Oil Shale, 2009, Vol. 26, No. 3 special, pp. 228–242
doi: 10.3176/oil.2009.3S.06
ISSN 0208-189X
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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* 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 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:

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

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):

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

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) – $P_W^{Max} = 35$ 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).

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:

$$DP = E(P(t) - EP)^2 , \tag{3}$$

where E – means mathematical expectation.

- Standard deviation σ_P:

$$\sigma_P = \sqrt{DP} . \tag{4}$$

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

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

where

$$C(P_D, P_W) = E\left[(P_D - EP_D)(P_W - EP_W)\right] . \tag{6}$$

- Autocorrelation function

$$C_P(\tau) = E\left[(P(t) - EP) \cdot (P(t+\tau) - EP)\right] . \tag{7}$$

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

$$r(\tau) = \frac{C_P(\tau)}{\sigma_P^2} . \tag{8}$$

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%.

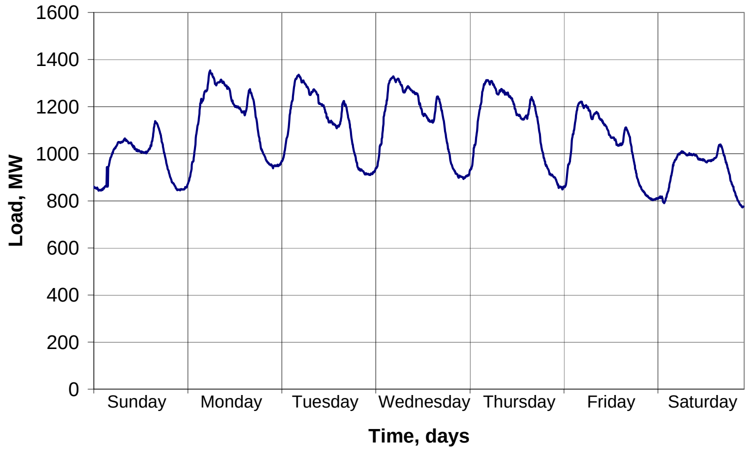

Fig. 1. Weekly load demand curve (3/30/2008–4/5/2008).

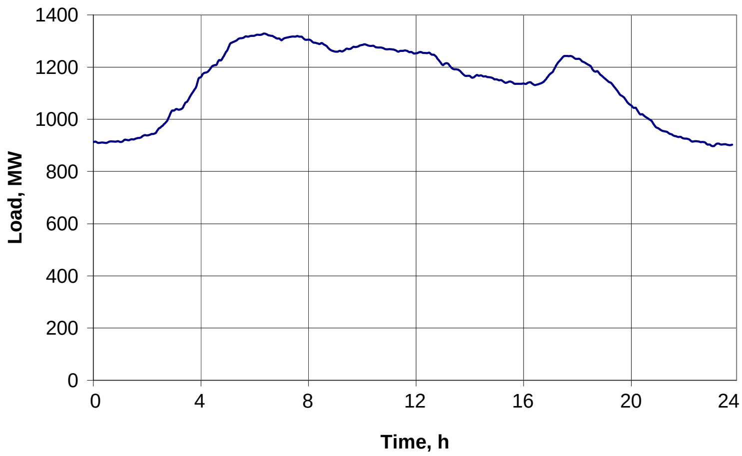

Fig. 2. A daily load demand curve $\tilde{P}_D(t)$ (4/2/2008).

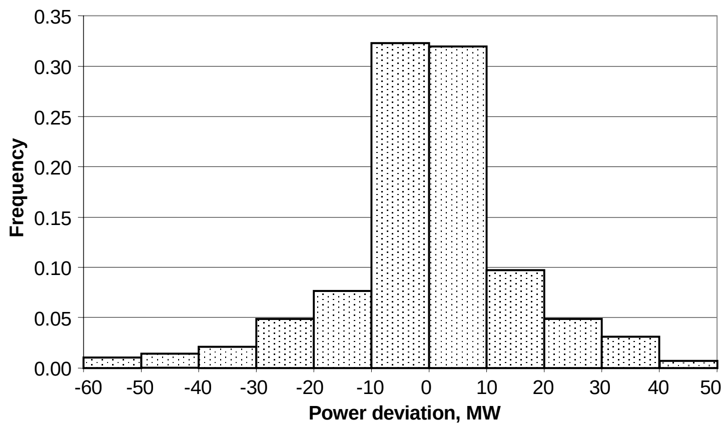

Fig. 3. A histogram of intra-hour load deviations (1/1/2008–5/31/2008).

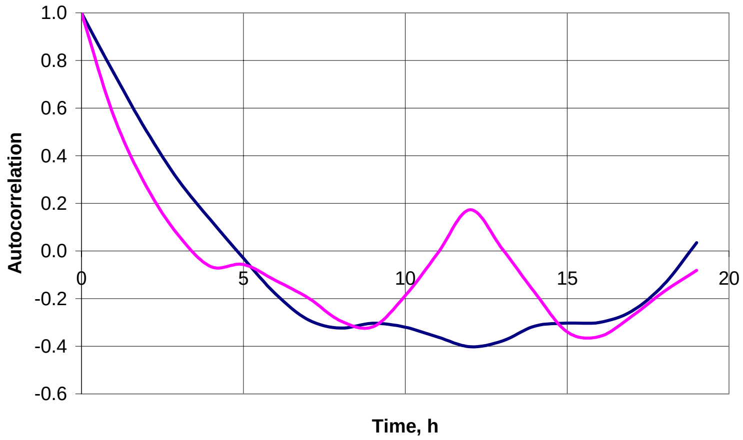

Fig. 4. Autocorrelation functions of power demand ($r(\tau)$).

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

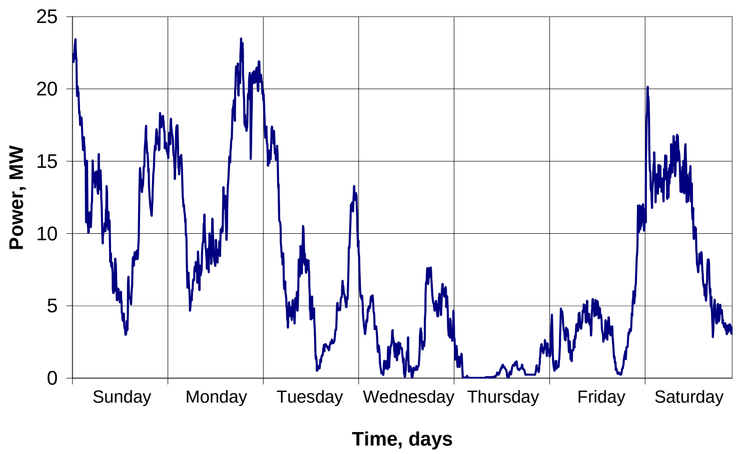

Fig. 5. Wind power generation curve internal a spring week (3/30/2008–4/5/2008).

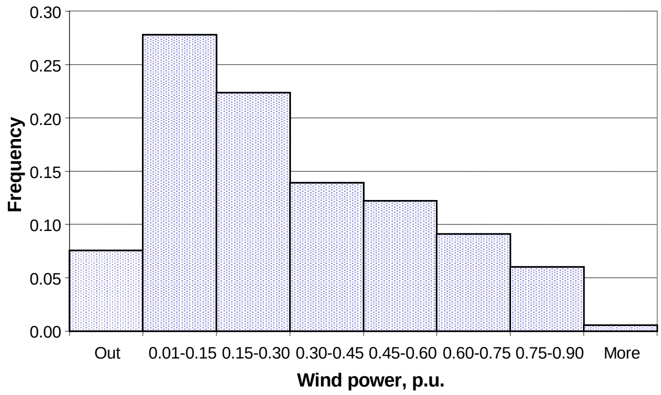

Fig. 6. Histogram of wind power generation (1/1/2008–5/31/2008).

***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:

$$P_G(t) = P_D(t)\,, \tag{9}$$

$$D_{PG} = D_{PD}\,. \tag{10}$$

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

$$P_G(t) = P_D(t) - P_W(t)\,, \tag{11}$$

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

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:

$$DP_G = DP_D + DP_W \tag{13}$$

and

$$\sigma_{PG} = \sqrt{\sigma_{PD}^2 + \sigma_W^2}\,. \tag{14}$$

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.

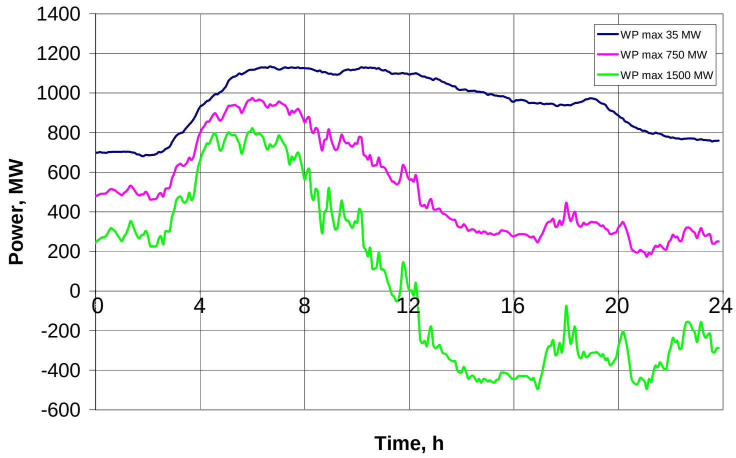

Fig. 7. Total net power generation curves of thermal power plants for different wind power capacity: Case A (blue) – $P_W^{max} = 35$ MW, case B (red) – $P_W^{max} = 750$ MW and case C (green) – $P_W^{max} = 1500$ MW.

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 in 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.

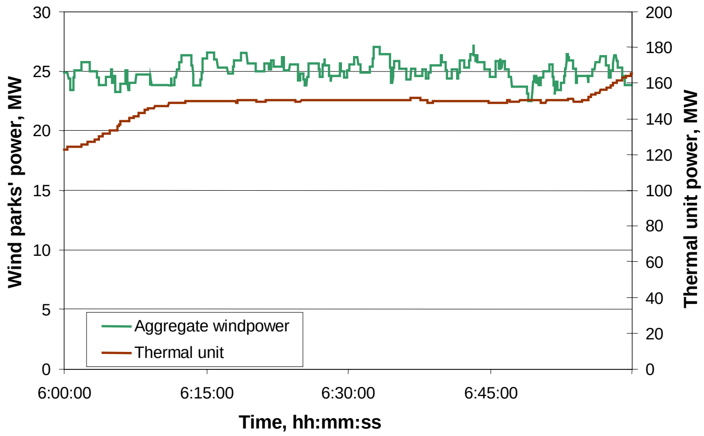

Fig. 8. Thermal power unit's load (right axis) compared to aggregated wind power (left axis) at 2/28/2009 (06:00–07:00).

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.

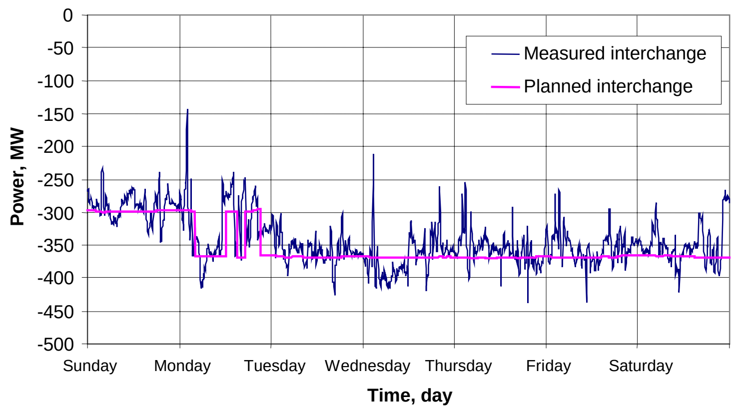

Fig. 9. Planned and measured interchange power curve at 3/30/2008–4/5/2008.

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.

Acknowledgements

Authors thank the Estonian Science Foundation (Grant No. 6762) for financial support of this study.

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Received April 29, 2009