Effect of atmospheric stability on the wind resource extrapolating models for large capacity wind turbines: A comparative analysis of power law, log law, Deaves and Harris model

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Abstract

To observe accurate wind climate from the available met mast measured wind data at different heights an accurate wind shear model is necessary. Since WAsP and windPRO is software package which provides the better representation of wind profile over homogeneous terrain only. Though, a separate module named as WAsP CFD has been added in both of the software to predict correct wind resource in complex terrain also. Nowadays wind resource assessment has been widely dependent on terrain and becomes a key issue for the researchers. It has been found experimentally from earlier work that model of Deaves and Harris shows a better representation of wind profiles on flat terrain at higher heights in comparison to other models such as the PL (power law), the LogL (log law) and the LogLL (Log linear law). This study presents a comparative analysis of three different wind extrapolation models. Based on two year measured wind data from the met mast the at 10 m, 50 m, 80 m, 100 m and 102 m heights, results were compared in different stability classes using Monin-Obukhov similarity theory. The RMSE (root mean square error) and NRMSE (normalized root mean square error) were found to be least in case of log-linear model which is 0.11 and 0.01784 respectively in comparison to the PL and Deaves and Harris models.

Keywords: Atmospheric boundary layer, LIDAR, Monin-Obukhov length, Richardson Number, WAsP, windPRO

Nomenclature

Abbreviations

WT Wind turbine
WAsP Wind resource analysis and application programme
windPRO Wind energy project design and planning
PL Power law
LogL Log-linear law
ABL Atmospheric Boundary Layer
MOST Monin-Obukhov similarity theory
LogLL log-linear law
MLM Maximum likelihood method
MMLM Modified maximum likelihood method
Ri Richardson number
CFD Computational fluid dynamics
LIDAR Light detection and ranging
PD Panofsky and Dutton (PD) model

Variables

v wind speed [m/s]
k shape factor
1. Introduction

Accurate measurement of wind resource is necessary to project a wind farm. The earlier method uses cup anemometer and wind vane to measure the wind velocity and direction. Due to the advancement of wind power technology attention of researchers had turned to increase the hub height. To measure the wind data at more than 100 m height by using conventional method through met mast is now becoming the costly and time-consuming process. Henry W. Tieleman 2008 compared the observations from the power law, the logarithmic law and Deaves and Harris model regarding mean wind speed and turbulence intensity. At 10 m height, nonneutral thermal stability affects the wind velocity profile and should not be neglected. Daniel R. Drew et al. 2013 observed that Deaves and Harris wind speed extrapolating model was found to be the best fit at nonequilibrium conditions in urban areas. Hideki Kikumoto et al. 2017 investigated the accuracy of wind speed measurement using the PL in low-speed region. The results were compared and analyzed with Doppler Lidar and ultrasonic measured wind data in the urban boundary layer of Tokyo Japan. Nicholas J. Cook 1997 compared the wind speed profile with the power law and D&H. The D&H model fitted the profile near the ground and top of the ABL due to satisfying the criteria of both boundary conditions. Giovanni Gualtieri, Sauro Secci 2011 compared and investigated the accuracy of prediction of wind speed over a flat and rough region at 10 m and 50 m height above ground level in which the role of atmospheric stability and surface roughness had discussed. Giovanni Gualtieri 2016 had investigated the time-varying relation of wind exponent with atmospheric stability. The model was compared with the power law and found to be the finest and accurate approach regarding wind speed profile and energy yield calculation in neutral conditions. Some equilibrium wind speed model name as the PL, the LogL and DH had been discussed by Davenport 1960; Simiu and Scanlan 1996; Deaves and Harris 1978. Panofsky and Dutton 1984 and Elliott 1958 studied the effect of the inner boundary layer with a step change in surface roughness for the wind profile predictions. Deaves 1981 utilized the concept for heterogeneous terrain in wind speed extrapolating methods.
Giovanni Gualtieri 2017 tested and compared the DH model with the PL with all stability conditions. The DH model found to be best fitted and tuned, and its accuracy has increased with height from 80 m to 140 m above ground level. Due to increasing demand for energy, wind resource prediction has become a crucial issue markedly for energy investors to accurately analyze the wind speed at a different hub height of wind turbine. It is essential during the feasibility study to abate the cost of wind farm installation. Many researchers worked on different wind extrapolating models such as the PL, the LogL, the LogLL, and DH. Every model has its significance and assumptions depending on the type of terrain where wind speed has predicted.

Sharma et. al. 2014 had optimized 150 m higher wind monitoring tower using ANSYS. Sharma et. al. 2014 extended earlier work with the incorporation of nano and piezoelectric materials in their design.

2. Wind Profile extrapolating models

It was the first time when Davenport 1960 originally proposed the PL to design the wind load, especially in structural engineering. Due to the simplicity of the PL model which can applied to larger height in compare to the logarithmic law subjected to various terrain conditions as per Counihan, 1975. Following models had generally been adopted for the wind profile predictions under certain assumptions:

2.1 Deaves and Harris (D&H) model

This model developed in two stages in strong wind conditions. In the first stage, it was developed for the ABL in equilibrium over uniform roughness and in the second stage to account for multiple step changes in roughness. The model was developed to a different kind of heterogeneous terrain. UK, Australia and New Zealand have adapted this model into its wind design codes. If \( u^* \) is the friction velocity, \( k \) is the von Karman constant = 0.4), \( z_o \) is the roughness length, \( h \) is atmospheric boundary layer height then velocity \( v \) has been defined as:

\[
\begin{align*}
V &= \frac{u^*}{k} \left[ \ln \frac{z}{z_o} + 5.75 \left( \frac{z}{h} \right)^2 - 1.88 \left( \frac{z}{h} \right)^3 + 0.25 \left( \frac{z}{h} \right)^4 \right] \\
h &= \frac{u^*}{f} \\
V_{geo} &\rightarrow V_G \text{ and } \frac{dv}{dz} \rightarrow 0 \text{ as } z \rightarrow h
\end{align*}
\]

\( V \) stands for the geostrophic wind speed satisfies the criteria of upper and lower boundary conditions to the ABL. Geostrophic wind speed calculated when the thermal flux generated by the heat and friction are equal.
2.2 Log Law model

The log law model derived from Eq. (5) and holds over a ground surface:

\[ V = \frac{u^*}{k} \ln\left(\frac{z}{z_o}\right) \]  

(7)

It is clear from Eq. (7) that log law satisfies the lower boundary conditions only not the upper one. Typically, it found that the power law does not fit well at the higher height range (typically more than 150 m).

2.3 Power law model

The wind speed at a height \( z \) uses the empirical formula:

\[ \frac{V}{V_{ref}} = \left(\frac{z}{z_{ref}}\right)^\alpha \]  

(8)

Here, \( V_{ref} \) refers to the wind speed at the height say \( z_{ref} \). The Power law indicates the increment of surface wind speed concerning height \( z \). The PL neither satisfies the upper boundary nor the lower boundary conditions. In comparison to log law model, it fits well with the wind speed profile at larger height, which is one of the critical reason for its preference. Though, it had not been recommended to use it very close to the ground. Most of the research matched well with the PL over the height value from 30 m to 300 m a.g.l. The value of \( \alpha \) varies concerning wind speed, height and surface roughness. In practice, the wind shear exponent \( \alpha \) often assumed as equivalent to the aerodynamic roughness length \( z_o \).

2.4 Estimation of Monin-Obukhov length

Monin defines the turbulence within the surface boundary layer- Obukhov length scale \( L \) as:

\[ L = \frac{\rho C_p u^*}{kgH} \]  

(9)

Where \( \rho \) stands for air density at temperature \( T \), \( C_p \) is the specific heat at constant pressure, \( k \) is the Von Karman constant \( u^* \) is the friction velocity, and \( H \) is the sensible heat flux. The Monin-Obukhov length scale \( L \) can calculate by computing the Bulk Richardson number which requires only single wind speed and temperature measurements at two heights. Gradient and bulk Richardson number defined as:

\[ R_i = \frac{g \Delta z \Delta \theta_{1}}{\theta_1 \Delta u} \]  

(10)

Where \( \Delta \theta = \theta_2 - \theta_1 \), \( \Delta z = z_2 - z_1 \) and \( \Delta u = u_2 - u_1 \) are the measured parameter at two height. When the temp. and wind speed measurement is available only a single height (Barker and Baxter, 1975)

\[ R_{bh} = \frac{g \Delta z \Delta \theta}{\theta_2 \Delta u} \]  

(11)

\[ \varepsilon = \frac{\varphi_m z}{\varphi_h} \]  

(12)

\[ \frac{z}{L} = \varepsilon \]  

\( z \) stands for the geometrical mean height of \( z_1 \) and \( z_2 \), and \( \varphi_m \) and \( \varphi_h \) are the nondimensional functions related to wind shear and temperature gradient, as per (Dyer, 1974) \( \varphi_m \) and \( \varphi_h \):

\[ \varphi_m = \begin{cases} \left(1 - \gamma \varepsilon\right)^\frac{1}{2}, & \varepsilon < 0 \\ \left(1 + \beta \gamma\right), & \varepsilon \geq 0 \end{cases} \]  

(13)

\[ \varphi_h = \begin{cases} \left(1 - \gamma \varepsilon\right)^\frac{1}{2}, & \varepsilon < 0 \\ \left(R + \beta \gamma\right) \varepsilon, & \varepsilon \geq 0 \end{cases} \]  

(14)

(Binkowski, 1975) found the following results, the function based on two stability conditions
\[ \varepsilon = \begin{cases} \frac{R_i}{R} (1 - \hat{\gamma} R_i)^{\frac{1}{3}} / (1 - \hat{\gamma} R_i)^{\frac{1}{2}} & R_i \leq 0 \\ \frac{R_i}{1 - \hat{\gamma} R_i} & 0 < \frac{R_i \beta^2}{R} < 1 \end{cases} \] (15)

\[ \bar{z} = \frac{z_1 + z_2}{2}, \quad \bar{z} \text{ is the mean height} \] (16)

\[ \frac{z_2}{L} = \frac{kR_i \beta^2}{G} \] (17)

\[ F = \frac{u}{u^*} \begin{cases} \ln \left( \frac{z_2}{z_o} \left( \frac{\eta_o + 1}{\eta_2 + 1} \right)^2 \right) + 2 \tan^{-1} \left( \frac{\eta_o - \eta_2}{1 + \eta_o \eta_2} \right), & L \leq 0 \\ \ln \left( \frac{z_2}{z_o} \right) + \frac{\beta z_2}{L}, & L \geq 0 \end{cases} \] (18)

\[ L \text{ depends upon two stability conditions} \]

\[ G = \frac{\Delta \theta u^*}{(-w^* \theta^*)} = \begin{cases} \frac{R \ln \left( z_2 / z_o \right)}{\left( \eta_2 + 1 \right)^2}, & L \leq 0 \\ \frac{R \ln \left( \frac{z_2}{z_o} \right)}{\left( \frac{\eta_o + 1}{\eta_2 + 1} \right)^2}, & L \geq 0 \end{cases} \] (19)

\[ \eta_2 = (1 - \gamma z_2 / L)^{\frac{1}{2}} \] (20)

\[ \eta_0 = (1 - \gamma z_o / L)^{\frac{1}{2}} \] (21)

\[ \lambda_1 = (1 - \gamma' z_1 / L)^{\frac{1}{2}} \] (22)

\[ \lambda_2 = (1 - \gamma' z_2 / L)^{\frac{1}{2}} \] (23)

Where \( \eta_2, \eta_0, \lambda_1, \lambda_2 \) are the function of Monin-Obukhov length \( L \). \( G \) is the function of \( R_i \) and mean gradient height \( z \). \( F \) stands for the logarithmic function of speed and friction velocity.

3. Observation and site details

Jamgodrani hills have a huge potential regarding power production. The 100 m mast located in District Dewas at Jamgodrani Hills. The elevation of the mast location is 573m above mean sea level. Site coordinate has been converted into UTM (Universe Transverse Mercator) system to perform line and area roughness calculation purpose using WASP and windPRO. There were five wind anemometers, and wind vane had mounted on the mast to measure wind speed and direction respectively. To verify the Monin-Obukhov Similarity theory two temperatures and one pressure sensor had installed. Table 1 and Fig.1 shows the mast details and location respectively.

| Site Coordinate          | (E)Longitude- 76°09’2.50” 
| (N) Latitude- 22°58’ 58.20” 
| UTM-2542426 N, 619480 E |
| Duration                 | 2015 to 2017 |
| Site name                | Jamgodrani Hills |
| District                 | Dewas |
| State name               | Madhya Pradesh |
| Mast Height              | 100m |
| Elevation                | 573mAMSL |
| Location of Anemometer   | 10m, 25m, 50m, 80m, 100m |
| Location of Wind vane    | 10m, 25m, 50m, 80m, 100m |
| Location of Pressure sensors | 2m, 10m |
| Location of temperature sensors | 2m, 10m |
Weibull parameter (k and c) calculated by two different methods namely as MLM and MMLM. It is very much clear from the Table 3 in comparison to Table 2 Weibull parameter are more than Table 2. Experimentally, it found that the Weibull parameters calculated by the MMLM provides more accurate results in comparison to MLM.

MLM is a widely accepted method to estimate the Weibull parameter. It required a more extensive tool for mathematical calculations. In the first step, k calculated by using the following equation.

\[
k = \left( \frac{\sum_{i=1}^{n} v_i^k \ln(v_i)}{\sum_{i=1}^{n} v_i^k} \right) - 1
\]

\[
c = \left( \frac{1}{n} \sum_{i=1}^{n} v_i^k \right)^{1/k}
\]

n stands no of observation of zero wind speed and vi, i\text{th} operation wind speed.

This method is similar to MLM and estimated by iteratively using the following two equations. It used when wind data is available in frequency distribution form. If vi is the wind speed related to bin i, f(vi) is the frequency range within the region of bin I, n is the total no of bins and f(v \geq 0) is the probability of wind speed.

\[
k = \left( \frac{\sum_{i=1}^{n} v_i^k \ln(f(v_i))}{\sum_{i=1}^{n} v_i^k f(v_i)} \right) - 1
\]

\[
c = \left( \frac{1}{f(v \geq 0)} \sum_{i=1}^{n} v_i^k \right)^{1/k}
\]

Table 2 Weibull parameter by MLM

<table>
<thead>
<tr>
<th></th>
<th>100m</th>
<th>80m</th>
<th>50m</th>
<th>10m</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>2.24</td>
<td>2.219</td>
<td>6.70</td>
<td>2.3621</td>
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<tr>
<td>c</td>
<td>7.131</td>
<td>6.25</td>
<td>2.164</td>
<td>4.193</td>
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</tbody>
</table>
Table 3 Weibull parameter by MMLM

<table>
<thead>
<tr>
<th></th>
<th>100m</th>
<th>80m</th>
<th>50m</th>
<th>10m</th>
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</thead>
<tbody>
<tr>
<td>k</td>
<td>2.431</td>
<td>2.42</td>
<td>2.57</td>
<td>2.45</td>
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<tr>
<td>c</td>
<td>7.67</td>
<td>7.24</td>
<td>6.78</td>
<td>4.736</td>
</tr>
</tbody>
</table>

*Roughness length=0.3183m, *Class= 2.8

4. Result & Discussion

Annual mean wind speed and mean turbulence intensity calculated at different heights from ground level. It is clear from Table 4 that the annual wind speed increase concerning height, but mean turbulence intensity decreases. Due to more predominate viscous and obstruction effect near the ground level wind turbulence is more. Turbulence intensity seems to decrease with the height due to a decrease in surface shear stress.

Table 4 Wind characteristics

<table>
<thead>
<tr>
<th>AMWS (Annual Mean wind speed) in m/s</th>
<th>Mean turbulence intensity (TU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 m</td>
<td>80 m</td>
</tr>
<tr>
<td>6.32</td>
<td>5.93</td>
</tr>
</tbody>
</table>

Fig. 2 Wind speed and direction variation (Source: windPRO 3.1) (a): Variation of hourly wind speed in m/s and Direction in degree, (b): average wind direction, (c): wind direction at 50 m, 80 m, and 100 m heights.
The hourly variation of wind speed and direction has been shown in Fig. 2 at 10 m, 50 m, and 80 m height respectively. Blue shown in Fig. 2 signifies the wind speed and direction at 100 m hub heights. Weibull parameters have been divided into 12 sectors with the given direction and typically illustrated in Fig.3 and Fig. 4 respectively at 80 m and 10 m height respectively.

Fig. 3 Sector-wise Weibull parameter distribution at 80m height a.g.l. (Source: windPRO 3.1)
Fig. 4 Sector wise Weibull parameter distribution at 10m height a.g.l. (Source: windPRO 3.1)
Fig. 3 and Fig. 4 shows the sector-wise distribution of Weibull parameter at 80m and 10m height respectively.

Fig. 5 Energy rose at 80m height (Source: windPRO 3.1)

Fig. 6 Energy rose at 10m height (Source: windPRO 3.1)
In Fig. 5 (April month) up to 20m/s wind speed shown, which produces maximum power density at 80m height. While Fig. 6 indicates that the maximum wind speed can be utilized for the power production is 3-5 m/s at 10m height. The measured wind speed at 10m a.g.l. can be taken for reference purpose. Further Wind speed has been extrapolated using the PL from 50m to 100m and 80m to 100m by $\alpha_{50-100} = 0.2483$ and $\alpha_{80-100} = 0.1474$ respectively. By taking the surface length of $z_0 0.3183$m, von Karman factor 0.4 and friction velocity $u^* 0.4316$ m/s the wind speed can be found using the LogL at 100m a.g.l as 6.20m/s.

The Monin-Obukhov Length similarity had applied at Jamogadrani hills which predict that the atmosphere is strongly stable and wind speed using D&H model found to be 6.68m/s. The Richardson Number is 0.35614 which has been used to calculate Monin-Obukhov scale.

Fig. 7 Mean wind profile using power law and LogL respectively
Table 5 Comparative analysis of different models

<table>
<thead>
<tr>
<th>Parameter/Results</th>
<th>Predicted by PL ($\alpha_{0.5a} = 0.2483$)</th>
<th>Predicted by PL ($\alpha_{0.5a} = 0.1474$)</th>
<th>LogL</th>
<th>D&amp;H model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed in m/s</td>
<td>6.580</td>
<td>6.135</td>
<td>6.204</td>
<td>6.681</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.26398</td>
<td>0.18085</td>
<td>0.111701</td>
<td>0.36485</td>
</tr>
<tr>
<td>NRMSE</td>
<td>0.04094</td>
<td>0.02905</td>
<td>0.017842</td>
<td>0.056139</td>
</tr>
</tbody>
</table>

It is clear from Table 5 that Log law fitted and best matches the wind profile. RMSE and NRMSE found to be least in case of Log low in compare to PL and D&H model. The actual measured wind speed by wind anemometer is 6.32 m/s at 100 m a.g.l. It can be seen from Fig. Seven that the accuracy of the LogL increases from the height above 80 m a.g.l.

5. Conclusion

To validate its reliability for addressing MW WTs, the PL, LogL and D&H model assessed at hub heights at 10 m, 50 m, 80 m and 100 m. Based on a two-year wind data of 10 min. Observations including temperature and pressure data from the met mast of Jamdani hills, all models were compared. The application of models required prior assessment of sites surface parameter such as $\alpha$ for power law, friction velocity and surface length for Log law and Coriolis factor, ABL height for D&H model. Though D&H model developed for strong wind conditions subjected to neutral conditions; it forced to apply for all stability regions.

The RMSE and NRMSE were found to be at least for the PL, the LogL, Deaves and Harris model up to height 80 m a.g.l. Within the extrapolating range. The result seems to the LogL capability of best producing at a higher level. This model was found suitable for strong adiabatic conditions. However, the overall accuracy of LogL model during these conditions should choose as a model’s key factor. Practically, in Indian conditions the DH model could not fit appropriate due to two limitations: i) reliable friction observation ii) accurate site’s surface length assessment. The value of $Z_o$ has the major effect on DH model.

Based on 10 min. Wind speed, pressure and temperature data the minimum RMSE and NRMSE found to be 0.11 and 0.01 respectively. The PL exhibited the more accuracy across all extrapolations ranges and for all stability criteria, which is used particularly in predicting wind speed profile variation. Currently, obtained results strongly encourage further uses of the PL, which would deem as a future research topic from a wind energy scenario. At Jamgodrani hills, the LogL proved to be the finest in the prediction of the extrapolated wind speed, thus supporting its validity over the entire ABL.

References


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