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The State of the Art of Generators for Wind Energy Conversion Systems

Y. Amirat, M. E. H. Benbouzid, B. Bensaker, R. Wamkeue and H. Mangel

***Abstract*—Wind Energy Conversion Systems (WECS) have become a focal point in the research of renewable energy sources. This paper provides then a comparative study of past and present generator technologies used in WECS. This study is based on an exhaustive review of the state of the art and on an effective comparison of the performances of the four main topologies that are permanent magnet generators, synchronous generators, induction generators and doubly-fed induction generators. The different generator-WECS schemes are compared on the basis of topology, cost, efficiency, power consumption and control complexity. Moreover, attempts are made to highlight future issues so as to index some emerging solutions.**

***Index Terms*—Wind turbine, WECS, generator, state of the art, comparison.**

I. Introduction

WIND energy conversion is the fastest-growing source of new electric generation in the world and it is expected to remain so for some time. At the end of 2003 the installed wind capacity stands at over 40000 MW, doubling since 1999, and it could exceed 95000 MW by the end of 2008 (Fig. 1). But the higher target is to achieve 12% of the world's electricity from wind power by 2020 [1].

Harnessing wind energy for electric power generation is an area of research interest and at present, the emphasis is given to the cost-effective utilization of this energy resource for quality and reliable power supply. During the last two decades wind turbines have been developed in size from 20 kW to 2 MW, while even larger wind turbines already are being designed. A lot of different concepts have been developed and tested.

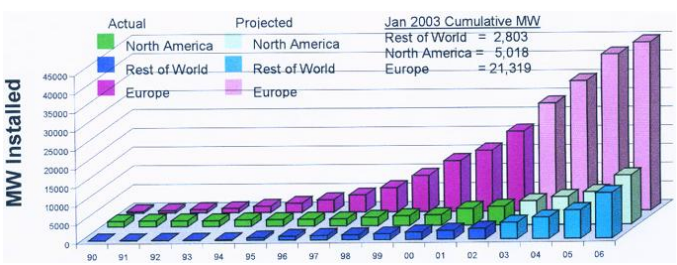

Fig. 1. Installed wind power [1].

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One important modification is the introduction of pitchable blades, where it is possible to control the wind power input the generator. Another development is on the electrical system, where new concepts also have been industrially implemented. These developments have led to conceive many WECS schemes based on many criteria such as fixed speed or variable speed wind turbine, implementation site (onshore or offshore), the rate of the power produced (small or large wind turbine) and the grid connection (islanded or grid connected wind turbine). Indeed, for some years efforts have been put into research and development of new generator concepts [2-5]. For illustration, in [6] a comparison of 7 new concepts is presented.

In this paper, an exhaustive review of the state of the art is presented regarding the four main generator-WECS schemes that are permanent magnet generators, synchronous generators, induction generators and doubly-fed induction generators. These different generator-WECS schemes are compared on the basis of topology, cost, efficiency, power consumption and control complexity. Illustration of the studied generators is provided in Fig. 2.

II. Wind Energy Background

A. Wind Power Conversion Characteristic

The wind turbine aerodynamic power P is given by

$$P = \frac{1}{2}\pi\rho C_p R^2 v^3 \tag{1}$$

where ρ is the air density, R is the turbine radius, v is the wind speed, and C_p is the turbine power coefficient that represents the wind turbine power conversion efficiency.

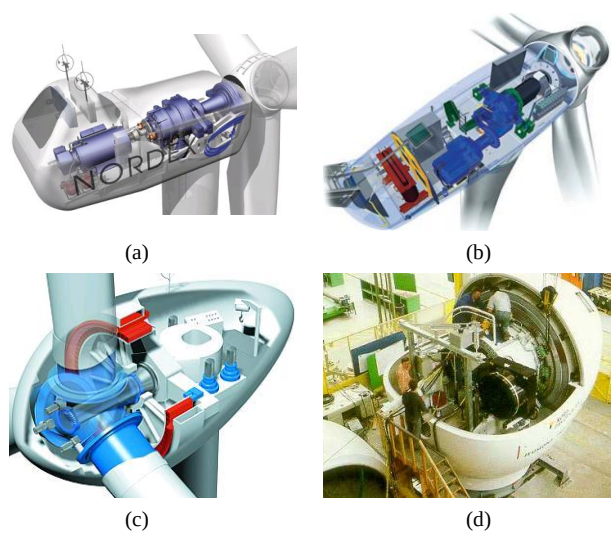

Fig. 2. Frequently used generator topologies: (a) Induction generator [© Nordex], (b) Doubly-fed induction generator [© NEG Micon], (c) Synchronous generator [© Enercon], (d) Permanent magnet synchronous generator [© Jeumont Industrie].

It is a function of the tip speed ratio λ, as well as the blade pitch angle β in a pitch controlled wind turbine. λ is defined as the ratio of the tip speed of the turbine blades to wind speed, and given by

$$\lambda = \frac{R\Omega}{v} \tag{2}$$

Where Ω is the wind turbine rotational speed.

The C_p-λ characteristics, for different values of the pitch angle β, are illustrated in Fig. 3. This figure indicates that there is one specific λ at which the turbine is most efficient. Normally, a variable speed wind turbine follows the C_{pmax} to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at λ_{opt}. Then it operates at the rated power with power regulation during high wind periods by active control of the blade pitch angle or passive regulation based on aerodynamic stall. Because wind turbine mechanical power at the rotor hub depends on both rotor speed and wind speed, harvested power can be represented on a three-dimensional surface. Figure 4 is an example of the characteristic power surface of a small turbine. Blade pitch is assumed constant. As expected, power out rises with increasing wind and increasing rotor speed for low and moderate values [7-9].

B. Wind Turbine Power Extraction

In important issue for wind turbines is the efficiency. Efficiency is important when comparing different systems because losses reduce the average power produced by the wind energy converter and, thereby, they reduce incomes [10]. Therefore, in the following sections, the various WECS that are able to obtain maximum power output for varying wind speeds are discussed (Fig. 5).

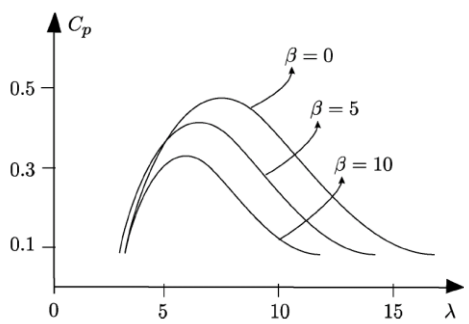

Fig. 3. C_p-λ characteristics, for different values of the pitch angle.

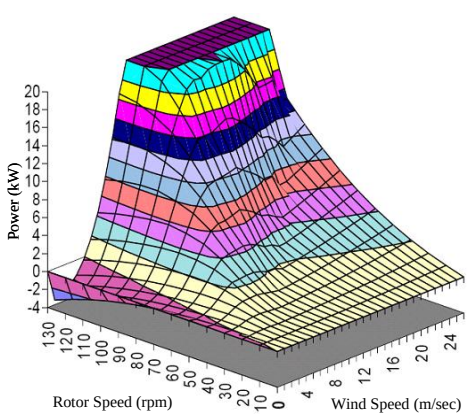

Fig. 4. Generic turbine power surface truncated to 20 kW [9].

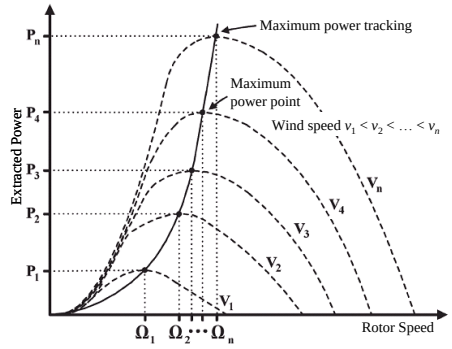

Fig. 5. WECS maximum power extraction.

Moreover, wind turbine and generator adaptation should be also taken into account. In fact, generators choice is done according the turbine size and wind class (Fig. 6) [2].

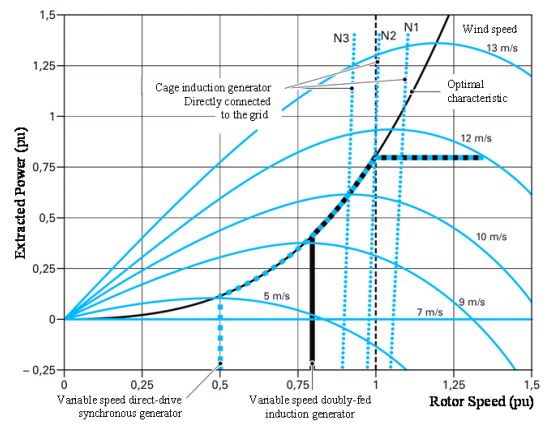

Fig. 6. Wind turbine and generator adaptation [2].

III. Literature Overview

Two types of wind turbines can be distinguished namely fixed speed and variable speed turbines. The first WECS were of fixed speed type due to limitations of machine technology and power electronics [11-12].

A. Fixed Speed WECS

In a fixed speed WECS, the turbine speed is determined by the grid frequency, the generator pole pairs number, the machine slip, and the gearbox ratio. A change in wind speed will not affect the turbine speed to a large extent, but has effects on the electromagnetic torque and hence, also on the electrical output power. With a fixed speed WECS, it may be necessary to use aerodynamic control of the blades to optimize the whole system performance, thus introducing additional control systems, complexities, and costs. As for the generating system, nearly all wind turbines installed at present use either one of the following systems: squirrel cage induction generator, doubly fed (wound rotor) induction generator, direct-drive synchronous generator. The most used wind turbine systems in this case are illustrated in Fig. 7. Using induction generators will keep an almost fixed speed (variation of 1-2%). The power is limited aerodynamically either by stall, active stall or by pitch control. A soft-starter is normally used in order to reduce the inrush current during start-up. Also a reactive power compensator is needed to reduce (almost eliminate) the reactive power demand from the turbine generators [13-14].

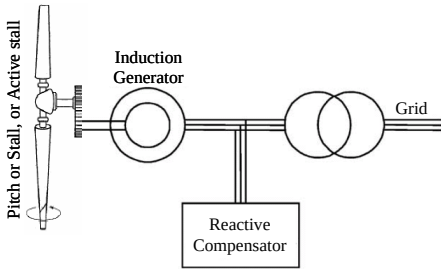

Fig. 7. Frequently used fixed speed WECS.

It is usually done by activating continuously the capacitor banks following load variation. Those solutions are attractive due to low cost and high reliability. However, a fixed-speed system cannot extract as much energy from the wind as a variable speed topology. Today the variable speed WECS are continuously increasing their market share, because it is possible to track the changes in wind speed by adapting shaft speed and thus maintaining optimal energy generation [15].

B. Variable Speed WECS

The variable speed generation system is able to store the varying incoming wind power as rotational energy, by changing the speed of the wind turbine, in this way the stress on the mechanical structure is reduced, which also leads to that the delivered electrical power becomes smoother. The control system maintains the mechanical power at its rated value by using the Maximum Power Point Tracking technique (MPPT) [16]. These WECS are generally divided into two categories: systems with partially rated power electronics and systems with full-scale power electronic interfacing wind turbines [13], [17-18].

Figure 8 shows two solutions in case of wind turbines with partially rated power converters. Figure 8a shows a WECS with a wounded rotor induction generator. An extra resistance controlled by power electronics is added in the rotor that gives a speed range of 2 to 4%. This solution also needs a softstarter and a reactive power compensator. Figure 8b shows another solution using a medium scale power converter with a wounded rotor induction generator. In this case, a power converter connected to the rotor through slip rings controls the rotor currents. If the generator is running super-synchronously, the electrical power is delivered through both the rotor and the stator. If the generator is running sub-synchronously the electrical power is only delivered into the rotor from the grid. A speed variation of 60% around synchronous speed may be obtained by the use of a power converter of 30% of nominal power. The other WECS category is wind turbines with a full-scale power converter between the generator and grid that gives extra losses in the power conversion but it will gain the added technical performance. Figure 9 shows in this case four possible solutions using induction generator, multipole synchronous generator and permanent magnet synchronous generator.

C. Generators

Most wind turbine manufacturers use six-pole induction (asynchronous) generators, while others use directly driven synchronous generators [4]. In the power industry, in general, induction generators are not very common for power production, but induction motors are used worldwide.

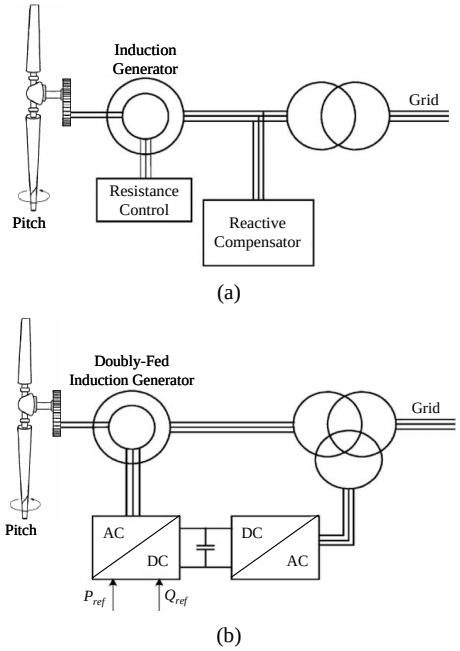

Fig. 8. Partially rated power electronics WECS: (a) Rotor resistance converter, (b) Doubly-fed induction generator.

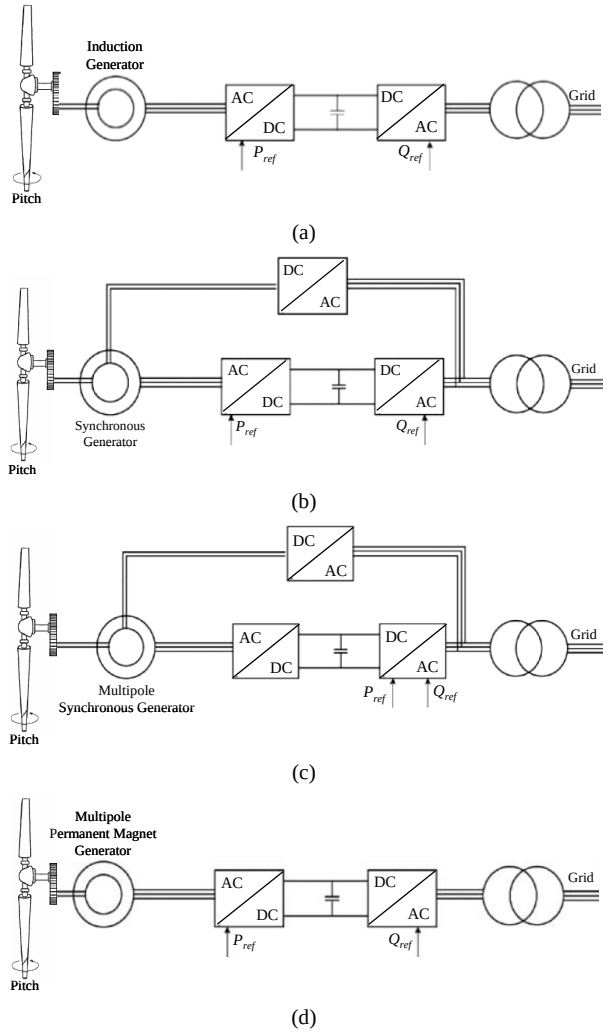

Fig. 9. Full-scale power electronics WECS: (a) Induction generator, (b) Synchronous generator, (c) Multipole synchronous generator, (d) Multipole permanent magnet generator.

The power generation industry almost exclusively uses large synchronous generators, as they have the advantage of a variable reactive power production, i.e. voltage control [19-21].

1) Synchronous generator. Synchronous generator are widely used in stand alone WECS where the synchronous generator can be used for reactive power control in the isolated network. To ensure the wind turbine connection to the grid a back-to-back PWM voltage source inverters are interfaced between the synchronous generator and the grid. The grid side PWM inverter allows for control of real and reactive power transferred to the grid. The generator side converter is used for electromagnetic torque regulation [22]. Synchronous generators of 500 kW to 2 MW are significantly more expensive than induction generators with a similar size. One should note that the use of a multipole synchronous generator (large diameter synchronous ring generator) avoids the installation of a gearbox as an advantage but a significant increase in weight will be accepted in counterpart. Indeed, the industry uses directly driven variable speed synchronous generators with large-diameter synchronous ring generator. The variable, directly driven approach avoids the installation of a gearbox, which is essential for medium and large-scale wind turbines [4]. Permanent magnet synchronous generator is a solution that is appreciated in small wind turbines but it can not be extended be extended to large-scale power because it involves the use of big and heavy permanent magnets [23-24].

2) Induction generator. Induction generators are increasingly used these days because of their relative advantageous features over conventional synchronous generators. These features are brushless and rugged construction, low cost, maintenance and operational simplicity, self-protection against faults, good dynamic response, and capability to generate power at varying speed. The later feature facilitates the induction generator operation in stand-alone/isolated mode to supply far flung and remote areas where extension of grid is not economically viable; in conjunction with the synchronous generator to fulfill the increased local power requirement, and in grid-connected mode to supplement the real power demand of the grid by integrating power from resources located at different sites. The reactive power requirements are the disadvantage of induction generators. This reactive power can be supplied by a variety of methods, from simple capacitors to complex power conversion systems [25-28].

Induction generators were used for a long time in a constant speed WECS, where the pitch control or active stall control are dictated for power limitation and protection, a softstarter is also used to limit transients when the generator is connected to the grid. For variable speed WECS, back to back PWM inverters are used, where the control system of the inverter in the generator side regulates the machine torque and consequently the rotor speed, therefore keeping the frequency within defined limits. On the other hand, the inverter in the grid side controls the reactive power at the coupling point. In this case, the doubly-fed induction generator is widely used. Indeed, amongst many variable speed concepts, WECS using doubly-fed induction generators have many advantages over others [9]. For example, the power converter in such wind turbines only deals with rotor power, therefore the converter rating can be kept fairly low, approximately 20% of the total machine power. This configuration allows for variable speed operation while remaining more economical than a series configuration with a fully rated converter. Other features such as the controllability of reactive power help doubly-fed induction generators play a similar role to that of synchronous generators [29-32].

D. WECS Efficiency Based Comparison

Table 1 briefly gives the pros and cons of the major WECS detailed in the literature. Moreover as previously mentioned, some of the reviewed WECS were also compared on an efficiency basis. Indeed, Fig. 10 given in [33-34] illustrates wind turbines comparison regarding their energy conversion. Moreover, in [5] is investigated the effects of drive train and power converter efficiencies on variable speed energy capture. In this study, it was found that the losses in the lower wind speed range for an induction generator operating at variable speed with conventional power electronics are fairly large. Switching to a hypothetical power converter with constant 90% efficiency over its operating range recovers the low wind speed losses as illustrated in Fig. 11. Using a direct drive permanent magnet generator with its high efficiency at low power rating improves the situation still further and provides a significant energy capture improvement over the entire operating range. This analysis clearly shows the importance of component efficiencies for capitalizing on the energy capture benefits of variable speed wind turbines [35].

IV. Wind Turbine Manufacturers

As for the generating system, nearly all wind turbines currently installed use either one of the following systems (Fig. 12): squirrel-cage induction generator, doubly-fed (wound rotor) induction generator, or direct-drive synchronous generator.

Table 1. WECS generator comparison.

Type	Pros	Cons
Induction Generator	✓ Full speed range ✓ No brushes on the generator ✓ Complete control of reactive and active power ✓ Proven technology	× Full scale power converter × Need for gear
Synchronous Generator	✓ Full speed range ✓ Possible to avoid gear ✓ Complete control of reactive and active power	× Small converter for field × Full scale power converter
Permanent Magnet Synchronous Generator	✓ Full speed range ✓ Possible to avoid gear ✓ Complete control of reactive and active power ✓ Brushless (low maintenance) ✓ No power converter for field	× Full scale power converter × Multipole generator (big and heavy) × Permanent magnets needed
Doubly-Fed Induction Generator	✓ Limited speed range -30% to 30% around synchronous speed ✓ Inexpensive small capacity PWM Inverter ✓ Complete control of reactive and active power	× Need slip rings × Need for gear

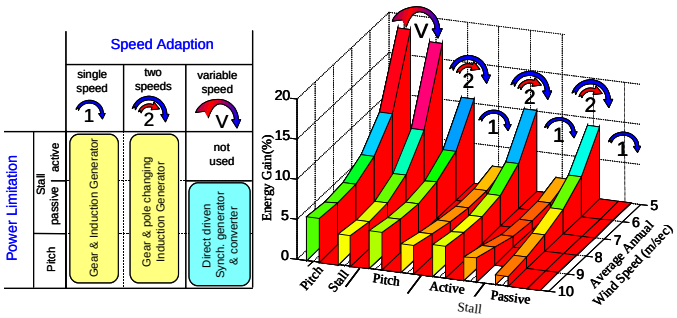

Fig. 10. WECS comparison regarding their energy generation [32-33].

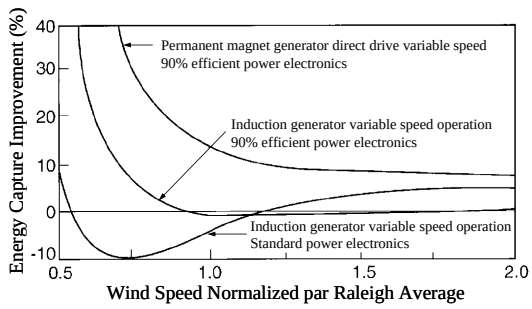

Fig. 11. Energy capture improvement for three WECS configurations [34].

Apart from these three mainstream designs, a number of manufacturers have developed other technologies over time. Some of these have survived; others have passed into oblivion (Table 2) [36].

V. Trends and Alternatives

During recent years, a substantial scaling up has taken place in the wind power area. This applies both to the size of the individual turbine and to the scale of the typical project.

Table 2. WECS manufacturers current designs and power ranges [36]: CT/CS (fixed speed, classic stall), CT/AS (fixed speed, active stall), VTDI (variable speed/pitch doubly-fed induction generator), VTDD (variable speed, direct-drive synchronous generator) VT/AGP (variable speed/pitch combined with induction generator), SVT/OSP (semi-variable speed/pitch combined with OptiSlip® [3]).

Manufacturer	Concept	Power Range
BONUS (Denmark)	✓ CT/CS ✓ CT/AS	✓ 600 kW ✓ 1 – 2.3 MW
DEWIND (UK/Germany)	✓ VTDI	✓ 600 kW – 2 MW
ECOTECNICA (Spain)	✓ CT/CS ✓ VTDI	✓ 750 – 1300 kW ✓ 1670 kW
ENERCON (Germany)	✓ VTDD	✓ 300 kW – 4.5 MW
GE WIND ENERGY (USA/Germany	✓ CT/CS ✓ VTDI	✓ 600 kW ✓ 900 kW – 3.6 MW
JEUMONT (France)	✓ VTDD	✓ 750 kW – 1.5 MW
MADE (Spain)	✓ CT/CS ✓ VTSGP	✓ 600 kW – 1.3 MW ✓ 2 MW
NEG MICON (Denmark)	✓ CT/CS ✓ CT/AS ✓ VTDI	✓ 600 kW – 1.5 MW ✓ 1.5 – 2 MW ✓ 2.75 – 4.2 MW
NORDEX (Germany)	✓ CT/CS ✓ VTDI	✓ 600 kW – 1.3 MW ✓ 1.5 – 2.5 MW
VESTAS (Denmark)	✓ SVT/OSP ✓ VTDI	✓ 660 kW – 2.75 MW ✓ 850 kW – 3 MW

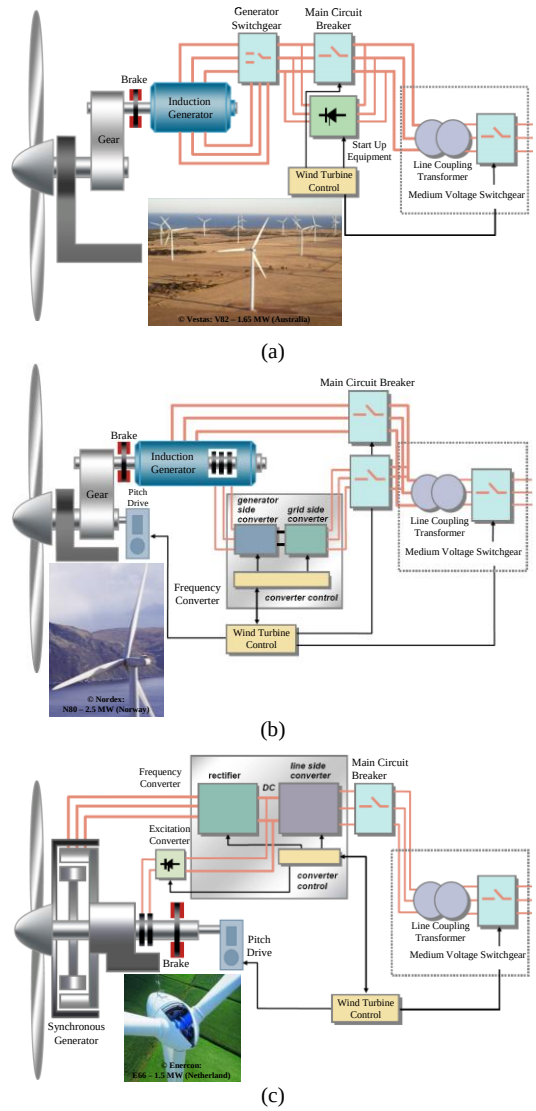

Fig. 12. Currently installed WECS: Induction generator directly coupled to grid, (b) Doubly-fed induction generator with slip energy recovery, (c) Gearless synchronous generator with high pole number.

For modern wind turbines of the multi-MW class, both the nacelle height and the rotor diameter are in the order of 100 m. Thus, at the vertical position, the blade tip can reach up to heights of 150 m. Figure 13 shows the German Enercon E-112 wind turbine, which, with a rotor diameter of 112 m and a nominal power of 4.5 MW, is currently the largest wind turbine.

Moreover, there is considerable growth potential for wind power. Much of the generating capacity is placed offshore, where higher wind speeds mean higher energy production. For that purpose, ABB developed a new wind power system called Windformer. WECS with Windformer have a high output of typically 3 to 5 MW. The Windformer generator has a variable-speed rotor with permanent magnets and is connected directly to the turbine. The voltage (over 20 kV) produced by the generator is converted to DC by means of diodes. The WECS are connected in groups, the power being transmitted by cable to a network station with inverter, linked directly to the utility grid. The Windformer concept includes a cable-wound generator, directly connected to the turbine. It does not have a gearbox thereby reducing both losses and maintenance (Fig. 14) [37].

Fig. 13. Largest wind turbine (currently): Enercon E-112 with a rotor diameter of 112 m and a nominal power of 4.5 MW.

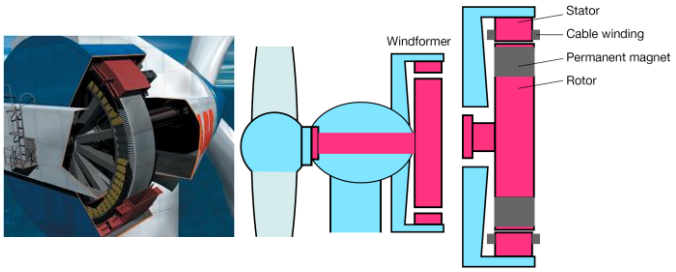

Fig. 14. ABB Windformer concept [37].

VI. Summary

This paper has review the state of art of wind energy conversion systems. The emphasis has been put on generators topologies. Indeed, it has been described the strength and the weakness of the most frequently studied (available literature) and used (industrial cases) wind turbine generators that are: induction generators, doubly-fed induction generators and synchronous generators. Moreover, attempts have made to highlight current trends and industrial alternative issue.

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