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State-of-the-Art in Wind Turbine Control: Trends and Challenges

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Abstract

Wind energy is one of the most rapidly growing renewable sources of energy due to the fact that it has little negative impact on environment. To meet the growing demand, wind turbines are being scaled up both in size and power rating. However, as the size increases, the structural loads of the turbine become more dominant, causing increased fatigue stress on the turbine components which can lead to early failure. Another area of focus in wind energy is lowering production cost to give it a competitive edge over other alternative power sources. From the control point of view, low production cost of wind energy can be achieved by operating the wind turbine at/or near the optimum power efficiency during partial load regime, guaranteeing reliability by reducing fatigue loads, and regulating generated power to its rated value in the high wind regime. Often, it is difficult to realize a control algorithm that can guarantee both efficiency and reliability because these two aspects involve conflicting objectives. This paper reviews various control strategies that are used in wind turbine systems, both in low and high wind speed regions focusing primarily on multi-objective control schemes. Emerging trends that are likely to influence the current or future wind energy production, either positively or negatively, are also discussed.

Keywords: Multi-variable controller, Large wind turbines, Power optimization, Emerging trends

1. Introduction

Owing to growing environmental concerns, focus has shifted to generating power from renewable energy sources such as hydro, tidal, wind, bio-, and solar which do not emit greenhouse gases. Among these renewable energy sources, wind energy has attracted a lot of attention due to its abundance and advancement of supporting technologies among other factors. Wind energy is harnessed by wind turbines which converts wind kinetic energy into mechanical energy and finally into electrical energy.

In spite of increasing global installed wind turbine capacity and favorable future projections [1], the cost of wind power is still high compared with other conventional power sources as a result of high initial capital investment, which in turn increases the production cost per unit of power generated.

Another challenge related to wind energy harvesting is the high operation and maintenance (O&M) costs, especially in offshore wind turbines located far away from coastal line due to logistical difficulties in accessing the production sites as well as high cost of transmission lines. But with the employment of robust structural health monitoring methods in conjunction with appropriate control strategies, especially in offshore wind farms, the cost of producing wind power can be further reduced.

Due to the obvious advantages, majority of modern utility-scale wind turbines produced today have three blades with horizontal-axis configuration [2, 3]. For instance, the entire rotor can be placed atop tall tower where it is able to capture 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.

As noted in [4], wind turbines can either be manufactured with a fixed-pitch or variable-pitch blades. Although, fixed-pitch turbines are initially less expensive, their inability to adjust pitch angle make them less popular in the realm of large wind turbines where structural loads are more pronounced. Moreover, wind turbines can also be variable-speed or fixed-speed [5]. Variable-speed turbines can also be operated around their optimum power efficiency, but this requires the use of additional power electronic processing unit to couple them to grid system. The use of converters guarantee that the power generated meets certain performance requirements before it is connected to the main grid. On the other hand, fixed speed wind turbine are simple and robust, 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. Furthermore, 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 majority of Mega utility-scale wind turbines that are manufactured nowadays are variable-speed, variable-pitch, and horizontal-axis turbines.

Generally, wind turbines are inherently nonlinear and interact with wind profile which spatially varies in both speed and magnitude [2]. Due to nonlinearities in wind turbine, it is difficult to develop a perfect mathematical model that can effectively capture all its dynamics. This challenge is further compounded by the fact that the dynamic behaviors of incoming wind are usually faster than that of turbine itself, unknown, and difficult to predict. Contrastingly, unmodeled dynamics in wind turbine can be compensated for by using appropriate control methods. Over the last few decades, several simulators such as GH Bladed [6], Fatigue, Aerodynamics, Structures, and Turbulence (FAST) [7], Flex5 [8], Automatic Dynamic Analysis of Mechanical Systems (ADAMS) [9] etc., have been developed for the purpose of designing and simulating wind turbine structural dynamics. Among these simulators, FAST and GH-Bladed, which are based on “Assumed Mode” method, are the most preferred in control design approaches because it is possible to extra control-oriented models. Compared to finite element-based models, “Assumed Mode”-based models are less computationally expensive, making them more attractive in control design applications.

Nowadays, most of utility-scale wind turbines are installed with individual blade actuation mechanism to control each blade independently. Furthermore, they are also equipped with several sensors on blades as well as on tower and nacelle, making them inherently multi-input multi-output (MIMO) systems. For this reason, standard single-input single output (SISO) controllers that are used in majority of utility-scale wind turbines are rendered ineffective in controlling such systems [10]. The additional measurements can also be used for monitoring the health status of various components in turbine and in condition-based maintenance (CBM) [11].

Unlike SISO controllers, MIMO controllers can realize multiple objectives such as elimination of structural loads and regulation of generated power at the same time. This is becoming an attractive control strategy since wind turbine maintenance cost can be lowered as well as extending oper-

ational life time. In recent years, a number of control strategies have been proposed to mitigate structural load on wind turbines and these include mitigation of loads in rotor blades [12, 13], minimization of tower deflection [14, 15, 16], and reduction of drive-train vibrations [17, 18].
In order to reduce the cost of energy (COE) in wind power generation, control strategies are hinged on efficiency, reliability, and safe operation of wind turbines. In this paper, a detailed review of existing and emerging wind turbine control schemes is presented, highlighting the approaches employed, and exploring their strengths and shortcomings. This paper is organized as follows: Section 2 gives a brief insight on wind turbine fundamentals, outlining control objectives and underscoring existing challenges in wind turbine control. In Section 3 various advanced methods employed in wind turbine control are discussed. Section 4, presents an analysis and discussion emanating from reviewed control methods is delineated. Finally conclusions drawn from various control strategies are summarized in Section 5.

2. 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.

2.1. Wind turbine basics

The maximum extractable power by wind turbines is limited to 59.3% of the available wind power [19]. This limit is referred to as Betz limit, which gives the maximum achievable aerodynamic efficiency in wind turbines. The power extracted by wind turbine P_a is expressed as

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

where ρ denotes air density, R is the rotor radius, v 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

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

where Ω denotes the angular rotor speed, R is the rotor radius and v is the incoming wind speed. For any wind speed there exist a rotor speed for which the value $C_p(\lambda, \beta)$ is maximum and this value corresponds to optimum tip-speed-ratio λ_*. This is illustrated in Fig. 1, which represents a typical TSR-β-C_p curve for a fictitious NREL, WindPACK 1.5 MW wind turbine model. Figure 1(a) shows a three dimensional plot of TSR-β-C_p, while Fig. 1(b) depicts the maximum C_p corresponding to a given TSR for a particular blade pitch angle. Specifically, this wind turbine model has a maximum power coefficient of 0.488 at TSR of 7 and optimum blade pitch angle of 2°.

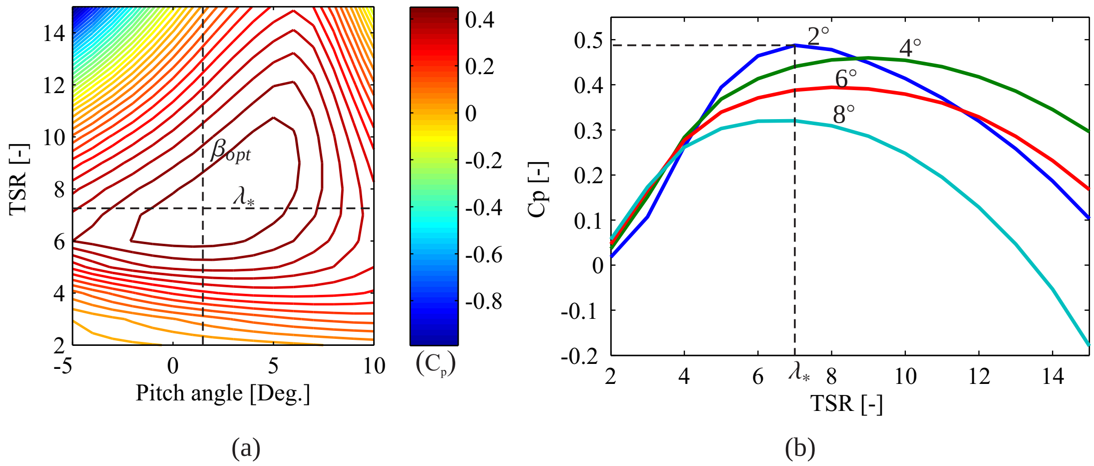


Figure 1: Tip speed ratio, pitch angle power coefficient curve for NREL WindPACT 1.5 MW Turbine

2.2. Standard control methods and control hierarchy

The wind turbine conversion system (WTCS) control hierarchy has three distinct levels; namely, supervisory control, operational control, and subsystem control [20]. The high-level or supervisory control is charged with turbine's starting-up and shutting-down procedures. The operational or turbine-level control is concerned 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 generator power electronic unit. Subsystem controls are usually considered as a black box since they are commanded by other control systems higher in the hierarchy [21]. The scope of this paper is limited to the review of turbine-level control strategies that realize specific operational goals.

In order to have an in-depth understanding of operational goals, the variable-speed wind turbine power curve can be used to distinguish the operational zones and the related control objectives thereof. As illustrated in Fig. 2, three distinct operation regions in variable-speed wind turbines can be identified: below the cut-in speed region (region I), the region between the cut-in wind speed and below the rated wind speed (region II), and the region above the rated wind speed (region III). Another important zone for control design is the transition region from partial wind to above rated wind speed. As noted in [2], the control objective changes depending on the prevailing wind conditions. The primary control goal in region II is to maximize the amount of power extracted by wind turbine, while in region III the objective is to limit the amount of power produced to avoid damage caused by exceeding mechanical and electrical limits. The transition region is designed to ensure that the turbine reaches the rated power at the rated speed.

To realize the two mainstream objectives of maximum power extraction and regulation of generated power, most of the installed wind turbines use proportional-integral, a collective blade pitch controller, and a torque controller. As shown in Fig. 3, rotor speed Ω 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.

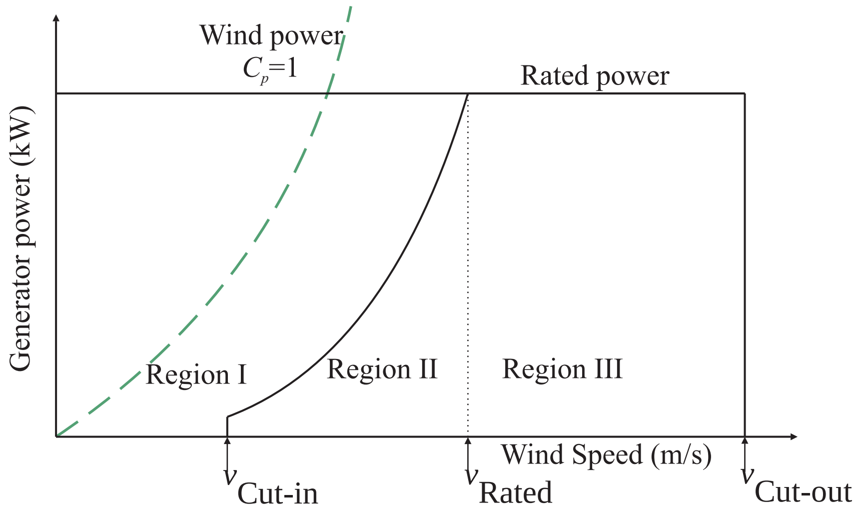


Figure 2: Generalized variable-speed wind turbine power curve

2.2.1. Generator torque control

When wind speed is greater than cut-in speed, but lower than the 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 $C_{p_{max}}(\lambda, \beta)$ by accelerating or decelerating rotor in order to track the speed of incoming wind. The turbine is operated at a constant tip-speed-ratio (TSR) λ_*, to yields maximum power. Normally, the rotor blades are pitched at optimum pitch angle β_{opt} to generate the highest possible lift.
The standard generator controller is expressed as

$$\tau_g = K_T \Omega^2, \tag{3}$$

where K_T is given by

$$K_T = \frac{1}{2}\rho\pi R^5 \frac{C_{p_{max}}(\beta_{opt}, \lambda_*)}{\lambda_*^3}. \tag{4}$$

Here, λ_* is the optimum tip-speed-ratio that corresponds to the maximum power coefficient $C_{p_{max}}$. It is clear from a simplified one-mass wind turbine model

$$J_r \dot{\Omega} = \tau_{aero} - \tau_g \tag{5}$$

that generator torque τ_g balances out with aerodynamic torque τ_{aero} at steady state, otherwise the rotor either accelerates or decelerates to maintain a constant TSR that yields the maximum power. This control method is popular and simple to implement. As outlined in [22], no accurate method for determining the constant gain K_T exists. Even when K_T is assumed to be accurately approximated either numerically or experimentally, wind speed varies spatially forcing the turbine to operate sub-optimally. It has been further observed that when the rotor speed is strictly tracking the speed of incoming wind in region II, very high mechanical stresses are induced in the drive-train due to torque variation. This in turn can cause severe excitation of poorly damped modes in the turbine [23].

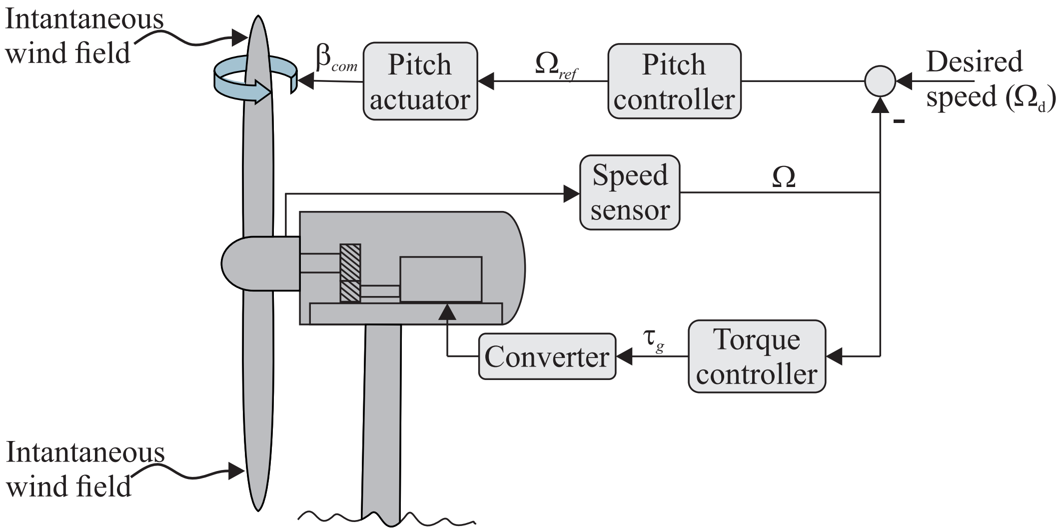


Figure 3: Wind turbine standard control loops

2.2.2. Standard collective pitch control

In region III, the main objectives is to regulate generated power around the rated value as well as limiting structural loads to avoid violation of mechanical and electrical constraints of the wind turbine system. In the standard traditional control scheme, this is achieved by holding generator torque constant, while deploying collective pitch control to regulate the generator speed to the rated value. Most of the commercial wind turbine use proportional-integral (PI) collective blade-pitch control controller [24] to regulate rotor speed above-rated wind speed regime given by

$$\beta_c(t) = K_p \Omega_e(t) + K_i \int_0^t \Omega_e(\tau) d\tau, \tag{6}$$

where $\Omega_e = \Omega_d - \Omega$ is the rotor speed error, Ω_d represents the desired rotor speed while K_p and K_i denote proportional and integral control constants, respectively. In most cases, a standard gain-scheduling type PI controller is employed to cope with nonlinearities caused by the pitch actuation mechanism and the deviation of operation point from the control design point. Likewise, anti-wind up and saturation limits are deployed to avoid problems related to integration of negative speed error which might be occasioned by gusty winds.

One of the major drawbacks of this control method is that all blades are assumed to have similar physical properties and are subjected to the same amount of aerodynamic load during operation which is seldom the case. As a consequence, the rotor disc is always acted upon by unbalanced loads which cause induced stresses that might lead to eventual failure.

2.3. Structural loads in wind turbines

As wind turbines grow in size and output power rating, the adverse effects of structural loads become more and more pronounced, especially those induced by aerodynamic and gravitational forces. If not mitigated, structural loads can cause undesirable performance or even lead to early failure of the whole wind turbine system. It is therefore imperative to know how structural loads

interact and/or influence wind turbine power generation and affect its life time.
Normally, wind turbines are subjected to intermittently variable wind profile which changes in both direction and magnitude, resulting into asymmetrical aerodynamic loads that vary spatially across the rotor disk. Incidentally, unbalanced aerodynamic loads are the main cause of the structural loads in wind turbines. Another cause of induced structural loads is gyroscopic effect which come about as a result of combined action of rotor rotation, blade pitching, and nacelle yawing. Like asymmetrical aerodynamic loads, gyroscopic forces can cause cyclic stress to the hub or induce cracks in blades. It is worth noting that the aforementioned loads act simultaneously during power generation, making it difficult to determine the contribution of each class of load to the overall structural load in wind turbine system. In large wind turbines, cyclic loads are the major cause of fatigue stress which, if not mitigated, may lead to premature failure of turbine [12].
For a 3-bladed turbine, rotor blades are 120° out of phase with each other, meaning that at any given azimuth position, each blade is subjected to unequal aerodynamic forces because of vertical wind shear. Indeed, each blade samples different aerodynamic forces for every cycle since the approaching wind varies in both speed and direction. Since wind exhibits turbulent behaviors, the resulting unbalanced loads have stochastic properties.
Vertical wind shear is another main cause of asymmetrical loads across the rotor. It is described as a change in horizontal wind speed and/or direction with altitude as shown in Fig. 4(a). Additionally, rotor load imbalance can be caused by the tower shadow which makes the wind speed to reduce as it approaches the turbine tower. Normally, the effects of tower shadow are more pronounced in upwind horizontal-axis wind turbine configuration compared to downwind configuration. The structural loads emanating from vertical wind shear and tower shadow are said to be deterministic in nature since they occur in a periodic manner for every rotor revolution. Since the wind turbine is influenced by the loads that have both deterministic and stochastic properties, it is difficult to effectively predict its dynamic response.
In the realm of large wind turbines, structural load mitigation is attracting a lot of attention, with most of the reported work focusing on mitigation of once per revolution (1p) loads using independent blade pitch controller [25, 26]. However, only a few attempts have been made to minimize higher harmonic loads [27]. It is usually presumed that fatigue damage is mainly contributed by 1p deterministic loads on rotor blades and 3p harmonic loads on the fixed structure, which might not be absolutely correct in large wind turbines.
The rotor blades, tower and drive train bending modes considered in regulation of structural loads are shown in Fig. 4(b)-(c). Here, the tower has fore-aft and side-side deflection modes, while the blade has flap-wise and in-plane deflection modes. Additionally, the drive-train is usually subjected to varying torsional stresses during generation of wind energy due to fluctuating wind speed.
In addition to the two mainstream objectives of power maximization and regulation of generated power/speed, mitigation of structural loads in wind turbines has attracted a lot of attention in the recent past. In literature, most of the control strategies have been developed to handle only a particular kind of deflection mode while disregarding the others, majority focusing on flap-wise deflection mode [25, 26, 12, 28]. Other authors have reported control methods that mitigate loads on turbine tower [15, 16] and drive-train deflection [17, 18]. From the aforementioned discussion, it can be concluded that it is important to consider structural load reduction from a global point of

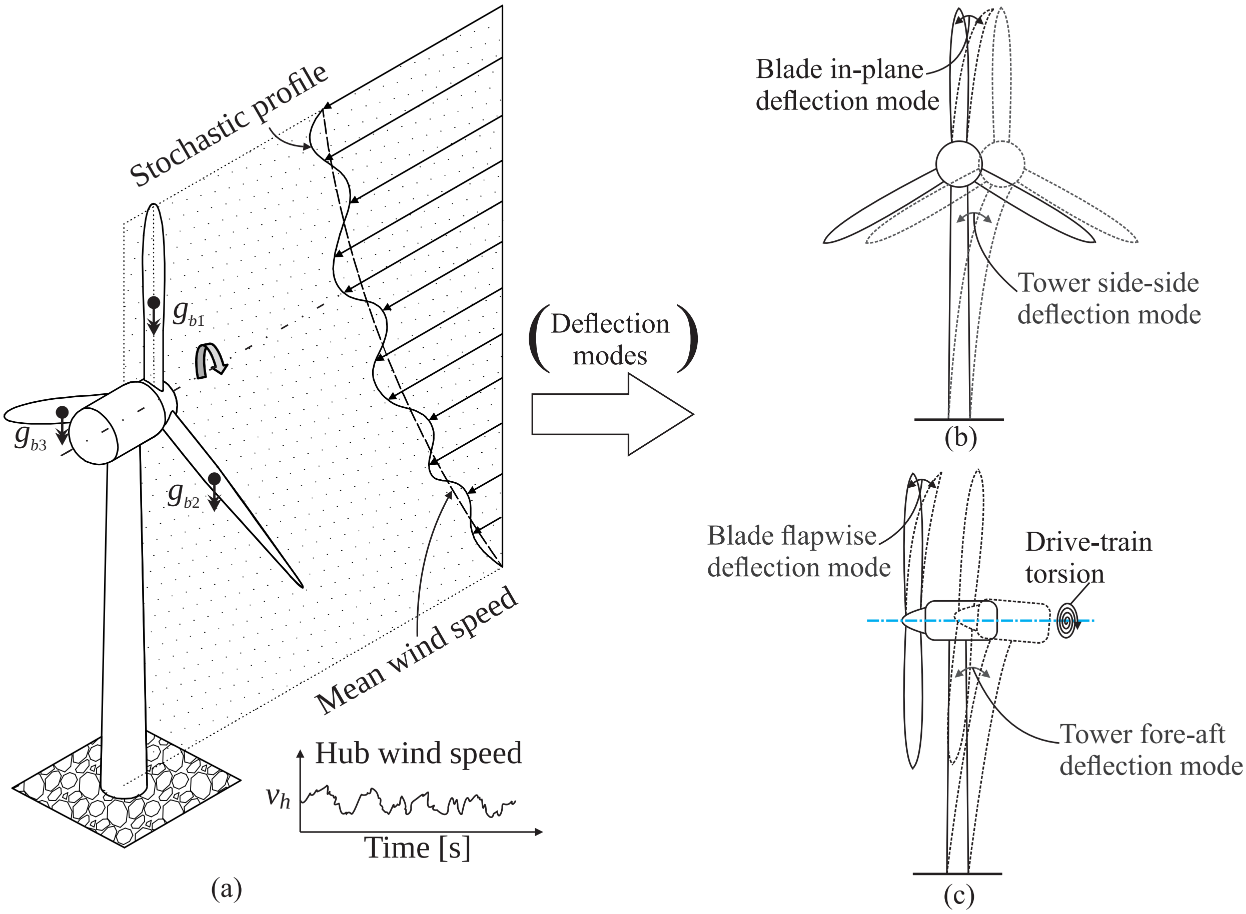


Figure 4: Tower and rotor blade deflection modes in wind turbines

view rather than accomplishing localized solutions for specific turbine parts. This can be achieved by designing multi-objective control strategies capable of reconciling different opposing control requirements.

2.4. Material-related aspects related to structural loads

Material consideration for various components in wind turbine plays an important role in determining the overall cost, performance, and structural load endurance in wind turbine systems. The suitable selection of materials in wind turbine harvesting systems is strongly affected by the location. Depending on the location (onshore, offshore, location related-wind profiles and properties), wind turbines are subjected to different operation conditions. This and also turbine dimensions strongly effect the materials choice because parts with special attributes are required as the turbine grows in size. Furthermore, it is inevitable to make material consideration with respect to all major components in wind turbine rather than focusing only on few components that are considered to be highly susceptible to failure. Generally, the development of new materials and manufacturing technologies are geared towards lowering the cost of producing wind power and investments into such developments should be viewed in terms of long term benefits since the initial investment capital might be higher than the existing ones. For instance, components made from materials of superior quality are likely to be costly, but on the other hand a materials-based extended lifetime (leading also to reduced maintenance cost) changes the cost, especially in the case maintenance cost are weighted higher (offshore applications).

Special attention should be paid to offshore wind turbines due to harsh environmental conditions they operate under. Normally, they are subjected to higher velocity winds and exposed to saline marine environment, making them more susceptible to corrosion [29]. As a result, the components for such turbines should have high mechanical strength, high fatigue strength as well as high corrosion resistance. Stringent material requirements, installation of offshore wind turbines is more capital intensive.

The rotor, which consists of blades and hub, is one of the most expensive component in wind turbine system, roughly accounting for 20% of the total wind turbine cost [30]. Rotor blades are more susceptible to damage due to intermittently varying aerodynamic loads and to different weather conditions. As stated in [31], rotor blades should possess the following qualities: high mechanical strength to handle extreme aerodynamic loads, high fatigue resistant, high stiffness strength to avoid collision with tower, and light in weight. Mostly, blades are manufactured using fiber-reinforced plastic (FRP) due to improved strength-to-weight ratio, with glass, carbon, and aramid fibers being the most commonly used [32]. The choice of these fibers as a reinforcement material primarily depend on the cost and the application requirements such as strength, stiffness, and corrosion resistant among others. As outlined in [33], glass fibers have high tensile strength and impact resistant, but low modulus strength making them unsuitable for large wind turbines applications. On the other hand, carbon fibers are preferred for high performance applications because they exhibit excellent resistance, although they have less impact resistance and poor interlaminar properties as compared ro glass fiber. Aramid fibers have high strength-to-weight-ratio and good impact resistance, making them suitable for applications that require high toughness and high modulus strength. To take the advantages of superior properties of glass and carbon fibers, hybrid composite made of glass and carbon can be used to enhance the mechanical properties [34]. It should be mentioned that the overall strength of any composite is strongly influenced by the volume of fiber content, with stiffness increasing proportionally up maximum (about 65%) then start deteriorating [35].

Likewise, the type of laminate material is crucial in determining load carrying capacity as well as the cost of fiber-reinforced composites blades. Epoxy, vinyl ester, and polyester resins are the commonly used laminate materials in wind turbine blades. As example, epoxy resin has strong advantages in comparsion to polyester and vinyl ester, but related to the cost it shows strong disadvantages. All resins are prone to degradation due to moisture absorption, but the rate of epoxy degradation is slower compared with polyester and vinyl ester, making them more suitable in offshore wind turbine application [36], while glass, carbon, and aramid fiber-reinforced polymer have been considered as suitable alternative choices for manufacturing wind turbine blades. According to [32] their production is highly based on petroleum-based resources and is negatively weighted by the authors. This has necessitated exploration on the suitability of using naturally occurring fibers as a substitute of petroleum-based fibers [37].

For wind turbine tower, material choice should be geared towards performance characteristics, ease of manufacturing and transporting so as reduce installation and manufacturing costs [38]. It

is imperative to note that material for offshore applications should be durable and have high corrosion resistance. Steel/concrete composite and fiber-reinforced composite have been proposed as an alternative solutions to building large wind turbine towers [39].
Gearboxes are used to transfer mechanical power from rotor to generator. During wind power production, gearboxes are subjected to varying mechanical stresses which might lead to fatigue damage. Therefore, the choice of material is critical in determining the service life of a gearbox. As delineated in [40], some of innovative material development processes used to enhance gear properties (increased wear and corrosion resistance and micro hardening) are: ultra-dispersed diamond power (UDDP), novel coating and surface treatment such as high velocity oxygen fuel (HVOF), and physical vapor deposition (PVD) process. Gearboxes are among the most expensive components in wind turbines, the manufacturers often include significant overhead costs to cover warranties due to their high failure rates and high maintenance cost [41]. Direct drivetrain are to replace geared drivetrains, also leading to effects of minimizing maintenance cost [42].
In the construction of wind turbine foundation, durability and related cost are the main factors that influence material choice, especially in offshore applications. The construction cost of offshore foundation constitutes a sizable portion of the overall cost of wind turbine and a trade-off between cost and performance requirements must be carefully considered in material selection. In fact, the construction cost increases with the distance from shore and increase in water depth [43]. As water depth increases, the foundation diameter is enlarged to preserve the required stiffness, resulting into increased material and installation cost [44].

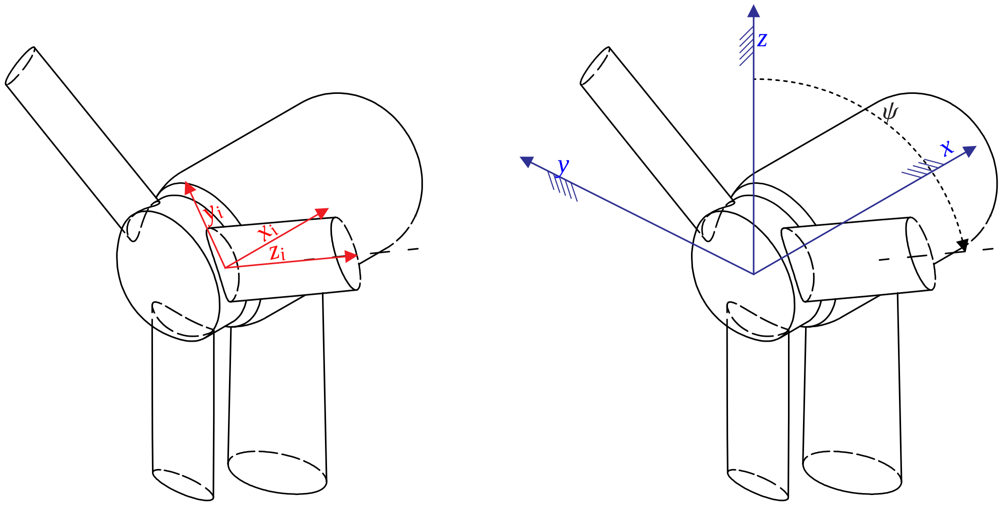
3. Advanced control methods

Nowadays, the focus in wind energy has shifted to lowering its production cost, improving the quality of generated power, safety, and reliability. However, to tackle these challenges, researchers have proposed various innovative control strategies to address the deficits of the standard control methods. Most of these advanced control algorithms are concerned with optimization and quality improvement of generated power, speed/power regulation, and/or reduction of structural load in wind turbines. This section discusses various advanced control methods that are employed in wind energy production.

3.1. Power/speed regulation and load mitigation problem

3.1.1. Classical methods

As mentioned, load mitigation is becoming increasingly important among the Mega-scale utility wind turbines. This is motivated by the need to guarantee reliability and to ensure that the quality of output power is not compromised. To reduce fatigue load emanating from asymmetric loads in the rotor disk, blades are normally manipulated independently using independent blade pitch controller (IPC).
As pointed out in [45], asymmetrical loads across rotor disk cause blades to be excited by a dominant once per revolution (1p) in addition to other higher order harmonic flap-wise load spectrum i.e., 2p, 3p, 4p, etc., whose frequencies depend on rotor rotational speed. On the other hand, non-rotating parts of the turbine are dominantly influenced by 3p harmonic load components plus their higher order integral multiples.



(a) (b)

Figure 5: Rotating and fixed coordinate of reference

Since wind turbines are inherently MIMO systems with measurements being taken from both the fixed and rotating structural members, it is important to design a controller with all state variables expressed with respect to a fixed coordinate system rather than in a mixed coordinate system. This can be achieved by transforming all dynamics of system model expressed with respect to rotating rotor to a fixed coordinate system. In literature, Multi-blade coordinate (MBC) transformation [46], also referred to as Coleman transformation is used to map all dynamic variables into a fixed coordinate system. As shown in Fig. 5, variables expressed with reference to rotating coordinate system x_i y_i z_i are mapped into a fixed coordinate system x y z. The fixed coordinate system is usually referred to as collective, cosine-cyclic, and sine-cyclic coordinates, respectively [47].
Most of the reported work on individual pitch controller concentrates on reduction of 1p harmonic rotor blade load [48, 26, 45]. Coleman transformation is normally used to express the root blade bending moments with respect to a fixed direct- and quadrature- orthogonal axes. Then two independent PI-control loops are designed to suppress loads on these two axes. Finally to generate the corresponding demanded individual pitch angle, inverse Coleman transformation is carried out. In [26], an alternative solution is discussed, where an LQG controller is used to generate the pitch angle for each blade instead of designing multiple PI-control loops.
An individual pitch controller is applied to a doubly fed induction generator (DFIG) wind power system to mitigate 1p harmonic loads on the rotor blades and 3p harmonic loads on the fixed structure of wind turbine is reported in [45]. To realize this goal, bending moments on the rotating rotor blades were transformed into fixed d-q coordinate axes moments (yaw and tilt bending moments) using Coleman transformation. Then two standard PI controllers were designed to regulate d-and q-moments. Since 1p harmonic load is the main source of fatigue loads on the rotor blades, a low pass filter was used to mitigate higher order harmonics from being transmitted to the fixed structure of the turbine. The results showed improvement in load reduction as compared to a collective pitch controller (CPC).
A study aimed at offering reconciliation between two competing objectives of reducing tower de-

flection and speed regulation in a two bladed wind turbine is explored in [49]. This is achieved through a combination of IPC and CPC control schemes. It was observed that CPC influenced blade aerodynamic torque and employing it to damp tower oscillation could lead to interference with the rotor speed control objective. On the contrary, IPC can reduce tower vibrations by allowing higher aerodynamic rotor loads for just a brief moment. Hence, by combining these two control approaches a trade-off between these two opposing objectives was realized. The reported results indicates improved trade-off between tower deflection reduction and rotor speed regulation when a combination of collective and individual pitch controller is used as compared with CPC or IPC independently.

Individual pitch control can also be utilized to reduce wind turbine torque fluctuation as demonstrated in [50]. This is achieved by the reduction of blade edge-wise bending moments which in turn minimizes rotor torque variation. The adjustment of individual pitch angles is based on multi-stage dynamic weight distributions which are evaluated depending on the rotor azimuth position, influence of tower shadow, and vertical wind shear. The performance of this control method was evaluated against a single neuron PID controller. This control approach does not only minimize torque variation but also smooths the fluctuation in the flap-wise bending moments, the yaw bending moments, and the tilt bending moments

The minimization of rotor tilt and yaw bending moments in order to suppress both the low frequency 1p harmonics on blades and 3p harmonics on fixed turbine structure is discussed in [51]. To achieve this, a 2 degrees-of-freedom IPC controller comprising of a multi-variable LQG and feed-forward disturbance controller was proposed. A simplified form of Multi-blade coordinate (MBC) transformation similar to that reported in [26] is used to convert all quantities defined in rotating coordinate system to a fictitious fixed direct- and quadrature-axes (d-q coordinates). This led to an exploitation of a well-developed linear control theory to reduce the structural loads. The results demonstrated a significant reduction in both tilt and yaw bending moments when feed-forward control loop was introduced.

As stated in [52], a fusion of two controllers is used to realize a trade-off between speed regulation and load reduction: Collective pitch control is used for speed regulation while individual pitch controller is used for structural load reduction. Both controllers are based on LQR control technique with integral action (LQRI) in order to cancel steady-state errors for step wind disturbances, and employ Kalman filter to estimate both system states and wind speed. Again, Coleman transformation is applied to convert linear time varying model into linear time invariant wind turbine model in order to design a linear controller. A feed-forward control loop is added to compensate for variation in wind speed. Results indicate improved rotor speed regulation as well as reduction in d- and q-bending moments which in turn reduces $1p$ rotor blade harmonics.

In [53, 54], a multi-variable $\ell 1$-optimal control scheme is used to minimize blade root bending moment while maintaining a constant rotor speed during high wind speed regime. To achieve this goal, two decoupled LTI models were derived using Coleman transformation in order to design CPC and IPC based on $\ell 1$-optimal control theory. It was noted that a multi disturbance model like the one described in [7] was not suitable for designing an $\ell 1$ controller, and some modifications to decouple irrelevant mode intersections were required. Blade root out-of-plane bending moment and low speed shaft bending moment are greatly reduced while tower fore-aft bending moment was slightly reduced.

A proportional resonant individual pitch controller for mitigating blade root blade, tilt, and yaw bending moments is examined in [55]. Unlike other load reduction control strategies in wind turbines, this method does not require measurement of blade azimuth angle or carrying out multiple complex Coleman transformations between rotational coordinate frame to fixed coordinate frame. Here, individual blade bending moments are converted into two orthogonal α- and β-axes using Clarke transformation, and then two proportional resonant (PR) controllers are used to reduce transformed bending moments in these two new axes. The transfer function of PR controller depends on bandwidth of resonant peaks and the harmonic of blade root bending moment that has to be minimized. Simulation results indicate that proposed PR-based individual pitch controller can effectively alleviate structural load in wind turbine. However, the influence of load mitigation on torque variation and generated power was not reported.

According to [56], higher harmonic loads can also contribute significantly to fatigue loads in larger wind turbines. So, it is necessary to mitigate higher harmonic structural load, especially in Mega-scale wind turbines. In literature, a number of higher harmonic controllers (HHC) [56, 27, 57, 58], with applications to wind turbines, have been investigated. Normally, individual HHC loops connected in parallel are designed to minimize higher harmonic loads in the rotor which in turn reduce 3p harmonic and its integral multiple structural loads on the fixed structure.

Most of the structural load reduction controllers in wind turbines that have been reported rely on blade load measurements. To avoid direct measurements of these loads, control methods based on the computation of structural aerodynamic loads using inflow conditions have been explored in [59, 25, 48]. Normally, pitot tubes are used to measure inflow conditions. In [25, 60], local inflow measurements on each blade were used to compute blade bending moments for designing an individual pitch controller. It was assumed that all blades were physically and aerodynamically similar since the properties of a single blade were used to compute future loading of all other blades.

A cyclic blade pitching control method for mitigating the slow varying rotor tilt and yaw moments is proposed in [59]. Here, pitch angles were adjusted depending on measured local inflow angle and relative velocity on each of the rotor blades. Compared with collective pitch controller, individual pitch controller greatly reduced blade tilt and yaw bending at the tower top. Nevertheless, in this contribution, it was not demonstrated how the compromise between structural load reduction and power regulation was achieved.

3.1.2. Disturbance observer-based controllers

Since not all system states are available for measurement and due to the fact that the dynamics of the incoming wind are unknown, it is reasonable to use few output measurements to estimate unknown system and disturbance states. More specifically, wind speed variation, nonlinearities, and other unmodeled dynamics can be estimated and compensated for using a suitable observer in conjunction with an appropriate control scheme. Next, various variations of disturbance observer-based controllers applied to wind turbine systems are discussed.

The idea of estimating and compensating for disturbance was first proposed in 1976 by Johnson [61] and has since then been referred to as disturbance accommodating controller (DAC). A fixed gain DAC has been applied successfully in regulating rotational speed of turbine rotor [62]. Later, the idea of compensating for persistent wind variations was extended to multi-variable control design methods [63, 12, 64], followed by the introduction of periodic gain DAC to mitigate asymmetrical loads across rotor disk [65, 62, 66].

In [67], the performance of a periodic gain controller for regulating generator speed in a two-bladed, variable-speed, horizontal axis wind turbine was investigated. In comparison with a constant gain controller, the periodic gain controller had marginal performance improvement with respect to speed regulation. In a different study [63], a similar conclusion was drawn when a fixed gain collective pitch DAC and a collective periodic DAC were compared in speed regulation.

A periodic disturbance accommodating controller for regulating rotor speed and mitigation of cyclic rotor blade loads is proposed in [65]. This controller was applied to a two-bladed downwind turbine, where blades were manipulated individually to realize these two objectives simultaneously. The algorithm utilized a periodic state estimator to reconstruct system and disturbance states using rotor speed and rotor azimuth position as the only measurement signals. Compared to the fixed gain controllers, periodic gain controller has better performance with regards to load reduction. Unlike the approach reported in [63], where marginal performance improvement was registered with regard to speed regulation, IPC periodic disturbance accommodating controller offers a reasonable trade-off between speed regulation and structural load reduction.

To effectively compensate for unknown disturbances in any controlled system, it is important to accurately estimate them. This is normally realized using disturbance observers. In which case the determination of the optimum gain is essential for achieve good results. While high gains are necessary for reasonable disturbance estimation, extremely high gains cause the disturbance observer to become sensitive to measurement noises and unmodeled dynamics [68]. One of the strategies for determining the optimum observer gain is discussed in [69], where the gains are on-line adapted.

A stochastic disturbance accommodating controller (SDAC) for stabilizing a system with unmodeled dynamics and unknown exogenous disturbance is presented in [70]. This approach uses an Augmented Kalman Estimator in the feedback loop to estimate the system and disturbance states using noisy output measurement. The results indicate good performance with reference to speed regulation and damping of drive-train vibration.

In [71], SDAC is used for output power regulation and structural loads reduction in wind turbine. This control method is motivated by the fact that wind turbine is normally influenced by aerodynamic loads with statistical properties. In this study, it was assumed that wind turbine was excited by both wave and stochastic process noises in addition to measurement noise. The controller mitigated 1p harmonic loads while maintaining a generator speed around the rated value.

To compensate for adverse effects resulting from the model uncertainties and unknown exogenous disturbances, a linear stochastic disturbance accommodating (SDAC) controller is proposed in [72]. Unlike the traditional DAC which treat external disturbances as a waveform with unknown magnitude, the SDAC considers disturbances as composed of both the waveform and stochastic components. This control method also uses the Augmented Kalman Filter to estimate both the system states and the disturbance (unknown inputs). Then the appropriate controller was designed to compensate for disturbances and stabilize the closed-loop system. Additionally, the stochastic stability analysis revealed that weighting gains for the Kalman filter must be lower-bounded to guarantee closed-loop stability. Similar work is reported in [73], where the focus is on studying the stability and on-line adaption of process noise covariance matrices of SDAC in order to stabi-

lize the closed-loop system.
A control strategy to suppress wind turbine tower vibration is presented in [16], where a disturbance observer-based controller was used to attenuate the disturbance at the top of the tower. Compared with proportional derivative (PD) controller, this control strategy had better performance in terms of dampening tower top deflection.
An adaptive collective blade pitch controller for regulating generator speed and disturbance rejection during high wind speed region is discussed in [74, 75]. In [74], a modified direct model reference accommodating controller (MRAC) with an ability to cancel the disturbance on the output is presented. While in [75], the turbine model is augmented with Residual Mode Filter (RMF) to compensate for modes in the system that might violate the requirements of the Almost Strict Positive Real (ASPR) plant for adaptive control design is discussed. Compared to the standard collective blade pitch PI-controller, the results indicate improved performance with respect to generator speed regulation for both step and turbulent wind inflow.
In another study, a supervisory control strategy to mitigate structural loads in wind turbine is discussed in [76]. This strategy is based on model predictive control, where a trade-off between structural load minimization and tracking of the maximum power is realized. It was observed that a significant reduction in rotor thrust dominant loads could lead to an increased low-speed shaft torsion moment, causing fatigue failure in drive-train system.

3.1.3. Multi-variant robust control

Robust control schemes have also been applied to wind turbines to mitigate adverse effects of variability of wind speed, with $\mathcal{H}_2$ and $\mathcal{H}_\infty$ being the most reported in the literature. As pointed out in [77], $\mathcal{H}_2$ controller is more appropriate in applications where disturbance rejection and noise suppression are crucial whereas $\mathcal{H}_\infty$ controller is suitable when the robustness to plant uncertainties is important. In both $\mathcal{H}_2$ and $\mathcal{H}_\infty$ control schemes, the task is to achieve stabilization while guaranteeing certain performance requirements such as disturbance attenuation, bandwidth limitation, and robust tracking problem.
A multivariate $\mathcal{H}_2$ controller for minimization of structural load is proposed in [78]. In this study, a multi-blade coordinate transformation was applied to the nominal wind turbine model. Then the resulting model was augmented with a stochastic wind model in order to design an observer-based independent blade pitch controller so as to estimate and compensate for wind speed variability. In comparison to collective pitch controller, the results of a multi-variant controller indicate improved performance regarding the reduction in yaw and tilt moments.
In [79], an $\mathcal{H}_\infty$-based individual blade pitch control for minimization of first axial tower bending mode as well as 1p fluctuations in blade bending moment is proposed. Since blade, rotor speed, and axial tower deflection modes are highly coupled, a multi-variable controller based on $\mathcal{H}_\infty$ design is proposed to stabilize the wind turbine while reconciling the conflicting requirements of structural load reduction and speed regulation. Again, d-q transformation was carried out to convert from mixed coordinate system to fixed coordinate system. The results indicated a significant reduction in structural loads, although at the sacrifice of the time required to settle to the reference rotor speed.
In another study, a $\mathcal{H}_\infty$-based multi-variable, multi-objective control strategy for regulating generator speed and reducing both the drive-train and tower loads during high wind speed is discussed

in [80]. These objectives were realized by designing two robust $\mathcal{H}_\infty$ multi-input single-output (MISO) control loops: One for generating a collective pitch angle and the other for determining generator torque signal. The two controllers were actualized by solving a $\mathcal{H}_\infty$ mixed sensitivity problem where notch filters were included in the control dynamics to achieve these objectives. Compared to standard pitch controller, the proposed strategy offered a compromise between speed regulation and load reduction.
A multi-objective control scheme for regulating generator speed and minimizing structural load reduction is described in [81]. This control scheme comprises of a linear matrix inequality-based collective pitch controller for generator speed regulation and an individual pitch controller for alleviating once per revolution frequency fatigue load on the rotor blades. The linear matrix inequalities (LMI) technique was applied to incorporate the constraints that satisfy the requirements of perfect speed regulation, efficient disturbance rejection, and allowance of permissible actuator usage. The strategy offers a reasonable trade-off between speed regulation and load reduction.

3.1.4. Multiobjective and model-predictive approaches

In [82], an LQG controller with capability of determining the optimal weighting matrices is proposed to regulate generator angular speed, active and reactive power for a DFIG wind turbine system. Instead of using a trial-and-error method to evaluate suitable weighting matrices for both the Kalman filter gain and state feedback gain, a Genetic Algorithm (GA) was used to automatically search for the optimal weighting matrices that can satisfy the required performance specifications.
An independent pitch controller based on fuzzy logic is proposed in [83]. This control scheme aims at mitigating 1p harmonic loads on rotor blades without adversely affecting the quality of generated power. Similar to [26], individual blade bending moments were transformed into yaw and tilt moments using Coleman transformation. Then PI-fuzzy controllers were designed to minimize tilt and yaw bending moments. The results indicate that an acceptable compromise between load mitigation and power regulation can be realized using this control approach.
A multi-variable control method is presented in [84], where a combination of nonlinear dynamic state feedback torque controller and a linear blade pitch controller is used to achieve the objectives of regulating output electric power and controlling rotor rotational speed. This control strategy satisfies both rotor speed and electrical generator power regulation goals. However, the variation of structural load which is an important aspect in large wind turbines was not considered.
In a different study, a MIMO nonlinear model predictive controller for a floating wind turbine is presented in [85]. The goal of this controller is to mitigate structural loads by minimizing yawing and pitching moments on the rotor. A model predictive strategy was employed to predict optimal future control input trajectory using the current measurement information as well as input/output constraints. The results indicate that the control approach is promising in reduction of rotor blade load of floating wind turbine.
Other similar work has been reported in [86], where model predictive controller (MPC) together with a feed-forward disturbance controller was used to minimize structural loads on wind turbine structure. To develop a control algorithm that could operate in both partial and full load regimes, the whole operation envelop was subdivided into a number of finite sub-regions, where linearized models were used to capture localized dynamics within each sub-region. Here, upstream wind

speed measured using LIDAR was then used as the gain scheduling variable to switch between the operating regions. In this case, prior knowledge of approaching wind speed was beneficial in MPC control design since the gain scheduling variable was known for the entire prediction horizon.
A model predictive-based IPC is proposed in [87] to regulate rotational speed while minimizing the effect of asymmetric load across rotor disk. Individual blade pitch angles are adjusted depending on the speed of incoming wind to reduce the blade root bending moment's fluctuations. To account for model uncertainties and variation of operation point, a linear control strategy together with a model that predicts effective wind speed were used for gain scheduling. The operating points were evaluated in accordance with LIDAR measurements, both for current and predicted operating point. In this study, it was observed that LIDAR measurements can significantly improve the performance of wind turbine, but error in computing wind propagation time can severely degrade the performance of the controller. Compared with standard PI controller, this control approach allowed for a trade-off between speed/power regulation and structural load reduction. However, it led to increase in pitch actuation duty cycle (ADC).
A multi-variable model predictive controller (MMPC) for realizing multiple objectives in both partial and full load regions of a variable-speed wind turbine is discussed in [88]. The controller aims at maximization and smoothening of generated power, mitigation of drive-train vibrations as well as reduction of pitching actuator activities. To cover the whole operation region, a number of linear models, each representing localized dynamics of a given sub-region were defined and appropriate switching mechanism to switch between sub-regions was also designed. During low wind regime, it was observed that MMPC had better generator speed tracking and higher aerodynamic efficiency compared to standard control method. Similarly, during above the rated speed region, the power fluctuation was considerably reduced in comparison with the standard collective pitch PI controller. Nonetheless, this led to increased fluctuations in generator speed.
As specified in [23], reduction of drive-train mode vibration can be realized by using small perturbed generator torque signal on the nominal value, especially in high wind speed region. However, generator torque control cannot effectively alleviate asymmetric rotor loads.
A multi-variable feed-forward/feedback controller for improving blade root bending moment reduction is reported in [89]. This control approach is based on the fact that either the full knowledge of incoming wind is known beforehand or the measurement by LIDAR system is possible. Results indicated improved performance with respect to blade load reduction. However, dynamics of actuation were not explicitly considered during controller design leading to high pitching rates. The two methods used for designing feed-forward controller were gain-scheduled model-inverse and gain-scheduled shaped compensator.
The use of disturbance feed-forward controller in conjunction with a standard feedback blade pitch controller is proposed in [90]. The focus is to reduce fatigue loads on wind turbines without significant compromise on power regulation. The study concluded that when the wind turbine is under influence of stochastic wind field, a significant structural load reduction could be realized without affecting the quality of generated power, if an additional feed-forward control loop is applied. This control configuration was implemented and tested on a real 3-bladed wind turbine as reported in [91]. The findings from this study pointed out that the use of a feed-forward control loop in conjunction with a feedback speed control loop could be utilized to further reject wind speed variations at low frequencies.

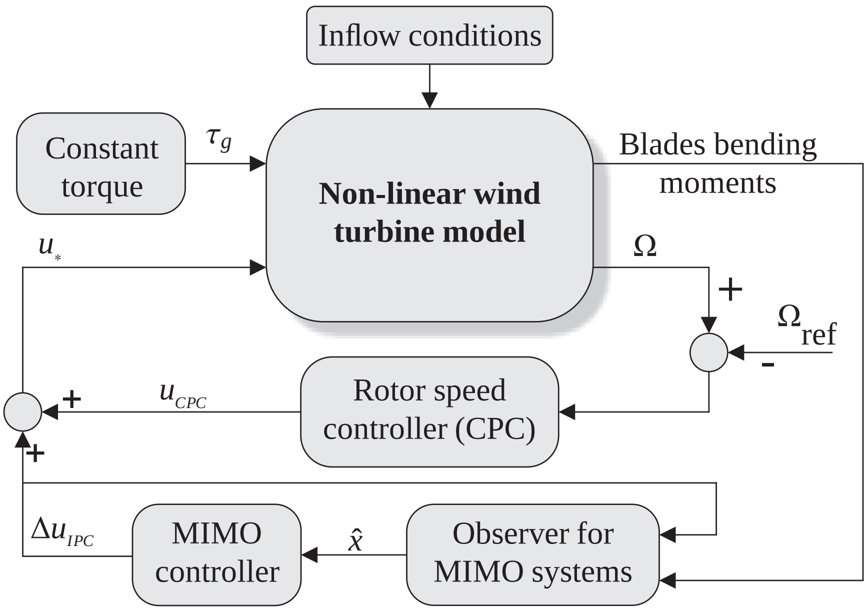


Figure 6: A generalized structure of observer-based individual blade pitch controller

An example for a multiple objective control framework is illustrated in Fig. 6. Here, the antagonizing control requirements of regulating generator speed/power as well as structural load reduction can be realized. The two control loops are employed: The first loop is utilized for regulating generator speed by generating nominal demanded pitch angle while the second loop is used for structural load mitigation. This approach is based on a linear model for during high wind speed. Different control design criteria can be used to realize these objectives. In this case the design should guarantee that the two loops do not interfere with each other by limiting the size of perturbed output MIMO signals Δu_{IPC} and to tune MIMO such that it does not attempt to regulate generator speed. In this example, blade bending moments measurement are used to design an observer-based MIMO controller, although other measurements can also be used depending on which structural member is under investigation. The overall manipulated variable u_* is computed by adding perturbed individual control signals Δu_{IPC} to the nominal control signal u_{CPC}.

3.2. Power optimization control problem

Another important goal in wind turbine is to maximize power extraction efficiency during low wind speed region. To tackle this problem, controllers are usually designed to track the maximum aerodynamic efficiency when the wind speed is below the rated value, although it is difficult to accurately determine the maximum power coefficient since it is a nonlinear function of tip-speed-ratio and blade pitch angle. Even in circumstances where its nearly optimum value can be approximated, blade aerodynamic properties are likely to change with time due to aging and corrosion, leading to sub-optimal operation. As shown in Fig. 1, for a given blade pitch angle, there is a maximum value for power coefficient C_p that corresponds to the optimal tip-speed-ratio λ_*. Next, in this section a number of control methods for maximizing power extraction in wind turbines are discussed. Some of these control methods assume prior knowledge of optimum operation condi-

tions, either computed through empirical data from experiments or using theoretical models like blade element momentum theory. Others control approaches assume that optimal TSR and blade pitch angle are unknown; hence, an on-line optimization solution to maximize generated power is usually sought.
As outlined in [92, 93], Maximum Power Point Tracking (MPPT) methods can be summarized as follow: Tip Speed Ratio (TSR) control, Optimal Torque (OT) control, power signal feedback (PSF) control, and Perturbation and Observation (P&O) control. Most of these MPPT methods usually require a priori knowledge of the optimum power coefficient [94]. However, in strict sense a perfect estimate cannot be achieved either by analytical methods or through experiments. In majority of MPPT control algorithms, pitch angle is normally held constant at a predefined optimal value and the optimal power coefficient is solely determined by tip-speed ratio [95, 96]. Despite the performance improvement in comparison with the fixed gain control methods, some of these power maximization control schemes have other shortcomings. For instance, the tip speed ratio control method utilizes wind as an input in order to compute the optimum value of the TSR; however, it is hard to accurately determine the effective wind speed from direct measurements [97]. On the contrary P&O method does not require prior knowledge of wind turbine characteristic curve rather a hill-climb search method is used to locate the local optimum power coefficient. However, this approach is bound to fail when used in large wind turbines under the influence of rapidly varying wind speed due to large inertial loads on turbine rotor [98]. Likewise, sliding mode approaches and extremum seeking control [99] take a lot of time to converge to the optimal operating conditions [100]. As a result, this might not give favorable results if the rate of wind speed fluctuation is very high. In [101, 102], a sliding mode controller based on MPPT algorithm is used to maximize captured power by tracking the optimum aerodynamic torque. This strategy is formulated to guarantee stability despite parameter uncertainties and model inaccuracies. Additionally, this control approach is designed in such a way that no induced mechanical stresses are transmitted to the drive-train system. The obtained results indicated good convergence of both the rotor speed and torque.
A nonlinear sliding mode control method for power production optimization on a variable speed wind turbine that is fitted with a DFIG is proposed in [103]. The control system consist of two cascaded controllers: a DFIG controller for tracking both the generator torque and rotor flux, and another control loop for tracking optimal rotor speed to maximize power capture. Although improved performance in terms of optimal torque and flux tracking was obtained, zero error tracking was not realized. This control method offers a trade-off between perfect reference tracking and escalation of chatter in drive-train.
A nonlinear cascaded controller for variable speed wind turbine that is equipped with a DFIG is demonstrated in [104]. Here, the aim was to optimize output generated power while avoiding induction of strong transient loads in drive-train. This was achieved by tracking optimal reference rotor speed generated using estimated aerodynamic torque and estimated effective wind speed. Compared with standard partial load control strategy, the proposed nonlinear controller led to improved power extraction efficiency while maintaining drive-train transient loads within acceptable range.
Unlike other control methods, which optimize power by manipulating generator torque only, optimal direct shooting control and Lyapunov-based controllers [105] can use both the generator

torque and blade pitch angle to attain the local maximum of the power coefficient. Application of multi-input multi-output optimal direct shooting control to maximize the aerodynamic power efficiency in partial load operation region has been presented in [100]. The effectiveness of the proposed algorithm was evaluated against the standard single-input single-output (SISO) torque feedback controller, where a noticeable improvement in tracking $C_{p_{max}}$ was observed. The requirement of prior knowledge of effective speed of incoming wind is the major weakness of this method. Furthermore, the influence of torque variation in drive-train was not investigated.

A Lyapunov-based control approach for maximizing generated power in partial load regime is studied in [106]. In this scheme common blade-pitch angle (β_{com}) and tip-speed-ratio (TSR) are varied to ensure that the turbine operates at optimum condition for maximum power extraction. The results indicated reasonable convergence to a predefined optimal value despite the variation of the incoming wind.

A robust control scheme for power capture optimization during low wind speed is described in [107, 108, 106], where Lyapunov-based approach is used to determine the trajectory of the desired rotor speed that corresponds to maximum power point for any given wind speed. Unlike MPPT methods, where optimum power point is assumed to be known, this approach searches for the best combination of blade pitch angle and tip-speed-ratio that lead to optimum power extraction.

Alternative control strategies where generator torque and blade pitch are both used to achieve various control objectives have also been reported in the literature. As discussed in [109], torque controller is used for track incoming wind trajectory in order to extract as much power as possible from wind whereas pitch controller is used for regulating the electrical power to the rated value. Both of these control loops are based on a SISO control configuration, thus limited in handling a multi-objective control problem.

In an effort to minimize uncertainties related to determination of the gain K_T corresponding to the maximum power coefficient $C_{p_{max}}$, adaptation torque control methods have been proposed in [20, 22, 110]. Here, a highly intuitive adaption gain was used to maximize power extraction in wind turbines during partial load region. The gain was adapted using large time steps in order to average out high frequency wind variation and sluggish turbine response to gust wind. Compared to the standard torque control, the proposed adaptive control method gives better performance in power maximization. Another variation of adaptive control scheme for computing optimum aerodynamic efficiency is proposed in [111]. Unlike other adaptive controllers used in partial load region, where a constant optimum blade pitch angle is assumed, this control method also varies pitch angles by small increments to enhance the efficiency of power extraction.

Other examples of advanced control algorithms for maximizing power extraction have been reported. For example, an adaptive disturbance tracking control (ADTC) is applied to track the optimum tip-speed ratio (TSR) in order to maximize power generation during low wind speeds [112]. In essence, this control method aims at regulating rotor speed so as to track the incoming wind speed, hence keeping TSR at its optimum value. A low order wind turbine model augmented with wind disturbance model was used to estimate incoming wind speed for use in ADTC algorithm. Other similar work has been reported in [113], where ADTC with different tracking ratios is used for smooth transition from low wind speed to high wind speed region. The transition region ensured that turbine reached its rated generator torque at its rated rotor speed.

3.3. *Power optimization and load reduction control methods*

While power optimization is crucial in low wind speed region, care must be taken not to induce undesirable torsional vibration on the drive-train. Therefore, reconciliation between these two conflicting requirements is required. This section explores different control methods that have been proposed in the literature to deal with this challenge. Most of the studies on maximization of power extraction during low wind regime have not investigated negative consequences of tracking the optimum power on the reliability of drive-train system. For instance, mechanical fatigue tresses are induced in drive-train by large generator torque variations during maximum power point tracking. To overcome this challenge, studies to reconcile the competing objective of maximizing power extraction and reduction of induced mechanical loads in drive-train have been proposed. In [114], an optimal control framework for variable-speed fixed-pitch wind turbine is discussed. In this study, wind speed was divided into a slowly varying component and rapidly varying component in order to determine the average position of operation point as well as generating high frequency variations around this point. A PI-controller was then designed to keep wind turbine system around the desired operation point, and a Linear Quadratic Gaussian (LQG) controller was used to compromise between maximization of wind power and minimization of generator torque variation. Simulation showed good control performance in wind power maximization. However, this optimization method assumed known optimum operating point.

Linear and nonlinear control strategies based on a two-mass nonlinear wind turbine model and a wind speed estimator is presented in [115]. The focus was to optimize power capturing and reduce drive-train load is realized at the same time. To realize this, Kalman filter in conjunction with Newton algorithm was used to estimate aerodynamic torque and effective wind speed using generator torque and generator speed as the only measurement variables. Then, the estimated torque and wind speed were used to calculate optimum reference rotor speed for tracking maximum power. Comparing the performance of both control methods, nonlinear controllers outperformed the linear controller, especially during high turbulent winds.

In a different study, a composite linear state space controller consisting of a disturbance tracking controller and an independent blade pitch controller [116] was developed to realize the goal of optimizing energy capture and reducing structural load on the rotor blades at the same time. The disturbance tracking controller was employed to optimize energy capture in low wind speed region despite persistent wind disturbances whereas independent blade pitch controller was used to minimize blade root fatigue loads. To avoid the interference with torque controller, independent pitch controller was designed so as not to actively regulate the rotor speed. A single-state control model like the one described in [117] was used to design a torque controller based on disturbance tracking theory (DTC) to maintain an optimum tip-speed-ratio for maximum power generation during low speed region. The results indicated that the proposed control method can reduce the structural load without sacrificing power optimization objective.

A multi-variable control strategy for regulating the speed and electrical power is proposed in [118]. To realize these two goals, a combination of nonlinear dynamic state feedback controller and linear pitch controller was used. A trade-off between speed regulation and power control was achieved by constraining power tracking error and pitch controller to regulate the rotor speed. To improve on the torque control response, small perturbed signals from a variable-pitch control were used. The results indicated improved performance in rotor speed and power regulation while maintain-

ing loads within acceptable limits.
It is important to consider advanced control strategies, either model-based or model-free, to trade off between maximizing energy production and guaranteeing the extended life time of the structural members.

3.4. Emerging trends and issues affecting wind turbine control

This section outlines technological developments and social economic issues that are likely to positively or negatively impact on wind power production. While it is important to explore enabling technologies that can lead to lowering wind energy production cost, sustainability and environmental impact assessment need to be considered before deploying such technologies.
In order to make wind energy more competitive compared to other energy sources, the turbine total life cycle (TLC) cost has to be lowered. This involves reduction of both initial investment cost and operation and maintenance (O&M) cost. These two classes of costs contribute separately to the TLC cost. For instance, initial investment cost can be drastically reduced if efficient manufacturing technologies for mass production are embraced in addition to using high quality and cheap alternative materials to manufacture various turbine components. A good example is to replace fiber reinforced plastic (FRP) rotor blades with hydroformed steel blades as proposed in [119]. In this study, it was noted steel has a recycling rate of 90%, making it an attractive substitute for manufacturing cheap blades. Although FRP has a number of advantages over steel, it is more susceptible to aging, more expensive, and problematic in recycling. On one hand the use of steel can reduce the manufacturing cost of rotor blade, but on the other hand, weight might present challenges in designing controllers due to high inertial loads.
Maintenance and operational cost can be reduced by employing suitable control strategies in combination with appropriate health condition monitoring methods. This aims at extending the operational life time of critical parts of wind turbine as well as indicating when a certain part is due to replacement. As a result, condition-based maintenance (CBM) [120] can be used to reduce unnecessary downtimes by carrying out maintenance only when it is necessary rather than on a scheduled basis. Among all wind turbine subsystems, the gearbox is one of the most expensive component and most susceptible to failure [121]. Any attempt to reduce the failure rate of wind turbine gearbox will significantly lower O&M costs and overall production of wind power. To avoid the problems associated with gearbox failure, some researchers have proposed direct-drive instead of geared-drive system, especially in utility-scale wind turbines.
While permanent magnet direct-drive systems are compact and robust, sustainability of its future production cannot be guaranteed because a rare earth metal, Neodymium, is required to make its permanent magnet [42]. Neodymium is an expensive and a scarce rare earth metal which is likely to be depleted over time if its demand keeps on growing. Additionally, its extraction has very adverse effects on environment and this can be a setback in producing environmental friendly power. The fact that 90% of the world total Neodymium production is produced by only a few countries and political influences makes it even more expensive [122]. These restrictions and political interference may hamper future prospects of manufacturing Mega-scale permanent magnet wind turbine generators. In a different study, ferrite permanent magnet generator was studied as possible substitute for Neodymium permanent magnet generator [123], however, it was concluded that the resulting generator would be too heavy because a large magnet volume would be required

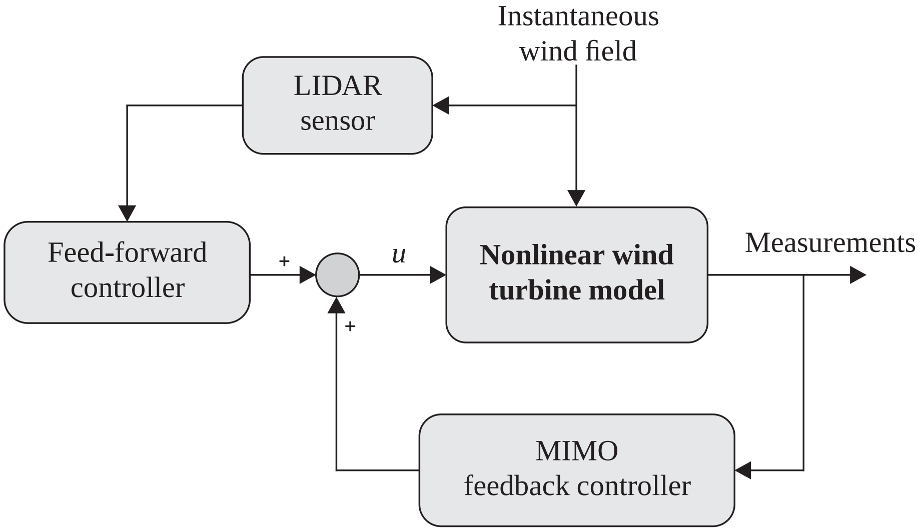


Figure 7: Wind turbine control system with a LIDAR feed-forward loop

to attain the same air gap flux density and voltage as Neodymium-based generator.

In recent past, the use of light detection and ranging (LIDAR) sensor in wind turbine control application has been investigated. As noted in [124], this measurement technology has been in existence since 1970s, but its wide spread use has been hampered by high cost. This sensor measures the upwind speed before it interacts with the turbine, hence allowing time for the turbine to respond to control output signal since the dynamics of incoming wind are faster than that of the turbine itself. This is very beneficial in large wind turbine where blades are massive; pitch actuation can be activated ahead of time to effectively minimize asymmetrical loads on the rotor blade. It is important to mention that this technology is still an active area of research, especially in Mega-scale wind turbines due to high inertial loads.

Figure 7 illustrates a LIDAR system can be integrated into wind turbine control loop. The upstream wind speed is measured using LIDAR system and the variation from nominal speed is compensated using the feed-forward controller. A multi-variable controller is used in the feedback loop to realize the objectives related to power/speed regulation and structural load reduction. This kind of control scheme can be desirable for large wind turbines that are subjected to rapidly varying wind speeds due to their slow reaction time.

As mentioned before, structural loads increase as the turbine grows in size. More specifically, it has been noted in [125] that blade root edge-wise stresses emanating from gravitational force increase as the blade size increases in size. On the contrary, flap-wise stresses due to aerodynamic loads are independent of blade size. Another challenge related to large wind turbines is slow pitching dynamic response due to massive inertial forces of the blades. To overcome the problems related to slow dynamic response of blade pitching due to large size and increased weight, a number of investigations combining active aerodynamic control devices and full span blade pitch control have been reported. In the literature, trailing edge flaps and micro tabs are the most used active aerodynamic control devices. As pointed in [126, 127], trailing edge flaps can be classified as rigid or deformable, with deformable trailing edge flap (DTEF) being most preferred. In comparison with individual pitch control, it has been observed in [128] that individual flap control (IFC) is more effective in mitigating high frequency loads in addition to reduction rate of pitching. It has been further noted in [127, 128] that active aerodynamic control devices have a potential of minimizing fluctuation of generator power in addition to damping tower deflection.

In a different study, the performance of a combined active aerodynamic load control (AALC) and IPC scheme on fatigue load reduction was investigated in [129]. The individual pitch controller similar to that described in [26] was used together with AALC based on proportional derivative (PD) feedback design. The PD controller employed blade tip deflection as the feedback signal and was used to actuate flaps in all the three blades. When active aerodynamic load controller was deployed, the results depicted significant improvement on root blade flap-wise moments reduction. Though the scheme did not explicitly investigate the variation of generated output power, the improvement on flap-wise bending moment reduction did not adversely affect other important turbine component such as drive-train and tower deflection.

Other issues likely to influence current and future production of wind power are social economic- and cultural-related [130]. Before any wind farm installation, a site with prerequisite climatic conditions has to be identified and acquired. This may sometime involve displacement of human population leading to conflicts. Setting up wind turbine installations near residential areas may cause interference due to emission of acoustic noise. Another challenge of onshore wind farm is disturbance of natural ecology and natural habitat. It has been concluded in [131] that offshore wind turbines offer greater potential in scaling up the power production capacity. This is due to availability and higher wind speeds in offshore wind farm sites. In addition, there is less interference with human settlements caused by acoustic noise and negative impact on landscape aesthetic. It is worth noting that due to some of advancements in wind energy industries; there are prospects of manufacturing wind turbines of even higher wattage and bigger sizes in offshore sites.

4. Discussion and evaluation

It is evident from literature survey that the focus of wind energy research has been on the reduction of its production cost, enhancement of safety and reliability, and improvement of the quality of produced power. From the control point of view, this can be realized by designing control strategies that can handle multiple objective problems for the whole operation range, i.e., during the partial and above the rated speed regions. More precisely, it is important to consider the power maximization against load reduction in the drive-train during partial load region and speed/power regulation against load mitigation during high wind speed region.

Different control approaches can be used to mitigate structural loads on different wind turbine subsystems. For example, IPC can mitigate rotor blade load and damp the side-side tower deflections. On the other hand, collective pitch control can minimize tower fore-aft deflection as well as regulating rotor speed during high wind speed. Additionally, generator torque controller can be utilized to minimize tower side-side deflection and drive-train torsional vibration. To reduce structural loads on different subsystems simultaneously, it is important to fuse more than one control approach; however, care must be taken to avoid them from interfering with each other by using appropriate filters.

Table 1 summarizes and compares various control methods used for power optimization in partial

Table 1: Comparison of control methods in low wind speed region

Control method	References	Manipulated variables	Short description
Tip Speed Ratio (TSR)	[92, 94]	Torque	Known optimal operation point is assumed. Wind speed measurement is required.
Power Signal Feedback (PSF)	[93, 96]	Torque	Requires the knowledge of the wind turbine's maximum power curve. Wind speed measurement is not required.
Optimal Torque Control (OTC)	[92, 94]	Torque	Requires the knowledge of turbine optimal characteristic curve. The reference torque is always proportional to the square of rotor speed.
Perturbed and Observation (P&O)	[95, 98]	Torque	Does not require knowledge of optimum point characteristic curve. Suitable for low inertia wind turbine systems.
Adaptive Disturbance Tracking Controller (ADTC)	[112, 113]	Torque	Based on linear model and tracks optimum TSR for a given speed.
Adaptive controller	[20, 22, 110]	Torque	Adapts the control gain depending on incoming wind speed.
Sliding mode	[101, 102]	Torque/Pitch	Does not guarantee finite-time convergence of the tracking errors. Leads to performance degradation if wind speed is rapidly changing.
Extremum seeking	[99]	Torque/Pitch	Take time to converge to optimal solution. Leads to performance degradation if wind speed is rapidly changing.

load region. The main challenge in this region is to compute the optimal operation point which in most cases is approximated.

Some of power the maximization methods cannot be used in Mega-scale wind turbines because of large inertial loads, especially those that require manipulation of both pitch angle and generator torque to reach the optimum operation point [106]. On the other hand, adaptive control methods can be effectively used in large wind turbine to track maximum power provided that the gain is adapted using large time steps in order to accommodate high variations in wind speed and slow response due to large inertia forces.

Strict tracking of maximum power curve can cause the induction of undesirable mechanical

Table 2: Comparison of control methods in high wind speed region

Control method	**References**	**Gain**	**Pitching**	**Short description**
PI-controller (gain scheduling)	[23]	Variable	Collective	Simple to design and robust. SISO controller.
Linear Quadratic Gaussian (LQG)	[26, 51, 82]	Fixed	Individual	Kalman filter is used to estimate system states. Loop transfer recovery is used to improve stability margins.
$\mathcal{H}_2/\mathcal{H}_\infty$	[77, 78, 80, 79]	Fixed	Individual	Used to reject unknown disturbance and suppression of measurement noise.
Linear Quadratic Regulator with Integral action (LQRI)	[52]	Fixed	Individual	An additional integral action is used to cancel steady state error.
Disturbance Accommodating Controller (DAC)	[12, 63, 64]	Fixed	Individual	Estimate system and disturbance states. Assumes measurement signal are noise free.
Stochastic Disturbance Accommodating Controller (SDAC)	[70, 71, 72]	Fixed	Individual	Estimation of system and disturbance states using measurements with noise.
Periodic Disturbance Accommodating Controller (PDAC)	[62, 65]	Periodic	Individual	Uses periodic model and is complex to design. Azimuth position is used to vary the gain.
Model predictive control (MPC)	[86, 87]	Variable	Individual	On-line optimization as well as input and output constraints handling.

stresses on the drive-train system, which can cause fatigue failure if not checked [23]. To reconcile these two contradicting requirements, independent pitch control and optimization algorithms can be used simultaneously to minimize induced mechanical load without significantly interfering with power maximization objective. More specifically, adaptive control method can be fused with IPC to achieve these two objectives at the same time. In this control configuration, IPC must be designed in such a way that it does not regulate generator speed hence, avoiding performance degradation. It is worth mentioning that employing IPC results into increased pitching activities, and thus care must be taken not to violate the limits of the pitch actuators.

In Table 2, different control methods developed for high wind speed region to regulate speed/power and mitigate structural loads are given. Most of these methods are based on linear control theory, meaning that they are only effective around a given operation point. Therefore, measures must be taken to compensate for uncertainties resulting from the change of operation point due to variation of incoming wind speed. Although the PI gain scheduling controller is simple to design and more robust, it has limitations in handling multi-objective problems since as it is a single-input single-output controller.

Linear quadratic methods can offer an optimal solution by trading-off opposing requirements by minimizing a given cost function. In most cases, full system state information is required to design this class of controllers, but not all states are available for measurements. This has necessitated the need to design observers to reconstruct unknown states. Observers can be designed using linear quadratic methods, $\mathcal{H}_\infty$, pole placement among others. In literature, LQG has been applied in regulating generator speed and reducing of structural loads, where it is assumed that wind turbine is influenced by disturbances and noise that have stochastic properties. Due to these strict requirements, LQG controllers are restricted in terms of applications. Another problem associated with LQG controller is poor gain margins which are improved using loop transfer recovery (LTR). To reduce the steady state error, the standard LQR controller is normally modified to include an integral action.

Another control structure that has attracted a lot of attention in wind turbine applications is disturbance accommodating controller (DAC). This is due to its ability to estimate system and disturbance states as well as compensating for unknown disturbances. In wind turbine application, the variation of incoming wind from its nominal value is considered as disturbance. Majority of the reported work in wind turbine application, compensate for unknown disturbances using static disturbance rejection method which assumes that disturbances influence the turbine through the same channel as the manipulated variables, resulting to poor performance when this condition is violated. On the contrary, dynamic disturbance rejection method can offer an effective means of compensating for unknown disturbances, nonlinearities, and uncertainties due to unmodeled dynamics.

As pointed out, wind comprises of deterministic and stochastic properties and the combined effect of these two properties is responsible for unbalanced aerodynamic load across the rotor disk. The unbalanced load due to deterministic wind property can be minimized by periodic disturbance accommodating controller. However, this control scheme is complex to design and has no performance advantage over DAC after carrying out multi-blade coordinate transformation. Multi-blade coordinate transformation converts a periodic model into an approximated linear time invariant model, and the resulting constant gain controller has similar performance as a period disturbance accommodating controller. If the turbine is assumed to be under influence of both the waveform and stochastic disturbances, stochastic disturbance accommodating controller can be used to reconstruct both the system and disturbance states using measurement signals with noise.

As noted, IPC leads to increased pitch duty cycle which may in turn cause early failure of pitching mechanism. To tackle this problem, MPC has been considered in many studies since it can explicitly take into account constraints during the design stage to avoid violation of pitching actuator

limits. To further improve the performance of MPC, LIDAR measurements can also be used to improve its reaction time.
Since most linear controllers are designed for a specific operation point, any significant deviation from this point may lead to performance deterioration. Hence, it is important to consider variable gain controllers such as gain scheduling and linear parameter varying controller in wind turbine application.
To realize the goal of improving the quality of generated power and guaranteeing the reliability in Mega-scale wind turbines, it is inevitable to employ multi-variable control schemes together with emerging technologies such as LIDAR sensors, hybrid drives, and active aerodynamic control devices such as trailing edge flaps and micro tabs. It would be important to combine more than one control strategy to mitigate structural loads in different subsystems rather than considering each subsystem independently as it is the case with most of the proposed controllers. In case of repair- or maintenance-induced replacement of WT components based on different material control strategies may be adapted to take into account the new properties.

5. Summary and conclusions

In this contribution, different control strategies used in large wind turbines, both in low and high wind speed regions, are outlined and compared with respect to different operational aspects. Special focus is given to structural load reduction and related control design. Taking the advantage of economies of scale, the cost of producing a unit of power by wind turbine can be reduced if the size and power rating are scaled up. Manufacturing turbines with massive sizes can lead into problems related to structural loads and poor quality of generated power. To fulfill such control demands with contradicting requirements, innovative control methods that can handle multi-objective problems are inevitable.
Although aerodynamic loads are not high during low wind speed region, tracking of maximum power can cause high variation torques in the drive-train, causing failure before reaching desired end of lifetime. To balance between optimum power production and load reduction in drive-train, a multi-variable control method that can manipulate both pitch and generator torque needs to be further explored since most of the reported controllers are single-input single-output. Similarly, in high wind speed region, power/speed and structural load reduction are realized by multi-variable control strategies. It is important to note that majority of documented control approaches for high wind speed region are based on linear models, and are only effective around the design point. Any significant deviations from this operation/design point results into control performance degradation. This can be circumvented by using variable gain controller that adapts the gain depending on the wind speed variation. Effective wind speed can be either estimated using turbine model or using LIDAR technology to measure upstream wind.
It has been pointed out that reaction time of wind turbine can be improved if a controller is designed using information on incoming effective wind speed before it interacts with turbine. This idea can be used during low and high wind speed, but a lot of publications have focused on high wind region. Additionally active aerodynamic control devices can also be used to complement the main control schemes to further improve their performance.

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