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Influence of Model Parameters in the Analytical Wake Profile of a Wind Turbine on Wind Farm Design

[1]Pranupa S,[2]A. T. Sriram

[1,2] Ramaiah University of Applied Sciences
[1]pranupa.ee.et@msruas.ac.in, [2]sriram.at.et@msruas.ac.in

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Abstract

This research paper compares the predicting capabilities of four different analytical wake models, namely Jensen, Frandsen, Larsen and Ishihara used in wind farm design. Generally, these models consist of few parameters to be adjusted for better prediction. The available wind turbine experimental data was considered for the accuracy of prediction. Among the four models, the velocity profile predicted from the Larsen model shows reasonably good agreement with the experiments. The Jensen and Frandsen model assume top-hat profile for wake velocity. The Larsen and Ishihara models allows variation of velocity in radial direction. Since the wake velocity affects the power production in the downstream turbine, the four models were compared for power production from a second turbine placed at downstream axial location. A maximum of about 18 % deviation in power production was noticed. Though the thrust coefficient (CT) is a turbine parameter and it vary with inflow velocity, a parametric study on CT describes that the power prediction from various models differs significantly with varying CT. Parametric study on wake decay coefficient and ambient turbulence were carried out to identify it's influence on velocity profile. As the models predicts difference in power, a comprehensive study of various models on prediction of wind farm power production is necessary to understand the overall characteristics of wind farm before performing high-fidelity simulations.

Keywords; *Analytical wake models, Ambient turbulence, Fransen, Ishihara, Jensen, Larsen, Thrust coefficient, Wake decay coefficient.*

I. INTRODUCTION

As there is increase in demand for electric power the fossil fuels are depleting and concern is more towards using renewable energy source to meet considerable amount of the demand. Land based wind farms are available in some parts of India and there is a potential for off-shore wind power. Wind farms are popular in other parts of the world. The primary requirement of wind farms is the availability of wind with high wind speed. The second criteria is the availability of land, to construct wind farm. The proper utilization of land is important to extract the wind power economically. Wind speed of about 8 m/s is required for the selection of site. About 20 to 40 wind turbines forms a typical wind farm. Once the power is extracted from the wind turbine, the velocity of the wind is reduced immediately downstream the wind turbine. Further, the flow forms a wake in the downstream. The wake is also termed as turbulent wake or negative jet [1]. Once, the downstream wind turbine is placed in the wake of upstream wind turbine, the power production decreases due to less effective velocity. The placement of the wind turbine should be in such a way that the wind velocity to be of high value and hence it should be away from wake of upstream wind turbine. Since the land cost and

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electrical grid connections are involved, the spacing between the wind turbines to be optimum value should be optimized.

The wind farms are designed to provide maximum power with minimum cost. Generally, a wake model is used to estimate the wind velocity. From the inflow velocity, the power production is estimated with wind turbine power model. It needs wake diameter and effective velocity to estimate the power generation.

The power generated from the wind turbine is proportional to swept area of the rotor, and also proportional to cube of wind velocity available immediately in front of the turbine. Many

efforts were made on design of individual wind turbine to extract more power. The noticeable improvement is on increasing the rotor diameter. Since the manufacturing technology is improved, current rotor diameter considered is also very large. As the rotor diameter increases, the wake diameter also increases. Since the power generation is cube of wind speed, immediately in front of the turbine any reduction in wind speed significantly affects the power generation.

For a wind farm owner, the total cost involves land cost, individual turbine cost, installation cost with the power grid and operational cost. A careful study will be made before purchasing number of turbines for the given land area and placement of the turbine to reduce the influence of the wake. An optimization tool is needed to estimate these quantities to meet the requirements. As the wind farms are attractive for power generation, much research work was undertaken in the past on optimization studies. In any analysis and optimization, the estimation of wake diameter and wake velocity is the primary requirement.

There are many wake models currently available. This can be classified into CFD simulation models solving (RANS) equation, vortex methods and simple analytical models with assumption of flow physics. The CFD simulations for the entire wind farm are much expensive and it is not preferable at the preliminary level of optimization studies [13].Though the vortex method is less expensive than CFD methods, it is difficult to implement in the wind farm. The easiest method is to use simple analytical models at the preliminary stages of wind farm design. These models are also helpful in model predictive control techniques in the operation[5].

The analytical model involves various parameter to incorporate physical effects. Hence, it is important to study the influence of various model parameters. The major input parameters for the analytical model are incoming wind velocity, rotor diameter and hub height. The axial induction factor of a wind turbine, which relates fractional decrease in wind velocity between the freestream velocity and the velocity at rotor plane is one of the important parameters. It is also related to C_T. Apart from these parameters, other parameters representing ambient turbulence is also important for accurate prediction. A good wake model helps in planning the wind turbine [4]

Four well-known analytical wake models, namely Jensen, Frendsen, Larsen and Ishihara models are considered in this study for its predicting capabilities and also for the variation in model parameters. Though there are few studies reported in the literature [7, 8] the present study is intended to analyze the results for physical interpretation.

II. REVIEW OF WIND FARM DESIGN

Wind farm design generally starts with selection of site, availability of wind speed, selection of suitable wind turbine with their characteristics, optimum location of wind turbine and integrating it with the grid along with different controls for improved power output and quality of power. Few aspects are discussed in this section with main focus on wake models of wind farm design.

The wind turbine aerodynamics is generally related to airplane propellers. The theories developed for propeller are utilized in modeling of wind turbines.

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It is basically arrived from momentum balance principle.

A. Wind Turbine Model

Wind turbine model is to provide the power generation from the wind turbine by considering the forces acting on the turbine. The actuator disk model with 1-D momentum theory and Blade Element Momentum (BEM) theory are most commonly used. The thrust coefficient and the power coefficient C_p are written as

$$C_T = 4a[1-a]$$

$$C_P = 4a[1-a]^2$$

where 'a' is axial induction factor. The actuator disk model provides the limits for maximum power and BEM includes geometrical effects on power generation.

The thrust co-efficient is one of the important parameters for analytical wake models. In general, the C_T is a characteristic of wind turbine. It varies with rotor tip speed ratio. Though it is possible to estimate the C_T, it is generally assumed as a parameter in analytical model. In the present study, variation in C_T is considered to identify its effect on wake velocity.

B. Wake Models

Wind turbine wake model serves as important base for the prediction of available power in wind farm. These models can be categorized into three groups, namely, Computational Fluid Dynamics (CFD) approach, vortex based computational approach and analytical wake model. In CFD approach, the Navier-Stokes equation is solved with different levels of accuracy. The theory developed for aerodynamics of aircraft wings based on vortex method is also used in estimation of wake profile. The vortex-based methods are relatively less computationally intensive than CFD based methods. The analytical methods are relatively simple and easy to perform calculations. The accuracy of the prediction and fidelity generally increases with intensive calculation. At the same time, less expensive models serve as design tool at the initial stages of design. The analytical models are still in industrial practice to evaluate the power availability. These models can also to be used in recent research on model predictive control. Hence, it is important to identify the characteristics of various analytical models.

III. ANALYTICAL WAKE MODELS

The analytical models are intended to predict the wake diameter (D_w) and wake velocity profile (v) across radial direction at any axial distance (x) downstream of the wind turbine. The major input variables are the inflow or freestream velocity (u), rotor diameter (D_o), turbine thrust coefficient (C_T) and some way of introducing free stream turbulence. The C_T is defined as thrust produced by the turbine blades from the available kinetic energy of the free stream wind for the disc swept area (A).

A. Jensen Wake Model

Jensen model [1] and latter modified by Katic, Hojstrup and Jenson [2] is one of the popular and earliest wake models. It assumes that the wake is linearly expanding in the downstream as

$$D_w = D_o + 2 \propto x$$

Where $\propto$ is entrainment constant, some researchers referring as decay coefficient. This model also assumes top-hat profile across the wake.

The balance equation for the mass flow rate at the rotor plane and at downstream plane by constructing appropriate control volume gives

$$\pi {D_0}^2 V_r + \pi\left({D_w}^2 - {D_0}^2\right)u = \pi {D_w}^2 v.$$

By substituting the relation for the unknown quantity V_r in terms of axial induction factor, the wake velocity is given as

$$v = u\left[1 - \frac{2a}{\left(1 + \frac{2\propto x}{D_0}\right)^2}\right]$$

In this model, the value of 'a' depends on C_T. Hence, it depends on turbine characteristics. However, the value of $\propto$ is generally considered to be 0.1. In the literature, it is related to turbine hub height, z, and terrain roughness, z_0, by Frandsen [3] as

$$\propto = \frac{0.5}{\ln\left(\frac{z}{z_0}\right)}$$

Further from a review paper by Gocemen et al [4], α is approximately equal to 0.4 times the turbulence intensity, TI. Though other modifications were made for Jensen model by various researches, the basic model is considered in this study.

B. Frandsen Wake Model

Frandsen model was developed by Frandsen et al [5]. Momentum balance of the flow through wind turbine rotor is utilized by considering a cylindrical control volume with area equal to wake area [5].
The wake diameter is expressed as:

$$D_w\,(\mathrm{x}) = D_0\,(\beta^{\frac{k}{2}} + \alpha s)^{\frac{1}{k}}$$

where α is a decay constant, k is a model constant, β is a wake expansion parameter given as

$$\beta = \frac{1 + \sqrt{1 - C_T}}{2\sqrt{1 - C_T}}$$

and S is the relative distance from the rotor (x/D_0). The value of α and k are obtained from experiments. In literature the value of α assumed as 0.075 [6] and the value of k is assumed as 2 or 3 [6, 7]

The initial wake diameter can be determined by square root of expansion coefficient times the wind turbine rotor diameter

$$\mathrm{D}_{\mathrm{initial}} = \sqrt{\beta} D_0.$$

The wake velocity is determined from

$$V = \frac{u}{2}\left(1 \pm \sqrt{1 - 2\,\frac{\Omega_0}{\Omega_w} C_T}\right)$$

where Ω_0 and Ω_w are swept area of the rotor and area of wake at distance x.

C. Larsen wake Model

Larsen performed series of research work on the contribution of analytical wake model development [9-12]. A simplified model [12] is based on Prandtl's mixing length theory. The wake radius is expressed as:

$$R_w(x) = \left(\frac{105 C_1^2}{2\pi}\right)^{\frac{1}{5}} \left(C_T \Omega (x + x_0)\right)^{\frac{1}{3}}$$

Where Ω being the turbine rotor area and C_1 is constant represents the non-dimensional mixing length

$$C_1 = \left(\frac{\mathrm{k} D_0}{2}\right)^{\frac{5}{2}} \left(\frac{105}{2\pi}\right)^{-\frac{1}{2}} (C_T \Omega\, x_0)^{\frac{5}{6}}$$

Where x_0 is given by

$$x_0 = \frac{9.6\,D_0}{\left(\frac{2\,R_{9.6}}{K\,D_0}\right)^3 - 1}$$

The value of k is estimated from:

$$k = \sqrt{(m+1)/2}$$

$$m = \frac{1}{\sqrt{1 - C_T}}$$

The wake radius at a downstream distance of 9.6 times rotor diameter (9.6 D_0)

$$R_{9.6} = a_1 e^{(a_2 C_T{}^2 + a_3 C_T + a_4)}\,(b_1\, I_a \,+\, 1) D_0$$

I_a is the ambient turbulence intensity, a1, a2, a3, a4 and b1 are coefficients that were empirically determined

Where u is the undisturbed upstream wind velocity

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$$\Delta\ U_1(x,r) = -\frac{u}{9}\left(\ C_T\Omega(x + x0)^{-2}\ \right)^{\frac{1}{3}}\ \left(r^{\frac{3}{2}}\left(3C_1C_T\Omega(\mathrm{x} + x_0)\right)^{\frac{-1}{2}}\ -\ \left(\frac{35}{2\pi}\right)^{\frac{3}{10}}\left(3\ {C_1}^2\right)^{-\frac{1}{5}}\ \right)^2$$

D. Ishihara wake Model

This model was developed by Ishihara et al [8]. It uses Mitsubishi standard wind turbine data to analyse the Ishihara wake model. The main advantage of using this model is it has the ability to predict the wake recovery at any turbulence and at any value of thrust coefficients. The wake recovery predicted by Ishihara model depends on the summation of turbulence caused due to atmosphere, rotor and downstream wind. Literature [4] states that the rate of wake recovery is directly proportional to the value of thrust coefficient C_T and it also states that the onshore wake recovery is high when compared with offshore because of higher turbulence intensity.

The Gaussian profile is assumed to determine velocity in Ishihara model. The velocity deficit is determined by:

$$\text{Udef} = \frac{\sqrt{C_T}}{32}U_\infty\left(\frac{1.66}{k_1}\right)^2\left(\frac{x}{D}\right)^{-P}\ \exp\left(\frac{-r^2}{D_{wake}^2}\right)$$

The wake growth is determined by:

$$D_{wake} = \frac{k_1 C_T^{\frac{1}{4}}}{0.833}D^{1-\frac{P}{2}}x^{\frac{P}{2}}$$

The turbulent intensity is represented as p and is given by:

$$p = k_2(I_a + I_w)$$

The ambient turbulence and turbine generated turbulence Ia and Iw is determined using the coefficients k1, k2 and k3 respectively used the values as 0.27, 6.0 and 0.004. These values are found in most of the literatures.

IV. RESULTS AND DISCUSSION

A. Validation of the wake models

The wind turbine used in the experiment [6] is considered for validation. The experiments were conducted with a small wind turbine in a close loop wind tunnel. The turbine rotor diameter is 80 mm with hub diameter equal to 18 mm. The turbine hub height, z, is 140 mm. The experiments were conducted for the inflow velocity of 5 m/s, 8 m/s and 10 m/s. Average velocities along the radial direction at various axial distance of 3D, 5D and 8D are reported [6]. For validation purpose, the results of velocity measurements at 3D axial location with inflow velocity of 8 m/s case is considered.

Initial studies with Jensen, Frandsen and Ishihara models for axial induction factor of 0.25 was shown good agreement with experimental value. For the case of Larsen model, the value of thrust coefficient 0.25 was shown good agreement with experimental data.

In case of Jensen model, the terrain roughness of 0.3 mm was used. For the case of Frandsen model, the value of α and k were set to the value of 0.075 and 2 respectively. For the case of Larsen model, the ambient turbulence of 0.05 was prescribed. For Ishihara model, the ambient turbulence of 0.15 was shown better prediction with the experiments.

The predicted velocity profile from four different models are shown in Fig. 1. All the models tries to predict the center line velocity close to experimental data. Fig. 1 also clearly shows the characteristics of Jenson and Frandsen models representing top-hat profile in the wake region. The wake width and minimum velocity predicted from Frandsen model is slightly lower than Jensen model. Larsen model predicts the velocity profile very close to the experimental value. The Ishihara model overpredicted the wake deficit velocity and wake width.

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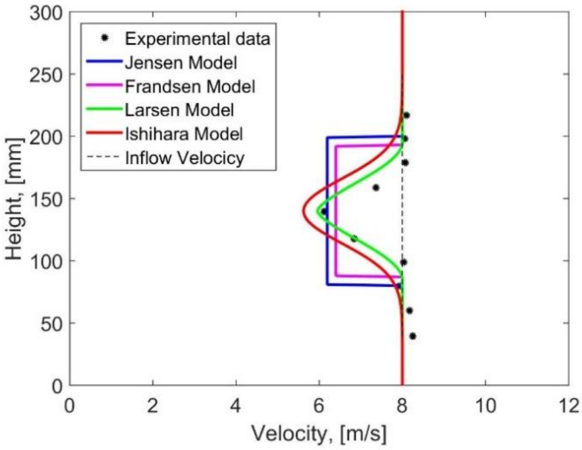

Fig. 1. Comparison of Velocity Profile Prediction from Various Models against Experiments [6].

In general, the Larsen and Ishihara model accounts for radial variation in wake velocity. Among the four models, the Larsen model shows good agreement to the experimental data.

B. Velocity field and power prediction

The velocity field, predicted from various models, is shown in Fig. 2. The Jensen model clearly shows the wake expansion, top-hat profile in the wake regions and gaining of wake velocity due to entrainment of outside fluid in to wake region. The velocity field of Frandsen model also reflects the top-hat nature of the model. The predicted wake width is less as compared with the Jensen model. Consequently, the wake velocity is less in Frandsen model due to less entrainment of outside air.

The velocity field of Larsen and Ishihara model shows the variation of wake velocity in the radial direction. The Ishihara model perturbs the velocity in most of the domain through the assumed Gaussian profile. Though the contours of Ishihara model in Fig. 2 shows large influence of the wake, the actual values are relatively less as seen on line plots at x = 3D$_o$ in Fig. 1.

Placement of second turbine in the wake of first turbine significantly affects the performance. In order to assess this effect from various model, normalized power is defined

$$\frac{P_j}{P_1} = \frac{u_j^3}{u^3}$$

The predicted normalized power from various models are shown in Fig 3. It reflects the trend on recovery of velocity with increasing the axial distance away from the upstream turbine. It is seen from the Fig. 3, that even placing the second turbine at 10D$_o$ downstream, the wake influences to extract reduction in power. The minimum reduction of 20 % is predicted from the Ishihara model against 38 % reduction from Frandsen model.

Fig. 3 shows that the recovery of velocity in the wake region is quite important for the power production of downstream turbine. Newer design of wind turbine with enhancement on wake recovery with blade tip modifications may help on overall performance of wind farm.

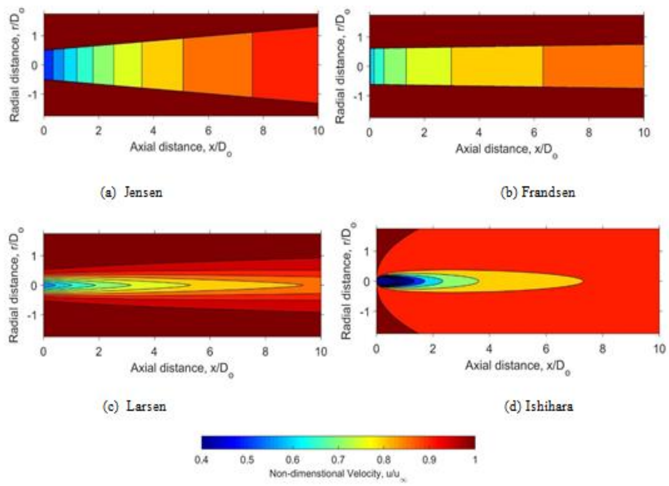

Fig. 2. Comparison of velocity counters predicted from various analytical wake mod

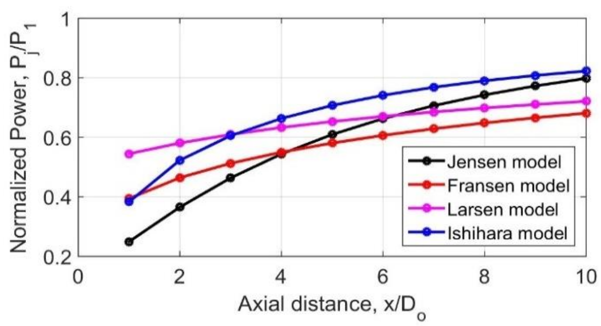

Fig. 3: Comparison of predicted normalized power from various analytical wake model by placing second turbine at various axial location

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C. Influence of thrust coefficient

A good design of wind turbine intends to have thrust coefficient close to one at operating conditions. Due to variation in design point and actual wind velocity, achieving the thrust coefficient to the value of one is difficult.

A study of variation in thrust coefficient is considered. The thrust coefficient of the first turbine is varied from 0.1 to 0.9. From the inflow velocity and wake velocity at $10D_o$, the normalized power prediction is plotted in Fig. 4.

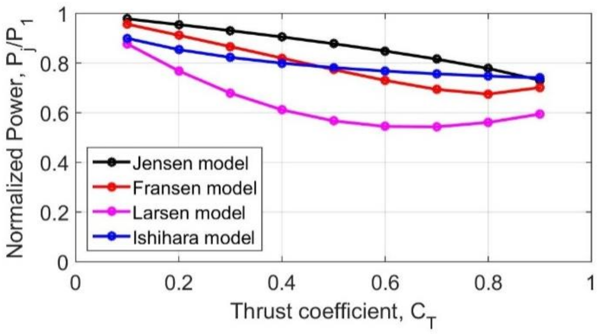

Fig. 4 Influence of C_T on the prediction of normalized power from various analytical wake model for second turbine located at 10 D

It is clearly seen from Fig. 4, the power produced by the second turbine decreases when the C_T of the first turbine is higher. The prediction from various models shows much variation in power production by the second turbine.

In the case of actual wind farm having about 40 to 50 turbines, the C_T variation affects overall performance. A good analytical wake model tuned to individual wind farm is important for the design stage, operational aspects of power extraction, grid connection and possibility of dynamic control of individual wind turbines.

D. Influence of other model parameters

In the case of Jensen model, the decay coefficient α is varied with the value of 3^0, 4.5^0 and 6^0. The predicted velocity profile at axial distance of $5D_o$ is shown in Fig. 5 along with experimental data. Increasing the decay coefficient increases wake width, as expected. When wake width increases the difference in velocity with respect to free stream value reduces. In principle, the decay coefficient α is related to atmospheric turbulence [4]. Here turbulence enhances mixing in the wake and recovers the velocity in the shorter distance. By varying the decay coefficient α from 3^0 to 6^0 the wake velocity is increased from 6 m/s to 7 m/s, equivalently 24.8 % increase in power production for the present case with freestream velocity of 8 m/s.

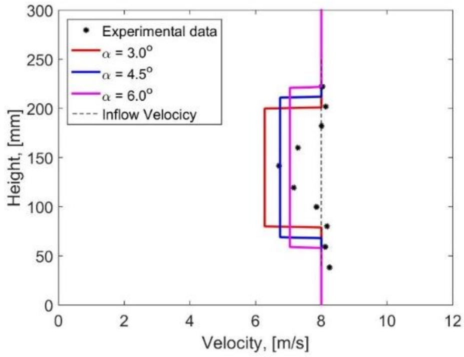

Fig. 5: Predicted velocity profile for the variation in decay coefficient α in Jensen Model

In case of Frandsen model, the value of k is chosen as 2, 2.5 and 3. The predicted velocity profile is shown in Fig. 6. As increasing Value of k, the wake deficit velocity increases by slightly adjusting the wake width. Parameter specific to wind farm is required for better prediction.

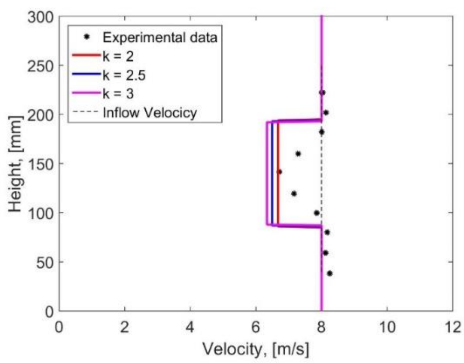

Fig. 6: Predicted velocity profile for the variation in the parameter 'k' in Frandsen Model

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Ambient turbulence is one of the important parameters for recovery of wake velocity. Larsen and Ishihara models explicitly provides it as model parameter. For the case of Larsen model, calculations were made with increasing I_a value of 2.5 %, 5 % and 10 %. The predicted velocity profile is shown in Fig. 7. As increasing I_a, the wake width increases and reduces the wake deficit velocity.

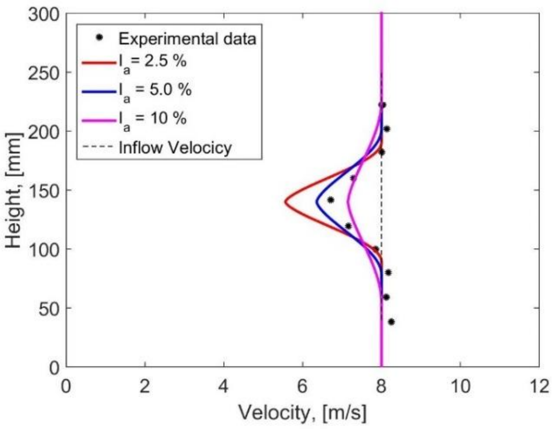

Fig. 7: Predicted velocity profile for the variation in ambient turbulence intensity I_a Larsen Model

For the case of Ishihara model, the I_a was varied to value of 2.5 %, 7.5 % and 15 %. This model also indicates that the increase in ambient turbulence reduces wake deficit velocity. Based on the results, any form of increasing ambient turbulence enhances the power production of the downstream turbines. This may be considered through effective design of wind turbine blade tips. The ideas from aircraft wing design on incorporating turbulator may be investigated on wind farm design.

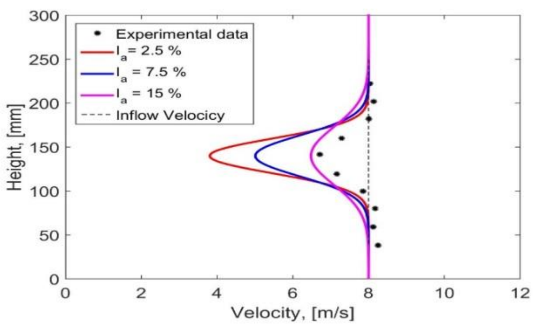

Fig. 8: Predicted velocity profile for the variation in ambient turbulence intensity I_a Ishihara Model

V. Conclusions

Four analytical wind turbine wake models were considered in this study to assess its predicting capabilities against wind tunnel data from small wind turbine. All the models predict reasonably good on the wake velocity along the axis. However, it differs along the radial direction. The contour plots of velocity distribution describe the characteristics of various models indicating the wake width and shape of the velocity field. Due to the variation in wake velocity prediction, the power of second turbine predicted shown about 18 % deviation among different models. The study of variation in C_T and other model parameters suggest that tuning of the models specific to individual site is important.

This study also provides intuitive ways of improving overall performance of wind farm. This include proper design and optimization of the wind farm by considering various aspects like selection of wind turbine to have better C_T value, utilization of various low fidelity design tools for not only prediction but also for identifying methods for better improvement, high fidelity simulation for selected cases to extract more physics, improving the terrain with sources for enhancing ambient turbulence and overall dynamic control of the wind farm with grid connectivity.

VI. ACKNOWLEDGMENT

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AUTHORS PROFILE

Ms. Pranupa. S is currently working as Assistant Professor in department of Electrical Engineering at Ramaiah University of Applied Sciences (RUAS), Bangalore. She has been active in IEEE Bangalore Section and also a member of IEEE Power and Energy Society (PES). Her research interest is on renewable energy, robotics, optimization and control. She may be contacted at *Pranupa.ee.et@msruas.ac.in*

Dr. A. T. Sriram received his Ph. D. degree from Indian Institute of Science, Bangalore. He has been involved in research activities in the field of Aero-Thermo-Chemistry and Control. He is currently working as Associate Professor in Department of Aerospace Engineering, Ramaiah University of Applied Sciences, Bangalore. His current interest includes mathematical modeling of engineering problems, multidisciplinary optimization and control. He may be contacted at *atsriram.aae.et@msruas.ac.in*

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