE	Loss Of Load Expectation
max	maximum
min	minimum
MW	Megawatt
NORDEL	Organization of Nordic Transmission System Operators
NPP	Nuclear Power Plant

NTC	Net Transfer Capacity
OHL	Overhead Line
PP	Power Plant
PSS/E	Power System Simulator for Engineering
p.u.	per unit
RES	Renewable Energy Source
RTU	Remote Terminal Unit
SCADA	Supervisory Control And Data Acquisition
SCGT	Simple Cycle Gas Turbine
TRANSCO	Transmission Company
TPP	Thermal Power Plant
TSO	Transmission System Operator
TTC	Total Transfer Capacity
TUT	Tallinn University of Technology
TWh	Terawatt hour
UCTE	Union for the Coordination of Transmission of Electricity

#### Unit prefixes

k	kilo, $10^3$
M	Mega, $10^6$
G	Giga, $10^9$
T	Tera, $10^{12}$

## LIST OF ORIGINAL PAPERS

The main results of present doctoral thesis are published in the following publications:

- I. M. Valdma, M. Keel, H. Tammoja, **K. Kilk** "Reliability of electric power generation in power systems with thermal and wind power plants", Oil Shale, 2007, Vol. 24, No. 2 Special, pp. 197–208
- II. M. Keel, **K. Kilk**, M. Valdma "Analysis of power demand and wind power changes in power systems", Oil Shale, 2009, Vol. 26, No. 3 special, pp. 228–242
- III. **K. Kilk**, M. Valdma "Determination of optimal operating reserves in power systems", Oil Shale, 2009, Vol. 26, No. 3 Special, pp. 220–227

In the Appendix A copies of these publications are included.

### Authors own contribution

The contribution by the author to the papers included is as follows:

- I. Kalle Kilk participated in writing the paper. He was responsible for data collection and some of the calculations. He had minor role in writing.
- II. Kalle Kilk is the main author of the paper. He was responsible for literature overview, data collection and some of the calculations. He had major role in writing.
- III. Kalle Kilk is the main author of the paper. He was responsible for literature overview, data collection and calculations. He had major role in writing.

## INTRODUCTION

Electricity has become such a commodity to today's civilized societies without which it is hard to carry out most of everyday tasks. Many vital processes rely on uninterrupted power supply and high security of supply has therefore become the backbone to a well functioning economy.

The aim of this paper is to study the impact of irregular power changes to the reliable operation of the power system. Power flows in and between different system areas and also power generated by different producers have started to behave in more erratic and unpredictable way due to several factors. Those factors are mostly connected to the aims of modern energy policy makers – to increase the share of energy traded through short term markets and to promote the energy produced from renewable energy sources (RES).

Livelier energy markets mean that primary energy resources are being used more efficiently by matching hourly demand curves to the supply curves by which always the least expensive sources are employed. But since the availability of least expensive sources varies in time, the actual supply sources also tend to vary thereby causing significant variation in power flows, both direction-wise and volume-wise. This phenomenon puts some pressure on the operational control of power systems and calls for improvements of methods used to keep the system stable.

The second challenge to the operational control of power systems derives from EU-s climate and energy policy targets. By promoting CO<sub>2</sub> free production and aiming at an increase in usage of RES for power generation, additional capacities are being connected to the system, which are differing substantially from conventional generation from the controllability point of view. Currently there are two types of power plants that have CO<sub>2</sub> free production and the potential to be used on a considerably larger scale than today – nuclear and wind power. Neither of those two have been of noticeable help to system operators in following the demand curve and keeping the real-time balance. In fact those two types of generation have one common property which is that both of them can be used as the only energy source in a power system when there is a possibility to store vast amounts of energy for a considerable time. Unless this possibility is present, there is always a need to have several other sources available at any time which, of course, decreases the economical performance of the overall system.

But besides the effect on the economy, the fluctuating characteristic of wind power production by itself creates varying flows in the power grid unless the reserve power plants are suitably placed and controlled to minimize those variations. For these purposes simple cycle gas turbines (SCGT) or hydro accumulation power plants (HAPP) can be used for instance or in some limited ranges also thermal power plants (TPP), CCGT-s or even CHP-s. One of the aims of this thesis is to study the effect of power variations in wind power generation on interchange power flows for those systems which have main other power injection entering the grid from thermal power plants.

The methods that are developed in this thesis of studying the effect of abovementioned factors are universal and suitable for any power system based on AC transmission. As a reference case the power system of Estonia is used here. Currently, the Estonian power system has a dominant share of electric power generated by oil-shale fired thermal power plants. During year 2007 the share of electrical energy generated from oil-shale was 94% [1]. In 2008 oil-shale fired power plants (PP) in Narva region had an overall installed capacity of 2000 MW, gas fired Iru PP 176 MW and small TPP-s 116 MW [2]. There was only 5 MW of power installed in small hydro power plants and all of those are run-through type with no water reservoirs. The maximum wind power capacity in 2008 was 35 MW. Estonian total installed power was 2362 MW and peak power demand approximately 1500 MW.

The installed capacity of wind power reached the level of ca 100 MW during the summer of 2009. According to Estonian official Electricity Development Plan [17] the target wind power to reach for Estonia is 900 MW, of which 400 MW is onshore and 500 MW offshore. This would correspond to more than half of the domestic peak load. Although the Development Plan also foresees the need to cover the same amount of power by reserve power plants, it can be the case that these reserve power plants are not built at the same rate as wind PP-s or are not utilized when needed due to economical factors. Therefore the system must always be controlled in such a way that the realisation of these extreme scenarios would not have a drastic influence on the security of supply and technical quality of power.

The laws of physics determine that in unified AC power systems many actions in one subsystem have strong influences over the operational state of other synchronous systems. This is one of the reasons why the operation of interconnected systems has to remain subject to strict multilateral agreements between system operators. The violation of these agreements might lead to geographically wide system disturbances and possibly even to black-outs. This is the reason why sufficient attention must also be paid to contractual agreements besides the sole technical capabilities of networks when discussing the possibilities of connecting new generation sources to the power system.

In the first chapter of the paper the principles of power system control are described including the methods of frequency control and also reserve and interconnection management. The second chapter aims at analysing the variations of active power in power systems and the impact of wind generation to these variations when the major part of all other generation is thermal, taking the Estonian power system as a reference study case. The third chapter focuses on general models of reliability and brings out suggestions on the basis of numerical examples. Also the methods of handling the reliability of interconnectors are elaborated in this chapter. The last chapter discusses the issues of reserve power management and studies the possibilities to develop the methods that could be used in order to cope with some of the expectations of the energy market without risking the reliable operation of the power system.

## ACKNOWLEDGEMENTS

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# 1. MODERN POWER SYSTEMS AND THEIR OPERATION

Power system is a technical system for producing and transmitting electrical energy. It consists of power plants and consumer appliances distributed over a certain territory and which are connected to each other by electric networks [18]. The production, transmission, distribution and consumption of electricity takes place almost simultaneously and thereby there is always power equilibrium between production and consumption.

## *1.1. Power systems and interconnected power systems*

In an electric power system both the active and reactive load are continually changing and the generation of reactive and active power has to be regulated correspondingly. The primary purpose of the active power generation control is to balance the generation against total system load and transmission losses in order to keep the desired level of frequency and power interchanges with neighbouring systems.

As the larger systems have better reliability, security and efficiency the separate systems tend to form interconnected power systems. Such interconnected systems of several sub systems have better quality of frequency and are less prone to occurrence of instable operating states. The control of interconnected systems used to be more or less centralised but during the past decades the course to have power systems operating mostly based on market relation has reduced the importance of centrally controlled functions. Thereby most interconnected power systems do not have one system operator but several operators, each of them responsible for maintaining the secure operation of the power system of their own area and interconnections to other areas.

The responsibilities for controlling the frequency in the interconnected system may either be shared equally among different areas of system (decentralized area control) or there can be one leading party regulating actual frequency deviations and the other parties can only control and balance their interchange values. The first scheme is used for instance in the continental European system and the second in Interconnected Power Systems of Baltic and Russia.

The load changes in the system which are not caused by the system itself through load's frequency response are mostly classified according to the time of their occurrence. Extremely fast changes with duration of no more than a few seconds have a rather small amplitude and are not to be regulated by power plants. The fast changes with duration of some minutes and a few times bigger amplitude and slow changes with even longer duration definitely have to be regulated. The fast changes are usually regulated by automatic means and slow changes by manual means.

The amplitude of fast load changes remains typically between 0.5-1.5 %. The slow changes have however quite remarkable amplitudes. Slow changes of load demand consist of deterministic and random components. The slow load changes can be described in different forms like load diagrams or load duration curves.

In Figure 1.1 are shown the typical daily load curve of a power system and the different zones of load.

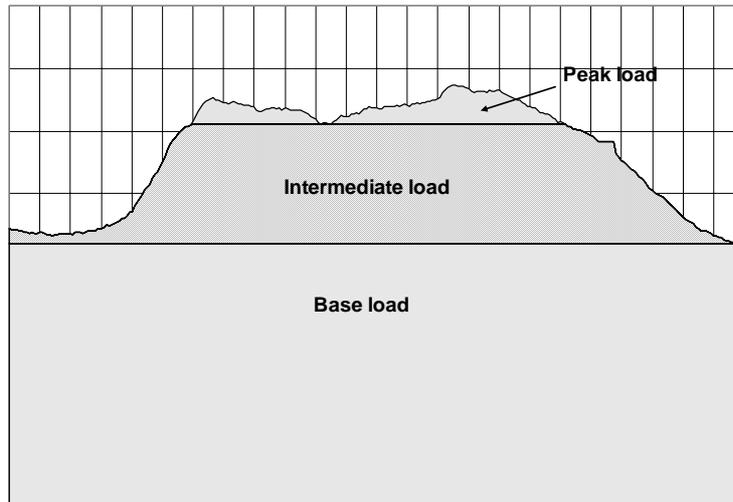


Figure 1.1 Daily load curve

The same load described as a load duration curve is shown in Figure 1.2.

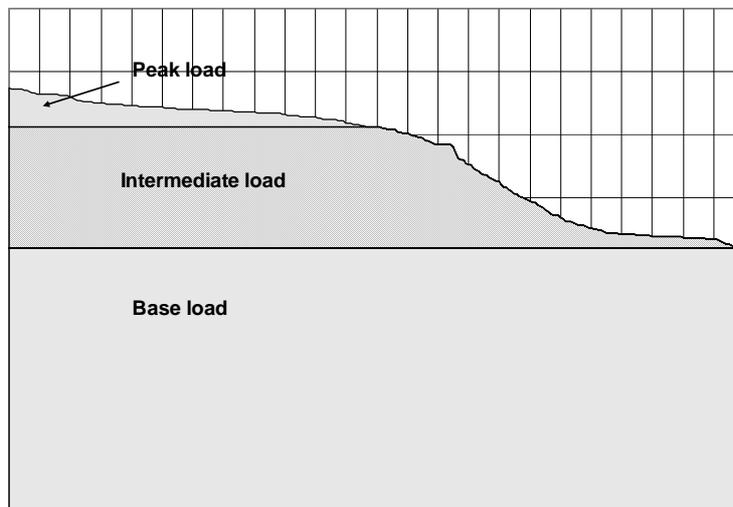


Figure 1.2 Daily load duration curve

The formation of power systems at the initial stage of power grid development started from several local networks around local production sources. The present power systems are geographically wide and operationally interactive. As it is more efficient to use the energy resources in the larger system, the separate and independent local power systems' tendency to join to larger systems began immediately after the creation of first power networks and this process is far from being complete today.

The second characteristic to describe a modern power system is the way the systems are controlled and used for energy transmission purposes. Not only the actual energy trades have changed the way systems run but also the principles of keeping the system balance and frequency are more and more thriving towards market based solutions.

### 1.2. Control systems

Estonian Power System Control Centre (PSCC) uses a SCADA system provided by General Electric to acquire telemetry data from power plants and consumers connected to the transmission grid and also from transmission lines and transformers. Most of the data is obtained directly from remote terminal units (RTU) that are located in the substations and belong to Transmission Network. Some measurements are acquired via communication links to client information systems. Data acquisition intervals from SCADA to RTU are 2 seconds, but only changes in the metered value that exceed the preset tolerance limits are transferred and stored in SCADA database. From the metering values average is calculated for each 5 minute interval and these values are separately stored.

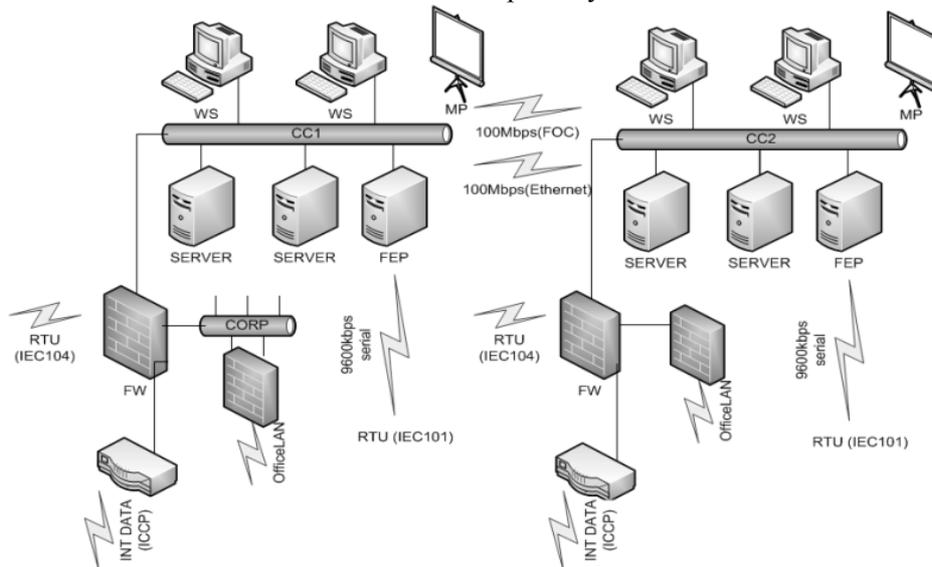


Figure 1.3 SCADA system

According to [18] the real time values of most generating units connected to power system are transmitted to Estonian PSCC.

The SCADA system is equipped with an AGC module, which enables to utilize the automatic secondary power regulation possibilities of power plants. The description of AGC functionality is given in the next paragraph.

### ***1.3. Principles of power system frequency control***

To maintain reliability and quality of supply of a power system, reserves of active power and reactive power are required. The operating generating power reserves are needed for compensating the load deviations from expected values and to cover the generation deficit in case of unexpected outages of power units [12-14].

The control of a power system is a multistage process. For every stage of control the adequate reserves are needed. The operating reserves are usually divided into 5 parts [15]:

- 1) primary control reserve (available mostly within 10 s)
- 2) secondary control reserve (available mostly within 30 s)
- 3) tertiary control reserve (available within 15 min or less)
- 4) slow scheduling reserve
- 5) contingency reserve, including instant reserve, rapid reserve and slow reserves.

The reserves must also be in the electrical lines and networks (transmission reserve, stability reserve, distribution reserve, reactive power reserve etc.).

Primary control is carried out through turbine speed or turbine governors of power plants [15]. Primary control is a decentralized control type – there is no communication and feedback between different power plants and there is no central controller. The aim of primary control is to stabilize system frequency after an event but not to restore the initial frequency value.

The deviation of frequency  $\Delta f$  can be expressed:

$$\Delta f = f - f_n \quad (1.1)$$

where  $f$  - actual frequency;

$f_n$  - nominal frequency.

The reaction of a generator to the change in frequency is described by the droop of the generator:

$$s_G = \frac{-\Delta f / f_n}{\Delta P_G / P_{Gn}} \% \quad (1.2)$$

where  $\Delta P_G$  - deviation of power generated by the generator;

$P_{Gn}$  - nominal power of the generator.

The contribution of generators with different droop values is illustrated in Figure 1.4.

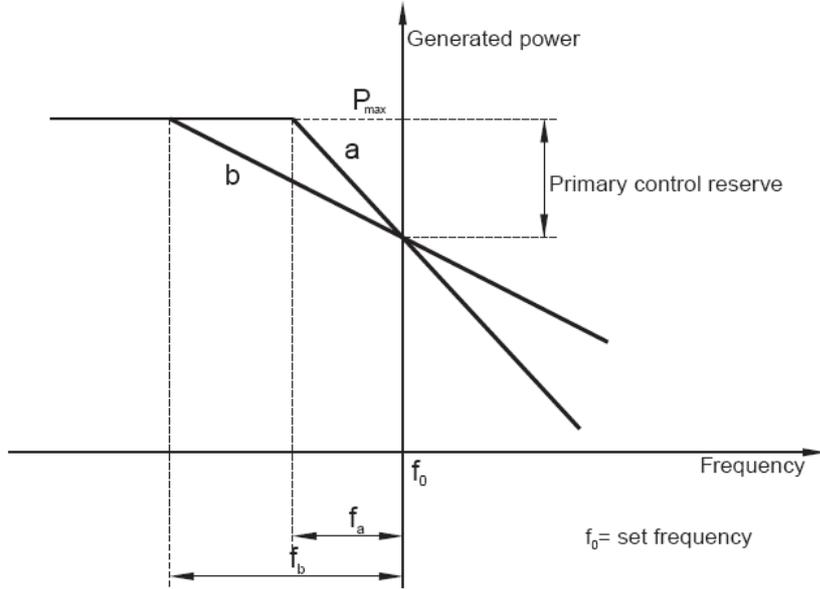


Figure 1.4 Primary control reserves of two generators with different droop values

The measurement cycle for primary control has to be between 0.1 to 1 second in European continental area.

Secondary control is supposed to balance the system taking into account the scheduled values of interchanges between control areas and to restore the system frequency to the nominal after incidents. Secondary control makes use of a centralised automatic control modifying the active power set points of generators in the time frame of seconds to typically 15 minutes. Within each control area, the individual area control error  $G_i$  (ACE) needs to be controlled to zero on a continuous basis. The ACE is calculated as the sum of the power control error and the frequency control error:

$$G_i = \Delta P_{INT,i} + k_i * \Delta f \quad (1.3)$$

where  $\Delta P_{INT,i}$  - deviation of interchange power from scheduled interchange for the control area  $i$ ;

$k_i$  - k-factor of the control area  $i$ ;

$\Delta f$  - deviation of frequency from nominal frequency.

The k-factor of the control area is calculated from frequency control gain, contribution coefficient of that area and the total system power frequency characteristic.

The behaviour of proportional-integral characteristic (PI) type secondary controller is described by the following equation:

$$\Delta P_{dt} = -\beta_i * G_i - \frac{1}{T_r} \int G_i * dt \quad (1.4)$$

where  $\Delta P_{dt}$  - the correcting variable of the secondary controller governing control generators in control area i;

$\beta_i$  - the proportional factor of the secondary controller in control area i;

$T_r$  - the integration time constant of the secondary controller in control area i.

The secondary controller has high requirements for acting speed – the total cycle time for the controller has to stay between 1-2 seconds. Also the transmission time of measurements from tie-lines has to remain below 2 seconds. Accuracy of measurements is limited to 1.5% of rated power and the maximal measurement cycle time is 2 seconds.

Tertiary control reserves are intended for restoring sufficient secondary power reserves. They can be started either manually or automatically. The maximum deployment time of tertiary reserves is not very specifically given in Europe but most of the power is usually gained within 15 minutes from the order.

Time control is a function to monitor and limit the difference in system frequency time in line with universal time coordinated (UTC). Time control can be utilized for instance by setting the master secondary controllers reference frequency to a different level from nominal for certain limited time.

In Figure 1.5 actions of different stages of frequency regulation are displayed on block diagram.

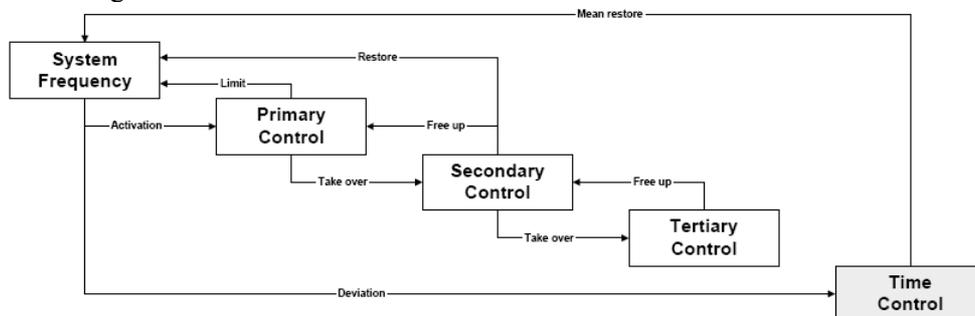


Figure 1.5 Stages of frequency regulation

All of the power reserves described above cause the following kinds of costs in power plants and networks:

- the capital costs of reserves
- the operational costs bounded with keeping of reserves
- the operational costs bounded with utilization of reserves.

Reliability and quality of power supply depend on the reserves and together with that also the losses of consumers bound with interruption of electricity supply and bad quality of electric energy. Therefore optimization of reserves is very important as for power plants and electrical networks, so for consumers.

#### ***1.4. Reserve capacity***

The main tasks of planning the reserves are to determine the optimal size and the geographical distribution of reserves around the power systems subject to reserves requirement [16]. Insufficient investments to new power sources or unsuitable allocation of reserves decrease the reliability and security of power system and may lead to system blackout.

There are different principles of determining the needed capacity for the operating reserve in different synchronous areas. In continental European synchronous area (UCTE area) the requirements for reserve capacities are given separately for primary reserve and secondary reserve [15]. The requirement for primary reserve is given by so-called “reference incident” which needs to be fully covered by primary reserves around UCTE area. This reference incident is defined as the maximum instantaneous deviation between generation and demand in the synchronous zone by the sudden loss of generation capacity, load shedding or interruption of power exchanges. The reference incident depends on the size of the synchronous zone, the size of the largest generation unit or generation capacity connected to the power system.

The size of secondary reserve to be held by each country is not precisely defined by UCTE. It can be derived from the defined purpose of secondary reserve, which is to restore the balance between generation and demand within each Control Block. Therefore the secondary reserve must cover both the unexpected outages of generation and power demand fluctuations. The part of secondary reserve related to unexpected outages of generation is equal to largest generating unit in the Block. It is recommended by UCTE to calculate the reserve for demand fluctuations as a function of system size:

$$R_{\text{sec}} = \sqrt{aL_{\text{max}} + b^2} - b \quad (1.5)$$

where  $a$  and  $b$  – empirical parameters established for power system;

$L_{\text{max}}$  – maximum load of the Control Block.

Within Control Blocks the secondary reserves may be divided according to agreements between countries.

The size of tertiary reserve (manual reserve) in UCTE is directly related to secondary reserve as the purpose of this reserve is to free up secondary reserve shortly after they are activated.

The planning of operating reserves in Interconnected Power Systems of Baltic countries and Russia (IPS/UPS) takes into account that most of the frequency regulation is done centrally by the Central Dispatching Unit situated in Moscow and the power plants used for this regulation are hydro plants of Volga river cascade. Therefore there is no need to have predefined primary reserves for frequency regulation in each separate power system of IPS/UPS. The reserve, which needs to be held in each separate power system, is slow reserve with an activation time from 3 to 30 minutes. These reserves are quite identical to the requirements of tertiary reserves in UCTE system as the activation of them is done

mostly manually. Determination of reserve capacity is done separately for load deviations and power plant outages.

The size of secondary reserve needed in power systems with load ranging from 400-2000 MW is displayed in Figure 1.6. Based on this, a power system with a size equivalent to that of Estonian system, the size of secondary reserve would be in the range of ~50 MW. This correspond to 2.9% of peak power.

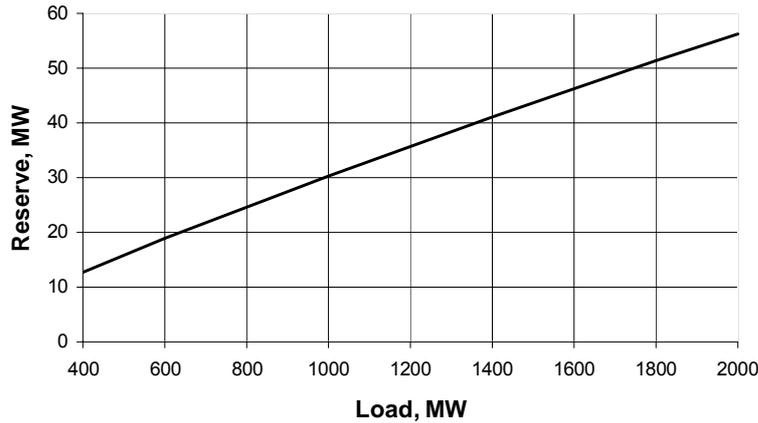


Figure 1.6 Recommended size of secondary reserve

The bigger the control block, the smaller the portion of reserve needed compared to peak load. For the control block with a size of three Baltic States with the peak power of 5 000 MW, the needed reserve power would decrease to 2.4% of peak power. For a control block sized equally to NORDEL area (peak power 70 GW) the reserve power would already be below 1% of peak load.

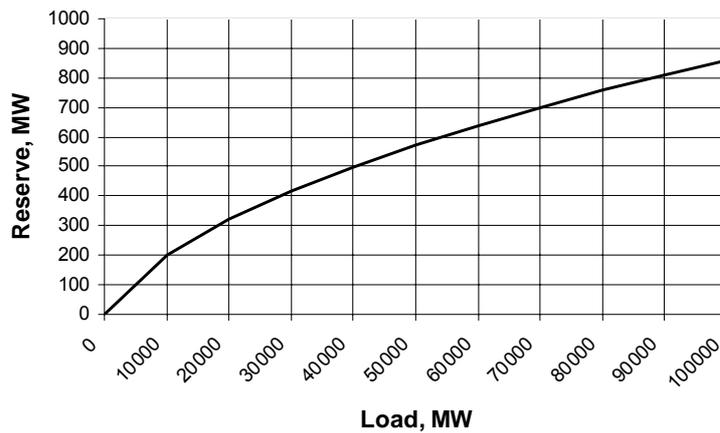


Figure 1.7 Recommended size of secondary reserve

### 1.5. Location of reserves

As well as concerning the capacity of reserves, there are also different philosophies of determining the location of operating reserve in different synchronous areas. In UCTE area the share of primary operation reserve to be handled by the Control Block  $i$  is determined by the coefficient of contribution. This coefficient is calculated as follows [15]:

$$C_i = \frac{E_i}{E_\Sigma} \quad (1.6)$$

where  $E_i$  – annual electrical energy generated in the  $i$ -th Block (including electricity generated for export to outside of the Block;

$E_\Sigma$  – annual electrical energy generated in the entire synchronous area.

The distribution of reserves within Control Block is subject to negotiations between the TSO-s of the Block.

In IPS/UPS the location of reserves is mostly influenced by two different contractual limits to each subsystem – one value for normal operation and second in case of disturbances (for instance when unexpected power generation outages occur). Therefore each subsystem may count on some system effect to cover its power deficit or surplus. The reserve for  $i$ -th subsystem can then be calculated:

$$R_{k,i} = \frac{P_{k,i}^{\max}}{P_i^{\max}} (P_i^{\max} - \sum_j R_{ji}) \quad (1.7)$$

where  $P_{k,i}^{\max}$  – largest generating unit in the  $k$ -th country of  $i$ -th Block;

$P_i^{\max}$  – largest generating unit in the  $i$ -th Block;

$R_{ji}$  – reserve power granted by Block  $j$  to Block  $i$ .

### 1.6. Procurement of reserves

The optimal planning of ancillary services nowadays has to involve market modelling [11]. Mostly three main modelling trends are identified:

- optimization models, which focus on the profit maximization problem for one of the firms competing on the market
- equilibrium models, which represent overall market behaviour taking into consideration competition among all participants
- simulation models, often based on multiagent systems, which are an alternative to the equilibrium models when the problem under consideration is too complex.

In practice centralized market based solutions (so called PoolCo market design) are widely used for purchasing ancillary services in Northern America [19]. An

example model of the ancillary market based on PoolCo market design can be seen in Figure 1.8. In this case an ISO is the single buyer party of the ancillary services to meet the reliability obligations set by FERC. It is also ISO-s objective to minimize ancillary services payments while encouraging GENCO's to provide sufficient services. The auction for ancillary services is conducted sequentially. A block scheme of sequential auction used by Californian ISO to procure ancillary services is shown in Figure 1.9. In this case the GENCO's are allowed to rebid their uncommitted resources in each round at a new price. And although each bid from GENCO includes in itself both capacity reservation bid (\$/MW) and energy bid (\$/MWh), the auction is cleared by Californian ISO solely based on capacity bids. Several alternative schemes for market clearing have been proposed though which would take into account both capacity and energy bids thus increasing the efficiency of the ancillary services market [19]

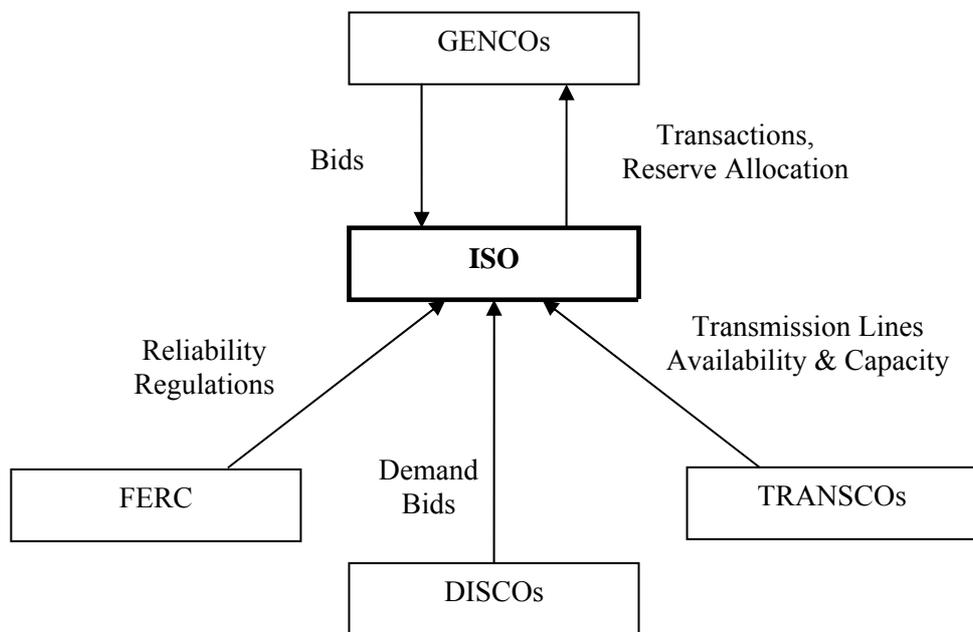


Figure 1.8 Structure of ancillary service market

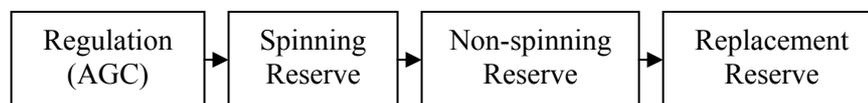


Figure 1.9 Sequential auction of ancillary services

It is believed that liberalized markets enhance the systems efficiency and quality of services but as a drawback also shortage of generation may occur in the long run due to insufficient investments [20]. This is one of the reasons why in some

countries some of the ancillary services are not purchased according to market based solution.

One type of the reserves that is mostly purchased not based on market principles is emergency reserve. The requirements for emergency reserve PP-s are such that in many cases the sources suitable for these purposes can only be built specially for this and are not competitive on open market. As emergency PP-s are not competitive on market, it makes it also impossible to rely on market based incentives to guarantee investments in such generation type. Usually in systems, where there are insufficient or unsuitable (without capable water reservoirs) hydro resources, the emergency reserve is managed either by long term contracts with customers with such demand to allow for fast load-shedding or by SCGT-s. The owner of such GT-s can be either the TSO or some other person having a contract with the TSO.

One other possibility to utilise market based solutions for system purposes is connected to a method that allows transmission over network with lesser security margins relying on market based retaliatory measures. Most common of those measures would be countertrade by which System Operator orders up-regulation of some power plants in the region of deficit when incidents in transmission network occur that limit the power transmission capability. The weakness of this method is that it assumes the availability of reserves in necessary regions. However under market influences only, there is no motivation for market players to keep such reserves unless they have some economical incentives for this. Therefore some hybrid model could be used involving a combination of separate capacity reservation which is reserved beforehand and reserve energy utilisation that is realized only when actual need arises.

### ***1.7. Operational control of interconnections***

It is quite important for the safe operation of large interconnected power systems to constantly manage power flows via interconnection power lines. Thereby alternating current tie-lines are handled in many ways differently from direct current tie-lines. Nowadays the interconnection capacity allocation is mostly performed according to market rules with predetermined safe power limits given.

In ENTSO-E the interconnection power given to the market participants is usually referred to as Net Transfer Capacity (NTC) [21]. NTC is calculated as follows:

$$NTC = TTC - TRM \quad (1.8)$$

where TTC – Total Transfer Capacity;

TRM – Transmission Reliability Margin.

The TTC is calculated based on assumption that all data concerning generation, demand and topology of the network is known and determined. By these initial assumptions the max transfer capacity is calculated so that all stability criterions are met.

To eliminate the effect of unknown variations in generation and demand, changes in network topology and measurement errors of telemetering systems, a reliability margin is introduced (TRM). This reliability margin also includes possible emergency trades between TSO-s for system security reasons.

Therefore for each trading hour the actual value of TRM may differ, as well as the value of NTC.

In Figure 1.10 the graphical view of NTC calculation and its possible variation over different trading hours is shown.

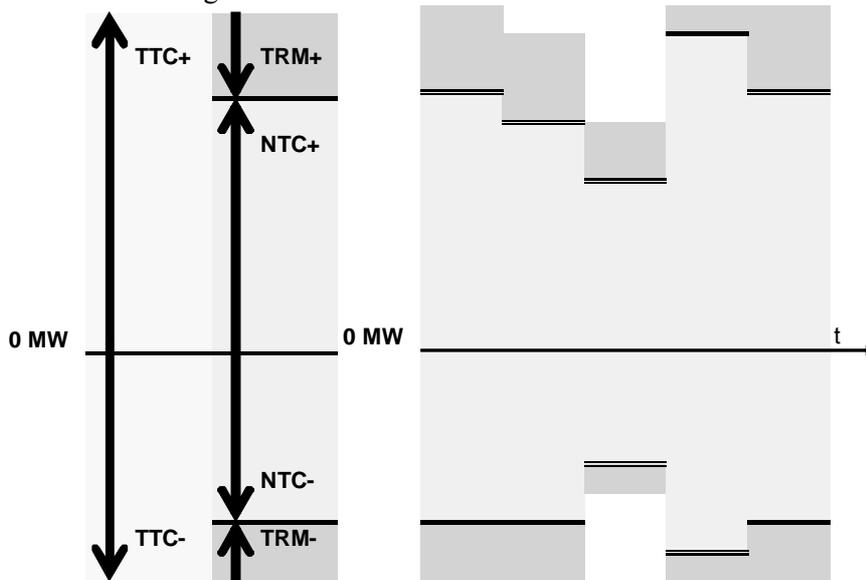


Figure 1.10 Calculation of NTC

The power networks of Baltic countries are operating synchronously with Russian Unified Power Systems of Interconnected Power Systems. (IPS/UPS). Poland is synchronously connected to the zone of continental Europe (former UCTE area). Scandinavian countries are operating in synchronous zone of NORDEL. Connection capacities given to the market between different zones in the region are as follows [2]:

- between Baltic countries (together with Kaliningrad area) and Russia (together with Byelorussia) max +/- 2700 MW (TTC)
- between Baltic countries and NORDEL +/- 350 MW
- between Baltic countries themselves max +/- 900 MW
- between Baltic countries and UCTE (Poland) 0 MW.

It must be mentioned that the actual capacity is strongly influenced by grid maintenances and generation distribution across different regions.

Connection between NORDEL and Russia has a rating of 1300 MW (with direction only from Russia towards NORDEL) and connection between NORDEL and UCTE area is 3400 MW in export direction and 2900 in import direction.

The peak load of NORDEL area is roughly 63 GW [3] while the peak for Baltic States has remained around 4.7 GW [4].

When comparing the interconnection capacities of different areas it can be noticed that for Baltic countries they are relatively much bigger than for NORDEL being about 57% of the peak load. On one hand this gives more opportunities to cover domestic demand with imported energy or to rely on the help of the bigger system in case of disturbances inside Baltic area. But on the second hand it also creates stronger dependence of domestic security from transit flows and disturbances outside Baltics.

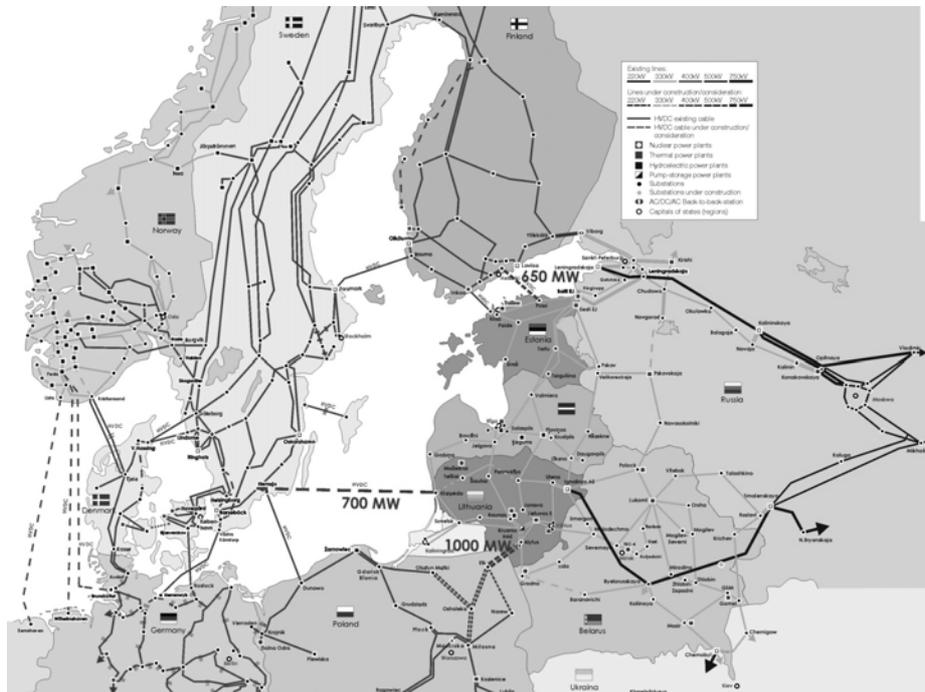


Figure 1.11 The power grids around Baltic Sea

The operation of interconnections has become more and more challenged by the growing market activities in the region. During the times before electricity markets started to exist the planning of interconnection power flows was easier as there were more stable commercial agreements between traders of different countries. Therefore it was easier to predict the actual volumes of power for the next several months or even years with fairly high accuracy. With the introduction of power market, the transactions between market participants became more volatile as the deals were no longer fixed for long periods but were mostly based on Day-ahead agreements. One direct effect of such trends is the pressure on TSO-s to increase the size of TRM in their capacity calculations, decreasing the capacities given to market participants in the same time.

The biggest challenge for the operation of interconnectors does not however appear to be deriving from increasing market activities but from the growing share of highly volatile power production units. With increasing inputs of wind power to the power system noticeable excess of energy can be expected which will lead to necessity of stopping high powered thermal or other conventional units [5]. This can turn out to be problematic as these units are generally required to cover the peak load and present long delay when starting up. A method has been proposed in [5] to estimate the equivalent capacity of wind parks that can be considered as a part of capacity to be used for calculating the share of wind powers participation in covering peak load.

Starting from a certain wind capacity however, the balancing of wind fluctuations is only possible in co-operation with neighbouring power systems [6]. So the amounts of energy transmitted via interconnection power lines shall become highly dependant on the actual wind production and its behaviour in time. It is therefore necessary to study the statistical behaviour of wind production and its influence on power changes in the power system more carefully to be able to give an assessment to the reliability of power system.

## 2. POWER CHANGES' DYNAMICS AND RANDOM CHARACTER

An electric power system must be able to meet the continually changing load demand, non-controllable changing of generating power and transmission losses for active and reactive power. Resulting from changes in load and generation in different regions of interconnected power changes, the power flows between those regions also change. In interconnected power systems the variation of interchange powers always has to be regulated.

The main parts in controlling the power systems' operation are [13]:

- the frequency and active power control (regulation) (f/P control)
- the voltage and reactive power control (regulation) (U/Q control).

Especially high requirements are established to the frequency and active power regulation as from that depend the quality of frequency and adequacy of interchange powers to the agreed values.

Formerly the power plants had to regulate the active power generation mainly correspondingly to the variations of power demand and interchange power. Now, when the application of wind power is increasing, the power systems need much more regulating power. In connection with wind power the serious power balance regulating issues have arisen in power systems.

The aspects of integrating wind power plants to power systems are thoroughly handled in the book edited by T. Ackermann [31]. It is shown in the papers [6, 27, 29] that the balancing of wind power fluctuations with thermal power plants causes the increasing of fuel losses and emissions in thermal power plants. Unit commitment issues for non-wind generating units have been handled in [30]. Several PhD theses about wind power integration to power systems have also been written [26-28].

The analysis is made on the base of initial data from Estonian power system in years 2008 and 2009.

### 2.1. *Methods of analysis*

In this paper the following components of active power balance equation are observed:

- gross load of power system or total power demand with power losses in electrical networks ( $P_D$ )
- net load or total net power generation of the traditional power plants (without wind power plant's generation) ( $P_G$ )
- total power generation of wind power units ( $P_w$ )

- total interchange power with others power systems ( $P_{INT}$ ): if  $P_{INT} > 0$  then the power is exported to other power systems and if  $P_{INT} < 0$ , the power is imported from other systems.

The changing of these variables represents the complicated random processes. These processes are connected by the active power balance equation of power system:

$$\tilde{P}_G(t) + \tilde{P}_W(t) - \tilde{P}_D(t) - \tilde{P}_{INT}(t) = 0 \quad (2.1)$$

where the marks on the symbols mean a random character of process.

The values of processes  $P_G(t)$ ,  $P_W(t)$  and  $P_{INT}(t)$  are measured and  $P_D(t)$  values are calculated on the base of equation (2.1):

$$P_D(t) = P_G(t) + P_W(t) - P_{INT}(t) \quad (2.2)$$

All processes were analyzed on the base of 2 seconds measurement data and 5 minutes mean values calculated on the base of measurement data of Estonian Power System in the period 1/1/2008–5/31/2008. The ranges of initial data for this period are shown in Table 2.1.

Table 2.1 Ranges of initial data

Process	Minimal value, MW	Maximal value, MW	Mean value, MW
$\tilde{P}_D(t)$	652	1707	1142
$\tilde{P}_G(t)$	582	1904	1171
$\tilde{P}_{INT}(t)$	-550	265	-197
$\tilde{P}_W(t)$	0	35	10.5

Since the part of wind power in Estonian power system was relatively small during the time for which the analysis are performed, in addition to the real case some fictional cases with enlarged part of wind power were analyzed:

- Case A (Real situation)      -  $P_W^{Max} = 35$  MW
- Case B                              -  $P_W^{Max} = 750$  MW
- Case C                              -  $P_W^{Max} = 1500$  MW

The initial data for cases B and C about  $\tilde{P}_W(t)$  were obtained by the linear extrapolation of real data (case A). No smoothing effect was considered as the best wind areas in Estonia are within a range of no more than 200 km, taking into account both wind conditions and possibilities of connecting the wind park to the grid. According to [26] the correlation between wind parks' production grows weaker only when distance between parks grows beyond 200 km.

In mathematical sense the analysis consisted of the following main steps:

Intra-hour changes were analysed on the base of 2-seconds measured data. Analysis processes in the longer periods (day, week, month and year) is made on the base of 5 minutes data.

Calculation of histograms, mathematical expectations, variances (dispersions), standard deviations, mutual correlation coefficients and their confidence limits for analysed processes followed.

Calculation of the functions of autocorrelation (autocovariation) for deviations of processes was also performed.

The variances, standard deviations, correlation coefficients and autocorrelation functions of processes were calculated assuming that fluctuations of processes are the stationary processes:

Variance  $DP$ :

$$DP = E(P(t) - EP)^2 \quad (2.3)$$

where  $E$  - means mathematical expectation.

Standard deviation  $\sigma_P$ :

$$\sigma_P = \sqrt{DP} \quad (2.4)$$

Correlation coefficient  $r(P_D, P_W)$ :

$$r(P_D, P_W) = \frac{C(P_D, P_W)}{\sigma_{PD} \cdot \sigma_W} \quad (2.5)$$

$$\text{where } C(P_D, P_W) = E[(P_D - EP_D)(P_W - EP_W)] \quad (2.6)$$

Autocorrelation function

$$C_P(\tau) = E[(P(t) - EP) \cdot (P(t + \tau) - EP)] \quad (2.7)$$

Normed autocorrelation function  $r(\tau)$ :

$$r(\tau) = \frac{C_P(\tau)}{\sigma_P^2} \quad (2.8)$$

## 2.2. Power demand changes

Changing of power demand may be divided into 3 groups [34]:

Very fast and irregular changes with small amplitude ( $\pm (0.1-0.5)\%$ ) and with duration of few seconds

Fast and irregular changes with noticeable amplitude ( $\pm (0.5-1.5)\%$ ) and with duration from some seconds to few minutes

Slow daily changes of loads described by loads curves, tables or diagrams.

Power plants do not have to react to the first group of changes. But they must react to the changes of second and third group in order to secure the quality of power frequency. Automatic frequency and power regulators will react mainly to

the changes of second group. Operation control of generated power consists of five stages:

- Primary control
- Secondary control
- Tertiary control
- Time control
- Slow control of generation.

The objective of primary control is to maintain the balance between generation and demand at the minimal deviations of frequency using turbine speed or turbine governors. Secondary control makes use of a centralized automatic generation control, modifying the active power set points of generators in the time-frame of seconds to typically 15 minutes. Secondary control is based on secondary control reserves. Tertiary control is any automatic or manual changing of working points of generators in order to restore secondary control reserve and to optimize the operation of power system. Time control aims to keep the synchronous time and astronomical times in accordance.

A weekly power demand curve compiled on the base of five minutes values is shown in Fig. 2.1. A daily power demand curve is presented in Fig. 2.2. Both curves are relatively smooth. The ratio of minimal load to maximum load is usually in interval 0.4–0.7.

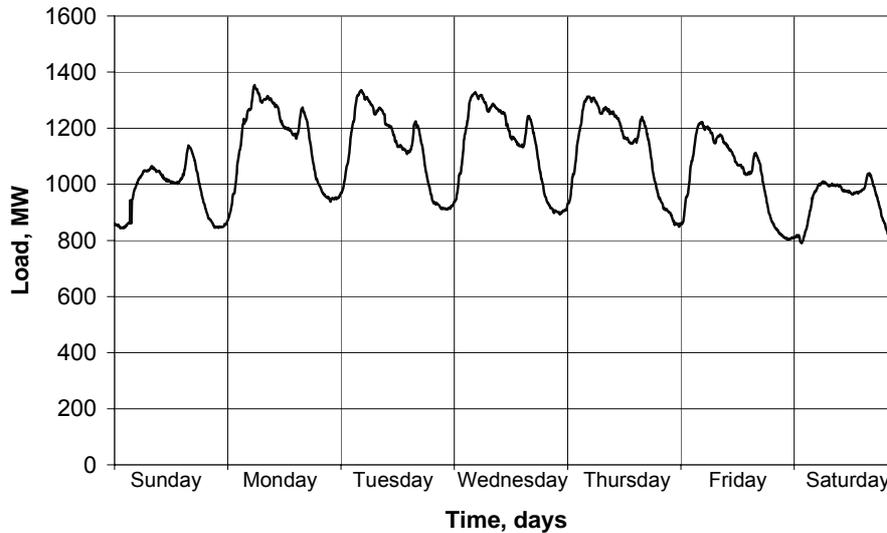


Figure 2.1 Weekly load demand curve (3/30/2008–4/5/2008)

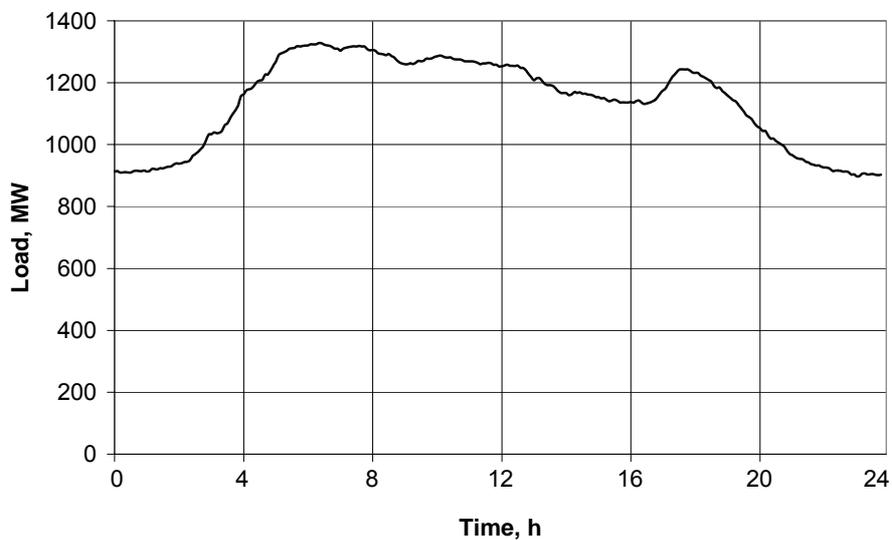


Figure 2.2 A daily load demand curve  $\tilde{P}_D(t)$  (4/2/2008)

The intra-hour changes of load demand are usually 0.2–0.4% of momentary load calculated from deviations between 5 minute measurements. A typical histogram of intra-hour load fluctuations in Estonian power system is shown in Figure 2.3. Distribution of fluctuations is similar to a normal distribution.

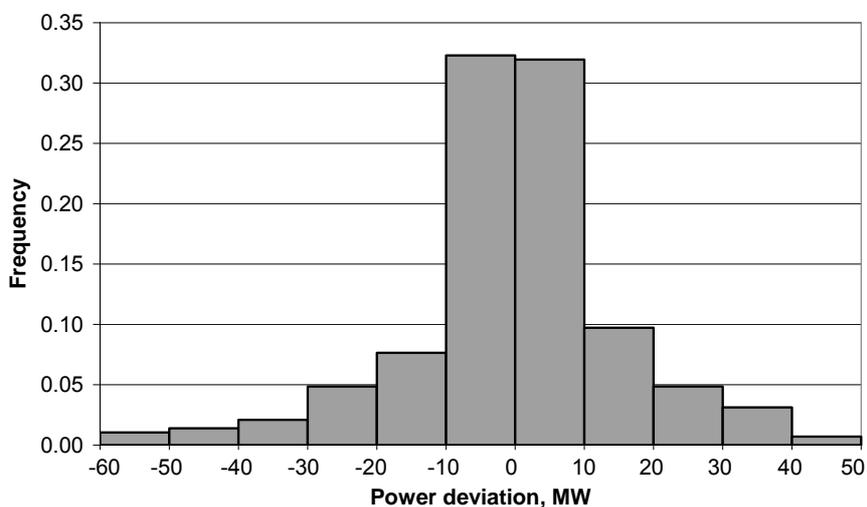


Figure 2.3 A histogram of intra-hour load deviations (1/1/2008–5/31/2008)

The functions of autocorrelation, calculated for load deviation processes, damp within 4–6 hours (Figure 2.4). The standard deviation of intra-hour load demand power changes is mostly in the range of 2–5%.

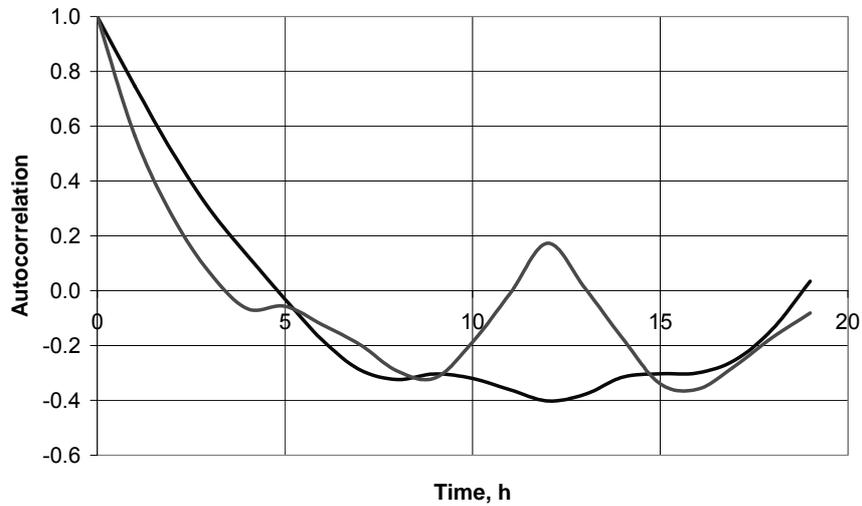


Figure 2.4 Autocorrelation functions of power demand ( $r(\tau)$ )

### 2.3. Wind power changes

The generation of wind power plants depends approximately of wind's speed in the third degree [33]. With changeful wind the generation of wind power plants may be changing very quickly from zero up to maximum power. Wind power plants may be stopped several times in an hour. But sometimes the changes of wind power may be smaller then power demand changes. The typical changes of wind power in a spring week are shown in Figure 2.5.

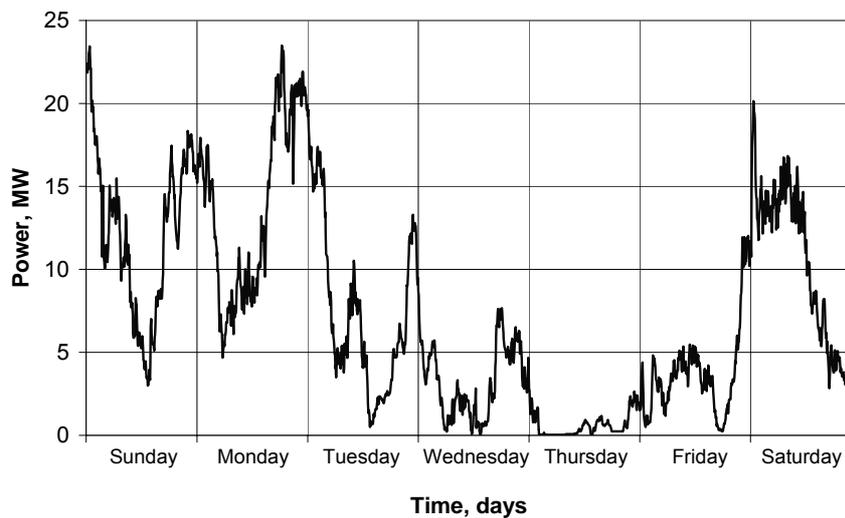


Figure 2.5 Wind power generation curve of a spring week (3/30/2008–4/5/2008)

A typical histogram of wind power generation is presented in Figure 2.6.

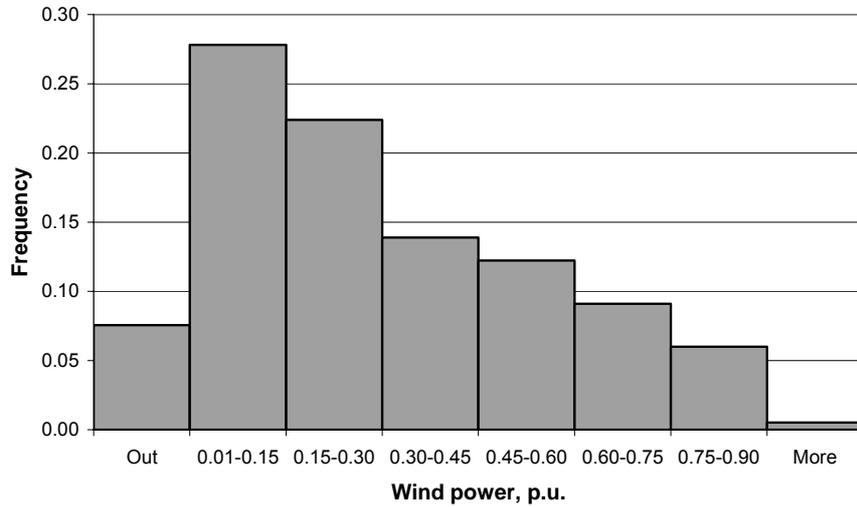


Figure 2.6 Duration of wind power generation (1/1/2008–5/31/2008)

More exact data about wind power plants (WPP) generation histogram are presented in Table 2.2.

Table 2.2 Distribution series of WPP (1/1/2008–5/31/2008)

Load intervals, pu $EP_w = 10.6$ MW $\sigma_{PW} = 8.7$ MW	Load intervals, MW	Total hours per interval	Statistic frequency
< 0.01 (WPP off)	< 0.5 (WPP off)	275	0.08
0.01–0.15	0.5–5.2	1013	0.28
0.15–0.30	5.2–10.5	816	0.22
0.30–0.45	10.5–15.7	506	0.14
0.45–0.60	15.7–21.0	445	0.12
0.60–0.75	21.0–26.2	332	0.09
0.75–0.90	26.2–31.4	237	0.06
>0.90	>31.4	19	0.01

These months were relatively windy. Five months average generation of wind power plants was 10.6 MW or 30% of total wind power capacity and standard deviation was 8.7 MW or 82% of average generation. From day to day these parameters may change within a wide range.

All wind power plants were off over 275 h (nearly 11.5 days). Distribution law of wind power generation is asymmetric (coefficient asymmetry is positive).

By extrapolating real data of wind power generation (Case A) the data of wind power generation for the cases B and C was obtained.

$$\text{Case B: } P_w^+ = 750 \text{ MW, } EP_w = 225 \text{ MW, } \sigma_{PW} = 185 \text{ MW}$$

$$\text{Case C: } P_w^+ = 1500 \text{ MW, } EP_w = 450 \text{ MW, } \sigma_{PW} = 369 \text{ MW.}$$

Thus on the occasion of large wind power parks the changes of wind power generation may be very large and fast.

For system aggregated wind power changes it is also important what is the geographical distribution of wind farms. According to [26] power changes of one single wind farm can reach up to 50–60% of installed power per hour. For several wind parks distributed over an area bigger than 200x200 km the hourly variations should not exceed 30%. According to [26] the correlation for wind production between parks is strong for parks closer than 100 km to each other and weak for parks over 200 km apart. The analysis of correlation based on Estonian data confirms this only partially. The correlation factor for Pakri and Rõuste wind parks was calculated to be 0.79 with the distance being 87 km between those two parks. For the time period analysed there were no wind parks more apart from each other to analyse the weakening of correlation by growing distance between the parks.

#### 2.4. Power generation changes

We consider the power generation changes in the isolated power system with condensing oil shale electric power plants. The load of power units is controllable in interval from 50 to 100%. Without wind power plants:

$$P_G(t) = P_D(t) \quad (2.9)$$

$$D_{PG} = D_{PD} \quad (2.10)$$

The condensing thermal power plants are regulating active power balance and frequency. The processes  $P_G(t)$  and  $P_D(t)$  are strongly correlated ( $C(P_G, P_D) \approx 1$ ).

If there are wind power plants connected to the power grid in an isolated power system, then the wind production behaves like negative load:

$$P_G(t) = P_D(t) - P_w(t) \quad (2.11)$$

$$DP_G = DP_D + DP_w - 2C(P_D, P_w) \quad (2.12)$$

The changes of power demand  $P_D(t)$  and wind power generation  $P_w(t)$  are practically not mutually correlated ( $C(P_D, P_w) \approx 0$ ) [13, 26].

Therefore the variances of power demand and wind power generation will join:

$$DP_G = DP_D + DP_w \quad (2.13)$$

and

$$\sigma_G = \sqrt{\sigma_D^2 + \sigma_W^2} \quad (2.14)$$

Consequently, wind power generation makes the active power balance regulation more complicated and expensive. If there are large wind parks connected to the system, the traditional power regulating plants must regulate generation in a wide range and with considerable speed. Also larger amounts of regulating reserves are needed.

Most of the oil-shale fired thermal units have a minimum operating power of approximately 50% of nominal. As daily load variation is usually 35–40% of day's peak load, most of the thermal units' regulating range is already being used to cover load demand changes leaving only 10–15% available for other uses such as fast power reserve for sudden load changes, generation outages and wind power variation. So it can be seen that on average if more wind power is installed to the system than 10–15% of daily peak power then the control of power system balance will become difficult even considering only the slow changes in demand and wind power.

Besides the regulating ranges also the ramping speeds of thermal power plants must be considered. According to operational instructions of ordinary oil-shale power plants the nominal gross power up-ramping rate for oil-shale fired power unit is 2.5 MW/min. Resulting from that it can be seen that with 4–10 thermal units in operation which would be needed to cover the load demand during the whole year, the ramp-up rate is ranging from 600–1500 MW/hour. Even in extreme conditions changes of no more than 50–60% of total installed wind power occur [26]. Therefore it can be noted that lack of ramping speed of thermal plants would not become the first limiting factor for wind power integration.

The experience from recent years shows that due to relatively high investment costs, the installation of wind power parks is correlated to subsidies by the state. But when the wind parks are already participating in the daily market then their production is more competitive than the energy from thermal PP-s as the marginal costs of wind energy are close to zero [31]. Therefore wind power has an advantage over conventional power and whenever there is wind blowing, all of wind power gets sold on the market and other power plants are pushed upward on the merit order list. Figure 2.7 shows how the thermal power plants must regulate power balance in isolated power system in the cases A, B and C if the power of wind PP-s is not curtailed.

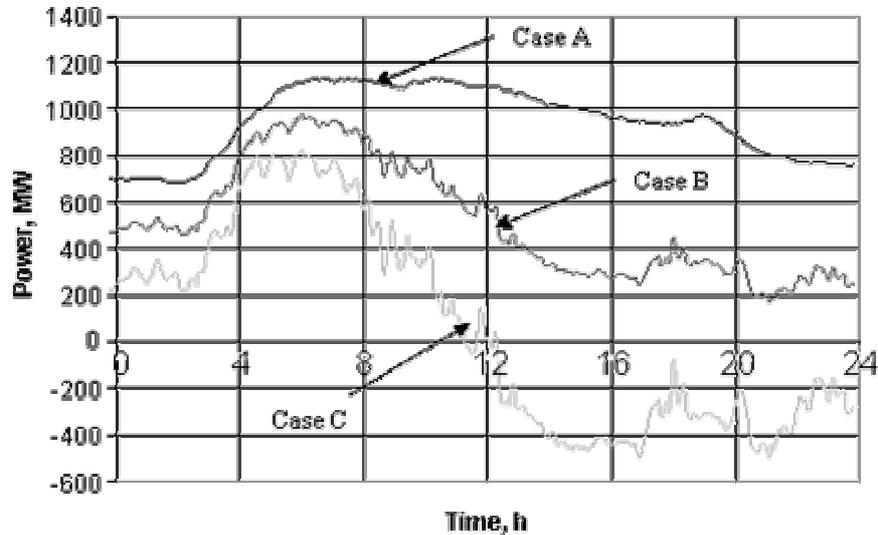


Figure 2.7 Total net power generation curves of thermal power plants for different wind power capacities

In case A the part of wind power is very small (35 MW) and thermal power plants are working by a relatively uniform load curve (Figure 2.7, upper curve) and they cope well with balance regulation. In case B, the part of wind power is much greater (750 MW). Now thermal power plants must work by a different curve (Figure 2.7, middle curve). Oil shale power plants are not able to cope with such operation having limited operating range. Therefore a power system can operate in an isolated state only when wind power generation is significantly curtailed. The permitted wind power ranges from close to zero at night's minimum load to 500–600 MW at day's maximum load as thermal plants' minimum operating power limits may not be violated. Periodical stopping of single boilers for night-time would give some rise for nightly permitted wind power, but this would already result in significant rise in costs of thermal plants.

Looking at case C where  $P_w^{\max} = 1500$  MW (Figure 2.7, lower curve) we can see that this is an even more unfeasible situation and because of similar curtailments as for case B even a smaller amount of actual installed wind power capacity may be utilised.

Generally every power system is expected to be able to operate also in an isolated state also as this can occur from time to time for different reasons. Therefore one conclusion from the above analysis that can be withdrawn is that even if the thermal power based power system is not operating in an isolated state, there has to be technical readiness for real-time curtailments of wind production in a very wide power spread both from the system operator's side and from wind parks' side.

When the power system is working in an interconnected power system, the situation is different from the case with the isolated system. For instance one possible approach in an interconnected power system is that the largest power system regulates frequency directly and other power systems regulate their interchange power participating by this indirectly also in frequency regulation. There is even a possibility that every power system does not regulate its own power balance completely for instance regulating only slow power changes. Then the imbalances caused by fast changes of power like wind power and fast power demand fluctuations must be regulated by other systems resulting that a large part of electric energy generated by wind plants in the first power system also goes to other systems. Also the same question of sufficiency and efficiency of regulating power arises in those other systems.

The regulating range of hydroelectric power plants is usually close to 100% from nominal power and their regulating losses are much smaller than in thermal power plants. The regulating range of thermal power plants with steam units that are running on solid fuel is usually only 50% of nominal and regulating losses are significant (10–20%). For that reason the compensation of wind power generation with thermal power units might not decrease but even increase the fuel cost and emissions in a power system [29].

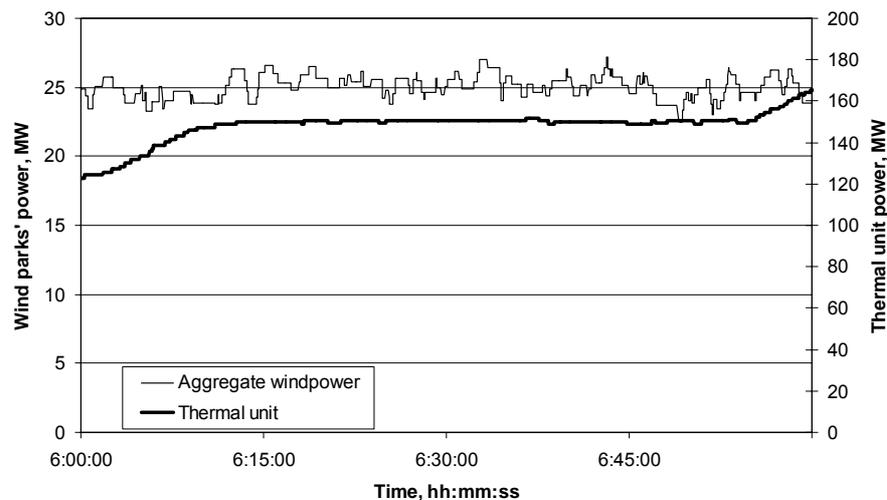


Figure 2.8 Thermal power unit's load (right axis) compared to aggregated wind power (left axis) at 2/28/2009 (06:00–07:00)

To analyse the actions of turbine governors and fast regulation of existing oil-shale fired generators the output power metering values were studied. The metering values acquired at 2 second interval were used. As it can be seen on the Figure 2.8 the fast power changes of a conventional thermal power unit are very limited reaching up to 1% of nominal power. Therefore it is evident that the power system with fairly small amount of installed wind power can be controlled with low expenses on fast power regulation.

With larger amounts of wind power penetration to the system thermal power plants should also be able to regulate fast irregular changes significant enough to activate secondary control system. For the Estonian example such changes should be of an amplitude over 10–15 MW. According to the data obtained for the period of 01.01.2008 – 31.05.2008 the standard deviation for intra-hour wind power deviation based on 5 minute intervals ranges up to 10% of installed wind capacity being from 0 to 6% for 95% of the time (Figure 2.9).

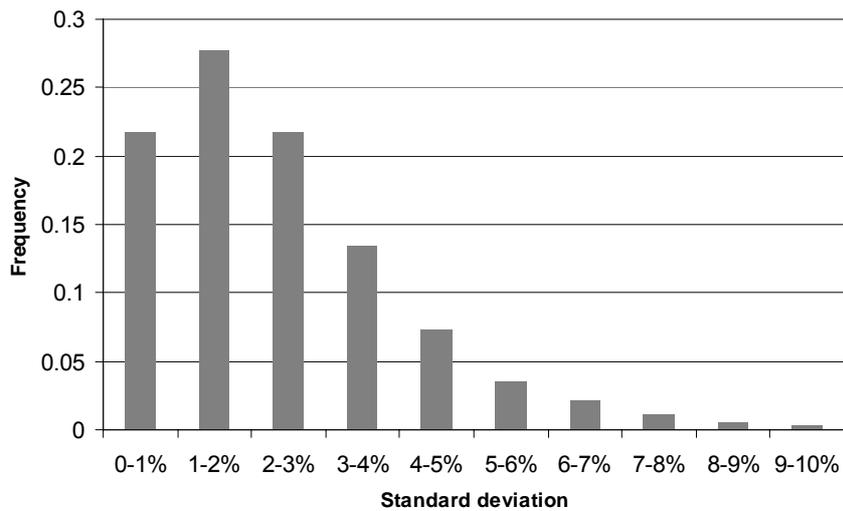


Figure 2.9 Statistical frequencies of standard deviations of intra-hour wind power fluctuations

As secondary regulation is carried out on the basis of momentary power measuring the action of the system and power plants connected to AGC module actually follows the oscillations in the power with duration of a few seconds. Therefore it is necessary to analyze these fast oscillations in more detail to assess their effect on the behaviour of conventional power plants. As an example a period of 48 hours in the beginning of October 2009 was studied for Estonian power system where power values of existing wind parks, system total load and some of existing conventional power plants were measured in 1 second intervals. These days were selected to characterize the magnitude of power changes in the system as the days were quite windy. The demand load and aggregate wind production for the period are shown in Figure 2.10.

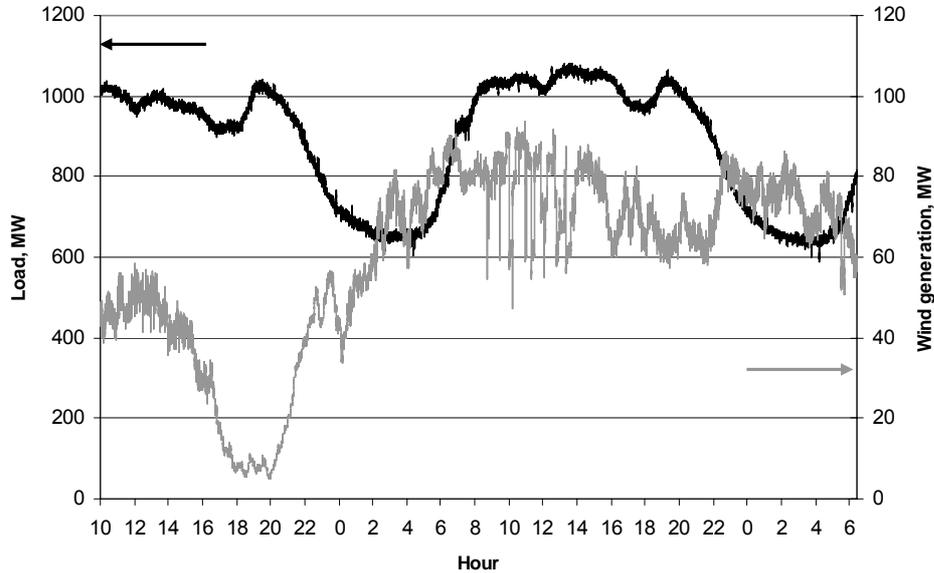


Figure 2.10 Demand load and wind production 06.10.2009 10:00 – 08.10.2009 06:00

The installed power of wind parks was 108 MW during this period and daily peak load 1081 MW. The standard deviations of load and wind power fluctuations and also their relative values compared to daily peak load and installed wind power were calculated for each hour. The ranges of results are given in Table 2.3.

Table 2.3 Standard deviations of load and wind power 06.10 – 08.10.2009

	$\sigma$ load, MW	$\sigma$ wind generation, MW	$\sigma$ load, %	$\sigma$ wind generation, %
Max value	45.4	10.9	4.2%	10.1%
Average value	14.0	4.1	1.3%	3.8%
Min value	5.3	1.1	0.5%	1.0%

The pattern of load variation reflects the daily power curve with the hours of maximal deviations being the hours of morning load increase and evening decrease. The pattern of wind power fluctuations is more random. The hourly variations of deviations are shown in the Figure 2.11. It must be noted that during the period in question one of the wind parks was being tested and during some hours some of the variations in wind power are caused by the testing procedures.

In order to evaluate the effect of wind power fluctuations to the regulation of conventional power plants we must calculate the composite  $\sigma_D$  according to formula (2.14). The composite standard deviation of average standard deviations was found to be 14.8 MW and maximum standard deviations is 45.6 MW. So it is

easy to show that when the level of connected wind power is approximately 10% of daily peak load, there is no notable effect of wind fluctuations to the secondary regulating needs.

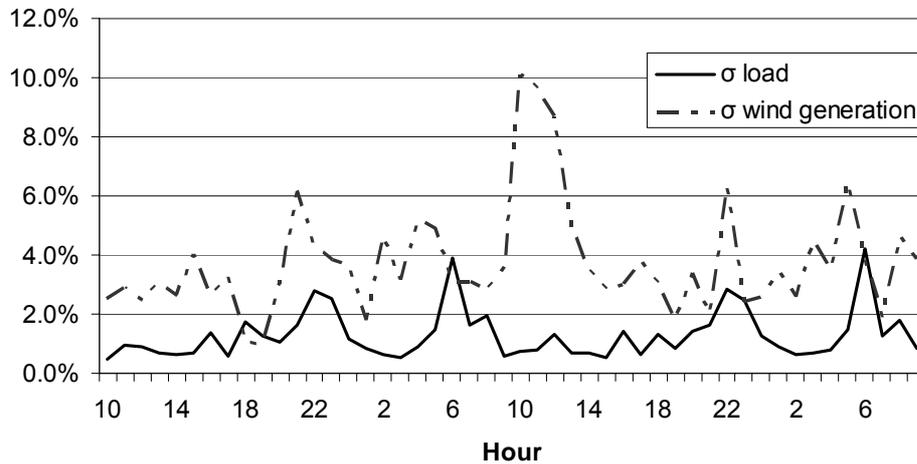


Figure 2.11 The changes in standard deviations

To analyze the hypothetical situation where there would be considerably more wind parks, two additional scenarios were created with linear extrapolation of the real wind power to the levels of 750 and 1500 MW-s of installed power. The resulting standard deviations of all those cases are given in Table 2.4.

Table 2.4 Standard deviations of fluctuations for different scenarios, MW

	$\sigma$ load	$\sigma$ load+wind fact	$\sigma$ load+wind 750 MW	$\sigma$ load+wind 1500 MW
Max value	45.4	45.6	76.3	152.0
Average value	14.0	14.8	32.9	59.4
Min value	5.3	6.0	15.5	20.5

The calculations show that if there were 750 MW of wind producers connected to the system, the need for momentary balancing would be more than doubled.

Therefore it can be expected that when the power of wind generators exceeds current values the secondary power controller will start to regulate the power interchange more often by means of changing the output of thermal units.

It is also necessary to evaluate the effect of the fast power fluctuations to the system frequency when it is operating in an isolated state. For this the power frequency characteristics of the isolated system are needed. As a result of this assessment the recommended capacities of primary reserves can be found that are needed to fulfil the quality requirements for system frequency.

The previous analysis concentrated on the situation where there are only onshore wind parks connected to the grid and they are fairly well geographically dispersed. If plans exist to integrate large offshore parks to the system they would require a separate analysis as the situations with a few offshore wind parks is characterized by more intense fluctuations in the minute ranges of their output power [36]. This is mostly due to the fact that an offshore wind park is situated in a very small and concentrated area where wind speeds at the turbines are much more correlated than the wind speeds at the turbines dispersed over a bigger area. Also the meteorological conditions offshore are different from those onshore.

The information by [36] states that for large offshore wind parks the power change can reach up to 25% of the parks installed power per 10 minutes. This is considerably more than shown by the above analysis about onshore distributed wind generation.

### 2.5. Interchange power variations

To analyse power systems ability to control area power balance, interchange power changes must be looked at. Usually there are set values of maximum deviations in interchange power values which guarantee safe operation of power systems and quality of electricity. Those values are subject to agreement between neighbouring systems and are dependent on power system peculiarities such as interchange transmission capabilities, system sizes and also possibilities to regulate power oscillations. For instance the current parallel operation agreement with neighbouring countries obliges the Estonian system to be balanced with area control error less than 30 MW. An example of actual measured interchange and planned interchange of Estonian power system for one week is shown on Figure 2.12.

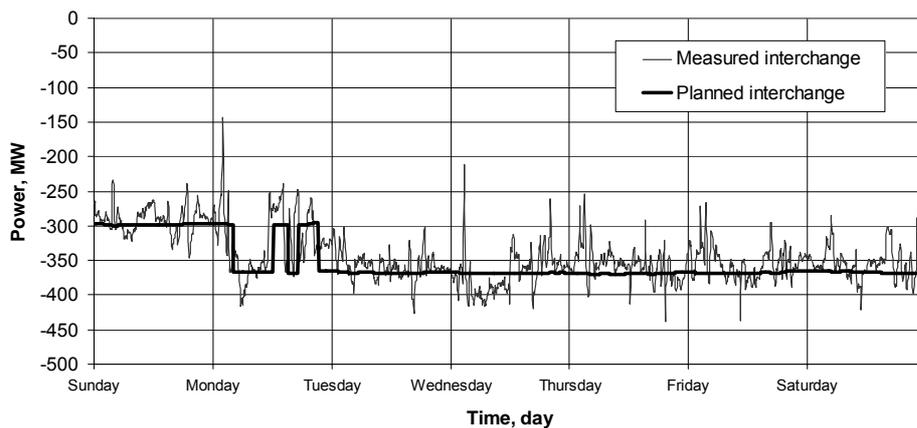


Figure 2.12 Planned and measured interchange power curve at 3/30/2008–4/5/2008

Analysis shows that even in a system without additional power changes caused by substantial wind power penetration there are interchange power changes that exceed allowed tolerances. Standard deviation of deviation between planned and measured interchange for the week illustrated above was calculated and found to be 28.0 MW. It can be seen that in order to be able to handle the penetration of generation with larger power oscillations some measures have to be taken not to hazard the parallel operation of unified power systems.

### 3. RELIABILITY OF POWER SYSTEM OPERATION

Reliability means the ability of a system to perform its required function under stated conditions for a given period of time [7]. Reliability is one of the most important properties of technical systems. Very high reliability and security is required from power systems, whereas interruptions of power supply and blackouts of power systems nowadays have catastrophic consequences. The primary requirement to guarantee the power system reliability is sufficiently high reliability and controllability of electric power generation.

Reliability is a fundamental requirement put to the power systems and their subsystems. Different probabilistic models [7, 14] are used for evaluation of the reliability of power systems. Yet the probabilistic models are not sufficiently general for reliability evaluation. In a power system the failures take place relatively seldom, and the failure-repair cycle changes in very large limits. The questions when a failure occurs and how long it will take to repair are rather uncertain or fuzzy events than probabilistic cases. Therefore also the perspectives of using uncertain and fuzzy models for evaluation of the power system reliability [9] are studied.

#### 3.1. Probabilistic models

Reliability in the strict conception is a probability that the system is operating without failures in the time period  $t$ . Let us look at the main probabilistic characteristics of reliability [8, 9, 14, 25].

Reliability function  $p(t)$  is a function, which gives the probability that the system will operate without failure in the period time  $t$  or longer then  $t$ :

$$p(t) = P\{\tilde{T} > t\}, \quad (3.1)$$

where  $\tilde{T}$  - random variable, period time to failure.

The function  $p(t)$  decreases. If  $t = 0$ , then  $p(t) = 1$ .

Failure probability function  $q(t)$  is a function, which gives the probability that a failure will happen in the period  $t$ :

$$q(t) = 1 - p(t) \quad (3.2)$$

Distribution function of time without failure  $F(t)$ :

$$F(t) = P\{\tilde{T} < t\} = q(t) \quad (3.3)$$

Density function of time to failure  $f(t)$ :

$$f(t) = \frac{\partial F(t)}{\partial t} = \frac{\partial q(t)}{\partial t} \quad (3.4)$$

If intensity of failures is constant the reliability function is an exponential function:

$$p(t) = e^{-\lambda t} \quad (3.5)$$

and

$$f(t) = \lambda e^{-\lambda t}, \quad (3.6)$$

where  $\lambda$  - intensity of failures.

The exponential reliability function  $p(t)$  and distribution function  $F(t)$  of power unit are shown in Figure 3.1.

Expected time to failure  $\bar{t}$  :

$$\bar{t} = \int_0^{\infty} t \cdot f(t) dt \quad (3.7)$$

In practice the reliability evaluation takes place on the basis of expected failure rate and expected repair rate or on the basis of mean time to failure and mean time to repair. At that the following probabilities are determined:

Unavailability (forced outage rate) of object  $q$

$$q = FOR = 1 - p = \frac{\lambda}{\lambda + \mu} = \frac{r}{m + r} \quad (3.8)$$

Availability of object  $p$

$$p = \frac{\mu}{\lambda + \mu} = \frac{m}{m + r} \quad (3.9)$$

where  $\lambda$  - expected failure rate

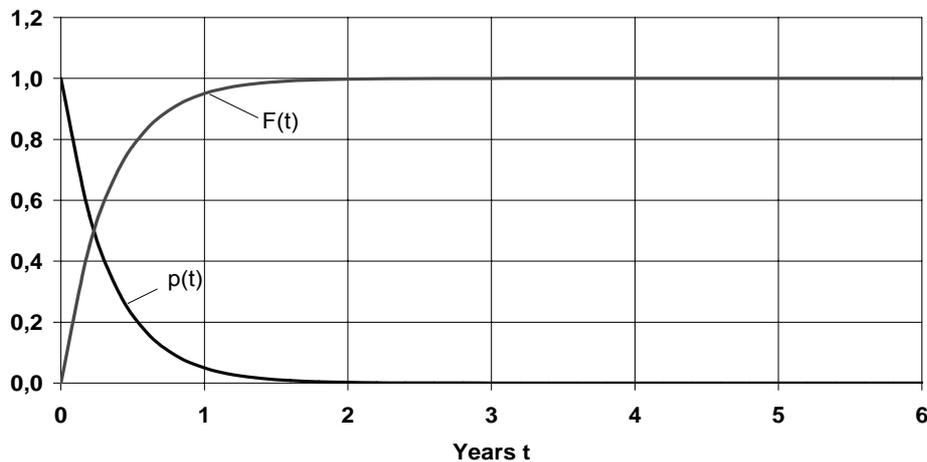


Figure 3.1 Reliability function  $p(t)$  and distribution function  $F(t)$  of power unit, with expected failure rate  $\lambda = 3$

The reliability indicators of oil shale power units working in Estonian power system calculated in probabilistic form are presented in Table 3.1.

Table 3.1. Intervals of reliability indicators of oil shale power units 200 MW ( $\lambda$  - expected failure rate;  $\mu$  - expected repair rate,  $m$  - mean time to failure,  $m = 1/\lambda$ ;  $r$  - mean time to repair,  $r = 1/\mu$ )

	Boiler	Turbine	Generator	Power unit
$\lambda$ min	1,40	1,00	0,14	
$\lambda$ max	4,67	1,50	0,29	
$\mu$ min	73	10	79	
$\mu$ max	250	190	584	
$r$ min	0,0046	0,0052	0,0017	
$r$ max	0,0137	0,1014	0,0127	
$m$ min	0,2143	0,70	1,75	
$m$ max	0,4286	1,00	7,00	
$p$ min	0,9494	0,8734	0,9977	0,83770
$p$ max	0,9936	0,9939	0,9993	0,96625
$q$ min	0,0064	0,0061	0,0007	0,03375
$q$ max	0,0506	0,1266	0,0023	0,16230

From Table 3.1 we can see that the reliability indicators of unit are changing in rather wide intervals. For this reason it is more correct to use the uncertain probabilistic or fuzzy probabilistic models for reliability evaluation.

### 3.2. Uncertain probabilistic models

If the value of intensity  $\lambda$  is not given exactly, the intensity of failures must be described as an uncertain variable in the crisp interval. Then the reliability function is an uncertain probabilistic function [8]:

$$p(t, \lambda_2(t)) \leq p(t) \leq p(t, \lambda_3(t)) \quad (3.10)$$

or if  $\lambda_2$  and  $\lambda_3$  are the constants

$$e^{-\lambda_2 t} \leq p(t) \leq e^{-\lambda_3 t} \quad (3.11)$$

The exponential reliability function  $p(t)$  and distribution function  $F(t)$  of power unit in uncertain form are shown in Figure 3.2. The intensity of failures is given by intervals:

$$2 \leq \lambda \leq 3,5 \quad (3.12)$$

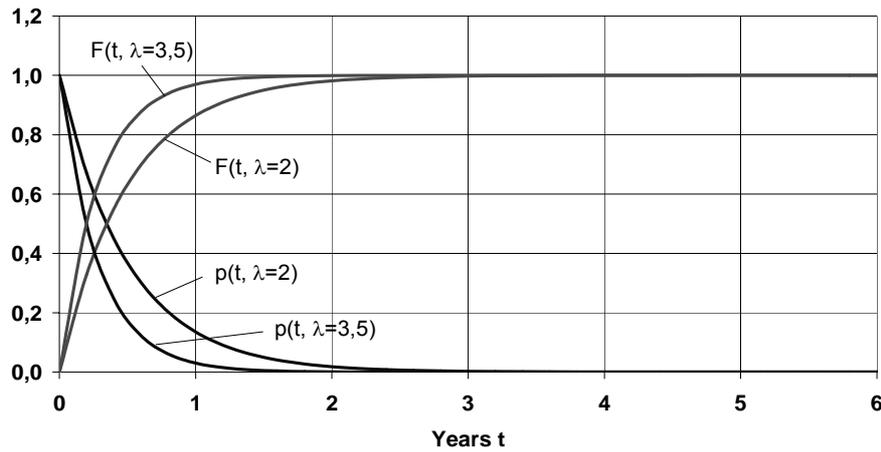


Figure 3.2 Reliability function  $p(t)$  and distribution function  $F(t)$  of power unit in uncertain form,  $\lambda_2 = 3,5$  and  $\lambda_3 = 2$

Analogically, on the basis of uncertainty intervals of expected failure rate  $\lambda$  and expected repair rate  $\mu$  it is possible to calculate the intervals of unavailability and availability for reliability analysis of power units.

The reliability indicators calculated for Estonian system in uncertain form are presented in Figures 3.3 and 3.4.

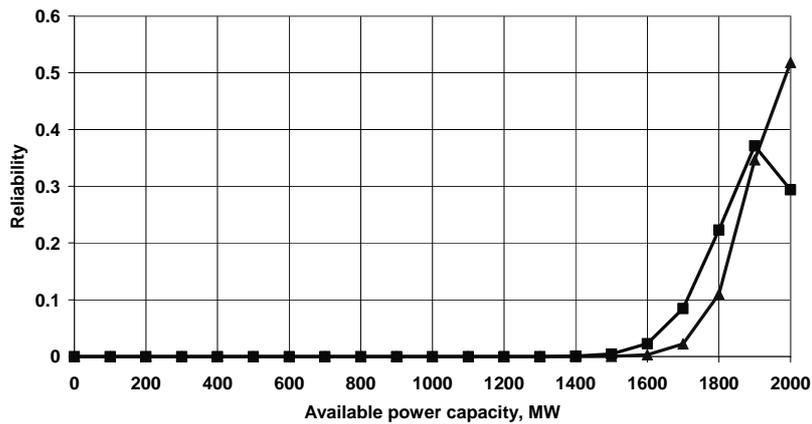


Figure 3.3 Uncertain probabilistic model of reliability for ten-unit electric power system generation

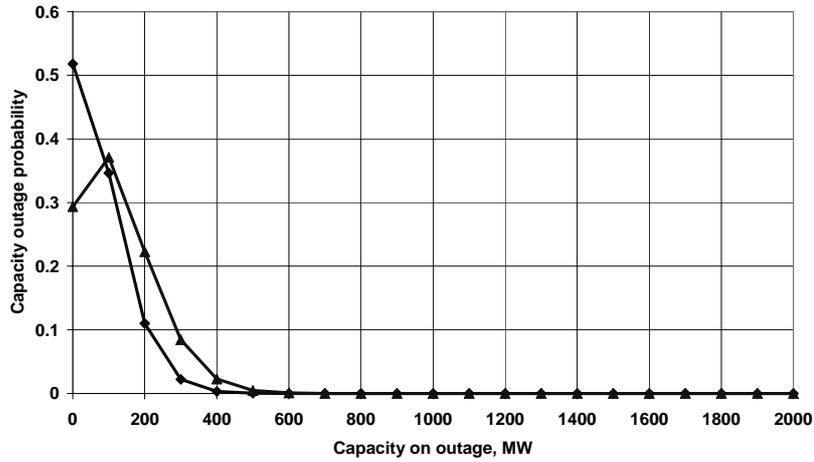


Figure 3.4 Capacity outage uncertain probabilistic function for ten-unit power system

### 3.3. Fuzzy probabilistic models

If the zones of reliability function are not known exactly, it is recommended to describe the reliability function in the fuzzy probabilistic form. For that we must describe the values of intensity  $\lambda$  in the form of fuzzy sets [9].

A fuzzy zone  $\tilde{A}$  is defined in  $U$  as a set of ordered pairs:

$$\tilde{A} = \langle x, \mu_A(x) | x \in U \rangle, \quad (3.13)$$

where  $\mu_A(x)$  is called the membership function, which indicates the degree of that  $x$  belongs to  $\tilde{A}$ . The membership function takes values  $[0, 1]$  and is defined so that  $\mu_A(x) = 1$  if  $x$  is a member of  $\tilde{A}$  and 0 otherwise.

At that, if  $0 < \mu_A(x) < 1$  the  $x$  may be the member of  $\tilde{A}$ .  $U$  is the given crisp set.

An example of the membership function  $\mu(\lambda)$  is shown in Figure 3.5.

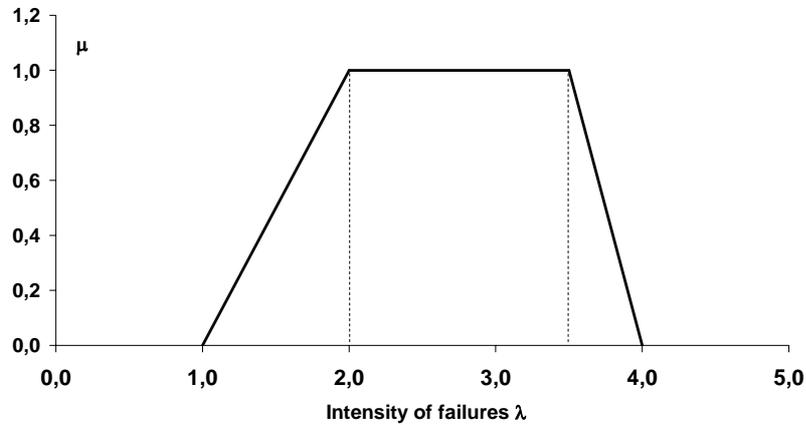


Figure 3.5 Membership function of  $\lambda$

Figure 3.6 shows the exponential reliability function  $p(t)$  and distribution function  $F(t)$  of a power unit in the fuzzy form if the membership function is  $\mu(\lambda)$ .

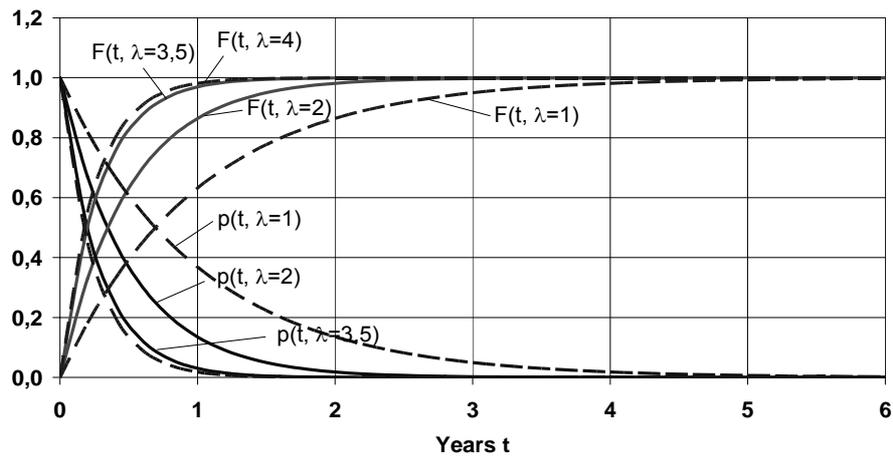


Figure 3.6 The reliability function  $p(t)$  and distribution function  $F(t)$  of power unit in the fuzzy form:  $\lambda_1 = 4,0$ ,  $\lambda_2 = 3,5$ ,  $\lambda_3 = 2,0$  and  $\lambda_4 = 1,0$

The information about unit reliability in Estonian power system in uncertain probabilistic and fuzzy probabilistic forms is presented in Table 3.2.

Table 3.2 Fuzzy intervals for reliability indicators

	Fuzzy essential points			
	$\underline{\mu}=0$	$\underline{\mu}=1$	$\overline{\mu}=1$	$\overline{\mu}=0$
$\lambda$	1.57	2.86	7.71	10.86
$r$	0.0039	0.0040	0.0072	0.0090
$m$	0.0921	0.1296	0.3500	0.6364
$p$	0.9406	0.9676	0.9818	0.9938
$q$	0.0062	0.0182	0.0324	0.0594

The fuzzy probabilistic models of reliability for power system generation in fuzzy probabilistic form are shown in Figures 3.7 and 3.8.

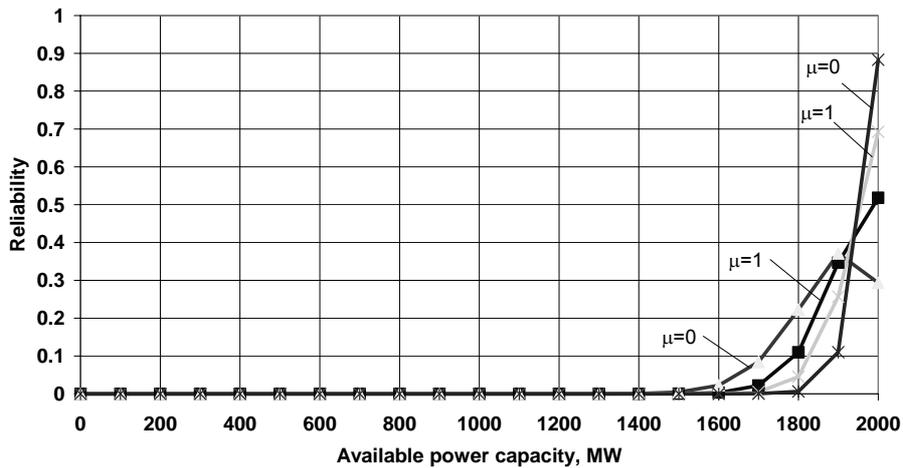


Figure 3.7 Fuzzy probabilistic model of reliability for ten-unit electric power system generation

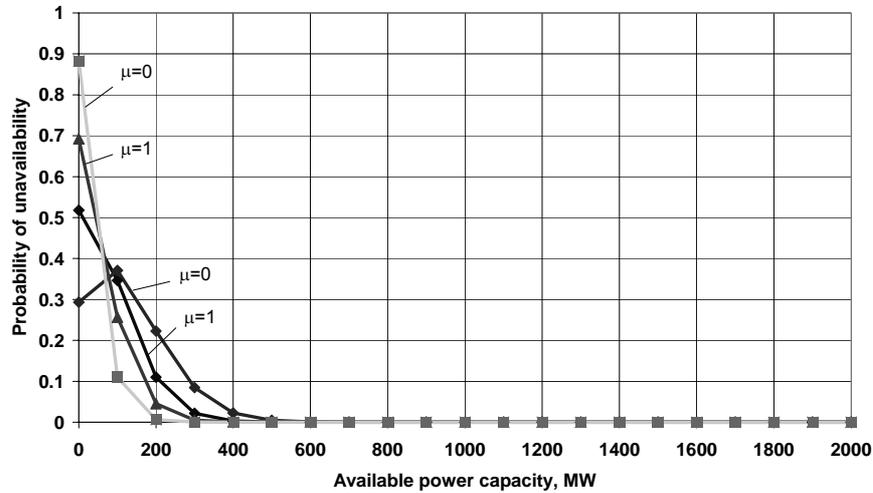


Figure 3.8 Capacity outage fuzzy probabilistic functions for ten-unit power system

Other indicators of reliability may be presented by the analogical way in fuzzy probabilistic form. The application of fuzzy systems in reliability analysis is nowadays expanding.

### 3.4. Reliability of wind generators

With increasing penetration of wind power to power systems the need to evaluate wind power plants' reliability and their effect on power system operation also increases.

Wind speed and power output of wind power plants are random processes. The functions of autocorrelation of wind power show large variations. In [10] the data about short-term power fluctuations of wind power plants is presented. Wind power is controllable only downwards and its value may change every second. Therefore the traditional reliability indicators are not very suitable for wind power plants.

In the case of wind power plants, both the value of power output and the duration of this value are random variables. For approximate description the loads of wind power plants, two-dimensional distribution functions may be recommended:

$$FWP(P(t), \tau(t)) = G(P!(t) < P(t)) \cap (\tau!(t) < \tau) \quad (3.14)$$

where G – probability;

FWP – distribution function of wind power;

P(t) – value of wind power;

$\tau(t)$  – duration of wind power value;

$P!(t), \tau!(t)$  – random variables.

On the basis of function (3.14) practical models may be derived for describing and compiling the prognosis for power outputs of wind power plants.

The distribution diagram and distribution function of output power duration for Pakri Wind Park is presented in Figure 3.9. For comparison the same diagram and distribution function for wind power plants in Denmark is presented in Figure 3.10.

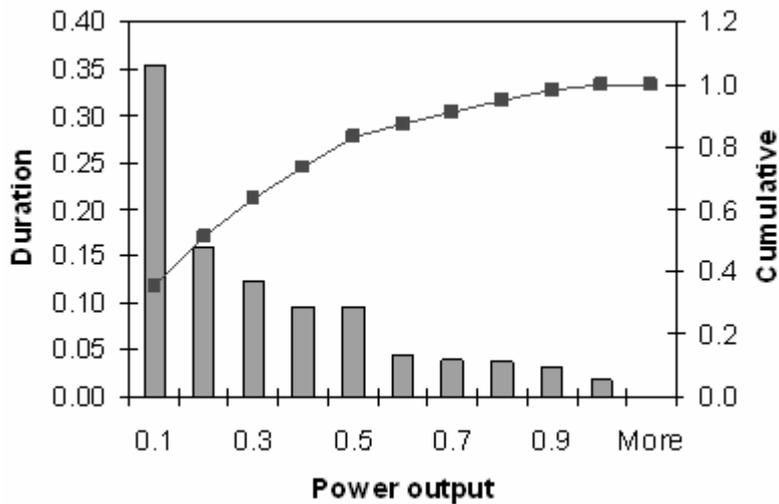


Figure 3.9 The distribution diagram and distribution function of output power duration for Pakri Wind Park (2006)

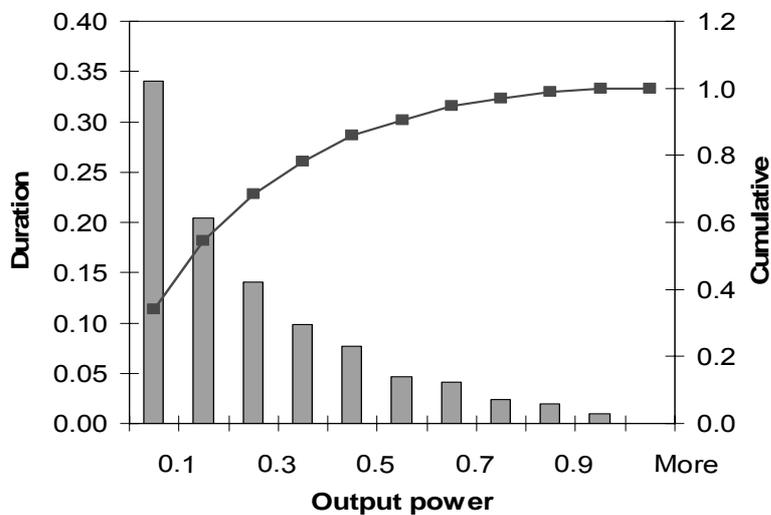


Figure 3.10 The distribution diagram and distribution function of output power for Wind Power Plants of Denmark (2006) [32]

It can be noted that the diagrams and distribution functions on Figures 3.9 and 3.10 are very similar.

### ***3.5. Reliability in interconnected power systems***

When power systems are interconnected the adequacy of the generating capacity in a power system is normally improved due to the diversity in probabilistic occurrence of load and capacity outages in different systems [14]. But the actual benefits of interconnections from the reliability point of view are also dependant on the installed capacity in each system, the total tie line capacity, the forced outage rates of these lines and several other factors.

Several probabilistic methods exist which provide a quantitative reliability assessment of interconnected system generation facilities. One of those methods is the loss of load expectation (LOLE) approach [14]. To calculate LOLE indices for interconnected systems for instance probability array or equivalent assisting unit methods could be used. In the first approach the capacity model is developed for both systems and an array of simultaneous capacity outage existence probabilities is then obtained from the individual models. The second method models the assisting system as an equivalent assisting unit which can be moved through tie lines and added into the existing capacity model of the assisted system. The computation of the risk then proceeds in the usual manner as for a single system.

Both of the methods above take into account the capacity of the existing tie line as a limiting factor. When planning tie lines between systems the effect of the capacity on the composite LOLE should be calculated in order to invest in reasonable amount of transmission capacity. But not only the effect of the capacity of interconnection on the reliability has to be taken into account as the line itself has a FOR of more than 0. When the number of tie lines forming the overall capacity is more than one, the reliability index of the interconnected system usually rises as the availability of the interconnection is then formed by the combined reliabilities of each single line. Also the capacity of overhead lines is changing in vast limits over time as the cooling conditions change considerably throughout the year. When the effect of tie lines is calculated, this variance in time has to be considered in order to fully evaluate their participation in improving the system reliability.

It is necessary to note that the calculation of interconnected system reliability based on purely probabilistic information can prove to be misleading as actually many parameters used in the calculations have uncertain nature. Not only the usable capacity of the tie line itself but also the demand and generation power fluctuations in all subsystems, largely varying generation reliability values and unwanted loop flows can cause quite big differences in actual situation compared to the expected one. Therefore uncertain probabilistic or fuzzy probabilistic models could be used.

### ***3.6. Reliable transmission capacity of interconnectors***

The reliability of transmission is guaranteed by calculating the secure transmission capacity for each interconnector and allowing the market to utilize

only certain share of this technical maximal power [21] which is usually referred to as NTC. In order to calculate NTC from TTC according to (1.8) first the reliability margin TRM has to be found.

TRM is calculated to eliminate the effect of unknown variations in generation and demand, changes in network topology, measurement errors of telemetering systems and to leave sufficient room for possible emergency trades between TSO-s for system security reasons.

$$\text{TRM} = \Delta P_{\text{var}} + \Delta P_{\text{N-1}} + \Delta P_{\text{SCADA}} + P_{\text{Em.Tr.}} \quad (3.15)$$

where  $\Delta P_{\text{var}}$  – variation of power in the interconnector;

$\Delta P_{\text{N-1}}$  – maximal effect of different outages of the system elements on the power transmission over the interconnector;

$\Delta P_{\text{SCADA}}$  – measurement error of SCADA system;

$P_{\text{Em.Tr.}}$  – maximal possible emergency trades between TSO-s.

Some components of this margin are changing in time, others are more or less stable. The measurement error of SCADA system for instance can be calculated according to the measurement errors of devices in the use by TSO and this component does not change much over time. Emergency trades can be subject to either long term or short term agreements. If only long term agreements are used, then this component of the formula can also be fixed. A set of  $\Delta P_{\text{N-1}}$  can be calculated for a long period ahead considering the normal system topology and for the most common cases where some elements of the system are in outage.  $\Delta P_{\text{var}}$  can be calculated according to statistical measuring data of power flows over the interconnector in question.

Assuming that the statistical component is stable in time, the overall value of TRM does change over time, but the variations in time are modest. Considering, however, that large amount of wind power connected to the grid does change the pattern of power deviations to become varying in large intervals, also this behaviour should be taken into account. One can assume the variations in power flows to be corresponding to the maximal value of momentary wind production all over time. But in practice the wind parks operate at their maximal power level for a very little percentage of time. So the assumption of maximal production would cause unnecessary rise in TRM and unnecessary limitation to actual market trades. To minimize the unnecessary limitations a method of constant reassessment must be introduced.

One possible way to reassess the reliable TRM value as the operational hour approaches is to take into account the wind prognosis. According to modern energy trade methods used by European markets, four different stages of planning the NTC values are needed:

- long-term security of supply reports (1 to 20 years ahead)
- year ahead announcement for summer and winter peak
- day ahead for each of the 24 hours of the next calendar day
- hour ahead.

Long-term reports are used by market participants to evaluate different business opportunities in the future. These reports have value for both power plant and consumer investments as the situation in the power market may change according to changes in power import-export capabilities. Announcements of available transmission capacities for the coming year are used by traders to compose their portfolio strategic plans. Long-term and year ahead estimates of transmission capacities are not binding to TSO-s as the level of uncertainty is too big for this time horizon. For actual trades only day and hour ahead capacities give the exact frames.

For day and hour ahead NTC calculation the statistical maximal values of intra-hour deviations on the interconnectors can be used. But in order to be able to give market a fair signal about future changes in NTC values there is a need for a method to assess the effect of future generation on the NTC. So all of the known plans to integrate large wind farms would also be investigated by evaluating the change in NTC they bring about. One possible method is described below.

To calculate future TRM according to (3.15) we can assume that  $\Delta P_{var}$  is the only variable to change over time and  $\Delta P_{N-1}$ ,  $\Delta P_{SCADA}$  and  $P_{Em.Tr.}$  will remain unchanged. Now  $\Delta P_{var}$  can be decomposed into two parts – one part that is existing today and can be calculated by statistical analysis from measuring data and the second part is an incremental part. This incremental part can be evaluated by the maximal standard deviations of intra-hour fluctuations caused by wind parks assuming linear growth in fluctuations for systems of geographically small sizes. For larger systems smoothing factors must be used.

In meshed networks where there is more than one interconnector, it is needed to calculate the loading factors of different interconnectors in order to find the effect of wind power fluctuation to the capacity usage of specific interconnector. The effect of power deviations on the TRM for each interconnector can then be calculated:

$$TRM_{incr}^i = k_p^i \Delta P_{incr} \quad (3.16)$$

where  $\Delta P_{incr}$  – increase of variation of power in the system;

$k_p^i$  – loading factor of interconnector i.

Assuming that intra-hour deviations are normally distributed random variables, the increase of maximum value of power deviation can be determined:

$$\Delta P_{incr} = 3\sigma_{incr} \quad (3.17)$$

where  $\sigma_{incr}$  – increase in standard deviation of power deviation.

As an example increase of TRM is calculated for Estonian power system for the case where there would be 1500 MW of aggregate wind power connected to the network.

There are currently two AC interconnecting corridors to be defined: Estonia-Latvia and Estonia-Russia. Let us take the loading factors for those interconnectors to be:

$$k_P^{EE-LV} = 0.3;$$

$$k_P^{EE-RU} = 0.7.$$

According to table 2.4 we see that for 1500 MW of wind power  $\sigma_{incr} = 152-45.6 = 106.4$  MW. Therefore  $\Delta P_{incr} = 3 * 106.4 = 319.2$  MW

Now the effect on each interconnector can be calculated:

$$TRM_{incr}^{EE-LV} = 0.3 * 319.2 = 95.8 \text{ MW};$$

$$TRM_{incr}^{EE-RU} = 0.7 * 319.2 = 223.4 \text{ MW}.$$

## 4. PLANNING OF CONTROL RESERVES

To maintain reliability and quality of supply of a power system, reserves of active power and reactive power are needed. The operating generating power reserves are needed for compensation of load deviations from expected values and for covering generation deficit in the case of unexpected outages of power units [12-14]. With growing share of wind power connected to the system, the needs for reserve power have to be thoroughly reviewed as the wind power generation has low controllability and random nature.

There are several possibilities to categorize control reserves, for instance by their usage purposes, by the time the reserves are available to be engaged or by the state (synchronized to the grid or not). The reserves divided by the usage purposes are [22]:

- automatic regulation reserves
- manual regulation reserves
- contingency reserves
- black start reserves.

Automatic regulation reserves can be either local (distributed) or centralised and they usually act on turbine governors. Manual reserves can be ordered by the system control centre or activated by a balance responsible party in order to regulate the balance of his balance region.

Contingency reserves are usually manually launched by the system operator in case of unexpected outages of power generation units creating large balance deviations or tripping of power grid elements creating threats to power system transmission stability. In some cases there is also a need to set up automatically started contingency reserves, where the time required for manual start up can prove to be too long for stable operation of the system. Such reserves can be realised for instance on the basis of automatic start up of HPP-s or on the basis of automatic disconnection of loads. Both of these methods have been used in UPS/IPS and plans exist to utilise them also in some Scandinavian countries.

Black start reserves are used to guarantee the system start up after a system wide black out. Black start functionality is usually integrated to HPP-s, GT-s and DEPP-s. The same reserve capability can also be realised with the aid of modern transistor based HVDC solutions.

On the basis of availability time the operating reserves are divided into three parts:

- 1) primary control reserve
- 2) secondary control reserve
- 3) tertiary control reserve.

When we assess the impact of growing share of wind power injected to the power systems, we need to investigate the impacts on the reserve requirements among other factors as well. As wind power can only be controlled by reducing the production and because its power output cannot be predicted with great accuracy, a

substantial increase in the proportion of power produced from wind has a significant impact on the way in which scheduling and dispatch are performed. If the wind power generation is viewed as a negative load, the uncertainty of this generation increases the uncertainty of the demand. As the uncertainty in demand is one of the factors to be looked at when the requirements for reserve are determined, this increased uncertainty has to be taken into account [23].

As reliability and quality of power supply are directly affected by the reserves, the task of planning sufficient reserves is very important. From the other hand over-sizing the reserve amounts leads to decreased efficiency of the system, excessive fuel waste and violation of environmental targets. Therefore this complex problem needs to be looked at thoroughly.

#### ***4.1. Principles of optimization***

In general there are different ways to optimize the value of reserves:

1. One-stage approach: The sum of reserves costs and losses of consumers associated with non-sufficient reliability and quality of supply is minimized to the determination of optimal reserves in the power systems and interconnected power systems.
2. Two-stage approach:
  - 2.1. The sum of reserve costs and losses of consumers is minimized to the determination of optimal requirements for reliability, security and quality of supply
  - 2.2. The sum of reserve costs is minimized to the determination of optimal reserves subject to the optimal requirements of reliability, security and quality supply.
3. Partial optimization – the sum of reserve costs is minimized to the determination of optimal reserves subject to the given requirements of reliability, security and quality of supply.
4. Optimization by market relations – optimization of the reserves in the market conditions, if the requirements of reliability, security and quality of supply have been agreed.

The methods of reserves optimization on the base of reserve costs and losses of consumers have been considered in many works [37, 38 and others]. One-stage approach (Approach 1) to the reserves optimization problems is usually too complicated. Most rational is the two-stage approach (Approach 2), where in the first stage the requirements of reliability, security and quality are optimized and in the second stage the power reserves are optimized if the requirements of reliability (indices of reliability), security and quality conditions are given.

Approaches 3 and 4 are simplified variants.

All these approaches are very complicated as they are bound with optimization problems under incomplete information [44, 45]. The problems of reserves optimization are in that sense similar to the optimal load distribution and unit commitment problems. As a first approach it is needed to study the reserves

optimization problems under probabilistic and uncertain conditions. The most suitable criterion for these problems is minimization of maximal losses or risk caused by incompleteness of information.

Power demand is a non-stationary complicated Markov process with continuous-time:

$$\tilde{P}_D(t) = \bar{P}_D(t) + \Delta\tilde{P}_D(t) \quad (4.1)$$

where  $\bar{P}_D(t)$  – mathematical expectation of power demand;

$\Delta\tilde{P}_D(t)$  – random component of power demand.

Assuming that the load forecast errors that need to be compensated by the reserves, are normally distributed random variables, the maximum value of an error can be determined by the standard deviation of forecast errors:

$$\Delta\tilde{P}_D^{\max}(t) = 3\sigma_{\Delta P}(t) \quad (4.2)$$

where  $\Delta\tilde{P}_D^{\max}(t)$  – maximum error of power demand forecast;

$\sigma_{\Delta P}(t)$  – standard deviation of  $\Delta\tilde{P}_D(t)$ .

In case there is significant wind power penetration in the power system, also the reserve needs for wind power have to be considered. When statistical data of wind power production at specific locations shows that the wind error predictions do not follow normal distribution laws. Instead there are publications showing that the wind power prediction error follows  $\beta$ -distributions [24]. However the large number and the geographical dispersion of the wind power turbines allow the application of the central limit theorem to justify the assumption of normally distributed wind power prediction errors, which is a common practice in the open literature [39-42].

According to [23] the standard deviation for the wind prediction error in case the wind farms are situated over a wide area can be calculated:

$$\sigma_w(t) = \frac{1}{5}G_{WF}(t) + \frac{1}{50}W_C \quad (4.3)$$

where  $G_{WF}(t)$  – wind power forecast;

$W_C$  – installed wind power capacity.

To evaluate the overall error to be covered by reserve the prediction errors of demand and wind power have to be combined. Since these errors are uncorrelated, the standard deviation of the combined error can be calculated:

$$\sigma_{CE}(t) = \sqrt{\sigma_{\Delta P}^2(t) + \sigma_w^2(t)} \quad (4.4)$$

where  $\sigma_{CE}(t)$  – standard deviation of combined prediction error.

Now we assume that the intervals of power demand for primary (i=1), secondary (i=2) and tertiary (i=3) control in the power system are given:

$$\Delta P_{Di}^- \leq \Delta P_{Di} \leq \Delta P_{Di}^+ \quad (4.5)$$

Then, solving the economic dispatch problem between power units, we can find the maximum upwards and downwards reserves for every power unit for primary, secondary and tertiary control. At last the characteristics of regulators must be accommodated with optimality conditions.

In practice solving reserves problems with the use of reserves markets is spreading nowadays [43].

#### **4.2. Generation reserve for enlarged transmission power**

When large amounts of power are being transmitted via relatively weak interconnections between different parts of power system, high enough security margins must be maintained to keep transmission system's state stable during and after disturbances. The classical approach for guaranteeing stable transmission is to set security margin factors for active power and voltage:

$$k_p = \frac{P_{\max} - P - \Delta P}{P} 100\% \quad (4.6)$$

$$k_U = \frac{U - U_{cr}}{U} 100\% \quad (4.7)$$

where  $P_{\max}$  – maximum power corresponding to the steady state stability limit of an interconnection;

$P$  – actual power transmitted through the interconnection;

$\Delta P$  – peak value of irregular power oscillations in the interconnection;

$U$  – actual voltage in the node;

$U_{cr}$  – critical voltage corresponding to the steady state stability limit of given load in the node.

According to current Estonian Grid Code [18],  $k_p$  must be at least 20% in normal operation and 8% in restorative operation while  $k_U$  must be at least 15% in normal operation and 10% in restorative operation. Those values are equal to those used all over IPS/UPS.

The stability limits may not be violated during operation of a system even for a short term. But frequently instead of stability the thermal capacity of the network becomes the limiting factor in power transmission. In other words, the desired power flow in the interconnection is greater than the thermal limit. Power of overload is usually calculated for the initial operating state:

$$P_{ij}^{overload} = P_{ij}^{desired} - P_{ij}^{safe} \quad (4.8)$$

where  $P_{ij}^{desired}$  – power flow through the interconnection resulting from marked needs;

$P_{ij}^{safe}$  – maximal power flow through the interconnection which guarantees resulting power flow after an outage in the network below thermal limit of remaining network elements.

As thermal overload of power lines or transformers is not hazardous during short intervals of time, there is a possibility to use non-instantaneous generating reserves as a remedial action against it. As the most efficient solution, the reserve should be activated in the power system region, which' deficit is causing the overload. However it is often unlikely to find excess reserves in regions that are already importing power or the cost of holding the reserves in those regions turn out to be uneconomical. There is a possibility to use the help of neighbouring systems in a meshed network so that the reserve itself does not necessarily need to be located in the importing power system.

Let us assume that power system  $i$  is importing power and power system  $j$  is exporting it. The interconnection between those power systems may become thermally overloaded if there should occur an outage of an element of the interconnection. To relieve overload on the interconnection, activation of generation reserves is needed. In a meshed network, activation of reserves in power system  $i$  has an effect on the interconnection less than equal to the power of reserve activated. This can be described by effectiveness factor:

$$k_{ij}^{eff(i)} = \frac{P_{ij}^{wo.res(i)} - P_{ij}^{w.res(i)}}{R_i} \quad (4.9)$$

where  $P_{ij}^{wo.res(i)}$  – power flow through the interconnection without the activation of power reserve in power system  $i$ ;

$P_{ij}^{w.res(i)}$  – power flow through the interconnection with the activation of power reserve in power system  $i$ ;

$R_i$  – power reserve activated in power system  $i$ .

Therefore the responsibilities for overloading an interconnection have to be shared between all importing power systems having the effectiveness factor greater than 0 on that particular interconnection. An additional reserve to be kept in power system  $k$  in order to use excess power transmission in interconnection  $ij$  for importing purposes can be calculated:

$$R_{ij}^k = P_{ij}^{overload} k_{ij}^{eff(k)} \quad (4.10)$$

When there is any incentive to locate the reserve to an other power system  $m$ , then the amount of reserve to be held in this other system must be calculated:

$$R_{ij}^m = R_{ij}^k \frac{k_{ij}^{eff(k)}}{k_{ij}^{eff(m)}} \quad (4.11)$$

With this approach it is possible to utilize higher transmission capacities given to market participants for hourly energy trading between different areas. Higher utilization of existing power lines helps to integrate market areas more strongly stimulating more efficient usage of primary energy sources as well as avoiding excessive investments in transmission infrastructure.

## CONCLUSIONS

### 1. General considerations

The growth of market activity and the increasing share of wind power connected to power systems have brought about the situation where the active power variations in systems are having a noticeable effect on power system reliability and preventive operational measures are more often needed to be taken. Methods that are used to evaluate power system reliability need to be modified in order to adapt to the changing patterns in the behaviour of the system. Also the philosophies used to guarantee sufficient reserves in power system for sustaining power equilibrium in all the operational states, need to be modified.

The aim of the current study was to analyse the active power variations in demand and generation in thermal production based systems and the impacts caused to the system by the growing share of fluctuating power sources. Based on the analysis some recommendations and additional measures against the decrease of reliability were proposed.

The main results of the study work are summarized below:

- 1) The method of analysing power demand and wind power generation processes has been developed.
- 2) Statistical analysis of active power variations has been conducted based on the data measured in Estonian power system after every 2 seconds and after every 5 minutes. Three cases of installed wind power have been used in the study: 35 MW, 750MW and 1500MW. In addition the changes of total net power generation and interchange power changes have been analysed.
- 3) The impact of power variations on the reliability of the power system which is mainly supplied by thermal power plants was analysed and a practical approach for re-evaluating the effect of considerable increase in installed wind power to transmission capacities of interconnectors was proposed
- 4) A method that enables higher utilization of transmission capacities, when the limitations are caused by the thermal overloading of power network elements was proposed based on reallocation of power reserves considering the loading effects of different reserve locations to overloaded lines.

### 2. Analysis of power changes

It can be seen from the analysis that a power system with majority of its electricity being produced by conventional power plants has noticeably less power changes in generation and interchange values than a system with large amount of installed wind power. The electric power system of an independent country that normally works as a part of interconnected power system must also be able to operate as an isolated power system. Power systems where active power balance is

regulated by oil-shale condensing thermal power plants like in Estonian power system can operate as an isolated power system only if the wind power connected to the grid is sufficiently small or significant curtailments in wind power generation have been conducted.

From the analysis performed for Estonian power system the following conclusions can be drawn:

- 1) For installed wind power below 8–10% of system peak load the effect on the control of the system is within tolerable limits. With wind power penetration over this limit the operation would require measures to be taken such as frequent utilisation of secondary power regulation by thermal power plants and frequent starting and stopping of thermal units.
- 2) With installed wind power reaching 50% of peak load, the fast variations of power would be more than doubled calling for enlarged instantaneous reserves. Also the isolated operation of Estonian power system would not be feasible with the combination of wind and oil-shale thermal power because of limited operating ranges of oil-shale PP-s.

### 3. Main results from reliability analysis:

- 1) The analysis of reliability indices in probabilistic forms is very sensitive to initial information errors. Therefore it is advisable that the power system reliability evaluation should be based on the uncertain probabilistic and fuzzy probabilistic approach also shortly described in this paper.
- 2) If the amount of installed wind power in Estonia would be at a comparable size to the peak load, then the net transmission capacities of Estonian interconnectors towards Russia and Latvia should be reduced by several hundreds of megawatts in order to keep the reliability of transmission on the same level.

### 4. Main results from the planning of control reserves:

- 1) Four approaches of optimization of operating reserves in power systems were presented.
- 2) A method for enabling higher utilization of transmission capacities was proposed which takes advantage of the short overload ability of power lines. The method is based on reallocation of power reserves considering the loading effects of different locations to overloaded lines.

### 5. Further studies

The possibilities of using wind power units in power systems where active power balance is regulated by thermal power plants are comparatively limited. Considering this there are some areas which need further studying:

- 1) Practical methods for determining the optimal limits for wind power integration need to be developed in order to keep the system's total reliability in tolerable limits.
- 2) In addition it is important to develop methods of deciding the optimal structure of power generation for long-term system development plans taking into account the effect of the generation structure to the reliability of power systems and the security of supply.
- 3) There is a need for a widely acknowledged method for assessing the impact of priority access to the network for some types of generation to the long term security of supply.

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## LIST OF PUBLICATIONS

1. M. Valdma, M. Keel, H. Tammoja, **K. Kilk** "Reliability of electric power generation in power systems with thermal and wind power plants", Oil Shale, 2007, Vol. 24, No. 2 Special, pp. 197–208
2. M. Keel, **K. Kilk**, M. Valdma "Analysis of power demand and wind power changes in power systems", Oil Shale, 2009, Vol. 26, No. 3 special, pp. 228–242
3. **K. Kilk**, M.Valdma "Determination of optimal operating reserves in power systems", Oil Shale, 2009, Vol. 26, No. 3 Special, pp. 220–227
4. **K. Kilk** "Congestion management and existing bottlenecks in Estonia", Mini-fora "European Electricity Regulatory Mini-Forum on Congestion Management", Public Utilities Commission of Latvia, 13-14.02.2005.
5. J. Ojangu, **K. Kilk** "20-110 kV network development plan for Saaremaa", 2nd International Symposium „Topical Problems of Education in the Field of Electrical and Power Engineering“ Tallinn University of Technology, January 17 – 22, 2005

## **ABSTRACT**

### **Variations of Power Demand and Wind Power Generation and Their Influence to the Operation of Power Systems**

The aim of the thesis is to study the impact of irregular power changes to the reliable operation of the power system. Power flows in and between different system areas and also power generated by different producers have started to behave in more erratic and unpredictable way due to increasing short term energy market activities and growth of installed capacities of wind power generation.

Livelier energy markets mean that supply sources tend to vary a lot in time thereby causing significant variation in power flows, both direction-wise and volume-wise. This phenomenon puts pressure on the operational control of power system and calls for improvements of methods used to keep the system stable.

The challenge ahead of the operational control of power system deriving from increase in wind power capacities connected to the grid is mostly caused by the fact that wind power is very little controllable, it does not help to follow the demand curve by generation power to keep the real-time balance between demand and supply. The other moment to be considered is that wind production is highly volatile and the fluctuations in wind power production have to be compensated by other types of generation. Depending on the types of other generators available for compensating wind power fluctuations, the capability to do so differs a lot. This thesis aims to study the effect of large-scale wind power to the reliability of a system where dominant share of power is being produced by thermal power plants with steam turbines. As a reference case the power system of Estonia is used as this system has over 90% of its current electricity being produced by oil-shale powered thermal condensing type steam units with fairly weak manoeuvrability. Since there exist plans to increase the share of power produced by wind generators in Estonia to the amount that is comparable with the size of the peak load in the country, it needs to be thoroughly studied, what will be the outcome on the system reliability when these plans are realized.

It is shown that the analysis of reliability indices in probabilistic forms is very sensitive to initial information errors and that it is advisable to base the power system reliability evaluation on the uncertain probabilistic and fuzzy probabilistic approach. Also a practical approach for re-evaluating the effect of considerable increase in installed wind power to transmission capacities of interconnectors is proposed.

The reserve management is a major influencing factor to system security. Among other things also the reserve needs need to be reconsidered when there is significant wind penetration to the system. Also a method to allow higher utilization of transmission capacities for energy market purposes, when the limitations are caused by the thermal overloading of power network elements, is proposed here, based on reallocation of power reserves.

## KOKKUVÕTE

### **Elektritarbimise ja tuulegeneraatorite võimsuse muutused ja nende mõju elektrisüsteemi talitlusele**

Käesoleva töö eesmärgiks on uurida ebaregulaarsete aktiivvõimsuse muutuste mõju elektrisüsteemi talitluskindlusele. Võimsusvood elektrisüsteemides ja süsteemide vahel, samuti ka genereerimisvõimsused on hakanud käituma aina etteaimatamatumalt tänu aktiveeruvamatele elektriturude tegutsemistele ja võrkuühendatud tuuleelektrijaamade võimsuse kasvule.

Aktiivsemad elektriturud tähendavad tootmisallikate kasutamise muutumist ajas, mis põhjustavad märgatavaid muutusi energiavoogude suuruses ja suundades. See avaldab survet elektrisüsteemi juhtimisele ja nõuab süsteemi juhtimis-põhimõtete modifitseerimist.

Suuremate tuulevõimsuste liitmine süsteemiga põhjustab elektrisüsteemi juhtimisele väljakutseid eelkõige tänu oma vähesele juhitavusele ja faktile, et tuulest elektri tootmine ei aita jälgida elektritarbimise kõverat hoidmaks süsteemi tootmise ja tarbimise vahelist tasakaalu. Teine asjaolu on, et tuuletoodang on väga muutliku iseloomuga ja tuuleelektrijaamade väljastatava võimsuse fluktuatsioonid tuleb teiste elektrijaamade poolt kompenseerida. Sõltuvalt kompenseerimiseks saadaolevate jaamade tüübist erineb kompenseerimise võime märgatavalt. Käesoleva töö eesmärgiks on uurida mastaapse tuuleenergia mõju elektrisüsteemi talitluskindlusele, kus enamik elektrist on toodetud auruturbiinidega soojus-elektrijaamades. Näidissüsteemina on kasutatud Eesti elektrisüsteemi, kuna üle 90% selle praegusest elektritoodangust on pärit üsnagi madala manööverdamisvõimega põlevkivikütusel töötavatest kondensatsioonielektrijaamadest. Kuna eksisteerivad plaanid suurendada Eesti elektrivõimsust, mis toodetakse tuuleelektrijaamade poolt, sellise suuruseni, mis on võrreldav sisemaise tiputarbimisega, tuleb hoolikalt uurida, kuidas sellised plaanid mõjutavad elektrisüsteemi talitlust.

Töös näidatakse ka, et töökindlusnäitajate analüüs tõenäosuslikus vormis on väga tundlik alginfo puudulikkuse suhtes ja et soovituslik on kasutada töökindlusanalüüsiks ebamäära tõenäosuslikku või määramatut lähenemist. Pakutakse välja praktiline moodus ülekandeliinide lubatavate võimsuste ümberarvutamiseks tuulevõimsuse olulise suurenemise korral.

Võimsusreserv on oluline elektrisüsteemi talitluskindlust mõjutav faktor. Tuulevõimsuse oluline kasv süsteemis nõuab ka reservide määramisel sellega arvestamist. Reservide meetodilise ümberpaigutamisega on mõningatel tingimustel võimalik ka ülekandeliinide kaubanduseks kasutatavat võimsust suurendada, milline praktiline meetod ka välja pakutakse.

## ELULOOKIRJELDUS

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Tallinna Tondiraba Keskkool	1995	keskharidus

### 4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Eesti keel	emakeel
Inglise keel	kõrgtase

Vene keel	kesktase
Soome keel	kesktase

#### 5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
2004	Invicta, Eesti
2002	Fingrid OYJ, Soome
2000	DC Baltija, Läti
1999	Power Technologies Inc., USA

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Töötamise aeg	Tööandja nimetus	Ametikoht
2009...	Elering OÜ	Juhatuseliige
2007-2009	Osaühing Põhivõrk	Juhatuseliige
2004-2007	Osaühing Põhivõrk	Sektorijuhataja
2001-2004	Eesti Energia AS Põhivõrk	Sektorijuhataja
1998-2001	Eesti Energia AS	Insener

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#### 8. Kaitstud lõputööd

Magistritöö: Elektrisüsteemi juhtimiskeskuse ülesannete analüüs

Bakalaureusetöö: Eesti energiasüsteemi talitluse reguleerimise analüüs

## 9. Teadustöö põhisuunad

Energiasüsteemide optimaalne juhtimine, reservide asukoha ning suuruse määramine, süsteemi töökindluse hindamise meetodid.

## CURRICULUM VITAE

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### 4. Language competence/skills (basic, average, fluent skills)

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Estonian	native
English	fluent
Russian	average

Finnish	average
---------	---------

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2004	Invicta, Eesti
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#### 6. Professional employment

Period	Organisation	Position
2009...	Elering OÜ	Member of the board
2007-2009	Osühing Põhivõrk	Member of the board
2004-2007	Osühing Põhivõrk	Head of division
2001-2004	Eesti Energia AS Põhivõrk	Head of division
1998-2001	Eesti Energia AS	Engineer

#### 7. Scientific work

Estonian Science Foundation grant project ETF6762 Application of Fuzzy System Theory in Power System Optimization and Reliability Estimation.

#### 8. Defended thesis

Master thesis: Analysis of the Functions of Power System Control Centre

Bachelor thesis: Analysis of the Regulation of Estonian Power System Operation

9. Main areas of scientific work / Current research topics

Optimal control of electrical power systems, reserve power value and allocation calculation, evaluation criterions and methods for system reliability.



## APPENDIX A

M. Valdma, M. Keel, H. Tammoja, **K. Kilk**. Reliability of electric power generation in power systems with thermal and wind power plants. *Oil Shale*, 2007, Vol. 24, No. 2 Special, pp. 197–208

## RELIABILITY OF ELECTRIC POWER GENERATION IN POWER SYSTEMS WITH THERMAL AND WIND POWER PLANTS

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*The principles of evaluation of the reliability of electric power generation in a power system including thermal and wind power plants are considered in this paper. Besides classical probabilistic models the use of uncertain probabilistic and fuzzy probabilistic models of reliability is recommended. Generation of electric power at wind power plants is treated as a non-stationary stochastic process controllable only to down. The paper presents numerical examples.*

### Introduction

Reliability is a fundamental requirement put to the power systems and their subsystems. Different probabilistic models [1, 2] are used for evaluation of the reliability of power systems. Yet the probabilistic models are not sufficiently general for reliability evaluation. In a power system the failures take place relatively seldom, and the failure-repair cycle changes in very large limits. The questions when a failure occurs and how long it will take to repair are rather uncertain or fuzzy events than probabilistic cases. Therefore also the perspectives of using the uncertain and fuzzy models for evaluation of the power system reliability [3] are studied.

In this paper we will introduce the probability, uncertain probability and fuzzy probability models of reliability and their applications for the analysis of electric power generation reliability. The paper is based on reliability studies of oil shale power plants and units.

The output power of wind power plants is treated as a non-stationary random process. Their reliability from the classical point of view is very low. Some special characteristics are used for describing the availabilities of wind power plants.

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## Probabilistic models

The reliability is regarded as the ability of a system to perform its required function under stated conditions during a given period of time [1]. In the strict conception the reliability is a probability that the system is operating without failures in the time period  $t$ . Let us look at the main probabilistic characteristics of reliability [2–5].

Reliability function  $p(t)$  is a function which expresses the probability that the system will operate without failure in the period  $t$ :

$$p(t) = P\{\tilde{T} < t\}, \quad (1)$$

where  $\tilde{T}$  – period without failures, continuous random variable;  
 $P$  – symbol of probability.

The function  $p(t)$  decreases if  $t$  increases,  $p(t) = 1$  if  $t = 0$ .

Non-reliability function or failure probability function  $q(t)$  is a function which expresses the probability that a failure will happen in the period  $t$ :

$$q(t) = 1 - p(t) \quad (2)$$

Distribution function of time without failure  $F(t)$ :

$$F(t) = P\{\tilde{T} < t\} = q(t). \quad (3)$$

Density function of time without failures  $f(t)$ :

$$f(t) = \frac{\partial F(t)}{\partial t} = \frac{\partial q(t)}{\partial t}. \quad (4)$$

If intensity of failures is constant, the reliability function is the exponential function:

$$p(t) = e^{-\lambda t}, \quad (5)$$

and

$$f(t) = \lambda e^{-\lambda t}, \quad (6)$$

where  $\lambda$  – intensity of failures.

The exponential reliability function  $p(t)$  and distribution function  $F(t)$  of a power unit are shown in Fig. 1.

On the basis of density function we can evaluate the expectation, variance and standard deviation of the period without failures.

Expected period without failure  $\bar{t}$ :

$$\bar{t} = \int_0^{\infty} t \cdot f(t) dt. \quad (7)$$

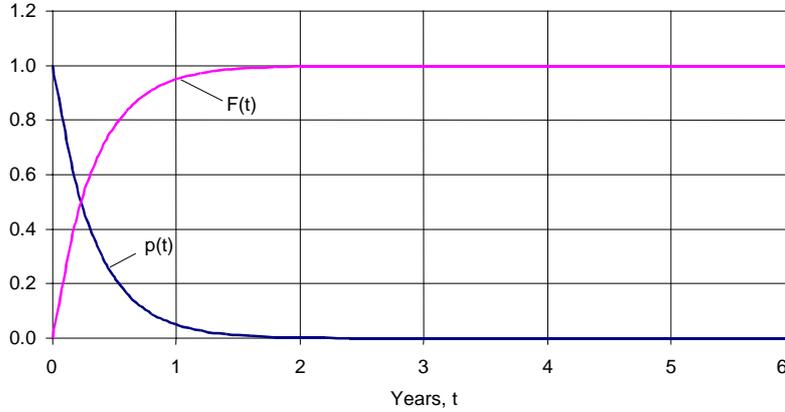


Fig. 1. Reliability function  $p(t)$  and distribution function  $F(t)$  of power unit,  $\lambda = 3$ .

Variance of period without failures, which measures the dispersion of values away from the expected time to failure:

$$D_t = E(t - \bar{t})^2 = \int_0^{\infty} (t - \bar{t})^2 f(t) dt \quad (8)$$

Standard deviation of period without failures:

$$\sigma_t = \sqrt{D_t} \quad (9)$$

In practice the reliability evaluation takes place on the basis of expected failure rate and expected repair rate, or on the basis of mean time to failure and a mean time to repair. According to that the following probabilities [2] are determined:

1) Unavailability (forced outage rate) of object  $q$

$$q = FOR = 1 - p = \frac{\lambda}{\lambda + \mu} = \frac{r}{m + r} \quad (10)$$

2) Availability of object  $p$

$$p = \frac{\mu}{\lambda + \mu} = \frac{m}{m + r} \quad (11)$$

where  $\lambda$  – expected failure rate;  
 $\mu$  – expected repair rate;  
 $m$  – mean time to failure,  $m = 1/\lambda$ ;  
 $r$  – mean time to repair,  $r = 1/\mu$ .

Here the probabilities  $p$  and  $q$  are the corresponding probabilities at some distant time in the future.

Statistical indicators of reliability for power units are often changing within great limits and confidence limits of probabilities are ordinarily very large. This indicates the need to consider uncertain and fuzzy factors in the reliability modeling.

### Uncertain probabilistic models

Uncertain probabilistic models are the probabilistic models, the parameters of which are given by crisp intervals and the values of parameters are uncertainties in those intervals.

If the value of intensity  $\lambda$  is not given exactly, the intensity of failures must be described as an uncertain variable in the crisp interval. Then the reliability function is an uncertain probabilistic function:

$$p(t, \lambda_2(t)) \leq p(t) \leq p(t, \lambda_3(t)) \quad (10)$$

If  $\lambda_2$  and  $\lambda_3$  are constants, we have

$$e^{-\lambda_2 t} \leq p(t) \leq e^{-\lambda_3 t} \quad (11)$$

The exponential reliability function  $p(t)$  and distribution function  $F(t)$  of a power unit in the uncertain form are shown in Fig. 2. The intensity of failures is given by intervals:

$$2 \leq \lambda \leq 3.5. \quad (12)$$

The other characteristics and indicators of reliability in the uncertain probabilistic form can be analogically described.

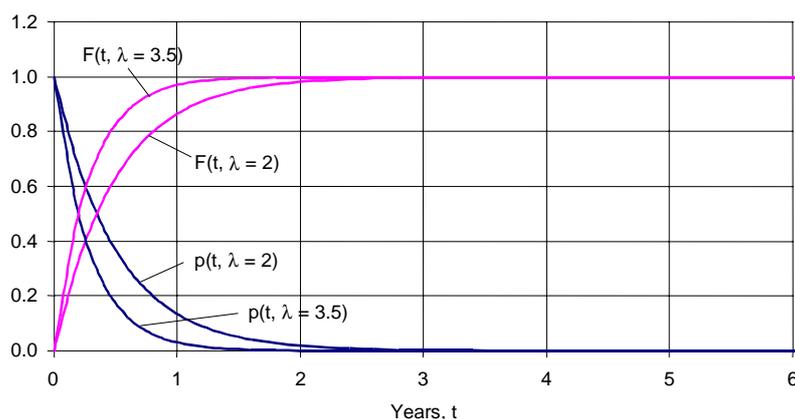


Fig. 2. Reliability function  $p(t)$  and distribution function  $F(t)$  of a power unit in the uncertain form,  $\lambda_2 = 3.5$  and  $\lambda_3 = 2$ .

## Fuzzy probabilistic models

Actually the limits of reliability characteristics are not given exactly. In reality the intervals of reliability characteristics values are fuzzy zones. Consequently we must use the fuzzy probabilistic models of reliability.

The fuzzy probabilistic models are the probabilistic models whose parameters are given by fuzzy intervals.

A fuzzy zone  $\tilde{A}$  is defined in  $U$  as a set of ordered pairs [5]:

$$\tilde{A} = \langle (x, \mu_A(x) | x \in U) \rangle, \quad (13)$$

where  $\mu_A(x)$  is called the membership function, which indicates the degree of that  $x$  belongs to  $\tilde{A}$ . The membership function takes values  $[0, 1]$  and is defined so that  $\mu_A(x) = 1$  if  $x$  is a member of  $\tilde{A}$  and 0 otherwise. At that, if  $0 < \mu(x) < 1$ , the  $x$  may be the member of  $\tilde{A}$ .  $U$  is the given crisp set. The application of fuzzy systems in reliability analysis is nowadays expanding.

A typical membership function of intensity  $\lambda$  is shown in Fig. 3.

Figure 4 shows the exponential reliability function  $p(t)$  and distribution function  $F(t)$  of a power unit in the fuzzy form if the membership function is  $\mu(\lambda)$ .

The other indicators of reliability may be presented in the fuzzy probabilistic form in an analogical way.

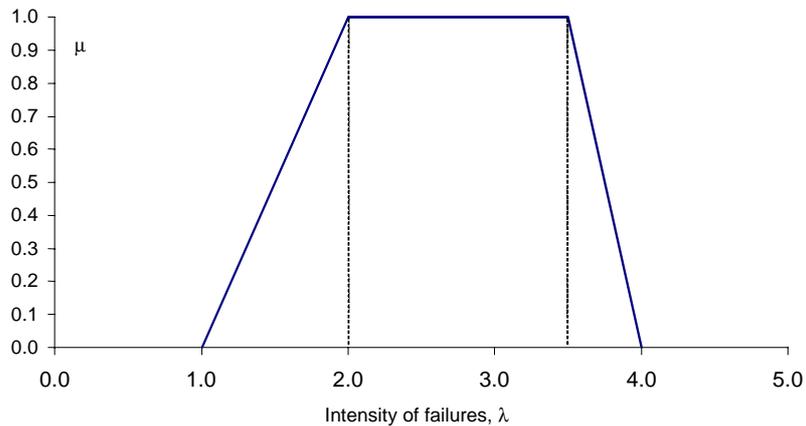


Fig. 3. Membership function  $\mu(\lambda)$ .

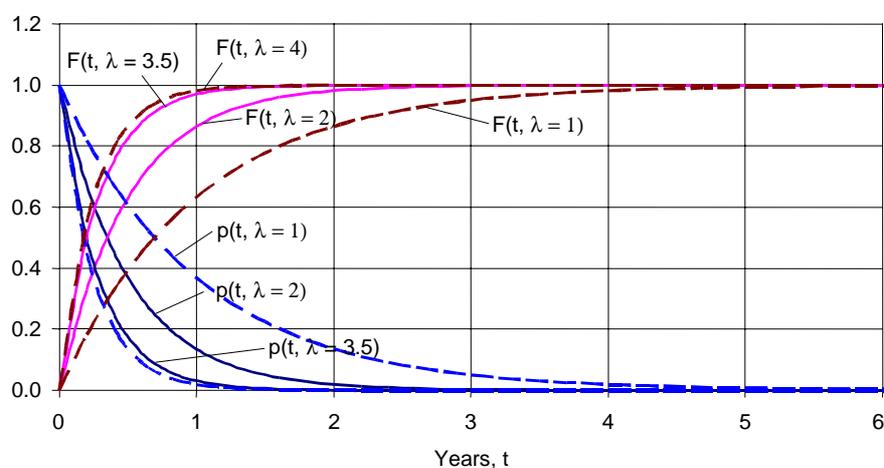


Fig. 4. The reliability function  $p(t)$  and distribution function  $F(t)$  of a power unit in the fuzzy form:  $\lambda_1 = 4.0$ ,  $\lambda_2 = 3.5$ ,  $\lambda_3 = 2.0$  and  $\lambda_4 = 1.0$ .

### Reliability of power units

The models described above were used for reliability analysis of oil shale power plants in the Estonian power system in the years 2000–2005. Power units have two boilers per unit. Capacity of a unit with two boilers is 200 MW, and with one boiler – 100 MW.

The uncertainty intervals of reliability indicators for boilers, turbine, generator and for the whole unit are presented in Table 1.

Table 1 shows that reliability indicators of the unit are changing within rather great intervals. Therefore the limits of intervals are inaccurate.

The probabilistic models of reliability for power system generation in the uncertain probabilistic form are shown in Figures 5 and 6.

Table 1. Intervals of reliability indicators of oil shale power units 200 MW ( $\lambda$  – expected failure rate;  $\mu$  – expected repair rate,  $m$  – mean time to failure,  $m = 1/\lambda$ ;  $r$  – mean time to repair,  $r = 1/\mu$ )

	Boiler	Turbine	Generator	Power unit
$\lambda$	1.40–4.67	1.0–1.5	0.14–0.29	7.71–10.86
$\mu$	73–250	102–190	79–584	138–252
$r$	0.0046–0.0137	0.0052–0.0098	0.0017–0.0127	0.0040–0.0072
$m$	0.2143–0.4286	0.7–1.0	1.75–7.00	0.0921–0.1296
$p$	0.9494–0.9936	0.9863–0.9939	0.9977–0.9993	0.94055–0.96765
$q$	0.0064–0.0506	0.0061–0.0137	0.0007–0.0023	0.03235–0.05945

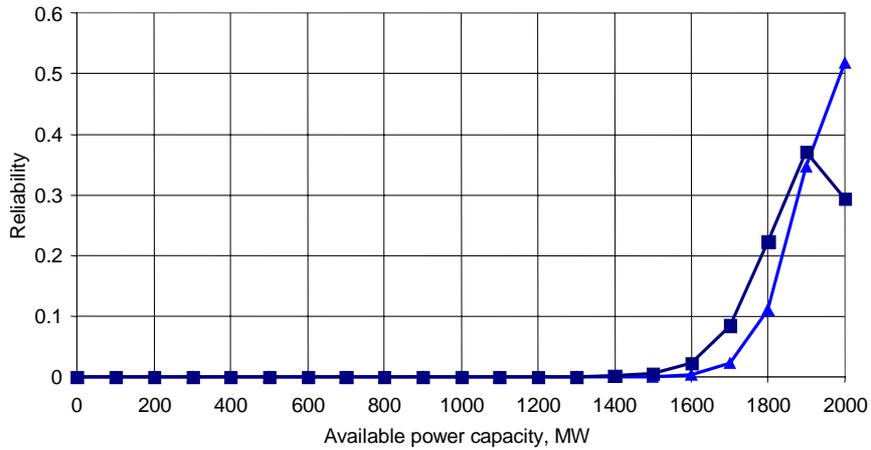


Fig. 5. Uncertain probabilistic model of reliability for a ten-unit electric power system generation.

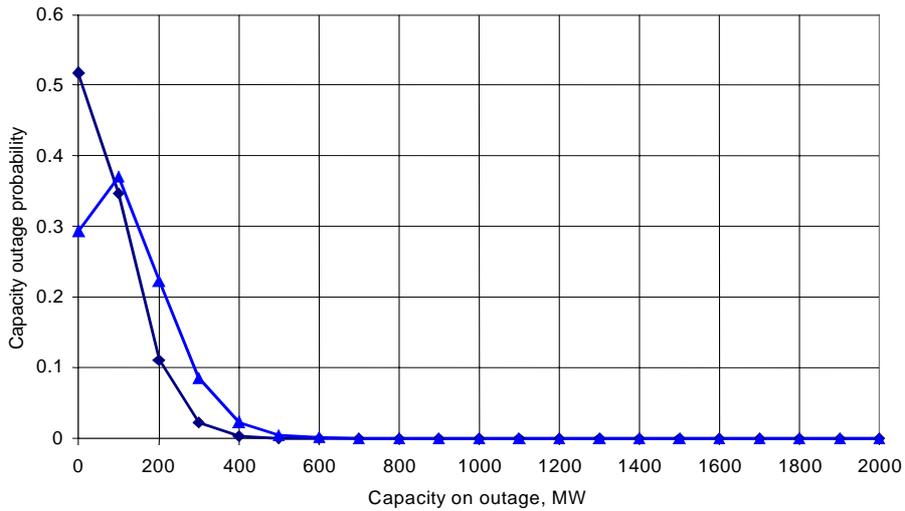


Fig. 6. Zone of uncertainty for probability of capacity outage for a ten-unit power system.

If we consider the inexactness of confidence limits, it would be expedient to present the information about reliabilities and probabilities of failures in the fuzzy probabilistic form.

The information about unit's reliability in the uncertain probabilistic and fuzzy probabilistic forms is presented in Table 2.

The fuzzy probabilistic models of reliability for power system generation in the fuzzy probabilistic form are shown in Figures 7 and 8.

Table 2. Fuzzy intervals for reliability indicators

	Fuzzy essential points			
	$\mu = 0$	$\mu = 1$	$\mu = 1$	$\mu = 0$
$\lambda$	1.57	2.86	7.71	10.86
$r$	0.0039	0.0040	0.0072	0.0090
$m$	0.0921	0.1296	0.3500	0.6364
$p$	0.9406	0.9676	0.9818	0.9938
$q$	0.0062	0.0182	0.0324	0.0594

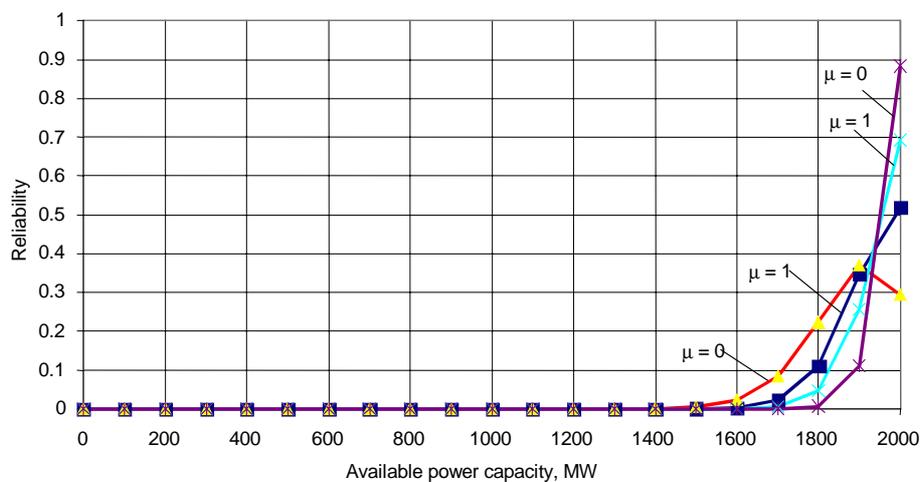


Fig. 7. Fuzzy probabilistic model of reliability for a ten-unit electric power system generation.

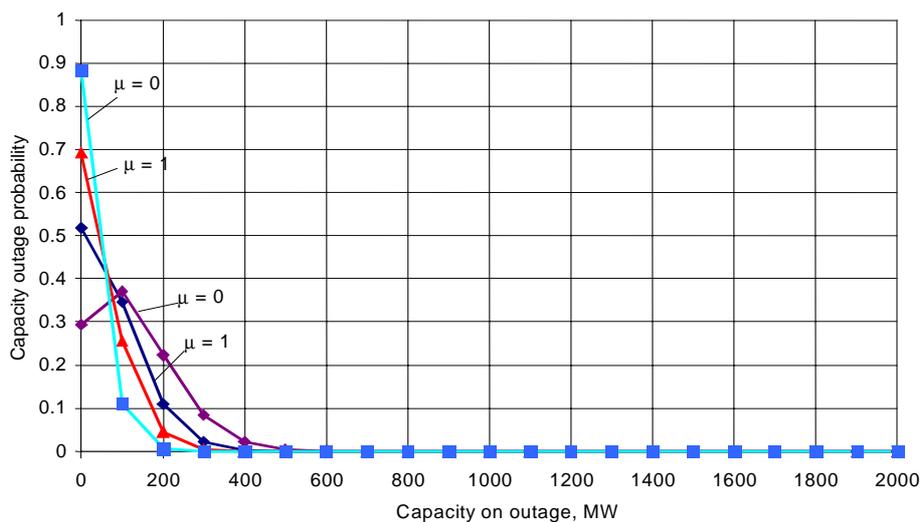


Fig. 8. Fuzzy probabilistic functions of capacity outage for a ten-unit power system.

The fuzzy probabilistic models enable to use exact probabilistic, uncertain probabilistic and fuzzy probabilistic information for describing the reliability characteristics and indicators of units.

### Reliability of wind generators

The usage of wind power plants shows an increasing tendency. With that the problems of wind power plants' reliability and their effect on power system operation are becoming extremely relevant.

Wind speed and power output of wind power plants are random processes. The functions of autocorrelation of wind power show large variations. In [6] the data about short-term power fluctuations of wind power plants is presented. Wind power is controllable only to down and may change every second. Therefore the traditional reliability indicators are not very suitable for wind power plants.

In the case of wind power plants, both the value of power output and the duration of this value are random variables. For approximate description the loads of wind power plants, two-dimensional distribution functions may be recommended:

$$F_{WP}(P(t), \tau(t)) = G(\tilde{P}(t) < P(t)) \cap (\tilde{\tau}(t) < \tau) \quad (14)$$

where  $G$  – probability;

$F_{WP}$  – distribution function of wind power;

$P(t)$  – value of wind power;

$\tau(t)$  – duration of wind power value;

$\tilde{P}(t), \tilde{\tau}(t)$  – random variables.

On the basis of function (14) practical models may be derived for describing and making the prognosis for power outputs of wind power plants.

Figure 9 shows the distribution of wind speed duration at Pakri Wind Park (Estonia), and Figure 10 – the distribution diagram of output power duration for Pakri Wind Park. For comparison the same diagram and distribution function for wind power plants in Denmark is presented in Fig. 11.

The diagrams and distribution functions in Figures 10 and 11 are very similar.

For comparison in Fig. 12 are shown the monthly generation factors  $K$  of Pakri Wind Park and wind power plants of Denmark. The monthly generation factor is:

$$K = \frac{\bar{P}}{P_{\max}},$$

where  $\bar{P}$  – average power output in month;

$P_{\max}$  – peak generation in month.

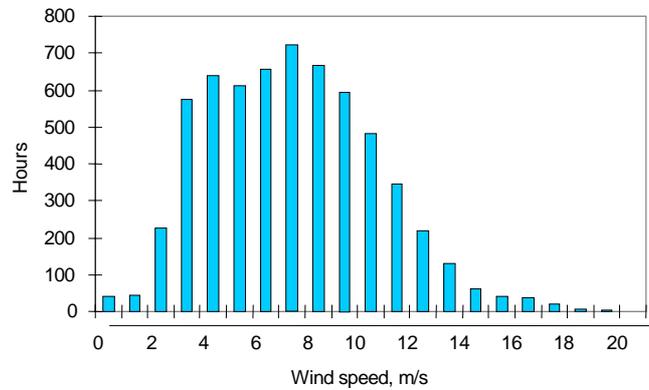


Fig. 9. Distribution diagram of wind speed duration in Pakri Wind Park (IV, 2005 – XII, 2005).

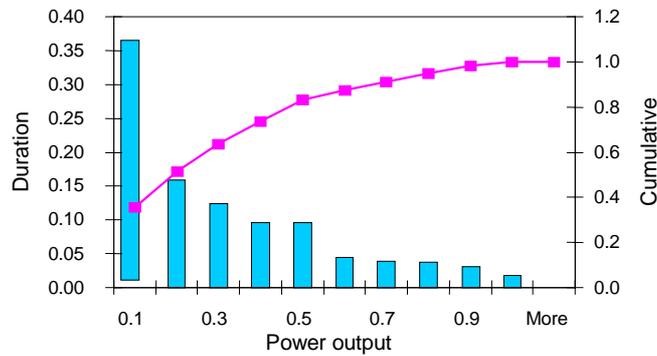


Fig. 10. The distribution diagram and distribution function of power output duration for Pakri Wind Park (2006).

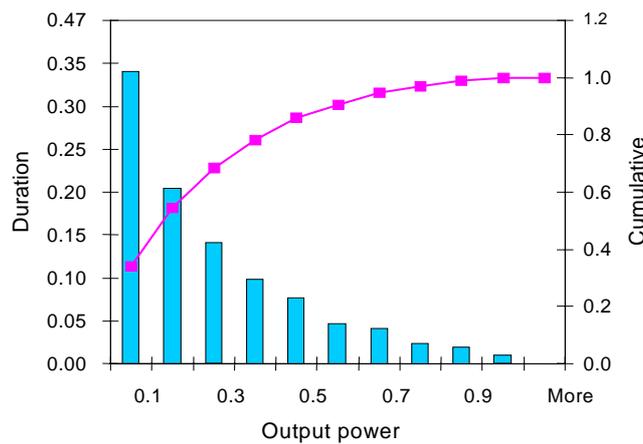


Fig. 11. The distribution diagram and distribution function of power output for wind power plants of Denmark (2006) [7].

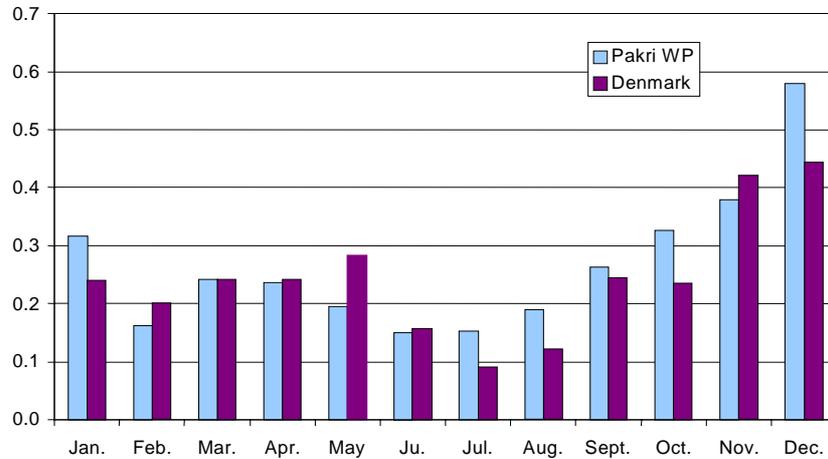


Fig. 12. Monthly generation factors changing in a year for Pakri Wind Park and wind power of Denmark

The average values of monthly generation factors of Pakri Wind Park and wind power plants of Denmark are 0.27 and 0.24.

## Conclusions

1. The use of uncertain probabilistic and fuzzy probabilistic models is a suitable method for the analysis and control of power system reliability, since they are more general and more complete than traditional probabilistic models of reliability.
2. Power generation at wind power plants is a random process. Two-dimensioned distribution functions of power values and power durations can be used for modeling and making prognosis of wind power generation.
3. Uncertain and fuzzy models have also a prospect for modeling wind power generation.

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## ANALYSIS OF POWER DEMAND AND WIND POWER CHANGES IN POWER SYSTEMS

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*In this paper the changes of power demand, power generation of oil-shale thermal power plants, the changes of wind power and interchange power are analysed. The analysis is made on the basis of 2-second and 5-minute data acquired from Estonian power system. From the analysis it is concluded that using of wind power plants in the power systems together with oil-shale power plants is quite limited. If the share of wind power should exceed this limit, notable losses in the ability to regulate power balance and power of oil-shale power plants may be caused.*

### Introduction

The regulation of generated active and reactive power is an important stage of the power system control. A single electric power system must be able to meet the continually changing load demand, non-controllable changing of generating power and transmission losses for active and reactive power. In the interconnected power systems the variation of interchange powers had always to be regulated.

The main parts regulation of power systems' operation are [1]:

1. the frequency and active power control (regulation) (f/P control),
2. the voltage and reactive power control (regulation) (U/Q control).

Especially high requirements are established for the regulation of frequency and active power as from that depend the quality of frequency and adequacy of interchange powers to the agreed values.

Formerly the power plants had to regulate the active power generation mainly correspondingly to the variations of power demand and interchange power. Now, when the application of wind power is increasing, the power systems need much more regulating power. In connection with wind power,

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serious problems of power balance regulation have been arisen in power systems.

The aspects of integrating wind power plants into a power system are thoroughly handled in the book edited by T. Ackermann [2] and in many others publications [3–6 and others]. In the papers [3, 4] it is shown that the balancing of wind power fluctuations with thermal power plants causes an increase in both fuel losses and emissions at thermal power plants. Methods to assess system reliability changes with adding wind power are proposed, and also the ability of wind generators to cover peak power has been investigated in [5]. Unit commitment issues for non-wind generating units have been handled in [6]. Several PhD theses about wind power integration to power systems have also been written [7].

The objects of this paper were:

- 1) to develop the method of analysing power demand and wind power generation processes,
- 2) to analyze comparatively the changes of active power demand and wind power generation,
- 3) to determine controllability requirements for generating power in a power system with thermal power plants,
- 4) to estimate the prospects of integration the wind power into the power system with thermal power plants.

This research is made in the Department of Electrical Power Engineering at Tallinn University of Technology. The analysis is made on the basis of initial data from Estonian power system in 2008.

A dominant share of electric power of Estonian power system is generated by oil shale-fired thermal power plants. During the year 2007 the share of electrical energy generated from oil shale was 94% [8]. In 2008 the installed capacity of oil shale-fired power plants (PP) in the Narva region was 2000 MW, that of gas-fired Iru PP 176 MW, and of small thermal power plants 116 MW [9]. There was only 5 MW of power installed in small hydro power plants, and those are of run-through type with no water reservoirs. The maximum wind power capacity in 2008 was 35 MW. The total installed power in Estonia was 2362 MW, and peak power demand approximately 1500 MW.

Most of the generating units in Narva PP have net production capability ranging from 155 to 165 MW. Two of the units are equipped with modernised boilers and can provide net output power up to 193 MW each. Ramp-up speed of one single oil-shale generating unit is 2.5 MW/min, ramp-down speed 7 MW/min.

The control centre of Estonian power system uses a SCADA system provided by General Electric to acquire telemetry data from power plants and consumers connected to the transmission grid and also from transmission lines and transformers. Most of the data is obtained directly from remote terminal units (RTU) that are located in the substations and belong to Transmission Network. Some measurements are acquired *via* communica-

tion links to client information systems. Data acquisition intervals from SCADA to RTU are 2 seconds, but only changes in the metered value that exceed the preset tolerance limits are transferred and stored in SCADA database. From the metering values the average is calculated for each 5-minute interval, and these values are separately stored.

### Method of analysis

In this paper the following components of active power balance equation are observed:

1. gross load of power system or total power demand with power losses in electrical networks ( $P_D$ ),
2. net load or total net power generation of the traditional power plants (without wind power plant's generation) ( $P_G$ ),
3. total power generation of wind power units ( $P_W$ ),
4. total interchange power with other power systems ( $P_{INT}$ ): if  $P_{INT} > 0$ , the power is exported to other power systems, and if  $P_{INT} < 0$ , the power is imported from other systems.

The changing of these variables represents the complicated random processes. These processes are connected by the active power balance equation of the power system:

$$\tilde{P}_G(t) + \tilde{P}_W(t) - \tilde{P}_D(t) - \tilde{P}_{INT}(t) = 0, \quad (1)$$

where the marks on the symbols mean random character of the process.

The values of processes  $P_G(t)$ ,  $P_W(t)$  and  $P_{INT}(t)$  are measured and  $P_D(t)$  values are calculated on the basis of Eq. (1):

$$P_D(t) = P_G(t) + P_W(t) - P_{INT}(t). \quad (2)$$

All processes were analyzed on the basis of 2-second measurement data and 5-minute mean values calculated on the basis of measurement data of Estonian power system in the period 1/1/2008–5/31/2008. The ranges of initial data for this period are shown in Table 1.

**Table 1. Ranges of initial data**

Process	Minimal value, MW	Maximal value, MW	Mean value, MW
$\tilde{P}_D(t)$	652	1707	1142
$\tilde{P}_G(t)$	582	1904	1171
$\tilde{P}_{INT}(t)$	-550	265	-197
$\tilde{P}_W(t)$	0	35	10.5

Since the share of wind power in Estonian power system is nowadays relatively small, in addition to the real case some fictional cases with enlarged part of wind power were analyzed:

- |                         |   |                                |
|-------------------------|---|--------------------------------|
| Case A (Real situation) | – | $P_W^{Max} = 35 \text{ MW};$   |
| Case B                  | – | $P_W^{Max} = 750 \text{ MW};$  |
| Case C                  | – | $P_W^{Max} = 1500 \text{ MW}.$ |

The initial data for cases B and C about  $\tilde{P}_W(t)$  were obtained by the linear extrapolation of real data (case A).

In mathematical sense the analysis consisted of the following main steps:

1. Intra-hour changes were analysed on the basis of 2-second measurement data. Analysis processes during the longer periods (day, week, month and year) are made on the basis of 5-minute data.
2. Calculation of histograms, mathematical expectations, variances (dispersions), standard deviations, mutual correlation coefficients and their confidence limits for analysed processes.
3. Calculation the functions of autocorrelation (autocovariation) for deviations of processes.

The variances, standard deviations, correlation coefficients and autocorrelation functions of processes were calculated assuming that fluctuations in processes are stationary processes:

- Variance  $DP$ :

$$DP = E(P(t) - EP)^2, \quad (3)$$

where  $E$  – means mathematical expectation.

- Standard deviation  $\sigma_p$ :

$$\sigma_p = \sqrt{DP}. \quad (4)$$

- Correlation coefficient  $r(P_D, P_W)$ :

$$r(P_D, P_W) = \frac{C(P_D, P_W)}{\sigma_{PD} \cdot \sigma_W}, \quad (5)$$

where

$$C(P_D, P_W) = E[(P_D - EP_D)(P_W - EP_W)]. \quad (6)$$

- Autocorrelation function

$$C_p(\tau) = E[(P(t) - EP) \cdot (P(t + \tau) - EP)]. \quad (7)$$

- Normed autocorrelation function  $r(\tau)$ :

$$r(\tau) = \frac{C_p(\tau)}{\sigma_p^2}. \quad (8)$$

## Results of analysis

### Power demand changes $\tilde{P}_D(t)$

Changing of power demand may be divided into three groups:

1. Very fast and irregular changes with small amplitude ( $\pm (0.1-0.5)\%$ ) and with duration of few seconds.
2. Fast and irregular changes with noticeable amplitude ( $\pm (0.5-1.5)\%$ ) and with duration from some seconds to few minutes.
3. Slow daily changes of loads described by load curves, tables or diagrams.

Power plants do not have to react to the first group of changes. However, they must react to the changes of the second and third group. Automatic frequency and power regulators will react mainly to the changes of the second group. Operation control of generated power consists of five stages:

1. primary control;
2. secondary control;
3. tertiary control;
4. time control;
5. slow control of generation.

The objective of the primary control is to maintain the balance between generation and demand at the minimal deviations of frequency using turbine speed or turbine governors. The secondary control makes use of a centralized automatic generation control, modifying the active power set points of generators in the time-frame of seconds to typically 15 minutes. The secondary control is based on secondary control reserves. The tertiary control is any automatic or manual changing of working points of generators in order to restore secondary control reserve and to optimize the operation of the power system. Time control carries to the accordance the synchronous and astronomical times.

A weekly power demand curve compiled on the basis of five minutes values is shown in Fig. 1. A daily power demand curve is presented in Fig. 2. Both curves are relatively smooth. The ratio of minimal load to maximum load is usually in interval 0.4–0.7.

The intra-hour changes of load demand are usually 0.2–0.4% of momentary load calculated from deviations between 5-minute measurements. A typical histogram of intra-hour load fluctuations in Estonian power system is shown in Fig. 3. Distribution of fluctuations is similar to a normal distribution.

The functions of autocorrelation, calculated for load deviation processes, damp within 4–6 hours (Fig. 4). The standard deviation of intra-hour load demand power changes is mostly in the range of 2–5%.

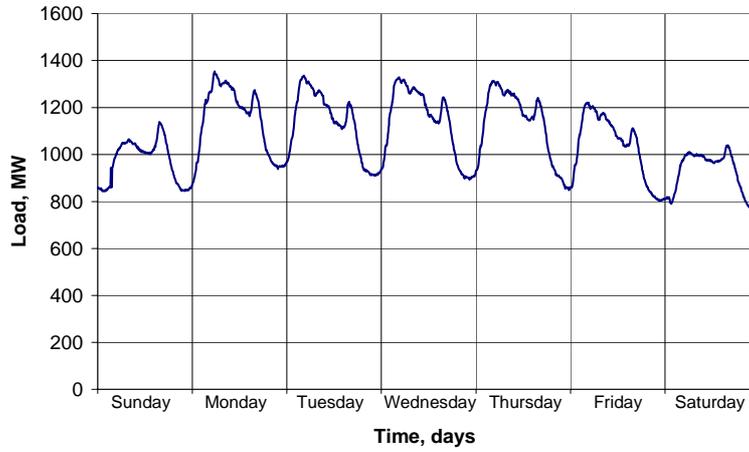


Fig. 1. Weekly load demand curve (3/30/2008–4/5/2008).

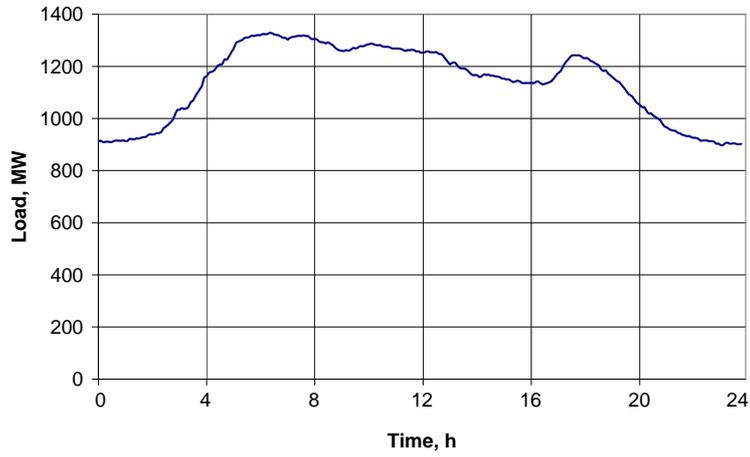


Fig. 2. A daily load demand curve  $\tilde{P}_D(t)$  (4/2/2008).

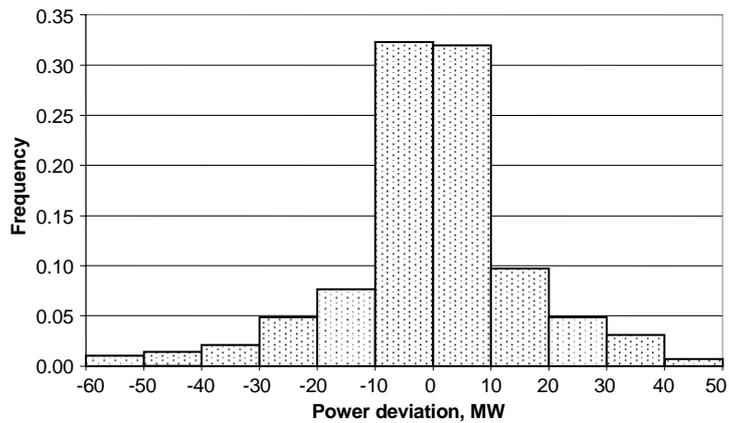


Fig. 3. A histogram of intra-hour load deviations (1/1/2008–5/31/2008).

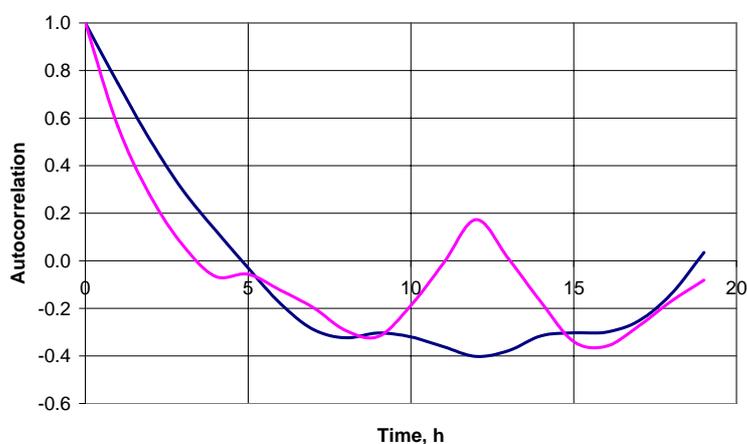


Fig. 4. Autocorrelation functions of power demand ( $r(\tau)$ ).

### Wind power changes $\tilde{P}_w(t)$

The generation of wind power plants depends approximately of wind's speed in the third degree. At the changeful wind the generation of wind power plants may be changing very quickly from zero up to the maximum power. Wind power plants may be stopped several times in a hour. But sometimes the changes of wind power may be smaller than power demand changes. The typical changes of wind power in a spring week are shown in Fig. 5.

A typical histogram of wind power generation is presented in Fig. 6.

More exact data about wind power plants (WPP) generation histogram are presented in Table 2.

These months were relatively windy. Five month average generation of wind power plants was 10.6 MW or 30% of total wind power capacity, and

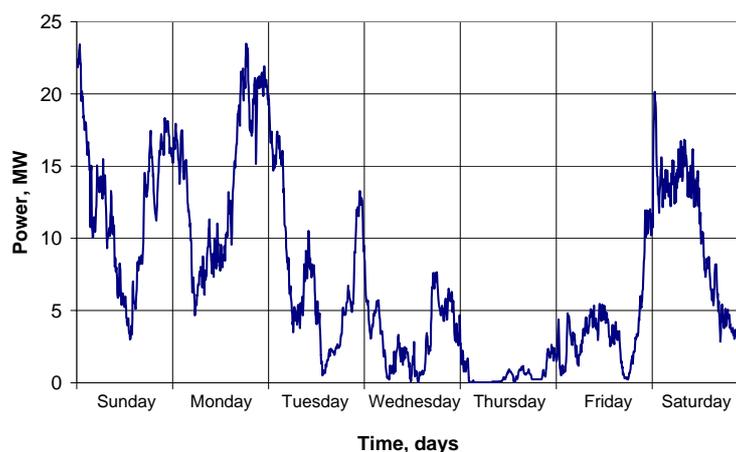


Fig. 5. Wind power generation curve internal a spring week (3/30/2008–4/5/2008).

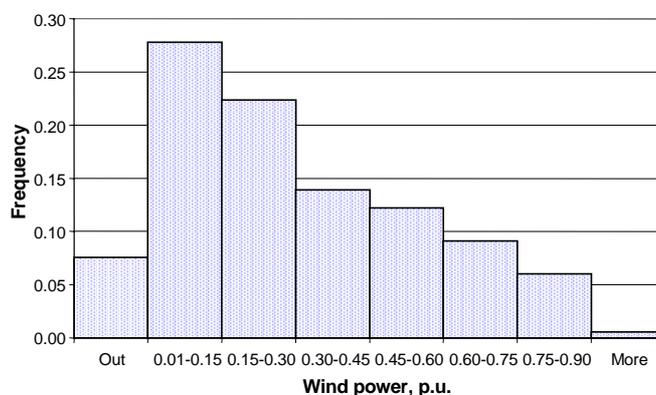


Fig. 6. Histogram of wind power generation (1/1/2008–5/31/2008).

Table 2. Distribution series of WPP (1/1/2008–5/31/2008)

Load intervals, pu $EP_W = 10.6$ MW $\sigma_{PW} = 8.7$ MW	Load intervals, MW	Total hours per interval	Statistic frequency
< 0.01 (WPP OFF)	< 0.5 (WPP OFF)	275	0.08
0.01–0.15	0.5–5.2	1013	0.28
0.15–0.30	5.2–10.5	816	0.22
0.30–0.45	10.5–15.7	506	0.14
0.45–0.60	15.7–21.0	445	0.12
0.60–0.75	21.0–26.2	332	0.09
0.75–0.90	26.2–31.4	237	0.06
>0.90	>31.4	19	0.01

standard deviation was 8.7 MW or 82% of average generation. From day to day these parameters may change within a wide range.

All wind power plants were off over 275 h (nearly 11.5 days). The law of probability distribution of wind power generation is asymmetric (skewness is positive).

By extrapolating real data of wind power generation (Case A), the data of wind power generation for the cases B and C was obtained.

Case B:  $P_W^+ = 750$  MW,  $EP_W = 225$  MW,  $\sigma_{PW} = 185$  MW.

Case C:  $P_W^+ = 1500$  MW,  $EP_W = 450$  MW,  $\sigma_{PW} = 369$  MW.

Thus on the occasion of large wind power parks the changes of wind power generation may be very large and fast.

For system aggregated wind power changes it is also important what is the geographical distribution of wind farms. According to [6] power changes of one single wind farm can reach up to 50–60% of installed power per hour. For several wind parks distributed over an area bigger than 200×200 km the hourly variations should not exceed 30%. According to [6] the correlation

for wind production between parks is strong for parks closer than 100 km to each other and weak for parks over 200 km apart. The analysis of correlation based on Estonian data confirms this only partially. The correlation factor for Pakri and Rõuste wind parks was calculated to be 0.79 with the distance being 87 km between those two parks. For the time period analysed there were no wind parks more apart from each other to analyse the weakening of correlation by growing distance between the parks.

### Power generation changes $\tilde{P}_G(t)$

We consider the power generation changes in the isolated power system with condensing oil shale electric power plants. The load of power units is controllable in the interval from 50 to 100%. Without wind power plants:

$$P_G(t) = P_D(t), \quad (9)$$

$$D_{PG} = D_{PD}. \quad (10)$$

The condensing thermal power plants are regulating active power balance and frequency. The processes  $P_G(t)$  and  $P_D(t)$  are strongly correlated ( $C(P_G, P_D) \approx 1$ ).

If there are always wind power plants in the isolated power system, then

$$P_G(t) = P_D(t) - P_W(t), \quad (11)$$

$$DP_G = DP_D + DP_W - 2C(P_D, P_W). \quad (12)$$

The changes of power demand  $P_D(t)$  and wind power generation  $P_W(t)$  are not mutually correlated ( $C(P_D, P_W) \approx 0$ ) [1].

Therefore the variances of power demand and wind power generation will join:

$$DP_G = DP_D + DP_W \quad (13)$$

and

$$\sigma_{PG} = \sqrt{\sigma_{PD}^2 + \sigma_W^2}. \quad (14)$$

Consequently, wind power generation makes the active power balance regulation more complicated and expensive. If there are large wind power parks, the traditional power regulating plants must regulate generation in the great range and fast. Also the great regulating reserves are needed.

Most of the oil-shale fired thermal units have a minimum operating power of approximately 50% of nominal. As daily load variation is usually 35–40% of day's peak load, most of the thermal units' regulating range is already being used to cover load demand changes leaving only 10–15% available for other uses such as fast power reserve for sudden load changes, generation outages and wind power variation. So it can be seen that, on average, if more wind power is installed into the system than 10–15% of

daily peak power, then the control of power system balance will become difficult even considering the slow changes in power only.

Besides the regulating ranges also the ramping speeds of thermal power plants must be considered. According to operational instructions of Narva power plants the nominal gross power up-ramping rate for oil-shale fired power unit is 2.5 MW/min. Resulting from that it can be seen that with 4–10 thermal units in operation which would be needed to cover the load demand during the whole year, the ramp-up rate is ranging from 600–1500 MW/hour. Even in extreme conditions changes of no more than 50–60% of total installed wind power occur [9]. Therefore it can be noted that lack of ramping speed of thermal plants would not become the first limiting factor for wind power integration.

Figure 7 shows how the thermal power plants must regulate power balance in the isolated power system at the cases A, B and C.

In the case A, the part of wind power is very small (35 MW), and thermal power plants are working by relatively uniform load curve (Fig. 7, blue curve) and they cope well with balance regulation. In the case B, the part of wind power is much greater (750 MW). Now thermal power plants must work by the red curve (Fig. 7). Oil shale power plants are not able to cope with such operation having limited operating range. Therefore the power system can operate in isolated state only when wind power generation is significantly curtailed. The permitted wind power ranges from close to zero at night's minimum load to 500–600 MW at day's maximum load as thermal plants' minimum operating power limits may not be violated. Periodical stopping of single boilers for night-time would give some rise for nightly permitted wind power, but this would already result in a significant rise in costs of thermal plants.

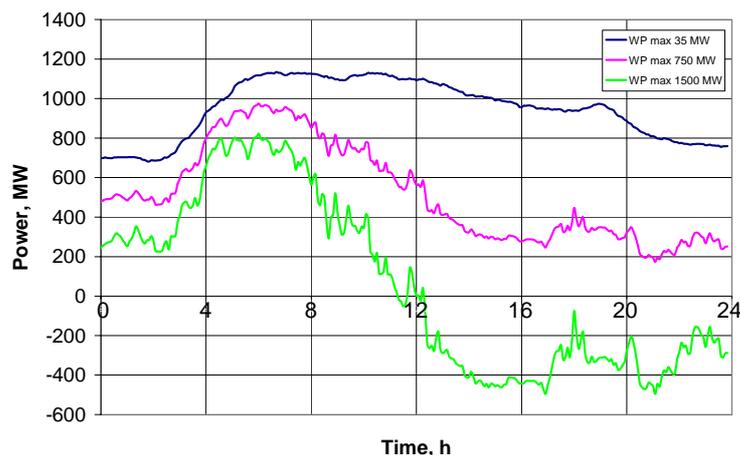


Fig. 7. Total net power generation curves of thermal power plants for different wind power capacity: Case A (blue) –  $P_W^{\max} = 35$  MW, case B (red) –  $P_W^{\max} = 750$  MW and case C (green) –  $P_W^{\max} = 1500$  MW.

Looking at the case C, when  $P_W^{\max} = 1500$  MW (Fig. 7, green curve), we can see that this is even more unfeasible situation and because of similar curtailments as for the case B, even smaller amount of actual installed wind power capacity may be utilized.

This raises the question how much wind power is optimal to install to the power system with thermal power plants. This depends first of all of power demand curves, of regulating capacities, losses and technical restrictions of thermal power units. Proceeding from general considerations the capacity of wind power may be only 5–6% of maximum power of regulating thermal power units. The question if a little more capacity of wind power can be allowed to the single power system with thermal power plants needs a more concrete analysis.

Generally every power system is expected to be able to operate in the isolated state also, as this can occur from time to time for different reasons. Therefore one conclusion from the above analysis can be withdrawn that even if the thermal power-based power system is not operating in the isolated state, there has to be technical readiness for real-time curtailments of wind production in a very wide power spread both from the system operator's side and from wind parks' side.

When the power system is working in an interconnected power system, the situation is different from the case with the isolated system. For instance, one possible approach in an interconnected power system is that the largest power system regulates frequency directly and other power systems regulate their interchange power participating by this indirectly also in frequency regulation. There is even a possibility that every power system does not regulate its own power balance completely, for instance regulating only slow power changes. Then the imbalances caused by fast changes of power like wind power and fast power demand fluctuations must be regulated by other systems resulting that large part of electric energy generated by wind plants in the first power system also goes to other systems. Also the same question of sufficiency and efficiency of regulating power arises in those other systems.

The regulating ranges of hydroelectric power plants are usually close to 100% from nominal power and their regulating losses are much smaller than in thermal power plants. The regulating ranges of thermal power plants with solid fuel are usually only 50% of nominal and regulating losses are significant (10–20%). For that reason the compensation of wind power generation with thermal power units might not decrease but even increase the fuel cost and emissions in the power system [3].

To analyse actions of turbine governors and fast regulation of existing oil shale-fired generators the output power metering values were studied. The metering values acquired at 2 second interval were used. As it can be seen in Fig. 8 the fast power changes of a conventional thermal power unit are very limited reaching up to 1% of nominal power. Therefore it is evident that the power system with a fairly small amount of installed wind power can be controlled with low expenses on fast power regulation.

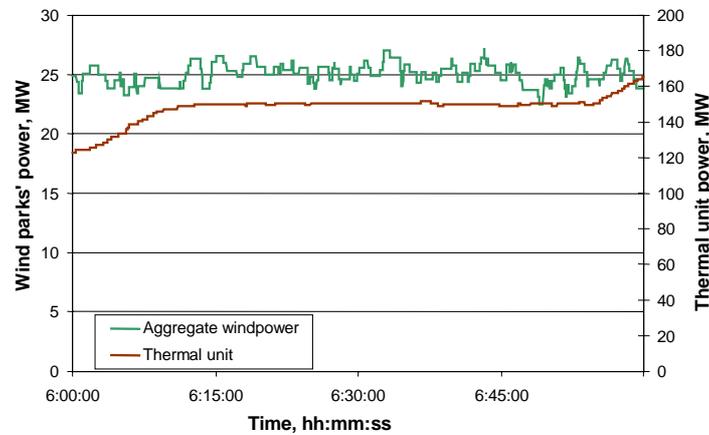


Fig. 8. Thermal power unit's load (right axis) compared to aggregated wind power (left axis) at 2/28/2009 (06:00–07:00).

With larger amounts of wind power penetration to the system, thermal power plants should be able to regulate also fast irregular changes significant enough to activate the secondary control system. For Estonian example such changes should be of an amplitude over 10–15 MW. According to the data analysed for this article, the standard deviation for intra hour wind power deviation based on 1-minute intervals ranges from 2 to 5% of installed wind capacity. Therefore it can be expected that when the power of wind generators exceeds 150 MW, the secondary power controller will start to more often regulate the power interchange by means of changing the output of thermal units.

### Interchange power changes $\tilde{P}_{INT}(t)$

To analyse power systems ability to control power balance of the area, interchange power changes must be looked at. Usually there are set values of maximum deviations in interchange power values which guarantee safe operation of power systems and electricity quality. Those values are a subject of agreement between neighbouring systems and are dependent on power system peculiarities such as interchange transmission capabilities, system sizes and also possibilities to regulate power oscillations. For instance currently parallel operation agreement with neighbouring countries obliges Estonian system to be balanced with area control error less than 30 MW. An example of actual measured interchange and planned interchange of Estonian power system for one week is shown in Fig. 9.

The analysis shows that even in a system without additional power changes caused by substantial wind power penetration there are interchange power changes that exceed allowed tolerances. Standard deviation of deviation between planned and measured interchange for the week illustrated

above was calculated and found to be 28.0 MW. It can be seen that in order to be able to handle the penetration of generation with larger power oscillations some measures have to be taken not to hazard the parallel operation of unified power systems.

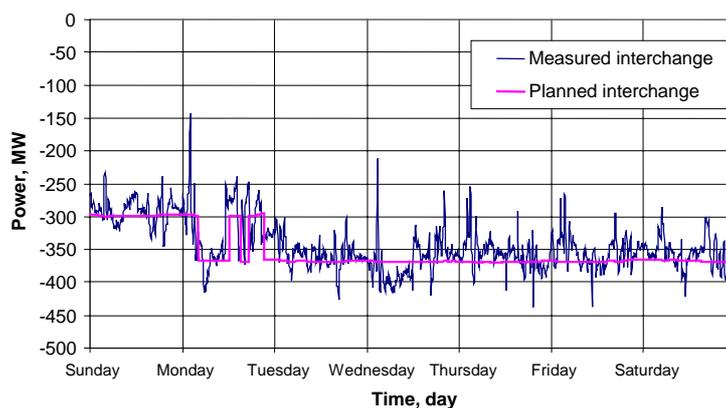


Fig. 9. Planned and measured interchange power curve at 3/30/2008–4/5/2008.

## Conclusions

1. It can be seen by the analysis performed by the authors of this article that a power system with majority of its electricity being produced by conventional power plants has noticeably less power changes in generation and interchange values than the system with a large amount of wind power installed and connected to the system.
2. The electric power system of an independent country that normally works as a part of an interconnected power system must be able to operate also as an isolated power system. Power systems where active power balance is regulated by oil-shale condensing thermal power plants like in Estonian power system can operate as an isolated power system only if the share of wind power generation is sufficiently small (smaller than 5–6% from the maximal power of balance regulating thermal power plants).
3. The presence of wind power plants in an isolated power system increases the power deviations that thermal power plants must regulate. According to [3, 4] with that the losses of regulation will increase (additional fuel consumption) and therefore fuel cost and emissions from thermal power plants might also increase instead of decreasing.
4. With a considerable share of installed wind power (>6%) in isolated power systems, wind power plants' curtailments have to be done in order to enable operation of regulating thermal power units. This reduces the production and efficiency of wind power in power systems.

5. When a power system is interconnected with other power systems, there is a possibility to lead generation of wind power plants to other power systems. At that case the regulating power plants in these power systems must regulate all the wind power changes, absorb most of the wind power production and also suffer the losses of wind power compensation.
6. From the analysis it can be seen also that for installed wind power below 8–10% of the system peak load, the effect on the actual control of the system which has other power generated by thermal plants is within tolerable limits. With wind power penetration over this limit, the operation of a power system requires already quite drastic measures to be taken such as frequent utilisation of secondary power regulation by thermal power plants and frequent starting and stopping of thermal units.
7. It was shown that operational agreements between neighbouring power systems that ensure reliable operation of a unified power system have to be taken into account when planning for the generation composition in each subsystem.
8. The possibilities of using wind power units in power systems where active power balance is regulated by thermal power plants are comparatively limited. The determination of limits for wind power integration depends on several factors and needs concrete feasibility studies.

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## DETERMINATION OF OPTIMAL OPERATING RESERVES IN POWER SYSTEMS

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*The paper is devoted to optimization of reserves and reliability level. The four approaches presented will need deeper scientific research. 1. The sum of reserves' costs and losses of consumers is minimized to the determination of optimal reserves. 2. Two-stage approach: 2.1. The sum of reserves' costs and consumers' losses is minimized to the determination of optimal requirements for reliability, security and supply, 2.2. The sum of reserves' costs is minimized to the determination of optimal reserves subject to the optimal reliability requirements. 3. The sum of reserves' costs is minimized to the determination of optimal reserves subject to the given reliability requirements. 4. Optimization of reserves by the market conditions. The paper also presents the possibilities to utilize higher share of transmission capacity avoiding violation of thermal transmission limits in network elements.*

### Introduction

To maintain reliability and quality of supply of a power system, reserves of active power and reactive power are required. The power systems and interconnected power systems cannot operate without reserves. The operating generating power reserves are needed for compensation of load deviations from prognosticated (expected) values and for covering generation deficit in the case of unexpected outages of power units [1-3].

The control over power systems is a multistage process. For every stage of control adequate reserves are needed. The operating reserves are usually divided into five parts [4]: 1) primary control reserve (available within 10 s), 2) secondary control reserve (available within 30 s), 3) tertiary control reserve (available within 15 min or less), 4) slow scheduling reserve, 5) contingency reserve, including instant reserve, rapid reserve and slow reserves. The reserves must be also in the electrical lines and networks (transmission reserve, stability reserve, distribution reserve, reactive power reserve, etc.).

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The power reserves caused the following kinds of costs in power plants and networks:

- the investment costs for creation of reserves;
- the operational costs bounded with keeping of reserves;
- the operational costs bounded with utilization of reserves.

Reliability and quality of power supply depend on the reserves and together with that the losses of consumers are always bounded with interruption of electricity supply and bad quality of electric energy. Therefore optimization of reserves is very important as for power plants and electrical networks, so for consumers.

Main tasks of planning the reserves are determination of the optimal size and geographical distribution of reserves around the power systems subject to reserves requirement [5]. Insufficient investments to new power sources or unsuitable allocation of reserves decrease the reliability and security of the power system and may lead to the system blackout.

One possibility to allow transmission over network with lesser security margins is to use market based retaliatory measures. The most common of those measures would be countertrade by which System Operator orders up-regulation of some power plants in the region of deficit when incidents in transmission network occur that limit the power transmission capability. The weakness of this method is that it assumes the availability of reserves in necessary regions. However, under market influences only, there is no incentive for market players to keep such reserves.

This paper describes the methods of calculation and optimization of operating reserves in the isolated and interconnected power systems. The paper is an extension of the work [5].

### **Traditional solutions of reserve problem**

There are different principles of determining the needed capacity for operating reserve in different synchronous areas. In the synchronous area of the continental Europe (UCTE area) the requirements for reserve capacities are given separately for the primary reserve and the secondary reserve [4]. The requirement for the primary reserve is given by so-called “reference incident” which needs to be fully covered by primary reserves around the UCTE area. This reference incident is defined as the maximum instantaneous deviation between generation and demand in the synchronous zone by the sudden loss of generation capacity, load shedding or interruption of power exchanges. The reference incident depends on the size of the synchronous zone, the size of the largest generation unit or generation capacity connected to the power system.

The size of the secondary reserve to be held by each country is not precisely defined by UCTE. It can be derived from the defined purpose of the secondary reserve, which is to restore the balance between generation

and demand within each Control Block. Therefore the secondary reserve must cover both the unexpected outages of generation and power demand fluctuations. The part of the secondary reserve related to unexpected outages of generation is equal to the largest generating unit in the Block. It is recommended by UCTE to calculate the reserve for demand fluctuations as a function of system size:

$$R_{\text{sec}} = \sqrt{aL_{\text{max}} + b^2} - b, \quad (1)$$

where  $a$  and  $b$  – empirical parameters established for power system,  
 $L_{\text{max}}$  – maximum load of the Control Block.

Within Control Blocks the secondary reserves may be divided according to agreements between countries.

The size of the tertiary reserve (manual reserve) in UCTE is directly related to the secondary reserve as the purpose of this reserve is to free up the secondary reserve shortly after they are activated.

The planning of operating reserves in Interconnected Power Systems of Baltic countries and Russia (IPS/UPS) takes into account that most of the frequency regulation is done centrally by the Central Dispatching Unit situated in Moscow, and the power plants used for this regulation are hydro plants in the Volga river cascade. Therefore there is no need to have pre-defined primary reserves for frequency regulation in each separate power system of IPS/UPS. The reserve, which needs to be held in each separate power system, is slow reserve with an activation time from 3 to 30 minutes. These reserves are quite identical to the requirements of the tertiary reserves in UCTE system as the activation of them is done mostly manually. Determination of reserve capacity is done separately for load deviations and power plant outages.

## Principles of optimization

The value of reserves may be optimized by different ways:

1. One-stage approach: The sum of reserve costs and losses of consumers associated with non-sufficient reliability and quality of supply is minimized to the determination of optimal reserves in the power systems and interconnected power systems.
2. Two-stage approach: 2.1. The sum of reserve costs and losses of consumers is minimized to the determination of optimal requirements for reliability, security and quality of supply; 2.2. The sum of reserve costs is minimized to the determination of optimal reserves subject to the optimal requirements of reliability, security and quality supply.
3. Partial optimization: The sum of reserve costs is minimized to the determination of optimal reserves subject to the given requirements of reliability, security and quality of supply.

4. Optimization by market relations: Optimization of the reserves in the reserves' market conditions, if the requirements of reliability, security and quality of supply have been agreed.

The methods of reserve optimization on the basis of reserves' costs and losses of consumers have been considered in many works [6 and others]. One-stage approach (Approach 1) to the reserve optimization problems is usually too complicated. Most rational is the two-stage approach (Approach 2), where at the first stage the requirements of reliability, security and quality are optimized and at the second stage the power reserves are optimized if the requirements of reliability (indices of reliability), security and quality conditions are given.

Approaches 3 and 4 are simplified variants. In practice nowadays the solution of reserve problems is obtained mostly by the use of reserve markets [7].

All these approaches are very complicated and important. They are bounded with optimization problems under incomplete information [8-10]. The problems of reserve optimization are in a sense similar to the optimal load distribution and unit commitment problems. However, all approaches appointed above need more deep researches.

At first it is needed to study the reserves optimization problems under probabilistic and uncertain conditions. The most suitable criterion for these problems is minimization of maximal losses or risk caused by incompleteness of information.

Power demand is a non-stationary complicated Markov process with continuous time:

$$\tilde{P}_D(t) = \bar{P}_D(t) + \Delta\tilde{P}_D(t), \quad (2)$$

where  $\bar{P}_D(t)$  – mathematical expectation of power demand;

$\Delta\tilde{P}_D(t)$  – random component of power demand.

We assume that the intervals of power demand for primary ( $i=1$ ), secondary ( $i=2$ ) and tertiary ( $i=3$ ) control in the power system are given:

$$\Delta P_{Di}^- \leq \Delta P_{Di} \leq \Delta P_{Di}^+. \quad (3)$$

Now, solving the economic dispatch problem between power units, we can find the maximum upward and downward reserves for every power unit for primary, secondary and tertiary control. Finally the characteristics of regulators must be accommodated with optimality conditions.

The optimization of reserve utilization, described above, enables to decrease fuel costs and emissions of thermal power plants.

### Location of operating reserves in large systems

Like in the case of the capacity of reserves, there are also different philosophies of determining the location of operating reserve in different synchronous areas. In UCTE area the share of primary operation reserve to be handled by the Control Block  $i$  is determined by the coefficient of contribution. This coefficient is calculated as follows:

$$C_i = \frac{E_i}{E_\Sigma}, \quad (4)$$

where  $E_i$  – annual electrical energy generated in the  $i$ -th Block (including electricity generated for export to outside of the Block);  
 $E_\Sigma$  – annual electrical energy generated in the entire synchronous area.

The distribution of reserve within Control Block is a subject to negotiations between Transmission System Operators (TSO-s) of the Block.

In IPS/UPS the location of reserves is mostly influenced by two different contractual limits to each subsystem – one value for normal operation and another in the case of disturbances (for instance when unexpected power generation outages occur). Therefore each subsystem may count on some system effect to cover its power deficit or surplus. The reserve for the  $i$ -th subsystem can then be calculated:

$$R_{k,i} = \frac{P_{k,i}^{\max}}{P_i^{\max}} \left( P_i^{\max} - \sum_j R_{ji} \right), \quad (5)$$

where  $P_{k,i}^{\max}$  – largest generating unit in the  $k$ -th country of the  $i$ -th Block;  
 $P_i^{\max}$  – largest generating unit in the  $i$ -th Block;  
 $R_{ji}$  – reserve power granted by Block  $j$  to Block  $i$ .

### Generation reserve for enlarged transmission power

When large amounts of power are being transmitted *via* relatively weak interconnections between different parts of a power system, high enough security margins must be maintained to keep transmission system's state stable during and after disturbances. The classical approach for guaranteeing stable transmission is to set security margin factors for active power and voltage:

$$k_p = \frac{P_{\max} - P - \Delta P}{P} 100\% \quad (6)$$

$$k_U = \frac{U - U_{cr}}{U} 100\%, \quad (7)$$

where  $P_{\max}$  – maximum power corresponding to the steady-state stability limit of an interconnection;  
 $P$  – actual value of power transmitted through the interconnection;  
 $\Delta P$  – peak value of irregular power oscillations in the interconnection;  
 $U$  – actual value of voltage in the node;  
 $U_{cr}$  – critical value of voltage corresponding to the steady state stability limit of given load in the node.

According to the current Estonian Grid Code [11],  $k_p$  must be at least 20% in normal operation and 8% in restorative operation, while  $k_U$  must be at least 15% in normal operation and 10% in restorative operation. Those values are equal to those, used all over IPS/UPS.

The stability limits may not be violated during operation of a system even for a short term. But frequently, instead of stability, thermal capacity of the network becomes the limiting factor in power transmission. In other words, the desired power flow in the interconnection is greater than the thermal limit. Power of overload is usually calculated for the initial operating state:

$$P_{ij}^{overload} = P_{ij}^{desired} - P_{ij}^{safe}, \quad (8)$$

where  $P_{ij}^{desired}$  – power flow through the interconnection resulting from marked needs;  
 $P_{ij}^{safe}$  – maximal power flow through the interconnection which guarantees resulting power flow after an outage in the network below thermal limit of remaining network elements.

As thermal overload of power lines or transformers is not hazardous during short intervals of time, there is a possibility to use non-instantaneous generating reserves as a remedial action against it. As a most logical solution, the reserve should be activated in the power system region where the deficit is causing the overload. However it is often unlikely to find excess reserves in regions that are already importing power or the cost of holding the reserves in those regions turn out to be uneconomical. There is a possibility to use the help of neighbouring systems in a meshed network so that the reserve itself does not necessarily need to be located in the importing power system.

Let us assume that power system  $i$  is importing power and power system  $j$  is exporting it. The interconnection between those power systems may become thermally overloaded if there should occur an outage of an element of the interconnection. To relieve overload on the interconnection, activation of generation reserves is needed. In a meshed network, activation of reserves in power system  $i$  affects interconnection less than equal to the power of reserve activated. This can be described by effectiveness factor:

$$k_{ij}^{eff(i)} = \frac{P_{ij}^{wo.res(i)} - P_{ij}^{w.res(i)}}{R_i}, \quad (9)$$

where  $P_{ij}^{wo.res(i)}$  – power flow through the interconnection without the activation of power reserve in power system  $i$ ;  
 $P_{ij}^{w.res(i)}$  – power flow through the interconnection with the activation of power reserve in power system  $i$ ;  
 $R_i$  – power reserve activated in power system  $i$ .

Therefore the responsibilities for overloading an interconnection have to be shared between all importing power systems having the effectiveness factor greater than 0 on that particular interconnection. An additional reserve to be kept in power system  $k$  in order to use excess power transmission in interconnection  $ij$  for importing purposes can be calculated:

$$R_{ij}^k = P_{ij}^{overload} k_{ij}^{eff(k)}. \quad (10)$$

When there is any incentive to locate the reserve to another power system  $m$ , then the amount of reserve to be held in this other system must be calculated:

$$R_{ij}^m = R_{ij}^k \frac{k_{ij}^{eff(k)}}{k_{ij}^{eff(m)}}. \quad (11)$$

## Conclusions

1. The optimization of operating reserves in power systems and in interconnected power systems is an important and complicated problem, which has not received sufficient attention so far.
2. The main attention has to be paid to the four approaches presented in the paper. At that the rational method of optimization of reliability, security and quality of supply and reserves includes the possibilities to take into account deterministic, probabilistic, uncertain and fuzzy information.
3. At planning of operating reserves one always has to take into account the possibilities of short-time overloading of generators and electric lines. There is a possibility to enable higher utilization of transmission capacities, when the limitations are caused by thermal overloading of power network elements.

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