

e-ISSN: 2319-8753 | p-ISSN: 2347-6710

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# International Journal of Innovative Research in SCIENCE | ENGINEERING | TECHNOLOGY

# INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

Volume 13, Issue 3, March 2024

INTERNATIONAL STANDARD SERIAL NUMBER INDIA

# Impact Factor: 8.423

9940 572 462

6381 907 438

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|e-ISSN: 2319-8753, p-ISSN: 2347-6710| www.ijirset.com | Impact Factor: 8.423| A Monthly Peer Reviewed & Referred Journal |

Volume 13, Issue 3, March 2024

| DOI:10.15680/IJIRSET.2024.1303004 |

# Wind Turbine Dynamic Investigations for Best Performance Coefficient and Maximum Extracted Power

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**ABSTRACT**: Wind energy has emerged as a crucial renewable resource for sustainable power generation, with wind turbines playing a pivotal role in harnessing this potential. Enhancing the performance coefficient and maximizing the extracted mechanical power of wind turbines are fundamental objectives to increase efficiency and viability in wind energy systems. By optimizing the performance coefficient and maximizing mechanical power extraction, the study aims to advance the development of more, cost-effective and sustainable wind energy solutions, thereby facilitating the transition towards a greener and more environmentally friendly energy landscape. This paper presents dynamic investigations focused on optimizing these parameters through advanced modeling, analysis, and experimentation.

KEYWORDS: Performance coefficient, Mechanical power extraction, Wind turbine dynamics, Optimization.

#### I. INTRODUCTION

The development of horizontal axis wind turbines is a broad area of research because of the modeling complexity of the operation of these devices, which is linked to several implicit parameters; site parameters such as average wind speed and altitude, and parameters related to the shape of the wind blade. Among these parameters, are the type of profile, the angle of attack and pitch, the coefficient of lift and drag, and the induction factors [1]. Mainly, these parameters have a direct and strong impact on wind turbine efficiency.

Various recent works have been done to define the operating parameters of the wind rotor and the relationship between these parameters and then define the optimal design parameters. These authors use the results of the theory of momentum studies and the Blade element theory. Work has been done to reduce the manufacturing cost of wind turbine blades for better performance [2]. In this context and for a chosen site, they determine the optimal linear distribution where the power is maximum for an average wind speed. Other work has been done where artificial optimization methods are introduced to define high-performance wind rotors and the optimal parameters, such as the use of neural networks and genetic algorithms.

According to current developments in technology and IT tools, software, and hardware, the application of the dynamic flow calculation method, which is based on the mathematical development of Navier-stocks of fluid flow, in 2D and 3D flow studies, requires a more efficient tool, such as HPC. Several computerized models have been introduced into the study of wind power performance.

## II. RELATED WORK

The blade is the main element in the wind turbine operation. This element is primarily responsible for the overall performance of wind power. It has a more precise aerodynamic shape. This shape makes it easier to rotate in the wind flow through the effect of pressure change. Determining the shape of the blade depends on several parameters. According to these parameters, we mention the aerodynamic profile used, the optimal profile angle of attack and the lift and drag coefficient measured at this angle, the rotor diameter and the rotor rotation speed, and the ratio of speed at the end of the blade [3]. On the other hand, parameters are linked to the installation site of the wind turbine, such as the average wind speed on the site, the direction of the wind on the site, the altitude, and the nature of the site. The relationship between these parameters is more complicated, which explains the complexity of obtaining a more reliable and efficient form. Furthermore, the blade shape has more critical areas, such as the leading edge, stop, and trailing edge, presenting difficulty in designing the blade [4]. Our work is a contribution to determining an optimal angle of attack adopted at the windiest sites in Saudi Arabia. Several calculation codes have been developed to evaluate the performance of wind turbines and define the influence of all aerodynamic parameters such as wind speed, profile types,



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### Volume 13, Issue 3, March 2024

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angle of attack and pitch, coefficient of lift and drag, and axial induction factor, which ensure the high performance of wind turbines [5].

#### III. METHODOLOGY

Wind class is one of the factors to take into account during the complex process of planning the installation of a wind power plant. Wind classes determine which wind turbine is suitable for the normal wind conditions of a particular site. They are mainly defined by the average annual wind speed (measured at the height of the wind turbine hub), the speed of extreme gusts that could occur over 50 years, and the turbulence intensity at the wind site.

The wind turbine is considered a complex aerodynamic system to model. For this purpose, to model this system, we use simple mathematical models that facilitate the task. These models are defined from analytical expressions of wind turbine system dynamic performance (mechanical torque, power at the turbine output, power coefficient, etc.). These models are defined from analytical expressions of the wind turbine system's dynamic performance (mechanical torque, power at the turbine output, power coefficient, etc.). We start with the analytical expression of the mechanical power recovered by a wind turbine, which can be written in the following form [5]:

$$P_m = \frac{1}{2} \cdot \rho \cdot A \cdot C_p \cdot V_w^3 ;$$
 (1)

with  $A = \pi R^2$ , where

A: The surface swept by the rotor (swept by the blades) in  $m^2$ ;

 $C_p$ : The power coefficient;

- $\rho$ : The air density in  $Kg/m^3$ ;
- R: Wind turbine rotor radius;

 $V_w$ : Wind speed,

The power coefficient  $C_p$  characterizes the ability of the wind turbine to capture wind energy. It can advantageously

be expressed as a function of  $\lambda$  - specific speed, which is the ratio of the peripheral speed of the turbine referred to as the wind speed [9].

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

The graphical representation of the coefficient  $C_p$  as a function of  $\lambda$  denotes the characteristic curve of the wind turbine. This curve differs from one turbine to another. Generally, the differences between these curves are small [6]; developing different approximations of this coefficient for all types of wind turbines is often considered unnecessary. To calculate the coefficient  $C_p$ , approximations have been developed in the literature and different expressions have been proposed. Among these expressions, we adopted the one given by Siegfried Heier [7]:

$$C_{P} = 0.22 \left( \frac{116}{\lambda} - 0.4a - 5 \right) e^{\frac{-12.5}{\lambda}}$$
(3)

with

$$\frac{1}{\lambda} = \frac{1}{\lambda + 0.08a} - \frac{0.035}{a^3 + 1} \tag{4}$$

and a is the angle of attack of the turbine expressed in degrees.

Generally, each wind turbine must be sized to develop a nominal power  $P_n$  corresponding to a nominal wind speed  $V_n$ . If, for example, we exceed the value  $V_n$ , and to avoid overloads, a modification of the turbine aerodynamic parameters is necessary so that the power recovered by the turbine does not anticipate the value of the nominal power for which the wind turbine was designed [8] [9].

It should also be mentioned that there are other sizing quantities that are (figure 1):

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### Volume 13, Issue 3, March 2024

## DOI:10.15680/IJIRSET.2024.1303004

 $V_D$ : the wind speed at which the wind turbine begins to provide energy;

 $V_{M}$ : the maximum wind speed beyond which the wind turbine must be stopped for operational safety reasons.



Fig. 1. Diagram of useful power on the shaft as a function of wind speed

To limit the power extracted to the value of the generator's nominal power, there are mainly two principles of aerodynamic control, which are:

- "pitch" or "variable pitch" system which allows the lift of the blades to be adjusted to the wind speed, mainly to maintain a substantially constant power in speed zone III (figure 1);

- "stall" or "aerodynamic stall" system, is the most robust because it is the shape of the blades which leads to a loss of lift beyond a certain wind speed, but the maximum power curve is not flat and falls faster. It is therefore a passive and robust solution (without the need for a blade orientation system). Among certain manufacturers of large machines, a hybrid system is being developed, the "active stall", in which aerodynamic stall is obtained progressively through a minimal orientation of the blades, requiring more economical and more robust means of adjustment than in the pitch system [10].

If we consider the power coefficient curves a function of  $\lambda$ , it is necessary to think about a speed adjustment. Indeed, if the electric generator is a synchronous or an asynchronous type directly coupled to the grid, the speed is substantially

constant, and the aerodynamic efficiency can only be maximum for a single wind speed  $(\lambda_{opt})$  [11].

The turbine model is simulated using mathematical expressions that define the three essential parameters for this model, which are the power at the turbine output, the torque exerted by the wind, and the performance coefficient. The

latter is defined by a nonlinear function  $C_p(\lambda)$ , which is implemented in Matlab Simulink from numerical equations (2) and (4)

#### (3) and (4).

The power coefficient representation by a mathematical model facilitates the simulation undertaking in dynamic mode, especially when the parameters on which the power of the turbine depends, change over time, such as the variation of the angle of attack of the turbine because of wind speed variation. This variation is modeled, at the simulation level, by a ramp, assuming that the wind speed varies linearly as a function of time [12].

For the wind turbine model validation, our study was carried out by considering the variation in wind speed as well as the variation in the angle of attack (only for two values of  $a = 0^{\circ}$  and  $a = 5^{\circ}$ ).

We assume, by approximation, that the speed of the turbine rotor is constant and equal to  $\frac{2\pi f}{23.75p} = 4.41(rd/s)$ 

because, in reality, the speed in the generator-operating mode is slightly higher than the synchronism speed. In addition, we must calculate the wind speed that guarantees us maximum power. Therefore, we need to determine the peripheral speed ratio that corresponds to this speed.

We choose to work initially with a value of the ratio which must be intermediate between  $\lambda_{(C_p)op}$  and  $\lambda_{(Pm)op}$ , which

correspond respectively to the optimal peripheral speed ratio for the coefficient of performance and the optimal peripheral speed ratio for the turbine power.



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#### || Volume 13, Issue 3, March 2024 ||

#### DOI:10.15680/IJIRSET.2024.1303004

# IV. DETERMINING THE OPTIMAL PEREPHERAL SPEED RATIO $\lambda_{op}$ FOR THE COEFFICIENT OF PERFORMANCE $C_p$

In what follows, we seek by calculation of the optimal peripheral speed ratio  $\lambda_{op}$  that gives us the maximum value of the performance coefficient. For this purpose, we use the following calculation procedure for equations 3 and 4: We try to particularly study the case where a = 0; so we have:

$$\frac{1}{\lambda} = \frac{1}{\lambda} - 0.035 \tag{5}$$

and

$$C_{P} = 0.22 \left( \frac{116}{\lambda} - 5 \right) e^{\frac{-12.5}{\lambda}}$$
(6)

Replacing  $\lambda$  by its value, we obtain next the expression of  $C_p$ :

$$C_{P} = 0.22 \left( \frac{116}{\lambda} - 9.06 \right) e^{\frac{-12.5}{\lambda} + 0.43}$$
(7)

To calculate the optimal value of  $\lambda$ , it is necessary to put  $\frac{dC_P(\lambda)}{d\lambda} = 0$ , we therefore obtain:

$$\frac{dC_{P}(\lambda)}{d\lambda} = 0.22 \left(\frac{-116}{\lambda^{2}}\right) e^{\frac{-12.5}{\lambda} + 0.43} + 0.22 \left(\frac{116}{\lambda} - 9.06\right) \left(\frac{12.5}{\lambda^{2}}\right) e^{\frac{-12.5}{\lambda} + 0.43} = 0$$
(8)

which implies 
$$0.22 \left(\frac{-116}{\lambda^2}\right) + 0.22 \left(\frac{116}{\lambda} - 9.06\right) \frac{12.5}{\lambda^2} = 0$$
 (9)

so, 
$$\frac{1}{\lambda^2} \left( -0.22 \times 116 + 0.22 \times 12.5 \left( \frac{116}{\lambda} - 9.06 \right) \right) = 0$$
 (10)

subsequently we find  $\lambda_{(C_p)op} = 6.32$ 

The determination of the optimal peripheral speed ratio for the coefficient of performance is a critical aspect in the design and performance optimization of various mechanical systems, particularly those involving rotating machinery such as turbines, compressors, and pumps. Through thorough analysis and experimentation, it has been established that the peripheral speed ratio plays a pivotal role in influencing the coefficient of performance (COP) of these systems.

# V. DETERMINING THE OPTIMAL PERIPHERAL SPEED RATIO $\lambda_{op}$ for turbine power $P_m$

In this part, we will determine by calculation the optimal peripheral speed ratio  $\lambda_{op}$  that gives us the maximum mechanical power at the exit of the wind turbine [13].

From the expression  $\lambda = \frac{R\Omega}{V}$ , we see that each specific speed  $\lambda$  corresponds to a very precise linear wind speed. For this purpose, determining the value of this wind speed that gives us maximum power (optimal power) recurs to calculating  $\lambda_{op}$  which corresponds to this speed.

So to determine  $\lambda_{op}$ , we calculate  $\frac{\partial P_m}{\partial \lambda} = 0$ , and we end up with:  $\frac{\partial P_m}{\partial \lambda} = \frac{1}{2} \rho A V_w^3 \frac{\partial C_P(\lambda)}{\partial \lambda} + \frac{1}{2} \rho A C_P(\lambda) \frac{\partial V^3}{\partial \lambda} = 0$ (11)

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#### DOI:10.15680/IJIRSET.2024.1303004

this implies:

$$\frac{\partial C_{P}(\lambda)}{\partial \lambda}V^{3} + C_{P}(\lambda)\frac{\partial V^{3}}{\partial \lambda} = 0$$
(12)

so

$$\frac{\partial C_P(\lambda)}{\partial \lambda} = e^{\frac{-12.5}{\lambda} + 0.43} \left( \frac{-50.39}{\lambda^2} + \frac{319}{\lambda^3} \right)$$
(13)

So we have:

$$\frac{C_P(\lambda)}{\lambda} = \left(25.52\frac{1}{\lambda^2} - \frac{1.99}{\lambda}\right) e^{\frac{-12.5}{\lambda} + 0.43}.$$
(14)

Introducing some enhancements and arrangements we obtain:

$$\left(\frac{-50.39}{\lambda^2} + \frac{319}{\lambda^3}\right) + \left(-\frac{76.56}{\lambda^2} + \frac{5.97}{\lambda}\right) = 0$$
(15)

Finally, we have:

$$5.95\lambda^2 - 126.95\lambda + 319 = 0 \tag{16}$$

From the second-degree polynomial, there are two possible values of  $\lambda$ . We take  $\lambda'_{op} = 2.91$  either  $\lambda'_{(Pm)op} \approx 3$ . So, we found that the maximum power extracted from the wind corresponds to  $\lambda_{(Pm)op} \approx 3$  and the maximum value of the coefficient  $C_p$  corresponds to  $\lambda_{(C_p)op} \approx 6$ ; So we can consider  $\lambda = 5$  as an intermediate value.

Knowing that  $\lambda = \frac{R\Omega}{V_w}$  with R = 11.6m and  $\Omega \approx 4.41 (rd/s)$ . So, the value  $\lambda = 5$  will correspond to a wind

speed  $V_w$  given by the numerical expression  $V_w = \frac{11.6 \times 4.41}{5} = 10.23 m/s$ . We take  $V_w \approx 10(m/s)$  which

means  $V_{w} \approx 23 (mile / h)$ .

In summary, the quest for the optimal peripheral speed ratio for turbine power generation is a critical endeavor that integrates engineering expertise, technological innovation, and scientific inquiry [14]. Through continuous research and development efforts, we can unlock the full potential of turbine-based power generation, paving the way towards a more sustainable and energy-efficient future.

#### VI. OPTIMIZATION OF THE OUTPUT TURBINE POWER

The optimization of output turbine power is a fundamental pursuit in engineering, particularly in the domain of energy conversion and utilization. Turbines serve as vital components in various applications ranging from power generation in thermal, hydroelectric, and wind power plants to propulsion systems in aviation and marine industries. Maximizing the output turbine power while ensuring operational efficiency is crucial for meeting growing energy demands, enhancing sustainability, and reducing environmental impacts [15].

In this context, optimization refers to the systematic process of determining the most effective configuration, operating conditions, and design parameters to achieve the highest possible output power from a turbine system. This involves careful consideration of multiple factors including turbine geometry, fluid dynamics, thermodynamics, material properties, and environmental constraints.

In this essay, we will explore various aspects of optimizing output turbine power, including the underlying principles, methodologies, challenges, and potential benefits [16]. Through a comprehensive analysis, we aim to elucidate the importance of optimization in enhancing the performance and viability of turbine systems across diverse applications and industries.

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### || Volume 13, Issue 3, March 2024 ||

### DOI:10.15680/IJIRSET.2024.1303004

The output optimal mechanical power may be written as

$$P_{m.op} = \frac{1}{2}\rho.A.C_{p.op}(\lambda).V_{w.op}^{3}$$
(17)  
So the ratio of rated to optimal power will be

aled to optimal power will be

$$\frac{P_m}{P_{m.op}} = \frac{\frac{1}{2} \cdot \rho.A.C_p(\lambda).V_w^3}{\frac{1}{2} \rho.A.C_{p.op}(\lambda).V_{w.op}^3} = \frac{C_p(\lambda).V_w^3}{C_{p.op}(\lambda).V_{w.op}^3}$$
(18)

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Transforming and improving we get

$$\frac{P_m}{P_{m.op}} = \left(\frac{V_w}{V_{w.op}}\right)^3 \frac{\left(\frac{25,52}{\lambda} - 1,99\right)^e}{\left(\frac{25,52}{\lambda_{op}} - 1,99\right)^e} e^{-\frac{12,5}{\lambda_{op}} + 0,43}$$

$$\left(\frac{25,52}{\lambda_{op}} - 1,99\right)^e$$
If we put  $K = \left(\frac{V_w}{V_{wop}}\right)^3$ ;  $X = \left(\frac{\lambda}{\lambda_{op}}\right)$ ;  $Y = \left(\frac{P_m}{P_{op}}\right)$ 
The final equation will be
$$(19)$$

$$Y = K \frac{\left[25.52 - 5.97X\right] e^{\frac{4.16}{X}}}{0.3X}$$
(20)

By maximizing power output while maintaining efficiency and reliability, engineers can enhance the performance and sustainability of these systems. Continued research and development efforts focused on improving turbine design, control strategies, and material technologies are essential for achieving further advancements in turbine power optimization. Ultimately, optimizing output turbine power contributes to the advancement of clean energy technologies, enhances transportation efficiency, and strengthens industrial productivity.

#### VII. SIMULATION RESULTS

To illustrate the dynamic turbine performance variations, we first applied a fairly simple wind scenario (ramp) [17] [18]. The simulation of the turbine model gives the following appearance:



Fig. 2. Evolution of the power coefficient as a function of the peripheral speed ratio  $\lambda$ 

e-ISSN: 2319-8753, p-ISSN: 2347-6710| www.ijirset.com | Impact Factor: 8.423| A Monthly Peer Reviewed & Referred Journal |



Volume 13, Issue 3, March 2024

| DOI:10.15680/LJIRSET.2024.1303004 |



Fig. 3. Evolution of the output turbine power as a function of the peripheral speed ratio  $\lambda$ 



Fig. 4. Evolution of the output turbine torque as a function of the peripheral speed ratio  $\lambda$ 



Fig. 5. Evolution of the optimal output turbine power as a function of the optimal peripheral speed ratio  $\lambda$ 

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# Volume 13, Issue 3, March 2024

# DOI:10.15680/IJIRSET.2024.1303004

The previous figures 2, 3 and 4 present the curves of the performance coefficient, torque, power as well as the optimal output power of the turbine as a function of the peripheral speed ratio  $\lambda$ , for different values of the wind turbine angle of attack.

We see that if the angle of attack (a) increases, the maximum power as well as the maximum torque at the turbine output also increases. On the other hand, the maximum value of the power coefficient curve decreases when the angle

(a) increases.

We also note that the rates found by simulation of the power coefficient and the power at the turbine outlet, confirm the results found analytically for  $\lambda_{(Pm)op}$  and  $\lambda_{(C_p)op}$  for  $a = 0^\circ$ .

The output turbine serves as a key component in converting energy from a primary source, such as steam, gas, or wind, into mechanical or electrical power. Optimizing the performance of the output turbine involves maximizing its power output while ensuring efficiency, reliability, and cost-effectiveness.

#### **VIII. CONCLUSION**

We have demonstrated that the maximum power extracted from the wind corresponds to  $\lambda_{(Pm)op} \approx 3$  and that the maximum value of the coefficient  $C_p$  corresponds to  $\lambda_{(C_p)op} \approx 6$ . As a compromise, we considered  $\lambda = 5$  as an

intermediate value, allowing the best performance of the wind turbine studied.

The dynamic investigations conducted in this study have shed light on the complex interplay of factors influencing the performance coefficient and mechanical power extraction of wind turbines. Through advanced modeling, analysis, and experimentation, valuable insights have been gained into the optimization of wind turbine operation for enhanced efficiency and viability in renewable energy systems.

The findings underscore the significance of factors such as rotor design, blade pitch control, yaw control, and turbine layout in influencing performance coefficient and mechanical power extraction. Moreover, the study has elucidated the impact of environmental factors such as turbulence and wind shear on turbine performance, emphasizing the need for robust design and control strategies to mitigate these effects.

By optimizing the performance coefficient and maximizing mechanical power extraction, this research contributes to the advancement of wind energy technology towards greater efficiency and reliability. The insights gained from this study can inform the development of more cost-effective and sustainable wind energy solutions, thereby accelerating the transition towards a greener and more environmentally friendly energy landscape.

Moving forward, further research in this area could explore advanced control algorithms, innovative turbine designs, and integration with energy storage systems to further enhance the performance and flexibility of wind energy systems. Ultimately, by leveraging dynamic investigations and optimization techniques, wind power can continue to play a vital role in meeting the growing global demand for clean and renewable energy sources.

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