Wind generator innovative blade design: variable twist and start-up control

Giuseppe Sirigu, Mario Cassaro, Manuela Battipede, Piero Gili, and Giacomo Frulla

***Abstract*—** This paper presents the preliminary results obtained in the VENTURAS (VENTo: Una Risorsa Altamente Sfruttabile or 'wind: a highly exploitable resource') project, funded by the Italian Environmental, Land and Sea Protection Ministry, within a call for the funding of research projects aimed at improving the energy efficiency measures and the use of renewable energy sources in urban areas. This project addresses to improve the efficiency and to widen the range of the wind speed at which the micro wind turbines operate effectively and safely. This goal is achieved by developing variable pitch blades, which have morphing capabilities that enables the control system to select the optimum twist law along the blade, to optimize the efficiency also in non-nominal conditions. The proposed control strategy aims at maximizing the rotor efficiency, by maintaining the rotor in the nominal working condition. The control algorithm is based on a finite state machine, which commands the twist law to the blades, according to different strategies, predesigned for each working condition. At low wind speed, the control system changes the blade twist law, in order to maintain the angular speed and maximize the electrical efficiency. In this paper, the performance of different start-up strategies are compared.

***Keywords*—** Wind generator, Morphing control, Variable twist, Mini wind turbine.

I. Introduction

SMALL and micro wind turbines represent a growing sector in the renewable energy market for different practical implications: the mini and micro wind turbines, in fact, are usually easily transportable, installable, maintainable, and can have an extremely wide geographical distribution, as they do not require special weather conditions to work effectively. State incentive programs, moreover, make micro and small turbines accessible and an increasingly more affordable solution for consumers who want to reduce their environmental impact and their energy bills. For the VENTURAS project, micro and small turbines represent an interesting application, as they are simple systems, which can be easily assembled and used as technological demonstrators or test rigs.

The class of micro turbines is characterized by a diameter size between 2 and 4 feet, and mainly used for battery-charging or similar applications. Small turbines are slightly bigger, being defined by a diameter size between 4 and 9 feet. Their main application include utility-compatible electricity production, from sailboats to telecommunications towers, residential homes and commercial retailers.

Cutting edge technologies play a crucial role in the large-scale deployment of clean, homegrown energy systems. Therefore, a solution that enables a more efficient energy harvesting in a wider wind speed range is of paramount importance as the wind turbine design is concerned. This is, in fact, the main objective of the VENTURAS project: to investigate, fabricate and test innovative concept design for widening the wind turbine working condition, while preventing efficiency deterioration of the whole system, made of the aerodynamic, mechanical and electric components.

The proposed innovative concept is based on applying an active morphing control to the rotor blades. The aeronautical propeller efficiency, in fact, is a function of the blades geometry and the advance ratio $V/(\omega \cdot R)$, where V is the wind speed, ω the rotor angular speed and R the propeller radius. The airfoil, the chord length and the pitch along the span define the blade geometry and the maximum efficiency for given advanced ratio is obtained by a unique combination of these parameters. However, properly varying only the propeller pitch results in a higher efficiency over a wider advance ratio range, with respect to a fixed pitch configuration of the same propeller [1].The idea behind the proposed turbine concept is to futher improve the efficiency by adjusting also the local pitch angle of the blade section. This is achievable by properly twisting the blade sections depending on the external wind condition. The combination of the variable pitch and twist is obtained through a motion system based on servomechanisms, which modify the collective pitch and the section blade angles, from hub to tip, in several points: smoothness on the blade is obtained through a thin composite skin characterized by high

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G. Sirigu is with the Mechanical and Aerospace Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (corresponding author, phone: +39 011-090-6868, e-mail: giuseppe.sirigu@polito.it).

M. Cassaro is with the Mechanical and Aerospace Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (e-mail: mario.cassaro@polito.it).

M. Battipede is with the Mechanical and Aerospace Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (e-mail: manuela.battipede@polito.it).

P. Gili is with the Mechanical and Aerospace Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (corresponding author, phone: +39 011-090-6854, e-mail: piero.gili@polito.it).

G. Frulla is with the Mechanical and Aerospace Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (e-mail: giacomo.frulla@polito.it).

bending stiffness and low torsional stiffness. The consequent higher complexity design is legitimated by the expected higher amount of energy harvested, with respect to the conventional wind turbine.

The greater advantage of the proposed technological solution is, together with the efficiency improvement at nominal conditions, the ability to work in extreme off-design condition where the standard turbine cannot operate for insufficient wind or excessive rotor speed danger.

Morphing technologies are currently meeting significant interest from the wind turbine community. Because of the large size of modern wind turbine blades, more similarities can be found with wing morphing research than with helicopter blades [2]. The most significant effect of applying morphing technology to large wind turbines lies in reducing fatigue loads for the continuous operation over a lifetime [3]. In fact, a considerable reduction, about 20-32%, of the blade root flap bending moments is demonstrated to be achievable by means of the active aerodynamic blade control. This allows for turbine blade lengths increment, without exceeding the original fatigue loads on the structure. Several solutions have been attempted for active aerodynamic control purpose as blowing/suction surface, heating surface and wing section modification by using ailerons, smart materials, tabs [4] or segmented blade sections [5].

The state of the art in large wind turbine design assesses them as a mature technology in the renewable energy field. On the contrary, small sized wind turbines have not benefited in the recent years of similar concern from the scientific and engineering community. This finds its reason on the claimed unsatisfactory economic return for the industry: the market is not yet sufficiently wide for significant profit to attract investment, with the exception of some micro-turbines, such as those used on boats. Moreover, the small companies operating in the sector do not have the technical capacity or financial forces to sustain and implement research activities. Consequently, small turbine design is often reduced to the effort of scaling large turbines, which is proved an unsuccessful method for mainly two reasons:

- Scarce productivity, because of the different environmental characteristics of the sites where the two type of wind turbine are installed.
- Malfunctioning, expensive maintenance and irreversible breakage deriving from the application of not optimized control technologies.

According to the state of the art [6], [7] statistic surveys of the overall wind turbine production assess that 76% of the commercial small turbines adopts blades with a fixed pitch, which is the cheaper, easier and more reliable solution. Only 23% use variable pitch of the solid blade to control power production. However, the majority of actively controlled wind turbines uses control strategies to prevent the turbines to outrange the nominal conditions. Their main objective is the system safety than the energy harvesting optimization. The common employed solutions consist of a mechanism that rotates the blade pitch-wise by the action of masses, subject to the centrifugal force (passive change in pitch), or of elastic elements known as tip aerodynamic brakes.

There are also solutions based on the rotation of the whole rotor about the vertical axis to align the rotor axis to the wind direction. Both active [8] or passive techniques (passive lateral yaw or furling) could be implemented for these purpose; the latter, exploits the effect of auxiliary aerodynamic surfaces or eccentric masses. Furthermore, systems that permit the vertical yaw (tilting) with the overturn of the whole rotor when the wind speed exceed a threshold are proposed. These solutions are almost entirely abandoned when the size of the rotor exceeds 8 - 10 m, due to the excessive loads that they may induce and the complexity of the mechanical devices.

II. Effectiveness of the Variable Twist Blade Concept

Two main issues concern the application to small wind turbines of active aerodynamic control through morphing technologies:

- the morphing must be realized by small enough actuators that should be contained inside the blade and the turbine's hub without affecting their aerodynamic and structural characteristics;
- the control action must be limited to preserve the energy profit of the entire system.

The first issue represents a physical constraint on the final design but not a real technological challenge, while the second issue is the heart of the project. As alleviating bending moment at blade roots is not critical for small turbines, the main reason to introduce variable twist active control is to improve the turbine energy harvesting performance. For aeronautical propellers, the advantages are self-evident and variable twist capabilities could be used as effectors to move the resultant thrust application point in a proper portion of the propeller/rotor disk for aircraft control purposes. This is conceptually similar to the cyclic command effect on the helicopter rotor, with the crucial benefit of avoiding the introduction of a transversal thrust component, caused by the rotor disk tilt.

For the wind turbine, the advantage of using a variable twist blade need still to be assessed. The blade optimal geometry, in terms of chord laws and pitch angle along the span, is defined for chosen optimal advance ratio γ (or its reverse $\chi=(\omega\cdot R)/V$, the working ratio), which depends itself on the turbine characteristics, mainly size and number of blades. The efficiency of the rotor is constant with the wind speed, if the rotational speed is allowed to vary unlimitedly to maintain the same working ratio (unless the slight effect of the Reynolds number is considered).

Figure 1 shows the trend of the torque versus the rotational speed, for two different blades, optimized for the two values of the working ratio, exactly $\chi=6$ and $\chi=10$. The efficiency values η are almost the same and remains constant if the working point stays on the two curves when the wind speed varies. However, it is worth noticing that the two blades are geometrically very different, being the latter (χ=10) much slender than the previous (χ=6). Figure 1 proves that the blade geometry variation is effective when the final goal is to maximize the rotor aerodynamic efficiency for different working ratios. However, to assess the actual benefits in employing a variable twist blade on small wind turbines the

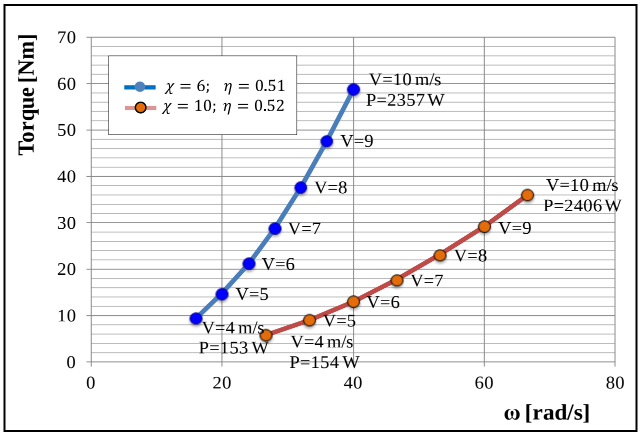

Figure 1. Aerodynamic efficiency for different values of the working ratio $\chi=(\omega\cdot R)/V$ for different wind speed values V.

entire chain of electricity generation must be considered. In fact, it is common knowledge that the electrical generator and the inverter, that are part of the chain, maintain high efficiency values in a very narrow working condition range in terms of rotational speed [9].

III. Mini Wind Turbine Layout

The wind turbine must be equipped by a control system consisting of software code, hardware, dedicated sensors and actuators that allow the turbine to pass from one operating condition to another, with the following functional specifications:

- System start-up: the control architecture should be able to ensure that the blades, in the presence of a certain wind speed, can pass from a situation of rest or idling to the state of normal operation;
- System shutdown: the control architecture should guarantee that the turbine could pass from a state of operation, characterized by power deliver, to a state of rest or idling;
- System transition: the control architecture should respond to wind speed changes by adjusting the blade twisting law according to a pre-selected map, which depends on χ values. This will permit to control the instantaneous power level extracted from the wind turbine.

The final layout identified for the proposed wind turbine is presented in Figure 2 (a) and described hereinafter to demonstrate how the morphing blades actuation is realized and how it affects the inner architecture of the entire system. Despite the classical outer structure, the pylon contains the

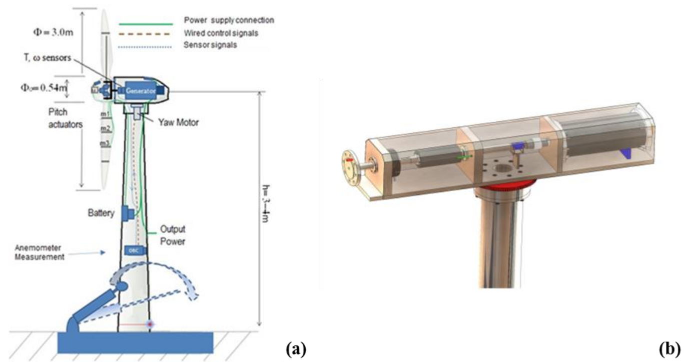

Figure 2. (a) Mini wind turbine architecture; (b) Nacelle 3D model.

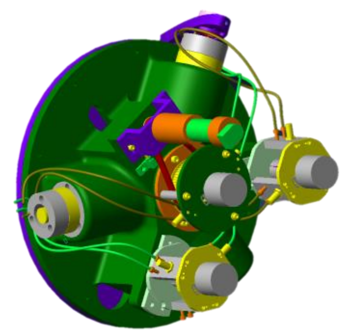

Figure 3. Rotor hub scheme.

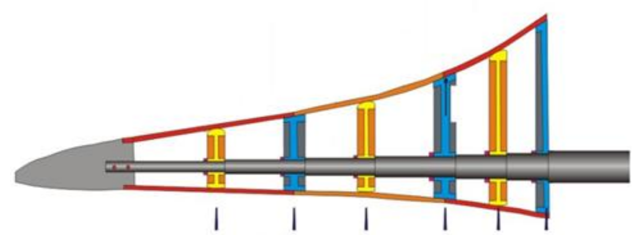

Figure 4. Blade and ribs structures with the actuation scheme (blue ribs are actuated, yellow ribs are dragged).

power supply and an On Board Computer (OBC) for the active control loop. The nacelle hosts the motors for yaw control (Figure 2 (b)) whereas the propeller hub shields the actuators, which control the section rotation in the three blades (Figure 3). The morphing motion is obtained by combining a collective and local pitch changes through the action of servomechanisms to obtain the proper twist law. The servos are distributed along each blade, from hub to tip, exactly at 18.5%, 34.5% and 83% of the blade span. Smoothness on the external surface is obtained by the proper design of a thin composite skin, characterized by great bending stiffness and low torsional stiffness. The outer blade cover is a two-layer 0/90° carbon fiber composite for the skin and a 0/±45° for the thin walled tubular structure. Figure 4 shows a sketch of the actuation mechanism designed on purpose for this application. All the internal ribs are free to rotate around the tubular structure. In detail, the blue ribs are actuated by the servomechanism, while the yellow ones are dragged and are inserted to reduce the deformation of the blade shape during twisting. The inner structural shaft passes through all the ribs and it is rigidly connected to the last actuated one, close to the tip [10]. The collective pitch is controlled by rotating this shaft and keeping the servos in a constant position. In this way the same angular motion is transferred to all the ribs and so forth to the entire blade. In the other two sections, the electric servomotors are rigidly connected to the ribs. The mechanical link obtained through a gear coupling with the inner supporting structure allows relative angular displacement. The actuation command irreversibility must be guaranteed to obtain a proper coupling of the global and local blade section motion. In fact, any backlash between the blade ribs would introduce errors in obtaining the desired twist law θ(r) compromising the entire control strategy.

IV. Control System

One of the windmill functional requirements, which must be satisfied during the power generation phase, is that the generated power must be maintained at the rated value, without exceeding specific tolerances. According to the windmill aerodynamic principles, though, the power that can be extracted from the wind varies proportionally to the cube of the wind speed, so that a consistent control activity must be provided for, in order to accommodate any wind fluctuation.

A higher number of degree-of-freedom, to guarantee greater versatility, characterizes morphing blade wind turbines. For this reason the control techniques than can be implemented are much more complex than the existing wind turbine, due to the increased number of parameters that must be controlled simultaneously.

At the state of the art, two different control strategies are mainly implemented in non-morphing blade turbines. In particular, according to reference [11], if the wind turbine is directly connected to the electrical network by means of an induction generator, usually the angular rate is maintained constant. This is necessary because there is a direct proportionality between the generator rotational speed and the frequency of the generated current. The controller, hence, varies the collective pitch of the blades as a function of the power error, which can be defined as the difference between the rated power and the power produced instantaneously and measured by means of a power transducer. Classical control techniques for the design of the control law (PID controller) are typically used; in [12], a particle swarm optimization has been used to control the pitch angle. Using the generated power error as feedback signal for the control algorithm is convenient, as power is the best measure of the wind effect on the turbine performance. Another important consideration is that the turbine dynamics is much slower than the controller dynamics. It follows that this control system is implemented to work on the moving mean error power, for which the time constant is significantly larger than the blade rotation frequency, with the consequent advantage of avoiding excessive and expensive control activity.

The other common strategy is applied to wind turbines that can work with different angular rates. In this case, the collective pitch is actively controlled, according to the wind speed variation, in order to adequately change ω and maintain χ in the optimal condition. This strategy is particularly interesting as it maximizes of the power production. Despite the very satisfactory response of this control scheme in steady conditions, though, this solution is ineffective in case of turbulence, as the rotor inertia prevents the control system to keep up with the rapid changes of the wind, with adequate accuracy, with the result of working constantly with a non-optimum average value of C_P. This is particularly critical for large wind turbines [5], whereas the inertial effect is understandably lower in the mini wind turbines. For large wind turbines characterized by intense noise, such as off-shore platforms, a more effective controlling strategy must be implemented to allow a more rapid response to wind speed changes. This strategy consists in controlling the rotational speed ω, while maintaining the working point as close as possible to the optimum C_P condition, by varying the resistant generator torque proportionally to the rotor angular acceleration. However, such control strategy is demanding in terms of control activity and, so forth, of energy consumption, resulting inconvenient unless a proper bandwidth is defined for the error signal filter. Barambones et. al. proposed a sliding mode control, which uses the vector oriented control theory in order to simplify the generator dynamical equations, and control the rotor angular speed [13]. What usually occurs in practice is that, to comply with the several structural or aero-acoustic requirements, the maximum rotational speed of the rotor is reached at relatively low wind speeds, typically below the rated one. Therefore, it is usually preferred to increase the torque demand at constant rotational speed until the rated power production is obtained. Such a strategy is obtained by decoupling the two control loops, pitch and torque, using a control logic that avoids simultaneous activations.

V. Mini Wind Turbine Morphing Control

For the mini wind turbine, the key point is to define a control strategy that maximize the beneficial impact of the morphing capabilities. The control parameter is θ(r), defined as

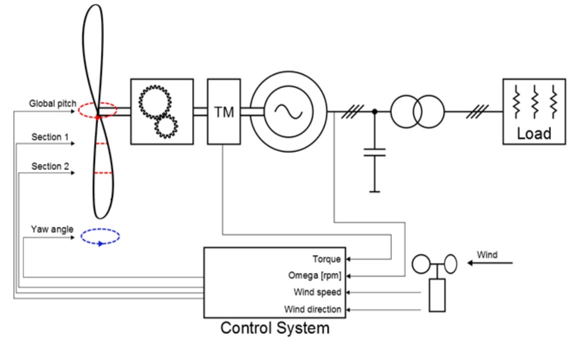

Figure 5. Block scheme of the active control loop.

the pitch angle distribution along the blade span, which can be imposed by actuating the three actuators connected to the moving ribs. The general idea of the control scheme, reported in Figure 5, is to obtain a twist law θ(r) to allow the optimal rotor operation for different combinations of χ and V. This would imply to follow a predetermined path on the P-ω maps.

An example of the map is shown in Figure 6: each line is obtained for given χ, and the circles represents the resulting P-ω combination for given wind speed discrete values. The blades' geometry of the proposed rotor are optimized in terms of chord law and base twisting along the span, for the design point χ=7 and V=7 m/s represented by the star symbol in Figure 6.

The other curves are obtained by maintaining unchanged the chord law and varying the twist law to optimize the aerodynamic efficiency for the different χ values. It is worth noticing that, despite the efficiency optimization realized with the variable twist, the global maximum for each wind speed value is always obtained for the design working line. This is due to the additional beneficial effect of the optimized chord law distribution. With this map, however, it is possible to make the rotor follow a predefined path P-ω, imposing the twist law that maximizes the efficiency even when the turbine works in non-nominal conditions.

As a general rule, the predefined path must be chosen to maximize the global turbine efficiency, calculated as the product of the mechanical and the electrical efficiencies.

$$\eta = \eta_m \cdot \eta_e \qquad (1)$$

The on-design working point, which implies the choice of the chord law, must be selected based on the wind distribution

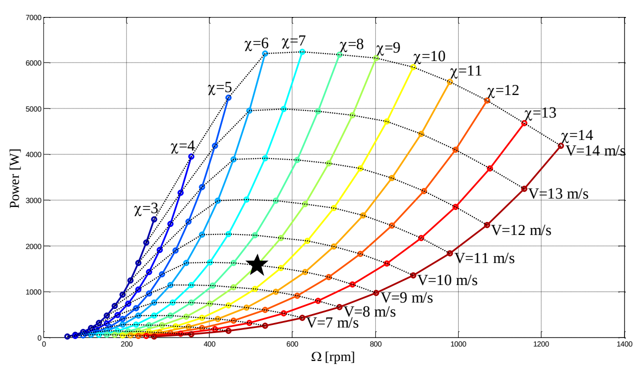

Figure 6. P-ω map with design point indication.

related to the installation site. Figure 8 reports the analysis results of a typical wind speed distribution, expressed as a percentage of the total measurements taken over a year, in the geographical site where the mini-wind turbine is supposed to be placed [11].

The continuous black line of Figure 7 represents one of the possible predefined paths that should be followed to optimize the global efficiency of a wind-turbine working in a sample site, for which a design point of χ=7 and V=7 m/s is the most

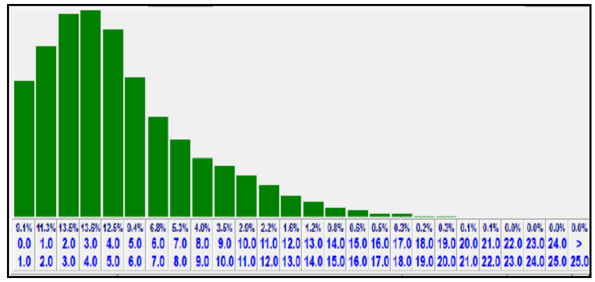
Figure 8. Wind speed distribution of a sample site.

appropriate. It must be noticed that the curve has been obtained by optimizing the efficiency only in static conditions. The control system can be exploited efficiently also to speed up the transients thanks to the fast active dynamic control loop response, obtained by cross correlating the information gathered by the three sets of sensors which measure the wind direction, wind speed and rotor rpm (Figure 2 (a)). However, if continuous actuation is performed to optimize the aerodynamic efficiency during transients, an unfavorable energetic balance of the overall system can be observed. A proper band-pass filter, acting on the error signal, is therefore necessary to limit the control activity. Under this assumption, it can be said that, for each combination of the three sensor values, only one working point is identified by the control strategy and provided to the Control System block of Figure 5. Given a set of input values, in fact, the Control System selects from a look-up table, for the actual working condition, the optimal twist distribution that maximizes the generated power. The twist distribution is parameterized by the collective pitch value and the angles of the two actuated sections. These signals are sent to the

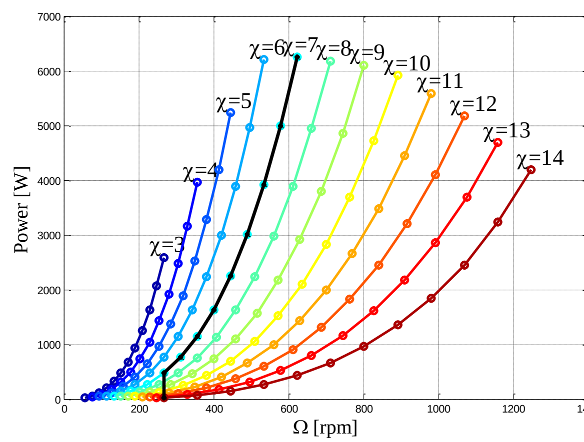

Figure 7. P-ω map with design point indication.

actuators, together with the yaw angle required to align the rotor axis to the wind direction.

Once the on-design rotational speed is reached, the controller changes its state to the power generation strategy and commands the blade twist to keep ω constant for low values of the wind speed. This means crossing different χ curves, until the condition χ=7 V=6m/s is met. In this phase, the load is connected to the electric generator and the resistant torque balances the aerodynamic torque, with the result that the rotor rotational speed is maintained constant. For higher wind speeds, the twist law is not modified and the rotational speed is controlled to maintain the rotor at the optimal working ratio, in order to maximize the power extraction, as shown by the dotted line in Figure 6. The black line in Figure 7 shows the power generation strategy.

VI. START-UP PHASE STRATEGY

During the rotor start-up, which is characterized by very low rotational speed, the electric and mechanical chain efficiency is very low and the power production would be negligible. In this phase, the rotor is unloaded, to speed up the transient and reduce losses. Thus, is necessary to escape this phase as faster as possible, in order to guarantee an overall higher power production. A deep analysis of different proposed start-up strategies was carried out, taking into account not only the time required to reach the nominal condition, but also the energy consumed for the blade pitch and twist control. The start-up phase was considered concluded when the angular velocity reaches the 90% of the nominal rotational speed Ω_{nom}=28 rad/s.

Four possible strategies were designed:

- Strategy 1: the blade assumes the shape optimized for χ=3, until this working ratio is met; then, the controller commands to twist the blades at the nearest higher χ.
- Strategy 2: the blades are in a flat condition (no twist) with the collective angle chosen to ensure the maximum airfoil efficiency; as the rotational speed increases, the χ=3 condition is met and the controller commands to twist the blades at the nearest higher χ so as to increase ω at low wind speed.
- Strategy 3: the blade assumes the shape optimized for χ=7, until the χ=3 condition is met; then, the controller commands to twist the blades at the nearest higher χ.
- Strategy 4: the blades assume the flat condition with the collective angle chosen to ensure the maximum airfoil efficiency until the nominal rotational speed is reached.

All these strategies are performed until the design rotational speed of ω=28 rad/s is obtained. To evaluate the performance

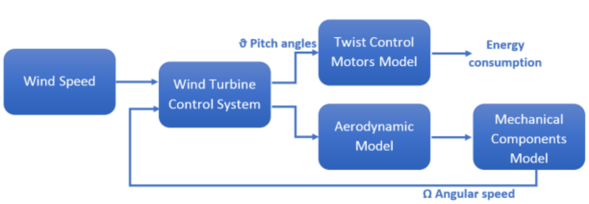

Figure 9. Wind turbine simulator scheme.

of each strategy, a simulator was created in the Matlab/Simulink environment. A scheme of the simulator is depicted in Figure 9.

The produced electrical energy was evaluated by using the model of the electrical chain, described in [14], which considers the total electrical efficiency to convert the mechanical power extracted by the rotor in available electrical power. Four different tests were realized, characterized by different wind speed time histories, in order to cover as much real conditions as possible.

A. *Test 1: Constant wind speed*

This test simulates the wind turbine behavior under a constant wind speed; wind speeds from 3 m/s to 14 m/s were considered. In Figure 10, the time required to reach the nominal rotational velocity is reported for each wind speed for the different strategies. As can be noticed, strategies 1, 2 and 4 guarantee a phase accomplishment time quite lower than the other strategies (Figure 10). At V_∞=3 m/s, the start-up time drastically increases for all the strategies. The energy consumption required by each strategy, for the different wind speed, is reported in Figure 11.

Strategies 1 and 3 result the most energetically convenient; conversely, strategies 2 and 4 are the most expensive, as they

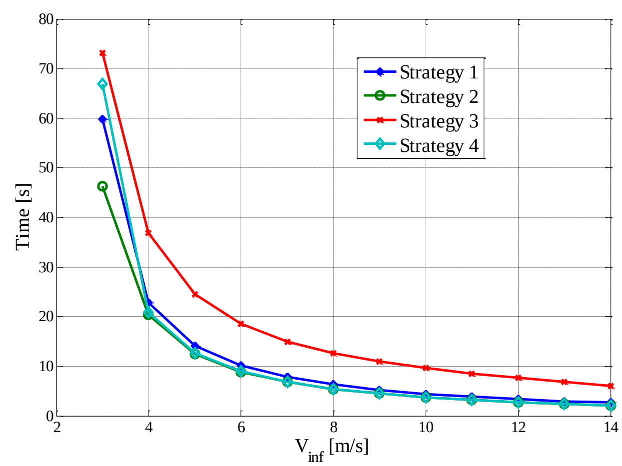

Figure 10. Test 1. Start-up time vs. wind speed for different strategies.

imply the highest control activity. If we consider only the energetic efficiency of each strategy, the strategy 3 is the most interesting for our application (Figure 12). It is possible to notice from Figure 12 that the strategies 1 and 4 always consume more energy than they produce. Test 2: Increasing wind speed

Table 1 Test 2. Start-up time for each strategy.

Strategy	1	2	3	4
Time [s]	95.97	92.47	109.19	94.31

During these simulations the wind speed was increased from 2 m/s to 7 m/s; these values were chosen considering the sample site described in Figure 8. The input time history is reported in Figure 13.

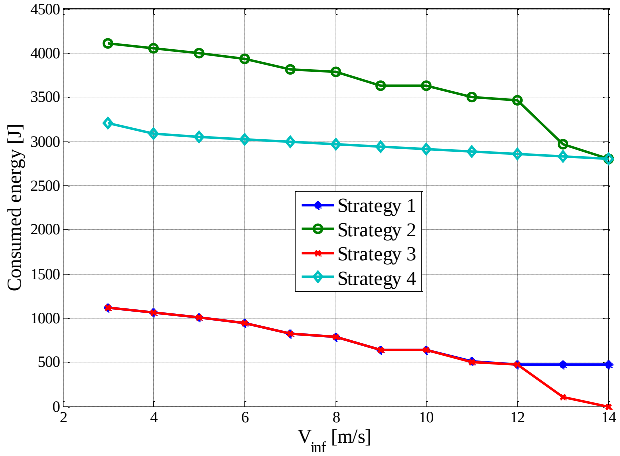

Figure 11. Test 1. Energy consumption vs. wind speed for different strategies.

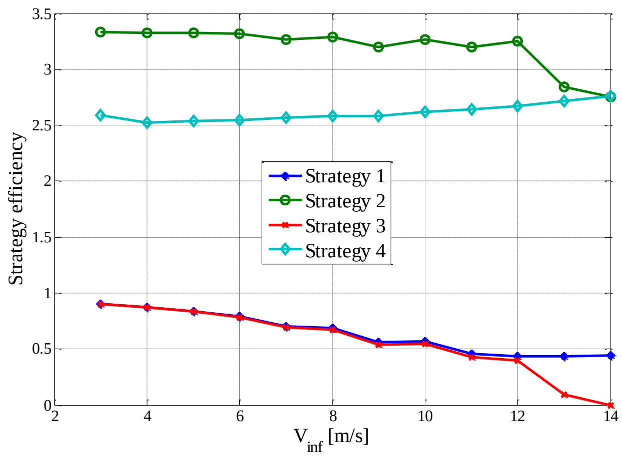

Figure 12. Test 1. Efficiency vs. wind speed for different strategies.

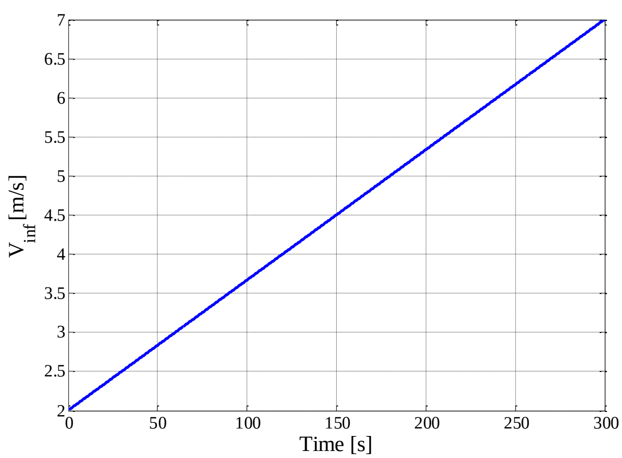

Figure 13. Test 2. Wind speed time history.

As in the previous test case, strategies 1, 2 and 4 ensure a faster accomplishment of the start-up phase, with respect to the other strategies (Table 1).

Table 2 Test 2. Consumed energy for each strategy.

Strategy	**1**	**2**	**3**	**4**
Consumed energy [J]	1104.62	4008.55	977.19	3097.59

Table 2 shows the consumed energy to control the blade shape for each strategy; also in this case, the strategies 2 and 4 are the most expensive from an energetic point of view and the consumed energy is greater than the produced one (Table 3).

Table 3 Test 2. Strategy efficiency analysis.

Strategy	**1**	**2**	**3**	**4**
Strategy efficiency	0.90	3.26	0.80	2.52

B. *Test case: Decreasing wind speed*

The test case 3 considers a decreasing wind speed from 8 m/s to 5 m/s (Figure 14). Table 4, Table 5 and Table 6 show the results of the simulations; when using strategy 3, the time

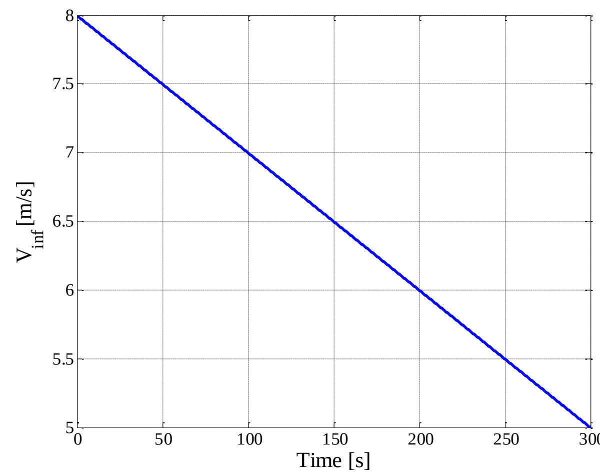

Figure 14. Test 3. Wind speed time history.

required to reach the nominal condition is the double of the one required when using strategies 1, 2 and 4.

C. *Test 4: Random wind speed*

A random wind speed is here considered with a medium value of 7 m/s and a maximum fluctuation of ±3 m/s; these values were chosen to analyze the turbine behavior under a turbulence around the design wind speed.

Table 4 Test 3. Start-up time for each strategy.

Strategy	**1**	**2**	**3**	**4**
Time [s]	6.31	5.46	12.70	5.46

Table 5 Test 3. Consumed energy for each strategy.

Strategy	1	2	3	4
Consumed energy [J]	793.10	3784.55	794.66	2969.25

Table 6 Test 3. Strategy efficiency analysis.

Strategy	1	2	3	4
Strategy efficiency	0.69	3.29	0.67	2.57

Table 7 Test 4. Start-up time for each strategy.

Strategy	1	2	3	4
Time [s]	7.76	6.78	15.62	6.80

Table 8 Test 4. Consumed energy for each strategy.

Strategy	1	2	3	4
Consumed energy [J]	1214.46	4628.80	2676.50	3690.54

Table 9 Test 4. Strategy efficiency analysis.

Strategy	1	2	3	4
Strategy efficiency	1.04	4.01	2.22	3.21

The same behavior found in the previous test cases can be noticed here (Table 7, Table 8 and Table 9): strategies 1, 2 and 4 are more convenient in terms of time spent to reach the generating phase; however, strategy 1 and 3 are the most attractive from an energetic point of view.

D. Start-up strategy

From the analysis carried out in this section, it is possible to define the best strategy for our application. If the goal is the energetic efficiency, the strategies 1 and 3 are the most attractive solutions to perform the start-up phase as it allow extracting the power while limiting the energy consumption necessary to actuate the control servomechanisms.

However, if we consider that the electrical chain work with a low efficiency under the nominal rotational speed [9], it would be better to escape the start-up phase as faster as possible; thus, the strategy 1 could be the best solution, as it ensures low start-up times and requires lower power consumption, with respect to the strategies 2 and 4.

VII. Conclusion

In this paper, an innovative wind turbine design, based on the active variation of the blade geometry, was presented. In particular, the presented application is related to micro and small turbines. It is based on the concept of morphing blade control, with the twist law scheduled to extract the maximum power in every wind condition while enlarging the working range.

It has been shown that, in steady state conditions, the aerodynamic efficiency varies with the working ratio but it is approximately constant with the wind speed variation. With non-morphing blades, the aerodynamic efficiency can be optimized by maintaining the nominal working rate within defined tolerances, and making the angular rates vary in order to accommodate any wind fluctuation. If the wind turbine is directly connected to the electrical network by means of an induction generator, though, the angular rate must be maintained constant to guarantee the correct frequency of the generated current. These wind turbines, thus, operate extensively in off-design condition and a reduction of the aerodynamic efficiency must be accepted.

Morphing blades, conversely, can maximize the aerodynamic efficiency for a spread range of working conditions. The morphing capabilities, in fact, permit to exploit also low wind speeds, where fixed twist blades do not work properly, while maintaining good levels of efficiency. This feature is fundamental in inhabited areas, where the mini-wind turbine should be installed, as wind is less frequent and usually speeds are lower or characterized by great variability, with respect to open areas.

One of the main issues to be addressed when facing with morphing control is the energetic convenience. Indeed, the actuation frequency must be sufficient to meet the requirements of maximize the generated power and, at the same time, it must not be excessive to reduce the energy consumption for the actuation. The proposed control strategy was designed to extract the maximum power at medium-high wind speed; in these working conditions, the control system leads the blade operating at the optimal working ratio, maintaining the nominal twist law. When the wind blows at low speed, the twist law is changed to maintain the rotational speed at a level such that the electrical efficiency is the highest, in order to maximize the power production also for these working points.

An analysis of different strategies to perform the start-up phase has been presented, based on the time required to reach the nominal rotational velocity and, thus, the generating phase and on the energetic performances. The strategy 2 allows reaching the generating phase in the lowest time, whereas the strategy 3, which consists in keeping the blade with the nominal shape until the χ=3 condition is met, resulted the most energetically convenient. A trade-off between these goals can be found by applying the strategy 1.

The presented control system will be implemented on the VENTURAS technological demonstrator; a test campaign will be carried out to evaluate the actual performance of the designed morphing control, with respect to a conventional non-morphing blade.

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G. Sirigu was born in Cagliari in 1987 and earned his Bachelor's and Master's degree in Aerospace Engineering at the Politecnico di Torino, respectively in 2011 and 2012.

Currently, he is a PhD student in Aerospace Engineering at the Politecnico di Torino. His research interests cover the control systems, route planning, multi-agent systems, and airport operations.

M. Cassaro is a PhD researcher at Politecnico di Torino, Department of Mechanical and Aerospace Engineering (DIMEAS), Italy. He got is PhD in April 2015 at Politecnico di Torino. During his PhD studies, he was also a visiting researcher before and an Adjunct Instructor later at Clarkson University, Department of Mechanical and Aeronautical Engineering, Potsdam (NY), USA. His academic interests are mainly concerned with (but not limited to), atmospheric flight mechanics and dynamics, aeroelasticity, modeling & simulation as well as guidance, navigation & control for fixed and rotary-wing aircraft.

M. Battipede got her Ph.D. in Aerospace Engineering in 2000 at the Polytechnic of Turin, where she is currently employed as Associate Professor in the Flight Mechanic field, teaching Ms. courses 'Aerospace Flight Mechanics', 'Aircraft Guidance and Control' and co-teching the Bs. courses 'Fundamental in Flight Mechanics'. After a period abroad at the West Virgina University, where she has worked as a Visiting Assistance Professor in the Mechanical and Space Department, she has collaborated with the major aeronautical Italian companies. She is co-author of more than 50 international journal and conference papers in the areas of Atmospheric Flight Mechanics, Modeling & Simulation as well as Guidance Navigation & Control Aircraft for fixed and rotary-wing aircraft. She is a reviewer for numerous international journals and conferences.

P. Gili has been doing research work at the Department of Aeronautical and Space Engineering in the Flight Mechanics sector since 1983, when he was appointed Researcher. In 1992 he held an appointment in Flight Test Techniques, and one in Flight Dynamics in 1997.

His research activity mostly focuses on fixed and rotating wing aircraft dynamics and control, satellite and lighter than-air-aircraft dynamics and control. His activity is supported by over 90 publications mostly written for International Congresses. The development of innovative control systems is the main subject of his research activity.

Gili was Visiting Research Associate Professor for the March-September 2002 period at MAE (Department of Mechanical and Aerospace Engineering), West Virginia University, working in the fault tolerant control systems area. In particular, the invitation was aimed at developing a partnership on the NASA F-15 Intelligent Flight Control System (IFCS) project.

He also holds a patent for the project "High-manoeuvrability aerostatic-type airship", which is jointly owned with the School of Engineering – Nautilus S.p.A and the patents "Smart Propeller. Elica o rotore a passo variabile con svergolamento variabile di rendimento ottimo" and "System and process for measuring and avaluating air and inertial data" owned by the Politecnico di Torino.

He was also Scientific Supervisor in charge of several Research Contracts. In particular, in recent years he has headed two important research projects co-funded by Piedmont that are carried out in partnership with external bodies. At the moment he's heading the project "MAS_Lab (Multipurpose Aircraft Simulation Laboratory)" in Clean Sky, ITD SGO (Systems for Green Operations) program and the project "Venturas" founded by Italian Ministero dell'Ambiente.

G. Frulla has been doing research work at the Department of Aeronautical and Space Engineering in the Structural Design and Aerospace Construction sector since 2005 as a Researcher and then as an Associate Professor. His research activity mostly focuses on critical and post-critical behavior of thin walled structural components (isotropic and composite flat plate and stiffened plate) with extensive correlation between theoretical/numerical and experimental results; he is also interested in aeroelastic behavior of slender structures under specific loading condition and pointing out non-conventional critical conditions.

His activity is supported by several publications both for journals and for international conferences. He has participated to EU funded projects devoted to the investigation and design of Solar HALE UAV. He has also participated to specific research activity involving the introduction of Hydrogen as a source of energy for aircraft applications. He holds the patents "Smart Propeller. Elica o rotore a passo variabile con svergolamento variabile di rendimento ottimo" (inventors GILI-FRULLA) owned by the Politecnico di Torino and participated to the research project VENTURAS funded by Italian Ministero dell'Ambiente devoted to wind energy improvements.