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Impact of Wind Parks on Power System Containing Thermal Power Plants

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TUT PRESS

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

Ivo Palu ……………….

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Tuuleparkide mõju soojuselektrijaamadega energiasüsteemile

IVO PALU

TTÜ KIRJASTUS

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ABBREVIATIONS AND UNITS

AC	Alternating Current
CAES	Compressed Air Energy Storage
CHP	Combined Heat and Power
CO	Carbon Monoxide
EMTDC	Electromagnetic Transients including Direct Current
EU	European Union
EWEA	European Wind Energy Association
FRT	Fault Ride Through
GEPP	Gas Engine Power Plant
GWEC	Global Wind Energy Council
GW	Gigawatt
GWh	Gigawatt hour
HVDC	High Voltage Direct Current
IPS/UPS	Independent Power Systems and Unified Power System
kV	kilovolt
kW	kilowatt
kWh	kilowatt hour
MAPE	Mean Absolute Percentage Error
NO_x	Nitrogen Oxides
PSCAD	Power Systems Computer-Aided Design
p.u.	per unit
RES	Renewable Energy Sources
RMSE	Root Mean Square Error
TSO	Transmission System Operator
TWh	Terawatt hour
THD I	Total Harmonic Distortion of Current
UHC	Unburned Hydro Carbon
WTG	Wind Turbine Generator

Unit prefixes

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

LIST OF ORIGINAL PAPERS

The present doctoral thesis is based on the following publications which are referred to in the text by their Roman numerals I-IV:

I. **Palu, I**., Tammoja, H., Oidram, R. Thermal power plant cooperation with wind turbines. *Estonian J. Engineering*. 2008. Vol. 14, No. 4. Estonia, 317–324 pp.
II. **Palu, I**., Oidram, R., Keel, M., Tammoja, H. Balancing of wind energy using oil-shale based power plants at erroneous wind forecast conditions, *Oil Shale*, Vol. 26, No. 2 Special, 2009, Estonia, 189–199 pp.
III. **Palu, I**., Agabus, H., Oidram, R. "Power quality in weak grids containing wind turbines," *IEEE Power Quality and Supply Reliability Conference 2008*, Pärnu, Tallinn University of Technology, 2008, 125-130 pp. Copyright IEEE
IV. Oidram, R., Landsberg, M., Agabus, H., Attikas, R., Ojangu, J., **Palu, I.** Problems Related to Grid Connection in Pakri Wind Park. In: *Grid Integration and Electrical Systems of Wind Turbines and Wind Farms: Nordic Wind Power Conference*, 22-23 May, 2006, Espoo, Finland. VTT, 4 pp.

In the Appendix A, copies of these publications are included.

Author's own contribution

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

I Ivo Palu is the main author of the paper. He is responsible for literature overview, data collection, and calculations. He had major role in writing.
II Ivo Palu is the main author of the paper. He is responsible for literature overview, data collection, and calculations. He had major role in writing.
III Ivo Palu is the main author of the paper. He carried out the power quality measurements and is responsible for literature overview, data analysis and calculations. He had major role in writing.
IV Ivo Palu participated in writing the paper. He carried out the power quality measurements in wind park and participated in data analysis and calculations. He had minor role in writing.

INTRODUCTION

Since the first power systems were set up hundred years ago, the main fluctuation, with small adaptation, has been the load variation caused by consumer habits. The water flow in hydro power station, usage of coal, oil-shale, gas and other fossil based energy sources in thermal power plants for power generation have been controllable if compared with load variations. During the century, the load predictability and consumption forecasting has improved to tolerable level. The power systems, with long payback times, long planning horizon and large investments are quite expectant to everything new and unproven and need time to overcome its inertia. So far, for all power plants regardless of the fuel used, there has been visible amount of supply and reserves from hours to years depending on the size and type of the power unit.

The intensive use of fossil fuel is leading mankind to situation where energy sources formed during millions of years will be depleted within centuries. The present situation in economy, society and to some extent in science is looking at renewable energy sources as a solution to continue spilling energy consumption day by day. Wind energy is taken to be new and infinite energy source that could spare us from reducing everyday energy consumption. Unfortunately, the reality today is that wind energy can replace energy supplied from conventional sources but not the need for most of their capacity. In case of wind energy, we are predicting the volume and duration of the supply and use it when it is available, not when it is needed.

The impact of wind energy on different power systems depends on the particular power system. Hydro power, on one hand is considered to be a fast regulating and good power source for balancing purposes and on the other hand suitable for covering base load. If we add the renewable label to hydropower, we get system with two renewable energy sources – wind and hydro – that can be mutually beneficial. In countries like Estonia and similar countries where electricity generation is basically based on thermal power plants, the impact of wind energy integration is considerably diverse.

The aim of this thesis is to analyze the capability of fossil fuel power plants to cooperate with wind parks. It is shown that the fuel economy and the reduction of greenhouse gases emissions in the power system consisting of mainly fossil fuel power plants are not proportional to the electricity production of wind turbines. Participation of thermal power plants in the compensation of fluctuating production of wind turbine generators brings up special concerns and with regards to these reduces the expected positive effect of wind energy. In addition to fuel economy analysis the impact of wind turbine generators to power quality in weak distribution grids is investigated. For the first time extensive power quality field measurements on Saaremaa island were made and analyzed. Results are interpreted using *PSCAD/EMTDC* modeling program and as an example of a weak grid Saaremaa is used.

ACKNOWLEDGMENTS

Special thanks to my good colleagues Hannes Agabus, and Jako Kilter for supporting me during preparation of this thesis. We will continue the work that we have started. I would like to show my gratitude to Nordic Energy Research, Estonian Science Foundation and Development Foundation of Tallinn University of Technology for supporting me on my research. My gratitude's for my supervisors' professor Olev Liik, professor Heiki Tammoja and associate professor Rein Oidram for their influence to my studies and contribution in papers and thesis. Also I would like to express my gratefulness to the whole Department of Electrical Power Engineering. For me it was easy to visit you with the question and leave with the lead for an answer.

I would like to acknowledge the importance of professor Olev Liik and associate professor Rein Oidram for leading me to the field of science.

In the end I would like to thank my parents, sister and dearest to me, my family for extraordinary patience and understanding during the critical times. Thank you Anželika, Luise and …

1. WIND ENERGY SITUATION IN THE WORLD, EUROPEAN UNION AND ESTONIA

In the beginning of year 2009, it was acknowledged by Global Wind Energy Council [1] that USA has become the leading country in the amount on installed capacity of wind energy, leaving the former leader Germany as the second and Spain as the third. If China continues to increase installing new wind energy installations (China's total capacity doubled for the fourth year in a row) China would be well on its way to overtake Germany and Spain to reach second place in terms of total wind power capacity in 2010 [1]. It must be instantly reminded that despite of large numbers of wind installations in USA and China, its share from total installed capacity is still modest, but expanding. On the same time, Denmark, as the country with the longest history of modern wind energy, is planning to have 30% of its electricity from renewable energy sources by year 2025 [2] and 50% by year 2050 [3, 4, 5]. At the end of 2006 European Union (EU) set its renewable energy target on 20% from overall energy consumption by year 2020 [6]. The proportion of wind energy could be as high as 14.3% of EU electricity demand according to European Wind Energy Association (EWEA) by year 2020 [7]. This means 180 GW of installed capacity of wind turbines, while in the end of year 2008 the total number in EU was 65 GW and met 4.2% of EU electricity demand [8]. The triple increase should take place within the next 11 years. All this will be integrated to grid already containing conventional power plants, like coal, oil-shale, gas fired power plants or nuclear power plants.

The total installed power generation unit commitment of EU in 2007 is seen on Fig. 1.1.

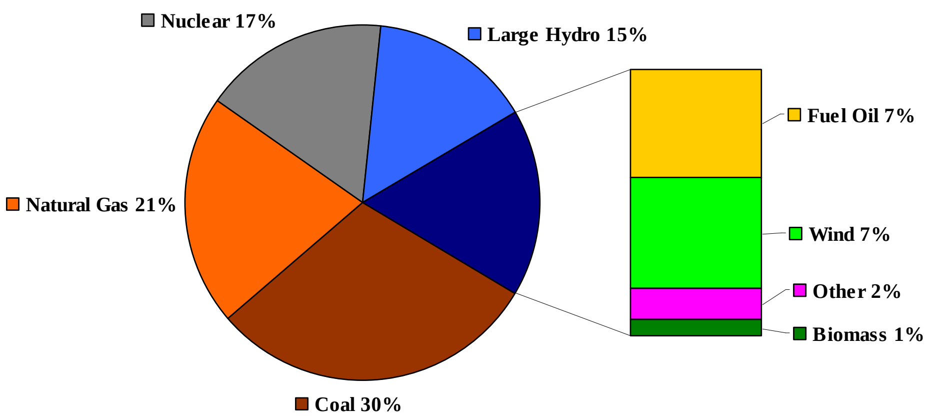

Figure 1.1. EU mix of installed power generation capacity (Total 775 GW) [8]

As indicated by Eurostat [9], the installed capacity of electricity generation plants, as well as the total power generated in the EU increased by 17% in the period from 1996 to 2006 and have been growing in a rather steady rate per year. Overall, in the case of the EU, the bulk of the installed capacity came from thermal power plants, which were accountable for 58% in 2006 with a 15% increase since 1996. In 2006, power generation for the majority of EU countries came mostly from thermal power stations with few exceptions. Between 1996 and 2006 power generation from thermal power stations grew by 19% in EU, while power generation from hydro declined by 5%. However hydro capacity grew by 5% in the last decade but its share in total installed capacity fell. In year 2008 according to [10] 43% of new installations in Europe were wind turbines and only 3% were hydro power plants.

During the negotiations with EU, Estonia set an indicative target for production of electricity from renewable energy sources. The electricity produced from RES must cover at least 5.1% (ca 400 GWh) of the gross inland electricity consumption by 2010. In spite of the availability of remarkable wind potential, only 75 MW of wind capacity was in operation by the end of year 2008 in Estonia. The total energy produced by renewable energy sources in 2008 was 182.4 GWh [11], which is more than 2% of Estonia’s in land energy consumption.

Wind energy projects were infeasible during a long period due to low electricity price and Estonia’s very limited subsidies for wind-generated electricity. Nowadays, the purchasing obligation and feed-in tariffs for electricity from RES have been written into the legislation and construction of wind generators has increased substantially [12, 13]. In the new Market Act, ratified by the Parliament in March 2007 [12], there are provided measures (purchase obligation) for supporting renewable energy. Network operator is obliged to buy electricity with a fixed feed-in tariff (0.074 EUR/kWh) produced from renewable sources within the network it is operating. This has recently caused a peak of interest in wind energy investments.

In the beginning of 2009 the largest wind park with installed capacity of 24 MW is situated in the eastern part of Estonia (Viru-Nigula wind park) [14], Pakri wind park on Pakri peninsula (18,2 MW) [14] and wind park with 13 turbines and 39 MW in total on the western coast of Estonia (Aulepa wind park) [15] is under construction. The overall amount of wind power capacity that is applied for connection is around 5000 MW.

It is a considerably large number compared to overall consumption. Winter peak load in 2007 reached up to 1525 MW and summer minimum was around 450 MW [16]. Consumption forecast, made by Estonian transmission system operator (TSO), is foreseeing winter peak load of 1665 MW for year 2010 according to most probable base scenario and 2016 MW for year 2020. So it is clear that the capacity of planned wind parks is decisively exceeding the foreseen peak demand until year 2020 [17].

2. NATURE OF WIND POWER

2.1. Power in the wind

The veracity of wind power plants is almost uncontrollable due to the fact that their power varies rapidly and frequently within a wide range as their output power is the function of wind velocity in the third power.

$$\text{power in wind} = \frac{1}{2}\rho A V^3 \qquad (3.1)$$

where,

ρ – air density,
A – swept area,
V – wind velocity.

The power in the wind is converted into mechanical rotational energy of the wind turbine rotor which results in a reduced speed in the air mass. The theoretical optimum for utilising the power in the wind by reducing its velocity was first discovered by Betz, in 1926 [18]. According to Betz, the theoretical maximum power that can be extracted from the wind is

$$P_{Betz} = \frac{1}{2}\rho A V^3 C_{PBetz} = \frac{1}{2}\rho A V^3 \cdot 0.59 \qquad (3.2)$$

If all the losses in WTG-s are neglected, the maximum power which can be utilised by wind turbines is still only 59%.

Thus velocity and direction of wind change rapidly with time and in tune with these changes, the power and energy available from the wind also vary. The variations may be short time fluctuation, day-night variation or the seasonal variation. Depictured on Fig. 2.1 are the seasonal wind velocity variations caused by changes in daylight during the year due to earth's tilt and elliptical orbit [19].

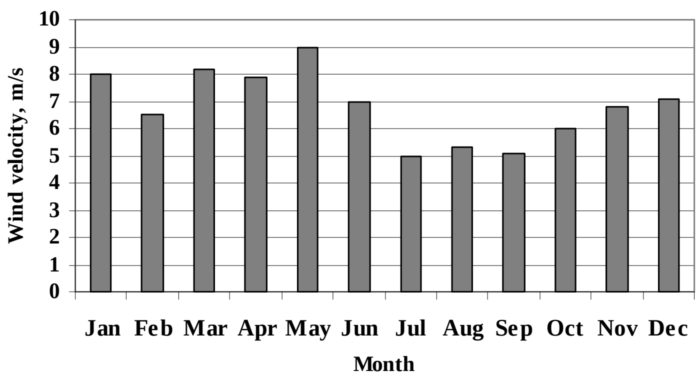

Figure 2.1, Monthly variations of average wind velocity [19]

The wind velocity values on Fig. 2.2 presented as 10 minute and 1 hour averages on top of 90 meter wind turbine [20]. Fig. 2.3 shows the electricity generation fluctuations at the wind park in December 2006 [I].

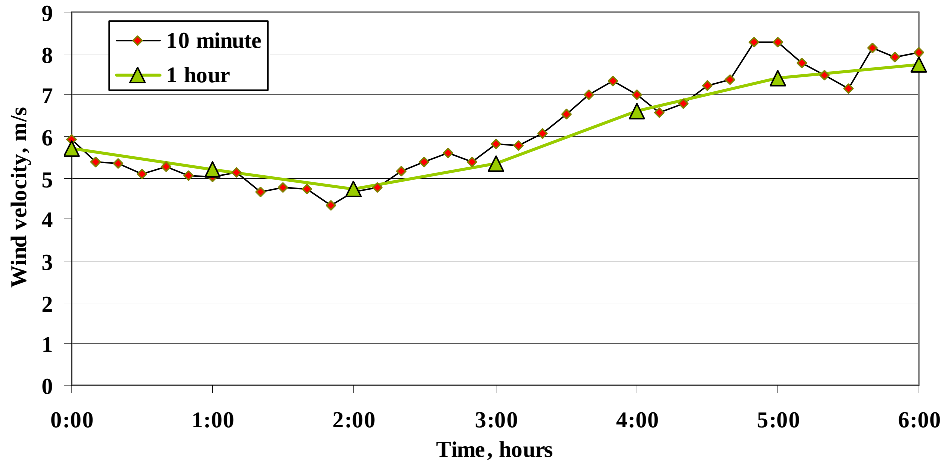

Figure 2.2. Wind velocity variations as 10 minutes and 1 hour averages [20]

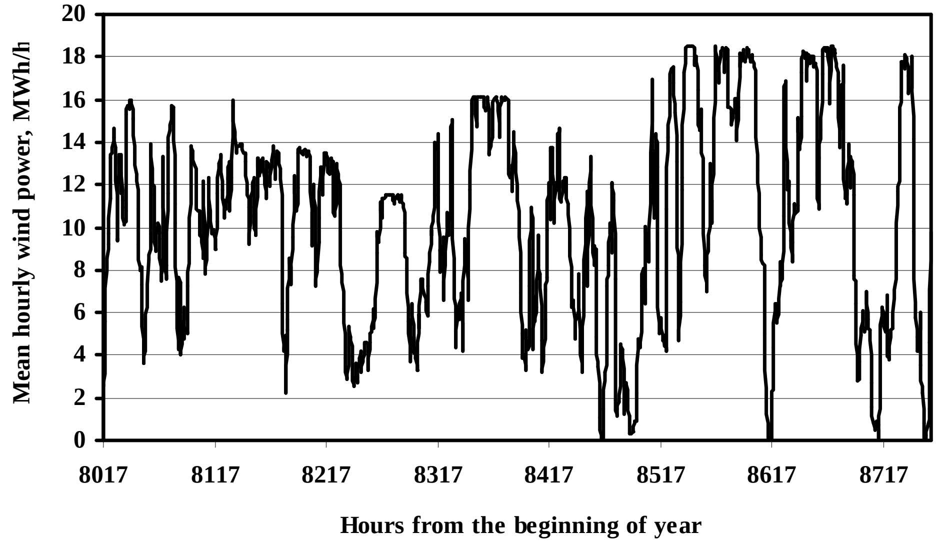

Figure 2.3. Wind Park's electricity generation per hour in December 2006 [I]

Wind velocity at which the rated generator power is reached (rated wind velocity) is approximately 12 to 15 m/s on modern wind turbines. Power curve of 2.3 MW wind turbine is presented on Fig. 2.4.

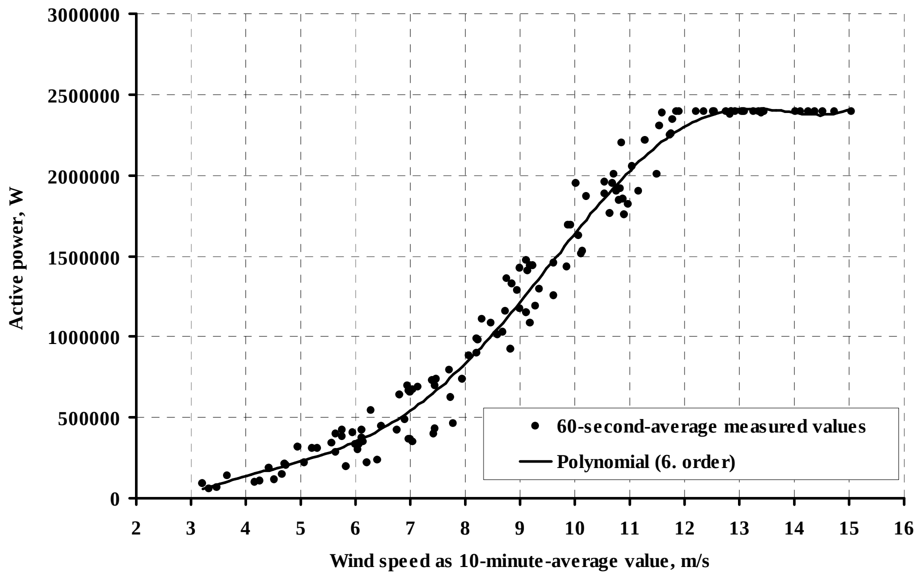

Figure 2.4. Power curve of 2.3 MW wind turbine [20]

When this value is compared to wind velocities on previous figures, we can see that most of the time WTG-s are not operating on rated power and during summer months not even close to that. The latter results in the low capacity factor which is the ratio between mean power production and installed capacity. The low capacity factor depends on wind resources and can be from 0.25 in low wind regions to 0.4 to high wind regions and offshore [18, 22]. On the same time the availability of wind turbines (fraction of time in a year that the wind turbine is able to generate electricity) is relatively high (from 97% to 99%) [23].

The utilisation time in hours per year is defined as

$$\text{utilisation time} = \frac{8760 \cdot \text{annual mean power}}{\text{installed capacity}} \tag{3.3}$$

In general, if the utilisation time is high, the unit is most likely to be operating at rated capacity comparatively often. Compared with base-load power plants, such as coal or nuclear power plants, the utilisation time of wind power plants is lower. This implies that in order to obtain the same energy production from a base-load power plant and wind park, the installed wind park capacity must be significantly larger than the capacity of the base-load power plant [18].

2.2. Wind power fluctuations

At low penetration levels, uncertainties in wind power generation will not have significant impact on power system operation because in this case the wind power can be regarded as a negative load. However, as the share of wind power in the system increases, the system operator needs to have more spinning reserves and dispatchable capacity to handle the fluctuations. This is the present situation in the power system of western Denmark as described in [24]. Massive development of wind parks in the area has resulted in a situation where the system operator is forced to sell exported wind power for a low price. Moreover, the unexpectedly low wind velocities can cause power deficit in the area which has to be covered by imports.

The Danish example referred from [25] reveals the offshore wind park active power fluctuations measured in Horns Rev A in Western Denmark, that the fluctuation can be much more intense than ever seen on the aggregated wind power production on land. The active power of the offshore wind park can change up to 100 MW in 15 to 20 minutes. In part, this can be explained by the large amount of wind power concentrated within a relatively small area (about 25 km^2) resulting in a stronger correlation of power outputs from the turbines in the wind park.

If we take the annual power generation of the wind park and transform it into a histogram, we get the picture seen on Fig. 2.5. Most of the working hours for that wind park were through year in the low generation part and average wind park power output was 4.88 MW which is 27% of installed capacity (18.4 MW).

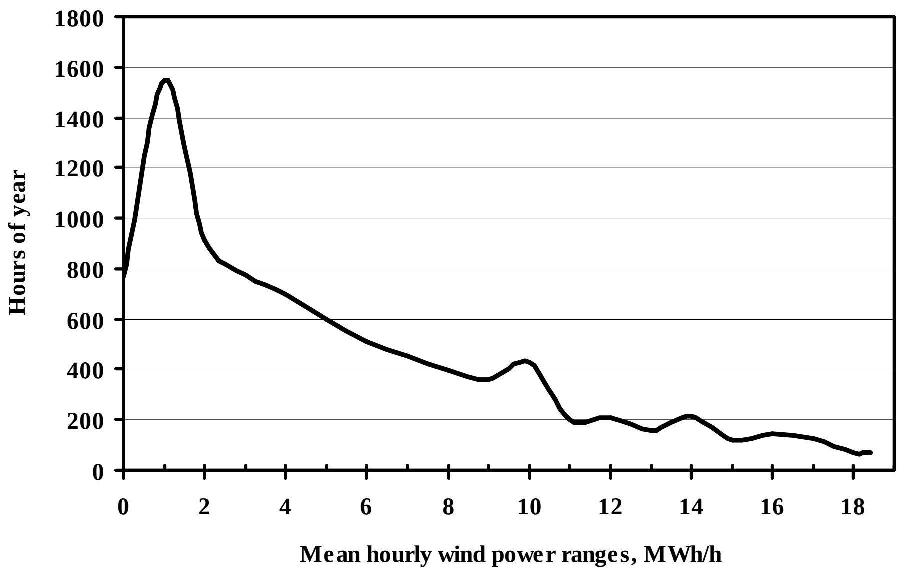

Figure 2.5. Wind park's annual electricity generation distribution [I]

2.3. Wind energy forecasting

Load forecast in the power system is made from several years and months up to hours ahead. If the wind power plant is considered as a conventional power plant, it must have its power generation forecast. Fig. 2.6 shows the hourly power fluctuations and forecast of wind energy. The presented forecast is given daily for the next 24 hours.

Used example for one power system might be exceptional compared to Germany or Denmark as only 50 MW of wind energy is forecasted in whole power system, but on the other hand it describes the patterns of forecasting situation perfectly since similar occurrences are pointed out in publications like [24, 26].

Generally, the root mean square error (RMSE) and the mean absolute error or mean absolute percentage error (MAPE) are the standard concepts for characterising forecast errors. With current tools, the forecast error, represented by the RMSE, for a single wind park is between 10% and 20% of the installed wind power capacity for a forecast horizon of 36 hours [27].

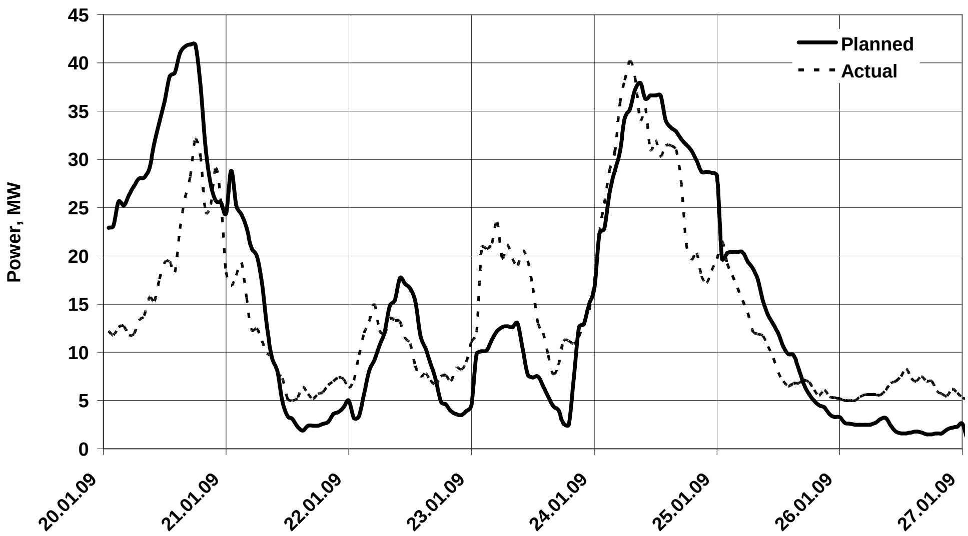

Figure 2.6. Planned and actual generation of wind energy in Estonian power system in January 2009 [11]

Following examples are referred from [18] and [27]:

1. Holttinen calculated the MAPE of wind power prediction to amount to 8–9% of installed capacity for the Nordpool electricity market.
2. Woyte found for different wind turbine sites in Belgium that forecast errors of less than 10% and 20%, occur only 60–70% and 80–90% of the time, respectively.
3. MAPE of the Prediktor system developed by Riso National Laboratory, is around 15% of the installed capacity. The performance of the prediction

model deteriorates very gently, as the error increases during 36 hours by less than 10%.

Wind speed forecasts, however, still remain less accurate than load forecasts given that the latter have more predictable diurnal and seasonal patterns. The uncertainties associated with weather forecasting can probably never be fully eliminated [28].

Review made by Costa *et al*. [29] gives an overview of the short-term prediction and points out further actions needed to improve forecast accuracy.

In Ireland, in 2004 only 80% of all forecasts were made within 85% accuracy and in 6% of cases, wind forecast accuracy was less than 75% [25]. The same report reveals that the maximum hourly change of wind power output was approximately 33% of the total installed wind power generation capacity and during some 15-minute periods the net change of wind generation could exceed 25% of the total installed capacity.

It is safe to conclude that the accuracy of the wind power generation forecast is generally between 10% and 20%, while some errors in high wind might be as large as 35% or more [30, 31, 32]. High quality forecasting of the power output of wind turbines is required for improving the management of the balancing power from traditional power plants.

2.4. Wind power cooperation with power system

Maintaining the capacity balance of the electrical power system and managing the power system in real time is one of the main tasks for the transmission system operator. As load varies, the generation must also vary. Under circumstances where generation starts to fluctuate and load remains constant, the other generation units must compensate it. The latter is the case for large scale wind energy.

As the capacity of the unpredictable sources added into the power system increases, occasions when available power from such sources cannot be used occur. If the penetration is substantial, there might be periods when the available power from renewable energy sources exceeds demand, or cannot be accumulated. However, Ferris and Infield in [33] appoint that even before this stage is reached, energy from variable sources will have to be shed because the power system would need to keep a minimum level of thermal plant generation in order to maintain adequate operating reserve.

Based on different studies made in the United Kingdom, Boyle in [26] sums them up by affirming that total conventional plant capacity will never be less than the peak load irrespective of the amount of added wind capacity. He also concludes that, as a consequence of the variable output, it is seen that wind power, among other renewable sources, can replace energy supplied from conventional sources, but not the need for most of their capacity.

The analysis demonstrated by Strbak *et al*. [34] showed that in order to accommodate intermittent generation it may be necessary to retain a significant proportion of conventional plant to ensure security of supply under conditions of high demand and low wind. Hence, the capacity value of intermittent generation will be limited as it will not be possible to displace conventional generation capacity on a “megawatt for megawatt” basis [34]. He also admits that intermittent generation is not easy to predict and various forms of additional reserves will be needed to maintain the balance between supply and demand.

Holttinen *et al*. [35] points out that the requirement of additional regulating/reserve capacity in Sweden is comparatively small, at least for the time horizon one hour and with an approach including probability and forecasts. By referring to another study Holttinen concludes that wind power integration costs are lower in hydro dominated countries (especially Norway) compared to thermal production dominated countries (Germany, Denmark). One of the reasons is the very low cost of hydropower production connected to part load operation and start-up, and the fact that hydro dominated systems are generally not constrained in regulating capacity.

In larger power systems with wide energy generation portfolio the regulating units most likely exist and wind will be additionally integrated to replace the oldest generating units. The amount that wind energy can replace fossil capacities is the capacity credit defined as the fraction of installed renewable capacity by which conventional capacity can be reduced without a loss in security of supply [34, 36]. The capacity credit varies for different regions and market sizes, but a large share of hydro storage allows to increase the capacity credit of wind turbines.

In countries, where first WTG-s will be installed and cognition for balancing requirement comes afterwards are probably in a more unprivileged situation, as investment requirement can be directly drawn to wind energy. The status of power station generation by type for Estonia, Poland, United Kingdom (UK), Denmark, Germany, Latvia, Finland and Sweden is seen on Fig. 2.7.

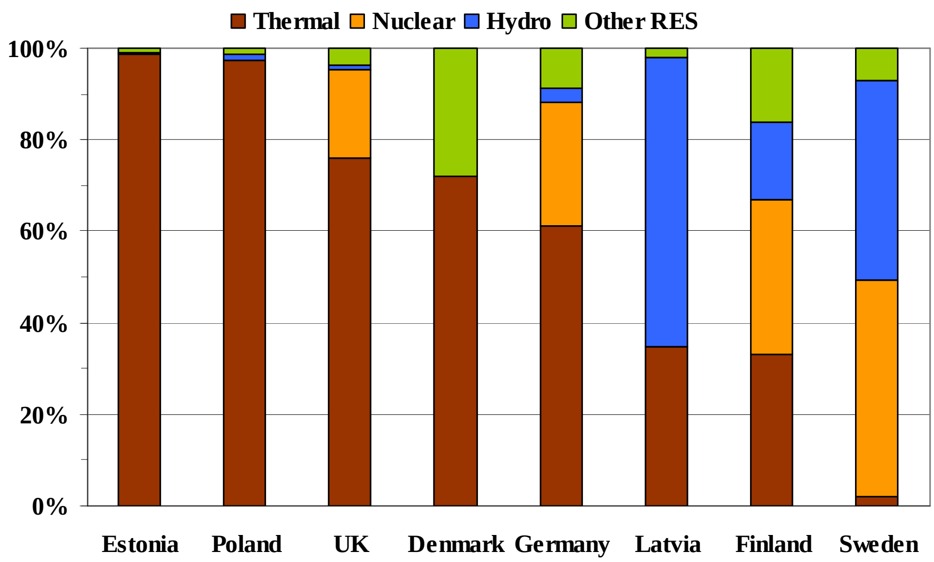

Figure 2.7. Power station generation in per cent by type for different EU countries [9]

It can be derived from Fig. 2.7 that the impact of wind power integration on the power systems can not be taken uniquely. If wind conditions can be taken to be relatively similar, at least in coastal areas, the technical conditions for example for Estonia and Poland are entirely different if compared to Sweden or Denmark. In addition to power plants, other technical conditions like local grid conditions, interconnections and even climate conditions must be considered. The amount of power that can be integrated without a major impact to the power system and the power that wind power can replace and emissions reduced are therefore different.

The Estonian authorities have reached the knowledge that fulfilling the expectations of EU by supporting renewable energy sources obliges balancing units in co-operation [38]. The best way to manage wind energy fluctuations, in a sense of emissions, is to cover these with other renewable energy sources, such as hydro power plants. As a contrast to this and as previously said, the power generation from thermal power plants grew by 19%, while power generation from hydro declined by 5%. During the same period the wind energy generation has grown almost 17 times [8].

It is stated in [39] that the regulation of wind power is not yet a problem for a hydro-dominated power system, but other issues are likely to arise before regulation. In case all the fluctuations of wind power can be compensated with other renewable energy sources, the integration of WTG-s does not cause additional emission and the environmental gain is linearly proportional to the amount of produced electricity. In power systems without hydro power plants or without considerable interconnections, the options for balancing large wind power fluctuations are therefore limited. One of the options is to use controllable power generating units like gas and coal or other fossil fuel based power plants, which is not a pollution-free way to support wind energy.

The possibility to increase renewable energy penetration in one country to 50% or more is analyzed in publications like [2, 27]. A technical system analysis with an increased wind power penetration in Denmark is performed by Salgi and Lund [40]. Their suggestion is to store surplus power by means of compressed air energy storage (CAES). Proposals for being able to achieve high penetration of renewables are explained in [2]. It is concluded that it can only be done if energy consumption is notable reduced, other renewable energy sources like photovoltaic, wave and biomass installations increased and efficient appliances taken into use. Nørgaard in [41] analyses the transport sectors potential in cooperation with wind power and points out that electrical vehicle concepts provide interesting and valuable potentials regarding environmental impact, fossil fuel dependency, energy system flexibility, and driving characteristics. Grid operators could use electric vehicle as an energy storage technology, proposes Georgilakis in [42]. Typically, electric vehicles charge their batteries at night when the cost of power is low. Consequently, their use increases the flexibility of the power system and allows the increased integration of wind power into the system.

The characteristic of wind energy, particularly its stochastic nature can be considered as negative aspect for large scale wind energy. As aforementioned, all renewable energy targets established by different institutions are set on the level around 20-30% from total energy consumption. Referring to that, majority of our consumption in near future will still be generated by means of conventional power plants.

3. THERMAL POWER PLANT MOBILITY AND REGULATING CAPACITY

Nature of production availability in Estonia and other power systems depending mainly on thermal power plants, e.g. slowly regulating thermal units (startup up to 14 hours), constitutes requirements. There are currently no fast regulating units available for balancing and reserve power for wind parks in Estonia, and therefore balancing power should be imported. For regulating purposes, it is only possible to buy energy from systems synchronously connected to Estonian power system. Scandinavian regulated market is only useable for Scandinavian TSO-s and power form spot-market can be bought two hours in advance. In addition, limitations due to transfer limits arise and may therefore not be useable for the export/import of additional power. Generally one should consider that Estonian export/import possibilities are 650 MW [I].

In power systems, the best solutions for covering rapid power fluctuations are the use of gas turbine power plants. Their working hours are traditionally kept relatively low (less than 1500 hours) and investment in that range of working hours is smaller compared to other generating units (see Fig. 3.1).

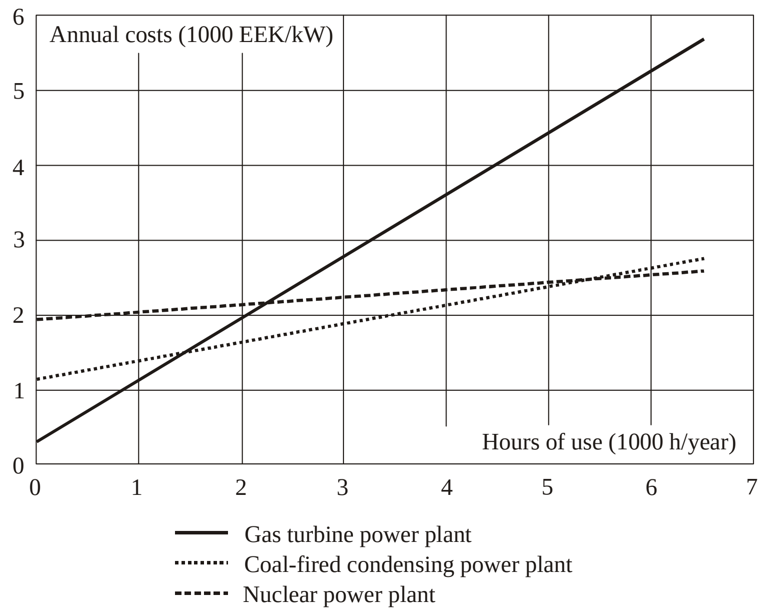

Figure 3.1. Annual costs of power plants per one kW, depending on hours of use of installed capacity [43]

Estonian TSO requires installation of fast-start generating units to be installed together with new connections of wind power – all new wind parks which are planned to be connected to the grid, after 1st of July 2007, are obligated to have fast regulating power plants on Estonian territory.

In any given power system, the amount of wind power being generated depends closely on the speed of the wind. The need to keep generation and consumption in balance at all times places constraints on the regulating capacity of the rest of the power system.

This happens at two timescales [44]:

- In the short term (minutes or hours), wind is relatively unpredictable and frequently delivers either more or less than the forecast amount of power. This means that conventional power plants have to make up the shortfall when wind speeds are lower than expected, and cut production when the reverse is true. Both courses of action lead to increased costs, which should presumably be covered by wind power.
- In the medium and long term (days and weeks), the variability of the wind means that there will be many times when little or no wind power is available. In the power system where wind makes up a substantial fraction of the generating capacity, either consumption will have to fall, or other forms of generation capacity will have to fill the gap. Again, this has both systems and cost implications.

3.1. Dynamic characteristics of the thermal power plant

During the constant load or during slow load changes the static input-output characteristics of boilers, i.e. the characteristics corresponding to steady state of the unit can be used. If the unit participates in covering rapid changes in the power system, the static characteristics are no longer valid and the dynamic characteristics of boiler must be used. In these conditions the boiler is operating in non-continuous operation. During the rapid increase of load, the relative heat loss with flue gas at boiler exit and relative heat loss due to unburned organic matter increase notably. Due to abovementioned reasons the boiler efficiency decreases and inevitably the relative fuel consumption increases. When the load rapidly diminishes, the losses exist as well due to deteriorate burning regime. It is complicated to calculate the precise operation point on dynamic characteristic especially for fossil fuel power plants. As the tests of this type are expensive to make and complex to measure, the literature lacks real dynamic characteristics of boilers and large scale power units. In [45], it is stated that efficiency will be reduced up to 1% during fast increase, which results in notable increase in cost characteristics. The dynamic and static characteristics based on measurements of 200 MW thermal unit based on natural gas are presented by Girschfeld *et al*. in [46]. Without knowing the precise dynamic characteristics of oil-shale power plant, we have assumed it to be higher similarly to thermal unit based on natural gas (see Fig. 3.2). Using the dynamic characteristics gives opportunity to get more realistic results than the linear methods of calculating fuel consumption and emissions.

Estonian oil-shale power plants contain several double power units, but these power units can also operate as mono power units. Double power units consist of two boilers and a turbine generator and its operation is therefore more flexible. Detailed overview of power plant optimization can be read from [43].

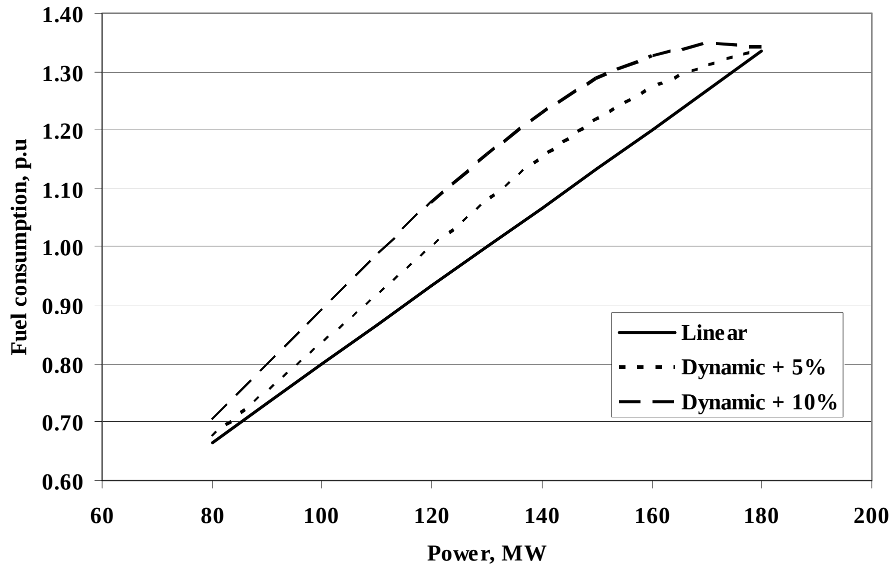

Figure 3.2. Static and dynamic characteristic of oil-shale power plant

Comprehensive description about oil-shale power plants is available in [47].

In the power plant where double power units operate as mono power unit, it is possible to optimize the load dispatch between power units and the unit commitment schedules of power units. In case of double power unit operation it is also possible to optimize load distribution between the boilers and boilers' commitment schedules. The fuel costs, consumptions and emissions can be read from the corresponding characteristics of thermal plants using calculated optimal powers.

If we deal with the necessity of compensating wind power fluctuations with thermal power plants, the fuel cost characteristics must be considered as dynamic values. Under dynamic characteristics the fuel cost depends on load and speed of load changes. When balancing fluctuations, the load changes are constantly changing in time as in equation (3.1).

$$B(P,t) = B\left(P(t), \frac{\partial P(t)}{\partial t}, t \right) \tag{3.1}$$

where

$\frac{\partial P(t)}{\partial t}$ - load changing speed of the power unit

In calculations used in papers [I, II], the time period is divided into intervals and the load in time interval *k* depends on the power in interval *k*, power in interval *k*–1, and speed and direction of the change of power as in equation (3.2).

$$B_k = B(P_k, P_{k-1}, k) \tag{3.2}$$

3.2. Regulating capacity of the condensing thermal power plant

Electricity unbalance between consumption and power generation causes several problems for system stability and must therefore it must be avoided. Base load in power systems are traditionally covered with large thermal power plants (Estonia, Poland, etc.), nuclear power plants (France) or hydro power (Norway). Gas turbines and gas engines are used only occasionally to cover peak loads. Due to relatively high operational cost, the working hours of gas turbine are kept as low as possible.

In Denmark in 2007 according to [48] the installed 741 MW of gas turbines generated 60 GWh of electricity, which results in utilisation period at maximum capacity only to 80 hours in a year. Good interconnections with neighbouring countries and usage of combined heat and power (CHP) plants with heat accumulators diminishes the utilization time of these costly power units. Because all that, when we start to use generation based on natural gas for balancing wind power, the working hours of gas based power plants are increasing together with emitted hazardous gases.

The power plant efficiency depending on load and partial load operation is undesirable because it reduces the power plant efficiency [49, 50]. The most effective electricity generation is performed when the unit is operating on a rated load (see Fig. 3.3). If we have to balance wind fluctuations, we will have to operate at times on partial load with higher specific fuel consumption. Every thermal power plant participating in the compensation operates inefficiently, but balancing reserve must be held. Constant fluctuations in large base load units reduce the lifetime of boilers and increase the frequency of planned maintenance [34].

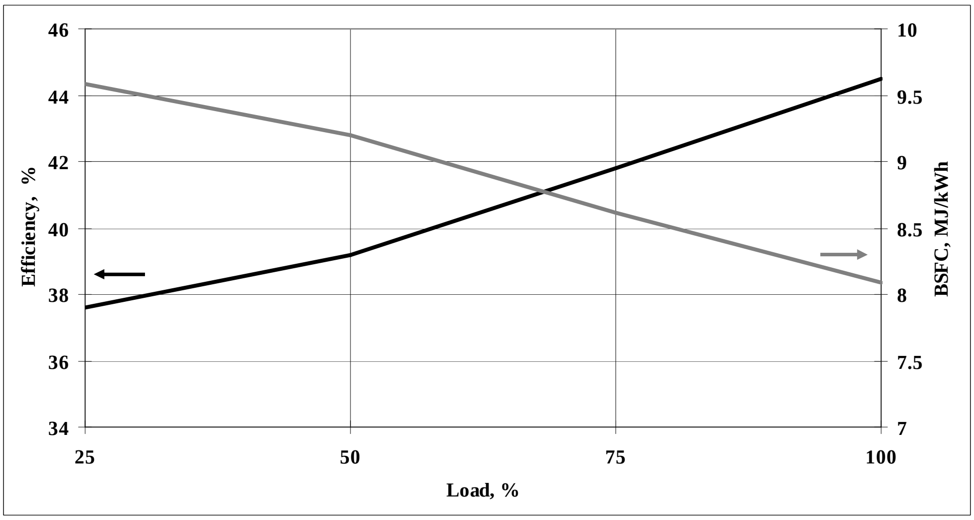

Figure 3.3. Gas engine power plant efficiency and brake specific fuel consumption (BSFC) dependency on load [51]

If we use unit for balancing small power variation, we are using the unit ineffectively, resulting in notably lower emission reduction as expected. Power plant operating on partial load with lower efficiency emits hazardous gases on a same level or even increases in partial load situations [48, 51]. The emission dependency of load is given in Fig. 3.4, where unburned hydro carbon (UHC), carbon monoxide (CO) and nitrogen oxides (NOx) are presented. Engine is designed to work most efficiently on rated power. When we start to manoeuvre with the load, we are moving along the efficiency curve. Wind power impact on thermal power plant load efficiency, specific fuel consumption and emissions are further analysed in Chapter 4 starting on page 29.

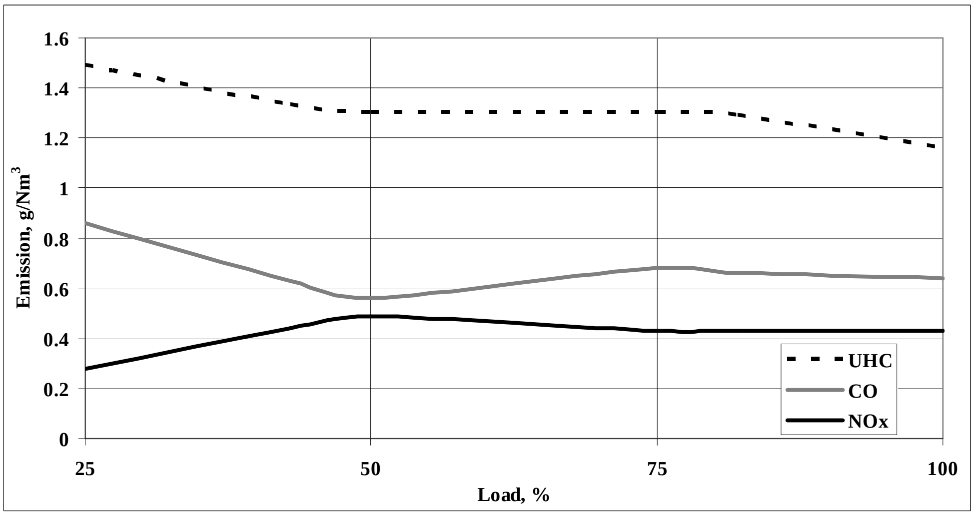

Figure 3.4. Gas engine power plant emission dependency on load [51]

3.3. Regulating capability of combined heat and power plants equipped with heat accumulator

Heat accumulators are used for storing energy in the form of hot water for district heating systems. When heat accumulators are used in combination with CHP that traditionally follow heat load, the flexibility of electricity generation is increased and is therefore available to balance wind fluctuations. Heat accumulators facilitate two types of response options for better integration of intermittent power into electricity system [52]:

- for storage of heat produced by CHP, operation of which is usually heat-demand driven.
- for storage of electricity surplus, coming from intermittent generators such as wind turbines, as another form of energy – heat, where heat is produced by heat pump or electrical boiler and reducing curtailment of intermittent power production.

When there is no district heating or low heat demand, but high electricity demand with high prices CHP can produce electricity until accumulator is filled up. It can stop operation and electricity production as long as heat accumulator is discharging and supplying heat. By using electrical boilers and heat pumps during low electricity price in case of surplus wind generation for heat production, CHP can directly save cost on unburned fuel and reduce emissions.

This results both in reduced randomness of wind power generation and in saved costs on district heating. One possible solution is depictured on Fig. 3.5 where wind turbine generators and cogeneration power plants with heat accumulators are presented.

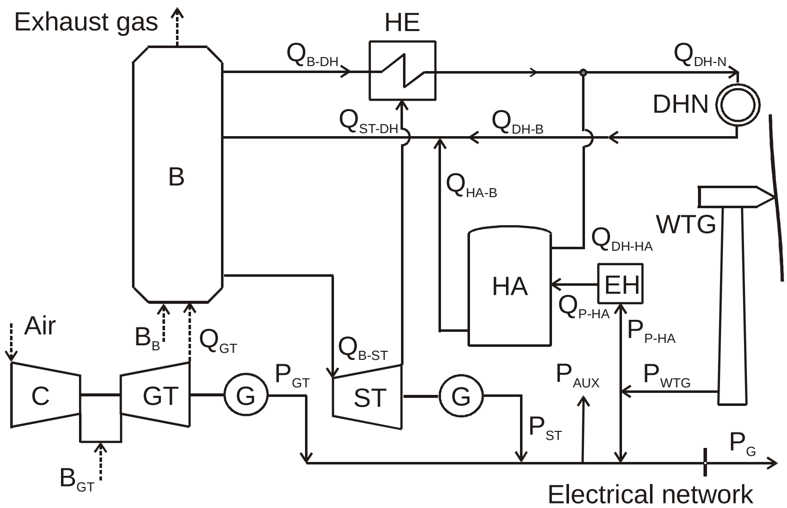

Figure 3.5. Cooperation of cogeneration power plant and wind turbines [VIII]

Here B – boiler, EH – electrical heater, C – compressor, GT – gas turbine, G – generator, ST – steam turbine, HE – heat exchanger, HA – heat accumulator, DHN – district heating network, WTG – wind turbine generator, BB, BGT – fuel consumption of boiler and gas turbine respectively.

3.4. Thermal power plant optimal operation with wind parks in power systems

Thermal power plant optimisation in power systems consist two problems:

- Optimal unit commitment
- Optimal load dispatch between operating power units

Optimal unit commitment depends mostly on start-up costs of power unit (Fig. 3.6) and specific fuel consumption characteristics (Fig. 3.3).

When thermal power plants have to balance power fluctuations of wind parks, the determination of optimal operation conditions is rather complex. Later results in increased cost over total power system, but in practice have no effect on wind park operators.

During normal operation the power plants are optimally loaded (it means their incremental fuel costs are even) [43].

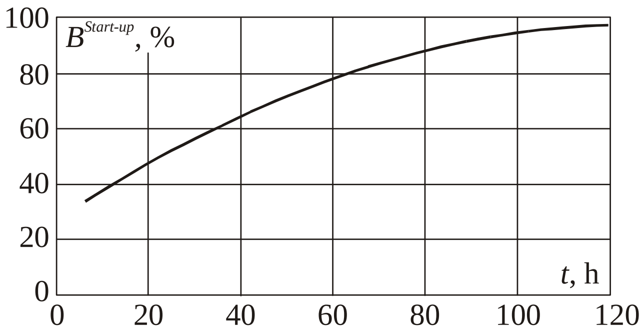

Figure 3.6. Start-up cost characteristics of the power unit [43]

If any plant must balance unintentional deviation, the operation is not any more optimal and fuel consumption augments. Overcost characteristics caused by deviations from optimal load is depictured on Fig. 3.7,
where,

$$\Delta P = P_{actual} - P_{optimal} \quad \textbf{(3.3)}$$

ΔP	– load deviation
P_{actual}	– actual load
$P_{optimal}$	– optimal load

Power system overall costs, including fuel consumption, are lowest when every contributing power plant is operating on optimum load that corresponds to existing power requirement.

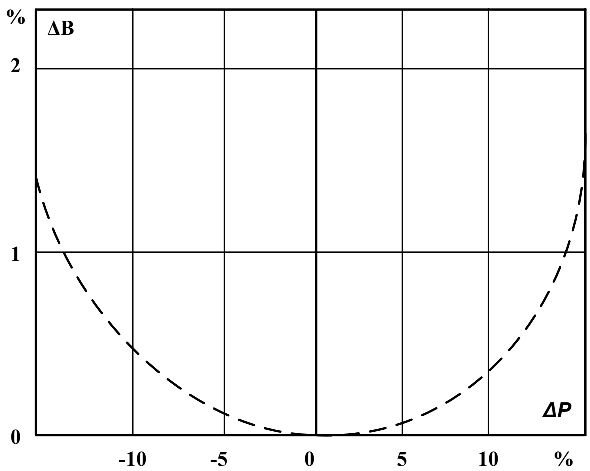

Figure 3.7. Power unit fuel overcost depending on load deviation

Deviation from optimum load operation is basis for increased fuel consumption as presented on Fig. 3.7. Figure depictures power unit fuel overcost ΔB depending on load deviation ΔP , between actual and optimal operation point.

$$\Delta B = \int_{P_O}^{P_A} b(P) \partial P \tag{3.4}$$

where

$b(P)$ – unit incremental cost characteristic

P_O – optimal operational point

P_A – actual operational point

Under the circumstances described, intermittent power from wind parks has direct impact on power system operation and cause fuel overcosts in thermal power plants.

4. BALANCING IMPACT ON EMISSIONS IN THERMAL POWER PLANTS

One of the options for dealing with increased fluctuations in the power system due to enlarged amount of fluctuating energy sources is the use of power generation forecasting. The obligation that the power delivered to the grid must correspond to the forecast must be introduced also for wind energy. Exceptions can be made during emergencies and if required by balance provider or TSO, but must be exactly described in contracts and used only when inevitable. During the normal operation one should keep to forecasted power either by increasing or decreasing available power generation if not according to prediction. Following analysis is based on assumption that this clause is introduced and two options for power systems containing mainly thermal power plants are introduced:

- The first approach is to investigate a small generating unit, in the range from 5 to 15 MW. The unit in this range can be a gas engine power plant (GEPP) [51, 53]. Device like this is in principle usable for wind parks to cover one's forecast error. By taking the average forecast error to be around 20%, the appropriate capacity of the wind park could be within the range of 25 to 75 MW.
- The second approach is to study a larger oil-shale power plant with balancing range up to 100 MW. In this case special attention is drawn to fuel consumption by investigating its dynamic characteristics. These power plants are generally base load power plants designed to cover base load. Power plant in this range could be appropriate for larger wind parks on-shore and offshore and even suitable for smaller power systems. By using the same forecast error (20%), the installed capacity on wind power could be approximately 500 MW.

4.1. Balancing wind energy fluctuations with gas engine power plant

Gas engine power plants can be used as backup units or power units for smaller power systems. By assembling several units into one power plant, the plant could start the engines and ramp-up to full load in less than ten minutes. Similar power plant is established in Montana, USA, which supplies reserve capacity to the electric power grid and also plays an important part in supporting the new wind energy resources being implemented in region [53].

Schematic description of the balancing mechanism of wind turbines with gas engine power plant is presented on Fig. 4.1.

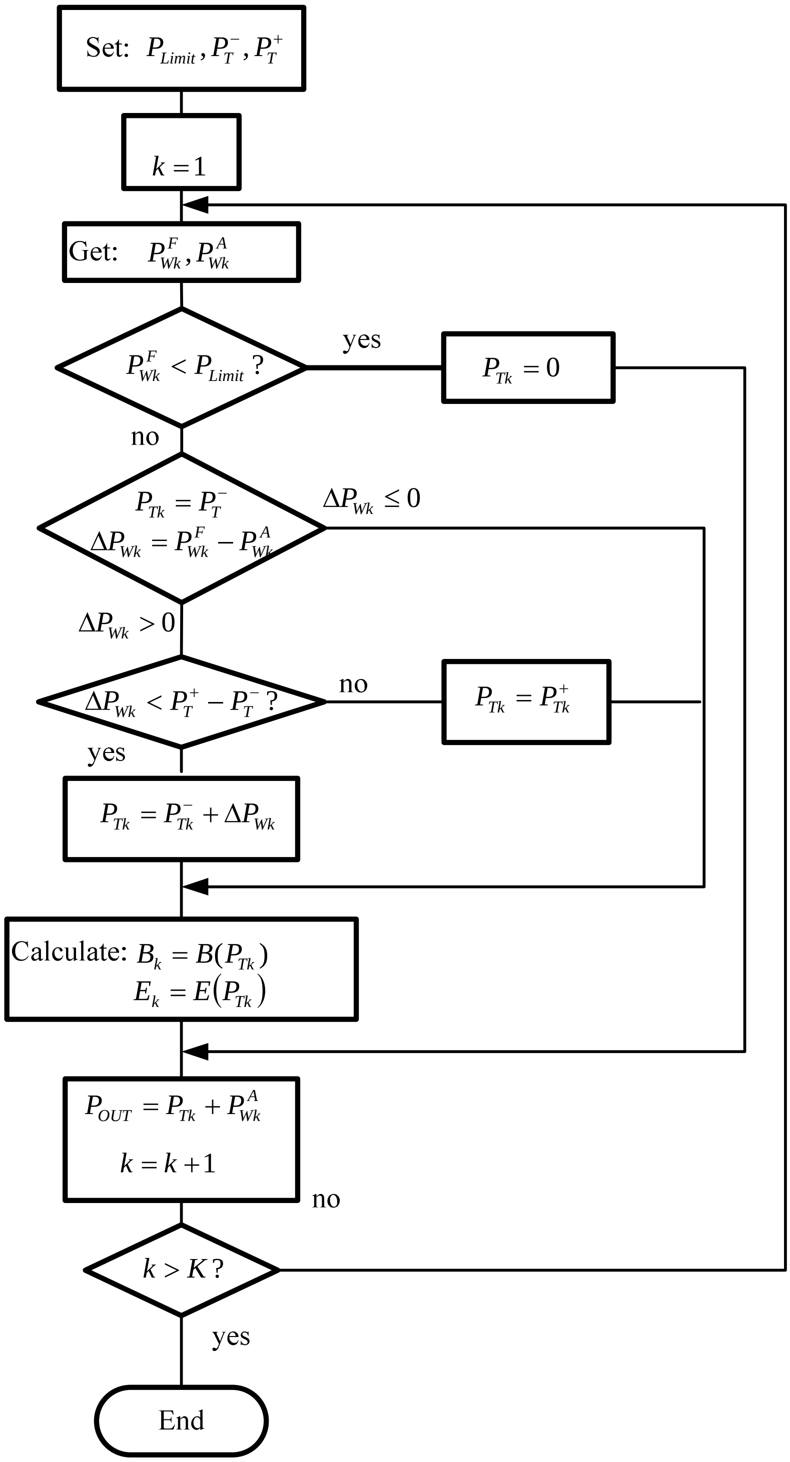

Figure 4.1. The balancing mechanism of wind turbines

Reference marks used on Fig. 4.1:

k – index of time interval,

K – number of time intervals in the given time period;

P_{Limit} – Minimum value of wind power forecast when thermal power plant is started

P_T^-, P_T^+ – minimum and maximum load of thermal power plant

P_W^F, P_W^A – forecasted and actual power from wind park

P_T – power generation of thermal power plant

ΔP_W – power forecast error

P_{OUT} – power output to grid

$B(P_T)$ – thermal power plant's fuel cost characteristic

$E(P_T)$ – thermal power plant's emissions characteristic

For this study several simplifications have been made. For example, it is estimated, that wind park operators must predict the next day hourly wind power output in advance for 24 hours. If actual power is less than predicted, the underprovided power must be covered by other means of generation (gas engine power plant in our case). The situation when the power output is more than predicted has not been analysed here as there are several options to solve it, like limiting power output of wind turbines or transferring the balancing problem to others by giving electricity away for reduced price or for free [24].

It is estimated that wind park operator stops the engine on periods when the wind power forecast is less than agreed power limitation.

$$P_{Wk}^F < P_{Limit} \rightarrow P_{Tk} = 0 \tag{4.1}$$

Possible limitations could be gas engine's rated power, certain percentage of installed wind park capacity calculations based on average forecast error or any other option.

The engine can balance forecast error, when power differences are not larger than balancing range

$$\Delta P_{Wk} < P_T^+ - P_T^- \tag{4.2}$$

If the error is larger than the corresponding range, the power plant is operating on full load and surplus power must be provided by other means or the penalty for inaccurate forecast must be accepted.

The power generated by gas engine power plant on specific hour is

$$P_{Tk} = P_{Tk}^- + \Delta P_{Wk} \tag{4.3}$$

and corresponding fuel consumption, efficiency and emissions are calculated based on that outcome.

Power delivered to the grid and the power that should correspond to forecast is

$$P_{OUT} = P_{Tk} + P_{Wk}^{A} = P_{W}^{F} \qquad (4.4)$$

where power generated by GEPP is added to actual wind generation.

The paper [I] is based on the previous method and it was found that in the case of 15% forecast error, 30 MW of wind turbines and 6.1 MW GEPP during one year would have generated 53.4 GWh and 15.6 GWh respectively by using 3.5 million m^3 of natural gas as a result. Due to the balancing wind energy shortages during the investigated year, the GEPP has emitted 2.2 t of CO, 1.6 t of NO_x and 4.5 t of UHC. The power plant has operated on partial load with average efficiency of 40.6%, compared to the efficiency at full load 44.5%. The concluding results are seen on Fig. 4.2.

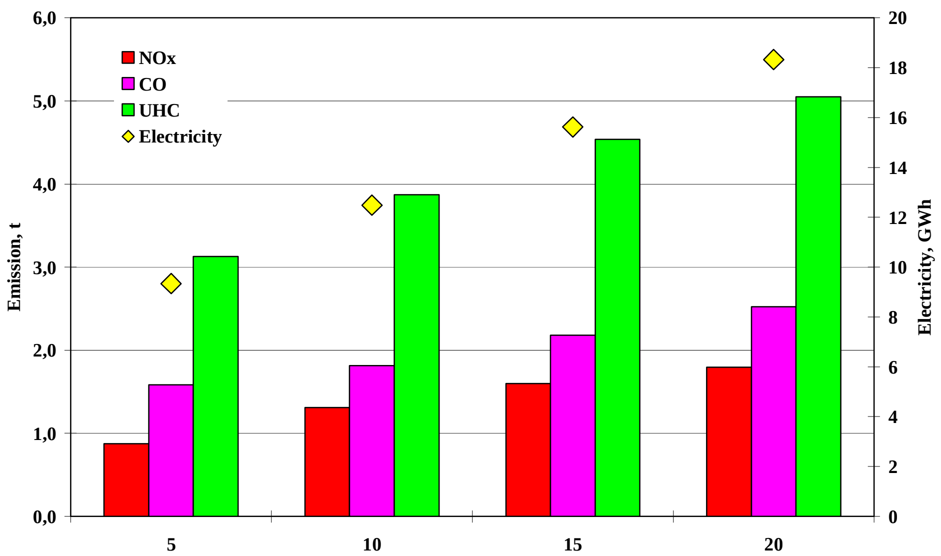

Figure 4.2. Annual electricity generation and emission of the gas engine power plant depending on the forecast error [I]

Despite the fact that surplus generation is caused by inaccurate forecast, larger forecast error results in higher utilization time of gas engine with higher total efficiency. Almost quarter (23%) of electricity generated within this system accounts to gas engine and owing to wind energy, 12 million m^3 of natural gas was not consumed and tons of hazardous gases were not emitted. As an advantage of this scheme most of the fluctuations were kept local and impact to total power system was mitigated.

There are several inadequacies in this system. For example, it does not appropriately take into account the situation where actual power generation is more than forecasted as the power plant is still operating on minimum load, while it could be stopped. In case forecasting errors are relatively small compared to rated power of the power plant, the power plant is operating extremely inefficiently. As a result, it does seem sensible to accept penalty for inaccurate forecast and to detach the power unit. Using higher minimum load or smaller units in parallel could solve the situation, but only to some extent, as it will possibly raise an economical dilemma. If forecasting errors are rapid and relatively large, the output from balancing power plant itself starts to fluctuate in opposite phase to wind power, resulting in the furthermore increase in fuel consumption. In practice, the constant manoeuvring with load marks moving along the efficiency curve, and as most of the hours will be in low load range, the fuel consumption, emissions and overall costs will increase. Frequent starts and stops, which inevitably take place in these conditions, have a negative impact on the lifetime of the device and cause excess fuel consumption during forced starts and stops.

4.2. Balancing wind energy fluctuations with oil-shale thermal power plant

It should be a known fact that most of Estonia's electricity originates from oil-shale. In Estonian new long-term public fuel and energy sector development plan until 2015 [54] construction of new oil-shale power plants are included. Until new power plants are under discussion, existing units must withstand the base load generation and provide necessary balancing capability. The following method is developed to analyse wind power balancing obligation impact on oil-shale power plant. The use of dynamic characteristic is under detailed inspection as it allows taking into account more details than linear characteristics. In order to keep the calculations on computable and easily understandable level, several simplifications are described hereafter.

On Fig. 4.3 the calculation mechanism of balancing differences between forecasted and actual wind power is presented. Following reference marks have been used:

$B(P_T)$ – fuel cost static characteristics of thermal power plant

$B^*(P_T)$ – fuel cost dynamic characteristics of thermal power plant

P_T^-, P_T^+ – minimum and maximum load permitted for balancing unit;

l – rate of power deviations (%) of neighboring time intervals;

k – index of time interval,

K – number of time intervals in the given time period;

ΔP_{Wk}, ΔP_{W0} – wind power forecast error in time interval k and in earlier time interval (i.e. $k-1$);

ΔB_k, ΔB_Σ – increase of fuel cost in time interval k and in the whole given time period;

P_{Wk}^F, P_{Wk}^A – forecasted and actual total generated wind power generation in time interval k.

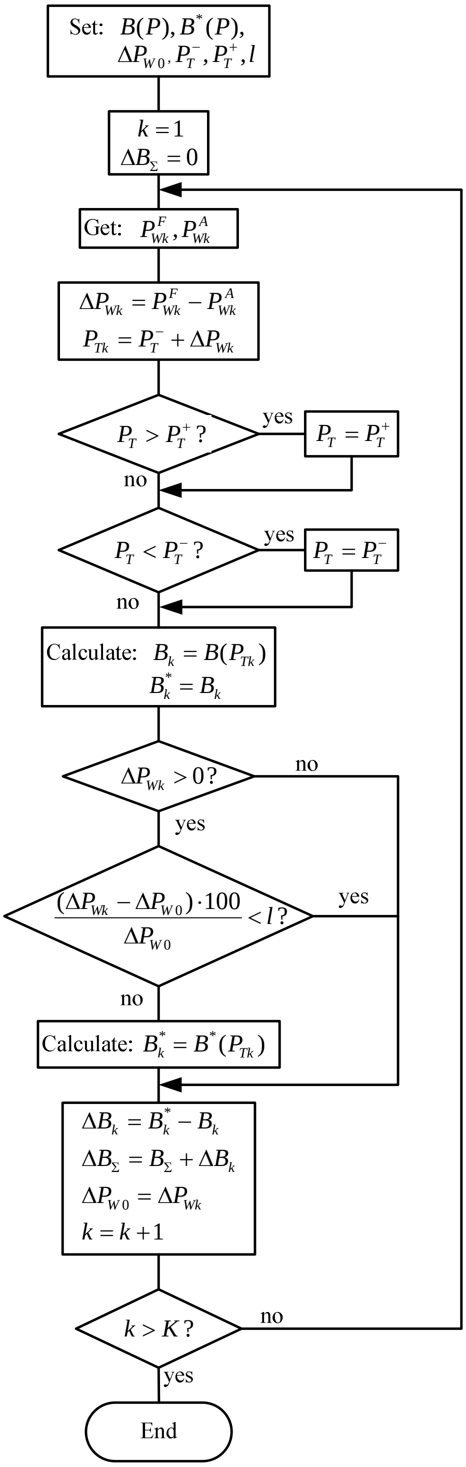

Figure 4.3. Algorithm for calculating the fuel overcost of balancing power unit

Wind power forecast, as also used in the previous example, is taken to be forecasted 24 hours in advance. Wind power errors in time period are

$$\Delta P_{Wk} = P_{Wk}^{F} - P_{Wk}^{A},\ k = 1, \ldots, K \qquad (4.5)$$

When the wind power forecast and actual generation differences are negative i.e. more wind power is generated than predicted, the power plant deregulates its generation down to minimum load P_{Tk}^{-}. Deregulation of the power plant in these calculations is done according to static characteristic. It is assumed that the fast drop in forecast error (predicted and actually generated power is equal or close to each other) do not need covering and the power plant is operating in continuous mode at minimum load.

The wind power forecast error (4.5) can not be larger than investigated power plant's balancing capacity i.e.

$$\Delta P_{Wk} \le P_{T}^{+} - P_{T}^{-} \qquad (4.6)$$

The thermal power plant load during the balancing is

$$P_{Tk} = P_{Tk}^{-} + \Delta P_{Wk} \qquad (4.7)$$

The boiler is not always operating according to dynamic characteristic. It is taken that power plant characteristics depend on forecasting error (power) and can be adjusted by changing the multiplier l within limits from 0 to 100% of the error of previous hour:

$$\frac{\Delta P_{Wk} - \Delta P_{Wk-1}}{\Delta P_{Wk-1}} \ge l,\ l \in L = \{0.1; \ldots; 1\} \qquad (4.8)$$

As this is not evident, it is assumed that when forecast error in the following time intervals differs more than certain percent (in our calculations $l = 0.2$ i.e. 20%), then on those periods the boiler is operating according to dynamic characteristic. The calculations are made according to three different estimations of dynamic characteristics (with the biggest differences from the static characteristic 1%, 5% or 10%), as differences between static and dynamic characteristics vary.
The calculations based on this method are published in [II]. Brief conclusion of the results is given hereafter.

In the paper two reference scenarios were selected, whereas the first, 50 MW scenario was based on the real situation in the end of year 2008. In Estonian power system 75 MW of WTG-s were installed, but as the largest wind park was not fully available, only wind parks with total of 50 MW were forecasted. The second, 200 MW scenario was chosen as it is approximately that amount of installed wind power which is currently supported by feed-in tariff and might be integrated by 2010. Both scenarios were calculated using double and mono power units.

Fig. 4.4 and Table 4.1 depicts the two analysed scenarios based on one week data. Referring to calculations in [II], it can be stated that covering wind energy forecast error with oil-shale power plant and taking into account the difference between static and dynamic characteristics, fuel consumption increases by 0.2 to 1.5% depending on nature of dynamic characteristic. The increase in emitted gases is expected to be within the same extent.

Most of the weaknesses are similar to the method used in [I], but in this case the starts and stops are even more expensive and what is more important, the startup time from cold state is considerably longer. If the wind power generation forecast is predicted to be low for days and base load power is not required, it can be stopped. Anyhow, frequent starts and stops must be avoided, as it has also an impact on lifetime of the power plant.

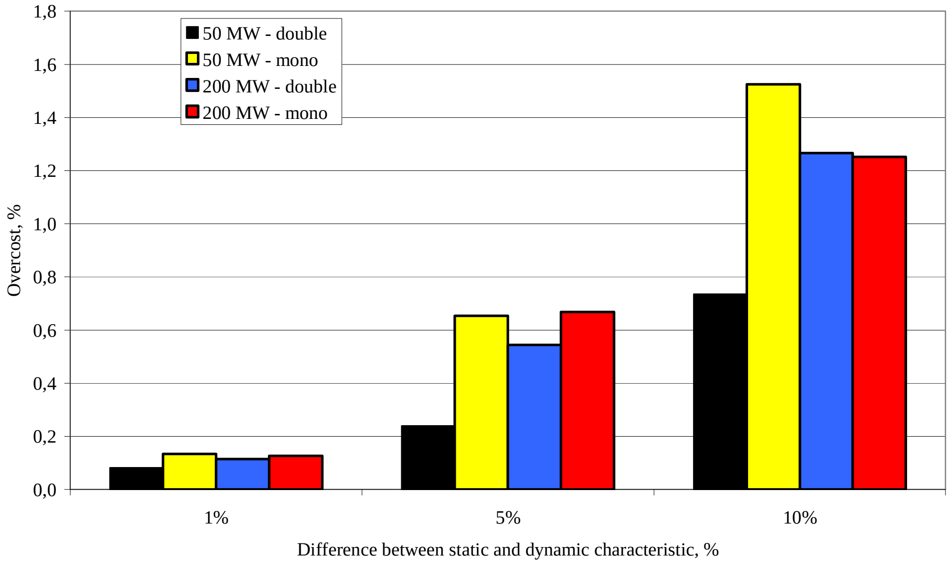

Figure 4.4. Oil-shale overcost in thermal power plant due to balancing obligation of wind energy

Besides that the calculations in this case do not take into account the real reduction and increase of wind generation, only the covering of power differences between forecasted and actual generation. By adding load following the actual overcost could be larger as more fluctuations are taking place.

Table 4.1. Balancing results of investigated system.

Unit	Reference scenario	Average wind generation MWh/h	Electricity generated by WTG-s, MWh	Average power unit generation MWh/h	Electricity generated by power unit, MWh	Ratio between power unit and WTG-s' generation, %	Increased emission, tons		
							1%*	5%*	10%*
Mono	50 MW	14	2446	43.4	7900	31	0.13	0.65	1.53
	200 MW	56	9782	51.4	9354	104	0.13	0.67	1.25
Double	50 MW	14	2446	83.0	15180	16	0.11	0.56	1.28
	200 MW	56	9782	92	17035	57	0.15	0.70	1.39

* - Difference between static and dynamic characteristics

4.3. Conclusions

Both methods briefly described hereinbefore and in details in [I, II] are based on the history of planned and generated wind power data and do not take into account information uncertainty and inaccuracy. This uncertainty is the basis for increased fuel consumption as information about wind patterns that is available for analysis afterwards is not present during real operation. As detailed data is difficult to obtain, one hour averages are used as an input to these calculations. Obviously the wind fluctuations are remarkably faster and deeper and using hourly average might be too simplified.

It is found that when gas engine power plant is covering wind parks' power error, a quarter from total electricity is generated by burning natural gas. The part load operation results in 4% lower efficiency compared to operating only on full power. If oil-shale power plant is used to cover forecast error, the difference between linear and dynamic cost characteristics is found to be in a range from 0.11 to 1.53%.

Truth is that the real situation is more complicated and simplifications made within this calculation may impose an effect on both ways from actual values. Taking that into account, it is clear that using fossil fuel power plants for balancing fluctuating wind power causes extra costs due to following reasons:

- increased fuel consumption due to operation in inefficient load area

- surplus fuel consumption due to fast regulation which causes heat loss with flue gas at boiler exit and unburned organic matter
- extra cost for starting and stopping the power plants during long periods of low wind
- increased maintenance cost and reduced lifetime of unit.

Participation of thermal power plants, especially oil-shale power plants, in keeping the reserve capacity for wind turbines and in the compensation of wind power fluctuations substantially increases fuel consumption and emissions. In systems containing mainly fossil fuel power plants, the positive effect of wind turbines is notably smaller than compared to power systems that contain hydropower or use intermediary storage. Taking everything into account, the positive effect of wind energy due to balancing obligations is reduced, when balanced with fossil fuels. It is popularly believed that the smoothing effect could help to level out the fluctuations, but when single operators have to keep balance, the smoothing effect disappears. Hence it must be agreed on what level and over which region the balancing must be held.

Study made by Liik *et al*. to find out the influence of increased wind penetration into Estonian power system is presented in [56, 57]. Similar impact in Germany is analyzed by Leonhard and Müller in [58].

5. POWER QUALITY IN WEAK GRID

In the early days of wind power when the turbines were relatively small (20-250 kW), they were intended to produce local power that could be used in the near vicinity [59]. Local generation and consumption is an obvious advantage to the power system, since it will reduce the losses in the grid. As long as the maximum power from wind turbines is less than the minimum load in the local grid, all their power will be consumed in the local area. From year to year, the larger wind turbines are being constructed and the advantage of local consumption is diminishing. When connecting large WTG-s or wind parks on an island in addition to grid conditions and wind velocity other issues such as nature preserve areas (Natura 2000) and bird nesting locations must be considered [60].

As balancing options of wind energy were introduced on two levels – gas engine for small scale fluctuations and oil-shale for large scale fluctuations – the power quality, in principle, could be divided based on local and system wide level.

Single wind turbine generators or smaller ones in groups have direct impact on local grids connected to substations in the vicinity. This involves mainly power quality issues like voltage fluctuations, flicker and harmonics.

Secondly, large scale impact of wind energy to power quality can be stated as impact to system reliability and therefore power quality issues like frequency deviations, voltage level stability, compensation of reactive power, fault ride through capability and requirement to fulfil the N-1 criteria.

Author has been involved with several papers [III, IV, V, VI, VII, IX] and reports [20, 20, 61, 62] during the last years related closely to power quality issues. In papers [IV, V] the impact of wind parks on the power system is analysed in the viewpoint of the possibility to withstand faults in power systems and the fault ride through (FRT) capability. The possibilities and impact to integrate 1000 MW offshore wind park into Estonian power systems is analysed in [VI]. Hereafter research on wind turbine generators impact on local distribution grid based on papers [III, VI] is briefly introduced.

5.1. Wind turbine generators in weak grid

Wind turbines have to be installed in locations with sufficient wind energy. In many cases these locations are neither densely populated nor industrial areas, which could guarantee an existence of stronger power grid. On the one hand it is good that wind turbines could be erected without disturbing local residents, but on the same time the absence of high voltage network makes the investment more expensive. Latter results in large investment requirement into reinforcement of the existing network in order to transport power to load centers. The instalment of wind turbines in low load high wind areas affects the operation of the existing grid and can cause deterioration or improvement of power quality. Wind turbines in the common strong power systems might have a direct impact only on voltage: voltage change, flicker, harmonics and transients. These are values which also characterise the so-called weak grid. Due to the unique character of every grid and different types of wind turbines it is difficult to evaluate the impact without measurements and/or modelling.

Load fluctuations cause voltage fluctuations in the steady-state operation, especially in weak grids with long transmission lines and relatively low voltage. Connecting wind turbines to this grid increases those fluctuations because of short and long-term changes in output power. If the grid is weak, the input of active and reactive power might change the voltage in connection point or in any point close to it. Capacitor switching, wind gusts, wind speed changes in the steep part of the power curve and fast changes of electrical torques caused rapid fluctuations of both real and reactive power. In combination with the short-circuit impedance of the network this causes voltage flicker. The flicker level caused by a wind turbine decreases with increasing network short-circuit power [28]. For wind parks connected to transmission networks, flicker is not an issue mainly due to the stronger connection point, but today also due to the use of variable speed turbines and the diversification of turbine locations.

Areas in Estonia with most wind resources are located far from main supply sources and have only 10-35 kV grids with low transmission capacity. When connecting wind turbines to the existing distribution grids it should be kept in mind that these grids are initially planned for unidirectional transmission of electric energy. Until recently the opposite direction of wind turbines' capacity and their special characteristics has not been taken into account in the grid development.

The most important factors in installing wind turbines and connecting the turbines to the existing grid are sufficient transmission capacity of the grid and the issues of power quality. If the grid is not substantially expanded, both problems can be considered technical restrictions that have to be fulfilled and used for calculating the permitted capacities of wind turbines connected to the grid depending on the planned connection point.

Variable speed turbines such as doubly-fed asynchronous generators and full converter units use pitch-control. The advantage of these systems is that they deliver power with greater power quality with less likelihood of flicker. This is because during a short lived wind gust the rotor speed increases and thus absorbs some of the fluctuation in power in the form of stored mechanical energy rather than directly translating the power fluctuations onto the grid with fixed-speed systems [25].

5.2. Overview of Estonian power system

Estonian power system is not the best place for wind power integration. The electrical networks in the coastline and islands, usually the best wind park sites, are weak. Estonian power system is operating in parallel with power system of IPS/UPS of Russia. Estonia, together with other Baltic power systems, Latvia and Lithuania, are only EU countries that belong to synchronous zone of IPS/UPS of Russia.

The transmission grid within Estonia comprises 1300 km of 220-330 kV lines and 3500 km of 110 kV lines. Estonia is interconnected with Russia and Latvia via five 330 kV AC links (see Fig. 5.1). Since the end of 2006, Estonia made interconnection available with Finland via HVDC submarine cable Estlink which made it possible for energy market participants to enter into the Nordic energy market. It is decided that there will be a second interconnection with Finland (Estlink 2) and it should be operational in year 2013. Interconnections to the neighbouring areas have a net transfer capacity of 200-1100 MW, depending on real-time operation of the power system [63]. Transit flows through Estonia are typically ±200 MW.

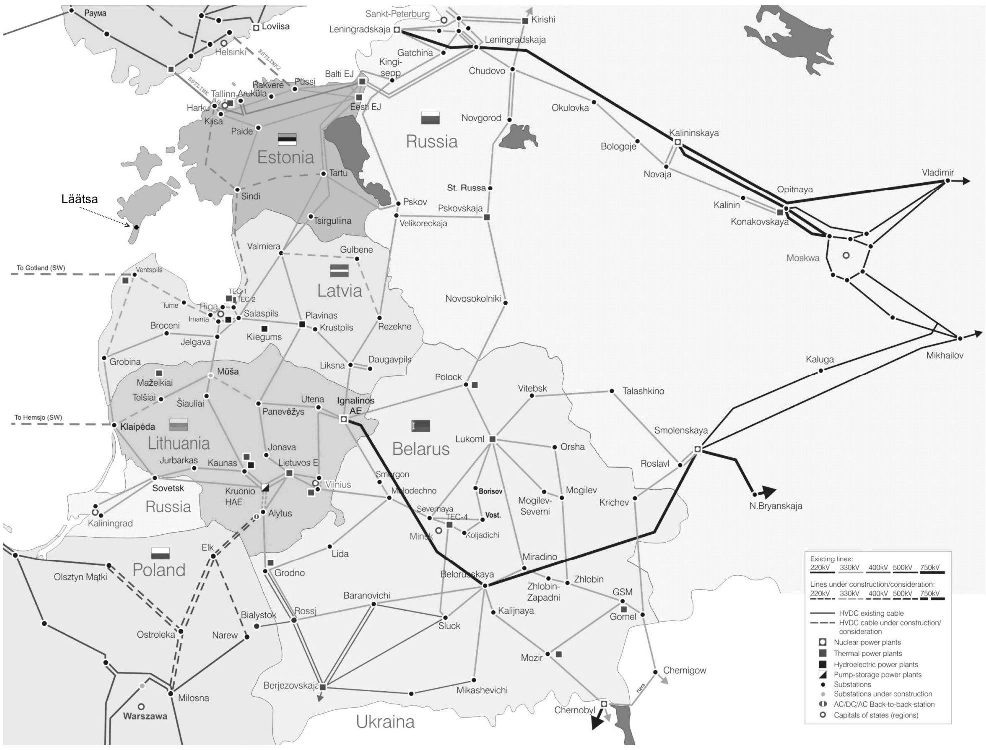

Figure 5.1. Power loop of IPS/UPS of Russia [V]

In 2007, approximately 90% of domestic electricity consumption, 7,2 TWh, in Estonia was covered by conventional thermal power plants burning local oil-shale [16]. The installed net production capacity in the Estonian power system is approximately 2315 MW – condensing oil-shale fired power plants 2000 MW, CHP-s ca 200 MW, wind parks 75 MW, all other power plants including hydro 40 MW. The peak load during wintertime is about 1600 MW and low load in summer decreases to 400 MW. The connection of considerable wind turbine capacity causes extensive network building, addition of sophisticated control and monitoring devices and active and reactive power regulating capability to the wind turbines, installation of gas turbines, reconstruction of primary and secondary regulators of existing thermal generation units, and more intensive and extending co-operation with neighbouring power systems [I, VII].

The island of Saaremaa has a large potential for wind energy use, but it cannot be considered as energy field for the whole country and today not even as the solution for covering the local electricity consumption due to various limitations mentioned hereafter. Peak load in Saaremaa reaches 40 MW during wintertime and low load decreases to 9 MW in summer. The island is connected to mainland through 110/35 kV transformers in mainland, six 35 kV marine cables and 35/110 kV transformers on the island. The weakness of the network is its poorly developed 35 kV Western part, which does not enable to connect larger consumers or wind parks into the network. The present network satisfies current loads and has enough resource left for 10 to 15 years. However, this network cannot guarantee needs of large consumers or wind energy projects. The main bottleneck is the connection to the mainland through Lihula 110 kV substation and the double circuit main 110 kV feed line of Saaremaa on the dam of Small Strait [I, III].

The most important requirements for the connection of wind parks into Estonian power system are described in Estonian National Grid Code (in force since July 1, 2003) [55]. Additional requirements affecting the wind parks are described in Estonian Electricity Market Act [12]. Estonian Grid Code covers specifications concerning supply security and technical requirements for electrical installation due to security of supply. The issues concerning the connection of power plants is covered in Chapter 3 of the Gird Code – "Technical requirements for production units" (incl. special requirements for WTG-s). The technical conditions for connection of wind parks to the grid are elaborated by the transmission system operator. According to the Grid Code, a wind park with installed capacity over 200 kW must be able to participate in the control tasks on an equal level with the conventional power plants, constrained only by the limitations imposed at any time by the existing wind conditions. All wind parks over 10 MW must be connected only to the transmission network. Excessive overview of Estonian requirements concerning WTG-s can be observed from [IV, V].

5.3. Measurements made in weak grid

Openness to wind and therefore higher wind speeds increase the interest to develop wind energy projects on the islands. It is a progressive idea, at least in principle. Unused wind potential and increased support from governments drive wind power developers to islands to utilize all available energy. Unfortunately due to relative isolation and absence of energy content factories the power grids on islands are usually sufficient for one way energy transport and are not suitable for wind energy integration.

During the implementation of this study, numbers of measurement series on several years were carried out in Saaremaa grid. The main interest was on Läätsa 35/10 kV substation, where at presently 3 MW of wind turbines are connected. First results were presented to Saaremaa distribution grid operator in [61] and further analyzed in [IX, 62].

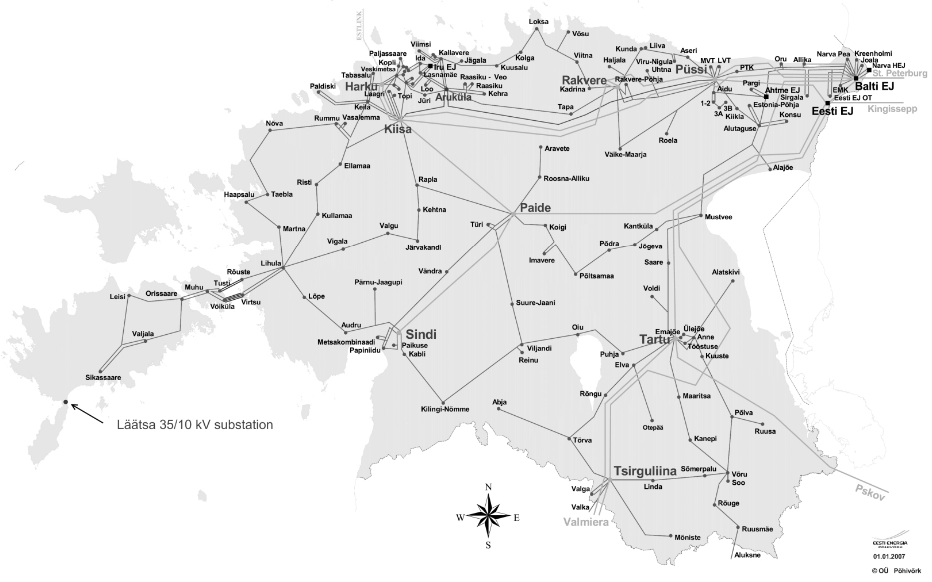

Figure 5.2. Map of the Estonian power system 110 – 330 kV [11]

Läätsa 35/10 kV substation is situated in the southwest corner of Saaremaa (see Fig. 5.1 and Fig. 5.2) and connection to main 110 kV substation is made through one 35 kV overhead line which limits the WTG-s installation in the region. The investigated wind park is connected to Läätsa 35/10 kV substation on 10 kV level. During the first measurements in 2004 the wind park consisted three 500 kW wind turbines. By year 2007 three 500 kW WTG were added and wind park contains 6 turbines with total capacity of 3 MW, two Vestas V-39 induction generators coupled directly to the grid and four 500 kW gearless, synchronous, Enercon E–40 generators. Further details about measurements locations, measured equipment and grid characteristics can be obtained from [III, 62].

On the basis of results it can be concluded that at times there are moderate deviations from average voltage quality including brief emersions from the limits set in the standard. Unfortunately there is no information about the voltage quality prior to the installation of wind turbines and therefore these measurements do not give cause to blame only the wind turbines for violating the voltage quality, although the incidents have occurred apparently are associated with them. Reactive power consumption or excessive production was not observed. Power coefficient during the full operation of wind turbines was close to one. The analysis shows that limiting values of fast voltage changes given in standard EN 50160:2000 [63] was frequently exceeded in comparison to nominal supply voltage. Permitted maximum value in an hour was exceeded several times. Also, large values of flicker and total current harmonic distortion have been noted during short periods. Based on measurements made in 2008, it was noticed that THD I in full or half power (wind park output was more than 1 MW) was within limits according to standard [63]. When the wind speed decreased and wind park generation was below 1 MW, the THD I value was exceeding its limit of 5%. According to [18], there is no known instance of customer annoyance or damage to equipment as a result of harmonic emissions from wind turbines based on induction generators. Same statement can be seen from [63] where harmonic measurement must be made only for wind generators with converter.

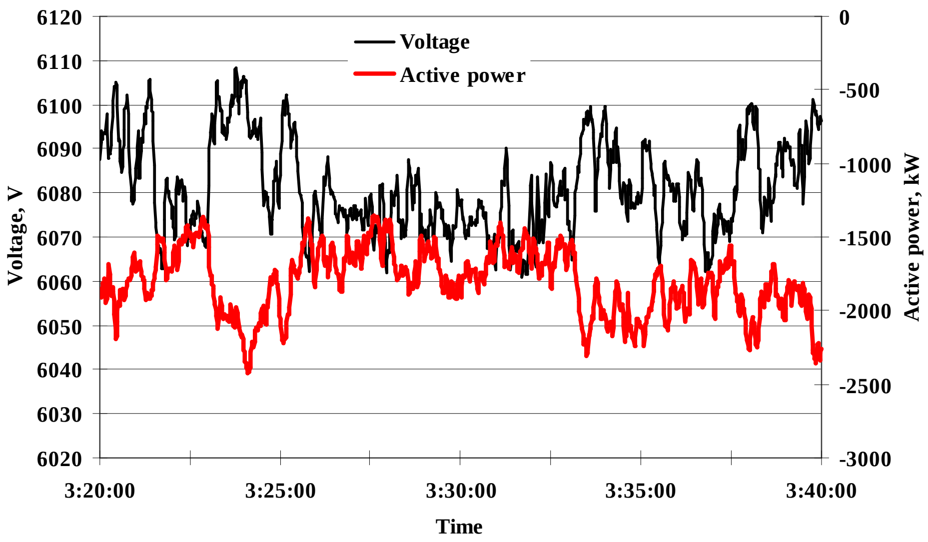

Figure 5.3. Voltage and active power fluctuations in Läätsa 10 kV substation

On Fig. 5.3, in order to present active power injection, time period during the night has been selected, as the overall consumption should be constant and only WTG-s power generation is fluctuating. The active power on is measured as negative load to the power system. The reactive power was also monitored, but during the normal operation no direct correlation to voltage was observed, but when active power generation increased, the increase in reactive power was noticed.

There have been some flicker values above limit set by standards, but they might be initiated by switching operations or by short circuits in local grid. What was noticed for the first time during the measurements were the differences of flicker values in different phases. In Phase 1 the value of flicker was 0.22 while in phase three it was 0.37. There is no information about single phase load, which might cause flicker unevenly between phases. Differences in phases were also noticed on 35 kV side in Sikassaare substation [III].

As there was no direct contact with wind park owners, thus source of any abnormal event caused by planned work or regulation in wind turbines was unnoticed. Graphics presented in this paper are valid only for this measured grid with abovementioned wind turbines and are not expandable as typical characteristics. As the EVS-EN 50160:2000 [63] standard standardises voltage quality in consumer connection point and does not regulate disturbances caused by single devices, the validity of standard EE 10421629 ST 7:2001 [64] has also to be considered when connecting the wind turbines.

5.4. Modelling of weak grid containing wind turbine generators

The impact of WTGs impact on the local grid was analysed using modeling software *PSCAD/EMTDC*. When modeling the weak grid, several simplifications were used.

The distance between investigated Läätsa wind park and main power stations in Narva (see Fig. 5.1 and Fig. 5.2) is relatively long and for modeling power quality in weak grid distribution grid the three-phase voltage source model is sufficient to be used. The source impedance is entered in rectangular $R+jX$ format and positive and zero sequence impedance values in ohms are as follows:

$Z_1 = 18.2967 + j54.9907$, $Z_0 = 18.3150 + j55.0127$

Substations are modeled without switching equipment, busbars, measuring and relay protection equipment and surge arresters. Transformers are modeled without tap changers and core saturation is not considered. For 110 kV power lines the frequency dependent model is used, whereas on lower voltage levels and on shorter lines the π-section models are used to increase the calculation time and solution step [66]. All the loads are presented as static load models and characteristics of different load classes for residential and commercial areas are taken from [67]. While minimum and maximum loads on Saaremaa vary between 9 MW and 40 MW the load in this case is 27 MW which corresponds to average load. Aggregated model of Saaremaa grid is given on Fig. 5.4.

The induction machine model was used for modeling wind fluctuations and impact of sudden power injection. The purpose of this modeling was to look at grid conditions and to look for the impact of power fluctuations on voltage as was distinguished during the measurements. Therefore under these circumstances the use of specific wind turbine generator type was taken to be irrelevant.

The wind source used in *PSCAD/EMTDC* model in this case in based on Anderson *et al*. model described in [68]. Anderson uses a four-component model defined by the equation (5.1)

$$V_W = V_{WB} + V_{WG} + V_{WR} + V_{WN} \tag{5.1}$$

where,

V_{WB} – base wind velocity

V_{WG} – gust wind component

V_{WR} – ramp wind component

V_{WN} – noise wind component

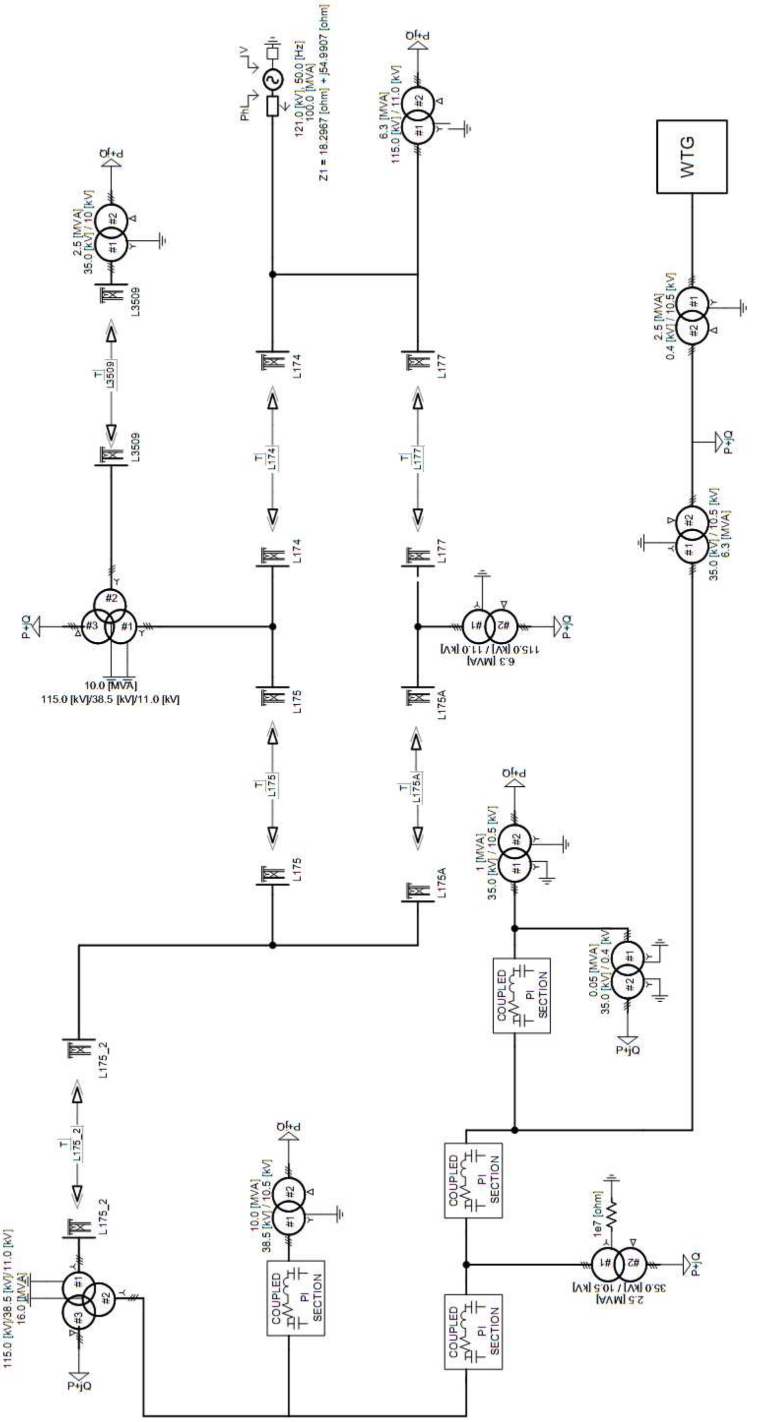

Figure 5.4. Aggregated model of Saaremaa grid in PSCAD/EMTDC

In the calculations used hereafter the impact of gust and noise component was observed. In the used examples, the highest gust speed was 8 m/s for duration of 3 seconds. The duration and amplitude of possible wind gusts was derived from [69].

Fig. 5.5 shows the resulting voltage fluctuations in per unit (p.u.) on 10 kV side depending on the installed power of the wind park. In this case for modelling only the noise wind component is used. It is obvious that in case of large number of installed power, the resulting fluctuations are the largest. If more WTG-s with higher capacities are installed, the voltage in the grid rises, but is not presented on figures, as no tap changers on transformers are modelled and the per unit values are calculated from average voltage on that installed power level not from voltage level without WTG-s.

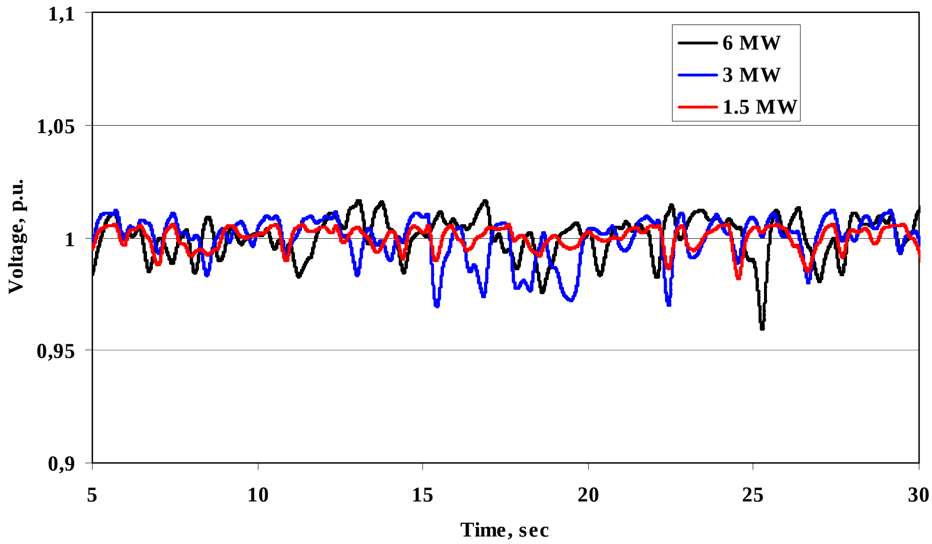

Figure 5.5. Resulting voltage fluctuations modelled at 10 kV side

In order to see the affect of rapid increase in active power on voltage the gust effect is introduced. Wind gust as 8, 6, 4, 2 meter per second higher then average wind velocities results in power increase by 1.2, 1.1, 0.9 and 0.5 MW respectively as seen on Fig. 5.6. On Fig. 5.7 the resulting voltage fluctuations are given. The rapid voltage changes during constant operation do not exceed 4% from nominal voltage and only in some cases the exceeding may be up to 6% [63]. Both limits are also depictured on Fig. 5.7. These results describe the impact of the wind park also to local consumption as they are connected to the same transformer on 10 kV side.

With the aim of controlling the correspondence to real grid conditions, the 3-phase short-circuit on 35 kV side was applied and merely 700 amps were measured.

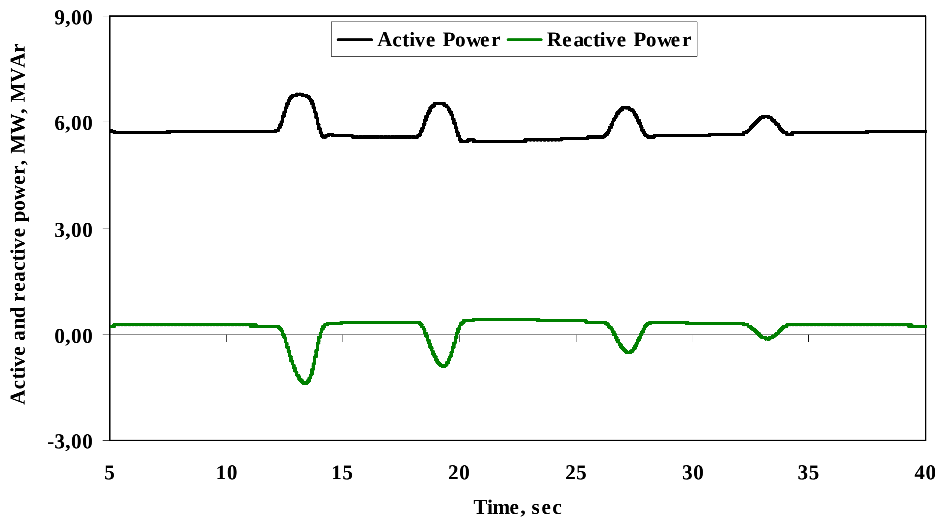

Figure 5.6. Modelled active and reactive power injections measured at 10 kV side

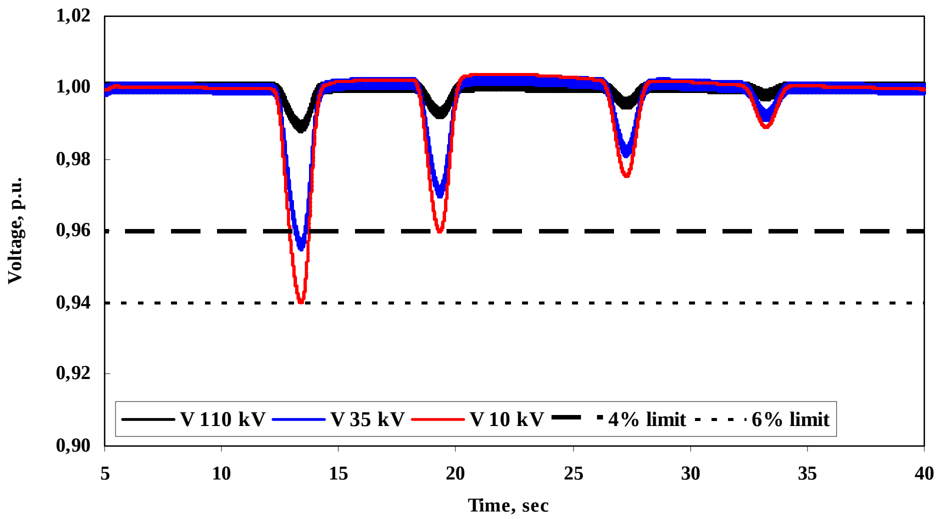

Figure 5.7. Resulting voltage fluctuations at 10, 35 and 110 kV side and voltage limits

If the values of current and voltage are known, the short-circuit power S_k can be calculated:

$$S_k = \sqrt{3} U_{line} \cdot I_k^{3f} \quad (5.2)$$

where,

U_{line} – line-to-line voltage

I_k^{3f} – 3-phase short-circuit current

Based on equation (5.2), the short-circuit power S_k in Saaremaa 35 kV grid is approximately 24,5 MVA a which corresponds to the real situation.

Estimating possible upper limit on power of WTG-s in Saaremaa 35 kV grid, it is taken that theoretical maximum power that can be generated by wind turbines without thermally damaging equipment is the situation where the local load is the lowest and output from the wind park is the highest i.e. $\underline{S}_{load} \approx 0$, and $S_{WTG} \leq S_{i\ \max}$. If we consider that the maximum allowed ampacity for AC-35 wire is $I_{35\ \max}$ = 175 A in 35 kV power lines, the total power output in best cases is less than

$$S_{35\ \max} = \sqrt{3}\ U_n\ I_{35\ \max} = \sqrt{3} \cdot 35 \cdot 175 = 10{,}6\,\text{MVA}. \qquad (5.3)$$

The real situation is that consumption in grid where AC-35 wire is used today is around 0.4 MVA and towards the end of line other wind turbines are already connected, which reduces the allowed amount of WTG-s even when no power quality issues are concerned.

5.5. Conclusions

Based on the measurements made in Läätsa 35/10 kV substation, according to EN 50160:2000 standard the wind park has caused considerable power quality crossings. Integration of wind turbines into weak distribution grid requires precise evaluation of grid conditions with reviewing the wind turbine characteristics. For avoiding later disagreements between wind park owners and grid operators on connecting WTG-s into weak grid, the field measurements in the connection point should be made prior to giving out the permission for connection.

Lowest power consumption on island during summer is 9 MW and as modelled on power system load on 26 MW the 6 MW of installed wind turbines results in considerable voltage fluctuations.

Based on the calculations presented here and the measurements, the existing grid does not withstand the instalment on considerable amount of wind turbines without grid improvement.

Conditions concerning power quality in Saaremaa are not improving until there are investments made into the local grid or the connection to mainland.. The first important thing to do for opening more extra WTG-s capacities in Saaremaa, is to replace existing six 35 kV cables with at least two 110 kV cables. The 110 kV cable is planned to build in 2014-2015. Also in mainland, the very important Lihula 110 kV substation must be renovated from 110 to 330 kV to provide more grid capacity and increased quality of supply. The renovation can be made together with other wind power projects on mainland, which could eliminate some of the bottlenecks in the transmission grid.

As the wind conditions on Saaremaa and offshore of Saaremaa are sufficient the grid conditions could be improved when bigger projects are planned to be connected on Saaremaa or Hiiumaa [VII].

6. CONCLUSIONS AND FUTURE WORK

Results presented hereinbefore are based on papers written during the last six years and gives an overview of author's field of research during those years.

The main part of the work is focused on the cooperation of wind turbine generators with thermal power plants. When larger number of fluctuating energy sources are introduced the power system must respond also with fluctuation. This increased fluctuation is basis for increased overall fuel consumption and depends on the participating power plants. It is assumed that similarly to conventional power plants, also the wind park operators are obligated to present their power generation forecast. If there is unbalance between forecasted and actual generation, the gap must be covered with additional generation.

Two different approaches with different additional generation unit sizes are used. Firstly, the opportunity to cover forecast error in a small wind park with 6.1 MW gas engine power plant is investigated. As a result inevitably emitted hazardous gases are calculated and the calculation method described. Secondly, the opportunity to balance large onshore or offshore wind park with oil-shale power plant with 100 MW balancing range is investigated. In calculations the linear cost characteristics are compared to dynamic load characteristics. The amount of the emitted hazardous gases and reduced efficiency of the working units shows that it is not an emission-free way to balance wind fluctuations with thermal power plants. The supplementary generation can not be avoided, because electricity balance in the system has to be guaranteed. Emission can be further reduced if we can raise the wind speed forecasting quality, but the need for keeping the balancing reserves still remains. It is concluded that the increase by two percent is inevitable as the balance in power systems must be guaranteed at every moment regardless of the connected generating units.

This information is essential for power system operators, thermal power plant operators and for governmental bodies and to all others who calculate fuel consumption, emissions and deal with long- term planning and decision making. It is useful for wind park operators in case the obligation to assure forecast accuracy is introduced and penalties for not fulfilling the forecasts are implemented.

In the second part the power quality issue in the weak power grid is investigated. It is measured and proved with modelling in *PSCAD/EMTDC* software that there are problems with power quality in the existing grid and before more wind turbine generators are installed the grid needs improvement. Provided results are useful for wind park developers who plan to install wind turbine generators, or to other consumers with sensitive power equipment that could be influenced by power quality not corresponding to set standards. Information is also essential to grid operators for planning investments. Grid operator on Saaremaa is aware of the measurement results presented hereinbefore.

There are several other sides of wind energy integration that are not analysed here. Deliberately so far no attention is drawn to economic questions as the situation can be entirely changed with support mechanisms. Suffice it to say that subsidies can be given and withdrawn, but physical principles can not be changed. The idea of economic impact is in progress as the requirement for balancing and grid improvement makes the integration of wind energy more expensive and extends the payback time of total investments.

The work with previously discussed issues does not end here. As the use of renewable energy sources is increasing, the methodology to calculate fuel consumption should be further developed to take into account the different power stations, longer data period and to get more accurate results. At the moment historical recorded data is used, but the uncertainty factor and incomplete information should be included to correspond to a more real situation.

The research on power quality continues with modelling, as at the moment several simplifications were used and several open issues remained unsolved. More elements and whole power system could be included to improve the accuracy of model. With a smaller model the impact of different types of wind turbines should be investigated which were currently excluded. Also the measurements should be continued as several new wind turbines are presently being erected on Saaremaa island and their direct impact on power quality is unknown.

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I. **Palu, I**., Tammoja, H., Oidram, R. Thermal power plant cooperation with wind turbines. *Estonian J. Engineering*. 2008. Vol. 14, No. 4. Estonia, 317–324 pp.

II. **Palu, I**., Oidram, R., Keel, M., Tammoja, H. Balancing of wind energy using oil-shale based power plants at erroneous wind forecast conditions, *Oil Shale*, Vol. 26, No. 2 Special, Estonia, 189–199 pp.

III. **Palu, I**., Agabus, H., Oidram, R. "Power quality in weak grids containing wind turbines," *IEEE Power Quality and Supply Reliability Conference, 2008*, Pärnu, Tallinn University of Technology, 2008, 125-130 pp. Copyright IEEE

IV. Oidram, R., Landsberg, M., Agabus, H., Attikas, R., Ojangu, J., **Palu, I.** Problems Related to Grid Connection in Pakri Wind Park. In: *Grid Integration and Electrical Systems of Wind Turbines and Wind Farms: Nordic Wind Power Conference*, 22-23 May, 2006, Espoo, Finland. VTT, 4 pp.

V. Kilter, J., Landsberg, M., **Palu, I**., Tsernobrovkin, O. Verification of Wind Parks and their Integration into Small-Interconnected Power System, In proceedings *IEEE PowerTech* 2009, 28 June - 2 July 2009, Bucharest, Romania, 6 pp.

VI. **Palu, I**., Agabus, H. Wind energy intecration impact on power quality in Estonia. In: *European Wind Energy Conference 2007*, Milano, Italy, 8-10 May 2007. 6 pp.

VII. Agabus, H., **Palu, I**. Tammoja, H. Hiiumaa large-scale offshore wind park integration into Estonian grid. In: *Proceedings 7th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms*, Madrid, Spain. Energynautics GmbH, 498 – 501 pp.

VIII. Oidram, R., Tammoja, H., Keel, M., **Palu, I**. Wind power cooperation with energy storing units and cogeneration power plants. In: *Proceedings of CIGRE NRCC Regional Meeting "Security and Reliability of Electric Power Systems"*: CIGRE NRCC Regional Meeting, Tallinn, Estonia, June 18-20 2007. 15 – 21 pp.

IX. Palu, I. Power Quality in Weak Grids Containing Wind Turbines, 7th conference proceedings: Investigation and usage of Renewable Energy Sources, OÜ Halo Kirjastus, Tartu, Estonia, 2006, 25 – 30 pp. (in Estonian)

ABSTRACT

Impact of Wind Parks on Power System Containing Thermal Power Plants

Electricity consumption is increasing all over the world and also in Estonia. European Union has set limits on allowed emissions for power generation and renewable energy sources are introduced to meet these requirements. Comparing to thermal power plants, where fuel deposits are collectable and power production therefore predictable and controllable, the renewable energy sources, especially wind energy, is variable and complicated to predict. Power systems where power generation is mainly based on thermal power plants, the capacity of wind turbines is not replaceable with the capacity of thermal power plants in one-to-one relation. One unit of generated electricity in the wind park does not reduce emissions from thermal power plant in same amount. Until presently the capacity of wind turbines could not be taken into account for planning peak load in the power systems.

The main idea of introducing wind turbines in its early stages was to reduce the dependence of imported fossil fuels. The obligation to reduce emissions with wind turbines is added recently. The latter requirement is very important in Estonia where most of the electricity is generated using fossil fuels. In order to reduce power fluctuations in the system, it is estimated in this thesis that wind park operators should provide wind parks power forecast for the next day and should be obliged to fulfil these forecasts by means of external generation. Two possible options are taken into consideration. Firstly, the opportunity to balance small wind fluctuations with fast regulating gas engine power plant in a range 5 to 15 MW is investigated. As a result of balancing obligation and operating on partial load, additional specific fuel consumption, reduction in overall efficiency and the cost of constant operation is calculated. Secondly, the possibility to use large oil-shale power plant for covering wind power forecast error is analysed. Power plant with regulating capacity of 100 MW is suitable for cooperating with large onshore or off-shore wind parks. In the calculations the differences between dynamic and linear fuel cost characteristics of the power plant are considered.

Wind turbine generators are mainly erected in regions with sufficient wind potential. These locations are not always with the strongest electrical networks and installing generating units into those regions might have impact on local power quality. Due to that reason the second part of the thesis is focused on power quality issues in weak grids. As an example of the weak power grid, Saaremaa island and wind park connected to Läätsa substation is used. During the implementation of this study several measurements on Saaremaa were carried out and collected data was analysed and results compared to modelling results by using *PSCAD/EMTDC* software.

The outcomes of this thesis are additional costs that occur when using thermal power plants for balancing wind power fluctuations. It is concluded that in the power system that consist mainly of thermal power plants, the positive effect of wind turbines in considerably smaller compared to the power system with variety of generating units.

KOKKUVÕTE

Tuuleparkide mõju soojuselektrijaamadega energiasüsteemile

Maailma, sealhulgas ka Eesti, elektritarbimine kasvab. Seoses Euroopa Liidu poolt kehtestatud piirangutega elektrijaamade poolt eraldavatele heitmetele võetakse järjest rohkem kasutusele tuuleenergiat. Võrreldes traditsiooniliste elektritootmistega, kus kütusevaru on reaalselt mõõdetav ning seega elektritootmine prognoositav ja juhitav, on tuuleenergia juhuslik ja raskesti prognoositav. Energiasüsteemides, kus peamisteks elektrijaamadeks on soojuselektrijaamad ei anna tuulikute süsteemi lisamine üks ühest võitu. Ühe ühiku elektrienergia tootmine elektrituulikutega ei vähenda samas mahus heitmeid, mis kuluks muidu soojuselektrijaamas selle ühiku tootmiseks. Elektrituulikute juhuslikkust arvestades, ei vähenda rajatud ühik tuulevõimsust soojuselektrijaamade koormust. Samuti ei saa arvestada süsteemi tipukoormuste prognoosimisel elektrituulikute võimsusega.

Elektrituulikute püstitamise peamine ja algne idee oli vähendada elektrienergia tootmisel imporditavate fossiilkütuste osakaalu. Alles viimasel ajal on tuuleenergiale pandud kohustus vähendada keskkonnasaastet. Just viimane asjaolu on Eestis väga tähtis, sest seni on elektrienergiat toodetud ja süsteemi võimsusbilanssi hoitud suurte põlevkivi põletavate soojuselektrijaamadega. Käesolevas töös on eeldatud, et kõik tuulepargi operaatorid peavad esitama oma järgmise päeva tuulevõimsuste prognoosi ja seda prognoosi vajadusel katma teiste genereerivate vahenditega. Vaatluse alla on võetud kaks võimalikku lahendust sõltuvana kaetava võimsuse vajadusest. Esimene lahendus oleks kiirelt reguleeritavad maagaasil põhinevad gaasimootorid suurusega 5 kuni 15 MW. Uuritud on nende talitlust osakoormusel ja sellisest talitlusest tulenevat kasuteguri langust, suurenenud kütuse erikulu ja tasakaalu kindlustamise tõttu tekkinud täiendavat ülekulu ja heitmeid. Teise võimaliku lahendusena on uuritud suurte põlevkivielektrijaamade kasutamist tuulevõimsuse prognoosivea katmisel. Selline, 100 MW tasakaalustamisvõimsusega elektrijaam oleks sobilik balansseerima suuremat tuuleparki maal või merel. Uuritud on kiireid muutusi elektrijaama töös, kasutades katla dünaamilisi karakteristikuid.

Tuulikuid paigaldatakse ennekõike piirkondadesse, kus on hea tuuleressurss. Tihti puudub seal aga piisavalt tugev võrk ning elektrituulikute paigaldamine piirkonda võib avaldada tuntavat mõju kohalikule pingekvaliteedile. Sellest tulevana on käesoleva töö teine osa pühendatud elektrienergia, peamisele pingekvaliteedi uurimisele nõrkades elektrivõrkudes. Näidisena on kasutatud Saaremaad ja Läätsa alajaamaga ühendatud tuuleparki. Töö valmimise käigus korraldati korduvalt mõõtmisi nimetatud alajaamas ning tulemusi analüüsiti ning hiljem modelleeriti kasutades *PSCAD/EMTDC* tarkvara.

Uurimustöö tulemusena on leitud täiendavad kulud, mis tekivad fossiilkütuseid põletavates elektrijaamades, kui neid kasutada tuuleenergia tasakaalustamiseks. On järeldatud, et elektrisüsteemis, mis koosneb peamiselt fossiilkütuseid põletavatest soojuselektrijaamadest, on tuulikute positiivne efekt märkimisväärselt väiksem kui näiteks hüdroenergiat tasakaalustamiseks kasutavas elektrisüsteemis.

ELULOOKIRJELDUS

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3. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Lõpetamise aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2005	elektroenergeetika eriala, tehnikateaduste magister
Tallinna Tehnikaülikool	2002	elektroenergeetika eriala, tehnikateaduste bakalaureus
Rakvere Reaalgümnaasium	1998	keskharidus

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

Keel	Tase
Eesti keel	Kõrgtase
Inglise keel	Kõrgtase
Vene keel	Algtase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija nimetus
2004	Gotland University College, Rootsi
2004	EMD International A/S, Taani
2003	Fachhochschule Stralsund, Saksamaa
2002	University of Vaasa, Soome

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2005 –	Tallinna Tehnikaülikool	Assistent
2002 – 2005	Tallinna Tehnikaülikool	Laborant
2002	AS Eesti Energia	Käidutehnik

7. Teadustegevus

- Leping Lep8065 "Tuulepargi "Virtsu 2" mõõtmine ja analüüs vastavalt dokumendile "Tuuleparkide vastuvõtukatsed", põhitäitja
- Välisleping V365 “Energiasüsteemi analüüsimudeli arendamine”, põhitäitja
- Leping Lep8101 “Virtsu alajaama lühisekatsega seotud mõõtmised ja analüüs”, põhitäitja
- Välisleping VE379 “Viru-Nigula tuulepargi elektrikvaliteedi mõõtmised vastavalt ettevõttestandardile EE10421629 ST”, täitja
- EL Phare CBC 2003 projekti „Tuuleenergia rakendamine ja integreerimine energiasüsteemiga Balti mere regioonis“ I etapi assistent, II etapp juht
- Leping Lep9031 “Eesti elektrisüsteemi eralduskatsega seotud mõõtmised ja analüüs”, täitja
- Leping Lep6016 Alalisvooluühenduse ESTLINK mõju uurimine pinge ja võimsuse kvaliteedile Harku alajaamas, täitja
- Välisleping V232 EL INTERREG IIIb projekt "Tuuleenergia Balti mere regioonis - planeerimine, ehitamine ja investeerimine", täitja
- Välisleping V292 „Elektrikvaliteedi mõõtmised vastavalt standardile IEC 61400-21“, täitja
- Leping 505L “ Võrku ühendatud elektrituulikute mõju hindamine elektrivõrgu talitlusele ja pingekvaliteedile vastavalt standardile EVS-EN 50160.2000 Saarte piirkonna Läätsa 35-10 kV alajaamas“

8. Kaitstud lõputööd

- Magistritöö: “Pingekvaliteet elektrituulikuid sisaldavas nõrgas elektrivõrgus”, 2005 juhendaja dots. Rein Oidram
- Bakalaureusetöö: “Maaühenduse modelleerimine Kehra alajaamas”, 2002 juhendaja dots. Rein Oidram

9. Teadustöö põhisuunad

Elektrituulikute ja energiasüsteemi koostöö modelleerimine, tuulikute võimsuse tasakaalustamisel tekkiva täiendava kulu analüüsimine, tuulikuid sisaldava nõrga võrgu pingekvaliteedi mõõtmine ja analüüs

CURRICULUM VITAE

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2. Contact information

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3. Education

Educational institution	Graduation year	Education (field of study/degree)
Tallinn University of Technology	2005	electrical power engineering, master of science
Tallinn University of Technology	2002	electrical power engineering, bachelor of science
Rakvere Real-Gymnasium	1998	secondary education

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

Language	Level
Estonian	fluent
English	fluent
Russian	basic skills

5. Special Courses

Period	Educational or other organisation
2004	Gotland University College, Sweden
2004	EMD International A/S, Denmark
2003	Fachhochschule Stralsund, Germany
2002	University of Vaasa, Finland

6. Professional Employment

Period	Organisation	Position
2005 –	Tallinn University of Technology	Teaching assistant
2002 – 2005	Tallinn University of Technology	Laboratory assistant
2002	Eesti Energia AS (Estonian grid company)	Grid technician

7. Scientific work

- Project leader of Phare CBC 2003 project “Introduction and integration of wind power in the Baltic Sea Region – Phase II”
- Estonian partner from TUT of INTERREG III B project “Wind energy in the BSR – Planning, Construction and Investment”
- Contractual work “Assessment of the effect of wind turbines, connected to the network in Läätsa 35/10 kV substation of islands region, to the network operation and voltage quality according to the standard EVS-EN 50160:2000”
- Contractual work “Power Quality Measurements of Viru-Nigula Wind Park acc. to Company Standard EE10421629 ST”
- Contractual work Electricity Quality measurements Acc. To IEC 61400-21 “Power Quality of Wind Turbines”
- Nordic Energy Research project “Model development for Power Systems”, Estonian side project leader

8. Defended theses

- Master Thesis: “Power quality in weak grids containing wind turbines”, 2005, supervisor assos. prof. Rein Oidram
- Bachelor Thesis: “Earth-fault simulation in Kehra substation”, 2002, supervisor assos. prof. Rein Oidram

9. Main areas of scientific work/Current research topics

Wind turbine generators cooperation with power system, analysis of additional fuel costs on balancing wind power fluctuations, measurements and analysis on weak grid containing wind turbine generators.

APPENDIX A

I. Palu, I., Tammoja, H., Oidram, R. Thermal power plant cooperation with wind turbines. *Estonian J. Engineering*. 2008. Vol. 14, No. 4. Estonia, 317–324 pp.

II. Palu, I., Oidram, R., Keel, M., Tammoja, H. Balancing of wind energy using oil-shale based power plants at erroneous wind forecast conditions, *Oil Shale*, Vol. 26, No. 2 Special, Estonia, 189–199 pp.

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