

Wind Energy in Estonian Western Farmlands

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ABSTRACT

Based on wind monitoring data in the Western-Estonian area the probable values of the wind speed fluctuations and frequency of the switch-on events are calculated. Using an empirical expression of the wind turbine power curve wind speed fluctuations is calculated to wind power fluctuations and voltage fluctuations on the bus of the substation. A study of existing load in Fortum Elekter Company shows restrictions for the rated capacity of wind turbine generators to be installed.

Key words: wind speed, wind power, bus voltage, fluctuation.

1. INTRODUCTION

Estonia is considered to be rich in wind. This point of view is widely accepted in the society and a number of Estonian farmers are interested in utilization of their fields as an additional source of income. Unfortunately a lot of objective and subjective problems exist in this case. The first problem is the inequality of wind speed over the territory: in the western archipelago and on the western coastal line it's really good ($5.5-7.5 \text{ ms}^{-1}$ @10 m¹), but there the density of population is low and the grid is weak. On the northern coast wind speed is rather good ($4.5-5 \text{ ms}^{-1}$ @10 m), but it has not been studied on the technological heights of 40–60 m yet. In the mainland, far from the coast wind speed has a low value ($3-4.5 \text{ ms}^{-1}$ @10m) due to large forest areas (47% of the Estonian total area is covered with forest). The electrical grid is rather well developed here.

Second problem is the grid itself supplied by inertial thermal power plants performing on local fossil fuel oil shale. The yearly load curve of the grid has a large (two times) difference in winter and summer. This quality will make more difficult the utilization of wind resource here, as we have proved below. For example, in Denmark the load in winter and summer differs only by ~30%.

The critics of wind energy refer to voltage fluctuations in the grid, caused by stochastic wind capacity, as a significant restriction. We will prove that is not the full truth. The voltage instability is the result of wind speed fluctuations (flicker, if they are frequent) and voltage dips, which are caused by switch-on of wind turbine generators (WTG).

A statistical approach to voltage *instability* is used in our work. The quality of voltage in grids, supplied by wind turbine generators (WTGs) is analyzed (Tande et al., 1997; Marques da Silva et al., 1998; Lemström et al., 1999; Estanqueiro, 1999; Parsons et al., 2001; Rosa et al., 2001; Mur et al., 2003; Jorgensen et al., 2003). It is essential to do such an analysis based

¹ The height is shown by the character „@“

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on local conditions. The analysis below is made in relative units and this kind of approach allows to finding numerical results for each particular event. The capacity of a WTG is denoted P_W^* , the capacity of a transformer is denoted P_T^* , the capacity of a load is denoted P_L^* , etc.

2. DATA SERIES USED

We use wind speed data at Harilaid site (HRL, 23°3' E 58°56' N), recorded in 1997–98 at the heights of $H \in \{50 \& 20 \text{ m}\}$. We use data at Kihnu site (KHN, 23°58' E 58°6' N) @27 m and 10 m, recorded in 1999–2000, Keibu site (Cape of Ristinina RSN, 59°17' N 23°44' E) @32 m in 2001–02 and Avaste Hill site (AVA, 58°37' N 24°05' E) @27 and 10 m in 2002–03 as well. The used data are averaged values of the wind speed and its standard deviation over 10 minute sampling periods.

Harilaid is a low islet in the middle of Hari Sound, without trees and population, at a distance of several kilometers from the surrounding bigger islands. This site is an example of offshore conditions. Kihnu site is located at the waterline on the coast of a small island and characterizes such ones. Cape of Ristinina is probably the windiest place on the North-Western coast of Estonia. Avaste Hill is located ~50 km away from the coast on the open farmland.

The data from RSN site are used to calculate generated wind power (by a virtual WTG @65 m) synchronously with the load of the local electrical substation Nõva (NVA). NVA is supplied by the grid of Fortum Elekter Company, which services the Estonian western county Läänemaa. These data are also used to find out the frequency of switch-on of WTGs and duration of pauses without generated wind power.

On the basis of load curves of the substations NVA and Lihula (LHL) a generalized model P_L^* of the countryside electricity consumption is calculated, to assess statistically based restrictions for the installed capacity of WTGs.

3. PROBABILITY OF THE CURRENT CAPACITY OF A WTG

For the RSN site the capacity of a virtual WTG is calculated transferring measured at 32 m height data to the height of 65 m using average Hellmann's coefficient $k_H = 0.25$ (Tomson et al., 2003), suited for the Estonian conditions. The results of analysis are shown in Fig. 1 and Fig. 2. In the analysis we refer on the load curve of a unified WTG, presented in (Tomson and Nõva, 2001).

Probable behavior of a WTG has three characteristic ranges:

- 1) Range of the zero production, where the relative capacity of the WTG P_W^* has the value $0 < P_W^* < 0.01$. Whereas the mean of probability has the value $\mu_{FP^*} = 16.1\%$ and it has the large standard deviation $\sigma_{FP^*} = 9.6\%$. The maximum probability of the down time exists in summer: it is backward correlated with the average wind speed.
- 2) Range of the rated power $P_W^* = 1$. There the mean of probability has the value $\mu_{FP^*} = 14\%$ and it has also the large standard deviation $\sigma_{FP^*} = 10\%$. The maximum probability of the full capacity exists in winter: it is correlated with the average wind speed.

Both ranges together are shown in Fig. 1. The monthly average value of capacity of WTG varies up to three times. The minimum average value of P_W^* in summer coincides with the minimum load in the grid.

- 3) Range of the variable capacity $0.01 < P_W^* < 1$ (Fig. 2) where the average probability has an exponential character $18.5 > \mu_{FP^*} > 2.5\%$ and its standard deviation does not practically depend on time (month) $2.4 > \sigma_{FP^*} > 1.3\%$, if $P_W^* > 0.1$.

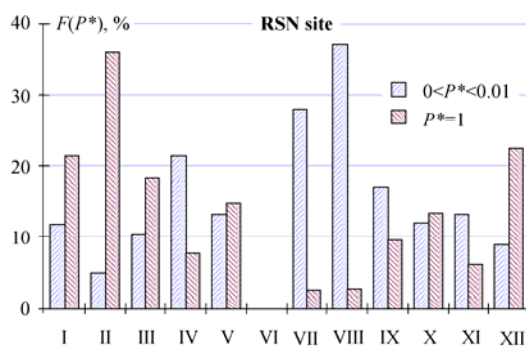


Figure 1. Frequencies of the extreme wind capacity.

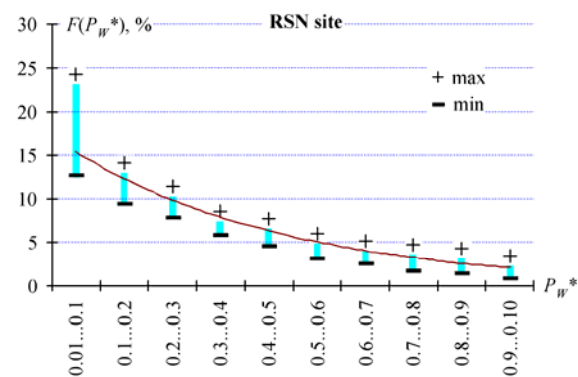


Figure 2. Frequencies of the wind capacities in the performance range.

It is essential that probabilities performing with zero or rated capacity are higher than those with any other capacity in the range between them. Therefore both the extreme ranges $P_W^*=0$ and $P_W^*=1$ require a full attention and their analysis has to be made at the proxy probability $\mu_{FP^*}=100\%$.

4. THE FREQUENCY OF VOLTAGE DIPS CAUSED BY SWITCH-ON OF WTGs

For the RSN site the frequency of voltage dips is found on the basis of transferred to the height of 65m wind speed data proceeding from the conditions $P_W^*=0$, if $u < u_{start}=3.75 \text{ ms}^{-1}$ and $P_W^*=0$, if $u > 25 \text{ ms}^{-1}$. The winds in Estonia are modest and during 2002 a virtual WTG in

RSN site was broken only five times:

05. II 02	00:50 – 02:50
25. I 02	06:40 – 02:20 (26. I 02)
09. III 02	15:40 – 16:00
1. V 02	16:00 – 19:20
21. XII 02	03:50 – 04:30

Only in the last case WTG was temporary started inside given time span, in other cases wind speed was continuously over the braking speed $u_{brake} > 25 \text{ ms}^{-1}$. The winds with high speed are, at the same time, stable winds (Tomson and Hansen, 2001). No power fluctuations can be found over the braking wind-speed. Corresponding the high probability of powerless situations $P_W^*=0$ they are much more significant. Their analysis is made also for the RSN site, selecting all events when for two samplings in sequence i and $i+1$, the conditions $P_W^*=0$ and $P_W^*_{i+1} > 0$ are followed. The results of the analysis show that the medium time-lag (interval) between two switch-on events is 9.25 hours and the medium duration of a powerless pause is 1.5h. The shortest interval is 20 minutes (the sampling interval is 10 min!) and the share of such events is 6.7%. The distribution law of intervals is close to an exponent and the longest interval was found to be ~ 10 days. The duration of powerless situation is of

the interest too. The shortest duration is 10 min and the longest ~ 1.5 days. The distribution laws of intervals F_i and durations F_d are both shown in Fig. 3. Minute-long and hour-long ranges are presented in the same time axis. All events in minute long-range belong also to the hour-long range “0...1h”, which is omitted in Fig. 3.

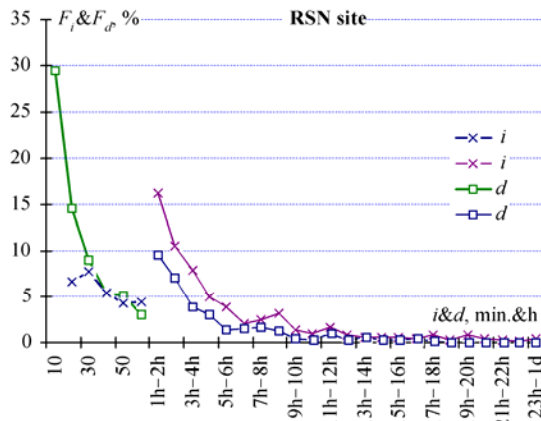


Figure 3. Frequencies of intervals with different length i . Duration of powerless pauses d .

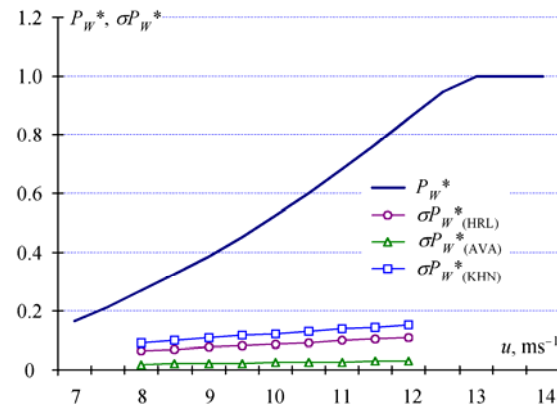


Figure 4. Average power curve of WTGs in the range of 1–2 MW and calculated deviation of the wind capacity.

Down times of WTGs due to still do not lead to “flicker” because of their low statistical frequency.

5. EVALUATION OF THE RISK OF POWER FLUCTUATIONS

5.1 Risky Range of Wind Speeds

Due to the nonlinear power curve $P_w^*(u)$ of any WTG (Tomson and Nõva, 2001) fluctuations of wind speed in the ranges $u > u_{stabil}$ ($\sim 12-13 \text{ ms}^{-1}$) and $u < u_{start}$ ($\sim 2.5-4 \text{ ms}^{-1}$) make no fluctuations of the instant capacity. In the range $4 < u < 8 \text{ ms}^{-1}$ the influence of wind speed to the capacity is insignificant and may be ignored. Therefore data series of wind speed at the upper sensor of each site are selected and analyzed only for samplings in the range $8 < u < 12 \text{ ms}^{-1}$. From the original ~ 8000 samplings (~ 2 -month long time span was analyzed for this target) the selected set contains ~ 2000 data for HRL and KHN sites and ~ 250 data for AVA site. The last one has low wind speed and limited number of samplings in the critical range. Data series in the RSN site could not be used for the following analysis, because there was an installed sensor only on the single height.

5.2 Standard Deviation of the Wind Speed at Different Sites and Heights

Results of the analysis are shown in Table 1.

Table 1. Average values μu and standard deviations σu of wind speed in different sites

Site	μu_{50}	σu_{50}	μu_{20}	σu_{20}	$\sigma u_{50}/\sigma u_{20}$
HRL	9.80	0.60	8.91	0.60	1
	μu_{27}	σu_{27}	μu_{10}	σu_{10}	$\sigma u_{27}/\sigma u_{10}$
KHN	9.94	0.84	7.53	0.96	0.87

	μu_{27}	σu_{27}	μu_{10}	σu_{10}	$\sigma u_{27}/\sigma u_{10}$
AVA	6.56	1.37	8.76	1.47	0.93

In HRL site standard deviations of wind speed are equal at the heights of 50 m and 20 m $\sigma u_{50} = \sigma u_{20} = 0.60 \text{ ms}^{-1}$. This phenomenon has two reasons: both sensors are mounted on the significant heights and the sea around has low roughness. There wind characteristics (as its dynamics) are equal on the different heights and rotor of WTG experiences no different fluctuations moving its position. Flicker can be expected due to the fluctuation of instant wind speed, hardly due to the rotation of blades.

In AVA site and in KHN site standard deviations @27 m and @10 m differ 7% and 13% correspondingly, due to lower position of sensors and higher roughness of the landscape in both sites. Altogether the differences in the dynamical behavior of wind on different heights are not significant and the main reason of wind power fluctuation lies in the fluctuation of wind speed, mostly invariant to the height.

5.3 Standard Deviation of the Wind Power at Different Sites and Heights

In the selected critical range of wind speed the averaged power curves $P_W^*(u)$ for number of Europe-made WTGs (powers range 1–2 MW) can be approximated with an empirical equation (Tomson and Nõva, 2001)

$$P_W^* = (u - u_{start})^{1.75} / 47 \quad (1)$$

From the derivate of that follows the sensitivity of WTG-capacity to the wind speed variations:

$$dP_W^*/du = (1.75/47) \cdot (u - u_{start})^{0.75} \quad (2)$$

Using the values of the standard deviation *Table 1*, which are rather modest² in Estonia, we can calculate desired fluctuations of wind power for each site.

$$\sigma(P_W^*) = \sigma(u) \cdot (1.75/47) \cdot (u - u_{start})^{0.75} = \sigma(u) \cdot 0.037 \cdot (u - u_{start})^{0.75} \quad (3)$$

From the latter equation we can see, that the standard deviation of wind power is a function of the average value of wind speed $\sigma(P_W^*) = f(u)$, shown in Fig. 4. Expedient is the maximum value of the calculated standard deviation of wind power, which corresponds to the site

HRL: $\sigma P_W^*_{50} = 6.1 \%$, AVA: $\sigma P_W^*_{27} = 8.4 \%$ and KHN: $\sigma P_W^*_{27} = 17.0 \%$.

The analysis of the year-long data series of the RSN site (44320 samplings) shows that the risk of power fluctuation (also of the voltage flicker) covers 29.5% of the time. Unfortunately our data cannot say anything about the frequency of fluctuations. It is known the most troublesome for the human eye is voltage flicker at 10Hz (Burton et al., 2001) and WTG has the quality of a low-pass filter with the cut-off frequency of 0.3 Hz.

The analysis of voltage fluctuations requires the knowledge of features of the grid, at the bus where WTG is connected.

² Formula (2) is not valid for large variations of the wind speed.

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6. LOAD CURVE OF THE SUBSTATIONS IN THE WINDY PLACES OF WEST-ESTONIA

6.1 Time Curve of the (Monthly) Average Load

In the work we have used the recorded with a sampling interval 15 minutes data of Fortum Elekter Company, which supplies the windiest areas in the western Estonian mainland. The monthly average load is shown in Fig. 5 together with the monthly average of generated wind power in RSN site. Data for the load in NVA are lacking in September, probably because of a failure in the recording system. In both investigated substation NVA and LHL some samplings with zero value $P_L=Q_L=0$ can be found, but while the load before and after such dips are always far from the minimum value, these events are considered as shortcut of lines or failures of the recording.

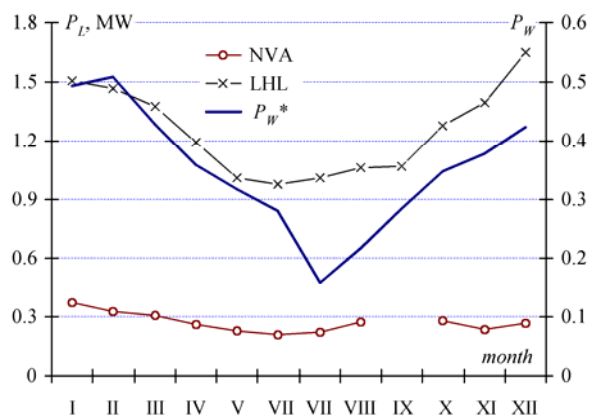


Figure 5. Load curves in Fortum Elekter substations NVA and LHL and the relative capacity of a virtual WTG in RSN site.

In any case we cannot consider these events as “zero loads” $S_L=0$ at the normal performance and they are ignored by the analysis. In the analysis we calculate relative to the average value standard deviation of the apparent power σ_s . In the relative units the distribution function of the standard deviation is practically constant invariant to the time of a year. The average over NVA and LHL distribution function of the standard deviation is shown in Fig. 6, compared with a normal distribution function at its standard deviation $\sigma_N=0.2$. Curves are close to each other and therefore we consider $\sigma_s=\sigma_N=0.2$. In Fig. 6 between the axial lines the interval of 3σ law is highlighted. The probability of any event outside the said interval is less than 0.1%. In the analysis the diurnal periodical component was not filtered out and the result shows total deviations from the average values.

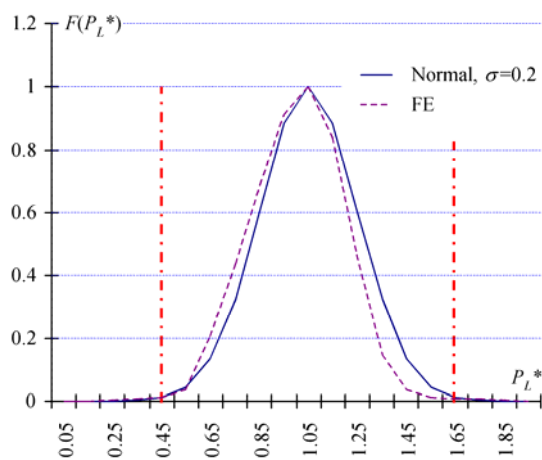


Figure 6. Comparison of the average power deviation of the Fortum Elektor Company and normal distribution diagram.

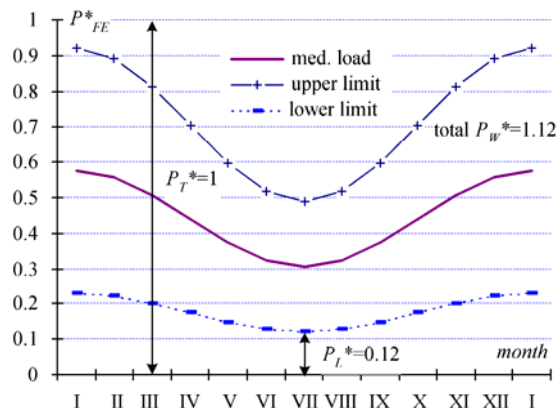


Figure 7. WTGs capacity, which can be installed, has restrictions.

6.2 Deviation of the Instant Load and the Limitation for the Installed Capacity of WTG

Considering the standard deviation constant $\sigma_s=0.2$ in relative units and varying value of the average load we can design an averaged load curve with limits of probable maximum and minimum load. A load has a stochastic value in the limits with the probability of 0.999. We can see the minimum load in parallel to WTG is 0.12 in the example Fig. 7, when we consider the rated capacity “1” with a small reserve (about 10%) over the possible maximum load. If the reserve were larger, for instance, twice of the maximum load, the relative value of the minimum should be 0.06 *etc.* The possible rated capacity of connected WTG equals to the rated capacity of the substation plus the minimal value of the local load in normal conditions. Failures with $S_L=0$ cannot be the basis for the design as the performance of a local load in parallel with the WTGs alone cannot be accepted and WTGs have to be switched off by each shortcut of the line. In the example Fig. 7 the rated capacity of WTG should be the sum of two vectors $P_W^*=P_T^*+P_{L^*min}=1+0.12=1.12$. As the analysis was made in relative units, there are no problems to find a numerical solution for the each particular case. We can conclude by this analysis, that a stabile load parallel to the WTG has some advantages. The Estonian geographical conditions with dark and cold winter do not support the utilization of wind energy; the conditions at the lower latitudes (Denmark, Germany, Spain *etc.*) are more favorable.

7. VOLTAGE FLUCTUATIONS FROM A CONSUMER'S POINT OF VIEW

Any consumer is interested to have a stabile voltage. How much does power supply fluctuate has no importance from his point-of-view. Local load $P_L \approx P_W$ with the capacity, close to the WTGs one and the grid with the infinite capacity $P_G \rightarrow \infty$ to the bus of the substation are connected. Between the bus and the grid a transformer is connected with its (leakage) reactance $X_T = u_k^* \cdot P_T$. Here $0.04 < u_k^* < 0.1$ is its relative short-circuit voltage, which has mostly the value $u_k^* = 0.06$. The transformer has normally light overcapacity concerning the WTG and their capacities are well correlated {600 kW \Leftrightarrow 630 kVA; 900 kW \Leftrightarrow 1MVA *etc.*}. Usually the condition $1 < P_T/P_W < 2$ is observed. With the help of the equivalent circuit (Fig. 8) the relation between the relative deviation of the bus voltage dU_W/U_W and WTGs power deviation dP_W/P_W can be found.

$$dU_W/U_W=(P_W/(P_L+P_T/u_k^*))^{0.5/2} \cdot dP_W/P_W . \quad (4)$$

In this equation there are too many variables. Observing $P_T/u_k^* \gg P_L$ the equation can be simplified. Considering $P_L=0$ and fixing $u_k^*=0.06=\text{const}$ the equation will be

$$\sigma_W=((0.06 \cdot P_W/P_T)^{0.5/2}) \cdot \sigma_{P_W} . \quad (5)$$

In (5) we have also substituted the relative variations dU_W/U_W and dP_W/P_W with their standard deviations. The variable σ_{P_W} is the standard deviation of current wind power, which leads to standard deviation of the bus voltage σ_{U_W} . Even at the largest turbulence of wind at KHN site $\sigma_{P_W} \approx 20\%$ the standard deviation of the voltage of the bus is in the range of $\sigma_{U_W} \approx 1...2\%$ Fig.9. Of course, we did consider here the grid being "ideal", without any "own" voltage variations.

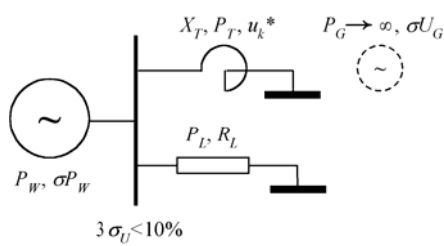


Figure 8. Voltage fluctuations can be calculated using the equivalent circuit.

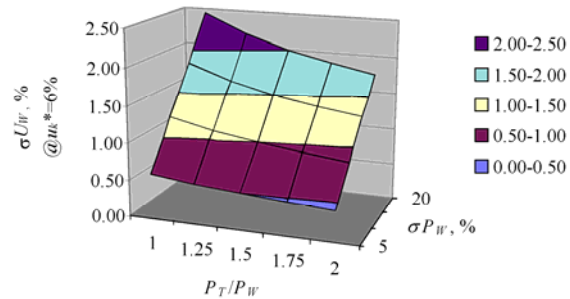


Figure 9. Voltage deviation on the bus can be calculated while the grid is ideal.

According to the investigations (Tomson et al., 2003) wind power and load of the grid have no correlation and because of that "own" disturbances of the grid σ_G and fluctuations caused by wind σ_{U_W} will be added geometrically. It is essential that the sum of disturbances should not exceed the limit $3\sigma_U < 10\%$. Proceeding from (5) a backward problem can be solved: how large could be the standard deviation of wind power if we limit the level of voltage fluctuation in the grid.

$$\sigma_{P_W} = 2 \cdot (\sigma_U^2 - \sigma_G^2)^{0.5} / (u_k^* P_W / P_T)^{0.5}, @\sigma_U = 10\% \quad (6)$$

The solution of (6) in the form of a diagram is shown in Fig. 10 and we can see that the share of disturbances due to wind power fluctuations is not comparable with disturbances of the grid itself. The problems with wind power fluctuations may appear only in case of a very weak grid at $3\sigma_G \rightarrow 10\%$.

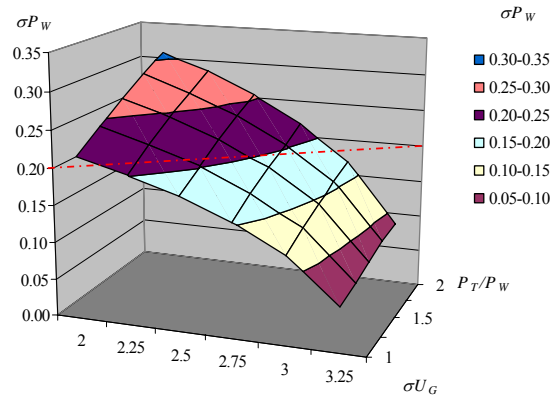


Figure 10. Permissible wind power deviation while the grid is real.

Real values of the voltage fluctuations on the bus, measured experimentally (Mur et al., 2003) are close to predicted theoretically values. Also a real wind turbine (E-40, 600 kW @63m) in Virtsu site (VRT, 23°30' E 58°36' N) had standard power deviation $\sigma_W = 6\%$ and average interval between switch-on events 8.2 hours during Nov.2002 till Oct.2003. These results show that predicted theoretically values are very close to the reality.

An abridged version of the investigation was presented in CIGR Agrar-Energy Conference, Budapest May 15 –19, 2004.

8. CONCLUSIONS

1. The switch-on events caused by still or overspeed of wind make no flicker problems due to their statistically low frequency for the Estonian consumers.
2. Winds with the power fluctuation risk cover 29.5% of time in Estonia.
3. Cut-off and performing at the rated capacity of WTG have both considerable probabilities. Each of them has essential variance, which is less if WTG is performing in the range of relative capacity $0.1 < P_W^* < 1$.
4. Fluctuations of the WTG capacity are in the range 6–18% in Estonia and they may involve fluctuations of the voltage on the substation bus in the range 1–2%. The normal load of windy countryside in Western Estonia is always over the zero value.
5. Fluctuation of the capacity of a WTG can limit its installation only for weak grids, which have “own” voltage fluctuations near the limit $3\sigma_G \rightarrow 10\%$.
6. Existing large yearly periodical component of the electrical load of the grid is a phenomenon, which makes restrictions for wind energy utilization in Estonia.

9. ACKNOWLEDGEMENT

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