Wind Turbine Control Challenges-A Comprehensive Survey

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Abstract. To enhance wind energy technology, the present status and challenges associated with the wind turbine controls have to be studied. The function of different wind turbine control strategies such as PID control, PI control, linear quadratic optimal regulator, linear quadratic Gaussian optimal regulator, Robust Multivariable control, prognostic control or regulator and adaptive tuning of parameter are comprehensively reviewed and limitations are presented. The challenges related to wind turbine control are identified. Some of the required future works to improve turbine energy capturing capacity and its lifetime are discussed.

Keywords: Wind turbine control · Energy capturing capacity · Challenges

1 Introduction

Since 3500 BC in Egypt wind energy technology was used to propel the boat. Later it was used for water pumping in China, grinding in Persia, and for irrigation purposes in France [1]. In 1888, Charles F. Brush created history by producing 12 Kilowatts of electricity [2] using windmill in Cleveland, Ohio. Near the beginning 1900s, electricity from wind turbines was used as a source of energy for peoples living in the country side of Europe and America. In 1921 Agricco produced AC power and connected to grid in New Zealand. In 1941 big turbine driven by wind (1.25 MW) was build in Vermont and from 1977–1983 in the United State of America numerous turbines with two blades were developed. Later upward oriented, variable speed and pitch controlled three blades wind turbines were produced. In the 1990s, because of community became more mature about environmental disaster such as increasing atmosphere contamination index and worldwide temperature rise encouraged interests use of renewable energy and hence wind turbine producers started manufacturing large-size wind turbines. The biggest commercialized wind turbine has an average rating of 8 MW and blade length of 81 m [3, 4]. 12 MW, 260 m tall, 107 m long blade wind turbine was Commercialized

M. A. Delele et al. (Eds.): ICAST 2020, LNICST 385, pp. 511–521, 2021.
https://doi.org/10.1007/978-3-030-80618-7_35

in 2017, while 15 MW wind turbines might be commercialised in 2030 [3]. Actually, when wind turbine dimension increases, there is large effect of loses due to driving train (gear box) which requires a cooling mechanism. One way to reduce lose is a direct coupling of the turbine to generators like a permanent magnetic synchronous generator (PMSG). One limitation of using PMSG is 100% of generated power passes through the two electronics convertors for frequency regulation which reduces overall efficiency. This limitation can be reduced when double-feed induction generator (DFIG) used in case convertors care only 30% of generated power even though the effect of gearbox exists in this case.

At the end of 2017 and 2018, about 539 GW and 600 GW of electric power were generated from wind power respectively [5]. As the report showed by [6, 7], by 2030s, 2,000 Giga Watt electric energy could be generated from wind. As the data on [8] PR China, USA and Germany respectively share 34.7%, 16.9% and 10.3% of the worldwide cumulative energy from wind. Even thought good potential wind resource exists in Ethiopia, the counter shared only 0.06% of global electricity from wind power. GWEO explores the upcoming of wind energy production until 2050. According to the IEA's guidelines, the state of affairs or scenario for wind energy and considering WEO as a reference, there are two states of affairs were specifically developed. These are GWEO modest scenario and the GWEO higher scenario. As per the higher scenario, the expected energy to be harvested from wind until 2030 is shown in Table 1; adapted from [6].

Table 1. Global wind power scenario [6]

Complete capability in Mega Watt	2013	2014	2015	2020	2030
Latest guidelines state of affairs	318,128	356,322	396,311	610,979	964,465
Modest state of affairs	318,128	363,908	413,039	712,081	1,479,767
Higher state of affairs	318,128	365,962	420,363	800,615	1,933,989

Energy from wind flow is recognized throughout the world as a cost-effective energy plant [3, 9] next to hydropower and biomass. It is an environmentally friendly solution to energy shortages, i.e. reduce climate change effect, greenhouse gas emission and protection for bio diversity. Wind power plant helps to reduce more than three Giga tons of carbon dioxide releases in a year [6]. The Wind is an inexhaustible power source that improves community health.

2 Wind Turbine Control Survey

As contemporary turbines driven by breeze become large by size they should have better power capture capacity and hence be more economical; they should have flexible parts that help turbine running under unsure surroundings. Mainly goals of wind turbine supervise and manage are improve turbine capacity of power capturing, enhance power quality, and reduce structural loading on the wind turbines. Wind turbines can be pitch controlled or stall angle types that is rotor blade can be rotate or may not be. Changeable blade-angle controlled turbine permits the entire or some of its blades to turn around its axis at the same time or individually. Also, turbines are of fixed- haste (speed) or of Variable- haste type. Variable-haste turbine runs near its highest aerodynamic performance for most of its operation duration, even though it needs power electronics converters to meet voltage and frequency requirement for gird connection.

Because of advancement in technology for generator and electronics development, variable-speed turbine is more accepted compared to fixed-speed turbine for gird connectable electricity generation from wind. This is due to the former capable to harvest more power than the later since it operates at higher performance for broad range of wind pace.

Ideal turbine can harvest approximately 59% of the energy in the wind (the Betz's Limit [10, 11]). But it is not possible to harvest total energy in the wind because of its fluid dynamics. As indicated in Fig. 1, operation goal of the turbine in the area 2 is to optimize power harvesting through rotor or generator speed control at most favorable tip-speed ratio. In area 3, generator speed is kept fixed by controlling blade angle. This is indicated in Fig. 2. Also, controller used to reduce vibrant loads on tower.

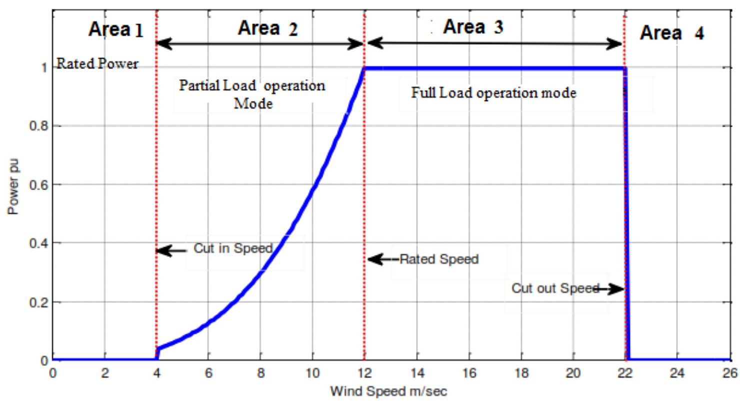

Fig. 1. Wind power characteristics of changeable haste and changeable blade angle controlled Wind Turbine.

Variations of the wind pace away from mean value in turbine rotor causes disturbance on turbine controller. Grid connectable wind turbine has supervisor and managing techniques. These are peak stage supervisory that acts on turbine to start or stop it against variation in wind pace, and examine turbine health; operation managing techniques that acts on turbine to accomplish its goals in the area 2 and area 3 as in Fig. 1. The third is components control system- controller that causes the machine side and grid side convertor electronics, yaw and pitch drive systems to execute what they intended to do. Figure 2 represents components control system diagram of wind turbines where $P_g(t)$, Ʈ(t) and $\omega_g(t)$ are generator output real power, torque, and speed respectively. $\beta(t)$ is the rotor blade angle.

The turbine rotor speed sensor/measurement (in operational control) in feedback basic control loop is used in both Area 2 and Area 3. The other measurement device

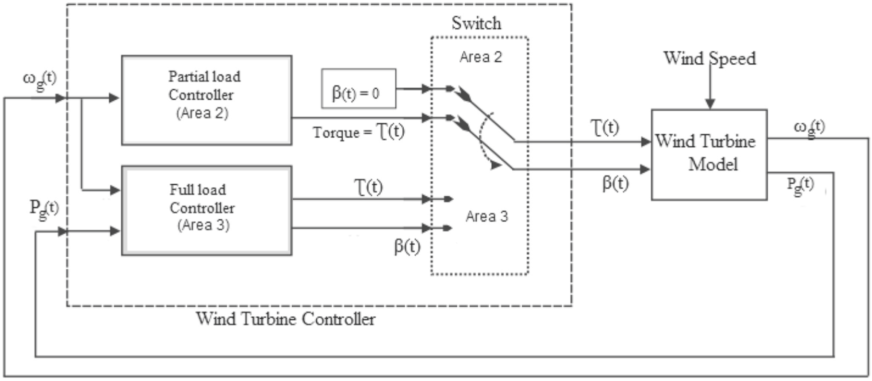

Fig. 2. Wind turbine supervisor and managing technique schematic for operation in area 2 and area 3

in the wind turbine control loop is an anemometer. It used for peak stage supervisory control function, specifically, to decide whether the wind pace is adequate to run turbine or extreme to cease the turbine. The energy recording tool is a vital device for components control loop to keep tracking of a turbine energy generation [10, 12]. Up to date grid connected wind turbines usually have three major categories of drives and their controls are as discussed below.

2.1 Generator Torque Control

Generation of electrical energy from wind energy requires turbine, electric machine, gearbox (accordingly), machine side and grid side electronics, and control systems. This makes the complete system complex. Wind turbine is the major element in production of mechanical energy from wind kinetic energy. The wind power passing through circular disc is

$$P_w = 0.5\rho\pi R^2 V_w^3 \tag{1}$$

for P_w represents power [W], ρ is atmosphere density [kg/m^3] and V_w is space and time-varying wind velocity [m/s] passes in circular disc of πR^2 [m^2], and R stands for blade length [m]. Wind turbine harvests some percent of energy that is accessible in wind pace. Power conversion coefficient is the division of harvested power – P [W] to wind power passing through predefined circular disc. That is.

$$C_p = P/\left(0.5\rho\pi R^2 V_w^3\right) \tag{2}$$

C_p is adjusted by β and λ [13].

$$C_p(\lambda,\ \beta) = 0.22((116/z) - 0.4\beta - 5)exp(-12.5/z) \tag{3}$$

.

$$1/z = 1/(\lambda + 0.08\beta) - 0.035(1 + \beta^3) \tag{4}$$

.

$$\lambda = \omega R / V_w \tag{5}$$

For λ, *β,* and ω represent fraction of rotor blade tangential tip velocity to the wind velocity, blade angle and rotor angular velocity respectively. The major goal of using controller is to maximize power conversion efficiency $C_p(\lambda, \beta)$. The power harvested using wind turbine is obtained when (2) is rearranged as

$$P = 0.5 \rho \pi R^2 V_w^3 C_p(\lambda, \beta) \tag{6}$$

According to the wind pace condition, β can be control or adjusted in (3) and set to zero as shown in Fig. 2; and hence power conversion efficiency $C_p(\lambda, \beta)$ optimized at optimal λ. In this case, wind turbine operates in area 2 as indicated on Fig. 1. The maximum aerodynamic available power (P_{wm}) can be related to rotor speed ω and C_{pm} as given by

$$P_w = 0.5 \rho \pi R^5 C_{pm} . \omega^2 / \lambda_{op}^3 \tag{7}$$

In (7) if C_{pm} will become maximum conversion efficiency and then power is too. For machine security beyond the machine rated value, it should be restricted by controller. According to [18] maximum achievable value of C_p ranges between 0.2 and 0.4 for wind turbines with three or more blades. In (7) for constant P_{wm} and ω, the torque acting on blade maintained fixed; though the wind haste varies and this can be achieved by the controller. Many electric machine drive system controllers are in application in different wind industries [14, 15].

2.2 Pitch Control

Most of the grid connected wind turbines are of three rotor blades and so that collective or independent pitch hydraulic actuators or drive motors are required, which are controlled as per wind speed situation. There are also turbines with two blades; in this case, there is teetering hinge that let the rotor to act in response to discrepancy in loads [16, 17]. The pitching speed is limited to about 5^0/sec. The turbine is able to extract maximum power up to eclectic machine capacity and restrict power capturing when wind haste become more than the rating.

Usually, in group or independently blade angle controllers are implemented to restrict power when the pace is over nominal with electric machine torque is at its maximum.

As shown in (1), the wind power fluctuates as cube of haste; hence, the turbine must generate power at low wind haste; and withstand loading effect for extreme haste.

Beyond optimal wind haste, blades must be adjusted to feathering condition or pitched to active stall position using controller to limit power to the rated value. For most of wind turbines in market when operates in area 3, it is commonly carried out by proportional-integral-derivative (PID) collective pitch control [18]. The PI Controller gains are scheduled because of the nonlinearity in area 3. At moment, turbine will be operated in the area as indicated in Fig. 1 and Fig. 2. The turbine controller yields command to blade actuator. It alters blade position angle/ velocity at accordingly [11, 20]. Typically the pitch rates range from 8^0/s to 18^0/s for 5 MW and 600 kW turbines respectively [19].

Also, single input single output regulators are used for blade angle control [20]. A lots of recent grid connectable turbines controllers permit blades to be adjusted separately. This can be achieved employing extra sensors and multi input multi output feedback controller for individual blade [21, 22].

2.3 Yaw Control

The second actuator is a yaw motor that adjusts the nacelle into or away the wind direction according to wind status. But, because of risky due to gyroscopic torques, turbines are never yawed at higher rates. The majority of the big turbine turned for rate fewer of 1^0/s [19] and hence sophisticated controllers to yaw wind turbine is not must. When the wind direction is changed yaw controller points turbine nacelle towards wind direction. Even for extreme wind speed, yaw motion can be used to twist the nacelle to diminish the influence due to high wind haste (cut out action). Recent turbines could furthermore comprise independent blade twisting moment recorders and sensors for tower deflection and nacelle motion.

2.4 Existing Control Strategies

As it was seen in Sect. 2.1 to 2.3 several control techniques have been proposed for wind turbine. Article [23] describes goal of the control that aimed to attain best rotational speed, without considering large deviation in wind haste (stochastic behaviour of wind speed). In this article important action of control for structural load minimization is not considered. Many control approaches were indicated in journals focusing on time independent linear model. Linear quadratic regulators (LQR) [24, 25] and linear quadratic Gaussian (LQG) [26] form of controllers are also employed for wind turbine. Robust controllers were initiated in [25, 27] and recently nonlinear control laws were proposed [28]. The adaptive control is presented in [29]. All these control methods fail in addressing nonlinearity characteristics of wind turbine aerodynamics, structural behavior including stochastic nature of the wind. Model Predictive Control (MPC) was discussed in [30, 31] for upwind speed measurements, optimization of power capturing and reduce tower loading effect. MPC implementation was limited due to computational burden. The feed-forward control method alternative to MPC was dealt [19, 32–34] by pre-processing wind pace data with predicting the upcoming turbine loads [32].

3 Challenges in Wind Turbine Control

Although there has been rapid increase of establishments of wind farms, still there are engineering defies specifically in designing, selection of material and suitable control strategy. The control to be designed should address improving the competence of its efficiency, functioning, and life span of wind turbines [11]. From many challenges in wind turbine control, some of them are presented below.

a. Turbine structure loading problems are due to time to time increase in wind turbine sizes. Different load types on the wind turbines and their effect analysis are described in reference [16]. For the growing rotor dimension; there is the spatial weight deviation alongside of blade. It is essential to act in response to loading effects due to wind shear, and turbulence.The wind fluid is generally not uniform due to wind shear that is deviation in the wind speed magnitude and direction profiles. When rotor axis is unaligned to wind direction, twisted wind will be created and results in turbulent formation that affects turbine aerodynamics. Turbulent formation can get several forms, for instance wind speed may come into view as a rising and falling on the way to turbine. Different controllers are proposed to reduce such problems were presented in [22, 35] but still, suitable controller has to be developed to mitigate the structural loading. Logical turbulent kinetic energy can be reason for extreme stress on a wind turbine that is occurred and observed between 40 – 120m above the ground, which is found to be the usual for grid connected wind turbine rotor height [36]. MIMO structure for independently driven blade angle control may valuable to decrease major weight or load 0n turbine [21, 37, 38]. Only 20% of turbulence load reduction was achieved as reported by [39] and hence it is required to prevent premature breakdown of the turbine and improve energy capturing efficiency [40]. Wind turbine tower oscillations (sideway and fore-aft towers) cause fatigue loads on the tower and then reduce tower life. Therefore, a suitable control loop is required to damp sideway and fore-aft tower vibrations in area 3.
b. Representation of stochastic behavior in wind data profile for realizing the performance improvement of the turbine is essential. This is not only helps for speed regulation and maximization of the power output but also for structural load mitigation of wind turbines [35].
c. Due to the complication in a wind turbine for energy conversion, stability of fully established controller for it is frequently hard to found. Several control loops act together as do many degrees of freedom for turbine grow to be bigger, having smaller normal frequencies of oscillatory behavior [41, 42]. As reported by [41], wind turbine drive train oscillates between 0–10 Hz frequency which proportionate on blade rotational velocity; in turn affects output power. Controller should have a way to get separate blade position sensors together with electric machine speed that can also use data from strain gauges recording structural motion of tower. Modern control strategies are required to reduce structural oscillation [43].
d. Wind turbine control was handled by 2 separate controllers for Area 2 and Area 3. Switching among these areas controllers may difficult. In several occasions, highest structural injure of turbines happen because of great exhaustion loads through changeover of these two operation areas. The 2-blades Controls Advanced Research Turbine (CART2) baseline controller utilizes an extra control area named ‘Area 2.5’ for changeover from Area 2 to Area 3, or in reverse. The main purpose of Area 2.5’ is to tie Area 2 with Area 3 controllers appropriately [20, 22]. Unluckily, the tie between these areas did not give even changeover. There is irregular gradient in torque control, which makes additional too much loading on turbine structure. For transition between the two regions as an option, a single controller that uses single reference for amplification of the two areas controller was developed. But reduced

grading of performance of the areas occurred. Hence, the use of Area 2.5 is not much attractive [44].

e. There are causes for turbines hurt by decision-making control to act to stop the turbine while very small or extreme wind velocity and grid faults. But, incredibly small energetic control was fabricated and used for turbine stopping at time of turbine failure case [19].
f. Well developed turbine damage identification techniques with safety mechanisms were required. As it was discussed by [45], observation of parameter for damage indication using Rotational Invariance Technique (ESPRIT) technique followed by Root- MUltiple SIgnal Classification (R-MUSIC) technique has very high detection accuracy for wind turbine generator related faults. But, their computation is more complex and limits its real-time implementation. Therefore, either improvement for computation complexity of these technique or other simplest fault detection mechanisms for a wind turbine is required.
g. The controllers' recitals are affected by model incorrectness. As example, 5% of replica formulation mistake only in tip speed ratio of wind turbine blade results in about 1%–3% wastage of energy when turbine operates in area 2. In this case, consider Ethiopia electricity generation only from wind plant that is 324 MW, which is running at 32% capacity factor with annual energy production of 908.237 GWh; for estimated price of energy production is $0.09 per kWh, 1% -3% wastage of energy at this wind plant is equal with $817413–$2452240 wastage per annual [19, 46, 47]. The other point is even though plant replica formulation mistake is very little; dynamical performance of wind turbine may alter now and then because of wear, rubbish builds on blades, and so on. To overcome this inaccuracy, suitable control strategies are required [37, 46, 48–51].

4 Conclusion and Future Study Areas

4.1 Conclusion

The wind resource is available in abundant and sufficient for global upcoming energy wants. Wind turbine size and wind energy are fast-growing industries, which leads to a huge requirement for improved replica formulation with control structure of wind turbines for realizable power capture. Because of doubts and complexity in sensing and recording the wind fluid, developing control system is challenging. Wind turbine control is affected by different factors like turbine configuration and its operation modes within uncertain wind pace conditions. Different controllers were designed and implemented for wind turbines. For instance, PI and PID controllers, linear quadratic optimal, linear quadratic Gaussian optimal, and Robust Multivariable, Model predictive and adaptive controls. These controllers have limitation in structural load mitigation, structural vibrations in area 3, wind turbine fault detection and model error tolerance. Modeling using system identification and other sophisticated control techniques has to be discovered in order to decrease price of wind energy and improve efficiency, operation, and lifetime of wind turbines.

4.2 Future Study Areas

1. Development of superior control schemes for wind turbines, which allows the active suppression of mechanical vibrations in tower and drive-train/other structural vibrations in area 3 is required.
2. A novel control strategy for wind turbine since it operates in an uncertain environment that takes in to account robust steady-state stability of the overall system.
3. Stochastic modelling of intermittent wind speed is required for wind turbine structural load mitigation. These may include identification and prediction of particular load types and their related effect on wind turbine i.e. to reduce (possibly elimination) their effects. Also, suitable controller strategies can be developed for load mitigation.
4. The controller should have means to each blade position angle sensors along with electrical machine/ generator speed and that of tower motion and strain.
5. Fault detection and monitoring mechanism (a smart sensor that should be cost efficient, energy-efficient, offer an opportunity for deploying sensor in inaccessible locations in/on turbine, electrical noise environment) and also sophisticated control techniques required to reduce the turbine damage.
6. Novel commercially accepted signal processing techniques to take out the main features of a signal to forecast wind turbine components health are to be used.

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