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THE INVOLVEMENT OF FLUID POWER IN THE FIELD OF RENEWABLE ENERGY

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Abstract: *Exploitation of renewable energy sources is the most convenient solution for reducing the negative effects of the use of fossil fuels: pollution, temperature rise, vegetation change, etc. Although there are numerous targets set worldwide, the concrete results are not at the expected level. This is why more and more technical fields are involved in finding solutions for increasing the amount of useful energy from renewable sources, as well as for solving other problems associated with energy production, such as its storage. The paper presents some achievements in which the field of fluid power is involved, with an emphasis on the systems developed in recent years, and which have been put into operation or have a high potential for this.*

Keywords: *Compressed air, hydraulic system, renewable energy, digital hydraulics*

1. Introduction

Renewables generated 28.3% of global electricity in 2021, similar to 2020 levels (28.5%) and up from 20.4% in 2011. Despite the progress of renewables in the power sector, the surge in global energy demand was met mostly with fossil fuels [1]. This amount of energy is produced with total installed capacities of 3146 GW, of which 314 GW were added in 2021, 17% more than the previous year. The conversion from solar and wind energy covers more than 10% of the total electrical energy consumed, the completion of up to 28.3% being provided by hydro energy (15%) and bio + geothermal (approx. 3%). Unfortunately, the burning of fossil fuels still provides a significant share of the electricity consumed, 62%, and the rest is produced in nuclear power plants, which are also the subject of some controversies.

There are also positive aspects: one of them is that, 10 years ago, the share covered by renewable sources was only 20% of electricity consumption, while the absolute values were significantly lower. However, the current trend of increasing the share of renewable energy and conversion capacities in the total of plants for the production of electricity is far from that required to reach the targets proposed for the years 2030 or 2050; this is why the forceful approach of commissioning as many renewable energy conversion units of various types as possible is necessary.

Hydraulic and pneumatic systems can be found, in recent decades, in various installations for the production of energy from renewable sources, and the number of fields in which they are involved is constantly increasing, as the technological advance and the appearance of new materials solve certain problems. One example is the emergence and use of biodegradable oils, making hydraulic systems compatible with onshore or off-shore applications.

In the following, some systems will be presented in which fluids under pressure (mainly air, water or oil) play an important role in various phases related to the production or storage of energy.

2. Pneumatic systems in the structure of energy production facilities

2.1 CAES system

The most well-known system based on energy storage in compressed air is the CAES system (Compressed Air Energy System); it solves the problem of the imbalance between energy production

and its consumption, by storing part of the energy produced in the form of compressed air, during the production surplus period. When energy demand exceeds production, compressed air is used to drive electric power generators, often with the help of gas turbines.
The first utility-scale diabatic compressed air energy storage project was the 290 megawatt Huntorf plant opened in 1978 in Germany using a salt dome with 580 MWh energy, 42% efficiency.

Fig. 1. Huntorf plant (Germany) and the principle of operation [2]

As one can see in the figure above, energy storage is based on air compression in special enclosures, at a pressure of several tens of bar (50...70 bar in operation); the compressors are powered by surplus energy, produced during periods of low consumption. Air is held in the reservoirs until consumption increases and requires the commissioning of additional capacity (turbines). These turbines, in which natural gas is mixed with pressurized air, use approx. 2/3 of the energy produced for air compression; therefore, using already compressed air, all the energy produced is delivered to consumers.
Other technical characteristics of the plant:
- It uses 2 caverns of approx. equal shapes and volumes (140,000 and 170,000 m^3, respectively)
- Vertical location between 650 and 800 m depth
- Maximum air flow used by the turbine: 417 kg/s.
The location and shape of the two caverns is shown in figure 2.

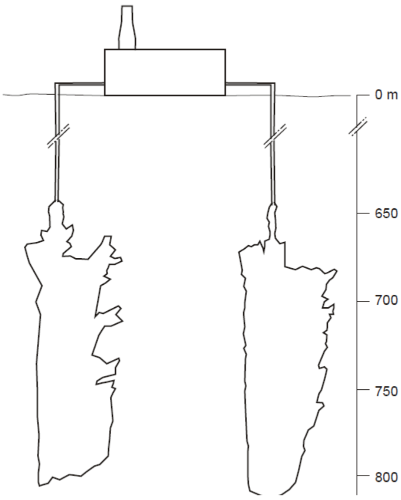

Fig. 2. The shape and location of the two caverns of the Huntorf plant [3]

Following the success registered in operation, a 110-megawatt plant with a capacity of 26 hours (2,860 MWh energy) was built in McIntosh, Alabama (1991). It uses a 540,000 m^3 solution mined salt cavern to store air at up to 75 bar. The stored energy is enough to cover the electricity consumption of 11,000 American homes for 26 hours.
Both of these plants use diabatic processes, and the technology is called D-CAES; starting from this and using the heat resulting from air compression, the A-CAES (Adiabatic – CAES) technology was developed, which is still at an experimental level.
In D-CAES applications, the energy stored in compressed air is used indirectly, the compressed air being mixed with natural gas for combustion; however, there are also applications where compressed air is used directly, to drive a pneumatic motor that, further, drives a generator. In this case it is of interest to know the amount of energy that can be stored in compressed air; a preliminary calculation can be made using the formula:

$$W = p_B V_B \ln\frac{p_A}{p_B} + (p_B - p_A)V_B \qquad (1)$$

where: W – stored energy (MJ), P_A, P_B – initial and final pressures in the enclosure, (MPa), V_B – volume of the enclosure (m^3). The formula can be used for isothermal processes.
If we consider the compression of air from atmospheric pressure to 100 bar, in an enclosure with a volume equal to 1 m^3, taking into account that 1MPa = 10 bar, we will get:

$$W = 10.0\,MPa \cdot 1\,m^3 \cdot \ln(0.1\text{ MPa}/10.0\text{ MPa}) + (10.0\text{ MPa} - 0.1\text{ MPa}) \cdot 1\,m^3 =$$
$$= 10 \cdot (-4.6) + 9.9 = -36.1\text{ MJ} \qquad (2)$$

Given that

$$1\,MJ = 0.2778\text{ kWh} \qquad (3)$$

it results:

$$W = -36.1 \cdot 0.2778 = -10.03\text{ kWh} \qquad (4)$$

the "–" sign shows that the gas absorbs energy.
Air compression in storage plants can be of three types: isothermal, adiabatic and diabatic. In storage plants that use isothermal compression, the heat produced during compression is removed at the same rate as it is produced, in order to maintain a constant temperature. An air cooler is used to remove the heat in the atmosphere, and a heater is used to use the stored air. In storage plants that use adiabatic compression, heat is stored and reused when exhausting the air towards a gas turbine. These plants can have an efficiency of up to 90 percent. Storage plants that use diabatic compression remove heat with the help of an air cooler, and when the stored energy is needed, the compressed air is released and heated by combustion to be used to drive a gas turbine. Nowadays all the companies are trying new methods to store the heat produced when compressing the air to be fully reused to maximize efficiency [4].

2.2 Ground-Level Integrated Diverse Energy Storage (GLIDES) technology

A step forward from the CAES principle and technology is the use of pressurized air only for energy storage, and an intermediate fluid (water, oil, etc.) is used to convert the stored energy into mechanical energy. In the following, two examples of such technologies are presented.
GLIDES is a laboratory technology, developed at Oak Ridge National Laboratory, USA, in the experimental model stage, intended to store energy in the form of compressed air, with the help of a "liquid piston", which is actually water under pressure [5].
The main parts of the system are: a reservoir for maintaining the liquid at atmospheric pressure, vessels containing air (or other gas) at an initial pressure, a pump with which the vessels are charged, as well as a mechanical energy generator (turbine of special construction). To these main components, some specific hydraulic components are added, to carry out the processes. For energy storage, liquid is pumped from the storage tank into pressure vessels using excess energy. The process takes place until the maximum storage pressure is reached. To use the stored energy, pressurized water is sent to a hydraulic turbine, which drives an electric generator.

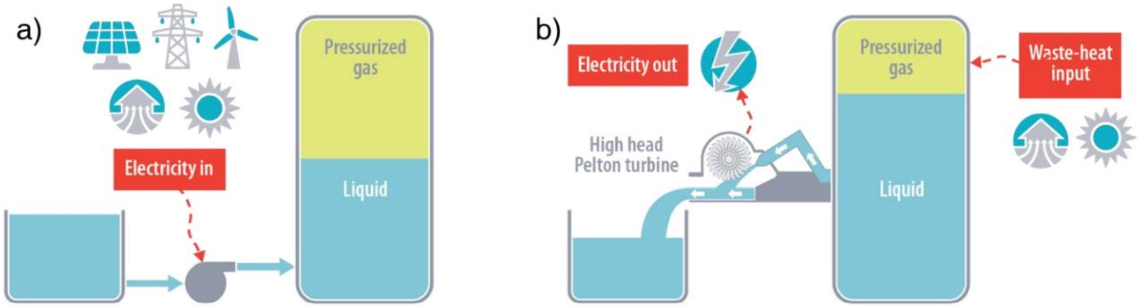

Fig. 3. "Liquid piston" technology - the working principle
a) storage phase; b) the phase of recovery / reuse of stored energy

The figures below show two phases of the operation of the experimental plant. In figure 4, the installation is in the energy storage phase, when the water is pumped into the storage containers; the water from the large capacity external tank (approx. 2000 l) is pumped into 4 tanks of 500 l each, up to a pressure of 130 bar. When this pressure is reached the water pump is stopped and the energy can be maintained without loss as long as needed.

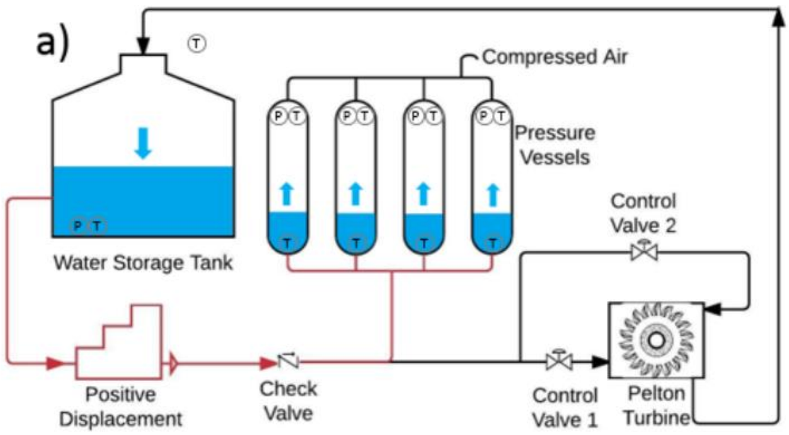

Fig. 4. GLIDES experimental installation - energy storage phase

In Figure 5, the installation supplies the stored energy and converts it from pneumatic energy to mechanical energy by means of a specially constructed 2-jet Pelton turbine capable of delivering 5.5 kW per jet. The unloading of the storage containers is done until the pressure reaches 70 bar. The water that drives the turbine is collected and returned to the outer tank without being lost. The minimum pressure in the storage tanks is monitored and restored whenever necessary.

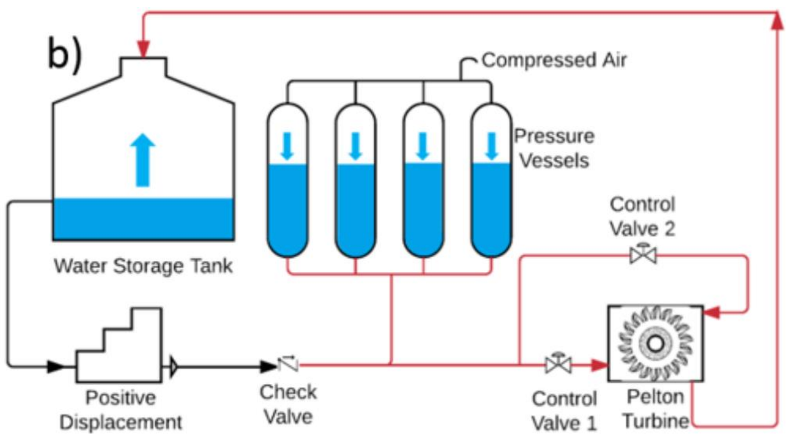

Fig. 5. GLIDES experimental installation – delivery of stored energy

This installation is experimental; there are also industrial applications, of significantly higher powers, but they must solve certain problems when moving from the phase of experimental installation to that of a functional solution. Such a solution was developed by the AUGWIND company.

2.3 AUGWIND air battery

The Israeli company AUGWIND was founded in 2012 by two researchers who started from the premise that the progress made in the conversion of renewable energy is not also found in the storage of the resulting energy, so that the energy is available for longer periods of time. The solution developed by the company is a combination of pumped hydro and compressed air energy storage. The system has the commercial name of AirBattery and has been implemented in several energy storage projects, which accumulate over 200 MWh [6].
The principle diagram is shown below; the pre-compressed air is found in some tanks placed in the ground, in which water is introduced until the air reaches a pressure of 40 bar. The pumps are powered by electricity from a renewable source (wind, solar, etc.); since the water is introduced gradually, the process is isothermal. Water pumped into pressurized tanks is stored in above-ground tanks.
After reaching the working pressure, the pumping process stops and the "battery" is charged; the supply of the stored energy is done by sending water under pressure to a hydro-mechanical converter, of the water turbine type, which drives an electric generator.
The key element of this system is the pressure tank, in which the water compresses the air; for large tanks, classic solutions such as metal tanks are not sustainable, due to high costs. The solution proposed by AUGWIND is based on an inner polymer lining, surrounded by a metal mesh with mechanical resistance. The resulting assembly, shaped like a classic cylindrical tank, is mounted below ground level and covered with concrete; this results in a pressure-resistant container with a long service life.

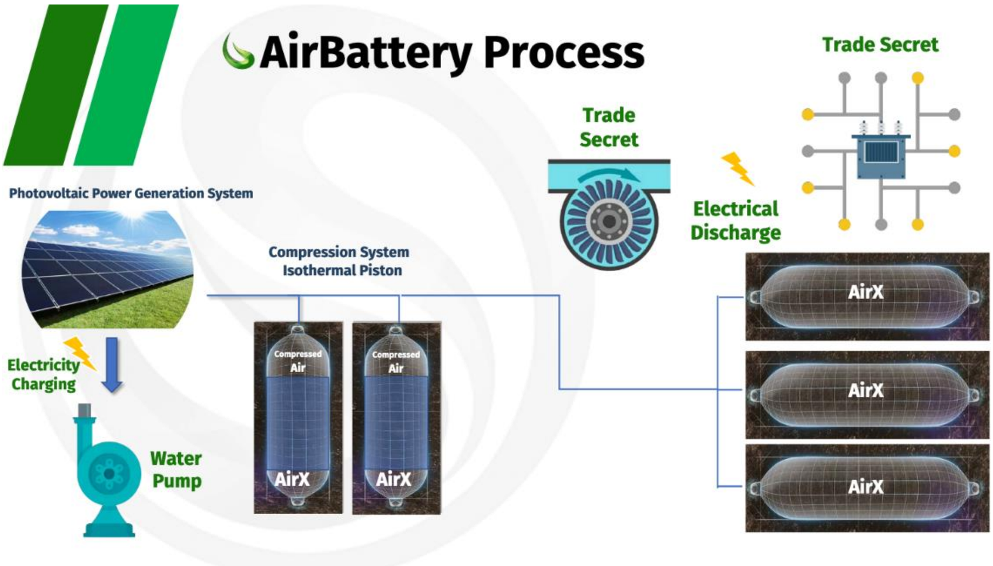

Fig. 6. Structure of the AUGWIND compressed air energy storage facility

The main advantages are presented below; it is important to note that since there are no components in relative motion, wear is very low and therefore the theoretical number of charge-discharge cycles is very high. The efficiency estimated by the company exceeds 80%.
Another advantage is given by the possibility of scaling the installation by adding a corresponding number of tanks; regardless of the number of buried tanks, the soil above them can be used for agriculture or energy production with solar panels or other technologies. However, a technical-economic analysis carried out by the company indicated that, for maximum efficiency, the storage capacity must be at least 5 MW.

Fig. 7. Advantages of the AirBattery system

3. Hydraulic systems in renewable energy conversion facilities

3.1 Hydrostatic transmissions with applications in the field of wind turbines

The previously presented solutions were based on energy storage in pressurized air, hence pneumatic applications; hydraulic systems, in turn, have a significant involvement in the conversion and storage of renewable energy, in various forms. However, the most widespread applications are those related to the transmission of energy with hydraulic sub-systems in the structure of wind turbines.

These turbines, mainly the horizontal axis ones, have the electrical generator mounted coaxially with the rotor, which significantly increases the mass of the assembly placed at height, which can reach tens of tons of weight. For this reason, the expenses related to the construction housing this assembly are high and are reflected in the final price of the turbine; another problem is the price of maintenance operations, which is higher if it is carried out at height.

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 V90/3000 turbine, with a power of 3 MW, the nacelle weighs 75 tons, the rotor 28 tons, and the tower minimum 155 tons.

At the level of 2022, the largest horizontal axis turbines have reached powers of 15...16 MW. Even if it is considered that the mass placed at height does not increase proportionally with the installed power of the turbine, the weight of the components is a significant one, and any reduction of it has favorable effects on the final price of the turbine and subsequent maintenance.

One of the possibilities to reduce the mass located at height is to mount the generator on the ground and transmit the energy from the rotor through a hydrostatic transmission; in this way the rotor and some hydraulic components remain located in the nacelle and the rest are located below. Research in this direction began in the 1970s, with the Rybak company putting into operation, in December 1980, the turbine model SWT-3, with an installed power of 3 MW.

In this turbine, the hydrostatic transmission is composed, at the level of the flow generators, of 14 hydrostatic pumps with constant flow, which feed a group of 18 motors with variable flow; a speed multiplier is used to increase the speed of the rotor, to be compatible with the drive speed of the pumps. Another gear transmission is mounted between the hydraulic motors and the generator.

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 [7].

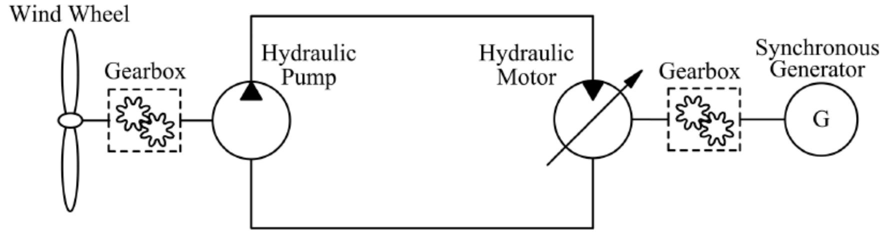

Fig. 8. Operating principle of the wind turbine with hydrostatic transmission

As in the case of the Rybak turbine, the pumping group is made with fixed flow pumps, and fixed and variable flow motors are used to drive the generators; one or both engines can be used to drive each generator, according to figure 9 (a).
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%.

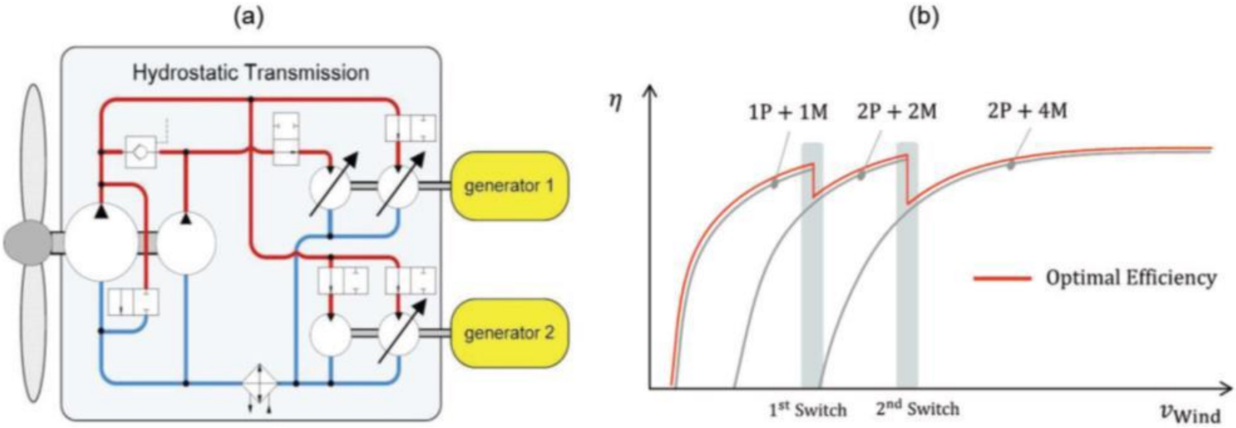

Fig. 9. Hydrostatic transmission (HST) for a 1 MW turbine developed at IFAS

A more complex scheme, using both pump and motor in digital construction, is shown in figure 10 [8].

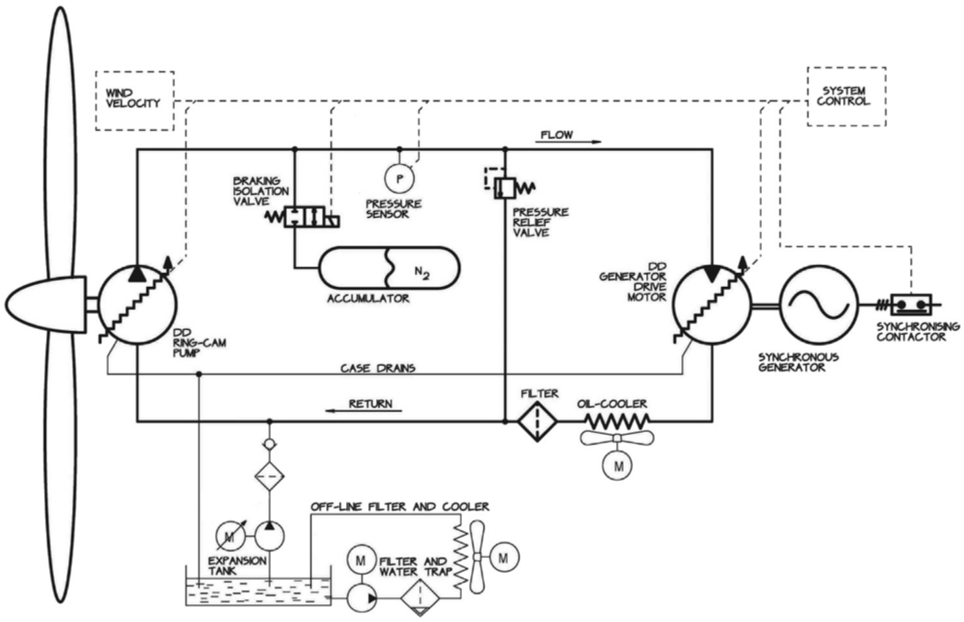

Fig. 10. Diagram of a hydrostatic transmission with digital elements integrated in a wind energy conversion system

The mechanical energy produced by the rotor is transmitted to the hydrostatic pump, which supplies high-pressure flow to a hydraulic motor that rotates the electric generator. This system works in a closed circuit and includes all the specific components; the oil in the circuit is cooled and filtered and water is removed, using an off-line circuit. A central control unit manages the operation of the system. The construction using the principles of digital hydraulics of the pump and the motor is based on 2 technological peculiarities: 1) intake and discharge valves with electromagnetic control, and 2) the parallel coupling of banks of cylinders to create digital pumps and motors of desired capacity. The solution was put into practice by the company Artemis Intelligent Power.
In 2009, this company made the first version of the digital pump designed to equip a hydraulic transmission for a turbine with an installed power of 1.6 MW. The test results indicated an efficiency of the turbine equipped with this transmission of over 90%, close to the efficiency of a classic turbine [9].
Artemis Digital Displacement (ADD) drivetrain is formed by a hydrostatic transmission followed by two parallel synchronous generators. For the 1.6 MW system (rated power), one low speed pump drives two 800 kW hydraulic motors. The hydraulic motors each drive one electrically excited high voltage synchronous generator. The most important optimization for the pump and motors consists in making the valve's operation independent of the angular displacement of the rotor shaft. This unconstrained dependence allows individual operation of each cylinder.

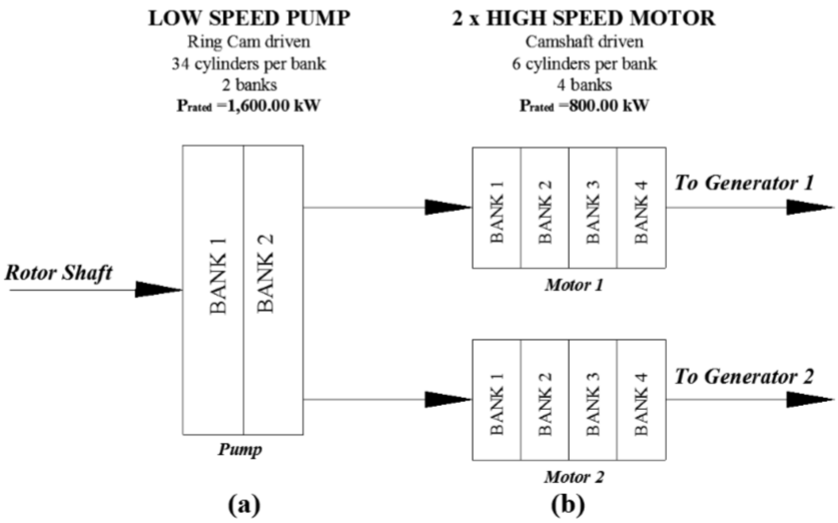

Fig. 11. Hydrostatic transmission for wind turbines proposed by Artemis Intelligent Power

The ADD low speed pump has a total of 68 cylinders (pistons) contained in two parallel banks; to drive the pump pistons, a cam ring is used, which is similar to a ring with lobes on the outer surface, but without any eccentricity. The pump pistons are forced to follow the lobes of the ring and in this way they perform their oil pumping function. The pump ring in the 1.6 MW transmission has 24 lobes, which actuate 34 pumping pistons; to achieve the required geometric volume, 2 packages of pistons are mounted together, according to figure 11.
Artemis Digital Displacement motor has a total of 24 cylinders of the same geometry. They are distributed in 4 banks. Each bank includes 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.

3.2 The use of various working fluids

The energy transmission systems from the offshore turbine component have certain constructive peculiarities, which take into account their location; an important problem related to the use of hydrostatic transmissions is the pollution that can occur when oil is lost in the circuit; to avoid this

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problem, some researches turn to the use of biodegradable fluids or even sea water, as is the case of the two examples below.
Figure 12.a shows the operating principle of an offshore turbine, where the electric generator is connected to a water turbine, driven by a jet of sea water that is pressurized with the help of a pump; it is driven by a hydraulic motor fed from a pump connected to the rotor of the wind turbine. If the hydrostatic transmission is located above sea level (on a platform, for example), the danger of pollution is eliminated or greatly mitigated. The solution was proposed and developed by Delft University.

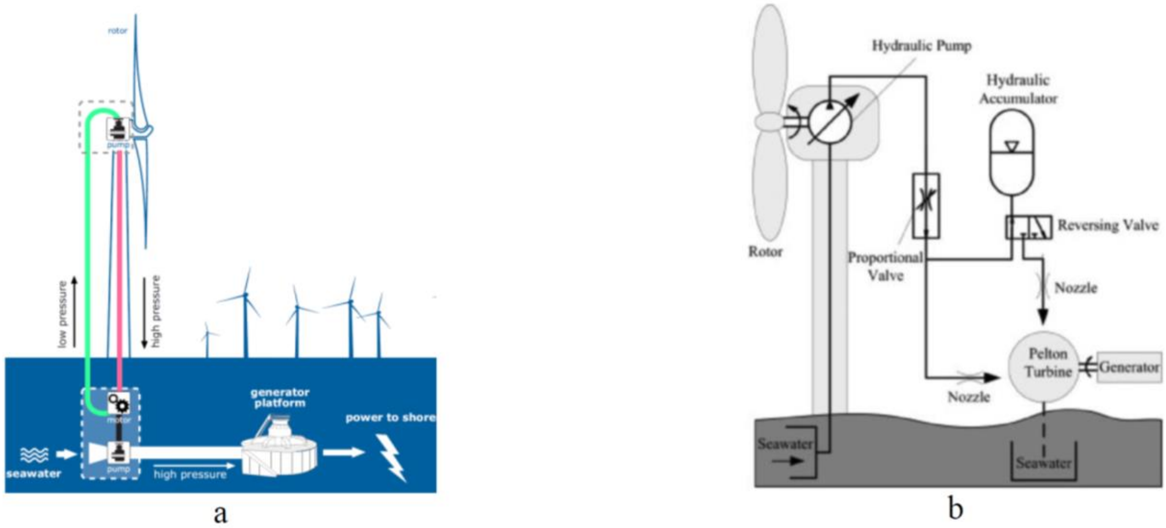

Fig. 12. Wind turbines that use sea water

A step further is achieved if hydrostatic transmissions are used that work with sea water as the working fluid, as shown in figure 12.b [10]; in this case, the hydraulic pump driven by the rotor works with sea water in an open circuit, sending the water to a Pelton turbine that drives the electric generator. For the (limited) compensation of the decrease in wind speed, a pneumo-hydraulic accumulator is installed, which is charged during periods of strong wind. The amount of stored energy is limited by the capacity of the accumulator; if this one is permanently connected, it can reduce the unevenness of the flow that drives the Pelton turbine.

4. Conclusions

Fluid power applications in the field of renewable energy are very diverse and constantly expanding. The compressibility of gases recommends them for storage applications in natural or artificial reservoirs, at pressure rates of 50...100 bar; with capacities in the order of hundreds of thousands of cubic meters, the tanks can store significant amounts of energy and have the advantage of a long operating life, while maintaining performance. The first plant of this type was commissioned in 1978 and is still active, proving the reliability of the CAES concept.
Along with the development of new materials and manufacturing solutions, the range of applications has also expanded; in addition to purely pneumatic applications, a current trend is that of "liquid piston" solutions, in which water compresses the air in the tank.
Regarding hydraulics, its involvement in renewable energy applications was initially found in pitch adjustment, yaw and rotor braking, lubrication; a newer direction is energy transfer. The involvement of hydraulics in these fields is due to the advantages it has over other types of systems (mechanical, electrical) - safe, reliable, with a good power density and competitive prices.
Regarding hydraulic power transfer, the future seems to belong to digital systems, at least for the main components of a transmission: the pump driven by the turbine rotor and the rotating hydraulic motor that drives the electric generator. If the initial solutions, such as the Rybak turbine that

appeared in the 80s, had a large number of pumps and motors that were actuated in turn, taking into account the transmitted power, today digital technology has penetrated the interior of rotating hydrostatic machines, as can be seen in the achievements of the ARTEMIS company.

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