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# ANALYSIS OF THE INDUCTION EFFECT ON THE PERFORMANCE OF WIND TURBINE

## ANALYSE DE L'EFFET DE L'INDUCTION SUR LA PERFORMANCE DE L'EOLIENNE

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## ABSTRACT

In real, the vortices created behind the wind turbine and around the blades due to the induction flow created by the difference in pressure in rotation plan and the rotational the blade moves, which summarized in Glauert's model as the axial and tangential induction factors. In this work, a Matlab code has been established to analyze the induction effect on the performance of wind turbine. This code based on the enhanced blade element momentum theory with considering the recent correction. The results demonstrate that the axial induction effect is the master responsible for increasing the mechanical stress effect that decreases the wind turbine performance at the low wind speed value. In another side the increasing of wind speed accompanied by the increasing of tangential induction effect at tip and root of blades with creating vortices, which put the rotor in the critical case with less efficiency.

**Keywords:** wind turbine, blade, induction, BEM theory, Thrust force, airfoil.

**RESUME**

En réalité, les tourbillons créés derrière l'éolienne et autour des pales dus au flux d'induction créé par la différence de pression dans le plan de rotation, et le mouvement de rotation des pales. Ce phénomène est exprimé dans le modèle de Glauert par le facteur d'induction axiale et tangentielle. Dans ce travail, un code Matlab a été établi pour analyser l'effet d'induction sur la performance de l'éolienne. Ce code est basé sur la théorie de mouvement de l'élément de pale améliorée par la considération de la correction récente. Les résultats démontrent que l'effet d'induction axiale est le responsable de l'augmentation de l'effet de contrainte mécanique, qui diminue la performance de l'éolienne à la faible vitesse du vent. D'autre part l'augmentation de la vitesse du vent accompagnée de l'augmentation de l'effet d'induction tangentielle au bout et au pied des pales avec création des tourbillons, qui mettent le rotor dans le cas critique avec moins d'efficacité.

**Mots clés :** Eolienne, pale, induction, Théorie MEP, la force de poussée, profil.

## INTRODUCTION

The recently market static of investment in renewable energy shows that the wind energy is a valuable alternative and green sources. In 2015, the production registered with increases of 22% (REN21, 2016). That explains the big amount of manufacturing wind turbine, such as the horizontal wind turbine which represents the efficient kind of wind turbine with efficiency coefficient over 0.4 (Hansen, 2008).

The performance of wind turbine related to the major parameter to his blade shape, which is the first organ responsible for extracting the kinetic energy of the wind. His design depends on winding turbine types. In the case, the variable speed horizontal wind turbine, the tip speed ratio is the master parameter, where the blade design based on a specific value of TSR which corresponds to the maximum of power coefficient. Hence the applied technologies of control for this type of wind turbine should ensure this value of TSR for any variation of wind speed until the rated wind speed. However for fixed speed horizontal wind turbine, the rotor speed is constant, and the value of TSR depends on the variation of wind speed. Here the design blade depends on the specific design wind speed and design TSR. That means the power coefficient reaches the maximum just at the design wind speed and decreases for another value of wind speed (Hansen, 2008; Lui, 2013). Furthermore, the performance of both turbine types related to their blade aerodynamic design parameters such as the chord and twist angle. The other parameters should be considered to determine the radial distribution of the aerodynamic design parameters of the blade by applying Blade element momentum theory. These parameters are the airfoil shape and design attack angle, for maximum lift to drag ratio and for a specific Reynolds number (Wang, 2012).

In reality, the wind turbine performance affected by the vortices effect created by the blades rotation, that generates an induction phenomenon (Hadid, 2012). In this work, we established a method of study and analyze the variation the aerodynamic parameters with the aim to determine the induction effect related to the variation of wind speed. In this context, we start with the mathematical aerodynamic model based on the enhance blade element momentum theory in the second section. The wind potential analyzes of Adrar site which chosen as the site of installation in the third section. A proposed wind turbine adapted to Adrar site for providing 50KW in the fourth section and as analyze the results and the recommendations in the last two section.

## AERODYNAMIC OF WIND TURBINE

The aerodynamic analysis of wind turbine performance based on the Gluaert mathematical model of blade element momentum theory. Gluaert has enhanced the one ideal model of wind turbine analysis established by Betz (Burton, 2012). This model regards the wind turbine as an actuator disk with infinite blade number spins in one-dimensional air flow as shown in figure (1).he supposed the air as an incompressible fluid with no rotational effect, no drag effect, the thrust on the disk is constant. Based on the ideal model the real airflow makes a flow angle $\varphi$ with rotation plan is defined by:

$$\varphi = \frac{U}{\Omega r} \tag{1}$$

The ideal distribution of Chord length and twist angle defined by Schmitz method as (Hansen, 2008):

$$C = \frac{8\pi r}{BC_l}(1 - \cos\varphi) \tag{2}$$

$$\varphi = \theta + \alpha \tag{3}$$

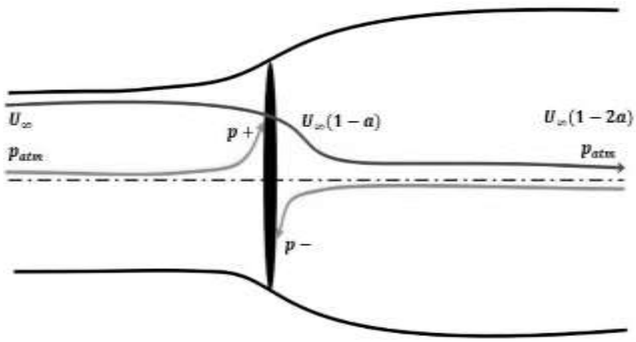



**Figure 1: Disk actuator model of wind turbine.**

In reality, the rotation of wind turbine creates a vortices sheet attached to the blades in the opposite direction. The air rotation velocity is greater than blade rotation velocity Glauert gave a model summarizes this phenomenon in bi-induction effect, where he introduces the axial and tangential induction term, presented by the axial induction factor $a$ and tangential factor $a'$. The elemental bi-dimensional analysis of blade element momentum theory showed in figure (2) gives the thrust force and torque in annulus elemental term as (Burton, 2012; Manwell, 2009):

$$dT = 4a(1-a)\rho U^2 \pi dr \quad (4)$$

$$dQ = 4a'(1-a)U^2 \Omega \pi r^3 dr \quad (5)$$

Where the thrust coefficient presented as the ratio of thrust effect by:

$$C_T = 4a(1-a) \quad (6)$$

Besides the airflow around the blade creates an aerodynamic force. As shown in figure (2) this force is the result of the lift force and drag force, which is determined by their coefficients $C_l$ and $C_d$ respectively. In another hand, the thrust force and the torque can be presented elementally based on the aerodynamic air effect as (Manwell, 2009):

$$dT = dF_N = B\frac{1}{2}\rho U_{rel}^2 (C_l \cos\varphi + C_d \sin\varphi) c dr \quad (7)$$

$$dQ = B\frac{1}{2}\rho U_{rel}^2 (C_l \sin\varphi - C_d \cos\varphi) c r dr \quad (8)$$

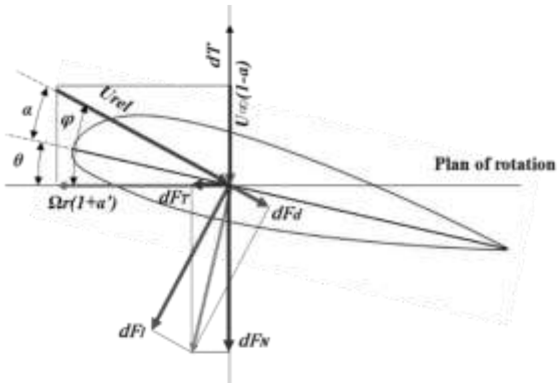



**Figure 2: Aerodynamic actions on the blade element.**

Where $C$ is the blade chord section, $U_{rel}$ is relative wind velocity, and φ can obtain them the flow angle (Tang, 2012):

$$U_{rel} = \sqrt{U^2(1-a)^2 + r^2\Omega^2(1+a')^2} \tag{9}$$

$$\tan\varphi = \frac{1-a}{(1+a')\lambda_r} \tag{10}$$

$\lambda_r$ is the local speed ratio aspired from the tip speed ratio $\lambda$ were given by:

$$\lambda_r = \frac{r}{R\lambda} \tag{11}$$

$$\lambda = \frac{\Omega R}{U_\infty} \tag{12}$$

The real wind turbine has a limited number of blades, the moves of each blade in the wake vortices created by the other blade that can cause concentrate vortices at the tip of blades, which known as tip losses phenomena. The classical momentum theory cannot define airflow behavior at the blade tip. Prandtl discussed this phenomenon by introducing their correction factor $F_t$, which well explains the reducing in the performance due by the tip vortices this factor, is given by (Hwang, 2013):

$$F_t = (2/\pi)\cos^{-1}\left(e^{\frac{-B(R-r)}{2r\sin\varphi}}\right) \tag{13}$$

By considering of tip losses effect, the thrust force and the torque equations changed to (Manwell, 2009):

$$dT = 4F_t a(1-a)\rho U^2 \pi dr \tag{14}$$

$$dQ = 4F_t a'(1-a)U^2\Omega\pi r^3 dr \tag{15}$$

From both definitions of thrust force and torque, presented in the equations (7) (8) (14) (15), the axial and tangential induction factor relationship became (Ashrafi, 2015):

$$a = \sigma C_n/(4F_t sin^2\varphi + \sigma C_n) \tag{16}$$

$$a' = \sigma C_t/(4F_t sin\varphi cos\varphi - \sigma C_t) \tag{17}$$

Then the thrust coefficient became (Burton, 2012; Tang, 2012):

$$C_T = \sigma(1-a)^2 C_n/(F_t sin^2\varphi) \tag{18}$$

Where:

$$\sigma = Bc/2\pi r \tag{19}$$

$$C_n = C_l cos\varphi + C_d sin\varphi \tag{20}$$

$$C_t = C_l sin\varphi - C_d cos\varphi \tag{21}$$

σ is the blade solidity, $C_n$ is the axial force factor, and $C_t$ is the tangential force factor.

Furthermore, the analysis of experimental data demonstrated the breakdown of classical Blade momentum theory at the value of axial induction factor greater than 0.4, the thrust coefficient decreases. That represents no compatibility with the experimental data (Glauert, 1926). In 2004, Buhl proposed a new empirical relationship based on the Glauert's correction of thrust coefficient relationship with introducing the effect of root and tip losses. This relationship shows more accurate with the experimental data and eliminates the numerical instability presented in previous work. It was summarized by the following expression (Buhl, 2005; Liu, 2012):

$$C_T = \frac{8}{9} + \left(4F - \frac{40}{9}\right)a - \left(\frac{50}{9} - 4F\right)a^2 \quad a > 0.4 \tag{22}$$

Where *F* represents the multiplication of tip and root loss factors and the root loses factor is given by (Burton, 2012):

$$F_r = (2/\pi)\cos^{-1}(e^{\frac{-B(r-rh)}{2r\sin\varphi}}) \tag{23}$$

In other definition, when the thrust coefficient was greater than *0.96F* (Buhl, 2005). The axial induction factor presented by:

$$a = \frac{18F-20-3\sqrt{C_T(50-36F)=12F(3F-4)}}{36F-50} \tag{24}$$

The wind turbine performance presented by the following relationship established by Manwall of power coefficient (Manwell, 2009):

$$C_p = \frac{8}{\lambda N}\sum_{i=1}^{N} F_i sin^2\varphi_i(cos\varphi_i - \lambda r_i sin\varphi_i)(sin\varphi_i + \lambda r_i cos\varphi_i)[1 - (\frac{C_d}{C_l})cot\varphi_i]\lambda r_i^2 \quad (25)$$

The mechanical power extracted from the blades is given by (Hansen, 2008):

$$P = \frac{1}{2}\rho\pi R^2 U_\infty^3 \eta C_p \quad (26)$$

$\eta$ is the mechanical efficiency factor.

## ADRAR WIND POTENTIAL ANALYSIS

According to The results of Algerian wind potential analysis, Adrar site is the windiest site in Algeria. It has 88% of energy producing time with high wind frequency is in the eastern direction as presented in the figure (3) (Hammouche, 1990; Benmedjahed, 2014). The recent potential wind analysis of Adrar site have done by Boudia et al. at 10m of high. From the results shown in the annual term. The wind speed covers a range of up to 12m/s with the highest value of annual wind average speed than all the sites studied equal to 6.37m /s, that push us to choose Adrar as the site to install our design wind turbine (Boudia, 2013).

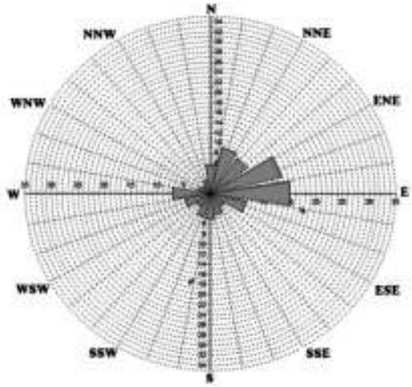



**Figure 3: The wind rose of Adrar site (Benmedjahed, 2014).**

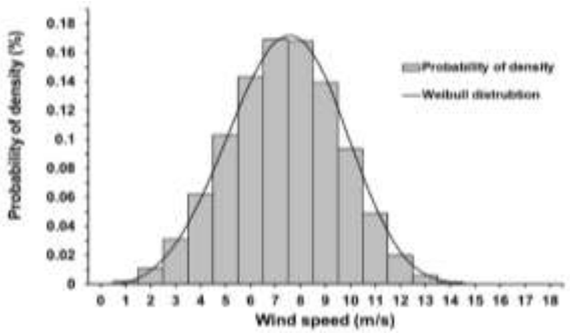



**Figure 4: Adrar wind speed density at 18m of altitude.**

## DESIGN MODEL

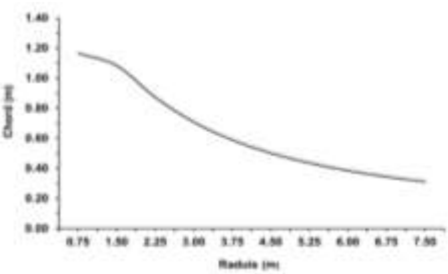
As a case of study, we have proposed a design for small-scale fixed speed wind turbine based on his significant advantage as it connected directly to the grid. The design has 18 m of tower's high to generate 50kw of electric power. It intends to Adrar site where the annual average wind speed measured at 18m of altitude is 6.92 m/s as presented the figure (4). According to IEC6400-2 standard, the design wind speed is 1.4 time of average wind speed of selected site in our case her value is 9.68m/s (Liu, 2013). The rotor speed is 74 rpm, and the blade length is 7.5m, which adapted to the value of tip speed ratio equal 6. The blade is a NACA23015 of aerofoil section, which has the value of 91 as a maximum of lift to drag coefficient measured in 10deg of attack angle at 10e6 of Reynolds number (Karunakaran, 2013). A Matlab code has been established to analyze the variation of the aerodynamic parameter and determine their effect on the performance of the proposed design wind turbine, which based on the following algorithmic steps:

1. Compute the flow angle, chord and twist angle from the equation (1), (2), (3) respectively.
2. Initialising the induction factor $a$ and $a'$ by the null value.
3. Compute the new flow angle and attack angle from the equation (10) and (13).
4. Define the aerodynamic coefficients ($C_d$, $C_l$) at the new value of attack angle.
5. Compute the force coefficients $C_n$ and $C_t$ from the equation (20) and (21).

6. Compute the new values of induction factors based on the equation (16) and (17). While the relative error between the initial values and the new of the factors stay big, go to step two with the new values. If it is small, go the next step.
7. Compute the power coefficient and the power value.

## RESULTS AND DISCUSSIONS

The results shown in the figures, (5) and (6) represent the optimal radial distribution of the Chord length, and the twist angle adapted to our rotor design case. The chord value decreases from 1.07m at the root to 0.3m at the tip of blade .thus the twist angle value takes 32deg at the root and -4deg at the tip of the blade.



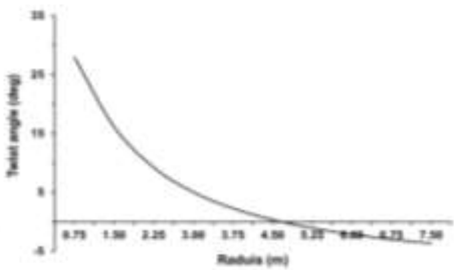


**Figure 5: The chord radial distribution. Figure 6: Twist angle radial distribution.**

The result showed in figure (7) represent a typical variation curve of power coefficient for fixed speed rotor obtained by our BEM code. The operating speed range starts by the value of 3m/s that represents the start-up of the almost wind turbine to the value 18m/s as the theoretical cut-out wind speed value. In general case, we noticed that the power coefficient obtained by our Code get 0.46 as the maximum value at 9.68m/s of wind speed value. That corresponds to 6 of tip speed ratio value. Away from this design point parameter, At Low and high wind speed, the power coefficient decreases rapidly. Despite the power coefficient, it is a maximum at this design point, but it does not represent the point of maximum power archived by this design of wind turbine. That shows more clearly in the figure (8), where the proposed design rotor takes his rated power at 12m/s of wind speed value. To explain these phenomena we have studied the aerodynamic parameters effects on the performance of our rotor.

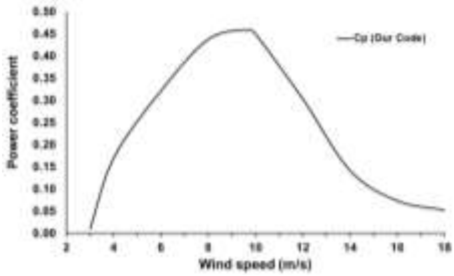



**Figure 7: The variation of power coefficient vs wind speed.**

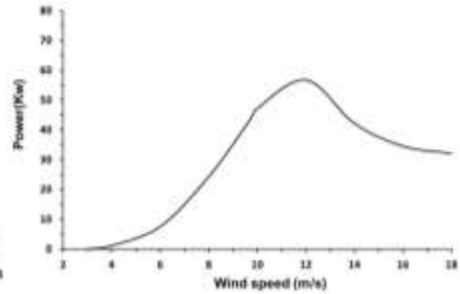



**Figure 8: The variation of archived power vs wind speed.**

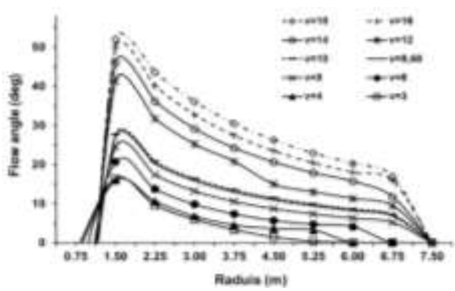



**Figure 10: Flow angle radial distribution.**

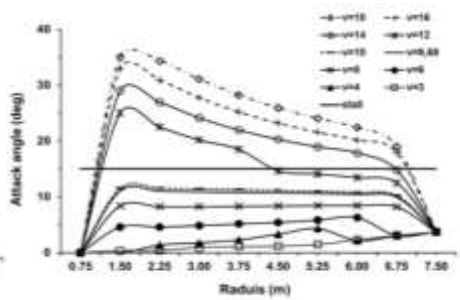



**Figure 9: Attack angle radial distribution.**

As a first analysis, the results presented in the figure (9) and (10) represent the radial distribution of the flow and attack angles for all wind speed range. In definition, the flow angle is the sum of the attack angle, and the twist angle in each blade section and the twist angle is taken constantly. That means the relativity of the variation of flow angle to the attack angle by reason of wind speed variation. The results show both angles dropped to the minimum value at the root and tip section for all value of wind speed. That corresponds to introducing the tip and root correction term in our study. In the others blade sections, they increase with increasing of wind speed where the flow angle balanced between 16deg to 52deg at 20% of blade length near the root and from 0deg to 17deg at the section situated at 90% of blade length. That means the variation of attack angle du by the changing the direction of the relative wind. which is the result of the real wind speed and the rotor speed considered on the opposite side. The axial and tangential losses effect considered and represented by axial and the tangential induction factors. The figures (11), (12) represent the radial distribution of the axial and the tangential induction factors for all wins speed values. In general case, both factors take the absolute unit at the tip and toot section respectively, and the tangential factor has the same radial distribution for each wind speed. At the design wind speed, our code gives an accord results with other works where the axial induction factor takes the optimal value 1/3 in overall section. At the value 10 m/s and 8m/s of wind speed, we notice a small variation of axial induction factor.

When the wind speed decrease to less than 8m/s.We have noticed that the axial induction factor dropped down nearby the root section .It takes the value higher than 0.4 especially in the sections after 50% of blade section towards the tip. Furthermore, both factors can take the absolute unit after 70% of blade sections towards the tip with decreasing of wind speed. That explains the maximum of the thrust effect at the value 3 and 4m/s of wind speed, as shown in the figure (13). The induction effect put the blade on high mechanical stress, and it can break the blade moves and dropped the efficiency of a wind turbine.On another side, it can break the blades if it exceeds the nominal resistance of the blade material. Furthermore, the decreasing of thrust when the wind speed increases that doesn’t mean a less dangerous. In this case, the wind turbine efficiency decreases by stall phenomena where the tangential induction effect considered with high values nearby the root and tip of blades, that put the blades moves under large vortices.

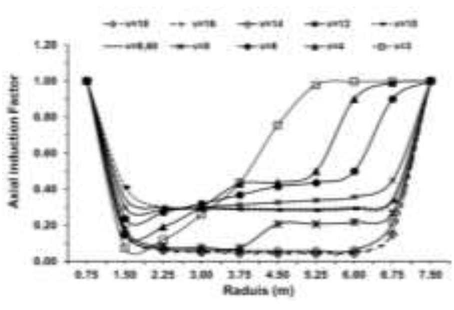


**Figure 12: The radial variation of axial induction factor.**

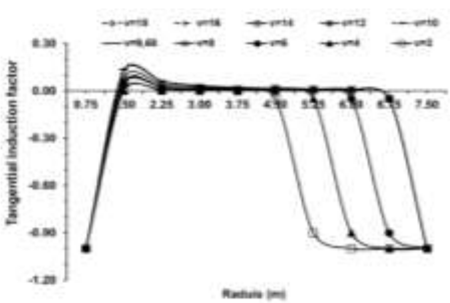


**Figure 11: The radial variation of tangential induction factor.**

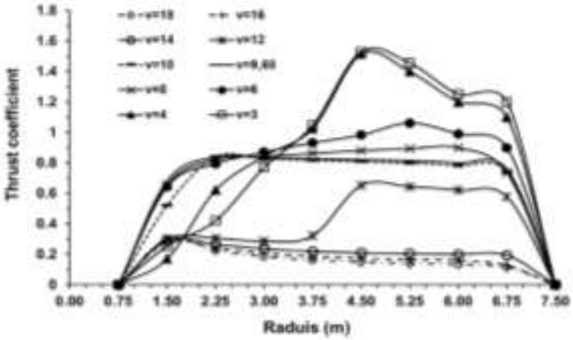



**Figure 13: The thrust coefficient radial distribution.**

## CONCLUSION

In this paper, an atypical case of study has established for analyzing the performance of a proposed design wind turbine with the aim to determine the induction effect created in the operating case. We have started by establishing a Matlab code based on the enhanced blade element momentum theory with including the tip-hub correction loses and the high induction effect. The wind turbine proposed with fixed speed and adapted to Adrar site, that situated in the south-west of Algeria. The design wind speed was taken equal to 6.92 m/s. This value represents the mean wind speed measured at 18m/s of altitude, which represents the rotor tower high. From the result obtained by our BEM code. The axial induction effect has the high influence, especially with the low wind speed. Furthermore, The thrust force increases, in this case, the blades can brake with high loses in total efficiency. Otherwise, the blades stay moves under a high mechanical stress can break them if the loads are higher the nominal material resistance. In the case, with higher the wind speed than the design value the decreasing of efficiency related to the high radial induction showed in the tip and root section of blades, that put the blades in high radial induction vortices even the total stall and dropping of efficiency.

**NOMENCLATURE**

| | |
|---|---|
| $\alpha$ | Attack angle ($deg$). |
| $\alpha_{stall}$ | Stall angle ($deg$). |
| $\theta$ | Twist angle ($deg$). |
| $\sigma$ | Solidity. |
| $\lambda$ | Tip speed ratio. |
| $\lambda_r$ | Elemental speed ratio. |
| $\rho$ | Air density (1.225 $kg/m^3$). |
| $\varphi$ | Flow angle ($deg$). |
| $\Omega$ | Rotation velocity ($rd/s$). |
| $\eta$ | Mechanical efficiency. |
| V | Mean wind speed ($m/s$). |
| $a$ | Axial induction factor. |
| $a'$ | Radial induction factor. |
| AR | Aspect ratio. |
| B | Blade number. |
| C | Chord length ($m$). |
| $C_l$ | Lift coefficient. |
| $C_d$ | Drag coefficient. |
| $C_n$ | Normal force coefficient. |
| $C_t$ | Tangential force coefficient. |
| $C_T$ | Thrust coefficient. |
| $C_{dmax}$ | Maximum drag coefficient. |
| $C_{dstall}$ | Stall drag coefficient. |
| $C_p$ | Power coefficient. |
| dr | Elemental radial length ($dr$). |
| $dF_d$ | Elemental drag force ($N.m$). |
| $dF_l$ | Elemental lift force ($N.m$). |
| $dF_N$ | Elemental normal force ($N.m$). |
| $dF_T$ | Elemental tangential force ($N.m$). |
| dT | Elemental thrust force ($N.m$). |
| dQ | Elemental torque ($N.m^2$). |
| $F_t$ | Prandtl tip loses factor. |
| $F_r$ | Root loses factor. |
| F | Loses factor. |
| $f_{Weibull}$ | Weibull wind frequency (%). |
| r | Radial position ($m$). |
| rh | Root radial position ($m$). |

| | |
|---|---|
| R | Radius ($m$). |
| TSR | Tip speed ratio. |
| U | Wind speed ($m/s$). |
| $U_{rel}$ | Relative wind ($m/s$). |
| AEP | Annual energy production. |
| BEM | Blade element momentum theory. |

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