Investigation of the complete power conversion chain for small vertical- and horizontal-axis wind turbines in turbulent winds

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Abstract. The study of wind turbines requires a multidisciplinary approach that covers the electrical, mechanical and aerodynamic aspects. Most wind turbine studies focus their modeling effort on a single aspect and rely on simplified models for the other ones. The present paper aims at a complete modeling and investigation of the energy conversion chain of small wind turbines (up to 100 kW), going from the turbulent wind resource to the electrical power injected into the grid. For that purpose, the following computational chain is set up: a synthetic turbulence is used as inflow to a Vortex Particle-Mesh method which computes the wind turbine coarse scale aerodynamics taking into account the rotor dynamics; the aero-mechanical results are used to feed an electrical simulation and the consistency of both simulations is ensured by using a common Maximum Power Point Tracking algorithm. We apply this methodology to compare the behavior of horizontal- and vertical-axis machines in a turbulent wind with two different turbulent intensities (low $TI = 8.3\%$ and high $TI = 16\%$).

1. Introduction
Most wind turbine aerodynamics studies have implicitly targeted utility-scale machines; this is especially true for the investigation of turbulence effects. Indeed, such studies become quite scarce when one considers smaller wind turbines in the power range of 50 to 100 kW, and thus rotor diameters of approximately 20 m. At such sizes, the interaction between the ambient turbulence and the rotor presents some specific features: the energy-containing eddies are of a size comparable to the rotor, which in turn can lead to fast dynamics at the machine level. This obviously has some important repercussions on the machine performance, both in terms of its average production and of the quality of electricity injected into the grid.

These challenges are made worse by a couple of factors: (i) these small machines are precisely targeted at installation sites in high-turbulence (e.g. urban) environments; (ii) non-classical configurations co-exist at such scales: horizontal- and vertical-axis wind turbines, passive and active yaw, etc. These hint at gains in production and in reliability that could be sought in the tailoring of control schemes, electro-mechanical conversion chains and machine designs to the site-specific turbulent conditions.
In this paper, we present a modelization chain for the study of the small wind turbines. This chain covers the whole energy conversion process with the wind resource assessment at site level, the rotor aerodynamics, its dynamics and their interaction with the electro-mechanical converter and the control scheme. Simulations of the complete conversion chain were performed in other studies, e.g. in [1, 2, 3], but often using simplified aerodynamic modeling tools. Here, in order to investigate the effect of atmospheric turbulence on the energy conversion, we use a higher fidelity CFD tool to simulate the aerodynamic response of the turbines. Due to space constraints, we restrict the present discussion to the machine-level parts and assume the wind to be given. Section 2 presents the modules of this modelization and their coupling. In Section 4, the resulting tool is applied to the comparative study of representative turbine technologies: a constant-speed HAWT with passive yaw, the same machine but with variable speed and active yaw, and finally, a VAWT.

2. Methodology

2.1. Mechanical model

2.1.1. Aerodynamics  The ambient turbulence, the coarse scale aerodynamics and the resulting wakes of the wind turbines are obtained through Large Eddy Simulation based on a massively parallel implementation of a Vortex Particle-Mesh flow solver. This method exploits a dual discretization. The advection of vorticity is handled in a Lagrangian fashion using particles whereas the right-hand sides of the evolution equations are evaluated efficiently on a mesh [4]; this includes the solution of the Biot-Savart law for the velocity field, here using a Fourier-based solver [5]. To this end, information is made available on the mesh, and recuperated from the mesh, by interpolating back and forth between the particles and the grid using high order interpolation schemes. Advantageously, this hybridization does not affect the good numerical accuracy (in terms of diffusion and dispersion errors) and the stability properties of a particle method [6].

The generation of vorticity along the blades is accounted for through an immersed lifting line approach [7]. The approach is very much akin to a Vortex Lattice method: the bound circulation is obtained from equating the lift expressions given by the Kutta-Joukowski theorem (see e.g. [8]) and by the local airfoil aerodynamic performance (i.e. the lift coefficient $C_l(\alpha)$). Streamwise and spanwise vorticities are then shed from the lifting line in order to account for spanwise and temporal variations of the bound circulation, respectively. We note that this aerodynamic performance can either be directly obtained from static polar data or computed dynamically to take into account unsteady effects through a Leishman-Beddoes dynamic stall model [9]. This work uses such a semi-empirical model and follows the recommendations of Dyachuk [10] and Scheurich [11]. Finally, the inflow turbulence is fed as a particle-carried vorticity field obtained from pre-computed 3-D synthetic turbulence boxes generated using the Mann algorithm [12].

2.1.2. Dynamics  We assume rigid body dynamics for the rotors: no blade bending or torsion is accounted for. We can thus use a standard Multi-Body System solver built into the VPM code for the rotor dynamics. The rotor dynamics only comprise the angular momentum balances along the rotor axis (between inertia and the sum of the aerodynamic and generator torques) and along the nacelle axis for the HAWT with passive yaw. The speed of the rotor is controlled by a standard PI (proportional - integral) controller which is displayed in Fig. 1. If the error between the actual angular velocity $\omega$ and the targeted velocity $\omega_{\text{target}}$ is $e = \omega_{\text{target}} - \omega$, the generator torque is determined by

$$T_{\text{gen}} = k_P e + k_I \int e \, dt,$$  \hspace{1cm} (1)
where \( k_P \) and \( k_I \) are the proportional and integral constants of the controller. Since the VPM uses an adaptive time-step, a continuous-time PI loop had to be implemented where the integral term is obtained by integrating in time the ODE \( \frac{d\omega}{dt} = e \) using the RK3 scheme of the VPM solver.

2.2. Electrical model
From an electrical point of view, wind turbines can be classified in 4 categories: Fixed speed, limited variable speed, Doubly Fed Induction Generator (DFIG) and variable speed with full-scale power converters. Small wind turbines are usually equipped with a permanent magnet synchronous generator with full scale converters allowing them to maximise their power.

Generally speaking, the full-scale frequency converter consists of a rectifier (AC-DC converter), a DC-link which can be a DC-DC converter or simply a capacitor and an inverter (DC-AC converter). For small wind turbines, the most common conversion chain is made of a diode rectifier, a boost and a voltage source inverter. This last solution was implemented in Matlab Simulink environment with the SimPowerSystems toolbox. For comparison, the fixed speed configuration was also implemented.

The implementation of the fixed speed configuration is straightforward since it is only made of an induction generator. Theoretically, a soft-starter and a capacitor bank should be inserted between the grid and the induction machine but they would have no influence on the present study and they would slow down the simulation.

The implementation of the variable speed configuration is more complex since it includes two controllers: the generator side control and the grid side control. The generator side control aims to extract maximum power. With the chosen configuration, i.e. a diode rectifier followed by a boost, the control is performed on the duty cycle of the boost. The rotor speed control is made of an internal loop and an external loop as illustrated by the block diagram in Figure 2, where \( \omega^*_r \) is the optimal rotor speed, \( \omega_r \) is the actual rotor speed, \( I^*_dc \) is the optimal current on the DC side of the diode rectifier, \( I_{dc} \) is the actual DC current and D is the duty cycle.

![Figure 2. Electrical side speed controller: block diagram](image)

The grid side control has two objectives. First, the DC link capacitor voltage is maintained constant in order to ensure the active power exchange from the generator to the grid. Second, the reactive power or the voltage is controlled. Therefore, the wind turbine can operate as a PQ or a PV node. In the present study, the reactive power is controlled to be equal to zero. These
two controls can be made separately. The first one is performed through the control of the direct voltage component, while the other one is achieved through the quadrature component.

2.3. Coupling strategy and power-tracking controller

We use a Maximum Power Point Tracking (MPPT) strategy to feed a target velocity to the speed controller of Eq. (1); this MPPT ensures that the machine operates at an optimal Tip Speed Ratio (TSR) for power capture. This MPPT based on the control of the rotor speed was proposed and also investigated for small wind turbines in [13]. Specifically, the selected MPPT sets the target velocity \( \omega^* \) to the velocity at which, if running at its optimal TSR \( \lambda_{opt} = \omega^* R / U \) (with \( R \) the rotor radius and \( U \) the wind velocity), the machine would generate the same power as in the current condition. If we assume that Reynolds number effects are negligible, the optimal power coefficient \( C_{P,opt} \) and TSR \( \lambda_{opt} \) are independent of wind velocity. The optimum production curve is thus

\[
P_{opt} = \frac{1}{2} \rho A \left( \frac{\omega^* R}{\lambda_{opt}} \right)^3,
\]

where \( \rho \) is the air density and \( A \) is the rotor swept area. The MPPT strategy will thus target a velocity such that \( P_{opt} = P \), leading to

\[
\omega^* = \lambda_{opt} R \left( \frac{P}{\frac{1}{2} \rho C_{P,opt} A} \right)^{\frac{1}{3}}.
\]

In order to limit the fast variations of the target velocity which can occur in turbulent atmospheres, the target velocity actually given to the turbine speed controller \( \omega_{target} \) is obtained by applying an exponential smoothing of the instantaneous target \( \omega^* \).

The parameters of the speed controller as well as the smoothing of the target angular velocity were determined through experiments with a 0-D model and the \( C_P \) curves were computed by means of preliminary VPM simulations without turbulence.

Fig. 3 summarizes the models and their coupling, which can be seen to be one-way: the time history of the aerodynamic torque on the rotor \( T_{aero} \) obtained in the VPM simulation is stored and then used as an input for the simulation of the rest of the conversion chain. This is justified by the important disparity in the temporal scales of the mechanical and electrical systems and by the MPPT essentially canceling feedback from the grid and the electrical system to the mechanical part. The one-way coupling for the variable speed wind turbines thus entails that the electro-mechanical simulation runs the same MPPT algorithm as the aerodynamic code and also solves the rotor dynamics. The electro-mechanical simulation is then expected to produce the same rotor velocity history as the mechanical simulation; this assumption will be assessed in Section 4.

For the fixed speed wind turbine, the coupling is straightforward since the speed is assumed to be constant in the VPM simulation even if it slightly varies.

3. Configurations

Based on an inventory of different technological configurations used by various manufacturers, three very distinct mechanical configurations have been chosen for comparison:

- **HAWT-CS**: a Constant Speed, downwind, passive-yaw HAWT equipped with an induction generator (model based on the AOC 15/50 [14])
- **HAWT-VS**: a Variable Speed, active-yaw HAWT equipped with a Permanent Magnet Synchronous generator with a diode rectifier, a boost converter and an inverter (adaptation of the AOC 15/50)
Figure 3. Schematic of the one-way coupling

- **VAWT**: a variable speed VAWT with the same power converters chain as the variable speed HAWT (model based on the Fairwind F180)

For the HAWT-CS, the passive yaw dynamics is simulated in the VPM simulation whereas the yaw orientation of the HAWT-VS is actually frozen to the mean wind direction. There is thus no yaw controller implemented for the HAWT-VS, we assume that a controller would align the turbine with the mean wind for the duration of the simulation. These machines are subjected to two representative turbulent wind scenarios: a low turbulence intensity one, $TI = 8.3\%$, and a high one, $TI = 16\%$. The computational domain extends over $L_x \times L_y \times L_z = (15 \times 8 \times 6)D_{HAWT} = 225 \text{m} \times 120 \text{m} \times 90 \text{m}$ in the streamwise, lateral and vertical directions, respectively. This size, which can be better appreciated in Figs 7 and 8, allows to feed very large, long-lived flow structures (i.e. gusts and lulls) in the domain and to capture the dynamics of the turbine wake over large distances. The mesh/particle resolution is set at 64 points per HAWT-diameter, leading to an initial mesh size of $n_x \times n_y \times n_z = 960 \times 512 \times 384$. As the domain is dynamic in the transverse unbounded directions, the ambient turbulence causes the domain to grow in those directions over the simulations and the grid size can eventually reach $960 \times 800 \times 544$. The simulations were run for 120 s and 240 s of physical time for the low and high turbulence intensities, respectively. The synthetic inflows consist in a 80 s-long Mann database, leading to its periodic recycling in the simulations.

4. Results

4.1. Average power production

We first assess the average efficiency of the three turbines through their power coefficient $C_P = P_{avg}/\frac{1}{2}\rho A\bar{U}^3$, with $P_{avg}$ the generator power averaged over a period of the inlet turbulence.

As can be seen in Table 1, the HAWT-CS is seen to be quite sensitive to the turbulence since its production is already significantly decreased for the low turbulence, and it is further deteriorated as the TI increases. On average, the velocity adaptations achieved by the HAWT-VS provide a very good efficiency at low TI for the HAWT-VS, as the $C_P$ is equal to its optimal value, and even larger due to the small difference between the average wind computed on the Mann box and its realization in the VPM simulation. When used with the VAWT, the controller is slightly less efficient at low TI than for the HAWT-VS. However, the low TI simulations were run for only 120 s and the system may not have fully reached its steady periodic regime. The deterioration of the performance at high TI is clear as the loss of production is 42% for the HAWT-CS, 32% for the HAWT-VS and 38% for the VAWT.

4.2. Rotor dynamics and control

This averaged behavior can be further investigated through the rotor speed and power histories, shown in Figs. 4 and 5 respectively. The curves are normalized by the optimal TSR and power based on the mean cubic wind. As expected, the variable speed machines exhibit rotor
Table 1. Averaged power coefficient in turbulent winds

|          | $C_{P, opt}$ | $C_P$ |
|----------|--------------|-------|
| HAWT-CS  | 0.490        | 0.433 | 0.282 |
| HAWT-VS  | 0.500        | 0.501 | 0.340 |
| VAWT     | 0.464        | 0.444 | 0.288 |

speed fluctuations which increase with the turbulence intensity. Furthermore, these rotor speeds exhibit means which, at low TI, are close to their optimal values based on the mean cubic wind speed but are significantly lower for high TI. The same trend can be observed for the power production. The power of the HAWT-CS fluctuates significantly but those fluctuations are damped when a controller is used and the episodes of very low, even negative, power production are then also suppressed. The production of the VAWT varies less than that of the HAWT-VS but is also lower on average, relatively to their potential optimum powers. Similarly, the rotor speed fluctuations are larger for the HAWT-VS than for the VAWT, probably due to the choice of identical controller parameters for this study.

Figure 4. Relative speeds for the HAWT-CS (black), HAWT-VS (red) and the VAWT (blue) at low and high turbulence intensities

The behavior in yaw of the downwind passive yaw HAWT-CS machine is presented in Fig. 6. The angle reached is very significant, especially in the high turbulence where it varies between -60° to +20°. The yaw rates also call for a comment as the rotor yaws from +20° to -48° in less than 20 s. The NREL report [14] cites measured yaw rates of more than 60°/s which are not reached here. Those excessive yaw rates, and the resulting excessive gyroscopic moments, had led the designer to include a yaw damper on the AOC 15/50. However, this yaw damper only engages when the yaw rate exceeds 45°/s, i.e. much higher than in the present simulation. This justifies that no yaw damper was added to the dynamic model.

4.3. Wakes and ambient turbulence
The flows past the HAWT and the VAWT, in the low turbulence case, are visualized in Fig. 7 using 3-D volume rendering of the vorticity magnitude. The colormap for vorticity has an intentionally high threshold: the small structures of the ambient turbulence disappear, which allows to identify the structures of the wake itself. The near wake of HAWTs mainly consists in helicoidal vortices emanating from the blade tips. In the presence of turbulence, this near wake
Figure 5. Power productions for the HAWT-CS (black), HAWT-VS (red) and the VAWT (blue) at low and high turbulence intensities

Figure 6. Yaw angle of the HAWT-CS in low (blue) and high (red) turbulence

quickly becomes turbulent and its coherent helicoidal structure can no longer be distinguished. Wake meandering is clearly present a few diameters downstream of the machine: the turbulent far wake is seen to be transported and deformed by the large-scale structures of the atmosphere. The near-wake of VAWTs does not exhibit helicoidal vortices and has a much more complex structure due to the unsteady loading of the blade during a rotor revolution. The structure of such wakes was studied in more details in [15]. The wake also transitions to turbulence and is subjected to some meandering.

The high TI cases are displayed in Fig. 8 for the three turbines, rather using hub height slices of the velocity magnitude. The significant yaw angle of the HAWT-CS is clearly visible as the rotor projection line is not at all perpendicular to the mean wind, blowing from left to right. These visualizations, for which the whole domain is displayed, make the large-scale turbulent structures of the atmosphere quite visible. The velocity deficit signatures of wakes can be observed just downstream of the turbines but they rapidly become indiscernible from the ambient turbulence. This is due to the high turbulence intensity which efficiently dissipates the wakes. Just behind the HAWT-CS and HAWT-VS rotors, a high velocity region can be seen in the centre of the disk. This is the hub jet and is due to the fact that the HAWT blades are not efficient near the rotation axis and, therefore, do not slow down the flow in the center of the
Figure 7. Flow structures in the low turbulence case: volume rendering of the vorticity magnitude $||\omega||$; the rotor swept area is denoted by a solid line rotor disk.

Figure 8. Flow structures in the high turbulence case: velocity magnitude $||u||$ in the midplane
Figure 9. Comparison of the rotor speed obtained in the mechanical and electrical simulations of the VAWT with TI = 8.3%

Figure 10. Comparison of the aero power, mechanical power and the electrical power delivered by the VAWT with TI = 8.3%

4.4. Electrical subsystem
The results of the electrical simulations allowed us to validate the one-way coupling strategy. Indeed, the rotor speed computed in the electrical simulations and computed in the mechanical simulations are very close to each other. This can be observed in Figure 9 for the low turbulence case of the VAWT. Results are similar for the other studied cases.

Furthermore, electrical simulations allowed us to determine the power that is actually delivered to the grid. It was concluded that the electrical power follows the same trend as the mechanical power but it is shifted a bit downwards due to the power conversion efficiency. This observation is illustrated in Figure 10 for the low turbulence case of the VAWT. The same conclusion is drawn for the other studied cases.

5. Conclusion and perspectives
In this work, we have developed a model chain for the simulation of the whole energy conversion process in small wind turbines, from the atmosphere to the electrical grid. This chain uses simulations of the wind behavior at the scale of an installation site (not discussed in the present paper) to predict the characteristics of the wind and the turbulence impacting the wind turbine. The wind turbine model comprises a mechanical submodule and an electrical one. The temporal
scale disparities and the use of an MPPT algorithm justify the use of a one-way coupling between these two modules. This assumption was validated by the good agreement between the rotor speeds computed by the mechanical and electrical modules independently.

The present coupling approach makes some simplifying assumptions that could be waived in future work. For instance, the present MPPT controllers are actually tracking the mechanical power curve, assuming a constant optimal TSR; an actual machine tracks the electrical power. For utility scale wind turbines, the efficiency between mechanical and electrical power is almost constant and near unity. Therefore, in this case, the mechanical power maximization involves electrical power maximization. However, for small wind turbines, the efficiency depends on the tip speed ratio. Consequently, electrical and mechanical optimum are not reached for the same rotor speed. The mechanical simulation should then be aware of the conversion efficiency either by using precomputed efficiency maps or by using a two-way coupling.

Three representative small wind turbine configurations have been simulated in low and high intensity turbulent atmospheres. The dynamics of a constant speed HAWT in a downwind/passive yaw configuration were investigated. The power production of this configuration was found to be quite affected by the ambient turbulence, as the passive rotor consistently lags behind the true wind orientation. The transposition of this machine to a more modern configuration with active yaw, variable speed and a MPPT algorithm brings some significant improvements. It allows to reduce the power fluctuations and was shown to be very efficient in the lower turbulence. In the high turbulence case, the controller was not able to harvest all the available wind power. In terms of average power production, the HAWT-VS was found to be slightly less sensitive in the high turbulence case than the VAWT. The latter is however much simpler mechanically and exhibits smaller rotor speed fluctuations. Nevertheless, the controller parameters were not fully optimized for the individual machines of the present study.

This last point actually hints at a first perspective of this work, namely the site-specific optimization of wind turbines and their control schemes. The present computational chain could indeed be exploited to tailor the control of small wind turbines to the specific characteristics of turbulence at a site (turbulent scales, time scales for wind direction changes, etc.). It is also envisaged that this computational tool be used for the production of reference results to support the elaboration of operational models for small wind turbines.

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