MATHEMATICAL MODELING
# CHAPTER-5

## MATHEMATICAL MODELLING

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CHAPTER-5

MATHEMATICAL MODELING

5.1. THE PERFORMANCE CHARACTERISTICS OF WINDMILL: The performance characteristics of windmill of a specific manufacturers are estimates the power output derived for different wind speeds. A specific manufacturer provides a performance characteristic that includes the cut-in wind speed, rated or nominal wind speed, cut-off wind speed and the performance curve for different wind speeds each of which is fixed measure for particular wind mill. In general the cut-in speed is in range 3.0-4.5m/s fixed for a wind mill, the cut-off speed is in range 20-25m/s and the nominal speeds vary from 11 to 15m/s depending on the power ratings. A typical performance characteristics curve is shown in the graph of figure. For windmills from vast majority of manufactures, the performance characteristics are piecewise linear. (The following curve can similarly assume to be linear due to reasons discussed next paragraph). The graph also shows the cut-off wind speed to be 22m/s, cut-in speed of 3m/s and a nominal rating of 1.25MW for 14m/s.

Fig: 5.1 Piecewise linear function.

A piecewise linear function can be described as follows:[170]
\[ W(V) = 0 \quad \text{for } V \leq V_c \quad (5.1) \]
\[ = 0 \sim 1 \quad \text{for } V_c < V < V_{rated} \quad (5.2) \]
\[ = 1 \quad \text{for } V \geq V_{rated} \quad (5.3) \]

Power ratio is zero when \( V \) is equal or below cut in velocity. Power ratio is in between 0 to 1 for \( V \) more than cut in velocity and less than rated velocity. Power ratio is equal to 1 that is maximum value where \( V \) is equal and greater than rated velocity. Cut in speed, cutoff speed and nominal speed vary depending on the power rating and size of turbine. The cut in speed is the wind speed required to set the blades in motion. As the wind speed rises above the cut-in speed, the power rises rapidly as shown in figure. However, typically somewhere between 12 and 17 m/s the power output reaches the limit that the electrical generator is capable of. This limit to the generator output is called the rated power output and the wind speed at which it is reached is called the rated output wind speed. At higher wind speeds, the design of the turbine is arranged to limit the power to this maximum level and there is no further rise in the output power. It is varies from design to design but typically with large turbines, it is done by adjusting the blade angles so as to maintain the power at the constant level.

Usually for water pumping windmills cut in speed is 2.5 m/s (about 9 km/hr). Similarly the cut in speed is required to rotate the blades for 600KW wind turbine is 4 m/s or 14.4 km/hr rated speed is 13 m/s and cut off speed is 25 m/s [Source Suzlon S52 600KW Wind turbine]. (FDV-1KW) 1kw Maglev Vertical Wind Turbine cut in speed
1.8m/s. rated wind speed 8m/s and cut out wind speed 45m/s
[source Wuxi Dayue International Trading Co., Ltd.]

Thus we have an approximate linear function that can be normalized in the range 0.0~1.0 with the following min-max normalization: Min-max normalization performs a linear transformation on the original data.

\[
W(V) = \frac{V - V_c}{V_{\text{rated}} - V_c} \quad \text{for } V_c < V < V_r
\]

(5.4)

\( Min. \) and \( max. \) are the minimum and maximum values of an attribute. A Min-max normalization maps a value, \( V \), of \( A \) to a value in the range [new-min, new-max]. Thus we have seen in equation (5.4) is useful to extract the mean annual energy output of a region where a region will have different mean hourly wind velocities throughout the year. The error due to the approximation of the above example performance curve (in figure 5.1) to piecewise linear model is negligible due to the fact that the area under the curve and that of the piecewise linear curve are approximately equal. Also the mean hourly wind velocities vary throughout the year resulting in the distribution of the performance of the windmills throughout the year. Windmills from most of the manufacturers have the performance characteristics that are nearly linear or linear unlike the one shown in figure 5.1. Performance of a windmill is the direct measure of the wind power output obtained from wind power density through averaging of wind speed is

\[
E_{\text{out}} = \frac{1}{2} \rho A V^3
\]

(5.5)

Where \( A \) is swept area of rotor in \( \text{m}^2 \), \( \rho \) is air density in \( \text{kg/m}^3 \).
However in practice the actual output from the windmill can be obtained by applying the following equation

\[ E_{out} = \frac{1}{2} \rho \varepsilon A Vr^3 \]  

(5.6)

Where: \( \varepsilon \) is conversion coefficient and is fixed for a particular windmill.[173]

It can be noticed that the conversion coefficient will add linear component to the cubic form of output.

### 5.2 Wind Speed Frequency Distribution (Weibull Distribution)

It is one of the most flexible distributions that can be used to represent various types of physical phenomena. It is important to know the number of hours per month or per year during which the given wind speeds occurred, i.e. the frequency distribution of the wind speeds. When the percentage frequency distribution (F%) is plotted against the wind, the frequency distribution emerges as a curve. The top of this curve being the most frequent wind speed. This frequency distribution is used also to identify the most suitable site for the wind turbine. The Weibull distribution (named after the Swedish physicist W. Weibull, who applied it when studying material strength in tension and fatigue in the 1930s) provides a close approximation to the probability laws of many natural phenomena. The probability that the wind velocity in a region exceeds \( V \) is given by

\[ P(V) = e^{-\left(\frac{V}{C}\right)^q} \]  

(5.7)

The corresponding probability density function is given by the Weibull distribution

\[ P(V) = \frac{q}{C} \left(\frac{V}{C}\right)^{q-1} e^{-\left(\frac{V}{C}\right)^q} \]  

(5.8)
Where: \( q \) and \( C \) are shape and scale factors respectively. There are several methods for deriving the values of \( q \) and \( C \). One of the methods described by me derive the values of \( q \) and \( C \) from

\[
V^n = C^n \Gamma \left[ 1 + \frac{n}{q} \right]
\]

(5.9)

Where \( \Gamma \) is Gamma function. Thus we have

\[
\frac{V^3}{\bar{V}^3} = \frac{\Gamma \left[ 1 + \frac{1}{q} \right]}{\Gamma \left[ 1 - \frac{3}{q} \right]} = \kappa
\]

(5.10)

\[
V = C \Gamma \left[ 1 + \frac{1}{q} \right]
\]

(5.11)

Energy pattern factor (EPF) is measured as the ratio given by the sums of cubes of the all individual hourly values considered in sample divided by the cubes of mean wind speed of the sample. Table 5.1 gives EPF for different stations.

The values of \( V \) and \( C \) can be found by trial and error method for generating values consistent with weibull distribution. As mentioned above, the Weibull distribution gives a good match with the experimental data. This is also mentioned in many references [152–159]. This distribution is characterized by two parameters: the shape parameter \( k \) (dimensionless) and scale parameter \( c \) (m/s). Recently Justus, Lysen, Darwish, Som, Jamil, Shabbaneh and Vogiatzis, references [152–159], have shown four different methods for the estimation of \( k \) and \( c \) parameters. The Weibull cumulative distribution function is written mathematically as
\[ F(v) = 1 - \exp \left[ -\left( \frac{v}{c} \right)^k \right] \]  

(5.12)

Where \( F(v) \) is the Weibull cumulative distribution function, \( V \) denotes the wind speed (m/s), \( k \) is the shape parameter and \( c \) is the scale parameter (m/s). \( T \) for time for one month. If we take 30 days per month we end up with the following equation, where the available mean power at 10 m per month is given by

\[ P_{\text{mo.}} = \frac{720}{1000} \frac{1}{2} \beta V^3 \text{ (kW/m}^2\text{ month)} \]  

(5.13)

However, for a height less than 100 m, to estimate the wind speed at any height \( h \) by using the wind speed at the standard height, recommended by the World Meteorological Organization (WMO), is 10 m above the ground level, Justus recommended the usage of the Hellman’s exponential law under two important conditions: the stability of the atmosphere and modest roughness of the site [160–164] as follows:

\[ V_h = V_{10} \left( \frac{h}{10} \right)^{-\alpha_r} \]  

(5.14)

Where \( \alpha_r \) is the roughness factor, this parameter is the wind speed power law index, which is considered to be 1/7 or 0.14, for surfaces with low roughness, as given by the one-seventh power law [155].

The value of the coefficient varies from less than 0.10 over the tops of steep hills to over 0.25 in sheltered locations [166]. Table 5.1 presents Energy Pattern Factor (EPF) for different stations.
Table 5.1 Annual average Wind Speed, EPF and Power Density [163].

<table>
<thead>
<tr>
<th>Year</th>
<th>Annual average wind speed</th>
<th>EPF</th>
<th>Power density</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>4.59</td>
<td>1.06</td>
<td>62.58</td>
</tr>
<tr>
<td>2007</td>
<td>5.28</td>
<td>1.09</td>
<td>98.06</td>
</tr>
<tr>
<td>2008</td>
<td>4.89</td>
<td>1.07</td>
<td>76.54</td>
</tr>
<tr>
<td>2009</td>
<td>5.28</td>
<td>1.22</td>
<td>109.37</td>
</tr>
</tbody>
</table>

In addition, the value of \( \alpha \) depends on the time of the day, the wind speed level, the wind stability and the surface roughness \((\alpha_r)\). This value varies from 0.10 to 0.40. In this analysis, \( \alpha \) is chosen to be 0.25 which presents a suitable value for Egyptian terrain and wind conditions.

Whereas, the effect of height on air density for the elevations under consideration is negligible, the power density of the wind above the ground level will be mainly affected by the increase in wind speed with height [164]. Therefore,

\[
P_h = P_{10} \left( \frac{h}{10} \right)^{3\alpha_r}
\]

(5.15)

5.3 PLANT LOAD FACTOR AND CAPACITY FACTOR

An important wind energy parameters is the plant load factor (PLF). This factor is used in determining the monthly and annual energy output of wind energy conversion system. The PLF is defined as the ratio between the actual power available in the wind and the
rated power of the WECS [165]. i.e.

\[
\text{PLF} = \frac{\text{Power available in wind}}{\text{Rated power for WECS}} = \frac{P_b}{P_r}
\]

(5.16)

5.4 ECONOMIC ANALYSIS

In this study the present value of money method has been used to estimate the cost of a kWh of energy produced by the chosen wind energy conversion system. In order to calculate the present value of costs (PVC) of electricity produced per year, following expression, given by Lysen and Habali is used in the present study under the following assumptions:

1. Investment includes the turbine price plus its 20% for the civil work and connection cables to the grid (I).
2. Operation, maintenance and repair cost was considered to be 25% of the annual cost of the turbine life time (Comr).
3. The interest rate (r) and inflation rate (i) were taken to be 15% and 12%, respectively (r and i).
4. Scrap value was taken to be 10% of the turbine price and civil work (S).
5. The lifetime of the machine was assumed to be 20 years.

The present value of costs (PVC) is:

\[
\text{PVC} = I + \text{Comr} \left[ \frac{1+i}{r-i} \right] \times \left[ 1 - \left( \frac{1+i}{1+r} \right)^t \right] - S \left( \frac{1+i}{1+r} \right)^t
\]

(5.17)
**Rated Power Output**

The power output from a windmill is directly proportional to the wind power density as specified in the following equation

\[ E_{\text{out}} = \frac{1}{2} \rho V^3 A \]  

(5.18)

is wind power density, the conversion coefficient \( \varepsilon \) called the Betz coefficient, decreases the actual power output \( E_{\text{out}} \). The theoretical maximum value of \( \varepsilon \) is 59.3% and it varies for different windmills. The Betz coefficient is available from performance characteristics due to the above equation can be written as

\[ W_R = \frac{1}{2} \rho V^{3_{\text{rated}}} \varepsilon A \]  

(5.19)

Where the rated power output \( W_R \) and nominal wind speed \( V_{\text{rated}} \) are known from characteristics curve. \( A \) is rotor swept area and \( \rho \) is air density of the region. It is clear from the equation (5.19) that the rated wind power is not the true output of a system for a given region with specific Weibull scale and shape factors. The mean annual output can be obtained by summing or integrating the outputs for different hourly mean wind speeds throughout the annual, each of these output depends on the performance or the actual output of the windmill at that wind velocity that is multiplies the normalized performance with the rated wind power. The final mean power at a mean wind speed \( V_m \) is the Normalized Performance Function power \( W(V) \) multiplied by the probability density distribution \( P(V) \) and summed (i.e. integrated) over all the range of wind speeds. Thus, the
mean power \( P_m(V_m) \) at a mean speed \( V_m \). We can thus extend the equation (5.19) as:

\[
E_{\text{out}} = \frac{1}{2} \rho A V_{\text{rated}}^3 \int_0^\infty P(V)W(V)dV
\]

(5.20)

**Capacity Factor:** Capacity Factor (CF) is the ratio of the actual energy produced in a given period, to the hypothetical maximum possible, i.e. running full time at rated power. Hence the capacity factor \( C_f \), is a very significant index of productivity of a wind turbine. It represents the fraction of the total energy delivered over a period, \( E_{\text{out}} \), divided by the maximum energy that could have been delivered if the turbine was used at maximum capacity over the entire period of \( 365 \times 24 \) hours one year, \( E_r = 8760 P_r \).

The capacity factor \( C_f \) of a wind turbine can be calculated as:

\[
C_f = \frac{E_{\text{out}}}{E_r}
\]

(5.21)

The total actual annual energy output is thus

As discussed above, the piece-wise linear function can be made to determine the value of capacity factor for a region. The reason is that the function \( P(V) \) is unalterable for a specific region and the wind-mill with appropriate wave function can be used to increase the CF in a typical wind farm.

In equation (5.5) enumerated for equation (5.4), decreasing the denominator \( V_{\text{rated}} - V_c \) will increase the overall power \( W(V) \) if there is an appropriate decrease in \( V_c \). In other words the wind mill with steeper ramp slope will yield higher throughput. For example the
values of $V_{\text{rated}}$, $V$ and $V_c$ are 11m/s, 10m/s and 4m/s respectively, if the value of $V_c$ decreases to 3m/s the power value increases as per the equation (5.3) from 0.857 to 0.875. The windmill with steeper ramp slope will yield higher throughput due to its slant value. In theory we can observe that the weibull and shape factor can be used to select windmill of specific performance function. For lower shape factors the probability of wind frequency distribution for lower wind speeds will be higher than that of the higher wind speed. In contrast, the probability of frequency distribution for higher wind speeds will be higher than that of the lower wind speed for moderate to higher shape factors for same scale factors. It thus follows that the windmill’s performance function parameters value should correlate with that of weibull distribution. Hence, for lower shape factor cut-in frequency has no effect on throughput. Higher scale factors (that is parameter C) is directly proportional to the average wind speed and is not considerable for selection of marginal windmill characteristics that is, cut-in and nominal wind speeds. Table 5.2 shows the comparison for three typical wind mill models’ (GE1.5sle, GE1.5s, SuzlonS64) characteristics functions. The cut-in ($V_c$) and rated wind speeds ($V_r$) are respectively (3, 4, 3) and correspondingly (14, 12, 12) as it is done by adjusting the blade angle so as to keep the power at the constant level [10]. The $q$ and $C$ values obtained by applying equations (5.3), (5.12) and (5.14) are found approximately equal to that of the one available in C-WET wind mill data sheets and is also listed. The CF achieved theoretically by applying equation (5.18) is correspondingly
listed for each windmill with given Vc and Vr. It can be noted that the
table justifies the equations described in above sections for the reason
that scale factor is scaling the throughput for any given windmill and
the CF is proportional to the parameter C. Also the lesser Vr – Vc
values, in general, yields higher CF and in particular the effect is
overridden by the lined q values as indicated by corresponding Vr – Vc
and CF columns.

Table 5.2 windmill characteristics functions

<table>
<thead>
<tr>
<th>S.No</th>
<th>Station</th>
<th>V</th>
<th>K</th>
<th>q</th>
<th>C</th>
<th>Vc</th>
<th>Vr</th>
<th>Vr - Vc</th>
<th>CF</th>
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<tbody>
<tr>
<td>1.</td>
<td>Kankora</td>
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<td>1.36</td>
<td>3.0</td>
<td>6.2</td>
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<td>3</td>
<td>12</td>
<td>9</td>
<td>0.29</td>
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<td>2.</td>
<td>Elephant Island</td>
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<td>14</td>
<td>11</td>
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<td>12</td>
<td>9</td>
<td>0.333</td>
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</tbody>
</table>

5.5 MODEL CALCULATIONS OF MODIFIED (SINGLE MOVING BLADE) VAWT

Power generated by the drag force is given by the formulae

\[ P = C_D \left( \frac{1}{2} \rho (V_w - V_r)^2 A V_r \right) \]  \hspace{1cm} (5.22)
Power generated by normal VAWT = \(1.1 \cdot \frac{1}{2} \rho (V_w - V_R)^2 AV_R\)  \hspace{1cm} (5.23)

Where: \(C_D\) on semicircular concave surface and convex surface are 2.3 and 1.2 respectively [167] and deference is 1.1.

\[A_{\text{convex}} = 0.40 \cdot A_{\text{concave}} \quad \text{(optimum area)}\] \hspace{1cm} (5.24)

Hence, Power generated by the drag force on concave surface,

\[P_{\text{concave}} = 2.3 \cdot \frac{1}{2} \rho (V_w - V_R)^2 V_R A_{\text{concave}}\] \hspace{1cm} (5.25)

Power generated by the drag force on convex surface,

\[P_{\text{convex}} = 1.2 \cdot \frac{1}{2} \rho (V_w - V_R)^2 V_R A_{\text{concave}} \cdot 0.40\] \hspace{1cm} (5.26)

\[P_{\text{convex}} = 0.48 \cdot \frac{1}{2} \rho (V_w - V_R)^2 V_R A_{\text{concave}}\] \hspace{1cm} (5.27)

Since the drag force on the convex side is opposing the concave side, net power generated from the Savonius rotor is

\[P = P_{\text{concave}} - P_{\text{convex}} = 1.82 \cdot \frac{1}{2} \rho (V_w - V_R)^2 V_R A_{\text{concave}}\] \hspace{1cm} (5.28)

\(C_D\) on semicircular concave surface and semicircular convex surface are 2.3 and 1.2 respectively.

Hence, Power generated by the drag force on concave surface, as per equation (4.2) is

\[P_{\text{concave}} = 2.3 \cdot \frac{1}{2} \rho (V_w - V_R)^2 AV_R\]

Power generated by the drag force on convex surface, as per equation (4.3) is

\[P_{\text{convex}} = 1.2 \cdot \frac{1}{2} \rho (V_w - V_R)^2 AV_R\]

Since the drag force on the convex side is opposing the concave side, net power generated from the Savonius rotor is
\[ P = P_{\text{concave}} - P_{\text{convex}} = 1.1 \times \frac{1}{2} \rho (V_w - V_r)^2 A V_r \]

Net power generated by conventional type savounius rotor is

\[ P = P_{\text{concave}} - P_{\text{convex}} = 1.1 \times \frac{1}{2} \rho (V_w - V_r)^2 V_r A_{\text{concave}} \]  
(5.29)

Increase in power \[ \frac{1.82 - 1.1}{1.1} = 0.65 \]  
(5.30)

From the above calculations, it is derived that the moving blade design has better efficiency than the general Savonius turbine design. It was proved that power factor of VAWT without moving blades is 29. Hence, theoretically, power factor of VAWT with moving blades design will be 29 x 1.65 = 47.85 %

5.6 MODEL CALCULATION FOR SAVONIUS MULTIPLE MOVING BLADE (AIRFOILS) WIND TURBINE

The power generated from drag force is given by formulae [167].

\[ P = C_D \frac{1}{2} \rho (V_w - V_r)^2 A V_r \]  
(5.31)

The power generated from drag force in the direction of wind

\[ P_1 = C_D \frac{1}{2} \rho (V_w - V_r)^2 A_1 V_r \]  
(5.32)

\[ = 2.3 \frac{1}{2} \rho (V_w - V_r)^2 A_1 V_r \]  
(5.33)

Power generated from drag force in the direction of opposite to wind

\[ P_2 = C_D \frac{1}{2} \rho (V_w - V_r)^2 A_2 V_r \]  
(5.34)

\[ = 1.2 \frac{1}{2} \rho (V_w - V_r)^2 A_2 V_r \]  
(5.35)

Net force generated is
\[ P_n = P_1 - P_2 = 1.1 \left( \frac{1}{2} \right) \rho (V_w - V_r)^2 A_1 V_r \quad (A_1 = A_2) \]

Which is very less this is a major drawback of this model turbine, so to increase its efficiency by changing rotor shape.

The power generated from drag force is given by formulae

\[ P = C_D \frac{1}{2} \rho (V_w - V_r)^2 A V_r \quad (5.36) \]

The power generated from drag force in the direction of wind (convex side)

\[ P_1 = C_D \frac{1}{2} \rho (V_w - V_r)^2 A_1 V_r \quad (5.37) \]

\[ = 2.3 \frac{1}{2} \rho (V_w - V_r)^2 A_1 V_r \quad (5.38) \]

power generated from drag force in the direction opposite to wind (concave side)

\[ P_2 = C_D \frac{1}{2} \rho (V_w - V_r)^2 A_2 V_r \quad (5.39) \]

\[ = 1.2 \frac{1}{2} \rho (V_w - V_r)^2 (0.25 A_1) V_r \quad (5.40) \]

\[ = 0.3 \frac{1}{2} \rho (V_w - V_r)^2 A_1 V_r \quad (5.41) \]

The area on the opposing side is reduced by 75% by providing movable blades

\[ \therefore A_2 = 0.25 A_1 \quad (5.42) \]

Finally the resultant drag power generated from Savonius turbine

\[ P_m = P_1 - P_2 \quad (5.43) \]
\[ P = P_{\text{concave}} - P_{\text{convex}} \]
\[ = 2.3 \left( \frac{1}{2} \rho (V_w - V_r)^2 A_1 V_r \right) - 0.3 \left( \frac{1}{2} \rho (V_w - V_r)^2 A_1 V_r \right) \]
\[ \approx 2 \left( \frac{1}{2} \rho (V_w - V_r)^2 A_1 V_r \right) \] (5.44)

\[ P_m = 2 \left( \frac{1}{2} \rho (V_w - V_r)^2 A_1 V_r \right) \] (5.45)

Net power generated by conventional type savounius rotor is

\[ P = P_{\text{concave}} - P_{\text{convex}} = 1.1 \frac{1}{2} \rho (V_w - V_r)^2 V_r A_{\text{concave}} \] (5.46)

Increase in power \[ = \frac{2 - 1.1}{1.1} = 0.818 \] (5.47)

Where \( V_w \) is speed of wind and \( V_r \) is relative speed.

From the above calculations, it is derived that movable blade design has better efficiency than the existing fixed blade design. Hence, theoretically, \( \text{Cp of VAWT with moving blades design} \) will be \( 29 \times 1.818 = 52.72\% \). From the above calculations it is found that movable blade design is more efficient than the existing fixed blade design.