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Aero-elastic coupled numerical analysis of small wind turbine–generator modelling

Jakub Bukala[1a], Krzysztof Damaziak[1b], Hamid Reza Karimi[2c] and Jerzy Malachowski[*1]

[1]*Department of Mechanics and Applied Computer Science, Military University of Technology, gen. Sylvester Kaliski 2, 00-908 Warsaw, Poland*
[2]*Department of Engineering, Faculty of Technology and Sciences, University of Agder, Jon Lilletuns vei 9, 4879 Grimstad, Norway*

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Abstract. In this paper a practical modelling methodology is presented for a series of aero- servo- elastic-coupled numerical analyses of small wind turbine operation, with particular emphasis on variable speed generator modelling in various wind speed conditions. The following characteristics are determined using the available computer tools: the tip speed ratio as a function of the generator constant (under the assumption of constant wind speed), the turbine coefficient of power as a function of the tip speed ratio (the torque curve is modified accordingly and generator speed and power curves are plotted), turbine power curves and coefficient of power curve as functions of the incoming wind speed. The last stage is to determine forces and torques acting on rotor blades and turbine tower for specific incoming wind speeds in order to examine the impact of the stall phenomena on these values (beyond the rated power of the turbine). It is shown that the obtained results demonstrate a valuable guideline for small wind turbines design process.

Keywords: small wind turbines; numerical analysis; FAST; generator; swt; wind energy

1. Introduction

Concerns related to the greenhouse gases emission (mainly carbon dioxide), the risk of fossil fuels depletion and energy independence issues present in several countries (importers of energy resources) are the main drivers for renewable energy generation development. Directive of the European Parliament and of the Council 2009/28/EC of 23 April 2009 and the subsequent Directive of the European Parliament and of the Council 2012/27/EU of 25 October 2012, set the mandatory targets for individual countries of the European Union up to year 2020 in terms of energy efficiency and renewable energy sources share of the total energy production (Directive 2009/28/EC, Directive 2012/27/EU)

One of the most important sectors of renewable energy sources is wind energy, development of

∗Corresponding author, Professor, E-mail: jerzy.malachowski@wat.edu.pl
[a] Ph.D. Student, E-mail: jakub.bukala@wat.edu.pl
[b] Ph.D., E-mail: krzysztof.damaziak@wat.edu.pl
[c] Professor, E-mail: hamid.r.karimi@uia.no

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which in the last decade was dynamic. Nowadays, wind energy is the most popular ecological energy generation technology in the world. In 2013, wind farms provided about 3% of world's energy demand. At the end of 2013, the cumulated capacity of wind farms worldwide was around 318.1 GW. The country leading in production of energy from wind was China: 91.4 GW (28.7%), followed by USA: 61.1 GW (19.2%) and Germany: 34.3 GW (10.8%) (Global Wind Energy Council 2014).

There is a distinct and separate group of devices developed within the wind energy sector called Small Wind Turbines. According to the IEC 61400-2 standard SWTs are characterized by a rotor area of less than 200 m^2 and rated power below 50 kW (International Electrotechnical Commission 2013). Wind power plants in this category are generally designed for small and individual customers such as households, farms, weather stations, road signalization and advertising systems. The quantity of small wind turbines operating worldwide grows every year. In 2012, the total number of such devices was about 800 000 worldwide (Gsänger and Pitteloud 2014). The growth rate is about 10%. The majority of small wind turbines (about 70%) is located in China, where the highest number of new installed units in 2012 was also noted. The second biggest market of SWTs is the United States of America, where around 155000 small wind turbines are operating at the moment. In Europe the leader is Great Brittan: 23500 units, followed by Germany: 10000, Spain: 7020 and Poland: 3200. Total SWT generation capacity installed in 2012 was equal to around 678 MW (576 MW in 2011). The majority of world's capacity (85%) belongs to three countries: China (274 MW), the USA (216 MW) and the UK (83.7 MW). Developing countries, unfortunately, play a minor role in small wind industry. Growth in 2013 was small, with just 90 MW installed across the region, for a cumulative total of 1,255 MW. It is exceptionally regrettable considering enormous wind power potential (best around the coasts and in the eastern highlands) (Gsänger and Pitteloud 2014).

The development and dissemination of small wind turbines involve great expectations in the field of eco-energy production. Some opinions suggest that without the dissemination of SWTs, the fulfilment of legal requirements for energy efficiency and energy production from renewable sources will be relatively difficult. In particular in the developing countries, small wind turbines can easily and fast contribute to electrify millions of people in rural areas. In order to create positive outcome, a big challenge awaits not only the authors of laws supporting investments in small wind turbines, but also engineers and scientists who should propose design solutions which will be appropriate to the realities of this energy sector (Aresti, Tutar *et al.* 2013).

To the authors' best knowledge, future small wind turbines should be characterized by the lowest possible price, while maintaining relatively high efficiency, particularly in the highest energy density wind speed range (for instance, around 7- 8 m/s for typical wind conditions in Poland (Bukala 2015). The reliability and maintenance issues of SWTs are also very important in terms of turbine costs. It leads to the conclusion that future small wind turbines should be characterized by simplicity of design and application of the best practices. Using a relatively simple synchronous generator working at variable speed is a design solution which can contribute to satisfaction of these requirements. Working principles of the generator determine many other aspects of the wind turbine operation including e.g. no need for active blade pitch control as passive drag control is sufficient (Gong and Chen 2015). It is therefore considered reasonable to determine the characteristics and impact of generator operation on the wind turbine structure using numerical simulations, which are a widely used tool in mechanical engineering (Spagnoli and Montanari 2013) (Yi, Yoon *et al.* 2014). The results obtained in this manner described the studied phenomenon with high accuracy (Kwansu, Changhee *et al.* 2014). It is worth pointing out that the relative low cost of such research methods is a great advantage in comparison to real experiments (e.g., wind tunnel tests). This fact and the remarks presented earlier are considered as reasons to undertake the issue described in the paper.

2. Materials and methods

2.1 The FAST software

The result presented in this paper is achieved using coupled nonlinear numerical simulations in the time domain, combining different models, including:

-aerodynamics,

-elastic deformation,

-servo-dynamics, generation and control systems.

Calculations are performed using the FAST Software package version 8.08, developed by NREL[†]. The FAST tool has been developed since the early 1990s, first by B. Wilson at the Oregon State University, and subsequently by A. Wright, N. Weaver, M. Buhl and J. Jonkman in NREL. Germanischer Lloyd issued a certificate of evaluation for FAST in 2005 (Buhl and Manjock 2006).

FAST is a set of individual modules such as ElastoDyn (structural response of the system), AeroDyn (aerodynamics), ServoDyn (control and electrical system), HydroDyn (hydrodynamics models for offshore structures), IceDyn (icing problems) and many others, responsible for different aspects of the wind turbine operation. From a technical point of view, FAST is a set various mathematical models which are implemented in distinct modules of the package which, owning to mutual data exchange (loose and tight coupling schemes – Eqs. (1) and (2)) between modules, carries out a global solution of the problem in the form of dynamic response of the system (Jonkman and Buhl 2005).

$$Gixen:\ p, x(0), x^d, [0], \& u \tag{1}$$

$$\dot{x} = X\left(x, x^d, z, u, t\right)$$

$$x^d[n+1] = X^d\left(x|_{t=n\Delta t}, x^d[n], xz|_{t=n\Delta t}, u|_{t=n\Delta t}, t|_{t=n\Delta t}\right)$$

$$0 = Z\left(x, x^d, z, u, t\right)$$

$$y = Y\left(x, x^d, z, u, t\right)$$

Index -1 DAE implies $\left|\frac{\delta Z}{\delta z}\right| \neq 0$, thus $\left|\frac{\delta Z}{\delta z}\right|^{-1}$ exists

If x^d exists, $x^d[n]$ is applied over $n\Delta t \leq t < (n+1)\Delta t$ in all equations

[†] The National Renewable Energy Laboratory, the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

$$u = \begin{Bmatrix} u^{(1)} \\ u^{(2)} \\ \vdots \\ u^{(N)} \end{Bmatrix}, y = \begin{Bmatrix} y^{(1)} \\ y^{(2)} \\ \vdots \\ y^{(N)} \end{Bmatrix} \tag{2}$$

$$u0 = U(u, y, t)$$

$$\text{with } \left| \left. \frac{\delta U}{\delta u} \right|_{y=const} \right| \neq 0$$

$$0 = U\left(u, Y\left(x, x^d, z, u, t\right), t\right)$$

$$0 = U\left(x, x^d, z, u, t\right)$$

The main advantages of this type of representation to numerical simulation (in contrast to universal simulation tools using FEA or CFD) are:

-complex, dedicated tool for the analysis of wind turbines, including, among others, simulation of the rotor, power transmission system, generator, nacelle and tower;

-derived from theory and fundamental laws of physics, with appropriate simplifications and assumptions;

-numerical code enhanced with analytical and numerical solutions and experimental data;

-tool developed to run on standard PCs (not supercomputers or clusters).

The latter means that the calculations performed using the FAST, due to the relatively low number of degrees of freedom are carried out almost in real time on current day PCs (Brusca, Lanzafame *et al.* 2014).

ElastoDyn module is responsible for determining the dynamic response of a system (i.e., deformations, displacements, accelerations, reaction forces) at a given time step, including the loads (i.e., aerodynamics, gravity), the parameters of inertia, stiffness, damping, etc. Nonlinear equations of motion (EoMs) are derived and implemented using Kane's Method (not an energy method, see Eqs. (3) and (4)). It utilizes relative degrees of freedom (DOFs), therefore there are no constraint equations and the final set of ordinary differential equations (ODEs) is solved instead of differential algebraic equations. Time integration is carried out using one of several explicit schemes such as 4th-order Runge- Kutta - RK4 (Jonkman and Buhl 2005).

$$F_r + F_r^* = 0 \quad (r = 1, 2, \cdots, NDOF) \tag{3}$$

where:

generalized active forces: $F_r = \sum_{i=1}^{w} {}^E v_r^{X_i} \cdot F^{X_i} + {}^E \omega_r^{N_i} \cdot M^{N_i} \qquad (r = 1, 2, \cdots, NDOF)$

generalized inertia forces: $F_r^* = \sum_{i=1}^{w} {}^E v_r^{X_i} \cdot \left(-m^{N_i}\, {}^E a^{X_i}\right) + {}^E \omega_r^{N_i} \cdot \left(-{}^E H^{N_i}\right) \quad (r = 1,2,\cdots,NDOF)$

$$M(q,u,t)\ddot{q} + f(q,\dot{q},u,u_d,t) = 0 \tag{4}$$

$$OutData = Y(q,\dot{q},u,u_d,t) = Y_r(q,u,t)\ddot{q} + Y_t(q,\dot{q},u,u_d,t)$$

Models of wind turbines in the FAST are characterized by limited flexibility, as it concerns a choice of turbine topology, reduced to horizontal-axis turbines (HAWT) with a 2- or 3-bladed rotor in both upwind or downwind configuration and a rigid or teetering hub. As a result, FAST models are characterized by 22 (2- blade) to 24 (3- blade) degrees of freedom (DOF), which is shown schematically in Fig. 1.

In terms of determining the elastic response of the system FAST offers different approaches: for small to moderate deflections – the turbine tower and blades are treated as Bernoulli-Euler beams under bending (no axial or torsional DOFs, no shear deformation), where mode shapes are specified as polynomial coefficients (Eq. (5)); for large deformations – full nonlinearity scheme is used – mode shape functions in a nonlinear beam model (Rayleigh-Ritz method) - including radial shortening effect (Eq. (6)), important for centrifugal stiffening, Coriolis and gyroscopic terms (Buhl and Manjock 2006).

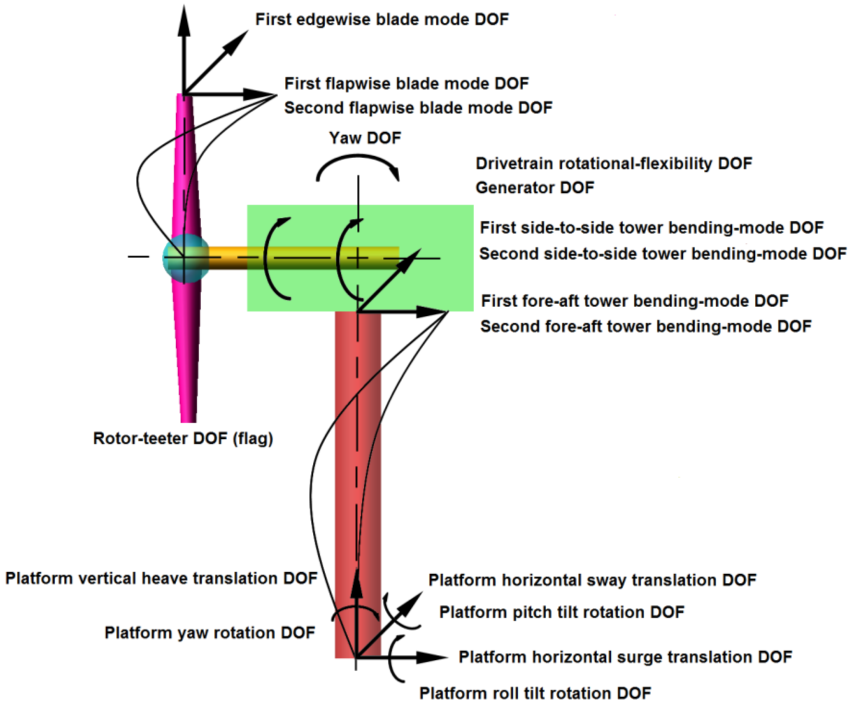

Fig. 1 Welding of the lap spliced bars according to the C.S.R.T.C (2008). 1: welding starts 10 mm from the bar end, 2: welding direction, 3: space between the welds

$$k_{ij}^{TFA} = \int_0^{TwrFlexL} EI^{TFA}(h) \frac{d^2\phi_i^{TFA}(h)}{dh^2} \frac{d^2\phi_j^{TFA}(h)}{dh^2} dh \qquad (i, j = 1,2) \tag{5}$$

$$k_{ij}^{TSS} = \int_0^{TwrFlexL} EI^{TSS}(h) \frac{d^2\phi_i^{TSS}(h)}{dh^2} \frac{d^2\phi_j^{TSS}(h)}{dh^2} dh \qquad (i, j = 1,2)$$

$$w(h,t) = \frac{1}{2}\int_0^h \left[\frac{\delta u(h',t)}{\delta h'} \right]^2 dh' \tag{6}$$

AeroDyn module is responsible for determining the aerodynamic forces at a given time step, taking into account the wind profile and the current location and velocity of turbine blades. An induction method in discrete beam elements (BEM) is applied (see. Eqs. (7) and (8)) - Betz and Glauert (1935), Leishman (2000), (Manwell *et al.* 2002), (Burton *et al.* 2001). Full-field turbulence using Taylor's frozen turbulence hypothesis, dynamically stalled flow field (Beddoes-Leishman) and blade tip-loss correction (Prandtl model), as well as tower drag and downwind shadow models are also included (Moriarty and Hansen 2005).

thrust

$$dT = B\frac{1}{2}\rho V_{total}^2 (C_l \cos\varphi + C_d \sin\varphi) c\, dr \tag{7}$$

$$dT = 4\pi r \rho U_\infty^2 (1-a) a dr$$

torque

$$dQ = B\frac{1}{2}\rho V_{total}^2 (C_l \cos\varphi + C_d \sin\varphi) crdr \tag{8}$$

$$dQ = 4\pi r^3 \rho U_\infty^2 (1-a) a' dr$$

2.2 Modelling methodology

FAST software does not have a graphical interface, thus all the input data for the solver executable are prepared in the form of text files, in which consecutive lines correspond to the physical quantities and working parameters.

In the presented analysis ElastoDyn, AeroDyn and Servodyn modules have been used, with separate batch files for each module. Further, a control file with characteristic extension .fst, and auxiliary files corresponding to mechanical and aerodynamic properties of the individual components of the wind turbine (tower, blades, etc.) are created. In these files, the topology of the turbine, its dimensions as well as mass, stiffness, damping and shape modes parameters, are defined. Another group of parameters consist of solver control values which define e.g. the frequency and range of the plotted results, the total simulation time and the analysis time step. FAST batch file structure is shown in Fig. 2.

In all analyses, which are the subject of the work, calculations are carried out with operating parameters listed in Table 1.

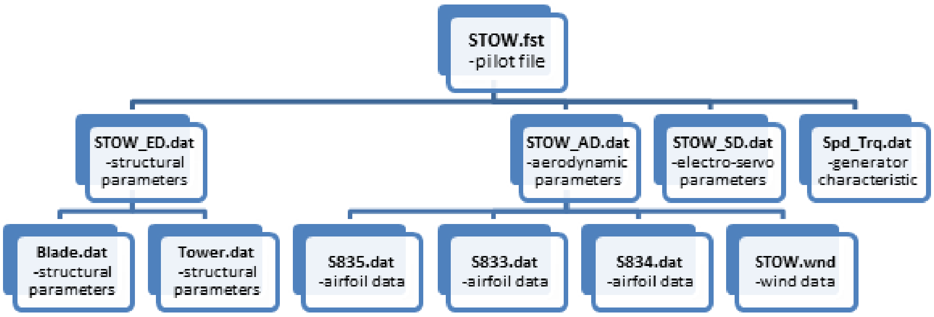

Fig. 2 FAST batch file structure used in the modelling procedure

Table 1 FAST analyses parameters

	FAST
Air density	1.21 kg/m^3
Kinematic air viscosity	0.000015 m^2/s
Time step	0.001 s
Induction-factor tolerance	0.005
Total run time	30 s

2.3 Test object

The model of a small wind turbine has been built based on available literature data and parameters defined using statistical analysis concerning small wind turbines operating in wind conditions typical to the area of Poland (Drew *et al.* 2015).

A model turbine has a classic three-bladed rotor system with a horizontal axis of rotation. Physical dimensions and operating parameters of the model are listed in Table 2. The turbine rotor operated in the downwind configuration, therefore the rotor is placed behind the nacelle considering the wind direction. This solution is characterized by a slightly lower aerodynamic efficiency, but does not need to have any electrical or mechanical yawing mechanism for the rotor. The blades geometry is based on S835, S833 and S834 family of aerofoils, with a variable chord length and a twist angle of 0 - 30 ° (see Fig. 3). These aerofoils are considered to be quiet, thick and natural-laminar-flow, therefore, they are suitable for the small wind turbines (Somers 2005).

The used generator model has the operating characteristics of a classic synchronous generator equipped with permanent magnets and working at variable angular speed.

2.4 Performed analyses

Small wind turbines are usually equipped with synchronous generators operating at variable angular speeds based on permanent magnets (e.g., neodymium magnets) (Goudarzi and Zhu 2015). There are at least two aspects to consider this problem. Firstly, small wind turbines typically operate in autonomous systems without connection to the grid, in which they directly power the heating and other loads that do not require stable electric parameters, which is dictated by economic issues. Potential expenditure related to connecting to the electrical grid exceeds the usual financial benefits of possible income from selling the produced energy. The other aspect is the fact that small wind turbines are generally simple devices and they are rarely equipped with sophisticated control systems such as blade pitch mechanisms. Given the fact that the aerodynamic profiles of the rotor blades work effectively within a certain range of the tip speed ratio λ (representing the ratio of the blade tip speed to the speed of the incoming wind – Eq. (9)), the easiest way to meet this requirement is the use of the aforementioned variable speed generator.

Table 2 Basic parameters of analysed turbine model

	STOW
Rated power	**3000** W
Rated wind speed	**12** m/s
Rotor diameter	**3.2** m
Axis height	**20** m
Blade length	**1.5** m
Rotor mass	**6.9** kg
Rated angular velocity	**350** rpm
Generator efficiency (PMG)	**90** %

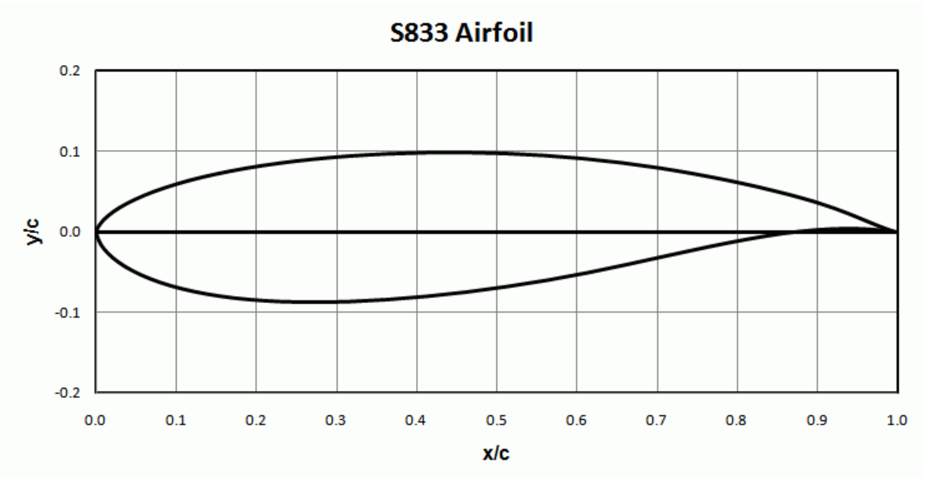

Fig. 3 S833 aerofoil proportions (used for the central portion of the blade) (Somers 2005)

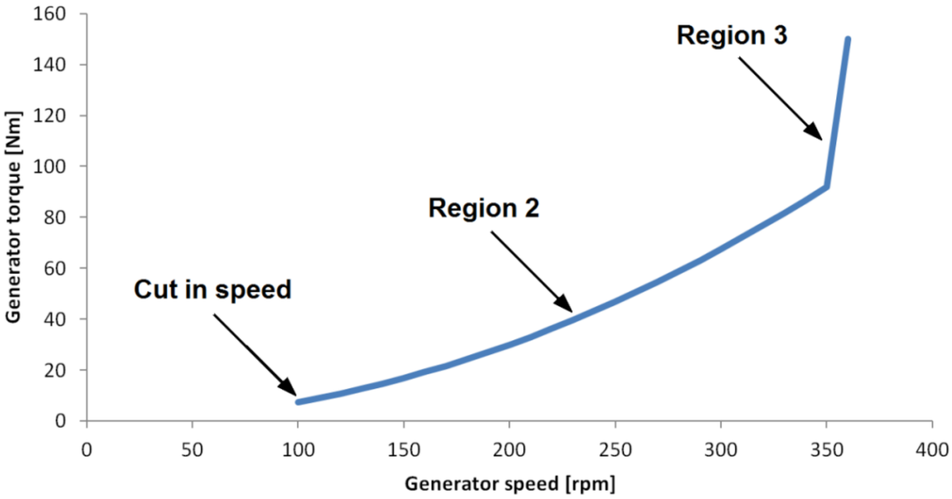

Fig. 4 Torque characteristic as a function of the generator rotor speed for a simple variable speed generator

$$\lambda = \frac{\omega R}{v} \tag{9}$$

where: λ, ω, R and V are the tip speed ratio, angular blade velocity, blade radius and wind speed, respectively.

There are three basic ranges of angular speeds in which this type of generator operates (Fig. 4) (Oh, Park *et al.* 2015). In the first region, the angular velocity (or torque provided by the rotor) is too small for the generator to operate and so no electric energy is generated. In the second region, the generator applies the torque as a function of the rotational velocity of the rotor, as to maximize the aerodynamic efficiency of the blades (by maintaining a constant, specific tip speed ratio). In this region the generator torque could be approximately described by Eq. (10).

$$T_g = C_{R2} \cdot \omega^2 \tag{10}$$

where T_g, C_{R2}, and ω are the generator torque, generator constant and blade angular velocity, respectively.

The generator constant depends on the structural parameters of the turbine, i.e., its dimensions, specific tip speed ratio of the blades, etc. Generator torques in region 2, for different constants taken into account in this analysis, are shown in Fig. 5.

The second region ends when the turbine reaches the rated power. With increasing wind speed, the generator torque significantly increases to stop the growth of the generator angular velocity. It results from, among others, structural determinants and issues related to noise reduction. In practice, the power output of the turbine above the rated speed (region 3) is fixed until the turbine is stopped, which is dictated by safety reasons.

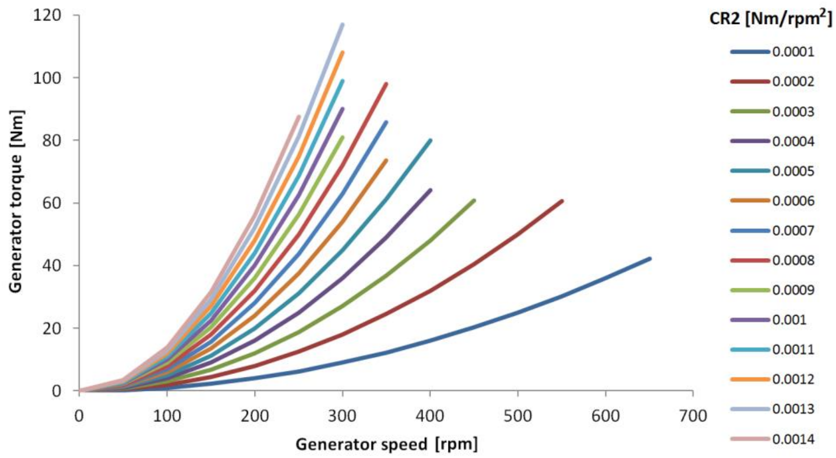

Fig. 5 Generator torques as functions of angular velocities for considered generator constants in region 2

However, the torque increasing at a relatively constant speed causes increasing power of the turbine generator. This power is dissipated onto the so called dummy load until the turbine shuts down due to exceeding the specified critical wind speed (which is carried out e.g. by mechanical deflection of the rotor axis direction in relation to the incoming wind).

Assuming that the increasing torque applied in region 3 does not allow for further acceleration of the rotor, with increasing wind speed, the tip speed ratio will decline. Accordingly, the aerodynamic profile should gradually decrease its efficiency to stall and the efficiency should decrease rapidly.

Firstly, a series of analyses is performed to determine the relationship between the generator constant and the tip speed ratio under the assumption of constant speed of the incoming wind for region 2. Also, the turbine coefficient of power as a function of the tip speed ratio is obtained. For this purpose, the torque curve is modified accordingly and generator speed and power curves are plotted. At a later stage the following characteristics are determined for the test turbine: power curve and coefficient of power curve as a function of the incoming wind speed (Lydia, Suresh Kumar *et al*. 2014).

The last stage is to determine the forces and moments acting on the rotor blades and the tower of a wind turbine for specific incoming wind speeds in order to examine the impact of the stall phenomena on these values beyond the rated power of the turbine.

In total, more than 200 numerical analyses using the FAST package were performed in a relatively short period of time, which would not be possible using CFD coupled with FEA.

3. Computational results

The dependence of the tip speed ratio determined as a function of the generator constant (which in turn determines the generator torque according to Eq. (4)) for the modelled turbine is presented in Fig. 6.

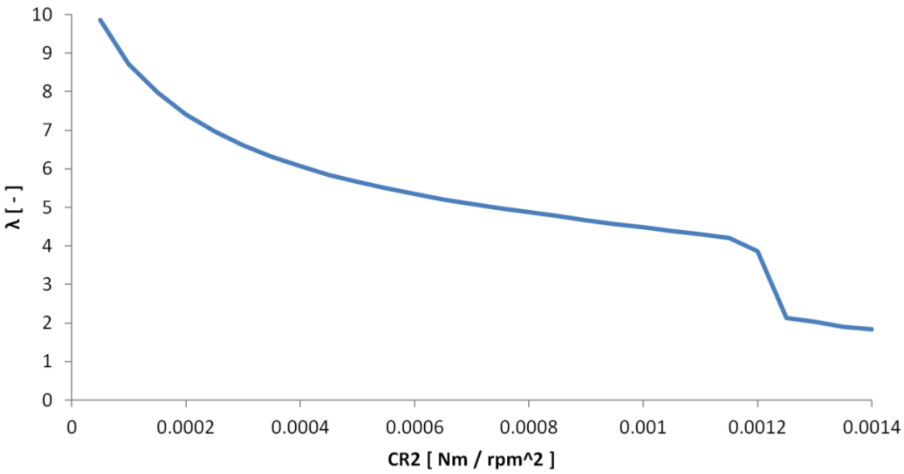

Fig. 6 Tip speed ratio as a function of the generator constant for region 2

It can be observed how with the increasing load of the turbine generator, the blade tip speed ratio decreases. Special attention should be paid to spot where $C_{R2} = 0.0012 \frac{Nm}{rpm^2}$, when the stall phenomenon occurs. Due to decreasing angular velocity (effect of an increasing load torque), at some point the critical angle of attack of the foil is exceeded causing a sudden reduction in lift and therefore a drastic reduction of efficiency and rotational velocity.

The impact of the declining tip speed ratio on produced power and hence the coefficient of power is shown in Fig. 7.

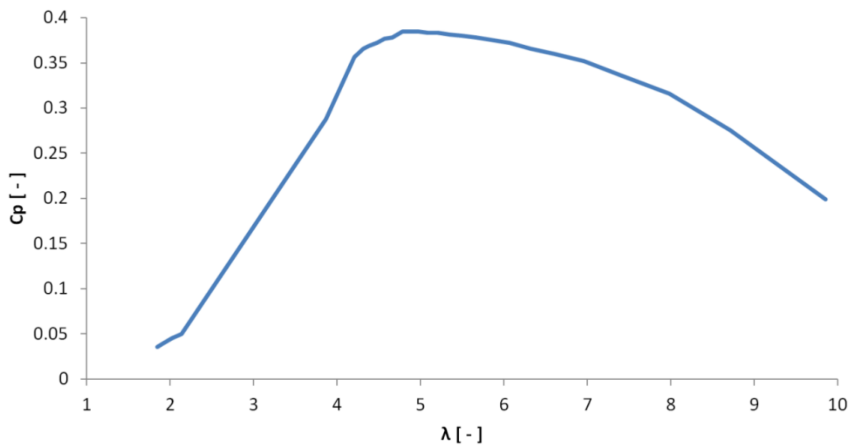

Fig. 7 Coefficient of power (efficiency) as a function of blade tip speed ratio

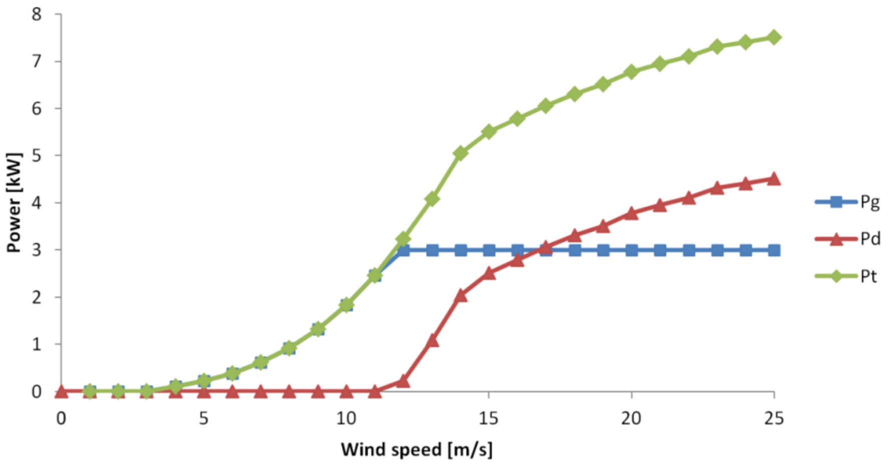

Fig. 8 Usable power (Pg), power lost on dummy load (Pd) and total power of the generator (Pt) as functions of the incoming wind speed

It can be observed that the highest efficiency rate (coefficient of power) is at the tip speed ratio around 5, which is an effect of chosen aerofoil characteristic. In addition, it can be stated that this parameter is more sensitive to the decreasing tip speed ratio, rather than on its growth. Therefore, it is important to preserve the TSR close to specified by the turbine aerofoil for the most of the turbine operation time.

The power curves (usable, lost on dummy load and total) of the generator are shown in Fig. 8.

In region 2, the power generated by the turbine generator increases and it is entirely considered as a usable power. Beyond the turbine rated power (3 kW) the usable power remains at the same level (the turbine rated power), while the power generated by the turbine generator continues to increase. The difference between the turbine generator power and usable power is dissipated on the dummy load to preserve the electrical components from the damage. It can be observed that the power resulting from the resistance on the dummy load exceeds the turbine power output at the extreme point. This raises questions about the possible resistance of the generator at such high currents.

A production coefficient (efficiency) curve of the modelled wind turbine as a function of wind speed is shown in Fig. 9.

Below the “cut-in” speed, the efficiency (the coefficient of power) of the turbine is equal to 0, therefore no energy is produced. In region 2, the efficiency remains at almost the same level, approximately in range from 0.35 to 0.4 (with the tendency to growth with the wind speed). Beyond the turbine rated power (3 kW) the efficiency decreases.

Subsequently, there is presented a series of charts showing forces and torques important from the structure point of view for selected components of the wind turbine (blade root – momentum – Fig. 10 and tower top – forces – Fig. 11) at wind speed of $v = 18\,m/s$ that is for region 3. The data gathering is performed from the 5th second of the simulation with a sampling frequency of 100 Hz.

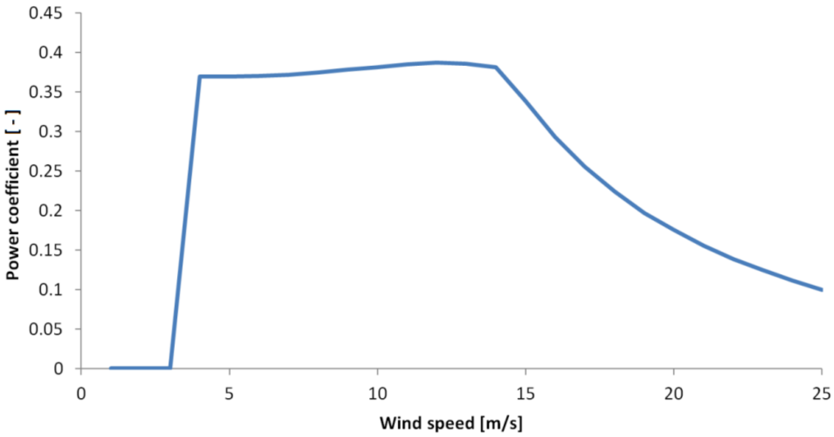

Fig. 9 Production coefficient (efficiency) of modelled STW as a function of the incoming wind speed

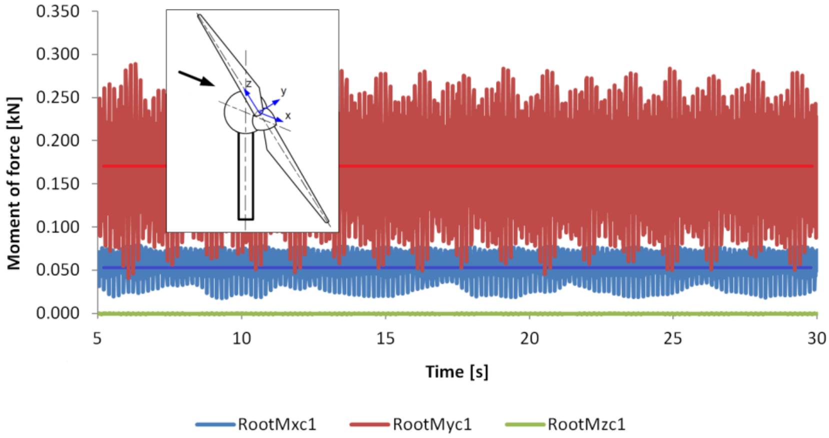

Fig. 10 Force momenta in the blade root recorded over simulation time

It can be observed that recorded quantities oscillate around the mean values (presented in Fig. 11 as horizontal lines). These fluctuations are highly periodic, and therefore, they are probably an effect of the tower shadowing phenomena which is a particularly significant factor considering the downwind design solution in this case. The observed fluctuations will certainly have a significant impact on turbine reliability (especially when it comes to the turbine blades), due to fatigue strength of blade and tower materials.

The following graphs show the results for the momenta recorded in the blade root in x-axis (Fig. 12), and Y-axis (Fig. 13) for particular incoming wind speed values and the forces on the top of the tower plant in X-axis (Fig. 14). The other direction components of this force are small enough that they are not significant from the structural strength point of view. There have been specified the minimum, maximum and average values of the time charts analogous to those described above.

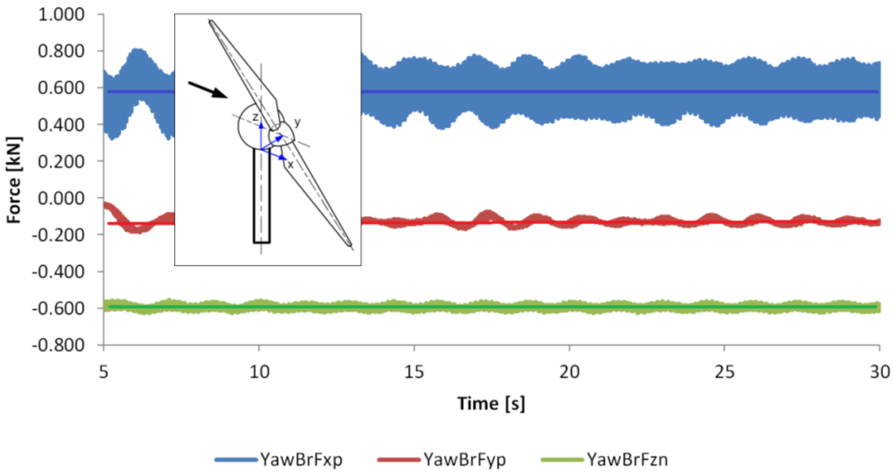

Fig. 11 Forces at the top of the tower recorded over simulation time

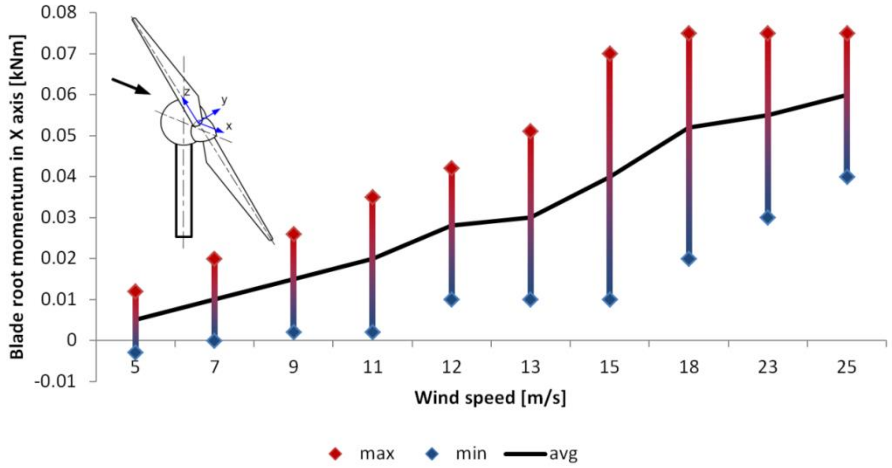

Fig. 12 Force momenta in the blade root (min., max. and average) in X-axis for the particular incoming wind speed values

The aerodynamic forces moment in X-axis is responsible for driving the drive shaft. It can be observed that the growth is approximately linear in regions 2 and 3. The greatest amplitude of moments corresponds to the value of approximately 18 m/s. The moment in Y-axis is the adverse load, however, it is impossible to avoid it. A linear increase of this parameter could be observed until wind turbine power closes to the rated, and then the curve flattens, reaching a maximum at approximately 18 m/s then the torque values in Y decrease. Unfortunately, the recorded amplitude increases with incoming wind speed.

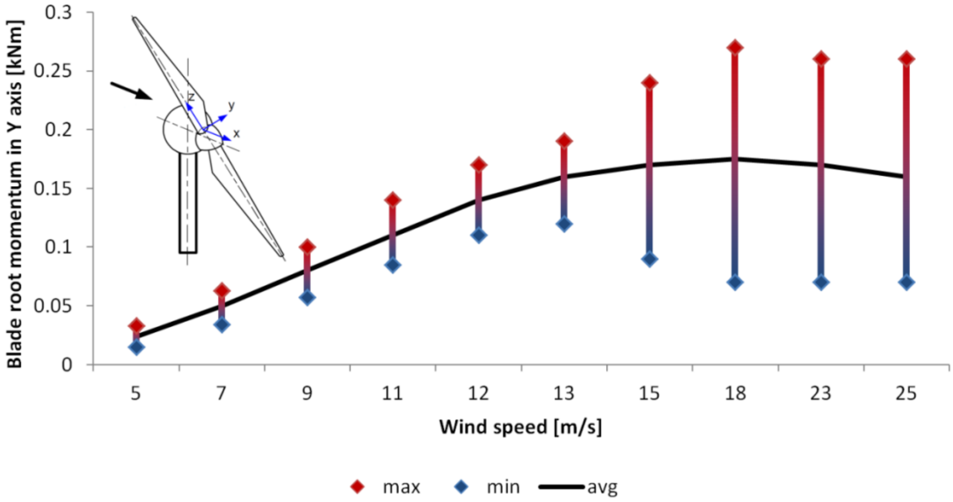

Fig. 13 Force momenta in blade root (min., max. and average) in Y-axis for the particular incoming wind speed values

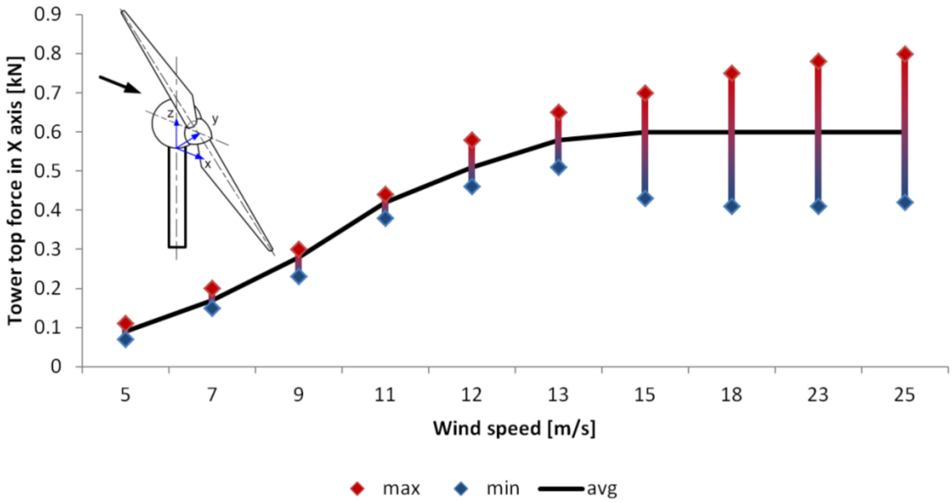

Fig. 14 Forces at the top of the tower (min., max. and average) in X-axis for the particular incoming wind speed values

In the case of the forces acting through the gondola on the tower of a small wind turbine, it can be observed an approximately linear increase as a function of the incoming wind speed through region 2. Once the turbine rated power is reached, observed mean value of this force is constant, but the amplitude increases.

4. Conclusions

Using the methodology of aero- servo- elastic- coupled numerical analyses, it is possible to carry out analysis of small wind turbine behaviour with a high degree of assurance in the accuracy of the results (both qualitative and quantitative). Worth noting is a relatively short time for such calculations, which in turn allows for the analysis of hundreds of variants computing in a relatively short time. An important issue is the low cost of such testing in relation to experimental studies of real models. Numerical analyses have provided in this case valuable guidelines for a future small wind turbine design process without the need of building a series of real models and performing numerous experimental tests which are significantly more expensive and time-consuming. The main goal in this case is to numerically investigate chosen aspects of SWTs operation and draw the conclusions at the preliminary stage of the project in order to choose the most promising design for further tests.

Based on the achieved results it is possible to draw the following conclusions:

- small wind turbines equipped with a simple synchronous variable speed generators can operate successfully without automated pitch or direction control systems;
- it is essential to choose the correct generator constant in correlation with the type of aerofoils used (tip speed ratio), to obtain maximum turbine efficiency;
- in the so-called region 2 of the turbine rotational speed (between the cut-in speed and rated speed) turbine operates with maximum aerodynamic efficiency while maintaining a relatively constant value of tip speed ratio λ;
- beyond the turbine rated power efficiency systematically decreases as a result of declining rates of tip speed ratio; turbine output power remains at the same level but the power lost on dummy load increases, even exceeding the power output, which raises legitimate questions related to the sustainability of the generator working in such conditions;
- the observed values of forces and moments on the important structural components of the turbine have a relatively high volatility (amplitude) as a function of time; it is concluded that they are largely the result of the negative impact of the tower (the downwind design was used in this case); the observed fluctuations will certainly have a significant impact on turbine reliability, due to fatigue strength of blade and tower materials;
- variability in the mean values of mentioned forces and moments as a function of the wind speed is characterized by a substantial increase in region 2, then the values stabilize, or even decrease in region 3. This means that the structure of a wind turbine works most severely when the turbine reaches its rated power. What is more, very high wind speeds, should not be a particular challenge for the device.

Further works in the presented field are currently being investigated by the authors regarding conclusions of the presented paper. The authors believe that the development of cheap and reliable small wind turbine will allow for a high growth rates for the installation of SWTs and therefore strengthen the small wind position in renewable energy programmes, especially in developing countries.

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