Design and construction of an offshore diffuser augmented wind turbine with a high efficiency alternator

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Abstract. This paper describes the design and the assembly of a new type of a ducted wind turbine with an electric power generator adopting permanent high coercive magnets embedded in the peripheral ring of the rotor. The nominal power is 20 kW, and the maximum diameter of the external duct is 9 meters. The project has been carried out within the Marine Energy Laboratory (MEL) funded by the Italian Ministry for Education, University and Research (MIUR) and collects the most advanced technologies of naval maritime engineering and combines them with energy and turbomachinery technologies. The presence of a divergent duct enables the interception of a greater air mass flow rate, allowing the reduction of the rotor diameter and the deflections of the blades; hence, at constant tip speed ratio, a higher rotational speed compared to conventional turbines and a better efficiency of the permanent magnet power generator.

1. Introduction

The proposed work describes the design and realization of an innovative ducted wind turbine characterized by a double shrouds architecture and a generator with permanent magnets embedded within a peripheral ring realized on the rotor, thought for offshore applications.

The overall reference architecture foreseen consists of a self-displacing floating complex supporting three wind turbines (Figure 1).

The activity is part of the MEL (Marine Energy Lab) project, funded by MIUR, which involves the construction of an offshore laboratory, whose original design is shown in Figure 2. The offshore lab is connected to an onshore lab by a series of cables for energy transfer and data transmission. The offshore laboratory houses the prototype turbine and the control and monitoring room.

The aim of the project is to create a flexible power generation system oriented to the needs of small, isolated marine communities with a system that allows for relatively simple operation and management.

It is foreseen that the plant will work in open sea, therefore in presence of undisturbed wind with a relatively high average value, that the efficiency of the turbine, with reference to both the fluid-dynamic and the electrical components, will be maximum, and that a system of energy transfer to the land will be realized with an optimized line of cables.
2. Ducted Wind Turbines

As is well known, on the basis of the classical theory of the Betz actuator disk [1], the maximum theoretical power that can be extracted from a wind turbine with free flow on the rotor is limited to a fraction $C_{p,\text{max}}$ equal to 16/27 of that contained in the undisturbed flow, a value very difficult to approach in actual achievements especially in small turbines. In the realization of large turbines a $C_p = 0.5$ could be approached. This limit is not valid in the case of ducted flow [2].

Wanting to maximize the obtainable energy with the same footprint with the adoption of a diffuser, theoretically one could reach a power coefficient $C_p$ close to unity.

For this type of wind turbine the design of the rotoric and statoric components and of the safety and orientation devices is more complex.

In the application developed, the objectives pursued were the maximization of the extractable power in relation to the area invested by the wind and the optimization of the efficiency in the production of electrical energy, incorporating the statoric part of the generator in the diffuser by means of windings made on multiple layers on printed circuit boards and including an array of permanent magnets with high coercivity in an annular rotor supported by the ends of the blades. In this way, taking advantage of the high peripheral speed of the rotor, it is avoided to introduce a mechanical transmission with function of multiplier of revolutions, necessary, in conventional applications, to have an acceptable efficiency of the alternator.

The realized turbine, shown in Figure 3, has a nominal power of 20 kW, an overall diameter of 9 meters and consists of a double diffuser whose internal structure supports the central steel hub on which the rotor is splined. The rotor has five blades and a peripheral ring on which the permanent magnets of the electric generator are mounted.

The main problem faced in the design of the rotor concerns the need to ensure adequate stiffness to limit to 12 mm the maximum gap between the permanent magnets installed on the peripheral ring and the stator in any operating condition, since it is not possible to use conductive materials in the vicinity of areas subject to high variations in magnetic flux. The peripheral ring has been realized by constructing 5 identical sectors connected to the ends of the blades and arranged with housings necessary to hold the high coercivity magnets in position with the necessary safety for the operators during assembly. A unidirectional fiberglass belt was wrapped around the ring to ensure strength and rigidity requirements. The stator has been realized with a steel supporting structure on which 16 composite sectors have been mounted, eight for each diffuser. On the internal diffuser the alternator windings are mounted on a printed circuit board.
For the execution of the preliminary tests, a support pole with relative orientation devices has been realized, which places the axis of rotation at 15 meters of height, as shown in Figure 4.

![Figure 3. Turbine on the ground in the assembly phase](image3)

![Figure 4. Turbine mounted on a pole for carrying out preliminary tests](image4)

3. Fluid Dynamics Design

For the design of a ducted wind turbine, the conventional blade element momentum theory, developed for free stream wind turbines, cannot be applied; hence, for this specific case, an original numerical model has been developed [2], and computational fluid dynamic (CFD) simulations were carried out for validation.

The diffuser consists of two distinct concentric annular wing shaped diffusers. This solution has been chosen in order to reduce the axial length of the diffuser. In fact, with a double diffuser, it is possible to obtain a greater diffusion without incurring in the risk of a flow separation, since the external air flow, which is channeled into the annular gap between the two elements (acting as a nozzle), accelerates energizing the boundary layer making it less keen to separate.

The aerodynamic profile of each annular wing has got a camber line designed according to a cubic Bezier curve with blade thickness defined according to the one of a NACA0004 profile. The use of the Bezier curves for the cumber line and the NACA 4 digits thickness distribution guarantees the continuity of the function that describes the profile and those of the first and second derived functions. This allows to have a more regular profile description with a lower tendency to flow separation and therefore a considerable improvement in the aerodynamic efficiency of the annular wing.

For the aerodynamic design of rotor blades, the design value of the tip speed ratio was set to $\lambda = \omega R / V_0 = 5$. The geometry of the blades was built starting from three basic profiles of the NACA 4 digits series, assigned at hub, midspan, and tip. In particular, the airfoil profiles used for the design of the blade are:

- NACA 6618 hub;
- NACA 5418 mid span;
- NACA 1318 tip.
Starting from these 3 reference profiles, parabolic interpolations were used to obtain 8 non-standardized intermediate profiles (always of the NACA 4 digits series), 4 between hub and midspan and 4 between midspan and tip.

The rotor tip radius is 3.2 m. The number of blades chosen for the rotor is 5.

The preliminary numerical model used to define the chord and twist distributions along the blade span is based on the resolution of the steady, incompressible, axisymmetric 2D, Reynolds Averaged Navier-Stokes (RANS) equations together with the mass conservation equation. Due to the low Mach numbers, it is possible to neglect the air compressibility. A finite volume approach is used to discretize the system of equations. The velocity field is obtained by solving the momentum balance equations, while the pressure field is extracted by solving a pressure correction equation in order to impose the mass conservation according to the SIMPLE algorithm (Semi Method Implicit for Pressure-Linked Equations) developed by Patankar [3]. For the turbulence closure, the standard k-ε model was used [4], which suppose an isotropic turbulence (Boussinesq hypothesis). This turbulence model was chosen being robust, computationally cost-effective, and reasonably accurate in a wide range of turbulent flows [5]. All viscous and convective terms were discretized using a first-order accurate upwind scheme.

In this preliminary phase, to avoid any excessive computational cost, otherwise required by a detailed blade-resolved simulation to evaluate the aerodynamic interaction between the blade airfoils and the flow, a hybrid approach was chosen. In the area swept by the rotor, the spatial discretization is similar to that of the rest of the domain, and, within these cells, source terms have been introduced that simulate the momentum exchange between blades and the flow. These source terms are introduced through appropriate User Defined Functions (UDFs), written in C language, and implemented into the CFD code. This approach was first proposed by Rajagopalan and Fanucci [6], who developed a 2D CFD code for Darrieus rotors and was applied in a 3D case by Torresi et al. [7]. The aerodynamic forces on each blade depend on the local velocity field, i.e. on the velocity inside each cell swept by the rotor. Therefore, an iterative approach is required to achieve solution convergence. Once both the local Reynolds number and the angle of attack have been evaluated, in each cell swept by the rotor, it is possible to compute the lift and drag coefficients, based on the polars of the chosen airfoils, and then recalculate the source terms. To obtain all the polars of the airfoils, the QBlade [8] software was used.

By drastically reducing the number of cells within the computational domain, it was possible to carry out many simulations by modifying each time the rotor geometry to evaluate the one capable of providing the best performance under the design flow conditions (see figure 5).

![Blade Geometry](attachment:blade_geometry.png)

Figure 5 - Chord and twist distributions along the blade span
4. Permanent Magnets Generator
The designed generator can also work as a motor, to speed up the start-up transient when the wind speed reaches the turbine start-up threshold. It consists of a rotor on which are installed permanent magnets with high coercivity with dimensions equal to 60 x 30 x 15 mm arranged with a pitch equal to 50.6 mm. On the stator are placed the windings obtained on multilayer printed circuit boards. For weight containment and easier integration with the wind turbine structure, the stator of the electrical machine is devoid of ferromagnetic circuitry. The radial thickness of the stator of the electrical machine is therefore reduced to a few millimeters. The use of printed circuits facilitates the industrialization of the machine and contributes to the containment of losses in the electrical circuits that would compromise the efficiency of the electrical machine at higher speeds in the presence of windings made with traditional conductors and in the absence of ferromagnetic material.

The realization of the alternator was preceded by a preliminary study and by the realization of a small scale test prototype necessary for the choice of the magnets, for the definition of the type of coils for the stator and for the design of the control electronics.

The test prototype has also allowed the verification of the results of the performance calculation made with finite element software.

Once known the typical speed regimes of operation of the wind turbine and the maximum permissible gap for an acceptable performance, the expected performances have been verified realizing a test prototype in reduced scale having the same peripheral speed, same magnets, same pitch and same gap.

The small scale prototype shown in Figure 6, with a rotor diameter of 1 m, was designed to allow a relatively easy replacement of the multilayer coils on a printed circuit board. Two possible types of coils configurations were tested, the first with two coils per layer on four layers, the second with four coils per layer on two layers.

The first configuration has a lower electrical resistance and therefore potentially higher efficiency. The second configuration has the advantage of being thinner and of having a limited axial encumbrance, with relative lower production costs; moreover, not having internal layers, although it possesses a higher electrical resistance, heat dispersion is easier. After the operating tests performed on the test prototype the configuration with two coils per layer has been chosen, leading to the definition of the electrical machine and its control electronics. Figure 7 shows the printed circuits made for the coils and their final arrangement on the stator of the wind turbine.
5. Mechanical Design

5.1. Rotor

The problems of strength and reliability of this type of turbine have not yet been the object of consolidated studies since the number of realizations is very limited. In the case of double diffuser architecture and with the realization of a rotor that has a peripheral ring supported by the blades and having the function of rotating part of the electrical machine, to the knowledge of the writers, we limit ourselves to the case illustrated here.

The maximum design loads of the blades, as in the classic case of horizontal axis turbines, are those related to abnormal operating conditions, capable of determining extreme stresses much higher than those found in the presence of maximum loads in ordinary operating conditions. In the specific case the blades, having to support the ring on which the magnets are mounted, have additional design requirements related to the relatively high moment of inertia, which introduces higher moments in the case of emergency braking and gyroscopic effects, however limited by means of yaw speed control.

On this basis, in accordance with the design requirements, a lay-up consisting of unidirectional and four-axial fiberglass mats was set up and verified. In particular, the lay-up was designed as a combination of two types of layers, differentiated with respect to the orientation of the fibers:

- Quadriaxial (QA) mats: they have fibers oriented at 0°, 45°, 90°, 135° of 300 g/m2 for a total thickness of 1.1 mm.
- Unidirectional (UD): parallel fibers of 1000 g/m2 with a total thickness of 0.9 mm.

The mechanical properties of the adopted stratifications have been determined through conventional destructive experimental tests and through advanced non-destructive experimental tests. The tests were conducted at the Official Materials Testing Laboratory "M. Salvati" of the Polytechnic University of Bari. In particular, some material samples representative of the used stratifications have been subjected to tensile tests in order to obtain the mechanical parameters in terms of stiffness (technical moduli) and strength, and to ultrasonic goniometric immersion tests by means of an innovative setup that allowed to determine all the independent components of the elastic tensor that characterizes the mechanical response of each composite sample QA and UD [9].

The composite layering was defined with reference to the radial position along the blade and is shown in Table 1 below.

| Radial interval[mm] | Layering | Total thickness[mm] |
|---------------------|----------|-------------------|
| 250-360             | 6QA+4UD+QA+4UD+6QA | 21.5              |
| 360-510             | 4QA+4UD+QA+4UD+4QA | 17.1              |
| 510-810             | 2QA+4UD+QA+4UD+2QA | 12.7              |
| 810-1110            | QA+4UD+QA+4UD+QA   | 10.5              |
| 1110-2750           | 6QA+4UD+QA+4UD+6QA | 21.5              |
| 2750-3050           | QA+2UD+QA+2UD+QA   | 6.9               |

A series of reference specimens, made with QA+2UD+QA layup, were subjected to static and fatigue tests with stress ratio R=0.1. The average ultimate stress obtained is 425 MPa (minimum value 396 MPa), while the fatigue strength curve has \( m = 7.9 \) with \( max = 127.5 \) MPa at 2-106 cycles.

A further critical element of the rotor is the peripheral ring in which the permanent magnets are embedded, as it is necessary to ensure adequate flexural rigidity to avoid interference with the stator under the action of radial elastic deformations. The radial clearance introduced at rest is 12 mm and is very limited compared to the external radius of the rotor of 3200 mm.

The ring connects circumferentially the end of the five blades and has the fundamental task of supporting the 400 permanent magnets each weighing 0.205 kg, positioned at a pitch of 50.6 mm
measured at the base of the magnet. In addition, to ensure adequate efficiency of the magnetic circuit, it was necessary to insert a peripheral winding of iron-magnetic plate.

The design and sizing, verified with a finite element analysis, have been realized considering the main stresses to which the ring is subjected and consisting of:

- Own weight of the structure;
- Centrifugal thrusts of the magnets and the ferromagnetic plate;
- Deflection induced by differential deformation of the blades (e.g. as a result of misalignment with respect to the wind and due to gyroscopic effects).

Figure 8 shows schematically the front and cross sections of the peripherical ring. The objective pursued was to reduce the thickness of the magnet retaining structure in the radial direction that occupies part of the air gap. For this reason, underneath the magnets, a unidirectional fiberglass belt wrapped circumferentially and contained in a U-shaped cradle made of quadriaxial mat has been realized in order to provide the necessary stiffness in the radial and circumferential directions.

The cradle is overall made of five equal arcs that were placed on a template, to allow the subsequent winding of the unidirectional. The positioning of a further cradle destined, to house the magnets, allowed the lateral winding of the unidirectional fiber to be carried out. A light filler was introduced to position the ferromagnetic plate at the intended radius, to distance the magnets during assembly and to dampen any vibrations under operating conditions. The crown was completed by winding a four-axial mat capable of transmitting to its structure the centrifugal force exerted by the magnets. The rotor assembled in all its components is shown in Figure 9. Auxiliary structures and components, such as the hub with its connections to the blades and the emergency brake, have obviously been made.

The blades engage on the hub by means of the so-called "Ikea" joint consisting of cylindrical pawls, transversely threaded and radially inserted in the base annular section of the blades, on which are mounted threaded steel shanks that engage the flanges present on the hub.

The emergency brake, suitably sized, is of the disc type and is operated by an electromagnetic actuator.

Figure 8. Sections of the crown
Figure 9. Rotor
5.2. Structure of stator and double diffuser
The function of the stator structure is to support the diffusers, the rotor hub with associated braking system, and to ensure adequate connection to the fifth wheel for yaw control for orientation.

In the offshore conceptual design, orientation is accomplished by means of the rotation of the polyhull vessel on which the turbines are placed.

For the realization of the prototype and the performance of functional tests, it was necessary to introduce the motorized rotary table for yaw control. Obviously, the flange made for the fifth wheel can be exploited to make a fixed assembly.

![Steel turbine structure with detail of yaw bearing area](image)

Figure 10. Steel turbine structure with detail of yaw bearing area

For road transport needs it has been necessary to realize a modular assembly that has directed the design choice on a steel structure (the project also provides an alternative in aluminum alloy) consisting of sixteen sectors, eight for the internal diffuser, eight for the external one. Each sector consists of two curved profiles with a hollow circular section that carry at the ends the connection flanges to suitably shaped flat profiles, as shown in Figure 10.

The structures of the aerodynamic profiles of the diffusers, made of fiberglass composite, are grafted onto the auxiliary transverse connections between the curved beams with circular section. There are a total of sixteen modules, eight for the inner and eight for the outer diffuser. Figure 11 shows the metal structure of the stator during the assembly tests of the modular elements of the diffusers. The structure was verified by adopting a FEM model.

Figure 11 shows the steel structure of the stator during the assembly tests of the modular elements of the diffusers.
5.3. Realization of the prototype and preliminary tests

The rotor, the diffusers on the stator and the floating support structure of the offshore laboratory were made by the company Cartflow in Castelvolturno (Naples – Italy), a leading company in the production of wind turbines with the ability to make molds with robotic management processes for a length of 50 meters and with a proprietary technique of construction of the blades defined “One-Shot”, which allows the direct introduction of shear webs in the blade structure. The prototype was assembled in the laboratories of the same company to carry out the functioning tests (see Figure 4).

The steel structure of the stator was made by the company Faver (Bari - Italy).

Tests have been carried out to verify the absence of interference in the rotational motion, the efficiency of the braking system, the starting of the turbine, the yaw control system. Tests related to the verification of the performance and management of the control electronics are in progress.

An unexpected test condition of resilience to exceptional weather conditions was determined by a storm with gusts of wind that exceeded 140 km/h, which resulted in damage to the roof of the Cartflow shed, but left the turbine unscathed.

6. Conclusions

The MEL project is innovative and has ambitious goals aiming at the development of the first offshore application of ducted wind turbines on a floating hull.

The presence of a divergent duct (the double diffuser) allows the interception of a higher air mass flow rate, allowing the reduction of rotor diameters at the same rated power, increasing rotor stiffness, reducing blade deformations, and increasing rotation speed compared to conventional turbines.

The electric generator with permanent magnets embedded in the rotor ring takes advantage of the high peripheral speed improving efficiency.

The size of the target turbine is smaller than currently installed multi-megawatt (MW) offshore turbines, but it can be mounted on the hull in a dry dock, greatly reducing installation costs, making it possible to periodically transport the platform to dry dock for maintenance, and thus ensuring a very long life. Also noteworthy are the lower costs for decommissioning, at the end of life, of these floating mobile turbines compared to traditional offshore wind turbines fixed on the seabed.

The research topic developed is in accordance with the themes proposed within the Great Research and Innovation Scope 4 “Digital, Industry, Aerospace” and 5 “Climate, Energy, Sustainable Mobility” of the National Research Program PNR 2021-27.
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