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# Simulating the dynamic behavior of a vertical axis wind turbine operating in unsteady conditions

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**Abstract.** The present work aims at assessing the reliability of a simulation tool capable of computing the unsteady rotational motion and the associated tower oscillations of a variable speed VAWT immersed in a coherent turbulent wind. As a matter of fact, since the dynamic behaviour of a variable speed turbine strongly depends on unsteady wind conditions (wind gusts), a steady state approach can't accurately catch transient correlated issues.

The simulation platform proposed here is implemented using a lumped mass approach: the drive train is described by resorting to both the polar inertia and the angular position of rotating parts, also considering their speed and acceleration, while rotor aerodynamic is based on steady experimental curves. The ultimate objective of the presented numerical platform is the simulation of transient phenomena, driven by turbulence, occurring during rotor operation, with the aim of supporting the implementation of efficient and robust control algorithms.

## 1. Introduction

The dynamic response of a rotor subjected to a turbulent flow is of the utmost importance in the mechanical design process as well as for the development of efficient control strategies. As a matter of fact, a reliable computation of the rotational motion, and of the associated tower oscillations, for a variable speed vertical axis wind turbine (VAWT) immersed in an unsteady wind, can provide reliable information about the expected life cycle of the rotor. In 1991 Sandia Laboratories performed some experimental investigations and also developed some dedicated tools, with the aim of simulating the aeroelastic behaviour of a mid-size VAWT [2]. Stochastic dynamic response analyses of floating VAWTs, based on fully coupled non-linear time domain simulations, have recently been undertaken with the aim of harvesting the potential of offshore wind resources in moderate and deep water [1]. Furthermore, More recently, DTU developed an aeroelastic commercial code, based on the cylinder actuator theory [3], capable of predicting dynamic loads and performances of multi-MW floating VAWTs.

This work proposes a simplified approach to investigate the dynamic behavior (rotation and displacements) and the effect of control strategies on small variable speed VAWTs. Such new simulation platform, called Vertical Axis Wind Turbines Dynamic Predictor (VAWT-DP) is



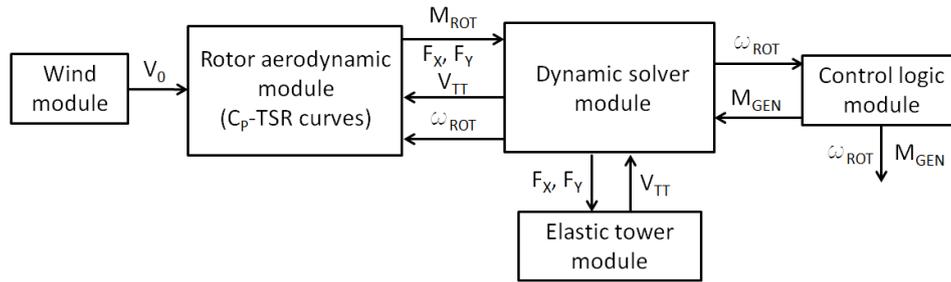


Figure 1: Scheme of main modules and data flow.

the core of a widespread software (development in ongoing) able to compute the whole DLC according to IEC 61400-2:13. The proposed code relies on some simplifying assumptions [4] with respect to the above mentioned Sandia and DTU aeroelastics codes , such as:

- small blades and pole deflection under operative loads (mainly centrifugal forces) lead to a rigid rotor modelling;
- since the tower is a slender element, it is modelled as a cantilevered flexible beam, in both longitudinal and lateral directions;
- the gusts approaching the turbine are bigger than the rotor scale (i.e., the rotor can be considered immersed into a uniform, but turbulent, wind);
- rotor aerodynamic is based on static functional maps (measured or numerically computed).

An investigation on the dependency between tower stiffness and loads has already been performed by [4]. The here proposed work wants to investigate also the effect of tower flexibility on the apparent wind speed perceived by the rotor. Rotor static performance maps were recorded by means of wind tunnel tests [5] and then the same rotor was installed and monitored in open field for about 18 months [6]. This work aims at both comparing open field and simulated data of a 1.5 kW VAWT (thus partially filling the lack of experimental data available in literature for VAWTs operating in turbulent winds) and validating the new simulation platform by resorting to such experimental data.

## 2. Code description

VAWT-DP is made of five modules [4], as shown in Figure 1, starting with the **wind module**, capable of generating winds of an arbitrary behaviour, such as: steady, ramps, waveforms, or to read time series from tables. For the present work, this module reads wind time series recorded during an open field measurement campaign and feeds them into the **rotor aerodynamic module**, capable of reading functional maps, measured during wind tunnel tests, and interpolating them for any requested operation point within the functional maps: thus, it interpolates both in wind speed and in rotor angular speed. Such a module is the most important, because an inaccurate maps interpolation could lead to a poor rotor performance evaluation. For further details about the implementation of the simulation code, the reader is referred to [4]. Is worth to mention that, in alternative to experimental map interpolation, the VAWT-DP can make use of a real-time BE-M routine. This approach proved to be less accurate for small VAWTs characterized by high solidity [7].

The third module is the **dynamic solver module**, which solves the equation of rotational motion ( $I_{ZZ}\ddot{\theta} = M_{ROT} - M_{GEN}$ ) by means of a Runge-Kutta method, computes the balance between the aerodynamic and generator torque and estimates the changes in rotor angular velocity.

The **elastic tower module** estimates the tower deflection and tower top horizontal speed ( $V_{TT}$ ) considering wind loads, tower stiffness and rotor centre of gravity offset.  $V_{TT}$  is then fed back to the rotor aerodynamic module in order to compute the relative wind speed and the updated  $M_{ROT}$ .

The fifth module is the **control logic module**, which monitors the turbine operational status in terms of angular velocity and electric torque, taking actions according to its logic. This module is based on a state-machine approach, where the controller's decisions are driven by a list of thresholds on the rotational speed. Such thresholds define several states: breaking, idling, power production, maximum rotational speed, emergency breaking. The power production state undergoes to a torque-RPM curve based on the wind tunnel test maps.

Finally, a post-processing routine was written only for validation purposes: such module compares the simulation output of VAWR-DP model with the experimental data by means of plots and statistics. Their agreement is quantified by Pearson's linear correlation coefficient: such coefficient tends to 1 if data have the same trend, but it cannot detect any offset between them. Wind time series are described by their mean values and turbulence index.

### 3. Wind turbine description

The wind turbine considered in this work is a three-bladed, helically shaped, H-Darrieus (Figure 2) with a swept area of  $4.44 \text{ m}^2$ , a diameter of 1.781 m and a chord length of 0.148 m [5] [8]. The design tip speed ratio (TSR) is 2.8 and the maximum aerodynamic power coefficient  $C_P$  is 0.23 (measured in wind tunnel). A synchronous three-phases permanent magnet electric generator, with a rated power of 1.5 kW at a nominal rotational speed of 379 rpm, is equipped with Hall effect probes capable of measuring both rotor angular speed and position. The inverter is capable of driving and controlling the generator, and thus the rotor speed, from 100 to 400 rpm with a nominal power of 1.6 kW (1.8 kW peak) and with an output tension of 230 V. A PLC dedicated to the overall turbine control, is based on a state-machine approach, where the controller's decisions are driven by a list of thresholds on the rotational speed defining several states: breaking, idling, power production, maximum rotational speed, emergency breaking. When the rotor angular speed crosses the predefined thresholds, the controller switches to the proper working condition. Real turbine settings were carefully loaded in the simulation platform.



Figure 2: Frontal view of the rotor, operated both in open field and wind tunnel tests.

### 4. Wind tunnel tests

The main target of the experimental campaign was to accurately measure rotor (steady) functional curves, in terms of thrusts (in both longitudinal and transversal directions) and torque acting on the rotor, for several wind speeds and angular velocities. Turbine performances were measured in the large scale wind tunnel of the Politecnico di Milano (IT), over a wide range of wind speeds (from 3 m/s up to 14 m/s, with a 1 m/s step) and angular speeds (between 90 and 380 rpm, with variable steps) [5].

### 5. Open field tests

After completing the wind tunnel campaign, the same rotor was tested in open field conditions [8], where further experimental data were collected. A wind mast, installed 14 m far from the turbine, was equipped with a 3D ultrasonic anemometer at 7.4 m above the ground (corresponding to rotor mid-span); for further details about the test site, see [9]. The data acquisition system gathered and sampled net electric power, rotor angular velocity, vibrations

at tower top (non-rotating), wind thrust acting on rotor and wind speed (from the wind mast). Both electric power and rotor angular velocity were collected from the inverter BUS, while vibrations were measured by means of bi-axial accelerometers installed on the non-rotating tower top. Finally, thrusts were measured by two strain-gauge bridges, placed normal to each other. Collected information was then sampled and stored on hard drives at 400 Hz, except for the ultrasonic anemometer, which was sampled and stored at 20 Hz. Meteorological quantities, like temperature, pressure and air density, were retrieved from the closest weather station to the site (990 m south, same elevation) and then properly matched with turbine data.

## 6. Code validation

The here presented validation aims at assessing the reliability of each module of VAWT-DP. This is performed in 2 steps: the first one aims at investigating VAWT-DP static performance prediction (see paragraph 7.1), in order to check both rotor aerodynamic and control modules. The second step is made of two sub-tasks, as follow:

- the first sub-task (see paragraph 7.2.1) stresses the dynamic solver by feeding into the model many wind time series (measured in open field), determining a rotor operation within its normal power production range. Thus, no other working condition is investigated (i.e. the state transition logic is not involved in this phase, but only the torque-RPM control law);
- the second sub-task (see paragraph 7.2.2) stresses the state transition logic by feeding into the model some wind speeds which force the angular velocity to cross some predefined thresholds (according to the settings defining the state transition), so as to get the control logic strongly involved.

Results are shown as a comparison between real data and VAWT-DP numerical predictions, as well as some statistics. Geometrical and inertial characteristics of the real rotor are implemented in VAWT-DP, while the numerical control system is described by the very same settings of the real wind turbine controller. In order to improve results reliability, the integrity of open-field recorded data was deeply checked before any validation process; sporadic errors in wind speed measurements were identified and corrected where possible, or data were discarded if corrupted. Finally, an investigation was carried out on data continuity: such investigation aimed at assessing if time series portions were lost during sampling and/or transmission operation, because data discontinuity may lead to illusory results. Furthermore, a selection of the most significant time series was conducted, in terms of average wind speed, gust slopes and turbine operating points.

## 7. Results

This paragraph describes the model results by resorting to Pearson's correlation coefficients for electric power and rotor angular speed, defined as  $P_{corr}$  and  $\omega_{corr}$ , respectively. Measured time series and simulated results are gathered on the same graphs, as shown from fig. 5 to 12, where the upper plot shows the wind speed modulus (parallel to the ground) measured in open field and fed into the numerical model, the medium plot shows a comparison between the real rotor angular velocity and the numerically predicted one and, finally, the lowest plot shows a comparison between the net electric power provided to the power network and the numerically predicted one. Each simulation is performed with the actual air density (measured very close to the test field); static validation is performed considering a stiff tower, while the dynamic validation considers a flexible tower.

### 7.1. Static performance validation

This first validation step helps assessing the reliability of two VAWT-DP modules: the rotor aerodynamic module (which is responsible of the interpolation within the real functional maps) and the control module (which operates the rotor according to the torque-RPM law, on the basis

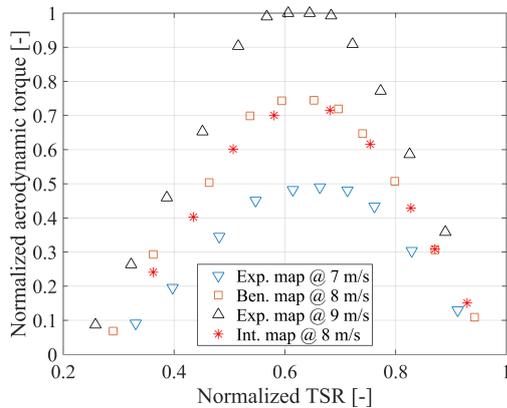


Figure 3: Bi-dimensional interpolation results.

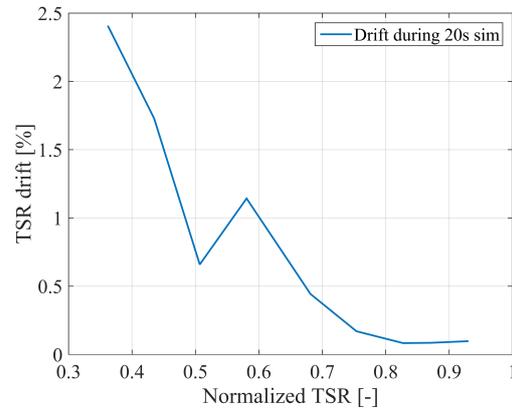


Figure 4: Maximum drift experienced by the rotor during 20 s of simulation under a steady wind of 8 m/s.

of the actual operating conditions, i.e. rotor angular speed). Three experimental maps were involved: the  $C_P - TSR$  map measured at 7 m/s, 8 m/s and 9 m/s. The first and the last maps are used as interpolation boundaries, while the intermediate map is used as a benchmark. The target of the validation process is to recover the rotor torque-RPM curve from an extrapolated  $C_P - TSR$  functional curve. Starting from the above mentioned first and last  $C_P - TSR$  maps, the model tries to estimate the map in between and, then, to determine the aerodynamic torque provided by the rotor. Then the real torque-RPM curve, measured at 8 m/s (benchmark), can be compared to the interpolated data, as shown in fig. 3: despite the interpolation was made with some gaps of 2 m/s between the available maps, a good agreement between the estimated torque curve (stars) and the experimental benchmark curve (square) is registered. This validation was performed in a worse condition than real simulations, which present gaps beside maps of just 1 m/s. Furthermore, maps may have different angular speed ranges: in this case, the algorithm can perform a linear extrapolation on missing data and then proceeds with the interpolation.

The validation process aims successively at investigating how much interpolation errors could affect the model's predictions; unless the aerodynamic torque is perfectly balanced by the control torque, the rotor undergoes to speed drifts, causing the turbine to work off the operating condition expected by the controller, thus such drift is due to torque unbalances and not to numeric error. For this purpose only, the control module embeds the experimental aerodynamic torque-RPM law, measured at 8 m/s (benchmark values), while the rotor aerodynamic module computes the aerodynamic torque based on the interpolated map. To evaluate interpolation's effectiveness a range of constant winds has been fed to the model, then the dynamic solver computes the TSR drift (as shown in fig. 4), according to the inertia of rotating parts and torque balance. The TSR drift indicates how the simulated working point is far from the nominal TSR working point described by the benchmark curve. The plot shows the percentage rotor TSR drift, computed with respect to the nominal TSR of each operation point ( $TSR_{drift} = 1 - TSR_{nominal}/TSR_{simulated}$ ), for a simulation period of 20 s. The control module has to match the aerodynamic torque with a proper resisting torque by varying the angular speed, the smaller the variation from the initial condition the better is the interpolation. The maximum TSR offset is 2.4%, which is assumed to be acceptable for the here presented computations.

## 7.2. Unsteady performance validation

VAWT-DP is here fed with experimental turbulent winds, sampled at 20 Hz, in order to evaluate its behaviour under unsteady conditions. This validation step aims at two targets:

- assessing the dynamic solver stability under unsteady wind time series, falling within the turbine's normal operating range (no state transition logic is involved);
- verifying if the control logic module has the same behaviour of the real turbine (i.e. comparing state transition occurring between several states).

VAWT-DP results are then compared with open field turbine measurements, to highlight similarities and/or differences.

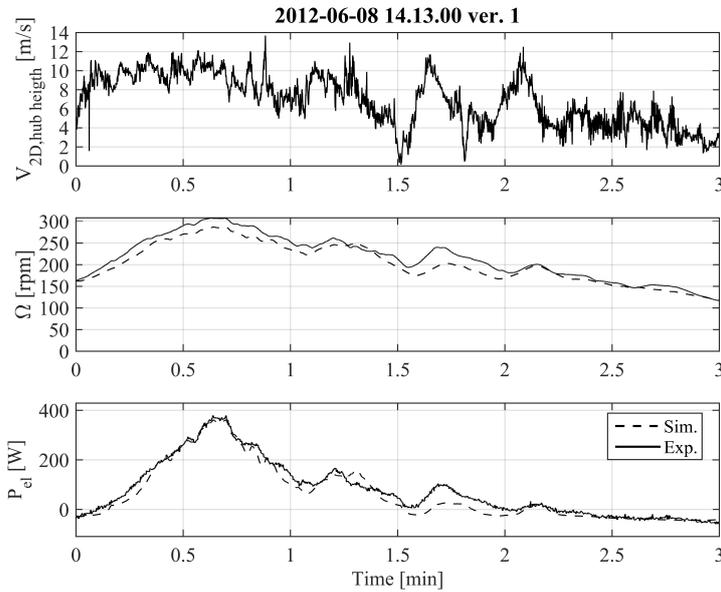
*7.2.1. Normal operation* This section shows simulations falling within the normal operational angular speeds (between 135 and 309 rpm) and below the cut-out wind speed (20 m/s): it is therefore possible to investigate the dynamic solver stability under unsteady winds. The first result (shown in Figure 5) concerns a quite interesting 3 min time series, where the wind speed ranges from almost 0 m/s up to 14 m/s, while the angular speed spans over most of the normal operational range. The time series begins with very steep wind speeds, from 8 m/s, and then it settles to about 10 m/s. The rotor accelerates from 160 rpm up to 300 rpm and the power dramatically increases, too; then the wind slows down to 7 m/s, rotor speed and power following the same trend. From  $t = 1$  min to  $t = 2.2$  min, the turbine experiences three deep wind drops and two steep gusts; finally, the wind falls down to 5 m/s and the turbine reduces its rotational speed accordingly, while the produced power becomes negative (i.e. electronic devices absorb energy from the grid). Despite the high turbulence level ( $I_{TU} = 0.38$ ), extreme values and time series general trends are well predicted and correlation coefficients between simulated and experimental data present a high value (about 0.98), see Table 1.1 To assess the effect of tower flexibility on the code prediction, the above mentioned wind time series is once more fed to the VAWT-DP, this time considering the tower as a rigid body (tower top velocity is zero); results indicate a negligible difference between the two simulations, because the speed at which the tower top vibrates is much smaller than the incoming wind speed (the model predict a maximum  $V_{TT}$  of 0.1 m/s), thus the relative speed does not change considerably.

The second proposed simulation, Figure 6, lasts 4 minutes and is based on a average wind speed of 8.2 m/s and  $I_{TU} = 0.22$ : the wind ranges from 2.4 m/s up to 13.6 m/s, the rotor speed ranges from 195 rpm up to 303 rpm, while the power spans from almost 10 W up to 385 W. The model can predict quite well both trends and extreme values; in this case, some overshoot and underestimation also occur. The correlation coefficients are below 0.8, see Table 2.

The third proposed comparison, Figure 7, lasts 3 minutes and yields many gusts with an amplitude of more than 6 m/s, while the average wind speed is about 6.8 m/s with an high level of turbulence (0.3). VAWT-DP seems capable of correctly reproducing real turbine behaviour, since both correlation coefficients indicate a high degree of trend similarities, see Table 3; extreme values are well predicted, too.

The fourth proposed comparison, Figure 8, shows a good agreement between simulated trends and experimental data; such time series yields a low wind intensity (about 6 m/s) which cause the turbine to work across zero power. This simulation shows the model ability to replicate the effect of on-board electronic power consumption, demonstrates the numerical stability of the simulations and confirms once more the prediction accuracy. Correlation coefficients are both above 0.9 and extreme values are well predicted, too.

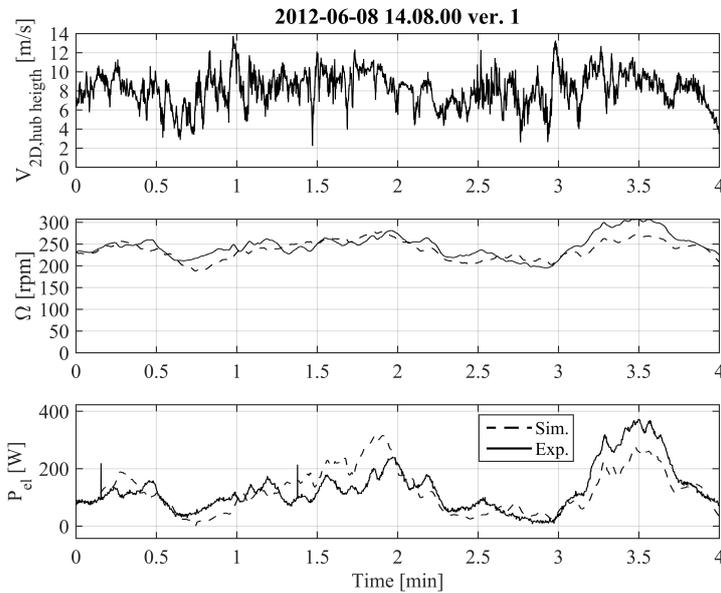
Finally, the last proposed comparison, Figure 9 yields a very gusted wind, ranging from 1.8 to 13 m/s; experimental power and angular speed show 4 main peaks, occurring at  $t = 0.6$  min,  $t = 1.1$  min,  $t = 2.55$  min and  $t = 3.1$  min. VAWT-DP seems able to catch just global events (peaks occurring at  $t = 0.9$  min and  $t = 2.75$  min) and yields a limited capability of predicting



$P_{corr}$	$\omega_{corr}$	$V_{ave}$	$I_{TU}$
[-]	[-]	[m/s]	[-]
0.98	0.98	6.9	0.38

Table 1: Main coefficients for 2012-06-08 14.13.00

Figure 5: Normal operation with wind gust, drops and almost constant wind, see Table 1.

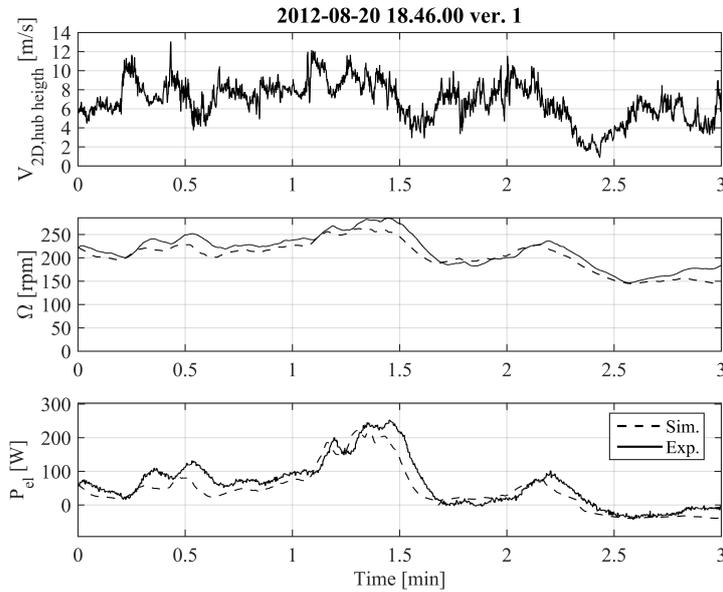


$P_{corr}$	$\omega_{corr}$	$V_{ave}$	$I_{TU}$
[-]	[-]	[m/s]	[-]
0.77	0.75	8.2	0.22

Table 2: Main coefficients for 2012-06-08 14.08.00

Figure 6: Normal operation with almost constant wind, see Table 2.

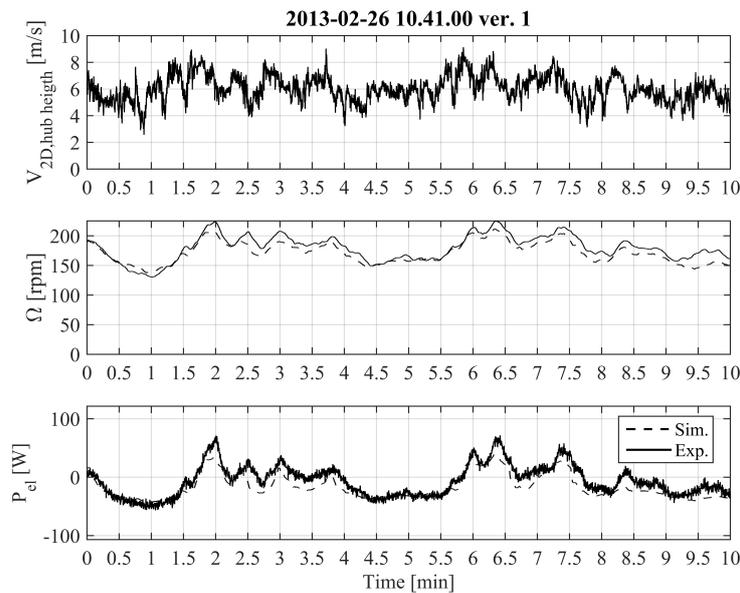
trends and values. The reason for such discrepancy can not be ascribed to errors occurred into the simulators, since at least the global behaviour is captured. Such result suggests that, for a deeper investigation on the turbine dynamic behaviour, an huge amount of operative conditions should be fed to the model, in order to collect statistical meaningful results.



$P_{corr}$	$\omega_{corr}$	$V_{ave}$	$I_{TU}$
[-]	[-]	[m/s]	[-]
0.95	0.93	6.8	0.30

Table 3: Main coefficients for 2012-08-20 18.46.00

Figure 7: Normal operation with several gusts.

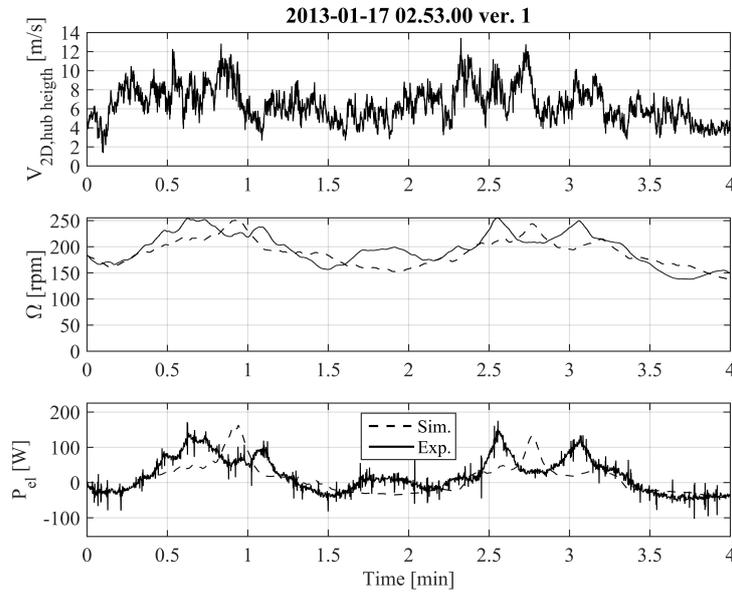


$P_{corr}$	$\omega_{corr}$	$V_{ave}$	$I_{TU}$
[-]	[-]	[m/s]	[-]
0.93	0.90	6.0	0.16

Table 4: Main coefficients for 2013-02-26 10.41.00

Figure 8: Normal operation with gusts.

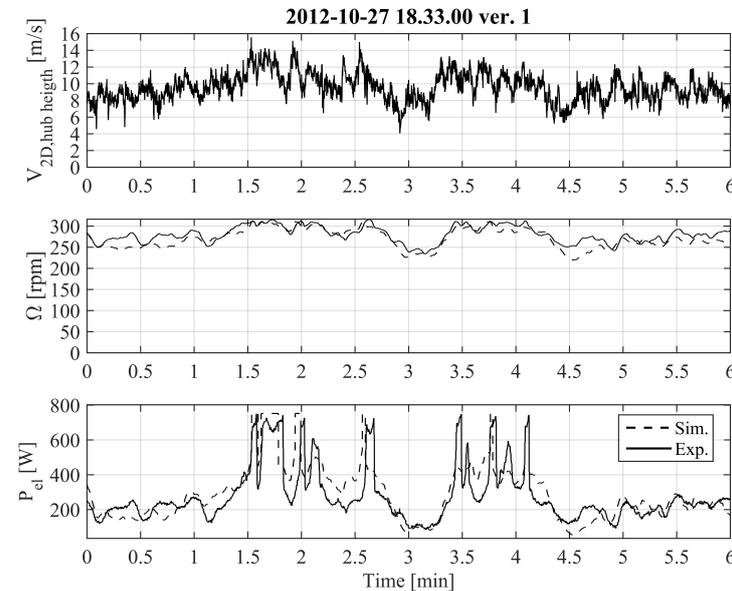
**7.2.2. State transitions** This result batch wants to asses the state transition logic ability to change its working state according to the applied boundary conditions. Such a module reads the rotor speed and takes decisions comparing actual values to set thresholds. The first proposed time series, Figure 10, begins with a wind speed up from 8 m/s to 13 m/s, then some gusts occur up to 15 m/s, as well as some drops down to 4 and 6 m/s. The model predicts very well the rotor speed throughout the whole simulation and the simulated electric power catches almost perfectly the power peaks due to state change. The control module switches from normal production to generator braking state when the rotor speed exceeds 309 rpm. In such a state,



$P_{corr}$	$\omega_{corr}$	$V_{ave}$	$I_{TU}$
[-]	[-]	[m/s]	[-]
0.74	0.67	6.5	0.29

Table 5: Main coefficients for 2013-01-17 02.53.00

Figure 9: Normal operation with gusts, partial trends prediction.



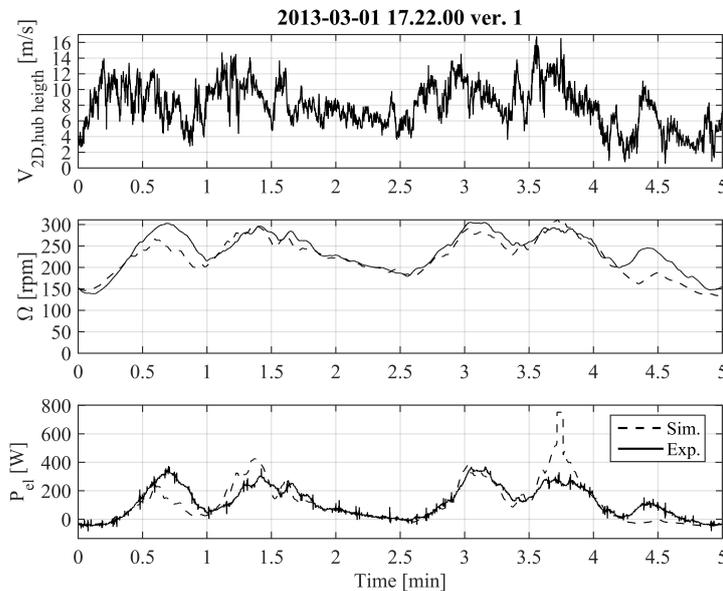
$P_{corr}$	$\omega_{corr}$	$V_{ave}$	$I_{TU}$
[-]	[-]	[m/s]	[-]
0.86	0.75	9.6	0.17

Table 6: Main coefficients for 2012-10-27 18.33.00

Figure 10: State transitions between normal production and generator braking state.

the controller drains the maximum allowed current from the generator circuits, which applies the maximum electric braking torque to the rotor; the turbine remains in this state until the rotational speed falls below 300 rpm (hysteresis loop), then the controller turns the state back to normal operation. Correlation coefficients and wind statistics are indicated in Table 6.

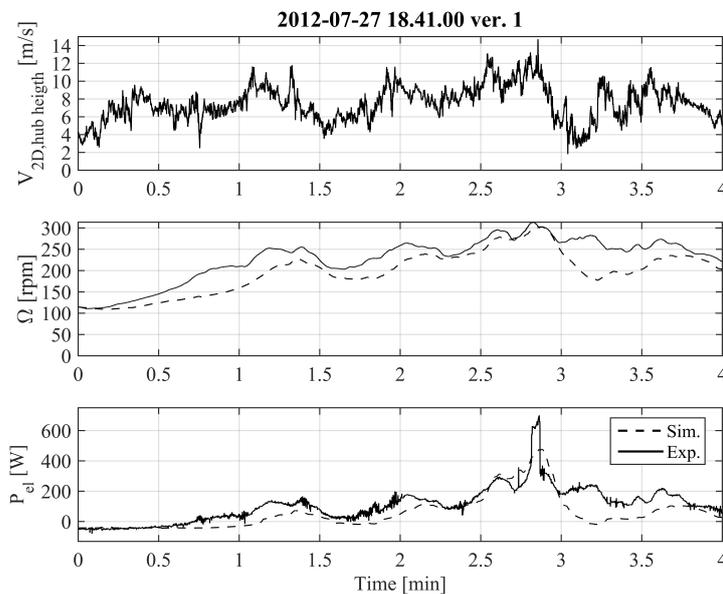
The second proposed time series, see Figure 11, begins with a steep wind speed-up (from 3 m/s to 14 m/s), then many gusts occur; the last gust (at  $t = 3.7$  min) causes the model to



$P_{corr}$	$\omega_{corr}$	$V_{ave}$	$I_{TU}$
[-]	[-]	[m/s]	[-]
0.90	0.81	7.9	0.34

Table 7: Main coefficients for 2012-03-01 17.22.00

Figure 11: State transition between normal production and generator braking state, overshoot.



$P_{corr}$	$\omega_{corr}$	$V_{ave}$	$I_{TU}$
[-]	[-]	[m/s]	[-]
0.91	0.84	7.5	0.25

Table 8: Main coefficients for 2012-07-27 18.41.00

Figure 12: Missed state transition between normal production and generator braking state.

switch from normal production state to electric braking condition, despite real data do not show such a behaviour. Nevertheless, correlation coefficients are still high, as shown in Table 7.

The third proposed time series, see Figure 12, begins with a very mild wind speed-up (from 3 m/s up to 14.5 m/s); the real rotor gently follows the wind trend until an abrupt state change occurs at  $t = 2.8$  min; the model does not predict such a behaviour. Nevertheless, the simulation yields high correlation coefficients, as shown in Table 8. The last two results suggest that several

simulations must be carried out in order to collect statistical meaningful information about the turbine and the behaviour of its sub-components.

## 8. Conclusion

VAWT-DP was verified for various operating conditions: almost steady wind, wind drops, gusts and different turbulence levels, by feeding to the model wind time series collected during open field tests. The substantial dynamic features of both rotational speed and generated power are well replicated for very different boundary conditions. This suggests that the main real turbine parameters are correctly implemented into the model. Moreover, the simulation results indicate that, even though the numerical model is based on static functional curves, its capability of reproducing time-dependent rotor operation is not compromised. VAWT-DP can therefore be used to develop new control algorithms and to investigate the reliability of their logic, as well as their impact on the turbine dynamics. On the other hand, the model could also lead to wrong state changes or make partial predictions of real events, thus such dynamic analysis needs an huge amount of simulations in order to collect statically meaningful operational conditions. The influence of tower flexibility on code's predictions is negligible, but as shown in [4] the rigid tower assumption may leads to loads underestimation. Therefore the validation process indicates that the simplifying assumptions behind the VAWT-DP model (rigid rotor, uniform turbulent flow and flexible tower) don't compromise dynamic prediction capability and then it is suitable as the core algorithm of more complex platform able to computes the DLC according to IEC 61400-2 standard.

Quality and continuity analyses were performed on the time series involved in the validation, confirming that great care should be taken in the data quality control. As a matter of fact, missing portions and/or not physical values may drive the simulation to unrealistic results.

Despite static functional maps embed themselves blade dynamic stall effects, when very steep wind variations occur, the performance prediction degree is, sometimes, quite low. Such behaviour may indicates that during fast gusts other phenomena arise, i.e. the real turbine wake takes a longer time to match the new operative conditions; it can be therefore concluded that further investigation is to be undertaken, especially on transient working conditions. Future works want: to asses the maximum turbine scale which can be modeled with this simplified approach and implement some basics structural computations.

## References

- [1] H. G. Svendsen, K. O. Merz, "Control System for Start-up and Shut-down of a Floating Vertical axis Wind Turbine", *Energy Procedia*, Vol. 35 (2013), pp. 33-42
- [2] G. F. Homicz, "Numerical Simulation of VAWTStochastic Aerodynamic Loads Produced by Atmospheric Turbulence: VAWT-SAL Code", SAND91-1194, SEPTEMBER 1991.
- [3] H. Aagaard Madsen, T. J. Larsen, U. Schmidt Paulsen, L. Vita, "Implementation of the Actuator Cylinder Flow Model in the HAWC2 code for Aeroelastic Simulations on Vertical Axis Wind Turbines." In *Proceedings of 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*. Chapter AIAA 2013-0913.AIAA.
- [4] G. Soraperra, G. Cimatti, L. Battisti, L. Zanne, A. Brighenti, "Dynamic modelling of the drive train of small vertical axis wind turbines", *EWEA 2012 Conference*, April 2012.
- [5] "Analysis of the fluid dynamic behavior of VAWT", Tozzi Nord S.r.l. internal report, 2009.
- [6] D. Sale, J. Jonkman, W. Musial, "Hydrodynamic Optimization Method and Design Code for Stall-Regulated Hydrokinetic Turbine Rotors", NREL/CP-500-45021, August 2009
- [7] I. Paraschivoiu, "Wind Turbine Design - With Emphasis on Darrieus Concept", Polytechnic International Press: Montral, Canada, 2002.
- [8] "Analysis of VAWT performances in open field", Tozzi Nord S.r.l. internal report, 2013.
- [9] D. Ionescu, L. Battisti, S. Dell'anna, E. Benini, "The influence of turbulence on the power curve at small power urban wind turbines", *INCER 2013 Conference*, Bucharest (RO).