Abstract- This paper addresses the topic of technology, control and reliability of wind energy systems. The paper presents the major constituents of wind energy systems, and the main types of control, such as stall, pitch and yaw. Probabilistic indexes are used to assess the reliability of the wind energy system, such as LOLP (Loss of Load Probability) and LOLE (Loss of Load Expectation). Finally, conclusions are drawn.

I. INTRODUCTION

In recent years it has been observed a significant increase in the use of renewable energy for several reasons: growth in energy consumption, economic, but mainly by environmental issues.

With the application of renewable energy sources, a decrease in the use of fossil fuels for power generation is expected, consequently reducing the greenhouse effect. This incorporation of renewable energy aims to deliver what was specified in the Convention on Climate Change in 1997, known as the Kyoto Protocol. The aim is to reduce emissions of greenhouse gases into the atmosphere at 5% compared to 1990.

Portugal is a country that has a considerable external dependency in terms of primary energy, higher than the EU average and similar countries.

It is therefore important for the country to develop alternative forms of power generation that do not contribute to emissions of pollutants into the atmosphere.

One of the most important power generation technologies today is wind power, reducing environmental problems. With the implementation of wind farms, power generation is much cleaner compared to other means to generate electricity.

In addition, energy from wind is inexhaustible and available globally. It is an indigenous resource, so its use can play a decisive role in reducing dependence on foreign energy and balance the energy bill.

Wind energy contributes to the diversification of energy sources and promotes decentralized power generation. This is reflected beneficially on system performance of the distribution of electricity, improving security of supply, increasing reliability and reducing losses.

This paper presents the main constituents of wind technologies, as well as its various main types of control. In addition, with the increase of installed wind power capacity, it becomes necessary to study the impact this has on the reliability of the electric energy system. Accordingly, a probabilistic example using indices LOLP (Loss of Load Probability) and LOLE (Loss of Load Expectation) is considered.

II. WIND ENERGY SYSTEM: TECHNOLOGY

A wind energy system can be considered isolated, hybrid, or connected to the network. This paper addresses mainly the wind energy systems connected to the network.

A wind energy system consists of several components that must work in perfect harmony, in order to achieve a greater final yield (Fig. 1).

![Wind energy system](image.png)

At present, the wind energy systems have not only a promising technology but also innovative, and already with a considerable level of maturity.

According to the World Wind Energy 2008 Report, after 59024 MW in 2005, 74151 MW in 2006, and 93927 MW in 2007, the installed capacity worldwide reached 120550 MW. Relatively to 2007, in 2008 the wind energy obtained an increase of the order of 28%, and all wind turbines installed by the end of the year 2008 were generating 260 TWh per year, that is the equivalent to more than 1,5% of the global consumption of the electric energy [2].

At the European level, in 2009 the installed capacity was of the order of 74767 MW, about 15% more than in 2008. Concerning Portugal, at the end of 2009 the installed capacity was of the order of 3535 MW, about 23% more than in 2008 [3].
There are mainly two types of wind turbines (Fig. 2), the vertical axis and horizontal axis, being the second type of turbines the most widely used around the world with three blades, rotors and nacelle positioned in front (upwind) [4]. This paper addresses mainly the horizontal axis wind turbine.

Both turbine height and diameter have increased year after year. From 2004, the wind turbines with a power output of 2 MW or more have dominated the market, but now the greatest wind generators have a continuous output of 6 MW or even 7.5 MW.

At present, the market is dominated by two generator conceptions, that is, the constant speed and variable speed generators. The traditional constant speed generators are directly connected to the electric network, with the generator speed imposed from the network angular speed.

Due to the lack of control of both active and reactive power, the technology of fixed speed wind turbines are increasingly being replaced by variable speed. The concept of the variable speed generators was only possible due to the using of the AC-DC-AC power electronics converters [6].

Basically the wind generators contain the rotor, the nacelle and the tower, and are ground-fixed by means the substructure (foundation).

The rotor is constituted of blades, usually three, attached to the rotor hub [7].

As for the nacelle, it is the place with the greate number of components (Fig. 3), and includes the principal axis, which is often supported by a cylinder self-compensator bearing. Inside, includes also the brake, the gear (when exists), the electric generator, the system of directional orientation (yaw) and the respective electric motors, the maintenance winch, a navigation light signal, (only in some), a direction sensor, and an anemometer, which send the informations to the controller.

On the other hand, the tower supports the nacelle and raises the rotor to a level where the wind speed is considerable and less disturbed.

In practice, there are several types of towers, which are tubular and constructed in steel or concrete, interlaced with three legs or secured with cables.

At present, the most used towers which create a lower visual impact are the steel tubular towers. These steel tubular towers can have inside several types of components, such as, for example, hatches (with contactors, circuit breakers, etc.), transformer, batteries, security circuit breakers, capacitor bank, stairs and/or lift, among others.

Finally, the substructure is one of the more important parts, because is greatly affected by the overturning moment of the tower, under wind extreme conditions. For tubular towers, the substructures can be made of slab, multi pilar or mono pilar. The slab substructures are used when the soil is robust, and both multi and mono pilars are used for fragile soils (argillaceous).

Concerning the interlaced steel towers, concrete pilars are placed on each foot of the tower [7]. Within the nacelle is the generator, which can be DC or AC (synchronous or asynchronous).

The direct current (DC) generators are usually used in isolated applications, in order to recharge batteries which accumulate the energy produced for later use.

At present, due to the development of power electronics, the synchronous generator with an incorporated rectifier is the most used [6].

In addition, the alternating current (AC) generators can be synchronous or asynchronous.

The synchronous generator is excited by means a direct current and operates at a constant speed (called synchronous speed) imposed not only from the electric network angular frequency, but also of the generator pole number.

When compared with the induction generator, the synchronous generator presents a strong advantage because do not need a magnetizing reactive current, i.e. there is not a capacitor bank to supply reactive power.

However, is much more expensive and mechanically more complicated.

The synchronous generators can present a wound rotor or a permanent magnet rotor (Fig. 4) [6].
serious disturbance in the network. The 7 to 8 times the continuous current, which can cause a starting current. Gradually connected using a softstarter in order to limit the absence of field excitation. This type of generator presents asynchronous are characterized by the rotor slip as well as by electric instability in the network. As previously referred, the induction generator is a consumer of reactive power while producing active power. With no other electric components to supply reactive power to the generator, this power comes from the network, but the transmission losses are higher, and in several situations causes electric instability in the network.

When compared with the synchronous generators, the asynchronous are characterized by the rotor slip as well as by the absence of field excitation. This type of generator presents also an inductive power factor, thus requiring the introduction of compensation capacitors.

The asynchronous generator can be of two types: squirrel-cage rotor or wound rotor (Fig. 5). Note that both allow a direct connection to the electric network, but power electronics converters can also be used in order to inject a variable and controlled reactive power in the network.

The asynchronous generator rotor winding may have two configurations: one in which the slip (or torque) is controlled by power electronics in the rotor circuit, and another setting that is the connection of a circuit for extracting power from the rotor, known as double fed generator [6].

To ensure the network connection, the generator is gradually connected using a softstarter in order to limit the starting current.

Note that without a softstarter this current can be equal to the 7 to 8 times the continuous current, which can cause a serious disturbance in the network.

As previously referred, the induction generator is a consumer of reactive power while producing active power. With no other electric components to supply reactive power to the generator, this power comes from the network, but the transmission losses are higher, and in several situations causes electric instability in the network.

As referred, to avoid this fact exists a capacitor bank that can be used between the generator and the network, and is usually located in the nacelle or in the tower.

III. CONTROL OF WIND TURBINES

The principal objectives of the control systems are as follows, among others: allow an automatic operation, coupling and uncoupling the generator, rotor direction, speed control, load control, pitch control, warning operators of failures or maintenance needs. The control structure for a wind generator includes several sensors, actuators, and a system with hardware and software to process the input signals for the sensors as well as to generate the output signals for the actuators [7].

Currently, modern wind turbines use two different principles of aerodynamic control to limit the power extraction of the wind turbine. They are known as: stall control and pitch control. Although in the past the majority of the wind generators used a simple stall control, however, with the increased size of the machines the manufacturers increasingly are opting for the pitch control system which offers greater flexibility in the operation of the wind generators.

The stall control is a passive system that reacts to the wind speed. The rotor blades are fixed in pitch angles and can not rotate around its longitudinal axis. The pitch angle is chosen taking into account that, for wind speeds higher than the continuous speed, the flow around the profile of the rotor blade detaches from the surface of the blade (stall) reducing the aerodynamic lift and increasing the drag forces. Lower aerodynamic lifts and higher drag forces act against the rotor power output increasing.

The wind generators with a stall control, when compared with the wind generators with pitch control, present usually the following advantages:

• Simple structure of the rotor hub;
• Lower maintenance, because the lower number of mobile components;
• Self-reliability of the power control.

However, at starting when the wind speed is lower the turbine with stall control has not a sufficient starting torque. Therefore, an auxiliary starting motor is required. Worldwide, the concept of the stall control is dominant. The majority of the manufacturers uses this simple possibility of power control, which needs a rotor constant speed, usually assured by the induction generator directly connected to the network.

The pitch control is an active system which usually needs an information from the system controller, whose the most important application consists in the control of the generator power output. When the power output of the generator is exceeded due to an increasing in the wind speed, the rotor blades rotates around its longitudinal axis, in order to assure that the turbine produces only its continuous power. The reduction of the angle of attack decreases the aerodynamic forces in the blade and, consequently, the power output production. Before all wind conditions, the flow around the profiles of the rotor blades is quite adherent to the surface, producing aerodynamic lift and small drag forces.
The turbines with pitch control allow the power active control under all wind conditions, and also under partial powers. In addition, reach the continuous rated power even under low air density and allow a soft rotor start by pitch changing. On the other hand, strong brakes are not required to perform emergency stops of the rotor, the rotor blades loads decrease with winds to increase above the continuous power, and it is possible to realize the flagging of rotor blades for small loads in extreme winds.

Fig. 6 shows different power curves of a 60 kW wind turbine with pitch control for different pitch angles. The nominal power of 60 kW is achieved at a wind speed of 12 m/s and small changes in pitch angle can cause a dramatic effect on generator power.

![Power output of a 60 kW generator with control of pitch angles](image)

In Germany 50% of all installed wind generators are of the type “pitch control”, because two of the biggest manufacturers prefer this type of control of wind turbines. Note that the, in the new generation of the 1 MW class turbines, many manufacturers changed from stall control to pitch systems.

The majority of the wind turbines with horizontal axis includes a yaw control system in order to maintain the nacelle oriented according with the wind direction for a better efficiency of the wind energy. On the other hand, the use of the yaw control to limit the energy production is obviously an interesting possibility, and is being successfully exploited in Italy with the prototype Gamma60 with 60 m of diameter (with an impressive yaw rotation of 8º/s). However, exist two factors that limit the rapid reply of the system to control the generator power output.

The first one is the high moment of inertia of the nacelle and of the rotor around the yaw axis, and the second is the relationship between the normal component of the wind speed of the rotor disc and the yaw angle. The second factor that limits the reply of the yaw system means that as small yaw angles there is a minimal reduction in the generator power output, and for the pitch system, if there is a change of the same magnitude, the generator power output could fall by half [9].

### IV. RELIABILITY

Reliability studies can be achieved primarily through two methods: deterministic or probabilistic (Fig. 7).

![Reliability methods of an electrical energy system](image)

When carrying out a study of the reliability of production, the probability of the out of service of the generator groups is evaluated, as well as the consequences related to the supply of the connected loads. Considering a system composed of several generators intended to supply a given load, the probability of each group to be out of service is given by FOR (Forced Outage Rate, or Availability) characteristic of each one [9]. The FOR can be calculated either by both failure and repair rates \( \lambda \) and \( \mu \), or by the MTTR (Mean Time To Repair) and MTTF (Mean Time To Failure) as can be seen in (1):

\[
FOR = \frac{\lambda}{\lambda + \mu} = \frac{MTTR}{MTTF + MTTR}.
\]  

In order to obtain the table related to the Out of Service Capabilities (OSC) for a system, one should begins by considering a system consisting only of lower-power group, and later to include the other groups by ascending order of their power outputs. In addition, it is necessary to know the OSC value for each group [8].

For a better understanding of the construction of the Out of Service Capabilities table for a system, one consider two groups, the first one with 5 MW and the other with 10 MW, and with an OSC respectively of 0,1 and 0,2. In Tables I and II are exposed the OSC probabilities for both groups.

#### TABLE I

<table>
<thead>
<tr>
<th>Group 1 – State</th>
<th>OSC (MW)</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>In operation</td>
<td>0</td>
<td>0,9 (P₁)</td>
</tr>
<tr>
<td>In failure</td>
<td>5</td>
<td>0,1 (P₂)</td>
</tr>
</tbody>
</table>

#### TABLE II

<table>
<thead>
<tr>
<th>Group 2 – State</th>
<th>OSC (MW)</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>In operation</td>
<td>0</td>
<td>0,8 (P₃)</td>
</tr>
<tr>
<td>In failure</td>
<td>10</td>
<td>0,2 (P₄)</td>
</tr>
</tbody>
</table>

By combining the data exposed in both Tables I and II, one obtains the OSC probabilities of the system, shown in Table III.
LOLP is defined as the probability of the installed power not being enough to feed the entire load, and can be calculated from the probability associated to the state for which corresponds an out of service capacity $X$, $C$ is the capacity of the out of service new unit, $x$ the FOR of the new unit, $P_i(X)$ the probability associated to the state $X$ on the table before the addition of $C$, $P_i(X-C)$ the probability associated to the state on the table before the addition of $C$, $e P_i(X)$ the probability associated to the state $X$ after the addition of $C$.

Therefore, one can calculate the LOLP (Loss of Load Probability) and the LOLE (Loss of Load Expectation). The LOLP is defined as the probability of the installed power not being enough to feed the entire load, and can be calculated from the CFS tables of the system in association with the load diagrams, by means the following equation:

$$LOLP = \sum_{i=1}^{n} P_i(X)P(L > X_{\text{max}} - X_i).$$

(4)

On the other hand, the LOLE indicates the load that the system will not power on over a given time period. Usually, one year should be considered and is defined by means the following equation:

$$LOLE = LOLP \times t.$$ 

(5)

In equation (4), $P_i(X)$ is the probability of loss of capacity $X_i$, $X_{\text{max}}$ the total installed capacity, $P(L > X_{\text{max}} - X_i)$ the probability that the peak load $L$ exceeds the available capacity in state $i$ and $n$ the number of states. In equation (5), a value of $t=365$ days should be considered.

As wind energy is an intermittent source of energy, its availability does not follow the peaks of the load chart, and thus contributes to a decrease in system reliability. However, there is an index used to estimate the equivalent capacity of intermittent sources, known as capacity credit. The capacity credit expresses the amount of conventional generation avoided or replaced by wind energy, and can be determined from several methods: Max Factor, Reliability Curves or Retrospection Approximation [8].

V. CONCLUSIONS

At present, the wind energy systems have a technology not only promising but also innovative and already with a considerable level of maturity. The wind energy is presented as a very important energy source, concerning both energy and environmental aspects. Taking into account the increasing of installed wind power, becomes necessary to study the impact that this type of energy presents in the electric system reliability. With the increase in oil prices and in order to reduce energy costs, the wind energy presents itself as an increasingly important solution in the energetic mix. However, is also necessary to invest in energy efficiency.

VI. REFERENCES