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WIND POWER PLANTS – TYPES, DESIGN AND OPERATION PRINCIPLES

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Abstract

Many countries worldwide support green energy production on large scale mostly by solar or wind energy subsidizing manufacture and operation of such systems. During the last two decades, there has been significant increase in wind energy production globally. Statistics show continuously growing investments in the development and installation of wind turbines and farms. Currently, wind energy is the second most important source of renewable energy after water energy. By 2016 global cumulative installed wind capacity surpassed 432 k MW [GWEC]. In last several years, most dynamic growth in wind power generation investments was recorded in Asia. Europe, in comparison, has less impressive but steady growth in wind power plants through the years. In this article, authors present global demand on energy in comparison to efficiency of wind power plants in relation to the local and global location as well as to the scale of installed system. Authors also present statistical data concerning wind power plants development. General classification, using number of criteria (ex. power output, construction size, rotor axis orientation and other) of wind to electric power converting devices is presented. Various types of devices, which authors describe in this article, can perform conversion of wind blow energy to the electric energy using different yet similar methods.

Keywords: *wind energy, wind power plants, energy conversion, renewable energy*

1. Introduction

During the last two decades, there has been significant increase in wind energy production globally. Statistics show continuously growing investments in the development and installation of wind turbines and farms.

Currently, wind energy is the second most important source of renewable energy after water energy [1]. By 2016 global cumulative installed wind capacity surpassed 432 k MW [8].

In the past most of wind power plants ware installed onshore, but currently offshore plants are becoming more popular. The reason for growing interest in offshore installations despite higher cost in comparison of offshore ones is more stable wind and possibility of building larger wind turbines grouped into large-scale wind farms.

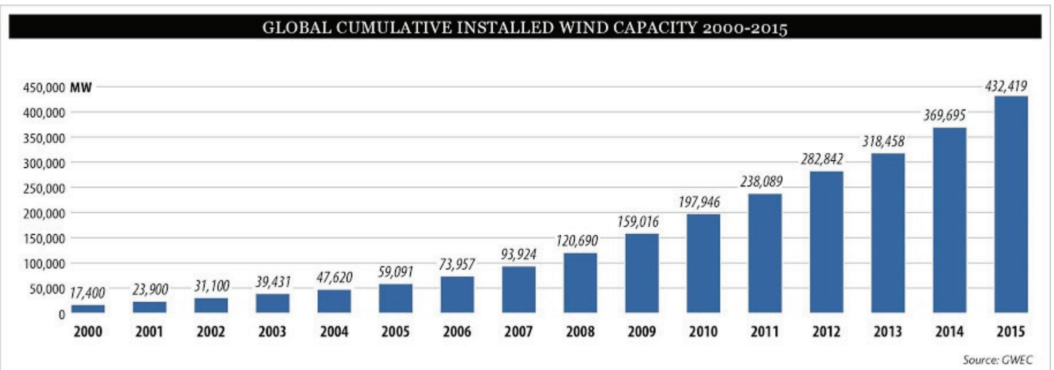

Fig. 1. Global cumulative installed wind capacity 2000-2015 [8]

a) b)

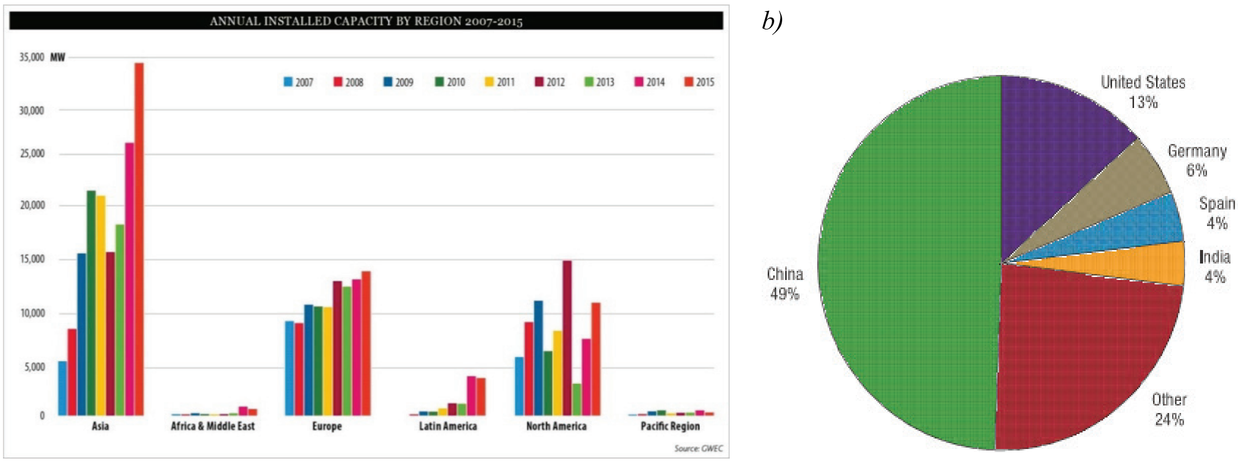

Fig. 2. Annual installed capacity by region 2007-2015 (a) [8]; largest producers of wind energy (b) [8]

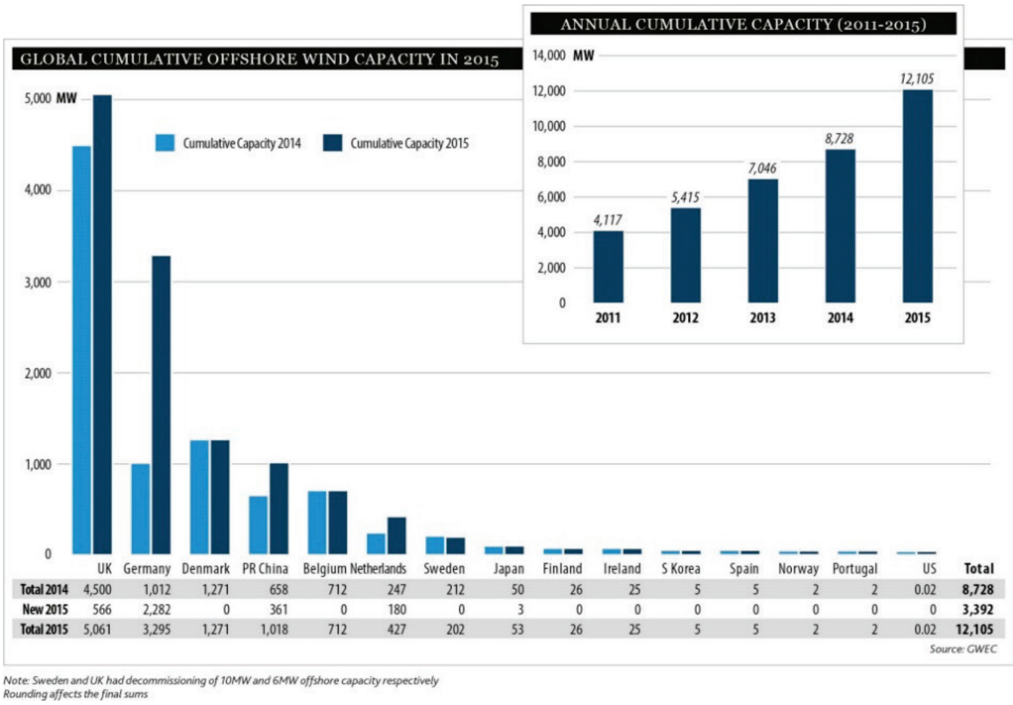

Fig. 3. Global cumulative offshore wind capacity in 2015 and annual cumulative capacity 2011-2015 [8]

New generation of wind turbines is more reliable than those from 1980's. This is necessary condition if energy production is to play an important role among renewable energy sources. Over the last 30 years, the size of wind turbines increased 7 times, as nominal power increased nearly 14 times. At present, turbines capable of producing over 10 MW of power are being developed. The main reason for continued growth of turbines sizes is to minimize the energy cost per kilowatt-hour. However, it is worth remembering that according to the „square-cube law", there is a maximum size after the surpassing of witch the cost of ever-larger turbines would grow faster than financial gain from the increased size. Fig. 4 illustrated the growth of wind turbines size during the last 3 decades.

Apart from expansive wind farms with large-scale turbines, there has been an increase in the area of small wind energy systems, the so-called off-grid or stand-alone systems, unconnected to the grid. The systems produce under 100 kW energy. Globally the number of manufacturers of small wind energy systems has been growing dynamically. In 2002, number was less 50, whereas in 2012 there were about 250 companies located in 27 countries.

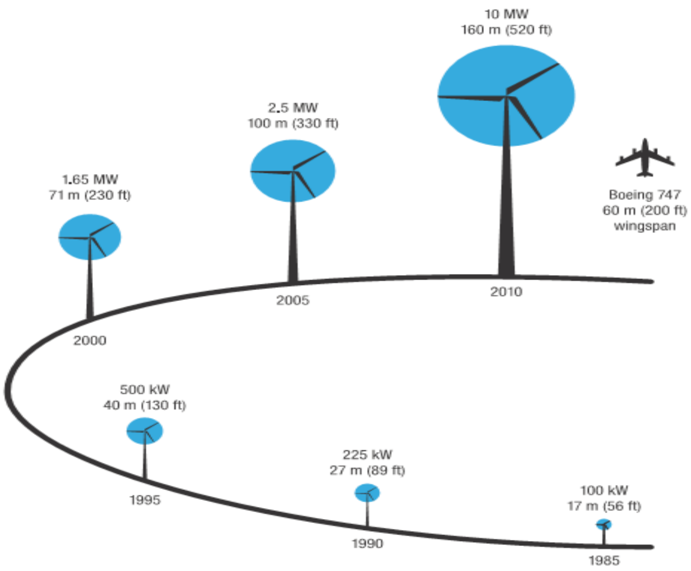

Fig. 4. Growth of wind turbines size [2]

2. Wind power plants – types, working principles, design

Conventionally wind power plants can be classified based on:

a) power output:
   - microplant, with the power output up t0 100 W, used to power off-grid ciurcuits,
   - small power plants with the power output from 100 W to 100 kW, used to power individual households or small enterprises,
   - large wind power plants with the power output of 100 kW and above, used for producing grid-tied energy,
   - utility-scale more than 1 MW,

b) construction size,

c) rotor axis orientation:
   - horizontal axis (HAWT),
   - vertical axis (VAWT),

d) other criteria:
   - wind energy utilization,
   - rotor speed (low, medium, high)
   - rotor and mast orientation relative to wind direction – upwind and downwind,
   - generator design: gearbox and direct drive.

Principal elements of wind turbine are rotor (blades and hub), drive and control system (Fig. 5a). The most important element of a turbine are blades because it is those elements that perform the actual energy conversion from kinetic to mechanical energy utilizing the principle of lift force creation on the blade airfoil. Currently horizontal three blades design is the most popular configuration (Fig. 7c). The three-blade design has proven to be the most energy efficient and the balanced [3]. Fig. 5b shows the effect of the number of blades on the power coefficient for particular tip speed ratio.

$$J = \frac{\Omega R}{V_0}, \tag{1}$$

where:

Ω – rotational velocity,

V_0 – wind speed,

R – blade radius.

In Fig. 5b, it is easy to see significant increase power coefficient as the configuration changes from one blade to blade. Future increase of the number of blades results in considerably smaller increase in the power coefficient, when friction-related efficiency losses are taken into account. However, three-blade configuration is preferable because it only has 2/3 of the load of two-blade configuration, generating less noise [4].

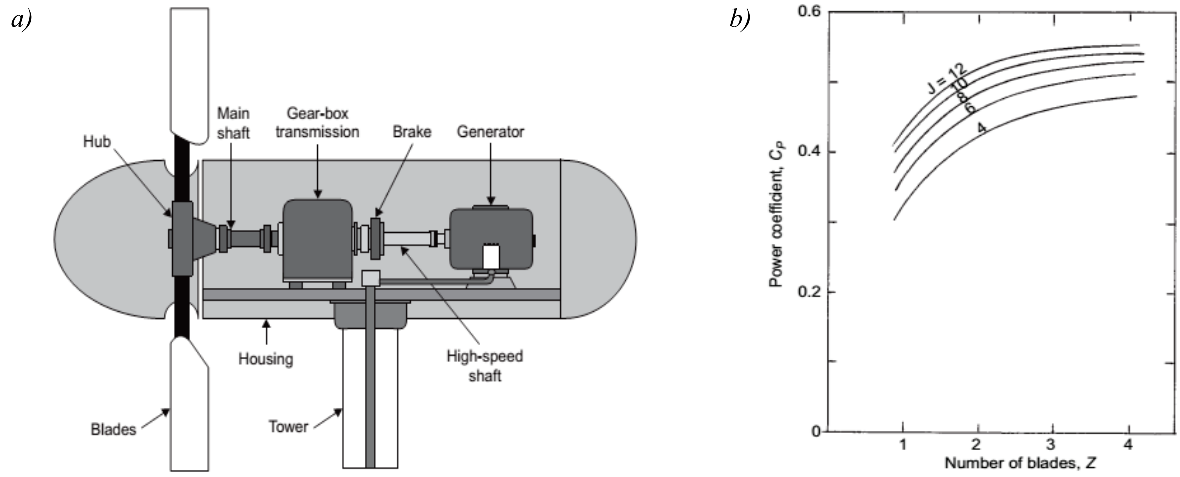

Fig. 5. Simplified wind turbine design (a) [4]. The effect of tip speed ratio and number of blades on power coefficient in zero friction conditions (b) [4]

As for axis orientation, VAWTs (Fig. 7e, f) designs being less efficient than HAWT ones, are used mainly for small-scale. A key factor causing lower efficiency of VAWT is that, each blade reaches maximum lift force only in a single point per rotation.

Maximum efficiency of wind turbines is indicates by Betz's low, which states that maximum amount of kinetic energy that may be theoretically derived from wind and converted into mechanical energy cannot be greater than 59.3%.

Figure 6 illustrates a comparison of power coefficients of several wing plant designs against BETZ's limit. It shows that the only promising solutions are two and three blade constrictions. Is should be noted that currently produced wind turbines do not reach 100% Betz limit, which is why a construction is considered to be well designed if it can reach power coefficient 35-45% [2].

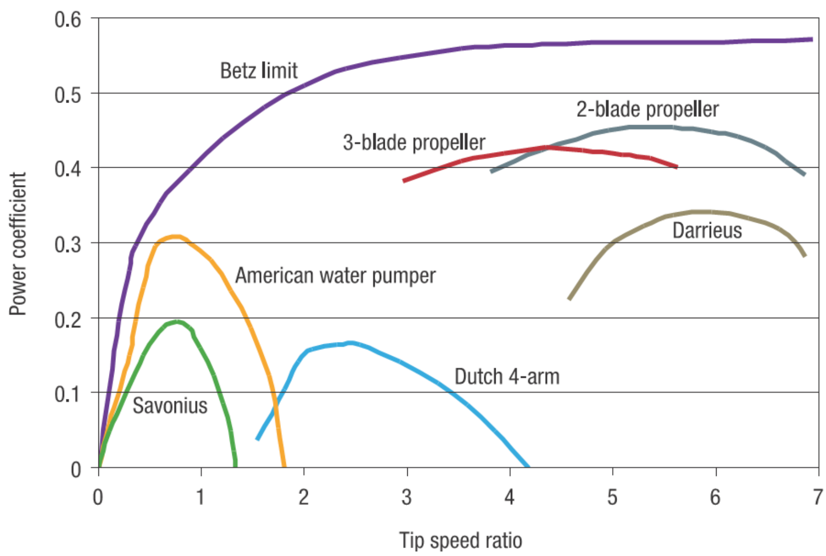

Fig. 6. Power coefficient in relation to wind speed ratio for different wind turbine designs against Betz's limit determining maximum aero dynamical efficiency [2]

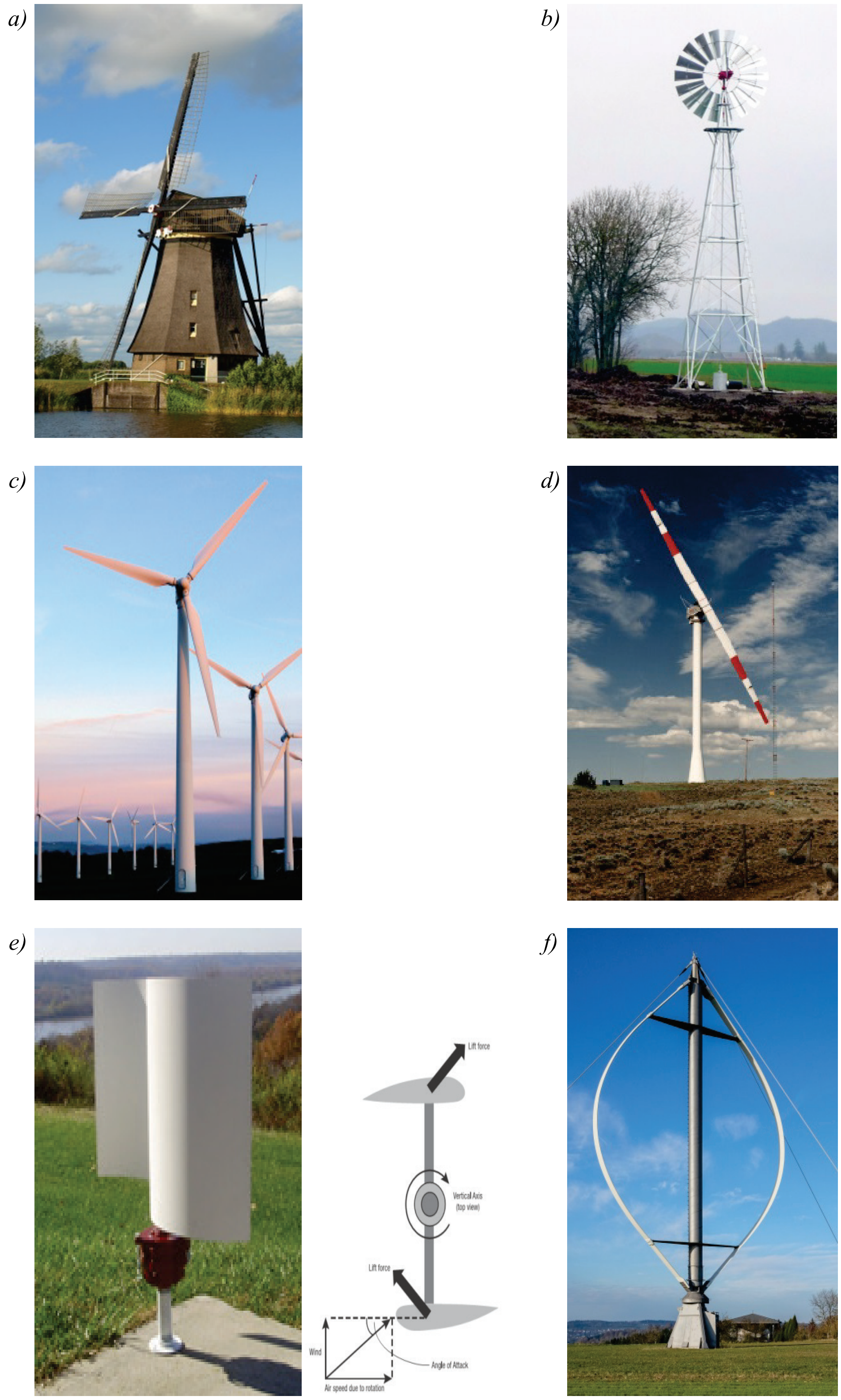

Fig. 7. Wind turbine designs: a) Dutch 4-arms, b) American water pumper, c) 3-blade design, d) 2-blade design e) Savonius, f) Darrieus

The power generated by wind turbines is expressed by the formula:

$$P = \frac{1}{2}\rho A V^3 c_p, \tag{2}$$

where:

P – rotor generated power,
ρ – air density,
A – swept area, described as circle drawn by rotating blades,
V – wind speed,
c_p – power coefficient.

Figure 8a illustrates relationship between the power generated by the wind turbine and wind speed. At wind speeds under 5 m/s the turbine generates no power at all. Maximum efficiency is achievable at speed of over 12 m/s. Fig. 8b shows the annual, hour-to-hour distribution of average wind speed for typical lowland area. Comparison the data in Fig. 8a and 8b it can be concluded that power plant can operate at nominal power only during 10-15% of time in a year.

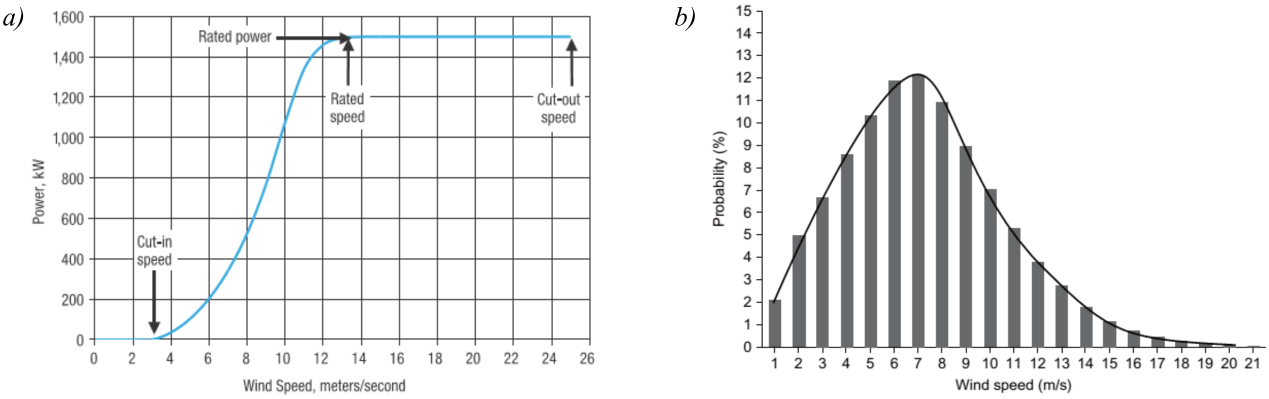

Fig. 8. Power curve for 1.5 MW wind turbine (a) [5]. The annual, hour-to-hour distribution of average wind speed for typical lowland area (b) [5]

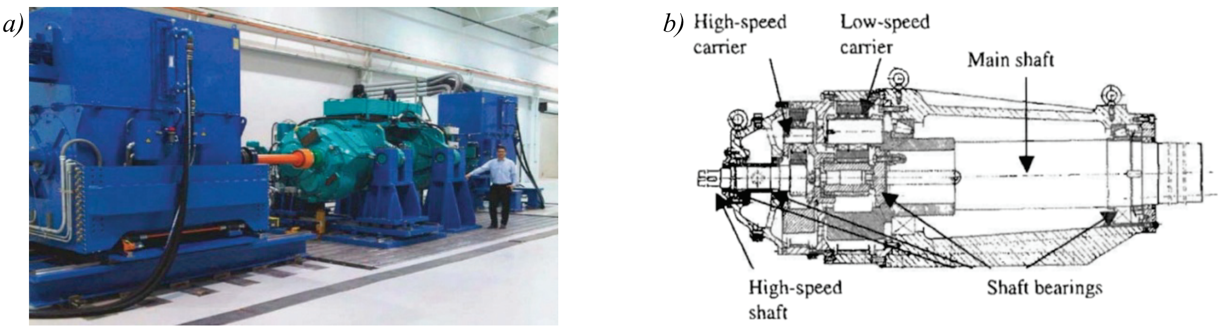

Fig. 9. Wind turbine gearbox on the test stand (a) [2]. Pertly integrated two-seed epicyclic gear (b) [5]

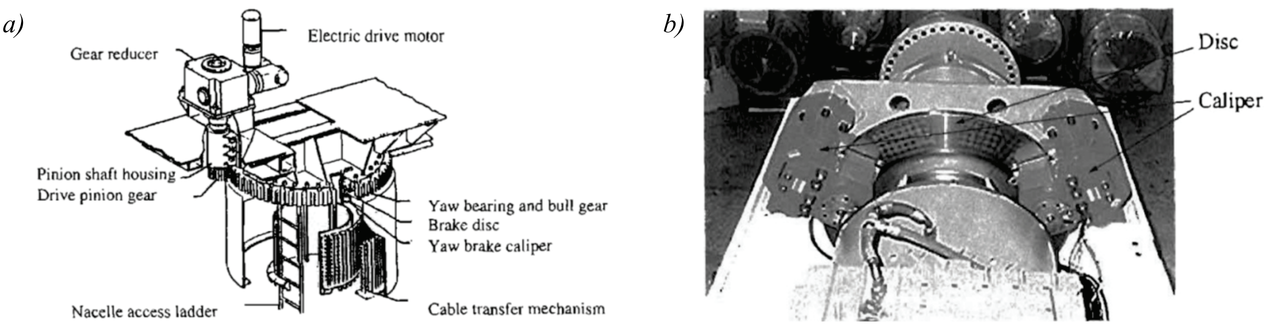

Fig. 10. Turbine nacelle rotation system with a brake (a) [5]. Braking system (b) [5]

The main differences in the approaches in wind turbines design are related to:

a) constant or variable operating speed,
b) direct drive or gearbox generators,
c) stall controlled or pitched controlled.

Wind turbine axle rotates at speed of 20 rpm or less. The aim of the gearbox is to increase of rotation speed up to 1200-1800 rpm, a speed that is better suited to generator operation. Changes wind conditions generates highly variable and difficult to predict high forces that place heavy load on the gearbox especially the bearings and the cogs. Some of the constructions utilize epicyclic gearing with planet gears turn around the sung gear, while others utilize worm drives, while manufacturers keep increasing the strength of gear wheels and bearings, gearboxes continue to require frequent servicing due to harsh operating conditions caused by variable wind loads. Gearbox repairs are among the most costly servicing actions. For example replacing damage gearbox in a large wind turbine generate an expenditure of up to 1 million Euro. Most of large wind turbines are equipped with hydraulic or pneumatic brake disc clamping system. Some of the turbines employ highly efficient braking systems; however, the standard solution is to switch to idle by using pitch change system and the braking system to stop only the rotor and preventing it from rotating freely.

3. Wind power plants generators and control system

An important part of the wind turbine is the generator converting mechanical energy to electrical. As the rotation speed of the generator increases, its size and weight decrease. The generators contain only one or two bearings, which are put under heavy load. Proper mounting of the generator shaft relative to the gearbox shaft is critical for the correct operation of the entire turbine system. Generators can be divided into three main groups:

a) induction generators,
b) permanent magnet generators,
c) synchronous generators.

In the past synchronous generators, ware rarely due to the necessity to adjust accurately to the frequency the electro energetic network. However, in recent years this type of construction successfully returns in turbines with a direct drive. In large-scale wind turbines, the most commonly used generators are induction generators producing alternating current (AC) of 50-60 Hz. The advantage of using induction generator is their simple construction and a certain flexibility in the rotational speed of approximately, which make it possible for the turbine system to adjust to occasional wind gusts. In the course of many years, the design of induction generators has undergone modifications, among which was the implementation of energo-electronic systems called power converters, which allows adjustments in the rotational speed. The power converters also synchronize the generators with the electro energetic grid.

Increasingly, utility-scale turbines have begun employing generators with permanent magnets. Permanent magnets used in modern generators designs are made of rare earth metals, which allows for the generation stronger magnetic field. The higher price of such materials is their major disadvantage. Despite the fact, permanent magnets generators are larger and more expensive than induction generators, their offer smaller power loss, increased reliability, and efficiency, even during operation under low load.

a) b)

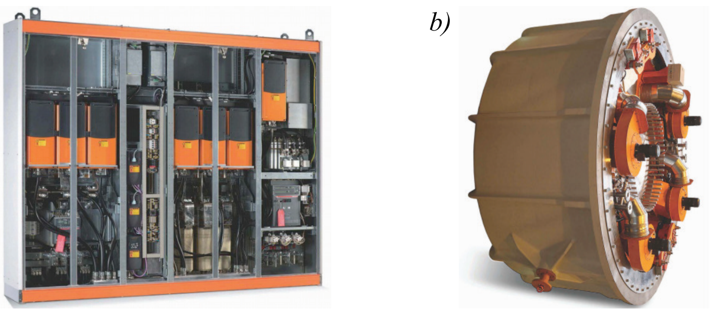

Fig. 11. Power converter (a) and permanent magnet generator (b) [2]

Nowadays, gearless transmissions are becoming increasingly popular. This trend is related to the fact that, apart from the torque, the transverse and lateral forces are also often relayed to the transmission through the main shaft [1]. Direct-drive generators are starting to be particularly popular in high power turbines at sea. This solution is beneficial due to the elimination of turbine gear servicing on marine farms where this operation can be complicated and time consuming. The lower rotational speed of direct-driven systems also increases the lifespan of the structure. The disadvantage of using direct drives and low speed generators is their resulting greater overall dimensions and hence the weight, which increases the cost of construction. Direct-drive turbines employ two-generator systems for low and high-speed operation. Another solution may be to use a variable speed generator. This, however, has its own disadvantages, because the result will be a variable current that forces the use of an AC-DC-AC converter, which again increases the cost of turbine production.

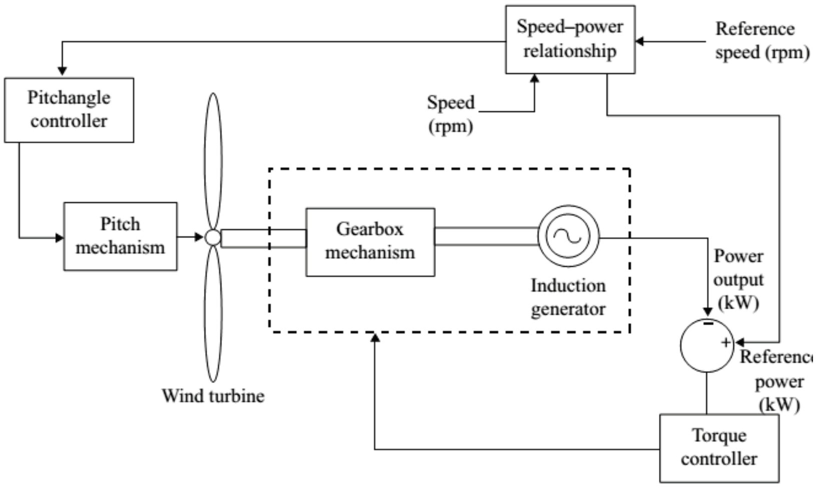

Fig. 12. A diagram of a variable-speed wind turbine with adjustable blade pitch [6]

Another important element of the wind turbine design is a control system integrating signals from many of the sensors installed on its components. This system optimizes turbine operation and ensures safety in the event of a malfunction or sudden deterioration of the weather conditions. The control system must continuously control many of the parameters responsible for the efficient operation of the turbine, such as:

a) positioning the blades in optimal direction relative to the wind,
b) setting the appropriate pitch of the blades,
c) starting and stopping,
d) energo-electronics,
e) cooling the components,
f) controlling the de-icing system,
g) diagnostics.

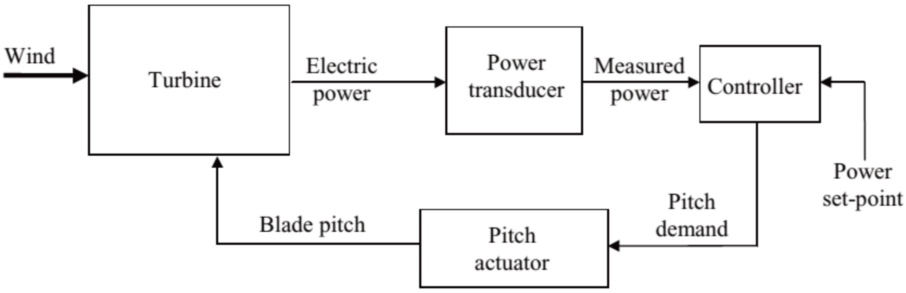

Fig. 13. A control loop for fixed-speed wind turbine with adjustable blade pitch [7]

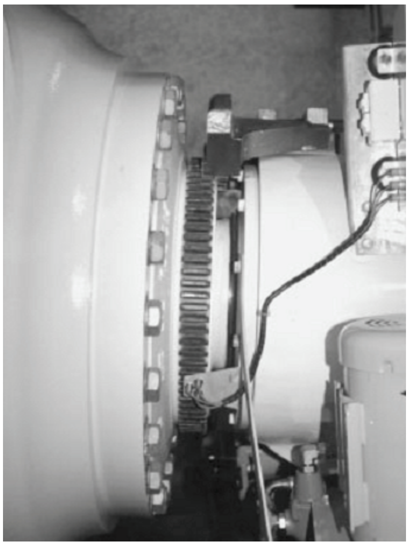

Fig. 14. A sensor system of a low-speed shaft collecting signals for the control and safety system [7]

4. Summary

Engineers are still working on improving energy conversion from wind. Many of the newly emerging concepts, though based on the ideas from decades ago, are only now able to materialize thanks to new materials and computer aided design tools. In parallel to the development of traditional solutions, innovative futuristic concepts are also created. Known as CWAT (compact wind-acceleration turbines), the concept is based on the known diffuser concept of increasing the wind speed before it reaches the rotor.

Wind turbines described in this article was designed for winds close to the earth's surface, at a height of 600 m above sea level; the wind speed is 2-3 times greater. Scientists wanting to take advantage of favourable winds think about hanging turbines even at the height of 9 km where there are fast moving air masses called "jetstream", and the air velocity reaches 65 m/s and power densities are in the range of 20,000-40,000 W/m^2 (at the ground level, the densities are around 500 W/m^2).

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