

# Wind Energy Conversion Systems and their use in Wind Systems

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## Abstract:

This article addresses some of the most widely used current solutions in wind generation systems, emphasizing the control fundamentals and design of individual applications of reduced power. The previous, oriented to small rural power systems or isolated, where the connection to the public electrical network is difficult or very expensive. The common elements and differences of the various existing proposals, advantages and disadvantages, their potential and what can be expected from their trends in the medium and long term are examined.

*Keywords* — Wind generation systems, control systems, wind turbines, generators, converters.

## I. INTRODUCTION

The problems of environmental pollution due to the burning of fossil fuels (coal, oil and natural gas) are already predominant issues in our society. Polluting gases cause global warming, acid rain and urban pollution problems. With the rapid increase in energy consumption, pollution is becoming a serious threat for the future. Emissions problems can be mitigated by the emphasis on environmentally clean renewable energy sources, such as hydraulics, wind and photovoltaics. The conservation of energy by the more efficient use of electricity and therefore a reduction in fuel consumption is not only a way to reduce environmental pollution, but also to preserve the dwindling fuel resources.

The wind is a source of renewable energy that is safe, environmentally clean and economical. The world has enormous resources of wind energy. Recent technological advances in wind turbines of variable speed, in power electronics and in machine drives have made wind energy a competitive form of energy, as well as the energy obtained from fossil fuels. Currently, wind technology is the fastest growing in the world [1, 2]. Germany is today the leading producer of energy from the wind with an installed capacity of 16,630 MW with more

than 15,000 turbines in operation [2]. It is followed by Spain with 8,260 MW. The USA is in the third place of world production with 6,740 MW of installed capacity, followed by Denmark with 3,120 MW and India with 3000 MW installed. Likewise, in Europe, Netherlands and the United Kingdom also have a strong development of the wind industry. Other countries with an interest in developing this type of energy, in an important way, are currently China and Australia [2].

## II. GENERATORS

The most frequent application of the wind turbines is the generation of electricity. For this, the use of an electric generator is essential. The most used structures in production systems of wind origin are shown below. All kinds of electrical machines can be used for the generation of wind power. Technical and economic factors define what type of machine should be used in each application. For small powers (<20 kW), the simplicity and low cost of synchronous permanent magnet generators (PMSG) explain their extensive use. In applications from 20 kW to 2 MW, the induction generator (IG) is more common and cheaper.

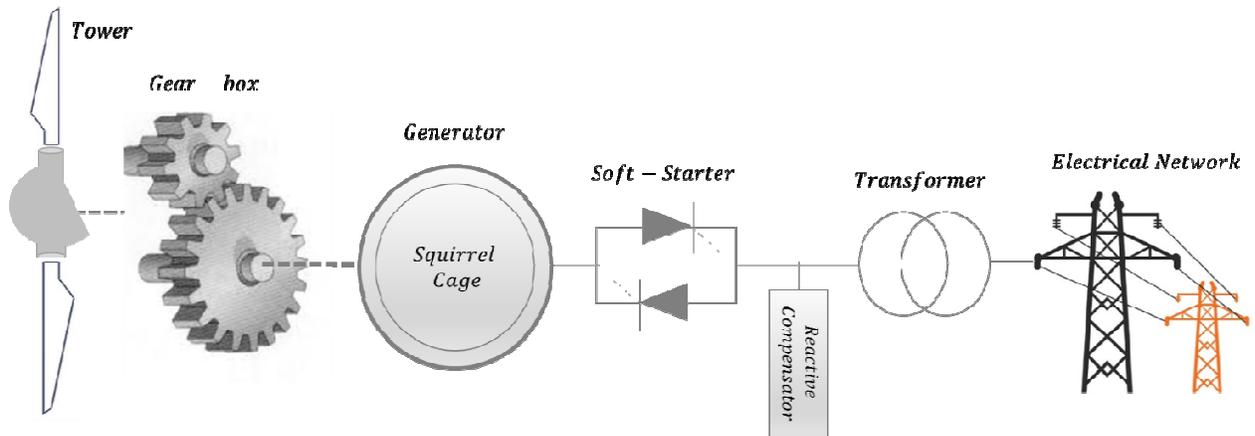


Figure 1. Wind conversion system with fixed speed SCIG

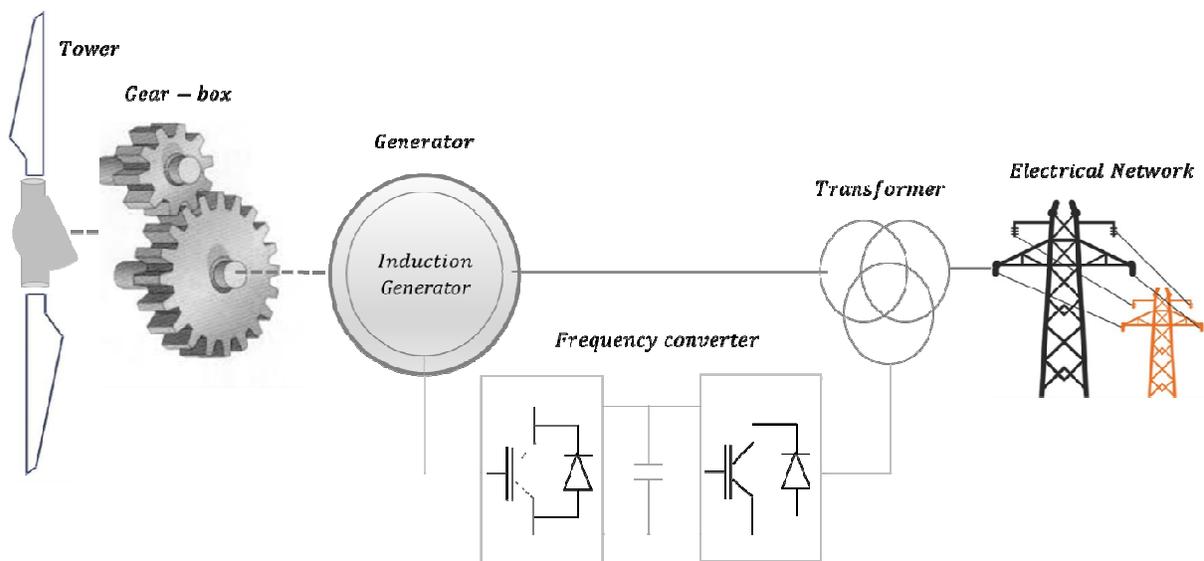


Figure 2. Wind conversion system with DFIG to variable speed.

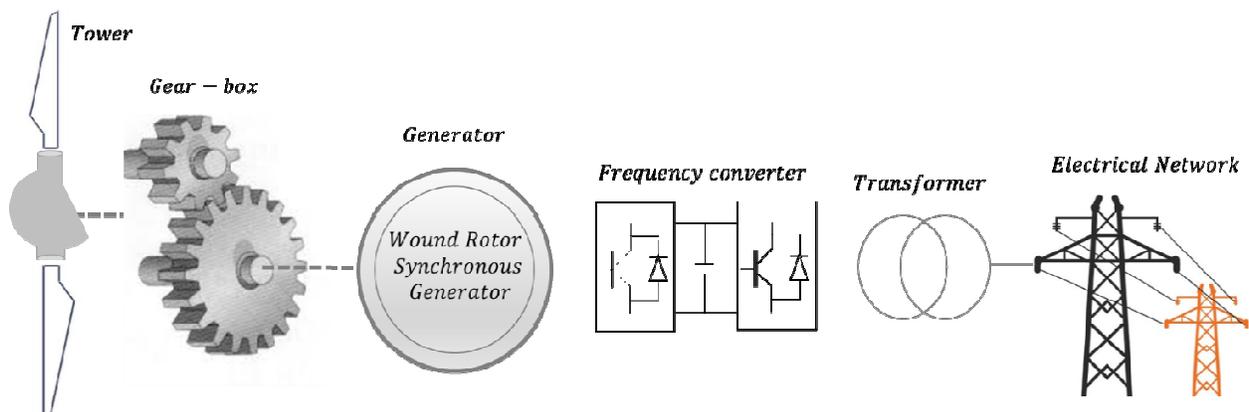


Figure 3. Wind conversion system with PSMG to variable speed.

### **A. Induction Generator (IG)**

The induction generator is widely used in medium and large wind turbines because it has the characteristics of robustness, mechanical simplicity and low price, for economies of scale, given its production in series. Its greatest disadvantage is the need for magnetizing reactive current in the stator.

#### *Squirrel Cage Induction Generator (SCIG)*

Until now, the SCIG is the prevalent choice due to its simplicity, high efficiency and low maintenance requirements [3]. The demand for reactive power is generally compensated by the connection of capacitors in parallel to the generator or by the inclusion of electronic power equipment, see Figure 1.

#### *Wound Rotor Induction Generator (WRIG)*

The rotor electrical characteristics of the WRIG can be controlled externally, so that the voltage applied to the rotor is materialized through a system of rings and brushes. Thanks to the electronic power equipment, the energy can be extracted or applied to the rotor circuit and the stator or rotor circuit can magnetize the generator. It is also possible to recover energy from the rotor circuit towards the output in the stator [3].

#### *Doubly Fed Induction Generator (DFIG)*

One of the fastest growing configurations in the wind turbine market is known as a double-fed induction generator (DFIG). This consists of a WRIG whose stator circuit is directly connected to the electric network and the rotor circuit connected through a voltage source converter (VSC) "back-to-back", which acts as a frequency inverter. The double feeding refers to the stator voltage is obtained from the network and the rotor voltage from the static converter. This system allows a variable speed operation in a wide but specific range. The converter compensates the difference between the mechanical and electrical frequencies by injecting a variable frequency rotor signal (see Figure 2). The advantages of DFIG are:

- It has the ability to control reactive power and decouple the control of active and reactive power through the excitation current of the rotor.

- It can be magnetized from the rotor circuit, without taking the necessary reactive power from the network.
- It is capable of producing or absorbing reactive power to or from the network for controlling the voltage.
- The size of the converter is not related to the total power of the generator, but to the chosen speed range. This implies that the cost of the converter increases when the speed range around the synchronous speed becomes wider. The disadvantage of this configuration is the need to use rings for the electrical connection of the rotor.

### **B. Synchronous Generator (SG)**

The advantage of the synchronous generator over the IG is that it does not need reactive magnetization current. The magnetic field of the synchronous generator can be created by permanent magnets or by conventional excitation winding. If the generator has a sufficient number of poles, it can be used for direct-drive applications that do not require a gearbox. It is probably better adapted for indirect connection to electrical network by means of an electronic power converter, which allows operation at variable speed, see Figure 3. For small units the use of the permanent magnet generator is simpler and cheaper. Over this power, the synchronous machine is more expensive and complicated than an asynchronous generator of equivalent size. [3].

#### *Wound Rotor Synchronous Generator (WRSG)*

The operation by direct connection to the electrical network causes the WRSG to rotate at a fixed speed, given by the network frequency and the machine poles number. The excitation is performed by the system of rings and brushes or by a brushless system (brushless) with a rotary rectifier. The multipolar system without gears of the operation at variable speed - indirect connection to the network - involves the use of a bulky and heavy generator and an ad hoc power converter equivalent to the total power of the system.

#### *Permanent Magnets Synchronous Generator (PMSG)*

The property of auto-excitation of the generator to permanent magnets, allows the operation at a high

power factor, with high efficiency, making it suitable for application in wind generation systems [3]. In fact, in the range of small turbines, its low cost and simplicity make the PMSG the most widely used. However, in higher power applications, magnets and the need for a static converter capable of handling all the power of generation make it less competitive.

#### *Others Generators*

Because the wind turbines connected to the power grid usually require a step-up transformer, the use of high-voltage generators is being evaluated, which, for the same power value, allows reducing the currents and consequently the losses  $per I^2R$  in the rotary machine as in the transformer. For this alternative, synchronous and induction structures are interesting options for wind turbines of more than 3 MW, although their high cost, safety and life-time problems limit their commercialization [3]. The characteristics of the switched reluctance generator (SRG) are the robustness, simple structure, high efficiency, reduced costs and the possibility of eliminating the gearbox [3]. However, its adaptation to wind turbines has not been studied in detail. It would have the disadvantages of having a lower power density and lower efficiency than a PMSG, and would need a converter that works at full power. The use of the transverse flow generator (TFG) is also under study. This would be an interesting alternative that, however, would still be insufficiently studied for its application in wind generation systems. It would allow a significant number of poles, for an application without a gearbox, but the significant number of components and a technology not yet developed limit its current use [3].

### **III. WIND TURBINE APPLICATIONS**

Unlike what happened in past centuries, the need to install wind systems directly where they were needed has disappeared. Except for a few special cases, wind turbines are currently used primarily for the generation of electric power [4]. When generating electricity, the possibilities for the use of wind energy are almost unlimited. Individual wind

generation systems (stand-alone) that supply energy to small communities are becoming more frequent. The intermittent wind characteristic gives rise to hybrid systems with diesel and/or photovoltaic backup for application in remote areas. As higher power applications, the turbines can be grouped into arrays (wind farms), transferring power to a power network through their own transformers, transmission lines and substations. The tendency of these parks is to move towards marine facilities (offshore).

#### **A. Stand-Alone Conversion System and its use in Wind Energy**

Isolated power systems that use wind technology and other forms of renewable energy are emerging as technically reliable options for energy supply. These systems are generally perceived as more suitable for local power feeding in developing countries, but the technological developments involved in them have considerable potential as distributed generation elements for large power networks in the first world. In recent decades, there have been considerable efforts at national and international level to implement wind power in local and regional power systems through the integration of small and medium-sized distribution systems [3].

Considerable works have been published and there is abundant literature on this. However, as the study and development of wind systems for isolated clients has been carried out mostly case-by-case, it has been difficult to extend the results from one project to another. In the area of rural electrification, there are usually two major methods of energy supply:

- Extension of the power network and
- Use of diesel generators.

In remote areas, both options can be overly burdensome. Therefore, the inclusion of renewable technologies can reduce the cost of providing energy

to these areas, because of the reduction of updated operating costs. Renewable technologies, other than biomass, are dependent on a resource that is not dispatchable; so the combination of a low cost renewable technology with a more expensive dispatchable technology provides a more applicable alternative. Power systems that use multiple sources of generation are better referred to as "hybrid power systems". These can incorporate different components such as production, storage, power conditioning and control system to supply energy to a remote community.

Classic hybrid systems include both a direct current (DC) bus for the battery bank and other alternating current (AC) for the generator and distribution. However, recent advances in power electronics and control systems are making AC single-bus systems more cost-effective. Renewable technology can be connected to either the AC or the DC bus, depending on the size and configuration of the system. Power systems feeding more than one house or several points normally provide AC power, although some loads can be connected to the DC bus. These systems can provide from a few kilowatt-hours (kWh) to several megawatt-hours (MWh) per day. Systems that feed small loads, of the order of a few kWh per day, preferably use only the DC bus, while for larger loads; there is a tendency to use systems where the AC bus is the main connection point. Recent advances in the fields of power electronics and control systems have allowed the development of smaller devices connected to the AC bus. Each DC production device includes its own power converter with integrated control, which allows the coordination of production. Each configuration can vary considerably.

#### *Hybrid systems*

In systems that rely on a DC bus, the battery bank plays the role of power container, smoothing short and long-term fluctuations in the load flow. The regulation is carried out almost by itself, based on some specific parameters of the battery. For AC systems, the goal is to achieve a balance of energy production, regulating voltage and load. To achieve an electrical signal of stable voltage and frequency,

various advanced technologies are used, including synchronous capacitors, dispatchable load banks, storage mechanisms, power electronics and control. In some cases, small wind turbines, both mechanical and electrical up to 20 kW, are connected to the power (load) devices directly. The most common are for pumping water, although other applications have been considered, such as ice making, charging batteries and compressing air.

#### *Hybrid DC systems for Small Remote Communities*

Figure 4 shows a small conventional DC power system with AC power through a power inverter. Most of these systems have a structure in which the DC bus of the battery is the central point of connection. In general, small wind turbines generate variable frequency AC voltages and currents that are rectified and applied to the DC bus. Then, the energy is stored or converted into AC (regulated) through an inverter to feed the load. The control of these small power systems is carried out according to the battery voltage. The wind generator must limit its voltage or divert the power generated when the battery is fully charged and cannot accept more power. The inverter and the load must be disconnected in order to stop the discharge of the battery when the voltage falls below a preconceived limit. Both actions involve a careful design of the system, in order to optimize energy resources and obtain a minimum amount of energy not supplied.

#### *Hybrid AC systems for Small Remote Communities*

The new topology that uses DC or AC generation components is viable given the recent advances in converters and their control. The different generating sources are connected to the common distribution bus AC through dedicated inverters, see figure 8. The main advantage is modularity, as it allows the connection or replacement of modules when additional energy is required. It also allows the installation of the components anywhere in the micro-network, which is not possible in the system with DC bus. However, there are disadvantages: its cost is high and it requires sophisticated technology, which makes its application in remote

areas difficult. In addition, when storing energy, it must pass from

the generation point to the AC bar and then the battery rectifier; this implies that in systems with significant amounts of storage, this structure has greater losses.

#### Wind-Diesel Hybrid Systems

In large isolated power systems, AC distribution is used incorporating both wind turbines and diesel generating machines. A wind-diesel system provides power using wind energy to reduce fuel consumption, safeguarding an acceptable supply quality. To be economically viable, the investment in extra equipment, required to take advantage of wind energy, must be recovered through savings in fuel and other benefits. Due to the large number of isolated mini-networks whose primary energy is diesel oil, existing both in the first world and in developing countries, the market for retrofitting these diesel systems to hybrid systems with renewable sources of low-cost energy - like wind power - it's substantial. One of the challenges posed by the incorporation of wind energy in diesel plants is the difficulty of controlling the tension and frequency of the system, because the production of wind turbines is determined by random wind conditions. This leads to distinguish two concepts that strongly influence the design of the system and its components, they are: the amount of energy expected from renewable sources (system penetration) and the ability to maintain the balance of power - production and demand - of the system.

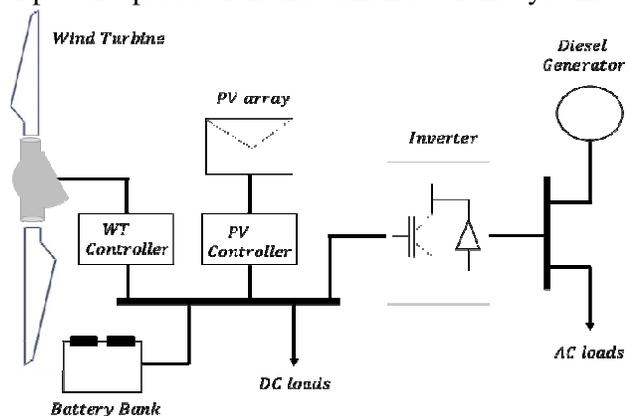


Figure 4. Renewable power system with DC bar.

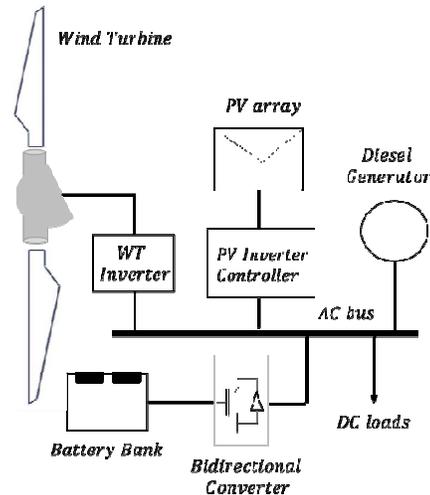


Figure 5. Renewable power system with micro-grid.

#### Penetration of the wind

By incorporating technologies associated with renewable energy sources in isolated power systems, the amount of energy obtained from renewable sources will influence the layout, performance and economy of the system. Instant penetration ( $P_{wind}/P_{load}$ ) is a technical measure that determines the layout, components and control principles to be applied in the system. The average penetration ( $E_{wind}/E_{load}$ ) is a measure of economic type that determines the cost of the energy of the system, and indicates the percentage of the total generation that will come from the renewable source. The optimum level of wind penetration depends on the relative difference of the cost of increasing the wind power - with the consequent increase in complexity - and the saving of replacing fuel with renewable resources.

#### A. Wind Systems connected to Large Power Networks

More than 95% of the world's wind energy capacity is connected to large power networks. The foregoing is explained by the fact that the operation of wind power plants in large networks has several important advantages [4]:

- The output power of wind turbines does not need to be controlled in accordance with the instantaneous power demand of some specific consumer.
- Conventional power plants compensate the lack of power delivered by wind turbines.

— The frequency of the large networks is also maintained by the other plants and can be used to control the rotation speed of the wind turbines. Therefore, the operation of wind turbines in parallel to the power network is technically less complicated than its isolated individual application.

#### *Distributed systems*

The operation of only one or a few wind turbines by private or industrial consumers was the first field of application that achieved commercial status. First in Denmark, where legislation, public subsidies for wind power generation and technical expertise in the construction and operation of wind turbines made this development possible since 1978. Since the 1990s, wind turbines in Germany have experienced a significant growth thanks to a law that stimulates electricity generation through renewable means [4]. The distributed installation of turbines is carried out almost exclusively in connection with the network of electrical companies. The user's consumption is recorded by the normal meter and the power produced by the wind turbine is injected into the network and registered through another meter. In this way, billing is done separately, according to consumption and energy production.

#### *Wind Farms (On-shore)*

Even considering the largest current turbines, with a nominal power of several megawatts, the power output of a single turbine is a small amount compared to the powers of a conventional power plant. On the other hand, in most countries, areas with technically usable wind speeds are restricted to some regions. This creates the need to group as many wind turbines there as possible, regardless of the local energy demand. Thus wind farms or wind farms are born, which consist of concentrations of numerous wind turbines in spatially interconnected and organized groups. The fact of doing this grouping offers considerable technical advantages. Also from the economic point of view, it is more efficient, in terms of installation costs and with respect to the cost of connection to the network, since long lines of interconnection with the

network are only justified for a relatively large number of

turbines. Between 1982 and 1985, the first large wind turbine arrays were made in the state of California, with small power units between 20 and 100 kW. In Germany, the use of wind energy has been based from the beginning on the installation of large and numerous turbines. The wind farms of several output megawatts are already part of the energy matrix of many countries, so this contribution cannot be looked at less [4].

#### *Wind Farms (Offshore)*

It is expected that in the next decade 25% of the installed capacity will come from the wind [2]. However, finding places for large farms is not easy. The development of systems in the sea (offshore) avoids the conflicts of the sites on land. There is also the advantage of having more consistent and less turbulent winds, which implies greater energy production with less mechanical stress in the turbines. Advances in technology make this alternative increasingly attractive. The current conditions necessary for the installation of marine farms are:

- Moderate height of the waves
- Shallow waters and
- Average wind of about 7 m/s[2].

Denmark is a pioneer in the development and implementation of this type of technology, and in 1991, it erected the first of these farms in Vindeby, composed of 11 turbines of 450 kW each. In addition, the two largest marine parks in the world are also Danish, Horns Rev entered into operation in 2002 and Nysted in 2003 with 160 MW of installed power the first (80 units of 2 MW) and 162.5 MW on second (72 units of 2.5 MW). These facilities involve approximately 600 MWh of annual energy in each park [2, 4]. Europe expects to supply 10000 MW in this way within 5 years, where Germany alone aims to reach 3500 MW by 2010. Ireland already gave the go-ahead for the construction a 520 MW park with 200 turbines in the Irish Sea. For its part, the US plans the installation of its first offshore farm of 420 MW and

130 units in an area of 65 km<sup>2</sup> in Massachusetts, to produce an average of 170 MW.

#### IV. WIND TURBINES CONTROL

The typical power curve of a wind turbine is shown in Figure 9. The system begins to generate when the wind speed reaches a threshold  $v_{cut-in}$ . This depends on various factors according to the conversion structures used. Then, the power increases until the nominal values of wind ( $v_N$ ) and power ( $P_N$ ) are reached. This wind value depends on the design of the system and is normally chosen between 11 and 15m/s. Between the nominal speed and the output speed ( $v_{cut-off}$ ), the wind turbine produces the nominal power. Beyond  $v_{cut-off}$ , the turbine can not continue to produce for safety reasons. The power generated by the turbine must be regulated, when exceeding the nominal wind speed, since the wind energy for winds higher than this level is greater than what the system can support. The most common methods of regulating the power are:

- The control of the angle of the blade (*blade pitch control*)
- The control at a fixed angle (*stall control*)
- The active control of the fixed angle (*active-stall control*)
- The orientation control (*yaw control*).

##### B. Rotor Aerodynamic Control

The expression of wind power (1) is widely known and used:

$$P = \frac{1}{2} \rho A C_p v^3 \quad (1)$$

Where  $\rho$  is the air density,  $A$  is the swept area of the blades,  $C_p$  is the power coefficient and  $v$  the wind speed. Without further indications, it is not evident any degree of freedom to think about realizing a control of the power of the wind turbine. However, when examining the power coefficient, it is verified that it is not a constant and depends both on the wind speed and on the turbine's rotation speed [1, 4]. The  $C_p$  has a non-linear behavior with respect to the speed ratio of the turbine (tip-speed ratio) and is characteristic of each type of turbine. Figure 9

shows the evolution of the  $C_p$  according to the type of turbine.

The expression of the tip-speed ratio is  $\lambda = \Omega R / v$ , where  $\Omega$  is the rotation speed of the turbine and  $R$  is the blade radius. The most commonly used control methods in medium and large wind turbines are shown below.

##### Blade Pitch Control

The control type most used in medium and large wind turbines is the control of the blade angle (blade pitch control). This makes an adjustment of the wind incidence on the blades, which modifies the angle of attack and the amount of power extracted by it. This control is carried out in accordance with the value of the wind measured.

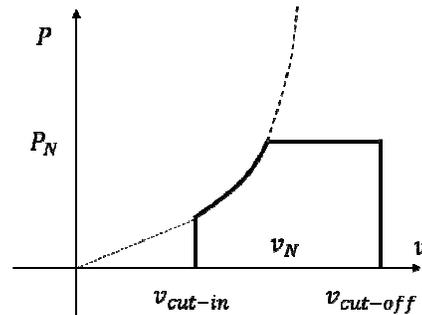


Figure 6. Typical power curve of a wind turbine.

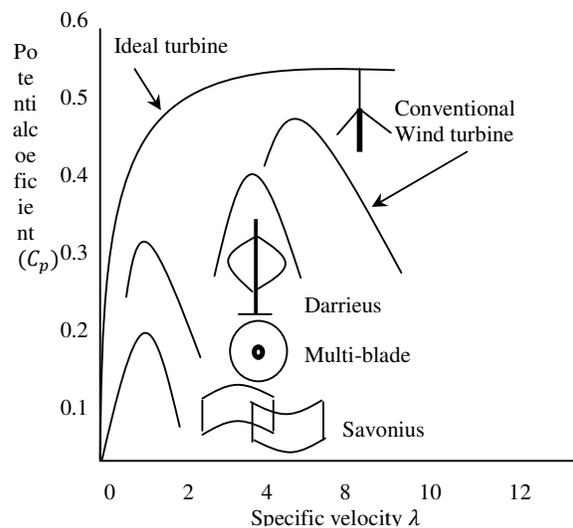


Figure 7. Power coefficients of wind turbines of other designs

With respect to the aforementioned power curve, with this type of regulation between the threshold and nominal wind speed, the control adjusts the angle of the blade to its optimum value, thus obtaining the maximum wind power. When exceeding the nominal speed, the control changes the angle of the blades in order to reduce the performance of the rotor, deriving the excess power by aerodynamic loss.

#### *Passive-Stall Control*

This type of regulation (stall) is carried out by means of the appropriate design of the profile of the blades. When the wind speed exceeds the nominal value, the air flow on the upper side of the blade tends to lose speed, which creates turbulence, causing a loss of aerodynamic lift on the blade and therefore, the dissipation of excess air. The control by adjustment of the blade angle (pitch) allows a more effective capture of the power at moderate wind by the ability to adjust to the optimum angle. However, movable parts must be introduced to make the adjustment which results in a disadvantage. In addition, the control system needs to have a high sensitivity with respect to wind variations, which increases costs. On the other hand, the stall control does not need any control system or adjustment mechanism. However, the blades must be specially constructed and for this a certain level of sophisticated technology is necessary. Also, without a careful aerodynamic analysis, vibration problems can occur [1].

#### *Active-Stall Control*

The most modern and high capacity turbines take advantage of both types of control already mentioned. With this method (active stall) the blades are oriented to obtain the best performance in light winds as the blade pitch control, but when reaching the nominal speed, the blades are oriented on the opposite side, forcing to enter the stall area, equivalent to stall control.

#### *Orientation Control*

Another method of power regulation is to partially orient the wind turbine away from the wind

direction for high wind speeds. This is called orientation

control (yaw control). For winds greater than  $v_{cut-off}$ , the position of the rotor is perpendicular to the wind, canceling all generation. The latter is called "furling". However, by partially orienting the rotor, important mechanical forces are created in the turbine that limit the application of this type of control, only, to small turbines.

#### *C. Electric System Control*

When consulting the specialized literature, it can be noted that the control is preferably carried out by the mechanical aerodynamic means indicated above. However, when reviewing the concepts of wind energy conversion, it is evident that another way to achieve the regulation of the power produced is by controlling the rotation speed of can be seen as a regenerative drive of a fan. Therefore, as seen in section 3, it is possible to make various configurations, with both induction and synchronous machines. This is where the area of electrical engineering machine drives is incorporated. For several decades now, this discipline has developed different forms of speed control, many of which are applicable to wind energy conversion systems. Below is a summary of some of the methods used and the latest trends in this regard, especially for small systems.

#### *Fixed/Variable Speed Systems*

Traditional systems typically operate at a fixed frequency, imposed by the power network to which they are connected. When working at constant frequency and therefore at fixed rotation speed, they have a single point of operation where they get the most out of the wind energy. Throughout the rest of the speed range, energy capture is sub-optimal. Variable frequency systems have several important advantages:

- The reduction of mechanical stresses in the power train,
- A better quality of the output power,
- Lower noise emissions and
- A greater energy capture [5, 6].

These use static converters that allow the conversion of variable frequency/voltage to fixed frequency/voltage for the connection to the network or to the power system they feed. Although the latter are more expensive, the improved energy capture means lower life costs.

*Variable Speed Systems with Adjustable Blade Turbines*

As already noted, blade adjustment control is based on the loss of aerodynamic power. In Figure 8 it can be seen that there is an optimal power value for each value of the angle of the blade, however, for angles other than the optimum, always the power generated will be less than the actual maximum. From the same figure it can be inferred that there is a single point where the power coefficient is maximized globally, for the optimum blade angle, which means that there is an optimal value of rotation speed for each value of the wind speed. Therefore, for smooth winds ( $v - v_N$ ), the control of the rotation speed of the system allows to help the pitch control in the following way: the angle of the blade is left in the fixed value that maximizes the aerodynamic efficiency (optimum angle), and the control of the electric machine can follow the optimal  $C_p$ , thus generating the maximum possible power for each wind value [7]. The control of the generator is much faster than the movement of the angle of attack of the blades, which also allows to handle fast variations that the system with pitch regulation cannot.

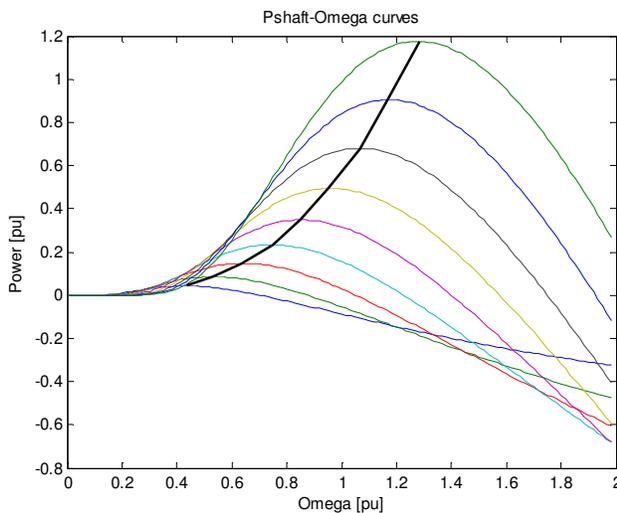


Figure 8.  $C_p$  in function of  $\lambda$  for angles different of the blades.

The previous thing, as much to avoid sudden changes in the rotor, which implies strong mechanical loads and wear of the material, as to take advantage of the energy that normally would be lost by the slowness of the adjustment of the blades. With respect to the operation at high wind speeds ( $v - v_N$ ), the fact of maintaining a fixed and regular angle only by speed implies the appearance of instability problems. The regulation of the system can be done by keeping the generator in a fixed operating point and leaving only the mono-variable pitch control. But this solution is detrimental to the dynamic response of the system. When acting together (control of generator and blade angle), which implies the use of uncoupled multi-variable control, good regulation is achieved, both the power and the speed of rotation. Figure 10 shows the control scheme proposed by [7].

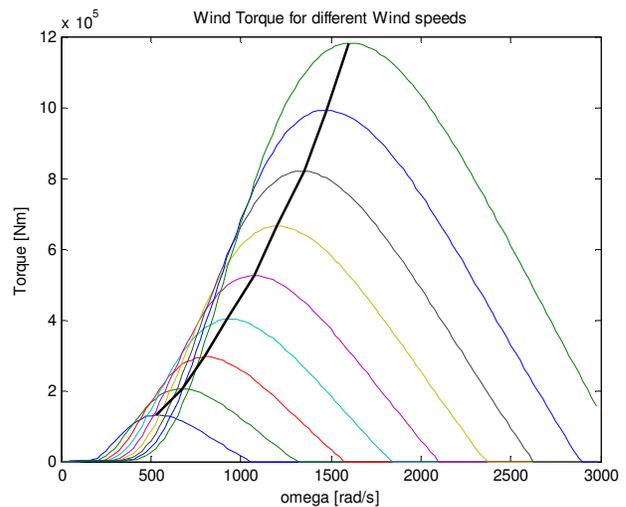


Figure 9. Wind torque for different wind speeds.

*Variable Speed Systems with Fixed Blade Turbines*

Schemes with a fixed blade angle (stall or single pitch), where the control of the generator makes the regulation, are possible both for individual AC systems [8], and for weak power systems [9] or for the connection to the power network [5, 10] just to mention a few. For these systems of medium to large size, various control structures have been developed. Some are based on schemes that combine linear and non-linear control

[9] or more sophisticated schemes such as fuzzy logic [5, 8] or designs based in energy [11].

Most use different stages, first to obtain or calculate the reference of the speed of rotation of the system and then for the control of the machine itself. Like the  $V/f$  or vector control for the induction machines and the  $dq$  control for the synchronous generators.

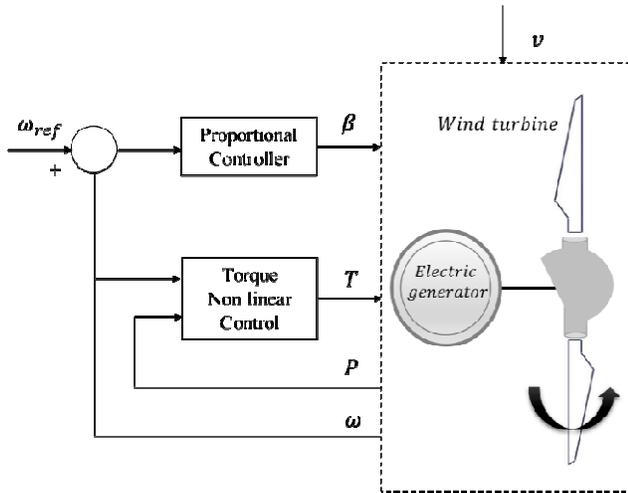


Figure 10. Example of multi-variable control proposed by Boukhezzer.

Several systems avoid making the wind speed measurement to avoid costly anemometers. In this way they use the optimal relationship between the speed of rotation of the machine and the power to produce, in order to make the comparison and correct the difference [5, 9]. Below is this relationship:

$$\lambda^* = \frac{\Omega^* R}{v} \rightarrow v = \frac{\Omega^* R}{\lambda^*}$$

$$P_{MAX} = \frac{\rho A}{2} C_p(\lambda^*) \cdot v^3 = \frac{\rho A}{2} C_p^* \cdot v^3 \quad (2)$$

$$\rightarrow P_{MAX} = \frac{\rho A}{2} C_p^* \cdot \left(R \frac{\Omega^*}{\lambda^*}\right)^3 = \frac{\rho A}{2} C_p^* \left(\frac{R}{\lambda^*}\right)^3 (\Omega^*)^3$$

$$\rightarrow P_{MAX} = k \cdot (\Omega^*)^3$$

In small wind turbines the adjustment mechanism of the blade angle is very expensive and is not justified. Consequently, the regulation of low winds, if any, is carried out by electrical means [12-

15]. Stall loss limits the power for high wind speeds for schemes with HAWT. For the VAWT, the regulation is continued through the control of the generator. Preferably, alternators are used to multipole permanent magnets that do not require a gearbox.

Although structures can also be found at controlled excitation, by rotor winding, [12]. Normally they are connected to banks of batteries, reason why they realize the control with respect to the DC voltage.

The control is designed to locate, in some way, the point of maximum power transfer. This is done following the point of  $\lambda^*$  (or  $C_p^*$ ), for light winds and then regulating the output when reaching nominal power. To achieve the above, intelligent structures are used that allow both types of control. Mainly programmable systems such as microcontrollers ( $\mu C$ ) and digital signal processors (DSP). The control variable commonly used is the duty cycle of some DC/DC power converter, either to impose a certain voltage on the generator's stator terminals [14, 15] or by excitation of the rotor circuit [12]. You can also find structures that regulate through the firing angle of a bridge rectifier to thyristors [13]. The optimal power ratio versus rotation speed (2), thus avoiding the use of anemometers. Some come to model the electrical system to obtain an optimal relationship between DC voltage and rotation speed [15]. The measurement of the rotation speed is done either by tachometer or by measuring the electrical frequency of the output signal of the generator. The basic schemes of the previous low power systems are summarized in Figure 11-14. Small wind systems without electrical regulation (only stall) and directly connected to battery banks are also used. These open loop systems are specially designed for the turbine-generator-battery set to produce maximum power without the use of feedback control.

## V. TRENDS

In addition to the installation of large offshore parks and the manufacture of increasingly larger machines, various research projects covering all relevant aspects of wind technology are being carried out. The above puts the hopes in developments of new designs that make this

technology a more attainable tool and therefore more competitive in the energy market.

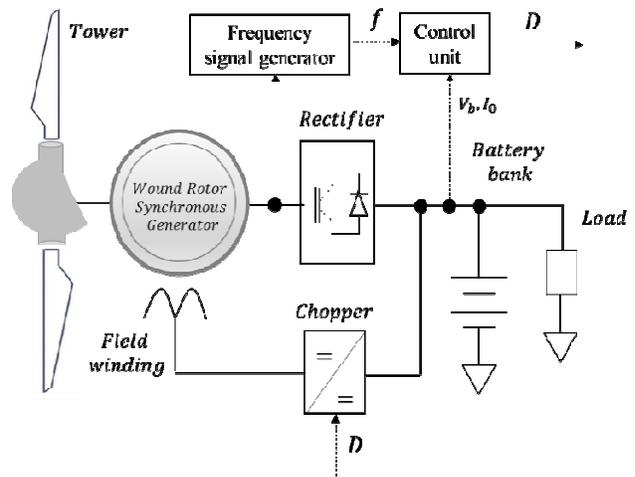
**D. The Mechanical System**

New types of gears, such as multi-stage planetary gearboxes and helical stages, are in development.

These should be translated into high efficiency systems with high mechanical powers. Higher values of torque and rotation speed imply more optimal electromechanical conversions in the higher speed generators. The design and manufacture of blades that incorporate advanced lightweight materials such as carbon fiber and hybrid carbon / glass compounds are being investigated. Although more expensive than commonly used fiberglass, carbon fiber is much stronger and lighter. Multi-MW turbines have generalized both the use of steel and concrete towers and the use of new production methods to reduce manufacturing and transportation costs.

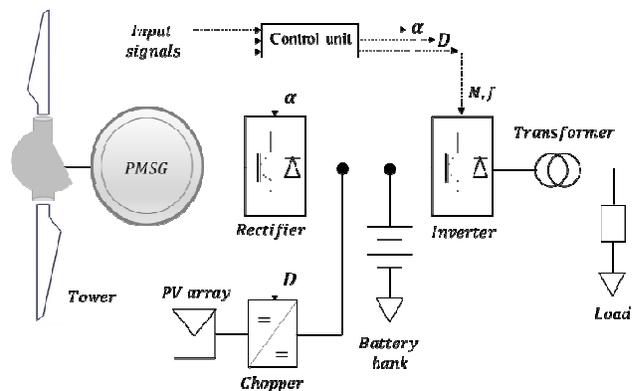
**E. The Electrical System**

New types of generators, including multi-pole configurations and high voltage, switched reluctance, axial and transverse flow machines, are being developed to reduce mass and improve generator efficiency. In order to reduce costs and increase efficiency, new improvements are frequently being made in the conversion of energy by electronic power components. In this context, new electronic power devices are being studied to explore the possibility of replacing silicon with silicon carbide (silicon carbide). The latter has the advantage of handling voltages and high currents and withstanding higher temperatures. The previous thing would allow to reduce the size of the power converters and make them more competitive.



**Figure 11.** Simplified diagrams of the structures applied to low power systems proposed by: Ermis, et. Al., (1992).

The use of medium voltage components to reduce the cost of conversion systems in large wind turbines is also studied.



**Figure 12.** Simplified diagrams of the structures applied to low power systems proposed by: Borowy and Salameh, (1997).

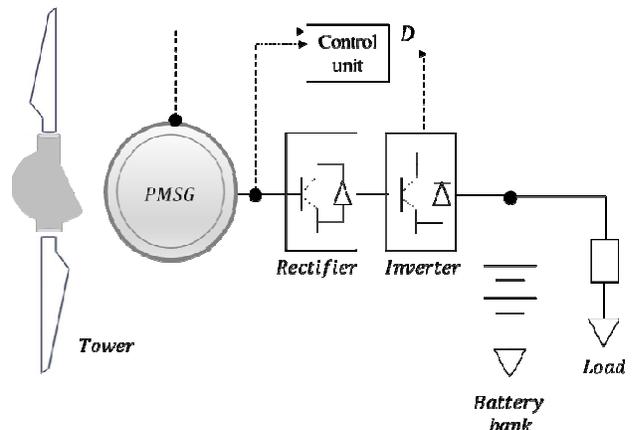


Figure 13. Simplified diagrams of the structures applied to low power systems proposed by: De Broe, *et. al.*, (1999).

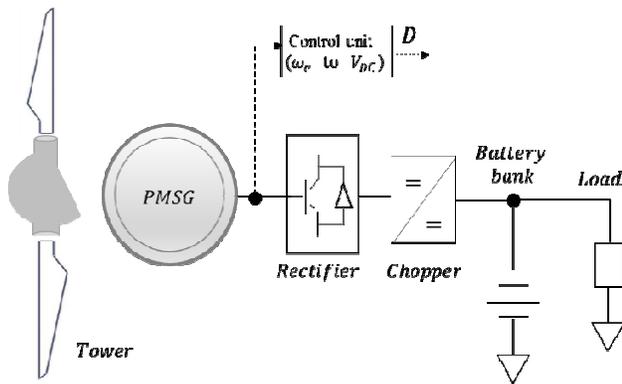


Figure 14. Simplified diagrams of the structures applied to low power systems proposed by: Knight and Peters, (2005).

Currently, various topologies of electronic power converters, of several megawatts, are being developed to provide a power conversion that is cost-efficient, has high reliability and a high-quality standard [2].

#### F. Integration of Wind Power and New Applications

Aspects such as the wind speed forecast and consequently the estimation of the amount of power contributed by the wind farms, will allow to predict with greater precision the value of the electricity produced by these. The above will help planning, programming and coordination of the generation with the demand of the system and, consequently, with the power supply contracts. Accurate models can ensure the success of these developments and get the most out of minimal risks. The rapid increase in wind penetration in the power grid presents major challenges for system operators. The productivity of wind farms fluctuates over time, while the electricity grid must maintain a constant balance between supply and demand. Currently, many studies are being carried out on the effects of this stochastic energy on the regulation and stability of the power system. The previous thing in order that the operators and planners of these systems feel with more confidence and knowledge about the impact associated to the increase of the energy of the wind in the network. One way to provide cheap

electric power and stabilize the operation in a network with wind production, is achieved by combining the use of wind power with hydraulic. In this sense, important investigations concerning the generation, transmission and economy of these integrated systems are being carried out. In addition to the applications in heating and pumping already in use, the exploration of new markets such as desalination systems, hydrogen production, etc., will open new opportunities for the use of clean energy at low cost in several other sectors, including water and transport systems.

## VI. CONCLUSIONS

Wind energy conversion systems have evolved, improving their performance and efficiency, reaching a capacity regime for the use of the kinetic

energy of the wider wind through the design of aerodynamic rotors and appropriate use of orientation systems and Blade Pitch Control. This paper provides an overview of the different applications that wind energy conversion systems can offer to wind systems. First, the different types of generators are described with their advantages and disadvantages, from which it is known that the DFIG is still the most used generator concept in high power wind systems, while the PMSG is preferred on small wind turbines. These wind turbines are currently used primarily for the generation of electric power, and the use of these systems to supply energy to small communities is growing. Several possibilities are exposed in this paper including the wind energy system as a stand-alone conversion system and hybrid systems as well. Nevertheless, the majority of the installed wind systems are connected to the large power networks. The survey made has led to the conclusion that several research projects related to the wind systems technology are being carried out with the aim to increase their efficiency, generate more power, reducing costs, without giving up on reliability. Likewise, the development of topologies of electronic power converters based on emerging electronic devices has allowed a better management and support of the energy generated and supplied to

the electrical network in local and regional power systems.

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