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CONSIDERATIONS REGARDING THE USE OF HYDROSTATIC TRANSMISSIONS IN WIND TURBINES

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Abstract: *Starting from some general considerations regarding the use of hydrostatic transmissions for increasing the efficiency of high power wind turbines, the authors present some basic schemes for hydrostatic transmissions, with and without pneumatic energy storage, for medium and small power wind turbines.*

Keywords: *Hydrostatic transmissions, wind turbines, pneumatic energy storage*

1. Introduction

In 2018, the electricity obtained from the conversion of wind power covered 5.5% of the total consumption worldwide, using capacities of energy production of 591 GW. Of the 181 GW representing new capacities installed in 2018 for electricity generation, 51 GW are wind turbines of various sizes. Romania has a total installed capacity of 3,029 MW, covering in 2018 approximately 10.2% of the country's electricity consumption. Most of this energy production is obtained with horizontal axis wind turbines. For this type of turbine, the location of the electric generator in the turbine platform leads to a significant increase in the mass of the platform, and implicitly the mass of the pillar supporting the turbine. In addition, the maintenance of the turbine becomes more difficult with the increase of the rotor diameter and the height of placement.
The platform (excluding the rotor) represents between 20 ... 35% of the total weight of a large turbine reaching in some cases the order of hundreds of tons. In the case of the VESTAS V90 turbine, the platform weighs 75 tons, the rotor 40 tons, and the tower 152 tons. [1]. In the case of small turbines, even if we do not have such heavy weights, the same values are kept as a percentage.
Other research has shown that in current offshore turbines, one of the main issues is gearbox failure, with current designs requiring replacement or capital intervention every 4 years. With the gearbox contributing to around 10% of turbine cost [2], such frequent replacements are very detrimental to the overall viability of offshore wind energy conversion. Danop Rajabhandharaks of San Jose State University states in his thesis [3] that it is not uncommon for a gearbox to fail on average every 5 years while the designed lifetime of a wind turbine is typically about 20 years.
On the other hand, there are wind turbines that have appeared in the last decades that differ from the classic solutions, and fall into the category of unconventional wind turbines; they have different shapes, are arranged vertically or horizontally at different heights, and in terms of power they usually fall into the category of low power turbines (below 100 kW), Figure 1. Regardless of their type and structure, in most of these turbines the generator is located near the rotor, at height.

Fig. 1. Unconventional wind turbines

Reducing the weight of the platform, and implicitly the weight of the support pillar, would be easy to achieve if the electric generator were located on the ground and the tower would support only the rotor and a few other auxiliary elements. Maintenance would also be much easier to achieve. As for the unconventional turbines, they are located in the most diverse places, and the reduction of the suspended mass and reduction of the gauge is likely to simplify the construction and improve the visual impact. While in the turbines with vertical axis located on the ground or near the ground, the generator has small dimensions and weight, in those placed on buildings or bridges, the location on the ground of the generator significantly simplifies the construction.
For all these problems ***the solution is the hydrostatic transmission*** of energy from the rotor to the generator, also giving up the gearboxes that multiply the reduced rotor speed (5 ... 40 rpm) to make it compatible with that of the generator (1500 ... 3000 rpm); by an intelligent use of some classic, modern hydraulic components, a high performance hydrostatic transmission can be achieved.

2. Examples of use of hydrostatic transmissions for wind energy conversion

Research on the hydraulic transmission of energy to wind turbines began as early as the 1970s. We mention the 3 MW turbine, model SWT-3, produced by Rybak company and put into operation on December 16, 1980. The movement of the rotor is taken over by a hydrostatic transmission with 14 fixed capacity pumps, located in the platform, and 18 engines with variable displacement. The pumps are connected to the rotor by a speed multiplier. The variable motors were connected to the generator by another multiplier [4].
In 2010, in Germany, the RWTH Aachen University developed an experimental platform that simulates a variable speed wind turbine and carried out experimental research with modeling and simulation. In this model, the fixed displacement pump supplies the variable motor, which drives the synchronous generator to obtain electricity. The results indicated that this hydraulic transmission of wind power can compensate the influence of the fluctuation of the wind speed on the output power, but also achieve an optimal efficiency of 85% [5,6,7,8].
In the same year, the American company EATON studied the technology of hydraulic energy transmission and proposed a hydraulic solution based on the use of a pump with radial pistons and axial piston engines. About 90% of the system was placed on the ground [9].
The fundamental principle of all the wind turbines mentioned above is shown in Figure 2. In this, the speed multiplier in the dotted area may be missing, depending on the type of pump.

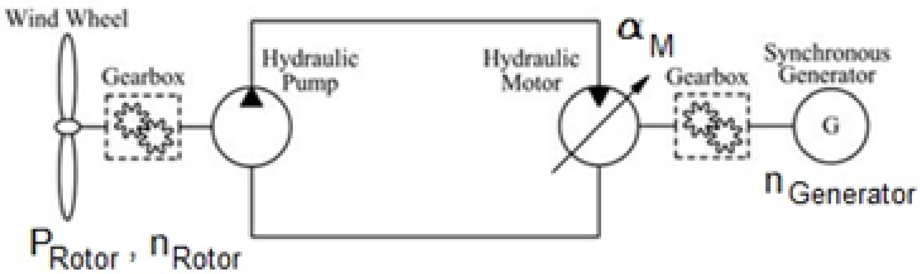
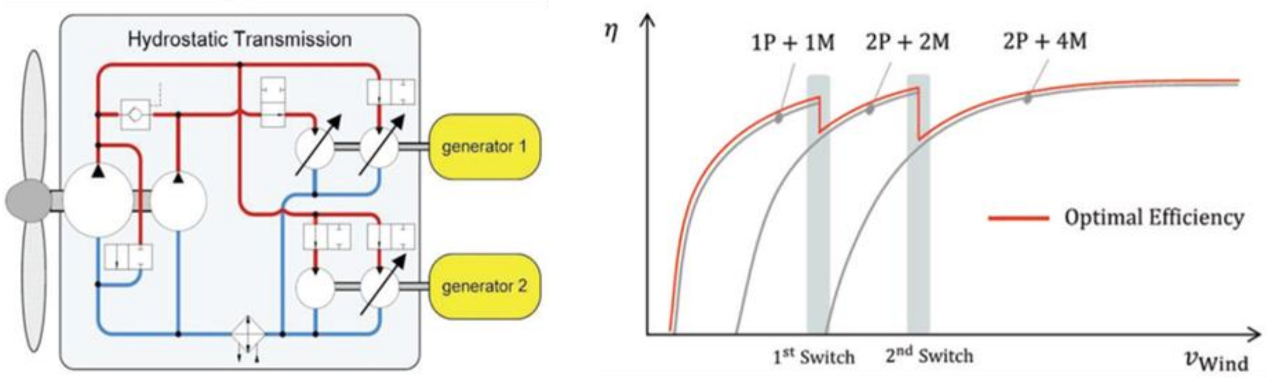


Fig. 2. Fundamental principle of hydrostatic transmision (HST).

Basically, the HST transfers the rotor power P_{Rotor} to the generator while transforming the variable rotor speed n_{Rotor} into the required constant generator speed n_{Gen}. The rotor speed is regulated using the motor's displacement setting α_m. Low wind speeds require low displacement settings as less flow is generated by the rotor, while higher wind speeds generate more flow and require larger motor displacements.
As a result of this variable power input, the system's efficiency will change according to the wind speed. Below the rated speed all the components will operate at part load conditions leading to decreased efficiency.

To ensure good efficiency throughout the wind speed range a switched displacement hydrostatic transmission (HST) for a 1 MW turbine has been developed at IFAS, see Figure 3(a). The new architecture allows individual pumps and motors to be switched on and off depending on the current operating point [10]. Two fixed displacement pumps convert the wind power into hydraulic power in the form of pressurized fluid. Two sets of motors are then used to drive two generators. Each component, except for the smallest pump, can be switched to idle mode, which allows different pump-motor combinations for different operating points. By allowing individual pumps and motors to be switched on and off depending on the current operating point the new architecture leads to an improved system efficiency throughout the operating range, see Figure 3(b).



a) b)

Fig. 3. HST for a 1 MW turbine has been developed at IFAS: **a)** Structure of the hydraulic scheme; **b)** Diagram of system efficiency.

As time has passed and technological advancement occured in the fields of wind turbine construction and hydraulics, the research has progressed in 2 seemingly divergent directions: on the one hand towards the implementation of hydrostatic transmissions to turbines of increasing power, in agreement with the increase of the installed power of the of commercial turbines, and on the other hand towards smaller power turbines, as the interest for the local production of energy from wind sources increases.

The stochastic nature of wind makes it difficult to integrate into a grid and causes frequent wind power curtailment [11]. The utilization of a storage system is a better solution to reduce or alleviate these problems.

The wind energy storage can not only solve the problem of randomness and volatility of the wind power, but also has the function of peak regulation and frequency modulation, which can greatly improve the reliability and economic efficiency of the power system [12].

In 2009, the Scottish Artemis Intelligent Power company applied a new digital hydraulic variable pump to the 1.5 MW hydraulic variable speed wind turbine aimed at storing wind energy and obtaining higher efficiency. Experimental results proved that the efficiency of the wind turbine can reach over 90% under most wind speed, which was equivalent to the efficiency of traditional wind turbines. However, ***this digital hydraulic variable pump design is strictly confidential and unavailable for others.***

Artemis Digital Displacement drivetrain [13] is formed by a hydrostatic transmission followed by two parallel synchronous generators as presented in Figure 4. The hydrostatic transmission is given by a high efficiency - low speed ring cam radial piston pump driving a high speed radial piston motor; dimensions, number of cylinders and configuration might be different between pump and motor. In general, the Artemis Digital Displacement machines can be considered as an optimized radial piston machines. The optimization consist in reducing slipping surfaces; but most important, by making the valve's operation independent of the angular displacement of rotor shaft. This unconstrained dependence allows individual operation of each cylinder. Discrete operation of cylinders helps to dramatically reduce leakage losses in preselected cylinders (those cylinders that are not required to fit the current load condition, are just idled). Also, effects due to transition regions (regions 2, 3, 5 and 6) are minimized by means of careful software tuning. Optimization is reduced to intelligent control of suction and discharge valves, which are triggered by electric solenoids.

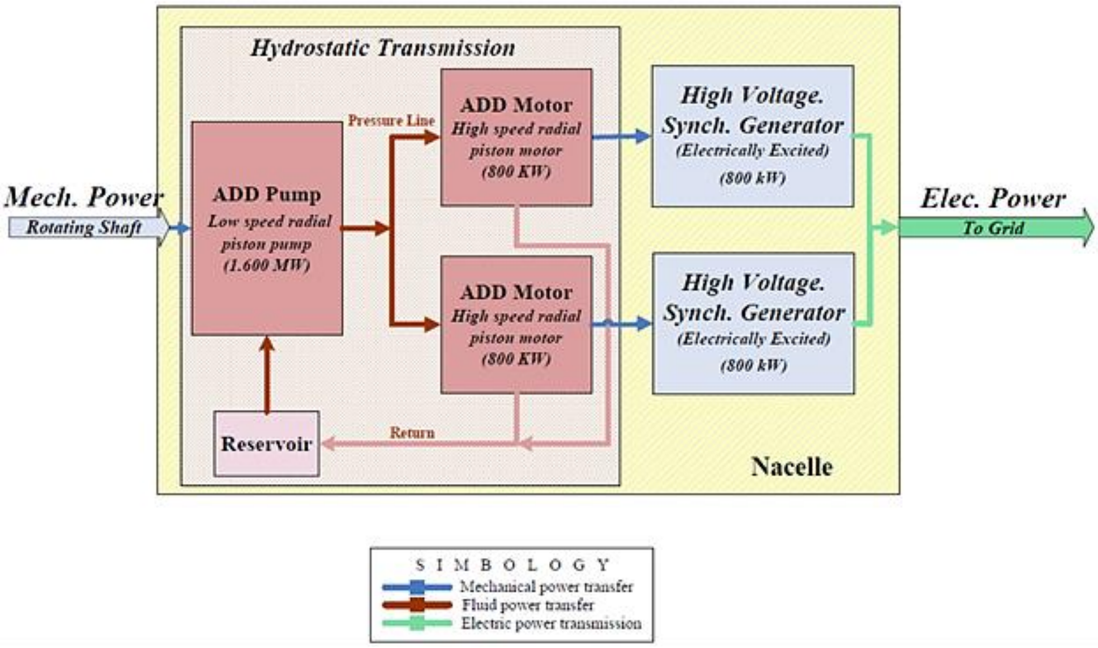


Fig. 4. Artemis 1.6 MW drivetrain system.

Software control makes possible to implement, and tune up, any kind of machine behavior (idling, braking, pumping or motoring) within the same hardware. For instance, it is possible to idle some cylinders (aimed to reduce leakage losses on those cylinders) while the rest works at rated power, making possible to fit any partial load condition with the minimum number of cylinders working at rated power.

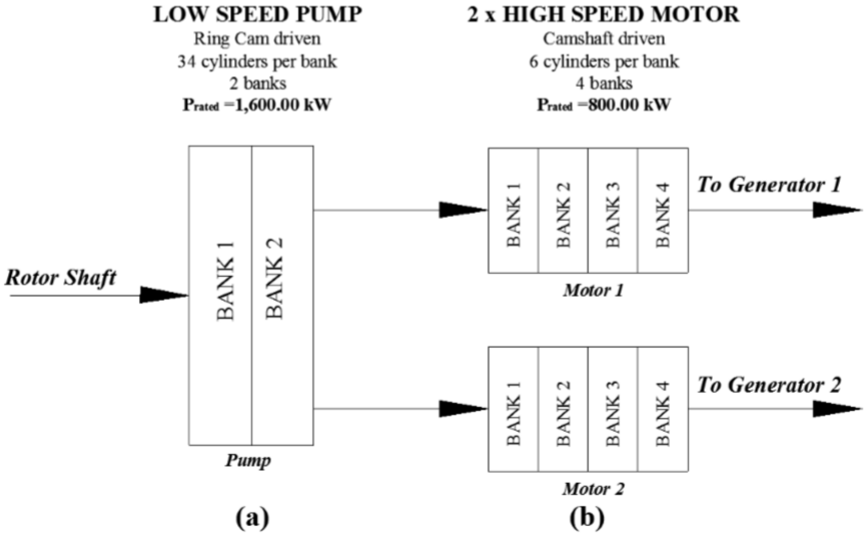


Fig. 5. Schematic representation of the ADD pump (**a**) and ADD motor (**b**).

Artemis drivetrain uses a low rotating pump driving a high speed hydraulic motor (s). For the 1.6 MW system (rated power), one low speed pump drives two 800 kW hydraulic motors. The hydraulic motors drive one electrically excited high voltage synchronous generator each one.

Artemis Digital Displacement motor has in total ***24 cylinders*** of same geometry. They are distributed in ***4 banks***. Each bank contains ***6 cylinders*** equally radially distributed. The banks are stacked over each other. One single camshaft drives the 24 cylinders so each cylinder had one full stroke any single revolution. A schematic view of the motor is presented in Figure 5(b).
On the other hand, the ADD ***low speed pump has a total of 68 cylinders*** contained in ***two parallel banks***, Figure 5(a). Although the principle of operation is similar to the motor, the ADD pump uses a different mechanism to drive the cylinders up and down: a ring cam. A ring cam is a large rotating piece concentric to the main axis of rotation. It does not have any kind of eccentricity. Instead, a ring cam had a sequence of specially shaped lobes over the all external cylindrical surface. The combination between lobes and rotation of the ring cam makes possible to drive the cylinder stroke. In the case of the ADD 1.6 MW pump, the 24 lobes drive up and down all cylinders 24 times per single revolution of the ring cam. The shape of the lobe determines the motion characteristics of radial coordinate r.
Figure 6 presents a simplified cross section of the ADD low speed radial piston pump. In there, the springs were removed to allow a clearer perspective. For a detailed view of the employed components for each cylinder, refer to Figure 7, where the cross section of a cylinder for a motor is presented. The components employed for piston and cylinder only differ in dimensions.

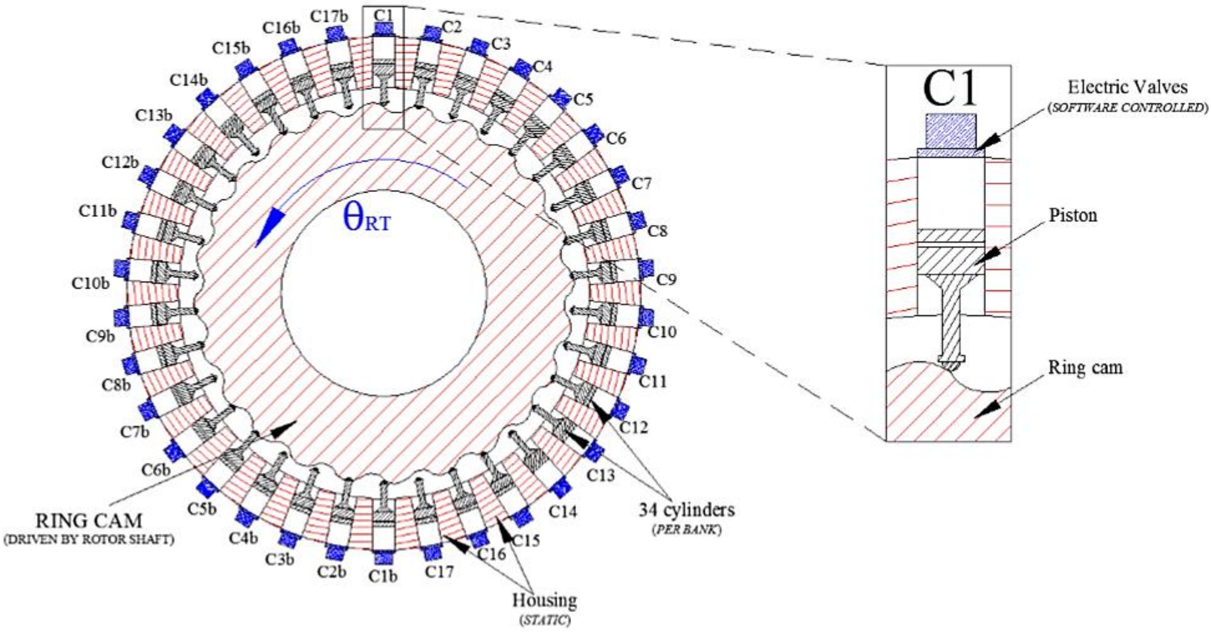


Fig. 6. Simplified cross section for one bank of low speed ADD pump.

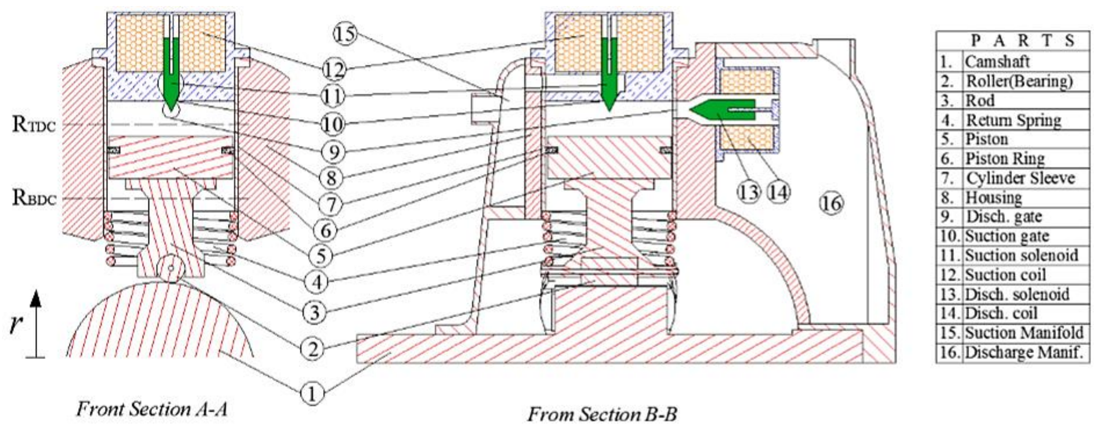
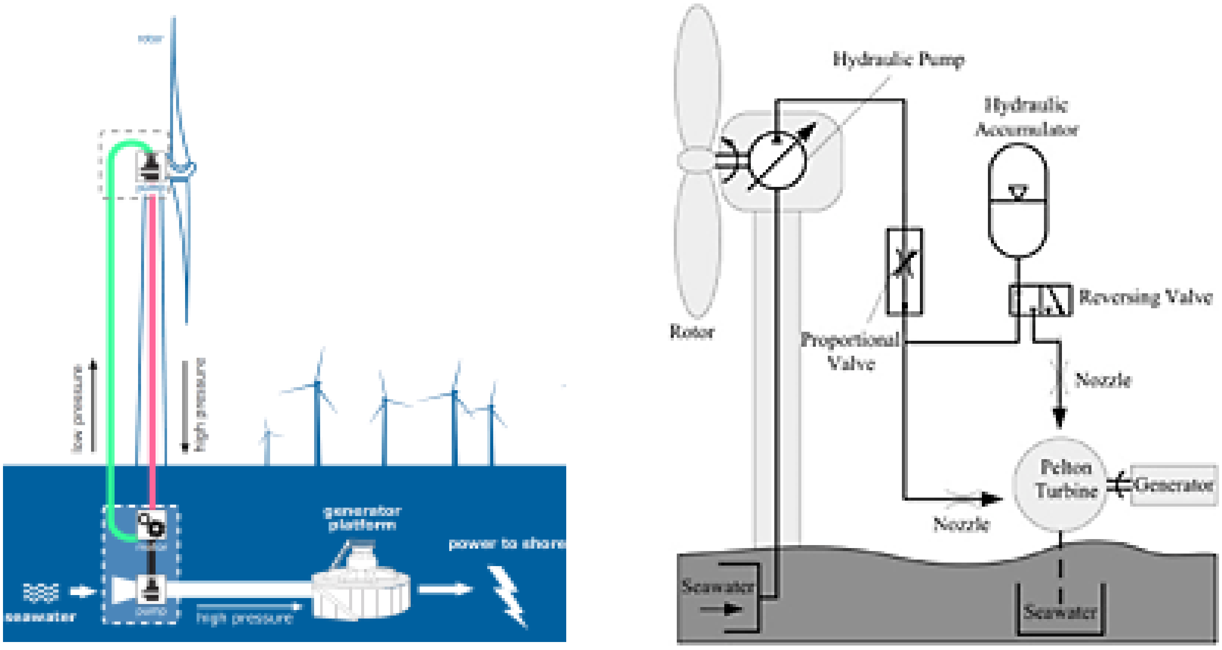


Fig. 7. One single cylinder set with electric valves.

Furthermore, the topic of digital pumps is addressed through theoretical and experimental research in other research units, as well; in Romania, in ***Politehnica University of Timișoara*** and ***Hydraulics and Pneumatics Research Institute in Bucharest***, there are current interests regarding this type of pump, which is studied also in doctoral theses. Also, in ***ICPE-CA Bucharest*** there have been researches and achievements for high frequency electromagnets, which are found to be key elements in the operation of the digital pump valves.
As a proof of the interests as to implementing hydraulic transmissions in low power wind turbines, there is also the research carried out in a thesis at ***Delft University of Techology***, which considered the implementation of a hydraulic transmission for a 10 kW offshore turbine [14]. The energy transmission system has 2 circuits as main components (Figure 8.a):

- a closed hydraulic circuit, which consists of a fixed hydraulic pump connected to the wind rotor, and transmits hydraulic energy to a high speed rotary hydraulic motor; this circuit uses hydraulic oil as a working fluid;
- an open hydraulic circuit, in which a hydraulic water pump, driven by the engine of the first circuit, sends pressure water to a Pelton type turbine; this circuit works with seawater.



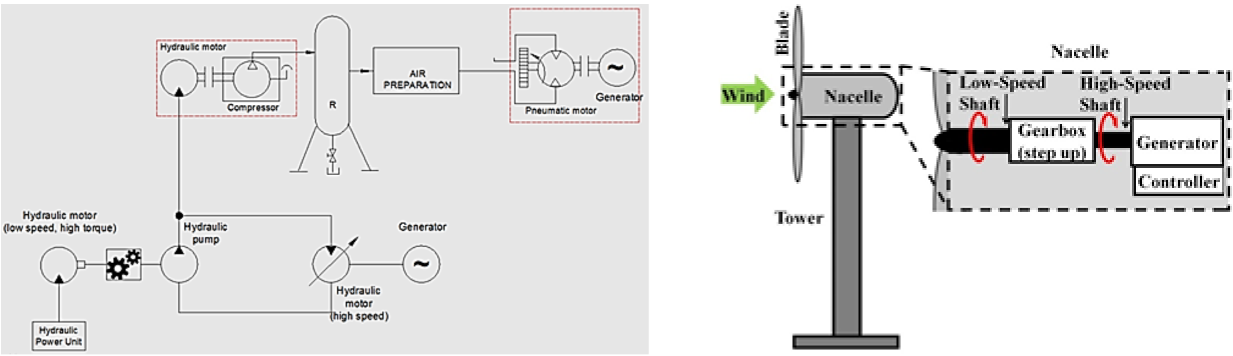
a) **b)**

Fig. 8. Offshore wind turbine with sea water: **a)** The principle works; **b)** Structure of the HST.

Another approach, also for an offshore turbine, is that in which the hydraulic pump driven by the wind turbine is the water pump itself, which sends pressure water to a Pelton turbine, driving a generator (Figure 4.b). As in the case above, a hydraulic accumulator is provided to supplement the flow that drives the turbine, as the wind speed decreases. This accumulator performs energy storage and reuse, but the idea has limited applicability due to the small volume of the accumulator, and the stored energy is mainly used to reduce the variation in the drive speed of the generator. [15]. As in the previous case, the system uses seawater as a working fluid.
One of the current trends in the field of renewable energy is the emergence of hybrid systems, which combine 2 or more systems to obtain a type of energy (mainly electricity), with storage in various forms. We mention the paper [16], which presents a system of energy pneumatic storage in the floats of an offshore turbine, thus assuming a dual role. Electricity is obtained from wind energy combined with wave energy.

3. Hydrostatic transmissions for low power wind turbines

The authors propose that, in addition to developing a hydrostatic transmission for a low power turbine (10 kW), to develop a pneumatic storage system, where the compressor is also driven by a hydraulic motor. After compression, the air is stored in a pressure tank, to be used for electricity generation using a pneumatic engine. The electricity thus obtained can be combined with that obtained in the main branch (hydrostatic transmission), but can also be used for auxiliary purposes (for example for auxiliary systems of the closed-loop hydrostatic transmission: cooling, additional pump drive, etc.). The diagram of the entire proposed installation, in parallel with the principle diagram of a classical wind turbine, is presented in Figure 9. The pneumatic storage facility was approached at theoretical level and by physical realization within INOE 2000-IHP in 2016. Following these researches, a patent application was filed.



a) b)

Fig. 9. HST combined with energy pneumatic storage system (**a**), compared to a classical turbine (**b**).

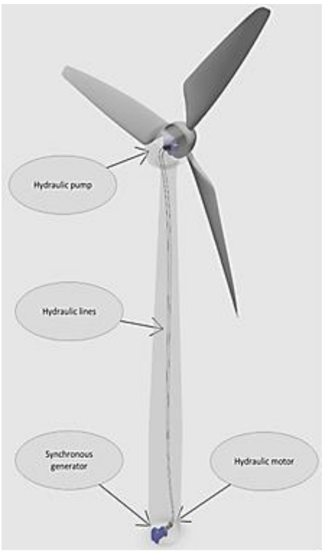


Fig. 10. The main components of the wind turbine equipped with HST, mounted in the nacelle, tower and base of the tower.

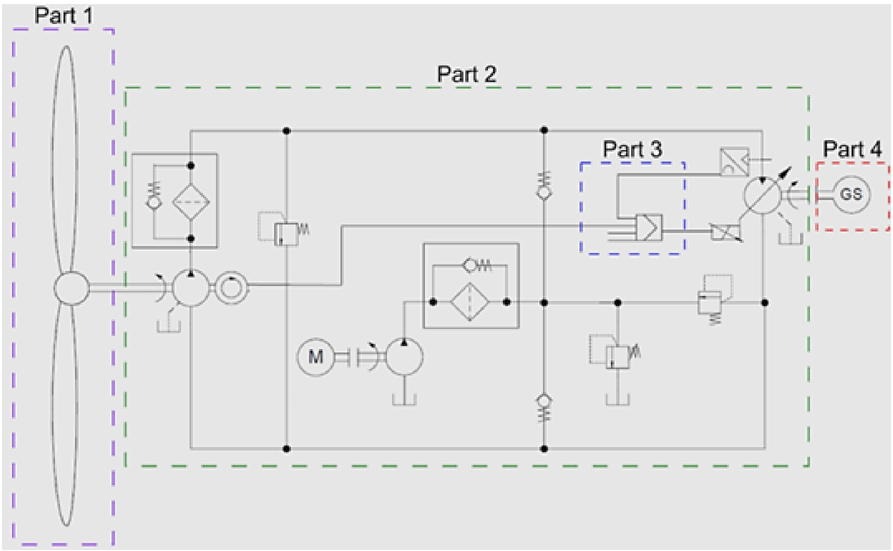


Fig. 11. The subassemblies of the HST testing bench: **Part 1** = wind turbine simulated with variable electric/ hydraulic motor; **Part 2** = HST for low-power turbines; **Part 3** = HST controller; **Part 4** = synchronous generator.

Figure 10 shows the location of the main components of the wind turbine equipped with HST: the rotor and the main pump - in the nacelle; the hydraulic lines - inside the tower; the electric generator and the rest of HST components at the base of the tower. Figure 11 shows the main subassemblies of the stand where the hydrostatic transmission will be tested. The stand will be

made by INOE 2000-IHP. The transmission will be executed in a closed circuit (excluding the volume loss recovery system). It will contain a fixed capacity main pump, a variable-capacity main motor, hydraulic circuits, hydraulic accumulators, safety valves, sensors, filters, heat exchanger, anti-cavitation volume loss compensation pump, hydraulic motor capacity controller with hydraulic circuit with feedback from the high pressure hydraulic circuit, aerodynamic rotor speed and wind speed.
This project comes to meet the energy efficiency improvement requirements of these small wind turbines (whose number is constantly increasing today), in the sense of extracting a greater quantity of the available energy of the wind, even at low wind speeds, by promoting a new solution. It is based on two main component systems: a classical hydraulic transmission (HST), containing two standard rotary volumetric machines (pump and motor), combined with a system of wind energy pneumatic storage (EPS). Consequently, it is proposed to develop a demonstrator, type experimental model, that is a 10 kW test platform, on which this technical solution, designed to ensure simultaneously energy efficiency and economic benefit of lowering to the ground components of the low power wind turbines, will be evaluated, experimentally validated and promoted.

Conclusions

The project aims to promote a hydrostatic transmission for low-power wind turbines in order to increase the extraction of electricity from the available wind energy and also to demonstrate the following advantages:
- the possibility of practical implementation of a transmission for low-power wind turbines, from standard and specially designed components, with a continuous variable ratio in the capacity adjustment range of variable hydraulic machines;
- increasing the efficiency of wind turbines equipped with HST by using control strategies dedicated to the wind turbine system comprising the wind rotor, the hydrostatic transmission and electric synchronous generator;
- the possibility of maintaining a predetermined constant rotational speed of the electric generator when braking or acceleration loads occurs at the wind rotor;
- the possibility of obtaining a faster response to sudden wind speed variations compared to mechanical or electromechanical transmissions;
- the possibility of low-maintenance of the turbine with reduced costs by placing some components on the ground.

Acknowledgments

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