Overview of Wind Energy Conversion Systems Development, Technologies and Power Electronics Research Trends

Sergio Toledo, *Member, IEEE,* Marco Rivera, *Member, IEEE* and José L. Elizondo, *Member, IEEE*

***Abstract*—Wind energy use has shown a remarkable increase in last years. In order to achieve the highest efficiency with the best characteristics in wind turbines, it is necessary to analyze relevant factors in wind energy conversion. In this review a state of the art is presented focused on modeling, constitutive elements, structure and control of wind generation systems and the increasing use of wind energy worldwide is evidenced.**

***Index Terms*—Wind Energy, Wind Turbine, Wind-energy systems control, Power Electronics**

I. Introduction

Nowadays and due to the well-known detrimental effect over the environment of fossil fuels, worldwide energy generation focus has shifted to generating power from renewable energy sources (RES) such as hydro, tidal, wind, bio-, geothermal and solar which do not emit green house gases [1]. Among mentioned RES, wind energy has attracted a lot of attention owing to its abundance and advancement of supporting technologies. Global annual installed wind turbine capacity has increased in last years, as shown in Fig. 1 with favorable future projections [2]. Furthermore, Fig. 2 shows expected growth in capacity and rotor diameter of wind turbines presented in [3] and based on a study made for the *European Wind Energy Association* (EWEA) at 2011. A capacity of 8 (MW) and a rotor diameter of 160 (m) was predicted for 2017, based on EWEA's study and subsequent market trends. However, now the largest wind turbine in serial production is the V164-8.0MW developed by the *MHI Vestas*® joint venture that has a capacity of 8 (MW) and a rotor diameter of 164 (m). Moreover, developments of 10 (MW) wind turbines have been announced by *Clipper*®, *Sway Turbine AS*®, and *Windtec-AMSC*®, and *GE Energy*® has ambitious plans to develop 15 (MW) turbines, as well as *Gamesa*® [3].

Even thought in most cases the cost of wind power is still high compared with other conventional power sources as a result of high initial capital investment, between 2008 and 2015, the average cost of land-based wind decreased by 35%. Even more, the levelized cost of electricity (LCOE) has seen significant reductions over the past two decades [4], [5].

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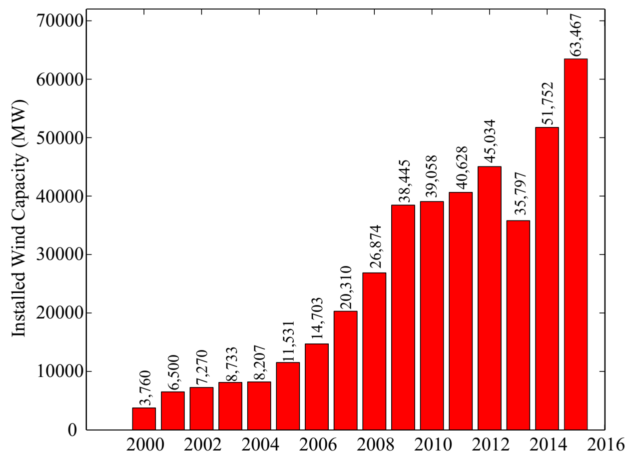

Fig. 1. Global annual installed wind capacity statistics provided by the Global Wind Energy Council (GWEC) [2].

In a growing number of cases, the LCOE of wind power is close to, or even below, the LCOE of fossil or nuclear options. For example, the lowest currently reported costs for land-based wind are USD 30-35 per megawatt hour (MWh) (Morocco) [6].

Reductions in the cost of wind power production have been greater for low wind-speed technology. This opens up new deployment opportunities closer to power demand promoting distributed generation (DG) approaches.

Another challenge in wind energy harvesting consists in the high operation and maintenance (O&M) costs, specially in offshore wind turbines. This kind of wind generation structures are located far away from coastline resulting into logistical difficulties in accessing the production sites as well as high cost of transmission lines [7]. The O&M costs of wind turbines constitute approximately 10-15% of the life-cycle cost in onshore installations and up to 30% in offshore installations. Nevertheless, employing robust structural health monitoring methods and appropriate control strategies, specially in offshore wind farms, the cost of producing wind power can be further reduced.

Referring about other structural issues, the majority of modern utility-scale wind turbines produced nowadays have three blades with horizontal axis configuration [8], [9]. Although in the 1980s and early 1990s some attempts were made to market one- and two-bladed wind turbine designs, three-bladed structure became the most popular, due to its

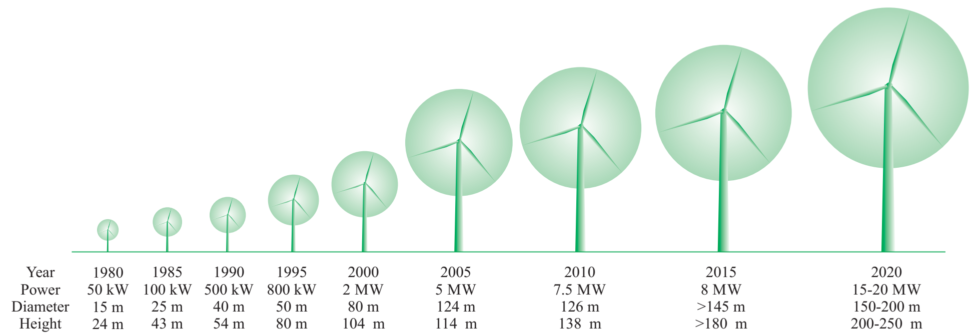

Fig. 2. Growth in capacity and rotor diameter of wind turbines (1985-2016).

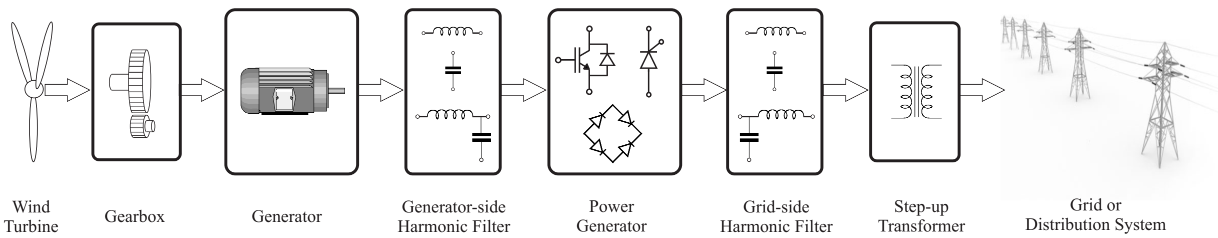

Fig. 3. Main components of a wind turbine system.

better aerodynamic characteristics. In general, horizontal axis construction is preferred over vertical axis, because the entire rotor can be placed atop tall towers where it is able to take advantage of higher velocity winds. Other advantages include: improved power capture efficiency, use of yaw mechanism to position rotor to face the direction of wind flow, easy installation and maintenance [10].

Wind turbines can either be manufactured with a fixed-pitch or variable-pitch blades [11]. Fixed-pitch turbines are initially less expensive, but their inability to adjust pitch angle makes them less used in large wind turbines where structural loads are more pronounced. Furthermore, wind turbines can also be variable-speed or fixed-speed. Fixed speed wind generators are usually used for low power applications because of some advantages such as low cost, operational simplicity, brushless construction and maintenance free operation [12], but they are not popular with megawatt-scale turbines due to ineffectiveness in extracting energy from wind and induction of mechanical stress in drive train during variable wind speed. Variable-speed turbines on their side, can be operated around their optimum power efficiency point, but this requires the use of an additional power electronic processing unit to couple them to the grid system [13]. The use of converters guarantee that the power generated meets certain performance requirements before it is connected to the main grid. Moreover, generator speed of the fixed-speed wind turbines is fully dependent on the grid frequency making them undesirable candidates for variable-speed operations. As a matter of fact the majority of MW utility-scale wind turbines that are manufactured nowadays are variable-pitch, variable-speed, and horizontal-axis turbines [10]. In wind turbine design, the maximization of the power coefficient is of fundamental importance in order to optimize the extraction of energy from the wind. The development of new, more reliable and efficient turbines is one way to answer this competitive pressure. The wind turbine structure design includes many considerations such as strength, stability, cost and vibration [14].

Also it is necessary to introduce power electronics as an interface between the wind turbine and the grid. The power electronics is changing the basic characteristic of the wind turbine from being an energy source to be an active power source. The electrical technology used in wind turbines has been discussed for several years but now the price per produced (kWh) is so low that these solutions with power electronics are now very feasible. The latter has attracted researchers attention in power control strategies related to wind power conversion. In order to reduce the cost of energy (COE) in wind power generation, control strategies hinged on efficiency, reliability, and safe operation of wind turbines [15], [16]. Recent researches propose the use of multiphase generators so as to provide infrastructure cost reduction for the same power handling capability and improving availability of the system [17], [18].

Next section presents the basics related to wind generation systems. In Section III the principles of wind turbines are addressed. The mechanical velocity and torque control reviews are shown in Section IV. Section V highlights important details related to electrical power control. New trends and challenges are presented in Section VI. Finally in Section VI, conclusions are presented.

II. Fundamentals of Wind Energy Generation

In this section a brief summary of wind turbine operation basics is given. Challenges in the standard control methods are highlighted. A Wind Energy Conversion System (WECS) is a structure that transforms the kinetic energy of the incoming air stream into electrical energy. This conversion takes place in two steps, as follows. The extraction device, named wind turbine turns under the wind stream action, thus harvesting a mechanical power. The rotor drives a rotating electrical machine, the generator, which outputs electrical power.

The main components of a wind turbine system are illustrated in Fig. 3. The entire system can be subdivided in two subsystems. On the one hand, mechanical part including a turbine rotor and a gearbox coupled to the axis of the generator that transform mechanical power to electric power. On the other hand, electrical subsystem consists on a power electronic system with its respective input and output filters, and a transformer for grid connection.

III. Wind turbine basics

Based at Betz's limit, the maximum extractable power in wind turbines is limited to 59.3% of the available kinetic wind power [19]. That gives the maximum achievable aerodynamic efficiency in wind turbines. The power extracted by wind turbine P_m is expressed as:

$$P_m = P_w C_p(\lambda, \beta) = \frac{1}{2}\rho\pi R^2 C_p \nu^3(\lambda, \beta), \tag{1}$$

where ρ denotes air density, R is the rotor radius, ν represents wind speed before interacting with turbine, and $C_p(\lambda, \beta)$ is aerodynamic efficiency which is a nonlinear function of the tip speed ratio (TSR), λ and blade pitch angle β. The TSR is defined as:

$$\lambda = \frac{\omega_m R}{\nu}, \tag{2}$$

where ω_m denotes rotor angular speed, R is rotor radius, and ν represents incoming wind speed. It is noticeable that, if maximum mechanical power is wanted, C_p should be maintained in its maximum value. There are mainly three numerical approximations for this parameter in the literature [20]:

1) Polynomial function model: considering that angle β is constant and variation depends only on λ, it is expressed by:

$$C_p(\lambda) = \sum_{i=0}^{i=n} a_i \lambda^i, \tag{3}$$

Some examples of used coefficients are shown in [20].

2) Sinusoidal function models: for sinusoidal models, a generic function is given by:

$$\begin{aligned} C_p(\lambda, \beta) &= (a_0 + a_1(b_0\beta + a_2)) \cdots \\ \cdots \sin\left(\frac{\pi(\lambda + a_3)}{a_4 + a_5(b_1\beta + a_6)}\right) &+ a_7(\lambda + a_8)(b_2\beta + a_9) \end{aligned} \tag{4}$$

3) Exponential function models: in relation with exponential models, a generic function is given by:

$$C_p(\beta, \lambda) = c_0\left(c_1\frac{1}{\lambda_1} + c_2\beta + c_3\beta^{c_4} + c_5\right) e^{c_6\frac{1}{\lambda_1}} + c_7\lambda, \tag{5}$$

A numerical approximation of the power coefficient for the wind turbine based on exponential functions is given by the following equation:

$$C_p(\beta, \lambda) = 0.73\left(\frac{151}{\lambda_1} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right) e^{\frac{18.4}{\lambda_1}}, \tag{6}$$

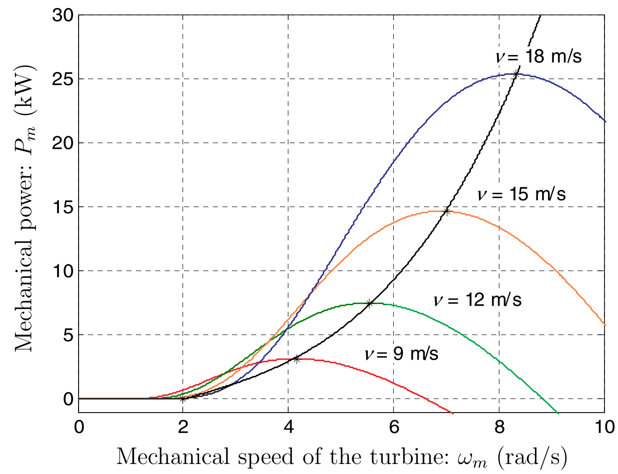

Fig. 4. Optimum captured power.

where $\lambda_1 = \left(\frac{1}{\lambda - 0.02\beta} - \frac{0.003}{\beta^3+1}\right)^{-1}$.

Fig. 4 shows an estimate of the generated power as function of the turbine angular velocity for different wind speed values.

The curve shown in Fig. 4 defines the maximum generated power as function of the optimal value of the turbine mechanical speed, which is the generator's rotor speed.

In order to extract the maximum available power from wind, mentioned both subsystems need to be controlled in a way to obtain desired performance of the entire system. Subsequent sections show control schemes commonly used in wind power generation systems.

IV. Standard mechanical velocity and Torque control

Regarding to the mechanical system, the velocity control of wind turbine conversion systems (WTCS) has mainly three distinct levels; namely, supervisory control, operational control, and subsystem control [10]. The high-level or supervisory control deals with the processes of starting-up and shutting-down of the turbine. Operational control deals with how specific control objectives are realized during the operation of wind turbine. The subsystem controls are responsible for various actuation mechanisms like pitching, yawing, and torque. Subsystem controls are usually considered as a black box since they are commanded by other control systems higher in the hierarchy. In order to have an in-depth understanding of operational goals, a generic wind turbine power curve can be used to distinguish the operational zones and the related control objectives. As is illustrated in Fig. 5, four distinct operation regions can be identified [21]: whether the wind speed is lower than the cut-in speed $\nu_{\mathrm{cut-in}}$, extracted output power is zero and turbine should be at rest. This is, the turbine operates in the *cut-in region*. Once the wind speed is higher than $\nu_{\mathrm{cut-in}}$, the turbine starts to extract the power that increases with the increment of the wind speed until it reaches the rated output power at the rated wind speed ν_{rated}. This operation region is called as *torque control region*. In this region, turbine should operate with the maximum power

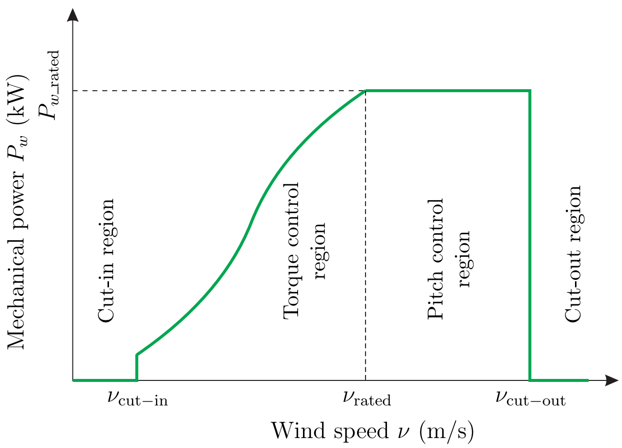

Fig. 5. Generalized variable-speed wind turbine power curve.

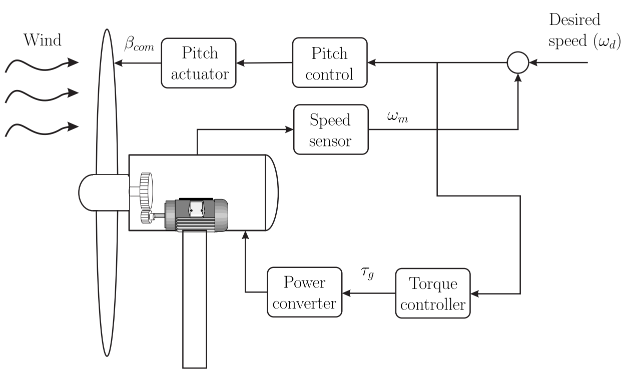

Fig. 6. Wind turbine standard velocity and torque control loops.

coefficient at the optimal tip speed ratio and a constant pitch angle. The primary control goal in this region is to maximize the amount of power extracted by wind turbine. Among ν_{rated} and $\nu_{\text{cut-out}}$, the wind turbine operates in the *pitch control region*, maintaining the power output at the rated value. The objective in this region is to limit the amount of power produced to avoid damage caused by exceeding mechanical and electrical limits. Above the cut-out level $\nu_{\text{cut-out}}$, the wind turbine should be shut down for safety of the system because beyond the cut-out level, the power output cannot be maintained at the rated power by varying the pitch angle. Some authors define Torque control region as Region II and Pitch control region as Region III. In these works, Region I consists in the cut-in region. Then, the control objectives can be resumed in: harness as much power as possible from wind in Region II and limit the generated power on the demand power or rated power in Region III. To realize the two mainstream objectives of maximum power extraction (Region II) and regulation of generated power (Region III), most of the installed wind turbines use proportional-integral, a collective blade pitch controller, and a torque controller [22].

As shown in Fig. 6, rotor speed ω_m is used as the only measured variable to generate either the demanded collective blade pitch angle β_{com} or demanded generator torque τ_g depending on the operational objectives to be realized. When wind speed is greater than cut-in speed, but lower than the

TABLE I
WECS GENERATOR COMPARISON [26].

Type	Advantages	Disavantages
Induction Generator	• Full speed range • No brushes • Active & reactive power control • Proven technology	• Full scale power converter • Need gearbox
Synchrous Generator	• Full speed range • Possible to avoid gearbox • Active & reactive power control	• Small converter for field • Full scale power converter
Permanent Magnet Synchronous Generator	• Full speed range • Brushless • No power converter for field • Possible to avoid gearbox • Active & reactive power control	• Full scale power converter • Multipole generator • Permanent magnets high cost • Demagnetization possibility
Doubly-Fed Induction Generator	• Sub-synchronous and supersynchronous operation is possible • Inexpensive PWM inverter • Active & reactive power control	• Need slip rings • Direct connect to grid is somewhat difficult • Need gearbox

rated value, standard generator torque controller is utilized to maximize generated power. This is achieved by operating the turbine at/or near the optimum power efficiency $C_{pmax}(\lambda, \beta)$ by accelerating or decelerating rotor in order to track the speed of incoming wind. The turbine is operated at a constant TSR λ, to yield maximum power. Normally, the rotor blades are pitched at optimum pitch angle β_{opt} to generate the highest possible lift. Several control strategies have been developed to reach the above objectives, some of them are: PID controller [22], fuzzy logic based control [23], combined PI and fuzzy [24], feed forward control [21] and model predictive control (MPC) [25]. Once the optimum mechanical velocity is reached, the next step is to control the electrical power.

V. GENERATED ELECTRICAL POWER CONTROL

The generator is found as the first element of the electric part. An electric generator is used to convert rotational mechanical-energy into electrical-energy. Over the past 30 years, many generators such as the squirrel-cage induction generator (SCIG), wound rotor induction generator (WRIG), doubly-fed induction generator (DFIG), permanent magnet synchronous generator (PMSG) and wound rotor synchronous generator (WRSG) have been developed for wind turbines [3].

The generator output voltage and frequency change with respect to the wind speed. The generator can be directly coupled to the grid or it can be interfaced through a power electronic converter. By arranging the power switching devices in different ways, possibly with the dc-link elements such as capacitors or inductors, numerous power converter topologies can be derived. A summary of these generators with advantages and disadvantages is presented in [26] and shown in Table I. When using converters, switching harmonics are inevitable. To solve this issue, harmonic filters are used in generator and grid-side converters. The harmonic filter on the generator-side reduces harmonic distortion of the generator voltages and currents. This leads to a decrease in harmonic losses in the magnetic core and winding of the generator. The harmonic filter in the grid-side converter helps to meet harmonic requirements specified by the grid recommendations

[27], [28]. The output of the grid-side harmonic filter is connected to a three-phase grid (or collection-point) through a step-up transformer, electric switch gear and a circuit breaker. By operating the power electronic converter at collection-point voltage level, the need for the step-up transformer can be avoided [3].

In reference of the electrical power control, probably one of the most widely discussed topology is the back-to-back converter system to interconnect the energy source to the electrical network (grid), focused on DG [29]. Moreover, on DG systems the most widely used power electronic grid-connected converter (GCC) is the active front-end (AFE), cascaded multilevel converters and neutral-point-clamped (NPC) topologies [30]–[32]. GCC topologies must ensure an efficient active and reactive flux control with minimum current and voltage harmonic distortions besides ensuring proper synchronization with the distribution networks. To accomplish this, several control and modulation methods such as: pulse width modulation (PWM), space vector modulation (SVM), vector control, fuzzy control, model-based predictive control (MBPC), etc., have been proposed [33]. Nowadays, most converters used for interconnecting the energy sources to the grid used storage energy elements (i.e. capacitor banks) which provide weight, volume and failure possibilities to the GCC topologies.

Recent research efforts have been focused in the development of a flexible power interface based on a modular architecture capable to interconnecting different RES and loads, including energy storage systems to the grid. These efforts converge in the multi-modular matrix converter (MMC) topologies whose main feature is the ability to provide three-phase sinusoidal voltages with variable amplitude and frequency using fully controlled bi-directional switches without the use of energy storage elements [34]. These characteristics makes plausible the use of MMC in applications where is required high power density and compact converters such as with wind power converter systems (WPCS), constituting an attractive alternative if it is compared with conventional converter topologies [35].

VI. New challenges and trends

Owing to its interdisciplinary nature, consisting of several branches of engineering and sciences, wind energy systematically presents new challenges and development topics for researchers. Wind energy is emerging as a major power source alongside other renewable as well as conventional energy sources. European countries have led this trend, and the wind market has also grown rapidly in the United States, due mainly to policy support [36]. In this respect, two aspects stand out as a trend. Firstly, the mainly development of horizontal axis wind turbine instead vertical ones. This is due to the drawback in conversion efficiency caused by the long wheelbase in vertical axis wind turbines. The second aspect is referred to grid connection. This is not a trivial issue and has attracted a lot of attention in last years. Several topologies for grid connection with the approach of distributed generation have been proposed. Finally, the common challenge found in the literature refers to environmental issues associated with wind power development including concerns about noise, visual impact and impacts on migratory species (such as birds and bats) from collisions during operation. Another critical issue is how to manage the stability of wind power output, specially for grid-connected systems. All the mentioned above can open new research topics, from new materials for wind generation structures to new control techniques and topology proposals.

VII. Conclusion

There is a pressing need to accelerate the development of advanced energy technologies in order to address the global challenges of clean energy. In this respect, wind power emerges as an excellent alternative which is evidenced by the globally increasing number of installed capacity in recent years. Wind energy is presented as a feasible alternative to meet the current energy demand, being a renewable energy and friendly to the environment. In addition, the conversion of electrical energy using power electronic devices has opened a wide area of research, which have made significant advances on control techniques and interconnection topologies.

Acknowledgment

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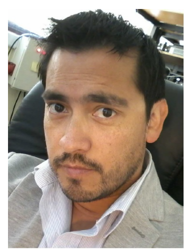

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Prof. Rivera was recipient of the Best PhD Thesis Award 2012, award given by the Chilean Academy of Science for PhD thesis developed in 2011 by national and foreign students in any Exact or Nature Sciences Program in Chile. In August 2015, Prof. Rivera was awarded with the Outstanding Engineer 2015 Award of the Electrical-Electronics Industry Association and the IEEE-Chile Section and also he received the Second Prize Paper Award in the 2015 IEEE Journal of Emerging and Selected Topics in Power Electronics.

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