

Review

A Review of Recent Aerodynamic Power Extraction Challenges in Coordinated Pitch, Yaw, and Torque Control of Large-Scale Wind Turbine Systems

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Abstract: As the impacts of environmental change become more severe, reliable and sustainable power generation and efficient aerodynamic power collection of onshore and offshore wind turbine systems present some of the associated key issues to address. Therefore, this review article aims to present current advances and challenges in the aerodynamic power extraction of wind turbines, associated supporting technologies in pitch, yaw, and torque control systems, and their advantages and implications in the renewable energy industry under environmental challenges. To do this, first, mathematical modeling of the environmental characteristics of the wind turbine system is presented. Next, the latest technological advances consider the environmental challenges presented in the literature, and merits and drawbacks are discussed. In addition, pioneering research works and state-of-the-art methodologies are categorized and evaluated according to pitch, yaw, and torque control objectives. Finally, simulation results are presented to demonstrate the impact of environmental issues, improvement claims, findings, and trade-offs of techniques found in the literature on super-large wind turbine systems. Thus, this study is expected to lay the groundwork for future intensive efforts to better understand the performance of large-scale wind turbine systems in addressing environmental issues.

Keywords: aerodynamic power extraction; environmental challenges; pitch/yaw and torque control systems; super-large wind turbine systems



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1. Introduction

Research investigations into the technologies that make renewable energy possible and strategies to enhance them have seen tremendous advances in the past few decades. Although global warming and climate change are regarded as severe warnings across the globe, many governments and organizations are taking action by imposing green rules on the energy sector [1–4]. The world-installed wind power capacity has grown to 12.4% in 2021 by reaching 837 GW, an increase of 93.6 GW from the previous high in 2020. In addition, 2017 recorded the second-lowest year for new onshore wind installations, but still reached a record high at 72.5 GW. At the same time, 2021 will be a record year for the offshore wind industry with over 21 GW of grid-connected wind energy systems [5]. This is a three-fold increase over the previous year owing to the superior power generation capacity, substantially lower cost, and minimal environmental impact [6–8]. Many experts and organizations have proposed various strategies for scaling wind turbines to meet the ever-increasing demand for power consumption [9]. This is because super-large wind turbines produce more net electricity and have a lower Levelized Cost of Energy (LCOE) [10,11]. However, trade-offs are associated with increasing scale, such as increasing the volume of

production and construction cost [12]. Therefore, it has always been a challenging feat to construct large-scale wind turbines (WTs) with optimal weight, volume, and mass [13,14].

WTs are often designed to endure extreme wind conditions but cannot tolerate high rotating speeds and torques. The turbine is configured with a cut-off speed that decelerates from top speed until it stops. Therefore, the absence of a cutout speed increases aerodynamic torque and rotational speed, placing enormous forces on the WT blades and different turbine elements and damaging the WTs. Vertical-axis wind turbines (VAWTs) and horizontal-axis wind turbines (HAWTs) are the two primary types of WT that have been implemented to meet rising energy needs [15,16]. Researchers have paid particular attention to HAWTs because of the many advantages that they provide, including high-power production efficiency [17,18], dependability [19], and variable speed operation [20,21]. In terms of maximizing energy extraction and minimizing structural stress, the performance of the WT is directly affected by the moving wind speed situation and the critical moment of inertia of the HAWTs.

On the other hand, climate change creates severe challenges to wind power generation by altering atmospheric dynamics and influencing wind patterns [22,23]. Wind output is difficult to predict due to the increased unpredictability of available wind resources. Annual wind density and wind quality variations are caused by climate change [24,25]. Wind speed is an essential factor in wind turbine systems (WTS) that can affect climate change. As a result, it is more important than ever to estimate the impact of future climate change scenarios on the various factors that can affect wind speed and wind output. Moreover, wind speed fluctuations complicate the process of determining whether or not a project is financially viable [26,27]. In this regard, among the many effects of climate change on the global meteorological system, the impact on wind resources and the wind energy industry is receiving more attention.

In the literature review, many research efforts have been undertaken to determine the influence of climate change on wind power in super-large WTS. Lately, climate scenarios have been used in the economic investigation of wind power generation schemes [22]. To evaluate the financial viability of wind energy projects across various regional climate scenarios, the authors of [28] predicted wind resources by forecasting future wind speeds in Europe. In [29], the authors analyzed potential offshore wind energy production in Greece and the Black Sea in regional climate scenarios. In a Brazilian case study, the authors reported that incorporating wind speed data into climate scenarios helps predict wind power generation [30]. In addition, the authors of [31] presented a quantitative analysis of the effect of climate change on the potential energy production of wind farms in South Korea. Subsequently, the financial and investment impacts of four wind farms in response to climate change in Spain were investigated [32]. It should be noted that climate change could limit electricity production from 8% to 10%. In addition, the LCOE of wind farms, annual fluctuations in electricity production due to climate change, and control methods to improve the resilience of super-large WTSs were presented in [33]. Several recent studies have promoted an understanding of wind energy concepts [34], dynamic system modeling, generator design [35], back-to-back converter control technology [36], and installation issues concerning onshore and offshore super-large WTSs [37–39]. In particular, the authors of [40,41] investigated maximum power point tracking (MPPT) techniques in hybrid power generation, such as wind and solar systems. Meanwhile, conventional and advanced maximum power extraction control techniques have been investigated for WTS in various wind conditions [42–44]. State-of-the-art wind turbines and their associated efficient control methods are prominently presented in super-large WTS [17,45]. However, no studies focused on the problems of aerodynamic power extraction and coordinated pitch/yaw and torque control technology for super-large WTSs under climatic impacts.

Motivated by the aforementioned discussions, this study provides an overview of the latest aerodynamic challenges of coordinated pitch, yaw, and torque control technology for super-large WTSs, including all factors concerned with extracting maximum aerodynamic power from climate variation. Furthermore, this study thoroughly examines the climatic

impacts on WT aerodynamics, coordinated pitch, yaw, and torque control technology and is distinguished by a comparative survey of the WTS. In this respect, the main contributions of this study are as follows:

1. This study represents the first attempt to review and evaluate the impact of climate change on the maximum aerodynamic power extraction of a super-large WTS.
2. Mathematical modeling of climate change, such as temperature and rainfall effects, is constructed to investigate power production techniques in WTS effectively.
3. A brief representation of coordinated pitch, yaw, and generator torque control technologies for super-large WTS are presented.
4. Finally, we present a variety of simulation case studies to demonstrate the impact of climate change on aerodynamic power generation in super-large WTS and the limitations of coordinated pitch/yaw and generator torque control techniques.

This article is structured as follows: First, the issue of aerodynamic power extraction in super-large WTS is discussed in Section 2. The temperature and humidity effects of the super-large WTS are presented in Section 3. The impact of rainfall on the power generation of super-large WTS is addressed in Section 4. Coordinated pitch, yaw, and generator torque control techniques are discussed in Section 5. Validation examples are discussed in Section 6. Finally, Section 7 concludes this study.

2. Aerodynamic Power Extraction Challenges in Super-Large WTS

Wind power output is affected by climate change due to a variety of reasons. As a result, component life spans are decreased, and maintenance expenses are raised. Interestingly, many studies have emphasized the need for accurate wind data forecasts for optimizing electricity production and distribution processes in WTSs. However, climate change continues to affect wind speed, and the values are uncertain among the perceived wind models. Therefore, the aerodynamic power extraction is automatically reduced. In this regard, the impact of climate change, such as hot and cold climates, should be assessed to minimize wind speed uncertainty. It should be mentioned here that aerodynamic power fluctuations in climate change can be accurately modeled using the following three environmental factors, (i) iced WT in cold climates, (ii) temperature with humidity effects, and (iii) rainfall effects.

Subsequently, much research has been focused on the impact of icing on WT blades, characteristics, and comparative investigations between the ice protection systems [46–48]. As a result, the annual power output of the super-large WTS is reduced by between 0.005% and 50%. To address this problem, the authors proposed an advanced ice-protection control technique for the super-large WTS. Furthermore, in [49], the authors presented a comprehensive review of ice protection schemes and their characteristics in the super-large WTS. On the other hand, the effect of temperature and humidity significantly impact wind speed, leading to a 20%~30% decrease in aerodynamic power [50]. Recently, the authors in [51] considered the temperature effects in aerodynamic modeling to propose maximum power extraction control techniques using cascaded neural networks. However, humidity effects are not considered in the aerodynamics of WTS. As a result, it was found that the effect of temperature and humidity significantly affected the air density impact on the amount of electricity produced by WTS. Therefore, a study on the function of WTS should be conducted to determine whether such an effect exists.

Raindrops significantly impact power generation losses even with the same amount of rainfall [52]. WT blades perform akin to bird feathers in heavy rain. A similar scenario occurs when the rain suddenly changes direction. In short, due to the abrupt change in wind speed and direction during poor weather conditions and the complex factors of WT control, the blade surface is attacked by wind along with the rainfall load, and the amount of power generation subsequently decreases, which in turn affects the performance of the WTS [53,54]. Recently, studies on the effects of rain have not been mentioned much, and there are only a few studies on the aerodynamic analysis or simulation of rain falling on the blades. In particular, the authors in [55] found that the power generator output of super-

large WTS is decreased by 26% under rainfall. Therefore, further investigation in this area is needed to understand the operational performance of offshore WTS and rainy climates. In this regard, this study seeks to inform researchers of the most delinquent technological and climate impacts, such as temperature and rainfall effects, on the maximum power generation of super-large WTS.

3. Temperature and Humidity Effects in Super-Large WTSs

The aerodynamic power extraction of a bladed WT represented in the (1) is the quantification of power by the mass of air moving at a certain velocity through a specific area.

$$P_{ad} = 0.5\rho AC_p(\lambda, \beta_b)\mathcal{V}_w^3 \quad (1)$$

where, $\mathcal{V}_w$ is the wind velocity in m/s, ρ is the air density in kg/m³, C_p is the power coefficient as a function of blade pitch angle β_b and tip-speed ratio λ . Usually, in the WT power extraction model, the area swept by the rotating blades A in m² and the velocity of wind $\mathcal{V}_w$ are considered the prime factors by assuming constant air density [56]. Customarily, in most of the research articles, the air density is assumed as $\rho = 1.225$ kg/m³ this is the density value calculated at an air temperature of 15 °C and with an air pressure of 1 atm with an altitude measuring 0 m above sea level [57–59].

The above assumption of constant air density is based on the annual average without taking into account seasonal and geographical constraints. In spite of this fact, the authors in [60] identified a maximum systematic error of 16% in wind power calculations for this assumption of constant air density. In addition, a 10% difference in power production has been proved for the variation in air density between a sunny day and an overcast day [61]. Moreover, a detailed study is conducted to approximate the variations in air density and power density from a global perspective utilizing the ERA5 [62] atmospheric reanalysis data. The authors extensively analyzed the impact of air density variations on seasonal energy production and evaluated an air density error map for four seasons. Additionally, a simplified model is introduced to calculate the air density considering the environmental temperature and specific humidity [63]. Further, the air pressure varies with the location's altitude from sea level. This also influences air density to a considerable extent. The available wind power is precisely proportional to the density of the air. As the air density increases, so too does the available power [64]. Air density is a function of air pressure and temperature. It grows when the air pressure or temperature decreases. Temperature and pressure decrease with altitude [65]. Consequently, changes in altitude significantly impact power production due to changes in air density. Based on this, the mathematical expressions for the altitude influence over the air density are discussed in [66,67]. The following section presents comprehensive and detailed mathematical modeling of the effects of temperature and humidity to understand the importance of aerodynamic power generation in super-large WTSs.

3.1. Mathematical Modeling of the Temperature and Humidity Effects in WTS

The aerodynamic performance of a WT is determined by the complex interaction between the blades and the surrounding wind. Hence, to approximate the effect of temperature (T), relative humidity (H_r), and altitude (h_s) on air density the following mathematical approximation can be utilized [65,66].

$$\rho(T, H_r, h_s) = \frac{p_d}{R_d(T + 273.5)} + \frac{p_v}{R_v(T + 273.15)} \quad (2)$$

where, p_d and p_v are the partial pressure of dry air and the water vapor, respectively. $R_d = 287.058 \text{ J/kgK}$ and $R_v = 461.495 \text{ J/kgK}$ are the specific gas constants of dry air and water vapor. T is the air temperature in $^{\circ}\text{C}$.

$$\begin{cases} p_v = H_r * 6.1078 \times 10^{\left[\frac{7.5T}{T+237.3}\right]} \\ p_d = p_h - p_v \end{cases} \quad (3)$$

where p_h is the absolute pressure at the given altitude, and it can be estimated from the value of absolute pressure of dry air (p_0) at the sea level by using the following formula [67]:

$$p_h = p_0 e^{\left[\frac{-gMh_s}{R(T+273.15)}\right]} \quad (4)$$

where M is the molar mass of dry air (0.0289652 kg/mol); g is the gravitational constant (9.80665 m/s^2), R is the universal gas constant (8.31446 J/(molK)), and h_s is the altitude of WT from sea level (for onshore WT it can be taken as 0). In Figure 1, we can clearly understand the block diagram of WT modeling in the effect of temperature and humidity.

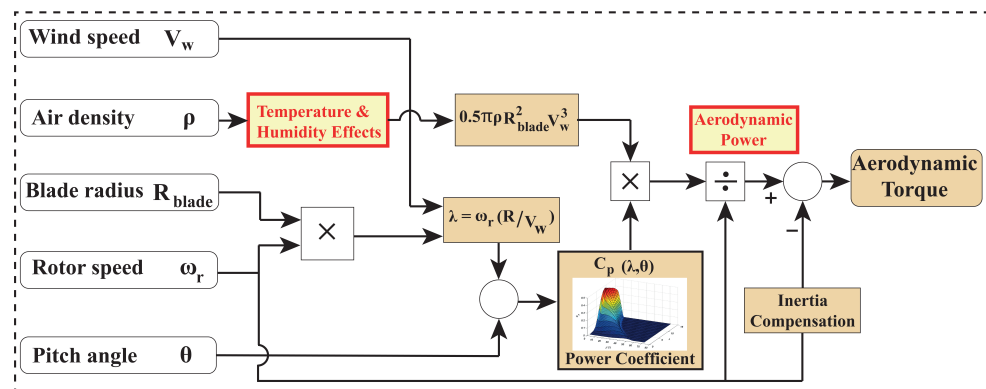


Figure 1. Block diagram of WT modeling with temperature and humidity effects.

3.2. Performance of WTS Operation under Temperature and Humidity Effects

The effect of different temperatures, humidity levels and altitude on air density is calculated analytically using the dynamics of (2)–(4) and the results are shown in Figures 2 and 3. Furthermore, Figure 2 indicates that the air density decreases linearly as the temperature increases. In addition, humidity also affects air density for temperature values below 20°C . However, air density is greatly affected by increased humidity. Furthermore, in Figure 3, it can be seen that the air density value is greatly affected by increasing elevation above sea level. The graph is presented for a constant relative humidity of 20%. In addition, the rate of change in air density due to the change in altitude decreases linearly as the temperature rises. For a change in altitude of 2000 m above sea level at a temperature of -10°C , the density of air drops from 1.3408 kg/m^3 to 1.1359 kg/m^3 , which accounts for a decrease in the air density of 15.5%. Then, for the same change in altitude of 2000 m under a different air temperature of 35°C , the air density decreases from 1.034 kg/m^3 to 0.9081 kg/m^3 with a percentage reduction of 12%.

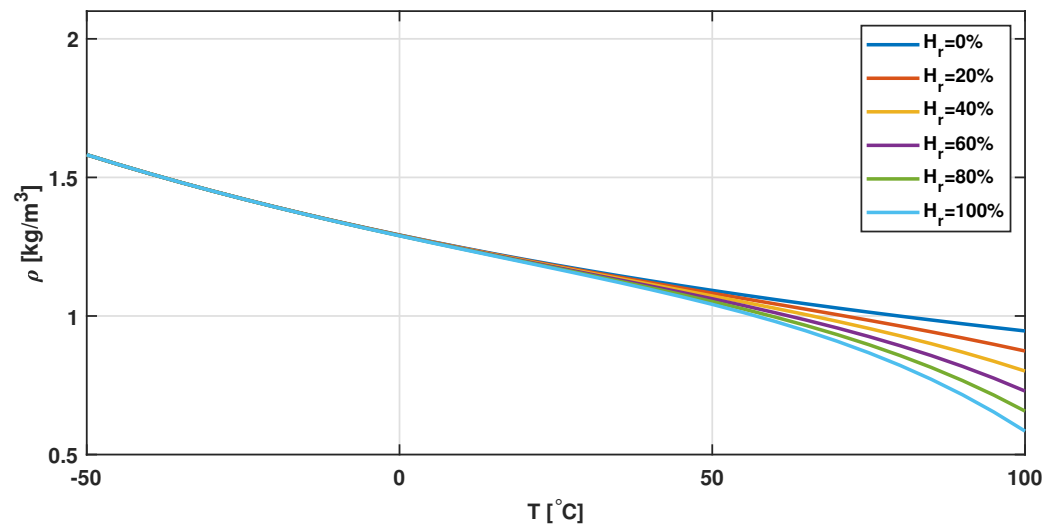


Figure 2. Temperature vs. air density with varying humidity.

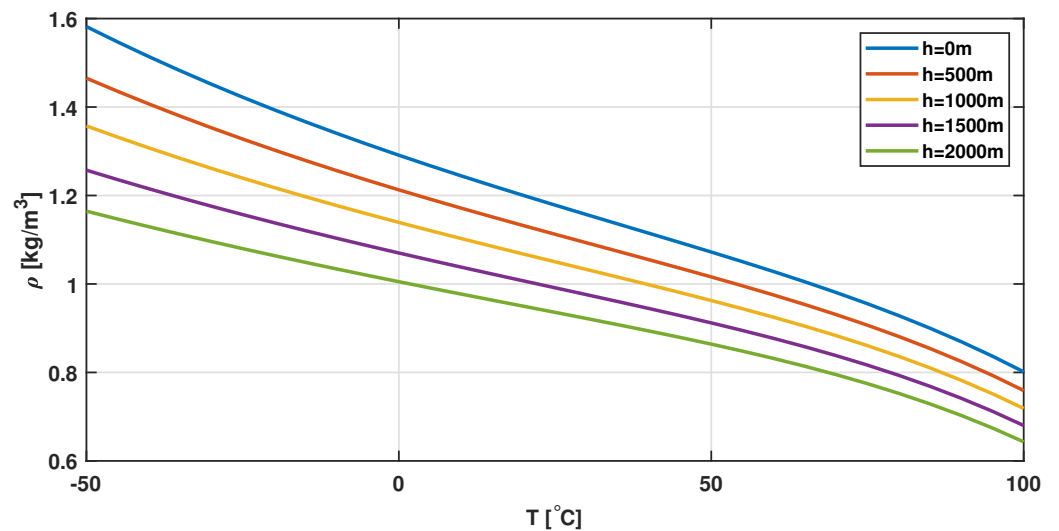


Figure 3. Temperature vs. air density with varying altitude.

Therefore, it can be concluded from the above discussion that environmental factors such as temperature and humidity greatly influence air density. Consequently, these environmental factors precisely reduce the aerodynamic power extraction of the WTS. Next, to quantify the effect of these factors on the aerodynamic power extraction of super-large WTS, we consider the 20 MW rating reference WTS as [68]. The aerodynamic and speed ($P_{ad} - \omega_m$) characteristics of the 20 MW WTS are evaluated, taking into account the specified rated wind speed (10.715 m/s). Figure 4 represents the characteristics of $P_{ad} - \omega_m$ according to the temperature change and Figure 5 shows the properties $P_{ad} - \omega_m$ at various altitudes. From Figures 4 and 5, we can confirm that the aerodynamic power and speed notably decrease according to the temperature and humidity effects.

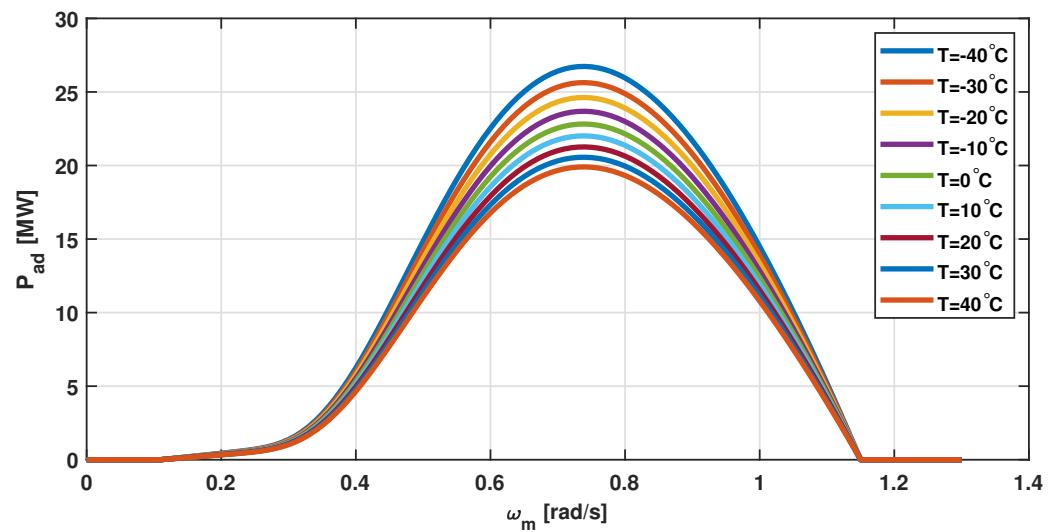


Figure 4. $P_{ad} - \omega_m$ curve with varying Temperature.

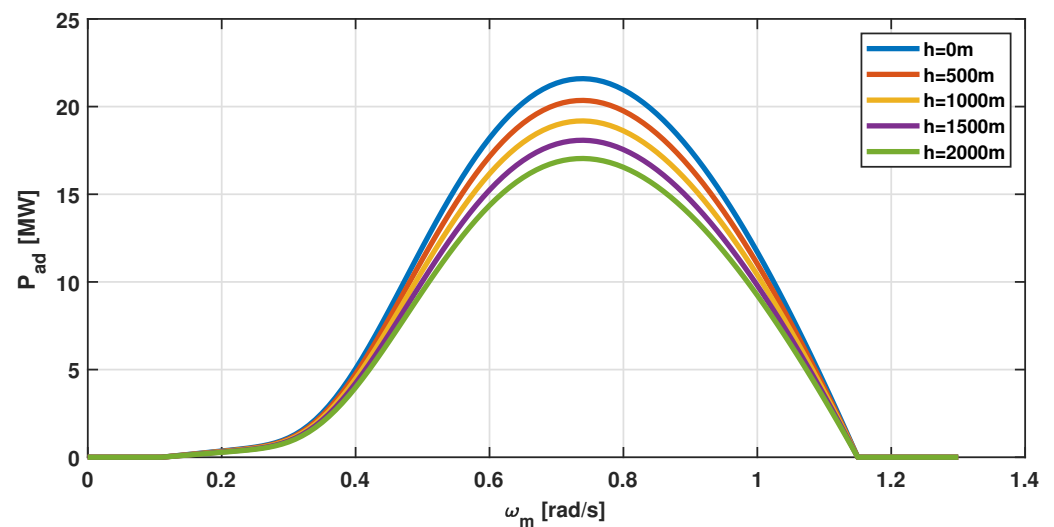


Figure 5. $P_{ad} - \omega_m$ curve with varying altitude.

Furthermore, the $P_{ad} - \omega_m$ characteristics of Figures 4 and 5 precisely match the parameter specifications of the 20 MW rated reference wind turbine for the standard temperature of 15 °C and an altitude value at sea level ($\rho = 1.225 \text{ kg/m}^3$, $P_{ad} = 21.2 \text{ MW}$, $\omega_m = 0.75 \text{ rad/s}$). However, when the temperature changes, the aerodynamic power extraction will linearly and negatively change with a change in air temperature [51]. Moreover, the aerodynamic power extraction exceeds the rated value at the rated speed operation for negative temperature values. This phenomenon can overload the components of wind turbines, generators, and power conversion systems. Therefore, the WT control system must be suitably adapted to these changes in WT characteristics. Moreover, the effect of altitude change on aerodynamic power extraction decreases with increasing altitude. This cannot violate the rated operation of the WT system. However, if parameter changes are not properly taken into account in the design of the control algorithm, there may be a possibility that the WT system will operate at a non-optimal operating point, which will enormously affect MPPT efficiency.

3.2.1. Simulation Results for Super-Large WTS under Varying Environmental Conditions

To analyze the impact of these environmental factors on super-large WTS operations, an analytically designed 20 MW permanent magnet synchronous generator (PMSG)-based WTS is used with optimized parameters to match the WT output discussed in the previous

section. The WTS parameter values considered in this study are presented in Table 1. MATLAB simulations are also performed with well-established industry-standard optimum torque controllers (OTCs) [69].

Table 1. Parameters of 20 MW PMSG-based WTSs.

Parameter	Description	Value
Grid parameters		
V_g (V)	RMS Grid voltage	6600
R_g (m Ω)	Filter resistance	1750
L_g (mH)	Filter inductance	2.1
Aerodynamic parameters		
P_{ad} (MW)	Rated aerodynamic mechanical power	21.2
R_b (m)	Rotor blade radius	138
λ_{opt}	Optimal tip-speed ratio	9.5085
$\mathcal{V}$ (m/s)	Rated wind speed	10.715
$C_{p_{max}}$	Maximum power coefficient	0.48
B_m (Nm s/rad)	Damping coefficient	200
J (Mnm)	Net inertia of rotating shaft	4.872
PMSG parameters		
P_{em} (MW)	Rated stator power	20
P_n	Stator poles	160
Ψ_m (Wb)	Stator magnetic flux	93
L_s (mH)	Stator inductance	27.49
R_s (m Ω)	Stator resistance	44.25
E_p (V)	Induced voltage in RMS	6800

3.2.2. Simulation Results for Super-Large WTS with Varying Temperature and Constant Relative Humidity

This section presents dynamic simulation results of a 20 MW super-large WTS at various temperatures and constant relative humidity. To do this, the optimum torque constant is calculated based on two cases to distinguish the power extraction of WTS for the variation in temperature with constant wind velocity and at sea-level altitude as follows:

- First, the given standard value of $\rho = 1.225 \text{ kg/m}^3$ is considered under varying temperature operations.
- The results are compared for an identical temperature profile with varying $\rho = f(T)$.

First, $\mathcal{V}_w$ is kept constant at a value of 10 m/s, and the temperature change is modeled as discrete steps from 40 °C to −10 °C. It changes by −10 °C every 100 s. The simulation result of the super-large WTS according to the temperature change is shown in Figure 6. The temperature change is depicted in Figure 6a. From Figure 6b, we can see that the tip-speed ratio (TSR) of the WT is gradually increased based on the temperature variation. The results show that the WTS operates with the optimal TSR considering the temperature dependence of air density for OTC. Otherwise, the TSR will not go to the optimal value considering the standard air density value regardless of the temperature change. As a result, the power coefficient C_p also deviates from the maximum value as pictured in Figure 6c. The response rotor speed ω_m is plotted in Figure 6d. Due to the constant value of k_{opt} in OTC, where the temperature changes during *case – i* operation, the speed deviates slightly from the optimum rotor speed. However, due to the adaptive nature of k_{opt} in OTC control, the speed continually tracks the optimal speed and keeps λ at the optimal value to extract the maximum output power. As a result, the aerodynamic power extraction under *case – ii* is slightly higher than the *case – i*, especially during the temperature values are away from the standard values of 15 °C. Then the significantly higher value of aerodynamic power and grid power delivered over periods of 100–200 s and 600–700 s can be witnessed in Figure 6e and 6f, respectively. To quantify the increase

in power extraction, the aerodynamic power extraction accounts for the value of 58.2 kW and 71.3 kW improvement during the duration of 100–200 s and 600–700 s, respectively.

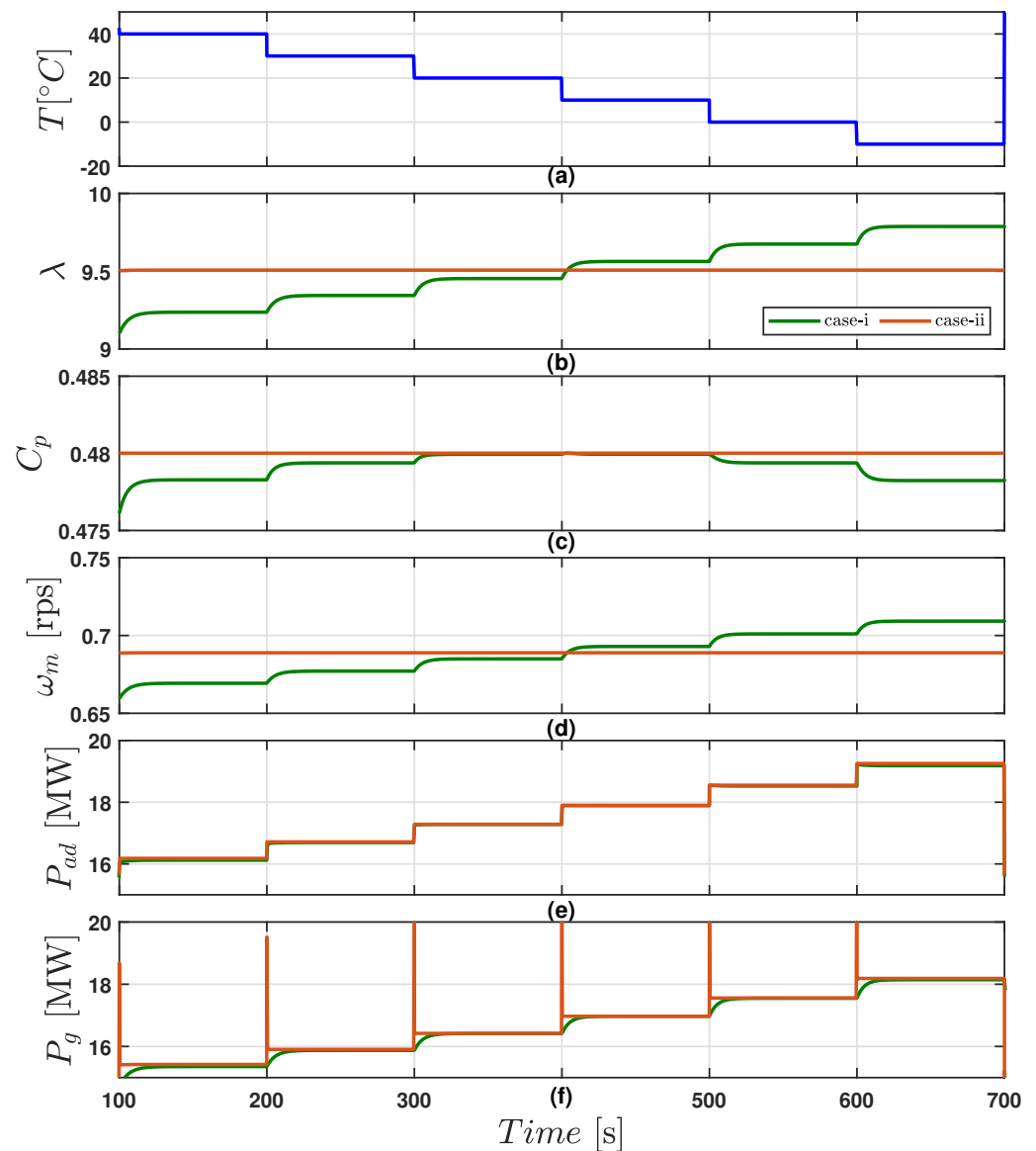


Figure 6. Simulation results of 20 MW WTS under varying temperature conditions. (a) Temperature. (b) Tip-speed ratio. (c) Power coefficient. (d) Rotor speed. (e) Aerodynamic power. (f) Power delivered to the grid.

3.2.3. Simulation Results for a Super-Large WTS with Constant Temperature and Varying Relative Humidity

This section aims to present simulation results for a super-large WTS with constant temperature and varying relative humidity. For this, OTC is considered for three cases where the temperature is held at 35 °C. First, the typical value of $\rho = 1.225 \text{ kg/m}^3$ is considered for different humidity operations (*case – i*), and the results are compared for the same humidity profile by $\rho = f(T)$ alone without considering the relative humidity (*case – ii*). We then approximate air density by taking the relative humidity into account in (*case – iii*), i.e., $\rho = f(T, H_r)$.

Initially, the wind speed remains constant at 10 m/s, and the relative humidity changes in discrete steps from 0% to 100%, with a step change of 20% for every 100 s. The simulation results are comparatively shown in Figure 7. Notably, the variation in relative humidity is clearly illustrated in Figure 7a. From Figure 7b, we can confirm that the WTS operates with

the optimal TSR considering the environmental factor to air density for OTC. Otherwise, the TSR will not reach its optimal value, considering standard air density values, regardless of temperature and relative humidity changes. As a result, the power coefficient C_p also deviates from its maximum value as illustrated in Figure 7c. Due to the constant value of k_{opt} in OTC with varying temperatures in *case – i* operation, the speed deviates slightly from the optimum rotor speed as portrayed in Figure 7d. However, in *case – ii* and *case – iii*, due to the adaptive nature of k_{opt} in OTC, the speed continues to follow the actual optimal speed, leaving λ as the optimal value. Consequently, the aerodynamic power extraction in instance *case – iii* is greater than in cases *case – i* and *case – ii*, as presented in Figure 7e. So, it is evident that the humidity and temperature variations greatly affect the aerodynamic performance of the WTS. At the same time, the produced electrical power delivered to the grid is shown in Figure 7f, respectively. These results showed that the temperature and humidity effects enormously impact the performance and output power production of the super-large WTS.

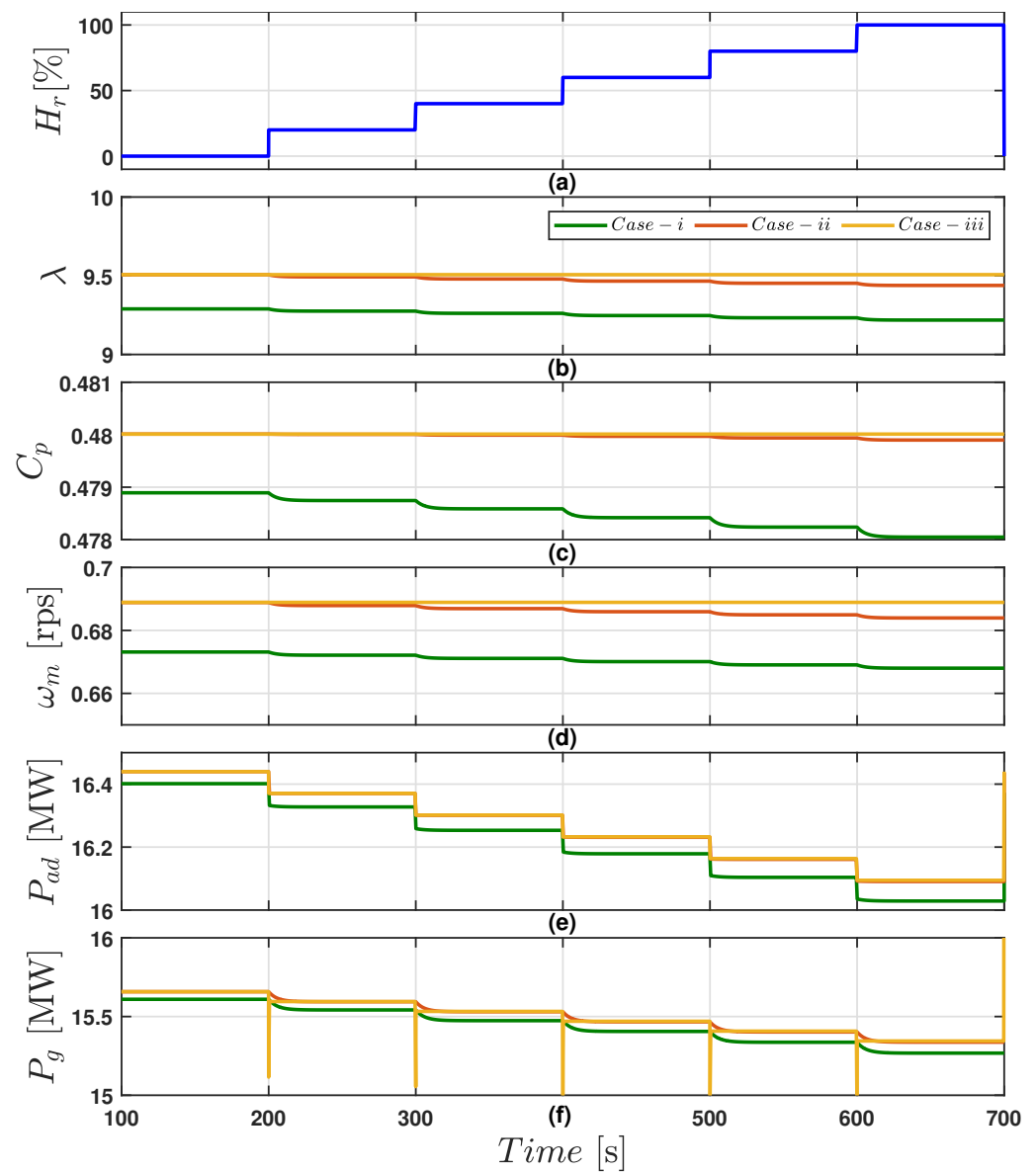


Figure 7. Simulation results of 20 MW WTS under varying humidity. (a) Relative humidity. (b) Tip-speed ratio. (c) Power coefficient. (d) Rotor speed. (e) Aerodynamic power. (f) Power delivered to the grid.

4. Rainfall Effects on Super-Large Wind Turbine Systems

The efficiency of a super-large WTS is strongly influenced by surrounding atmospheric conditions across various situations. For instance, hail, snow, rain showers, wind gusts, ice, severe temperatures, lightning, seawater, UV radiation, and sandstorms harm the wind turbine blades during its operational life [54,70,71]. In stormy conditions, raindrops interact with the approaching wind field as they fall, modifying the wind field's micro-turbulence and altering the WTS's aerodynamic performance due to the action of gravity and horizontal wind force. Annual energy production losses for wind turbines can range from 2% to 25% with increasing drag and decreasing charge [72]. Because rain is a pervasive climatic factor, considering its impact on WT efficiency is crucial when choosing a site for installing a new wind farm. For wind power to succeed, mainly in locations offshore or in humid areas, more work is needed for functional operation under these disorderly conditions. Little research has thus far been published on the effect of rainfall on the performance and output of wind turbines [73]. Numerous studies have investigated the modeling and analysis of the aerodynamics and dynamics of turbine tower blades [52,74], VAWT [75], and HAWT [76] structures. Raindrops are modeled for offshore WT blades in [70]. At the same time, the authors in [77] numerically investigated the effects of raindrops on offshore WT blades. In [53], the authors presented the aerodynamic performance of large-scale WTS under yaw and wind-rain effects. Recently, the authors proposed a novel method to analyze the output of VAWT and HAWT in rainy conditions [75,76]. Meanwhile, the authors of [78] investigated the pitch controller performance and output power extraction of an extra-large WTS. Based on the above discussion, the characteristics of rainfall effect modeling in WTS are (i) raindrop diameter, (ii) impact velocity, (iii) raindrop impact angle, and (iv) raindrop density. In this regard, the mathematical modeling of these characteristics and rainfall effects in the super-large WTS is summarized in the following section.

Mathematical Modelling of Rainfall Effects in Super-Large WTSs

Generally speaking, wind and rain are related to each other. When the WT comes into contact with rain, it tends to be affected by the diameter and impact velocity of rain droplets on the WT blade, leading to losses in power and performance. When raindrops come into contact with the blade, their speed becomes immediately reduced to zero. This phenomenon can be modeled according to Newton's second law as

$$\int_0^{\tau} \vec{f}(t) dt + \int_{v_r}^0 m d\vec{v} = 0 \quad (5)$$

where $f(t)$ and m represent the force and mass of the raindrop. v_r is the velocity of the raindrops on the blade. τ is the time difference between the speed of the raindrop from v_r to zero. Assuming the raindrop is spherical, $m = (1/6)\sigma\pi d^3$ and $\tau = d/2v_r$ are also taken into account. where d is the diameter of the raindrop and σ is the density of the water. Therefore, the force of raindrops acting on the blade can be described as

$$F_d = F(\tau) \frac{\alpha W}{S} \quad (6)$$

where

$$F(\tau) = \frac{1}{\tau} \int_0^{\tau} f(t) dt = \frac{mv_r}{\tau} = \frac{1}{3}\sigma\pi d^2 v_r^2 \quad (7)$$

The term $F(\tau)$ signifies the force of a single raindrop affecting the blade surface during the τ time interval. Furthermore, $S = \pi d^2/4$ is the area covered by raindrops. W is the

width of the structure relative to the rain. The volume occupancy of each type of raindrop is given as

$$\alpha = \frac{1}{6}\pi d^3 N \quad (8)$$

here, N refers to the number of rain droplets of diameter in between d_1, d_2 in a unit volume of air which is calculated as follows:

$$N = \int_{d_1}^{d_2} n(d) dd \quad (9)$$

In the above equation, d_1 and d_2 are taken as 0.1mm and 6mm, respectively, and $n(d)$ is the distribution size of the raindrop which is pictured in Figure 8. Numerous observations have indicated that the size of raindrops follows a negative exponential distribution, also called the Marshall–Palmer (M-P) spectrum, widely used [79] as follows:

$$n(d) = n_0 e^{-\Lambda d} \quad (10)$$

where $n_0 = 0.08 \text{ cm}^{-4}$ for all rainfall intensity and slope coefficients $\Lambda = 4.1I^{-0.21} \text{ cm}^{-1}$ in that I is the rainfall intensity, which is listed in Table 2.

Table 2. Classification of Rain Intensity.

Classification	Light Rain	Moderate Rain	Heavy Rain	Rainstorm
Rain intensity (mm/h)	2, 5	8	16	32
Classification	Heavy rainstorm (weak)	Heavy rainstorm (moderate)	Heavy rainstorm (strong)	Heavy rainstorm (extreme)
Rain intensity (mm/h)	64	100	200	709, 2

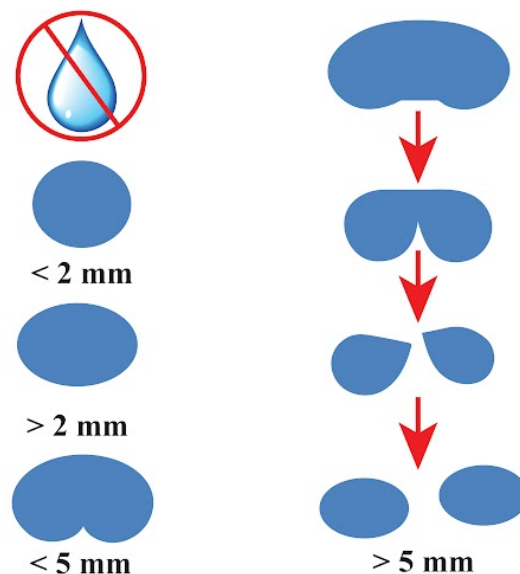


Figure 8. Morphological changes of a falling raindrop.

Substituting $F(\tau)$, S , α into (10) the rainfall's impact force is given as follows:

$$F_d = \frac{2}{9} N \sigma \pi d^3 \mathcal{V}_w^2 W \quad (11)$$

F_d is described using the tail-wind, cross-wind, and downward direction as illustrated in Figure 9. The wetness function (W) is explained in the following subsections. The power output generated is dependent on the rain and wind velocity. This analysis method can simplify and reduce the problems and complexity during calculations.

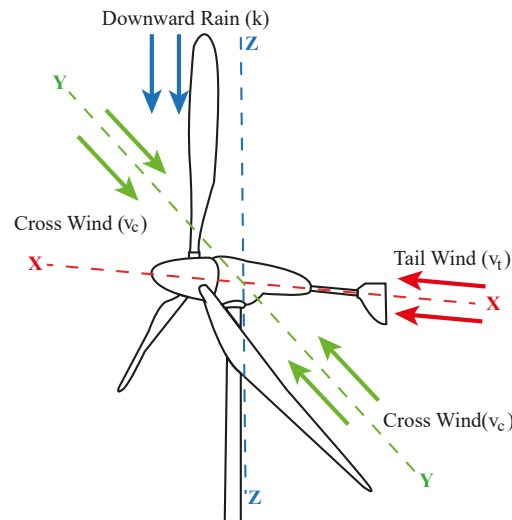


Figure 9. Visual representation of the impact of tailwind, crosswind and downward rain on F_d .

Wetness Modeling of the WT Blades

In (11), W refers to the wetting function, which is taken into account because the rainfall area is considered as the total area covered by raindrops hitting the blade during rotation. The WT blade's swept area equals the number of raindrops in contact with the rotating blade. Therefore, a geometric measure can be utilized as an overall wetting index.

In [78], it is assumed that the rainfall is uniform and the rain droplet velocity is constant (i.e., no gusts), $\vec{v}_r = \{v_t, v_c, -k\}$ so that all the represented values of tail-wind(v_t), cross-wind(v_c), and downward rain(k) are positive. In addition, the horizontal wind velocity $\vec{V}_w = \{s, 0, 0\}$ determines the constant speed of the blade. Q is where the raindrop will touch the blade at time t . Thus, the rain droplet reaches the swept area at a point $Q + v_r t$. The point's starting location is given by $P = Q + v_r t - V_w t$. Thus, for each exposed point P on blades at time 0, point $P + (v_r - V_w)t$ falls under the rain region for $0 \leq t \leq 1/s$, which implies that the rain region is in line segments parallel to apparent rain vector $\vec{v} = \vec{v}_r - \vec{V}_w$, each of length $\|\vec{v}\|/s$. Thus, the total wetness is equal to the blade's swept area multiplied by magnitude of $\vec{v}/s$. Swept space of a turbine is roughly assumed as a spheroid or bi-cone and, $\vec{v}/s = v_t - s, v_c, -k/s$. Total wetness function W for oblate spheroidal swept space with radius R and half-thickness of the swept area a can be stated as follows [80]:

$$W(s) = \frac{\pi R \sqrt{R^2(v_t - s)^2 + a^2 v_c^2 + a^2 k^2}}{s}. \quad (12)$$

It can be seen that $W(s)$ tends to limit the values for the region (πR^2) as $s \rightarrow \infty$. It decreases strictly at $(0, \infty)$ for $v_t < 0$ (no tailwind), and at the only critical point, we get an absolute minimum for $v_t > 0$ (with a tailwind). Once again, the optimal speed is higher than the tailwind speed v_t .

$$S_{opt} = \frac{R^2 v_t^2 + a^2 v_c^2 + a^2 k^2}{R^2 v_t} \quad (13)$$

where, a is the swept area, length of the blade is denoted as R .

Finally, using the parameter set for the power coefficient of the super-large WTS, the effect of rainfall on the generated power is defined as follows:

$$P_d = \underbrace{\frac{1}{2}\rho\pi R^2 C_p(\lambda, \beta_b) \mathcal{V}_w^3}_{\text{WT Output Power}} - \underbrace{\frac{2}{9}N\rho\pi d^3 v_r^2 W \mathcal{V}_w}_{\text{Rainfall Impact}} \quad (14)$$

here, P_{ad} is expressed as the final output power of WTS, considering the rainfall effect. Moreover, the aerodynamic power extraction of WTS during rainfall is analyzed through Figures 10–14. In Figure 10, the impacts on the output power of wind turbines under rainfall (dashed lines) are compared with the case of no rainfall (solid lines) for varying wind velocity at different constant values of rotor speed. Next, the $P_{ad} - \omega_m$ characteristics under different wind velocities are pictured in Figure 11. The solid lines and the dashed lines differentiate the performance under no rain and rainfall conditions. From this, the reduction in power extraction under rainfall can be easily quantified and the MPPT curves are also pictured for the rainfall case and no rainfall case.

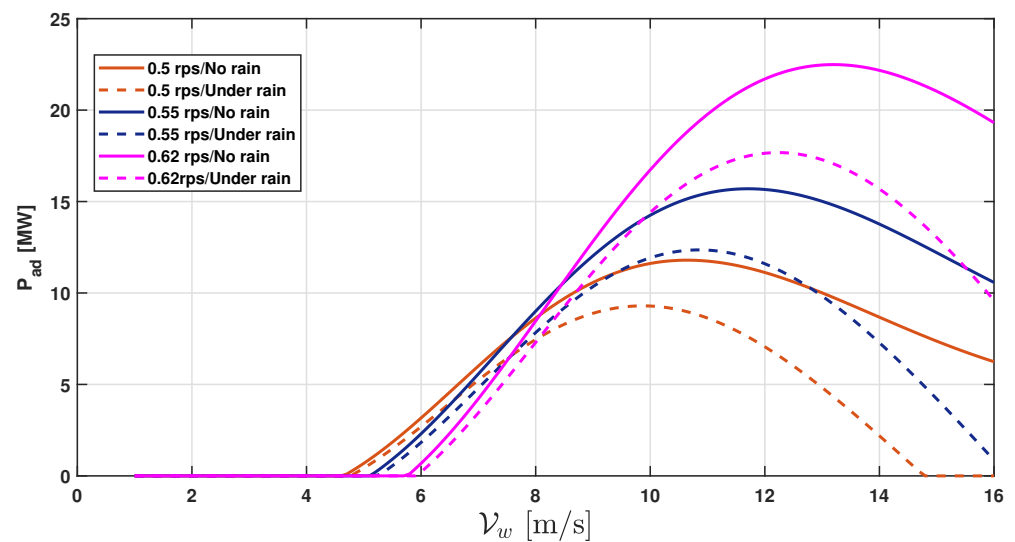


Figure 10. Analytical results of $P_{ad} - \mathcal{V}_w$ corresponding to different rotor speeds ω_m .

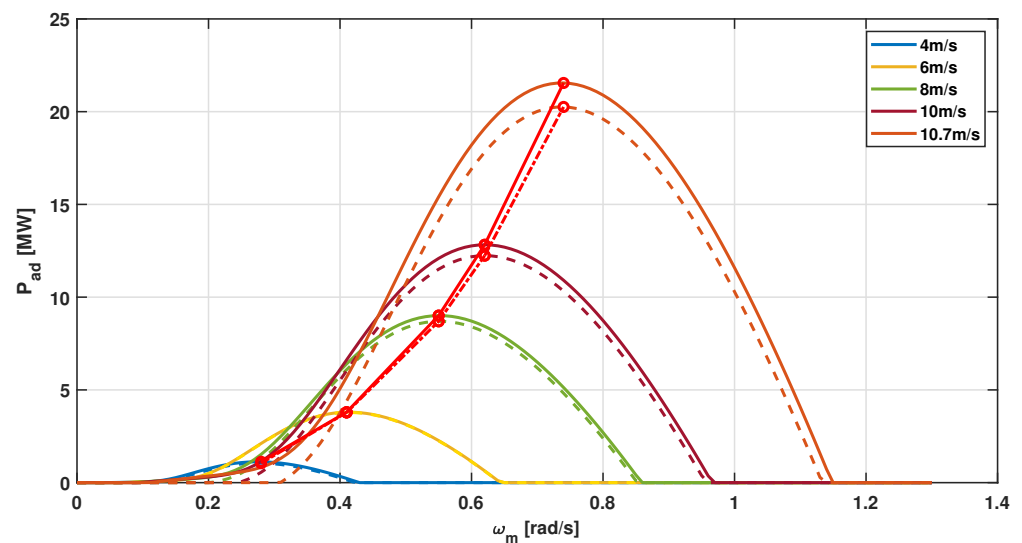


Figure 11. Analytical results of $P_{ad} - \omega_m$ corresponding to different wind velocities $\mathcal{V}_w$.

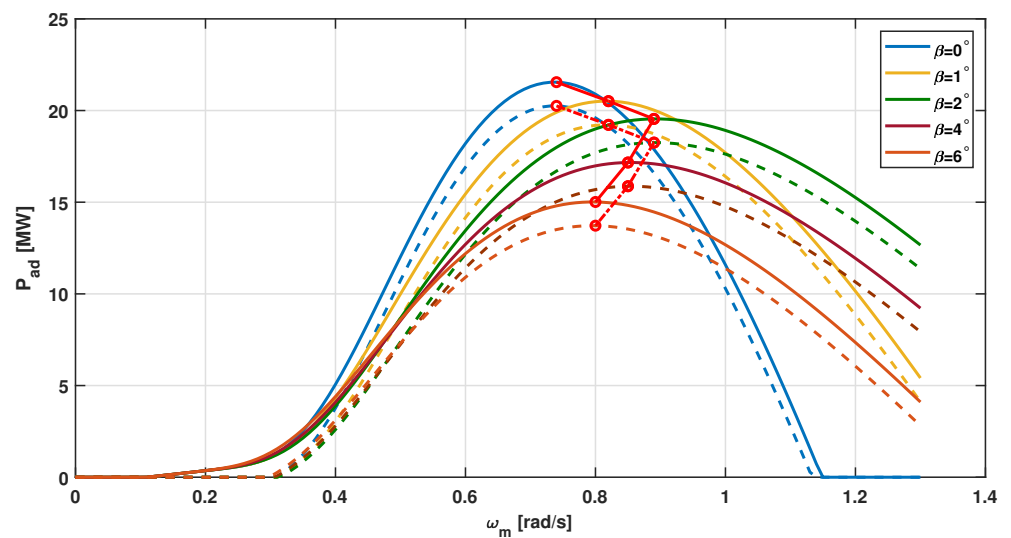


Figure 12. Analytical results of $P_{ad} - \omega_m$ corresponding to different blade pitch angles β_b .

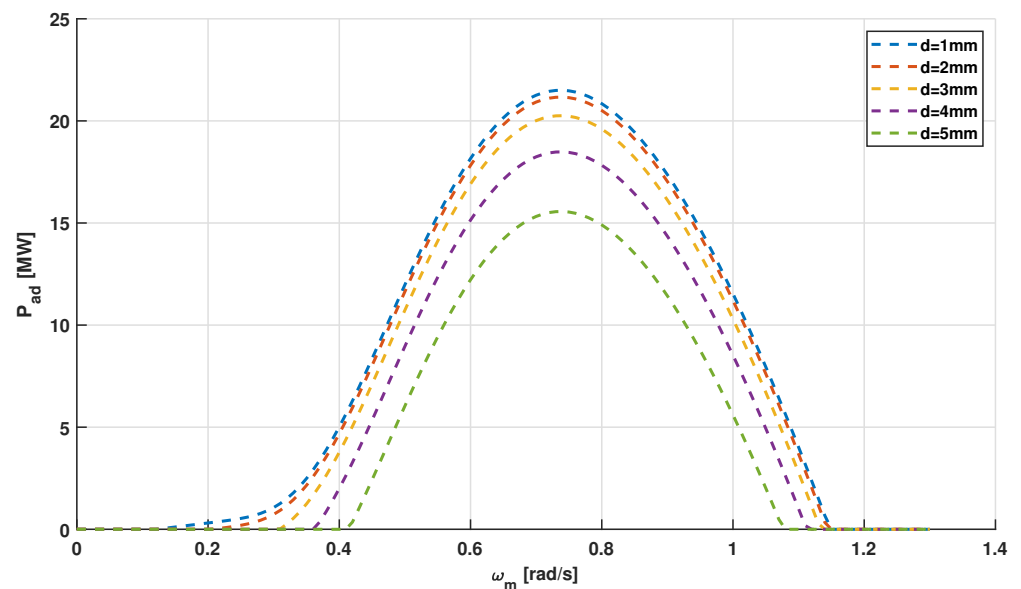


Figure 13. Analytical results of $P_{ad} - \omega_m$ corresponding to different rain drop diameters d .

Further, a comparative analysis of power extraction is distinguished by the solid and dashed lines, respectively, under no rain and rainfall cases with varying pitch angles and rated wind velocity are illustrated in Figure 12. Moreover, the effect on power extraction for various values of raindrop diameter is illustrated in Figure 13 for various diameters. Furthermore, the dependence of aerodynamic power on the density of rainfall is given in Figure 14 under raindrop diameter $d = 0.3$ mm and wind velocity $V_w = 10.715$ m/s. Figure 15 illustrates the block diagram of the mathematical modeling of WT under the rainfall effect.

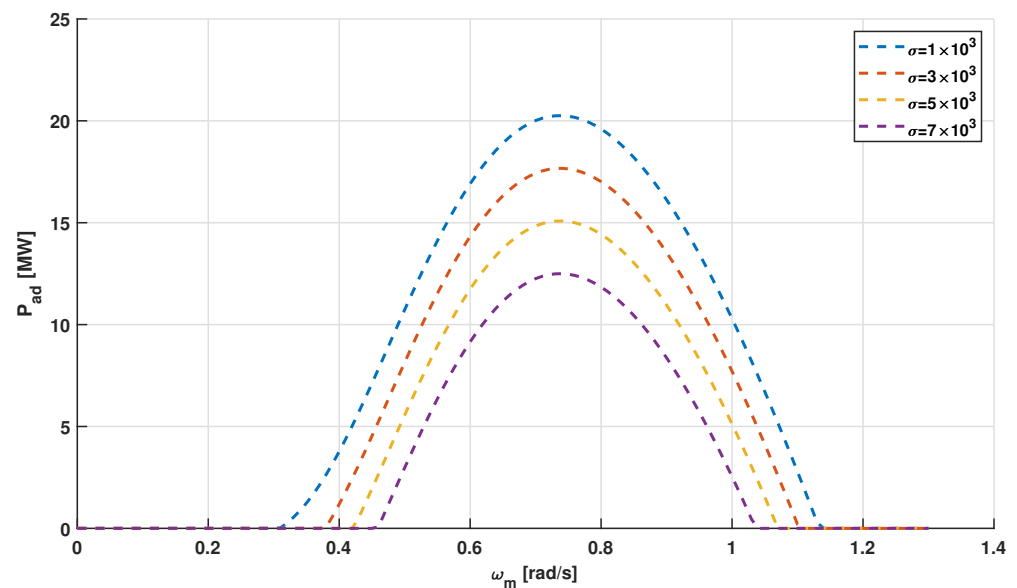


Figure 14. Analytical results of $P_{ad} - \omega_m$ corresponding to raindrop diameter $d = 3$ mm and different raindrop densities σ .

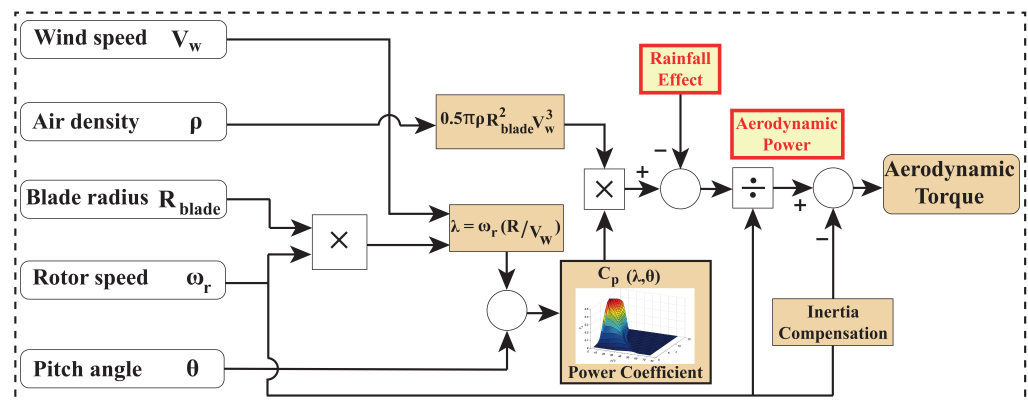


Figure 15. Block diagram of the WT modeling considering rainfall effects.

5. Recent Pitch, Yaw, and Torque Control Methods for Super-Large WTS with and without Environmental Changes

This section presents a recent study of coordinated pitch/yaw and generator torque control techniques for super-large WTS with and without environmental conditions. The authors in [81] presented a comprehensive review of recent developments and pitch angle-based control strategies in wind energy conversion systems. In [82], the authors present a complete review of the expert pitch control methods developed in recent years and provide control solutions approximating the conditions of various WTSs. The authors also found that by combining fuzzy systems, neural networks, and search algorithms, they could build diffuse neural networks with evolutionary capabilities to implement and represent human thoughts in pitch-controlled systems effectively. Following this, a complete review of the collective and individual pitch control, damping control, and pitch actuator control of large-scale wind energy converters was investigated in [83]. However, these reviews have not focused broadly on investigations into the coordinated pitch/yaw and generator torque control of super-large WTSs. Thus, this study presents a comprehensive review of coordinated control strategies for a super-large WTS with and without considering environmental factors. A block diagram of the complete coordinated pitch/yaw and generator torque control method is shown in Figure 16.

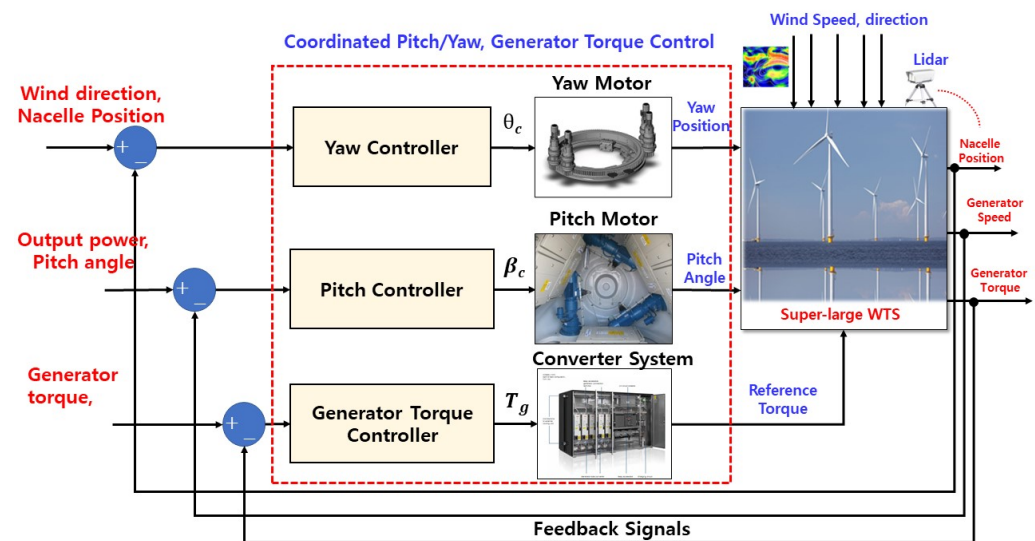


Figure 16. Block diagram of the coordinated pitch/yaw and generator torque control method for super-large WTS.

5.1. Review of Pitch Control for Super-Large WTS

Pitch control allows the system to adjust the aerodynamic performance by changing the pitch angle of the WT blades. The pitch angle is a vital WT factor since it controls the wind's angle of attack. Thus, rotating the blades around the axis modifies the rotor's relative wind flow and the aerodynamic load. The pitch angle also affects the power factor $C_p(\lambda, \beta_b)$, which affects the WTS's power capture. Therefore, pitch angle control serves power management and load reduction. This is especially noticeable when operating in region-3, where power must be kept to a minimum, and high wind speeds strain the WT structure and rotor significantly. Over the years, various concepts have been proposed for power control and load reduction in WTs. The aerodynamic properties of the blades were used to control the initial WT passively. The airfoil is built with passive stall control to stall in windy areas. Since no additional actuators were required, simple and inexpensive power control was possible. However, the controllability was limited because it was based on a spontaneous stall phenomenon without active control. The WT is subjected to greater power fluctuations, torque spikes, and varying load efforts from passive stall control [17].

In region-3, the pitch control system accelerates or decelerates the turbine while adjusting pitch angle, wind torque, and speed. The control objectives of region 3 are as follows,

- (1) To maintain a constant rotor speed, the generator torque must often remain constant to achieve stable output power operation.
- (2) To track the active power reference and real-time balancing between the aerodynamic (input) and electric (output) power of the super-large WTS.

The pitch command values are often the same for all three blades in collective pitch control, and the pitch control loop uses the rotor speed as feedback [84–86]. Furthermore, the rotor mechanical output is used directly as feedback [87–89]. In addition, discrete pitch control techniques are also the subject of on-going research explicitly aimed at reducing the load while maintaining the output power at its rated value. This is achieved by individually adjusting the pitch angle of the three blades to reduce various flap direction bending moments and low rotor loads [90–92].

5.2. Coordinated Pitch and Generator Speed Control for Active Power Regulation of Super-Large WTSs

This subsection shows the coordinated pitch and generator speed control for active power regulation of the super-large WTS. While supplying a specific demand, super-large

WTs must follow desired power standards to provide active power control. Rotor speed control (RSC) and pitch angle control (PAC) approaches can be used for variable speed and variable pitch WT, but the latter, which uses WT inertia as an energy buffer, has less pitch activation and is consequently more desirable for wind energy. In the conventional PAC method, the pitch actuator is activated when the operating speed reaches the upper-speed limit of the power reference. This PAC control requires a higher pitch operating speed and significant fatigue load for the pitch servo system of the super-large WTS [93,94].

Furthermore, in the conventional P_{ref} tracking of the WT control, the maximum speed limit of the pitch actuator ω_u is the optimal power curve $P_{opt}(\omega_m)$ of WT intersects the P_{ref} line in $P_{ad} - \omega_m$ curve. As per the definition of MPPT and (2), we can write:

$$P_{opt}(\omega_m) = K_T \omega_m^3 \quad (15)$$

$$K_T = \frac{0.5\rho(T, H_r, h_s)\pi R^5 C_{P_{max}}}{\lambda} \quad (16)$$

In the condition $P_{ref} < P_r$, the turbine must run at the speed $P_{ref} = P_{opt}(\omega_m)$. The operating speed at this point for a given P_{ref} can be expressed as ω_l and the existing pitch control scheme assigns $\omega_u = \omega_l$. However, the pitch control operation can be enhanced by utilizing the kinetic energy buffer of rotor inertia, as depicted in Figure 17. The torque assignment to the generator through reference current is switched based on the rotor speed ω_m , and the constraint used for switching is given in Figure 17. Here, the activation speed of the pitch controller is set to $\omega_u = \omega_r$. So Wt works in MPPT mode for $\omega_m < \omega_l$ and switches to power tracking mode for $\omega_l < \omega_m < \omega_u$ [95]. Furthermore, temperature and humidity effects on air density are considered for MPPT operation.

The above-adjusted rotor speed and pitch actuation control improve WT operation, but the rotor speed range $\omega_l - \omega_u$ is utilized for tracking P_{ref} only at zero pitch angle.

In addition, an integration mechanism is introduced to achieve minimum pitch operation in order to improve the method discussed above. Figure 18 shows a block diagram of active power regulation with simultaneous rotor speed and pitch angle. For $\omega_m > \omega_l$, the WT system utilizes a variable speed range of $\omega_l - \omega_u$ to track the reference power as a change in rotor speed. Pitch operation is then activated for active power control for further increases in wind speed. Furthermore, if the rotor decelerates below ω_u due to reduced wind speed, the pitch angle is kept constant at an arbitrary value to take advantage of the range of rotor speed fluctuations first. For further deceleration from ω_m below the value of $\omega_l + \Delta\omega_m$ until the pitch angle is 0 to keep P_{ref} will be adjusted. When the wind speed drops further, the WT switches to MPPT mode of operation [84].

Further improvements in active power control can be achieved with an increased disturbance range of non-pitch regulation. The method illustrated in Figure 18 takes the ω_l as the point at which the P_{opt} intersects the P_{ref} line. Moreover, for the variation in speed under non-pitch regulation with some arbitrary pitch angle, the $P_{opt}^{\beta_b}$'s intersection point with P_{ref} line is denoted as $\omega_{opt}^{\beta_b}$. Hence, the speed $\omega_{opt}^{\beta_b}$ increases the range of speed variation under non-pitch regulation operation as depicted in Figure 19 as discussed in [96]. In all these co-ordinated methods, the $K_T = f(T, H_r, h_s)$ is used for MPPT tracking operation.

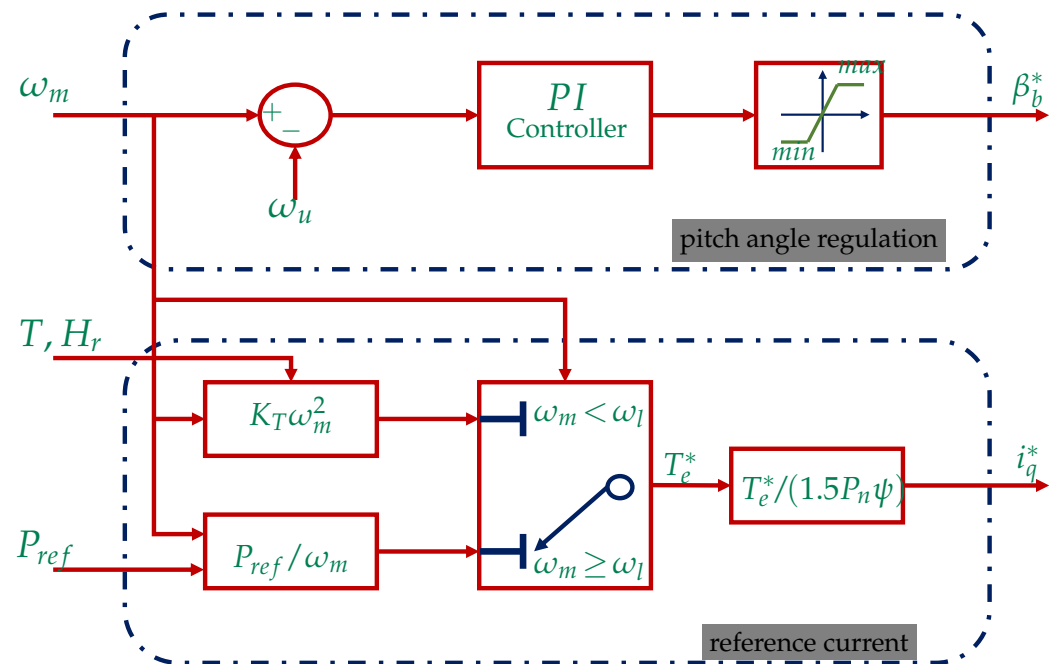


Figure 17. Active power control for reference power tracking with rotor speed control.

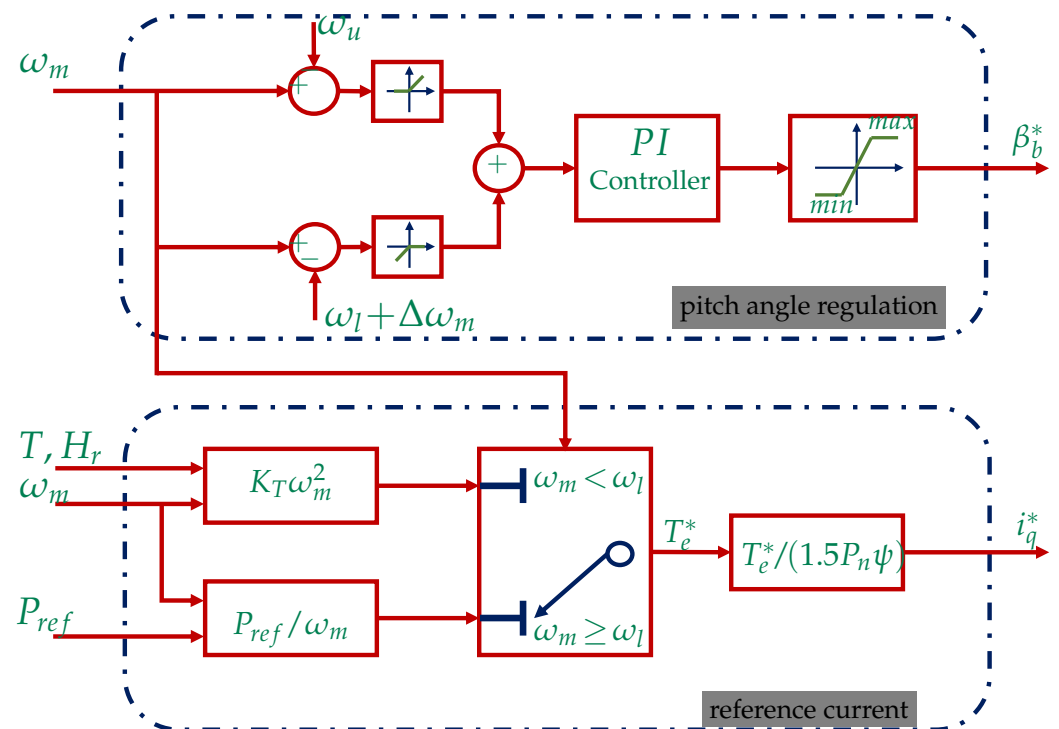


Figure 18. Active power control for reference power tracking with pitch angle control.

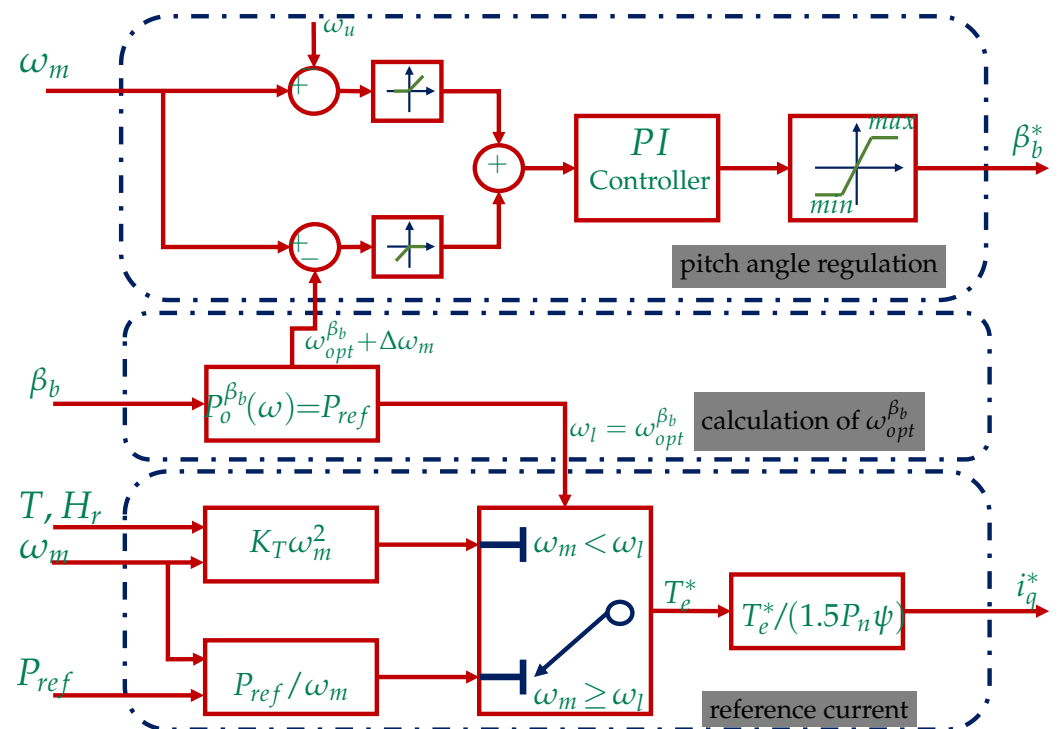


Figure 19. Active power control for reference power tracking with pitch angle control.

5.3. Review of Yaw Control for Large-Scale WTS

The yaw control method is used to ensure that the turbine rotor is always pointed in alignment with the direction of the wind to maximize output, reduce loads caused by yaw misalignment, and reduce the wake effect in wind turbines. Usually, while dealing with the pitch control and generator torque control of the wind turbine, the rotor of the WT is assumed to be facing the wind without any error, which implies that the yaw controller is ideal. However, there is always a yaw misalignment present during WT operation because of the varying wind direction and the slow-moving yaw mechanism. This will considerably impact the power extraction efficiency of a large-scale wind turbine. The yaw control of WT has the following primary objectives [97],

- (1) Maximizing the energy capture of a wind turbine by aligning the nacelle of WT exactly with the direction of wind velocity under region-2 operation.
- (2) Ensuring load reduction and maximum energy capture by establishing a coordinated pitch and yaw control with minimum actuation for efficient operation.
- (3) Decreasing a single WT's fatigue load, and maximizing the total amount of power produced by a wind farm while optimizing load.

An environmental-impact-incorporated zero-point shifting diagnosis of wind turbine yaw angle is proposed in [98] to stabilize variations in output power at different yaw angles. The work utilizes sparse Gaussian process regression to incorporate the zero-point shifting diagnosis procedure. The individual and coupling effects of temperature are analyzed and validated through real operation data. The above work has justified the improvements in diagnostic accuracy and calibration based on zero-point shifting with temperature information, contributing to an increase in wind turbine profit by around 9%.

Next, a quantitative evaluation of yaw-misalignment and aerodynamic wake-induced fatigue loads of offshore wind turbines is analyzed in [99,100]. A wake redirection control is introduced to redirect the wake by purposely yawing the upstream turbines. A comprehensive database for tower and blade damage loads is established in addition to a polynomial load assessment model. In addition, the wind velocities and turbulence intensity are identified as the dominant factors of fatigue load. Further, yaw-offset and wake

effects are interchangeably more important than others, respectively, for rated conditions and below-rated condition operation.

In addition, coordinated control of WTSs via optimized operation either with power coefficient C_p or yaw angle offsets for the maximization of net energy production was introduced in [101]. Although, the method employed in [102] introduced a multi-objective particle swarm optimization-based method to optimize the control parameters of yaw actuators through which the yaw actuation requirement is significantly reduced without affecting the power extraction efficiency.

Alternatively, an energy capture efficiency enhancement of wind turbines via stochastic model predictive yaw control based on intelligent scenarios generation is presented in [103]. The inaccuracy in prediction of wind direction is addressed through intelligent scenarios generation-based stochastic model predictive yaw control. In this work, the uncertainty in wind direction prediction is characterized by intelligent scenario generation and the yaw actions are optimized to improve energy capture efficiency. The significant improvement in profit was verified as was the energy capture improvement. Other than this, the cooperative-suspension-maglev yaw control system [104], differential yaw reduction approach [105], MPPT-integrated control [106], optimal control [107], and induction yaw control [108] present few of the techniques worth mentioning here regarding the control aspect of super-large WTSs.

6. Validation Example

To validate the influence of temperature and humidity over the aerodynamic power extraction, a comparative analysis is conducted by considering two different cases. In *case – i*, the temperature T is assumed to be 15 °C and relative humidity is taken as 0% then for *case – ii*, T is taken as 35 °C and H_r is assumed as 30%. The various operating parameters of the validation example are depicted in Figure 20. Figure 20a shows the wind profile considered for the validation followed by the rotor speed ω_m in Figure 20b. The responses of TSR λ and power coefficient C_p are depicted, respectively, in Figure 20c and Figure 20d. Next, the response of the PMSG electromagnetic torque is given in Figure 20e. The aerodynamic power and generator output power are pictured, respectively, in Figures 20f,g. Finally, the pitch actuation response β_p is shown in Figure 20h. The differences in response of the parameters exemplify the influence of environmental factors in wind turbine operation.

Further, the active power regulation schemes pictured in Figure 17 (*case – i*) and Figure 18 (*case – ii*) are validated by drawing a comparative response. The power reference P_{ref} is set as 15MW and the validation results are as shown in Figure 21. As discussed in the previous validation example, Figure 21a shows the wind profile considered for the validation followed by the rotor speed ω_m in Figure 21b. The responses of TSR λ and power coefficient C_p are depicted, respectively, in Figure 21c and Figure 21d. The electromagnetic torque response of the PMSG is given in Figure 21e. The aerodynamic power and generator output power are pictured, respectively, in Figure 21f,g. Finally, the pitch actuation response β_p is drawn in Figure 21h. From observing Figure 21h, it is clear that in *case – ii* the pitch angle is maintained constant for a while by utilizing the variation in rotor speed from the optimum value to the rated value as shown in Figure 21b. Whereas in *case – i*, the rotor speed is maintained at the optimum speed for power tracking operation. In conclusion, both methods achieve the objective by tracking the reference power and the latter one in *case – ii* utilizes the rotor speed variation by minimizing the actuation of the pitch controller. A detailed discussion and analysis can be found in [84,96].

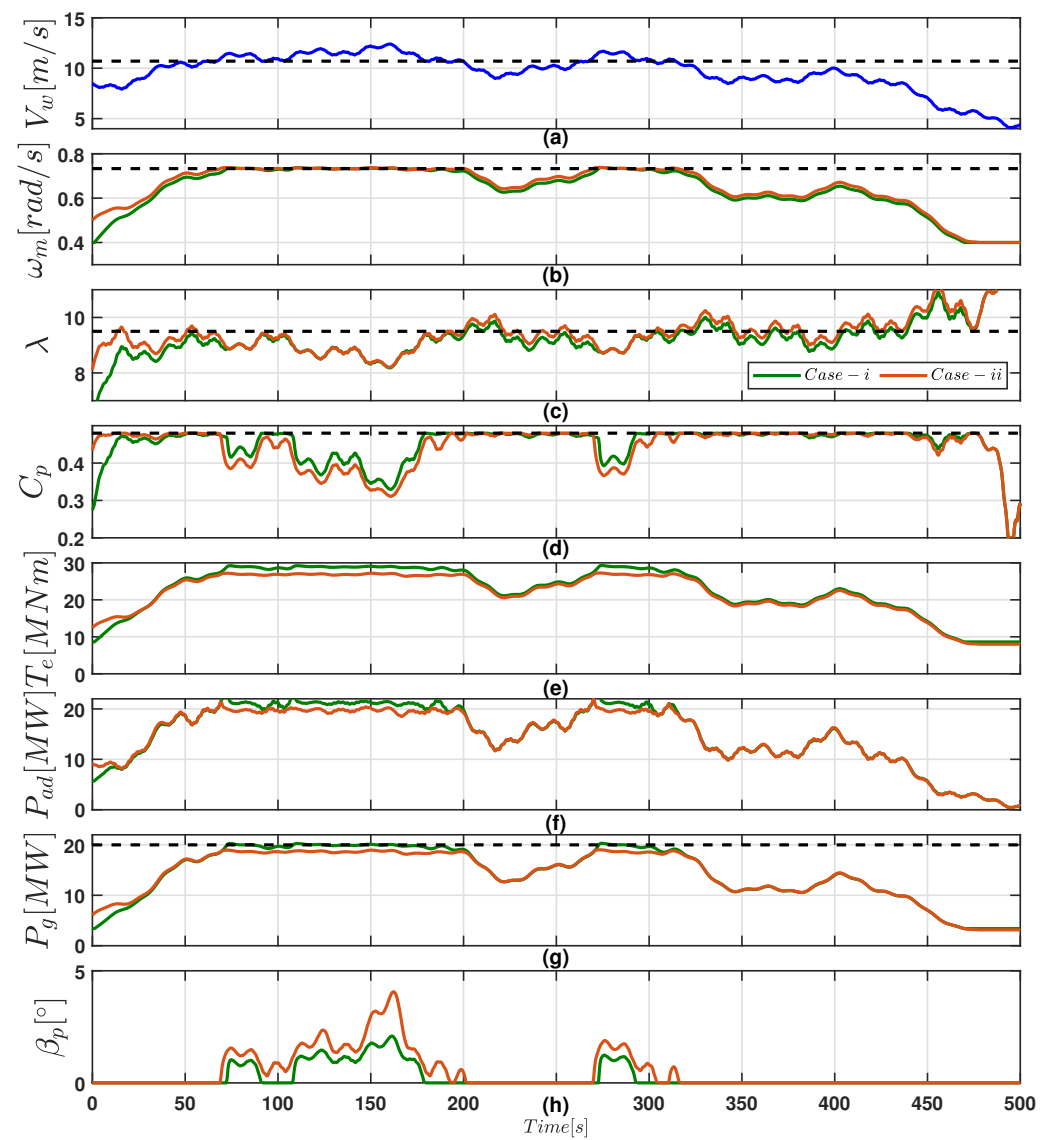


Figure 20. Comparative results to validate the influence of environmental factors in aerodynamic power extraction.

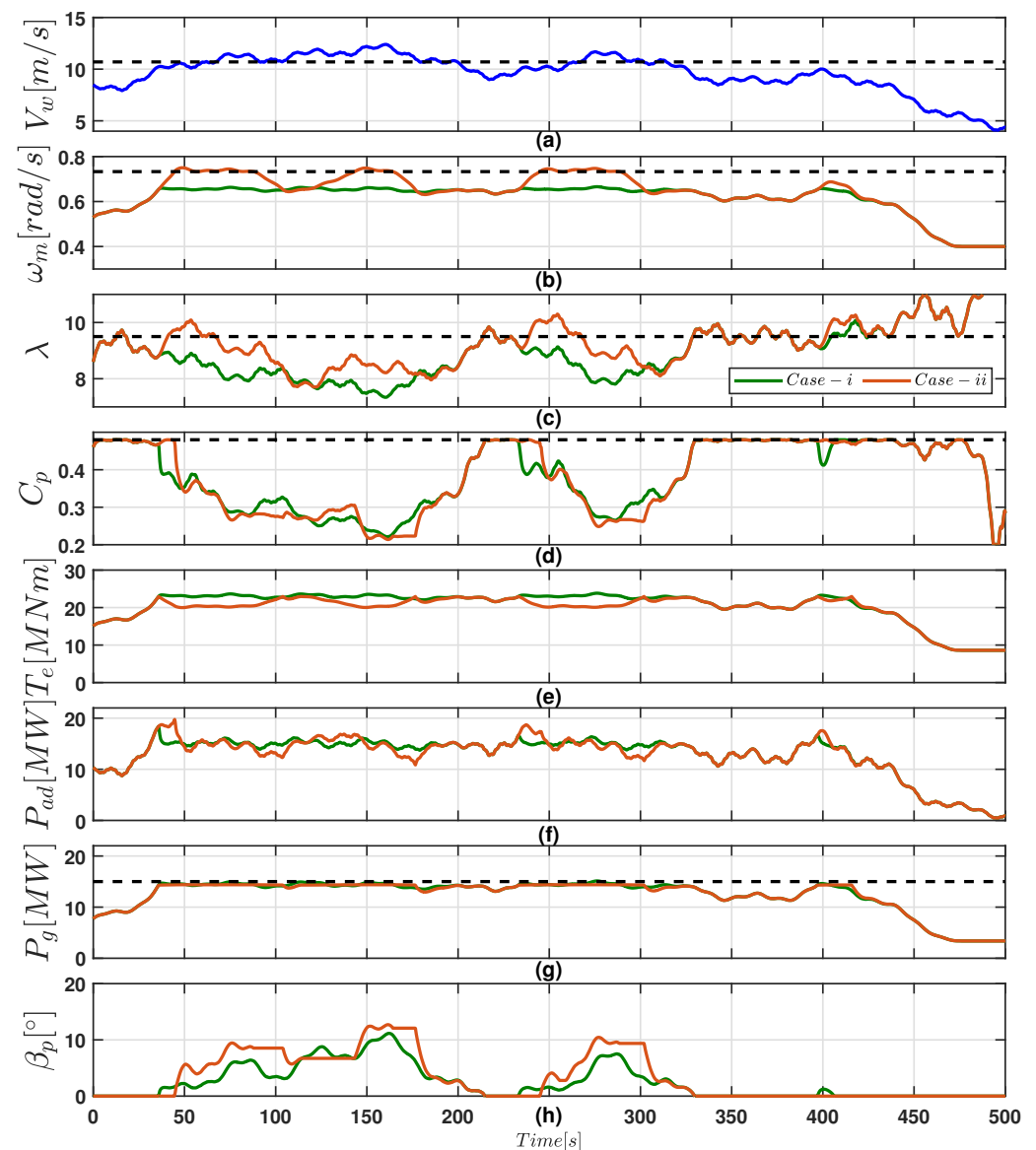


Figure 21. Comparative results to validate the active power control for reference tracking.

7. Conclusions

In this article, the impact of environmental parameters (temperature and rainfall) on the power extraction of super-large wind turbines was reviewed employing various studies from the literature. Mathematical modeling of temperature and rainfall effects was then produced and the analytical performances of 20 MW-rated super-large WTSs were evaluated. Further, the simulation results were presented to demonstrate the importance of considering environmental impacts in the control of wind turbines. Subsequently, the recent pitch, yaw, and torque control techniques were discussed along with their advantages and implications under fluctuating temperatures and rainfall. Additionally, the coordinated pitch and torque control utilizing variations in rotor speed were presented for reducing pitch actuation in region-2 control. Further, the pitch and yaw control strategies were categorically segmented based on their objectives. Thus, this review has provided an insight into the various control objectives of wind turbines considering environmental factors.

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