The unsteady aerodynamic effects on small scale wind converters

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Abstract
The effects of unsteady flow on wind turbines are extensive. Wind, as one of the sources of energy, in a period when conventional sources of energy are becoming increasingly more economically demanding, comes to the fore. It is characterized by its variability and it is necessary to proceed with its description not only in terms of steady and thus "theoretical" flow, but in terms of unsteady flow in particular. Currently, extensive research is ongoing in the area of unsteady flow. Nevertheless, this phenomenon is still not understood sufficiently. This, in turn, translates into incorrect predictions and understanding of non-stationary phenomena. Despite this, there is only a limited amount of resources available in Slovakia dealing with this issue. The aim of this paper is the characterization and description of unsteady steady flow and their effects on small scale wind devices. On the basis of the simulation of flow on wind device, we are interested in quantifying the influence of unsteady effects and thus pointing at other areas in the development of wind turbines, in order to increase their performance and move toward the theoretical maximum.

INTRODUCTION

Small-scale wind turbines are mostly used throughout the world as separate sources of energy. Stand-alone wind systems are applied in remote locations (distanced from network), in boats, on farms or in small towns, cottages and other places used for tourism. Any such system can not only be practical but also economical for users. A small-scale wind turbine with a capacity of 100 to 500 W on a good windy location (with an average wind speed of more than 5 m/s) is able to economically supply energy into the battery and thus provide power e.g. for lighting, domestic hot water resistive heating, appliances, and heating.

The use of small-scale wind turbines by autonomous users has proved to be more beneficial than use of, for example, diesel generators, or resorting to power line extensions. The advantage is that the wind systems are not only relatively small, but it is possible to build them in a short period of time. In many countries, extending the electrical network to the customer by one kilometer is more expensive than the cost of building a small wind system.

Even though wind turbines are characterized by higher investment costs than diesel generators, their operation is virtually free and there are no problems for the owner in terms of fuel provision and transport.

Experience shows that energy produced by a wind turbine for a daily consumption at the level of one kWh is cheaper than energy from a diesel generator, electrical network extension or energy from photovoltaic cells. This applies to places where the annual average wind speed exceeds 4 m/s. The economy of wind turbines continues to improve to cover increasing daily consumption. For a turbine with an output of 10 kW, a wind speed of mere 3-3.2 m/s is sufficient to ensure that wind power is the cheapest alternative. There are only a few places in the world where the average wind speed is lower than 3 m/s. The purchase costs of small wind turbines, with respect to one watt, decrease with the power increasing.

Most of turbines are designed to charge the batteries and come already with their own charge controller which prevents batteries from overloading. The turbine itself consists of rotor blades, the alternator or dynamo, and the control electronics. A rudder, tightly coupled with the rotor, can serve to ensure the orientation of the rotor in the wind direction. To regulate the speed and secure the rotor against sharp wind gusts, a regulating rudder can be used. It either diverts the rotor from the direction of the wind at provided wind speed, or shuts it down by fully rotating the rotor axis perpendicularly to the direction of the wind.

The blades are usually made of fiberglass and shaped to avoid damage while rotating. The generator frequently has a permanent magnet excitation and often does not require maintenance. Regulatory and control electronics ensure maximum efficiency and safety of the entire device and keep the load of the alternator on a level not higher than the allowed maximum rotor speed, regardless of the battery status. The battery regulator frequently checks the status of wiring, adjusts voltage loss and monitors recharging. After a full recharge, the regulator shuts down recharging, so the battery does not damage.

WIND DEVICE TOWER

Small-scale wind turbines are often placed on suspension masts anchored by ropes. The advantage of this solution is particularly a significant weight reduction and subsequent reduction of investment costs. The main disadvantage, however, is more land occupation and more difficult accessibility, given the fact that the anchor ropes usually describe a circle with a significant diameter in comparison to the base of another type of tower construction. This disadvantage is reflected in particular in cases when the plant is located in an agricultural country, where the land is worked by machine.

The choice of the tower's height, due to the size of the rotor and the nominal output of the generator, is an important stage in the design of a wind turbine plant, primarily because in the case of insufficient height (by saving certain volume of investment), wind energy attributable to the area of the rotor and the related volume of captured energy, and therefore its production, will not be sufficient when compared with a slight increase in the height of the tower with an appropriate increase in investment, which would, however, also bring a significant increase in energy production due to the nature of volume dependence of energy carried by the wind flow on its speed.

The optimal height of the wind turbine plant tower is a function of:

- the price of each metre of the tower
- wind shear, depending on the orographic factors and surface roughness class,
- the purchase price of the kWh of electricity, etc.

A key consideration in wind turbine design is the avoidance of resonant tower oscillations excited by rotor thrust fluctuations at rotational or blade-passing frequency. The damping ratio may be only 2–3 percent for tower fore-aft oscillations and an order of magnitude less for side-to-side motion, so unacceptably large stresses and deflections could develop if the blade-passing frequency and tower natural frequency were to coincide. Rotational frequency is less of a concern, because cyclic loadings at this frequency only arise if there are geometrical differences between blades. Wind-turbine towers are customarily categorized according to the relationship between the tower natural frequency and the exciting frequencies. Towers with a natural frequency greater than the blade-passing frequency are said to be stiff, while those with a natural frequency lying between rotational frequency and bladepassing frequency are said to be soft. If the natural frequency is less than rotational frequency, the tower is described as soft–soft (Burton et al., 2001).

THE UNSTEADY EFFECTS ON WIND DEVICE

The study of unsteady aerodynamics phenomena related to wind turbines is rapidly becoming one of the major issues of interest within the wind energy community. The reason is that wind turbines operating in a field environment suffer dramatically from effects associated to the ever-changing upstream wind conditions. In fact, a uniform stream flowing parallel to the axis of the turbine happens to be an ideal assumption that is almost never encountered in daily practice. Sudden wind gusts, yawing of the rotor disk caused by changes in wind direction, the influence of the ground and of other wind turbines located nearby all contribute to the complexity of problem modeling in such a way that oversimplified theoretical and quasi-empirical models no longer provide fully reliable answers to basic design questions (Bermudez, 2000).

These effects are even more important in a situation where the economic performance of the turbines is being closely monitored; that is, wind energy should not merely be fashionable, it should also be competitive. In particular, unsteady aerodynamics effects are of paramount importance for structural and mechanical design because of the fact that time-dependent loading dramatically affects component failure, therefore, leading to a shortened turbine life that may have negative consequences on its economic viability. Also, due to system integration concerns, power output must be adequately predicted, not only on an average but also with regard to its time variation (Bermudez, 2000).

Unsteady aerodynamics effects are, in part, a consequence of the time-history of the induced velocity from the vorticity contained in the shed wake, coupled with the induced velocity contributed by the circulation contained in the trailed wake. In blade element models there are two aspects of the problem of defining and modeling the aerodynamic environment. The first is an outer problem, which is to model the effects of the induced velocity field produced by the vortical wake trailed from behind each blade. The second, the inner problem, is to model the resulting local unsteady aerodynamic response at each of the blade elements. Physically, of course, these two parts are intrinsically connected together, but for both the understanding of the problem and also for modeling purposes, it is convenient to treat them separately (Leishman, 2002).

SOURCES OF UNSTEADY EFFECTS

Leishman (2002) summarizes the various aerodynamic sources that may affect the airloads on a wind turbine, which can be decomposed into a variety of essentially periodic and aperiodic contributions (Fig.1). The net effect is that the wind turbine operates in an adverse, unsteady aerodynamic environment that is both hard to define using measurements and also to predict using mathematical models. The overall difficulties in predicting the performance and structural loads have led to higher capital investment and operating/maintenance costs for wind turbines, making it difficult for wind energy devices to compete with other forms of renewable and nonrenewable energy sources.

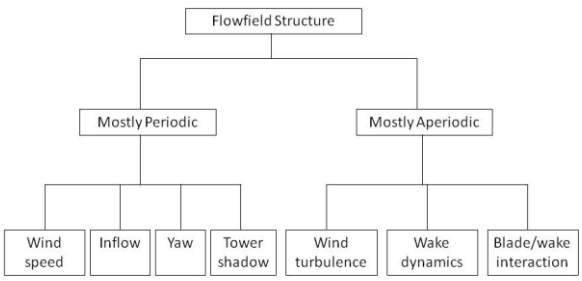

Fig. 1 Summary of the various aerodynamic sources

TOWER SHADOW AND NONSTEADY WAKE INDUCTION EFFECT

For downwind turbines the passages of the blade through the tower wake or shadow results in transient changes in Angle of Attack on the blade element. Upwind machines also suffer from the effects of the tower. This interaction effect may involve effective reduced frequency that exceed 0,2. The resulting blade loads cannot thus be predicted accurately using quasi steady assumptions. Such problems also involve steep velocity gradients in the flow. Experience suggests that there may be a 30 % reduction in the local velocity wind speed behind the tower. This problem is example where there is need to distinguish properly the effects on the airloads on the blades arising from assumed uniform change in uniform Angle of Attack across the blade element from the effects, resulting from nonuniform velocity field (Leishman, 2002; McSwiggan et al., 2012).

Tower shadow effect to changes in the power supply has been the subject of several analyzes. There are several options for its description. One possibility is to use the description of fast Fourier analysis on the performance of wind farms, which confirms the reduction of the frequency of oscillation by tower shadow. This effect can be synchronized and towers across the wind farm can increase the amount of electricity generated by wind farm (McSwiggan et al., 2012).

The physical tower shadow gives the full and real tower shadow, including velocity deficit and turbulence. Such physical representations (of, e.g., the tower shadow) are often used in research through model scale experiments. These model scale experiments cannot be used directly to ’explain’ the behaviour in full scale models, but they are much cheaper to carry out and the information can be used to enlight trends on a comparative basis (Burton et al., 2001; Kim et al., 2011).

Time varying aerodynamic conditions at the rotor will have an effect on strength and position of vorticity shed and trailed into downstream wake. This process has a hereditary effect depending on the prior time history of the rotor airloads and appears as a temporal lag in the development of the inflow at the rotor disk (Leishman, 2002).

The wake of a wind turbine is typically divided into a near and a far wake (Vermeer et al., 2003). The former is the region from the turbine to approximately one rotor diameter downstream, where the turbine geometry determines the shape of the flow field, determining the performance of the turbine. The axial pressure gradient is important for the development of the wake deficit. The latter is the region in which the actual rotor shape is less important, but the focus lies on wake modeling, wake interference (wake farms), turbulence modeling and topographic effects (Sanderse, 2009; Sanderse, 2011).

In reality the vortex system and velocity profiles are not as ideal as presented in the sections above. The difference in velocity between the air inside and outside the wake results in a shear layer, which thickens when moving downstream. In the shear layer turbulent eddies are formed. Due to the ambient shear flow, the turbulence in the shear layer is non-uniform, i.e. the turbulence intensity in the upper part is larger than in the lower part. In the near wake this leads to two peaks in the turbulence intensity, but in the far wake they are no longer discernible (Sanderse, 2009; Sanderse, 2011). Ainslie (1988) estimates that the maximum velocity deficit is attained after 1-2 rotor diameters (D), but for low ambient turbulence levels this might be longer. The expansion region length is also about 1 D (Coton et al., 2002). Based on the best comparison with experiments, Schepers uses 2.25 D as the distance where the wake is fully expanded (Sanderse, 2009).

CHARACTERIZATION OF IMPACT OF UNSTEADY EFFECTS ON SMALL SCALE WIND DEVICE

As a small scall wind device we took wind device located in the flow of the so called domain was created using the SolidWorks CAD software. The tower considered was columnar with a diameter of 0.4 m and a height of 8.63 m. The rotor diameter was 9 m and proposed power was 5 kW. One of the objectives of the CFD simulation was quantification and description of aerodynamic effects in the interaction of the tower and the blade. In the following paragraphs, we provide the influence of this interaction on the forces acting on the wind device, and therefore also on the device's performance.

The wind device tower itself is an obstacle to the air flow. In the area in front of the tower where the blade rotates (1-1.5 m), there will be a decrease in speed of approximately 7%, from the original speed of 7 m/s to 6.5 m/s. Torque shows a similar pattern as thrust force. The decrease in torque caused by one rotor blade passing in front of the tower represents 8.8%.

Fig. 4 shows distribution of vorticity magnitude. It is possible to observe wake structure.

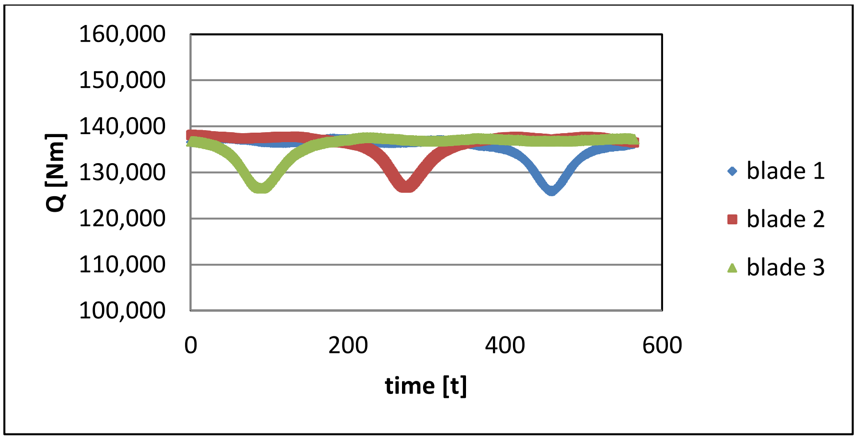

Fig. 2 Torque on up-wind wind device

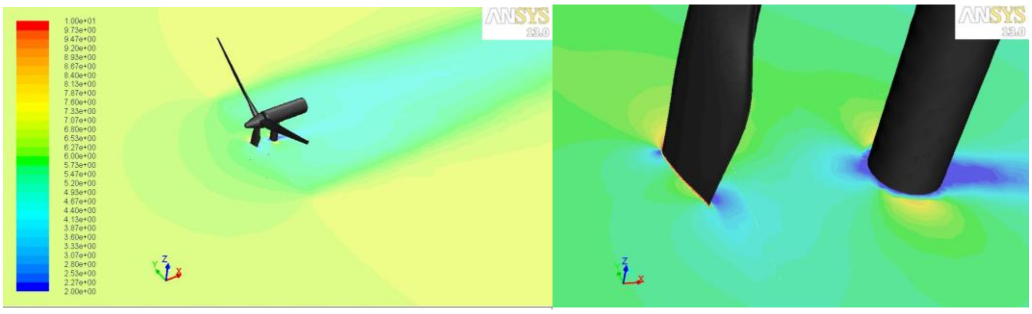

Fig. 3 Velocity field - Blade tower interaction based on speed distributions at height 1.5 m under the rotor axis

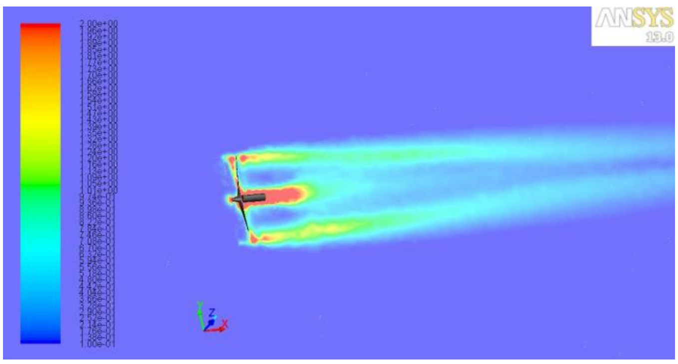

Fig. 4 Countours of vorticity magnitude blind up-wind wind device

According the our simulation in the distance 6D behind the wind device has velocity profile shape of Gaussian curve, which is far wake region. It can be caused by sharp end of gondola. Maximum velocity deficit is up to 1D behind wind device. At position 6D still is wind speed decreased to 5.5 m/s.

In the area behind the tower, where the blade rotates (1-1.5 m), there will be a significant decrease in speed of approximately 33%, from the original speed of 7 m/s to 4.5 m/s.

Torque shows a similar pattern as the thrust force (Fig.6). The decrease in torque caused by one rotor blade passing behind of the tower is 10,61 %.

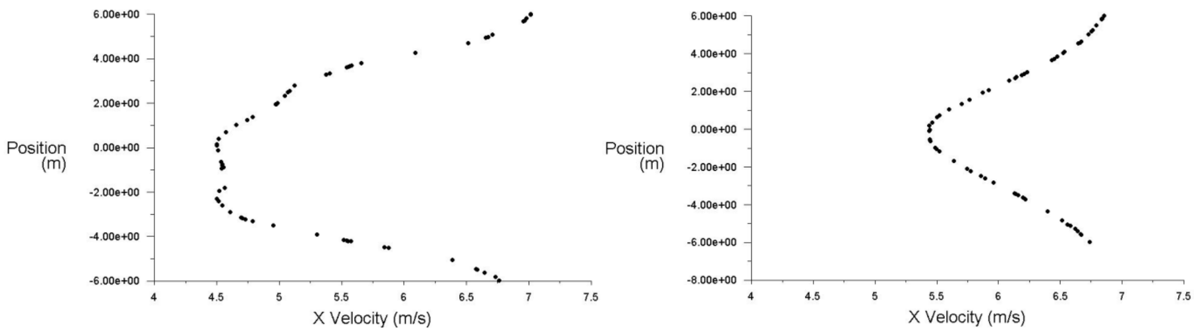

Fig. 5 Velocity profile at distance 1D and 6 D behind wind device (upwind)

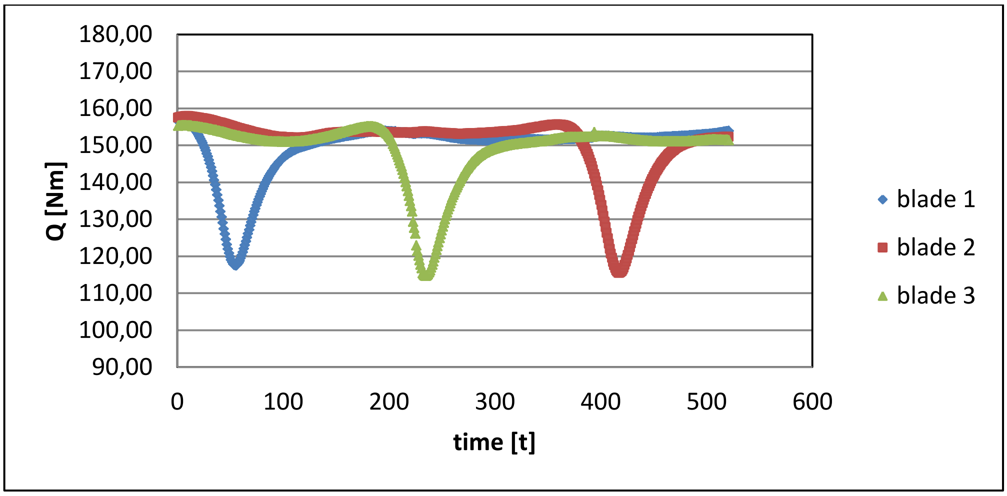

Fig. 6 Torque on down-wind wind device

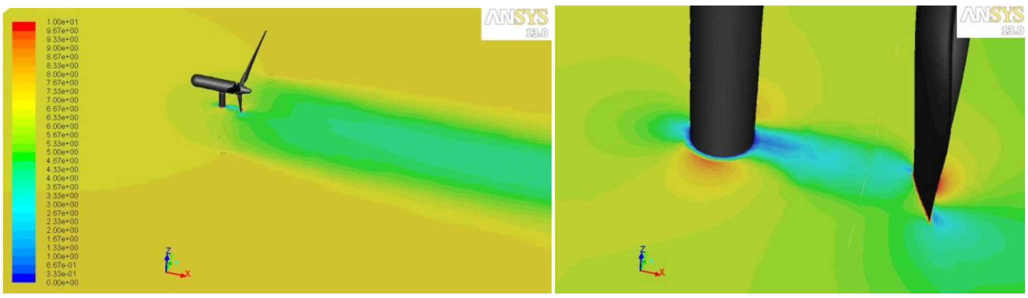

Fig. 7 Velocity field - Blade tower interaction based on speed distributions at height 1.5 m under the rotor axis (down-wind)

According the velocity profiles at distance 1D – 6D behind wind device, the maximum velocity deficit is at position 3D behind rotor (Fig. 9).

The speed of wind flow at ground level, i.e. in an area of the passing of the tip of the rotor blade (5.5 m above the ground) is reduced from the original 7 m/s to 6.77 m/s. The speed is 7.05 m/s at the maximum height of the rotor. Even though the speed difference is only 4%, this fact can change the aerodynamic parameters of the rotor of a wind device. If the angle of attack is greater than projected during the passing of the blade through the so called top dead center, the angle of attack during the passing of the blade near the ground is lower.

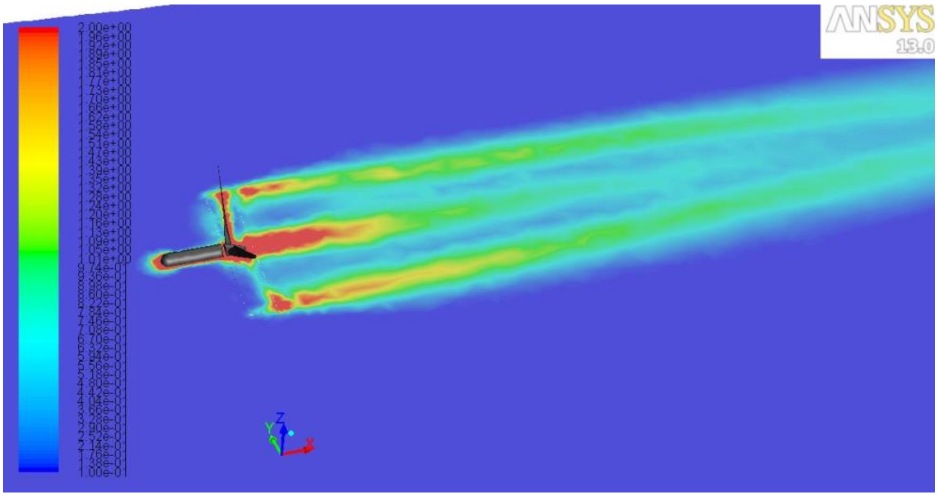

Fig. 8 Countours of vorticity magnitude on down -wind wind device

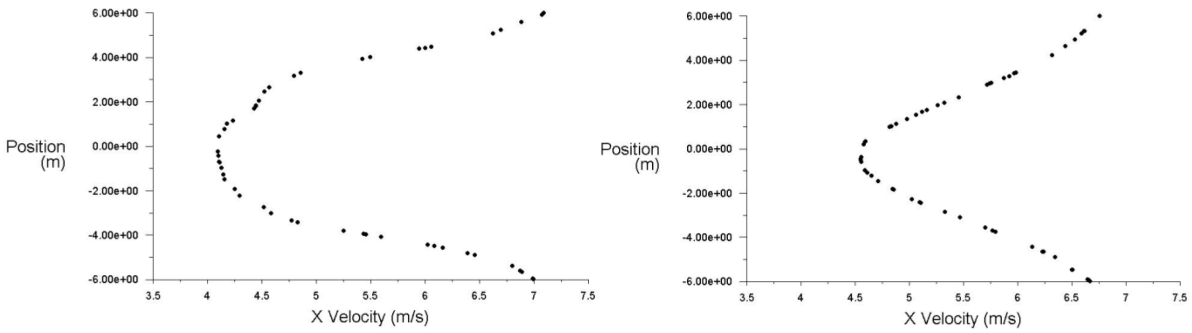

Fig. 9 Velocity profile at distance 1D and 6 D behind wind device (upwind)

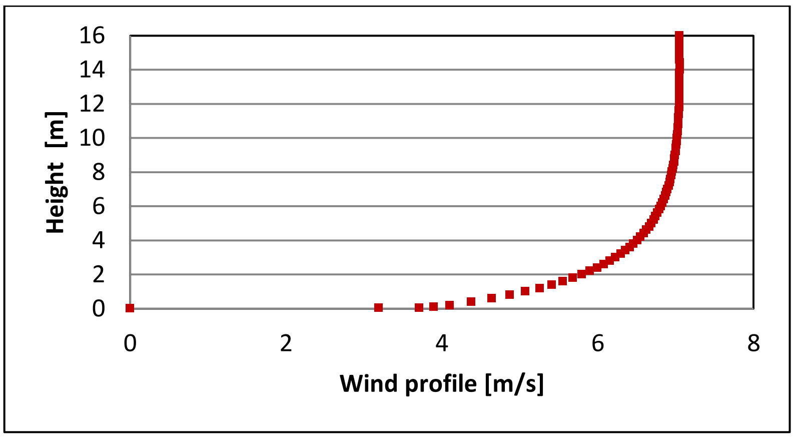

Fig. 1 Wind profile for roughness height 2 m

CONCLUSION

Based on the findings, it is possible to express that the influence of the tower on the blade is significant, which means a decrease in speed in the area where the blades of the rotor pass by about 9% - up-wind, 33% down-wind, 50% down-wind using lattice structure. This fact affects the overall performance by approximately 4% in the case of a wind device with a columnar tower. The influence of the tower and blade is more pronounced in the down-wind arrangement in respect to the change of speed. Here, the change in performance did not show significantly.

The difference in wind flow on the tip of the rotor at the lowest and the highest point during rotation in the boundary layer of the atmosphere is between 4 and 7% at given rotor dimensions and given height of the tower.

Acknowledgement

„This contribution/publication is the result of the project implementation OPVaV-2009/2.2/02-SORO, Centre VUKONZE.

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