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# Sixth Order Model of Wind Turbine Voltage Flicker Taking Into Account Impact of Vertical Wind Shear

**Datta. S. Chavan[a] Jaywant Sankpal[b] Anupama Singh[c] Divya Parashar[d] Shital Gaikwad[c] Vivek Saahil[c] P.B. Karandikar[c] and Himanshu[c]**

[a] *Bharati Vidyapeeth Deemed University, College of Engineering, Pune, India.*
[b] *G H Raisoni College Of Engineering & Management, Pune, India*
[c] *MAEER's Maharashtra institute of Technology, Pune, India*
[c] *Army institute of Technology, Pune India*

***Abstract :*** Various flicker models are developed by researchers. Each model has its own drawback. In this model various order models are compared. The models consist of various wind turbine parameters like number of wind turbine blades, wind turbine blade length and wind turbine blade width. Sixth order model is most suitable for wind turbine voltage flicker.

***Keywords :*** *Voltage Flicker; vertical wind shear; wind turbine; wind energy.*

## 1. CURVE FITTING

In curve fitting a curve can be constructed. That curve is best fitted to a series of data points. In curve fitting mathematical function can also be formed. In curve fitting interpolation is used. In interpolation exact fit to data is required. In curve fitting smoothing also be used. In smoothing smooth function is used. In smooth function data is fitted approximately. Sometimes regression analysis is also used. In regression analysis uncertainty of fitting the curve with data is found. Fitted curve is useful in finding the missing data. With fitted curve relation between two variables can be found. In extrapolation fitted curve is used to find the data beyond range of observed data.

Mark E Weber studied the radars used for ground based wind shear. Wind shear with low altitude consisting of thunder storm outflow hampers the operation of the airplane severely while take off and landing. Doppler weather radars are installed at airport to provide wind data to the pilot. These Doppler radars detect wind shear and protects airplane. He provided comparative analysis of radar with various points like radar sensitivity, ground clutter, rejection capability etc. [13]

Xue Zhu LV studied impact of vertical wind shear on hurricane eye. Powerful winds are generated by tropical cyclones. Torrential rainfall is also caused by tropical cyclones. Prediction of cyclone is also significant task for meteorologists. Hurricane eyes are normally circular on satellite images. [15]

Q Jin computed availability of wind farm taking into account impact of vertical wind shear. He studied wind speed distribution. He computed the wind speed at 60 m using power law. He used least square method, modified methods to compute wind parameters. Wind speed changes with height because of friction of surface. [18]

K Reddondo studied the measurement of flicker in wind turbines. He used digital differentiation for voltage flicker measurement. He used hogh rate of sampling. The he performed analysis using simulated waveforms and field measurement in Spain. The frequency response of digital differentiation is important in computing voltage flicker. [21]

J.J. Gutierrez studied voltage flicker measurement for wind generation system. He developed a system to assess voltage flicker. His research is useful in certification of wind turbines. In his voltage flicker measurement system there are two modules. The first module is a signal register in which established voltage and current series according to wind speed is stored. The second module processes the stored series in comparison with standard data. The equipment developed by him can store data of three phases [1]

H Kasem developed a voltage flicker minimization technique in doubly fed induction generator wind energy system using reactive current management. Due to voltage variation in wind turbines there is a limitation in connection of wind power to the grid. Ali H Kasem developed a voltage flicker reduction algorithm. In the algorithm optimal reactive current flow is used. The modeling of wind turbine system is done in Matlab. Kasem considered the losses occurred due to reactive power flow in his flicker mitigation system. He developed a mathematical equation for reactive current of rotor. It is used to reduce the losses of doubly fed induction generator under various conditions of power factor. [24]

## 2. FITTING OTHER CURVES TO DATA POINTS

A range of curves is used. The curve may be elliptical, hyperbolic and circular. Sometimes trigonometric functions are utilized as well. In trigonometric function sine and cosine function may be used. For trajectories of objects, parabolic curve can be used. For tidal data, sine wave may also be used. Sometimes addition of two sine waves may be utilized to consider sun and moon effect.

## 3. VARIOUS MODELS FOR WIND ENERGY

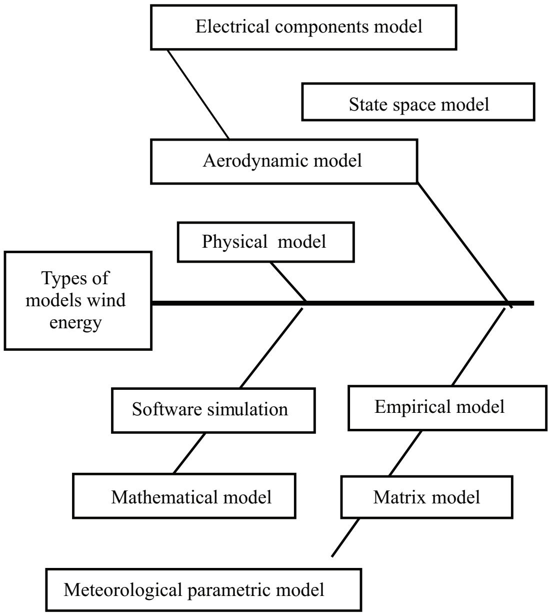

**Figure 1: Various of models of wind energy**

Various types of models can be developed for wind generation system. Fig. 1 gives various types of models that can be developed for wind energy. In this paper empirical model of voltage flicker initiated in a wind turbine is developed.

Fig. 1 gives various models of wind energy. Physical model most commonly referred to simply as a model is a smaller or larger physical copy of an object. The object being modeled may be small (for example, an atom) or large (for example, the Solar System).

Aerodynamic model of wind turbine can be developed. Aerodynamics is a branch of dynamics concerned with studying the motion of air, particularly when it interacts with a solid object, such as an airplane wing. Aerodynamics is a sub-field of fluid dynamics and gas dynamics, and many aspects of aerodynamics theory are common to these fields. The term aerodynamics is often used synonymously with gas dynamics, with the difference being that "gas dynamics" applies to the study of the motion of all gases, not limited to air.

In models using electrical components, model of generators, transformers and transmission lines can be developed using elements like resistors, inductors and capacitors. In wind energy system model of wind generator can be developed. Models of squirrel cage induction generator, slip ring induction generator and permanent magnet synchronous generator can be developed.

Software simulation models can be developed in various software like Matlab, PSCAD andEtap etc. Complete wind energy system can be simulated in a software. By changing various parameters system can be studied.

Meteorological model are developed using meteorological parameters like wind speed turbulence intensity etc. In this research impact of vertical wind shear on voltage flicker initiated in wind turbine is studied.

Empirical modeling refers to any kind of modeling based on empirical observations rather than on mathematically describable relationships of the system modeled. In this research , empirical model of voltage flicker is developed.

A mathematical model is a description of a system using mathematical concepts. The process of developing a mathematical model is termed mathematical modeling. Mathematical models are used not only in the natural sciences such as physics, biology, earth science, meteorology and engineering disciplines like computer science, artificial intelligence, but also in the social sciences like economics, psychology, sociology and political science. Physicists, engineers, statisticians, operations research analysts and economists use mathematical models most extensively. A model may help to explain a system and to study the effects of different components, and to make predictions about behavior

In control engineering, a state-space representation is a mathematical model of a physical system as a set of input, output and state variables related by first-order differential equations. "State space" refers to the space whose axes are the state variables. The state of the system can be represented as a vector within that space.

Sometimes matrix models are also developed. In mathematics, a matrix is a rectangular array of numbers, symbols, or expressions, arranged in rows and columns. The individual items in a matrix are called its elements or entries

## 4. ASSUMPTIONS MADE WHILE PROPOSING VOLTAGE FLICKER MODELS

This section gives various assumptions made during development of the models of voltage flicker initiated in a wind turbine due to vertical wind shear

1. The tower considered is a tubular tower as for larger turbines lattice tower is not favored. Even for lattice tower 3 $p$ effect will be dissimilar than tubular

2. Wind turbine considered is of large size ranging from 1 MW to 7 MW.
3. Wind speed ricocheted is in between cut in and cut out speed. Normally cut in speed is 3 m/s, cut out speed is 25 m/s and rated speed is 11 m/s. Wind turbines operate in this speed range and are connected to grid.
4. Turbine is upwind turbine. Majority of the turbines are upwind turbines and downwind turbines are rarely used.

## 5. PROPOSED SIXTH ORDER MODEL OF VOLTAGE FLICKER IN WIND TURBINE

Equation 1 is a proposed six order equation.

$$P_s = V_{shr}^{6} - B\,V_{shr}^{5} + C\,V_{shr}^{4} - D\,V_{shr}^{3} + E\,V_{shr}^{2} - F\,V_{shr} + G \quad (1)$$

Table 1 gives look up table for proposed sixth order model. The values in the look up table are found from the experiment on the wind turbine in a laboratory test set up.

**Table 1**
**Look up table for proposed sixth order model**

| *Constant* | *Value* |
|---|---|
| A | 0.054 |
| B | 1.703 |
| C | 21.835 |
| D | 146.18 |
| E | 538.61 |
| F | 1034 |
| G | 809.02 |

Fig. 2 gives comparison of curve fitting model of voltage flicker and proposed sixth order model. The model is represented by a dotted line. Sixth order model is represented by a continuous line.

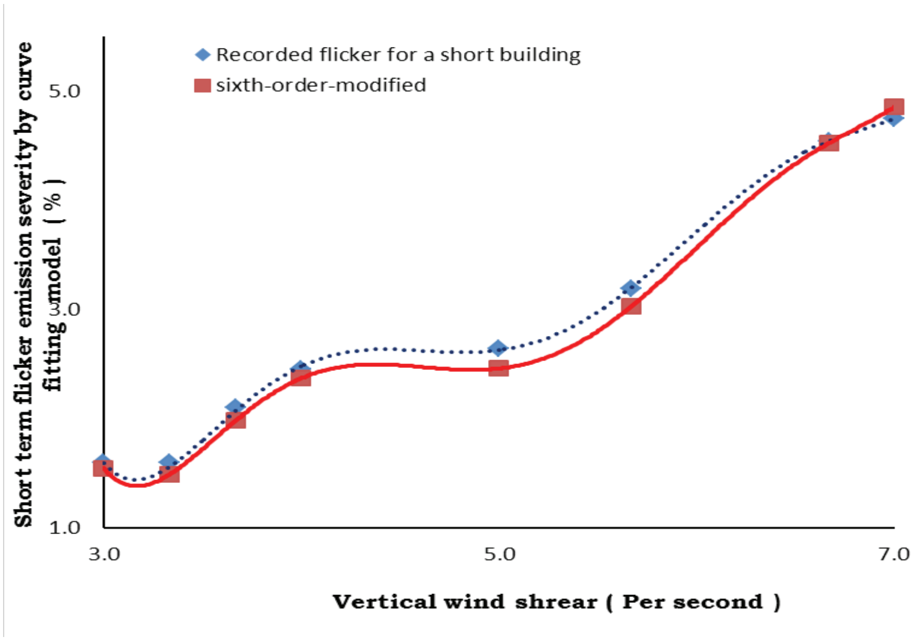

**Figure 2: Sixth order model or hexic model or sextic model**

## 6. PROPOSED SIXTH ORDER MODELS FOR DIFFERENT NUMBER OF BLADES

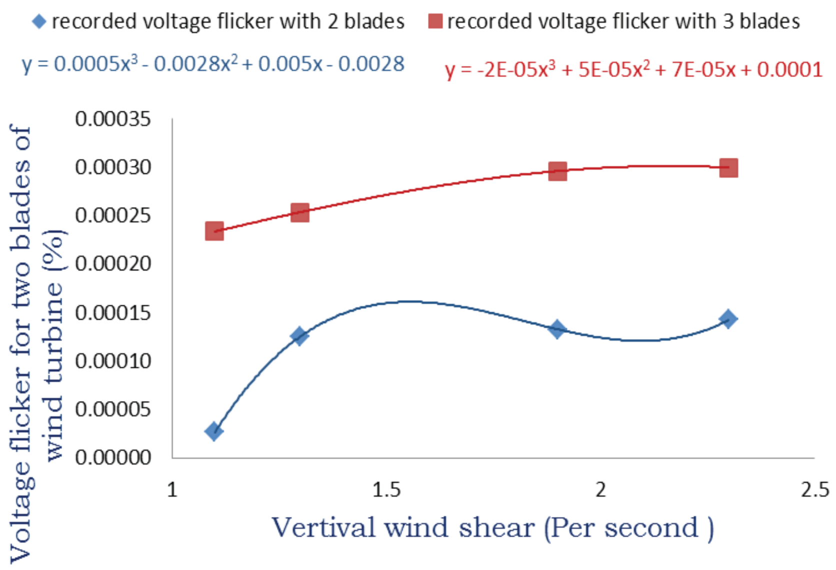

**Figure 3: Comparison of flicker initiated by different number blades of wind turbine**

In the fig. 3 impact of number of blades on flicker initiated in wind turbine is represented. For three blades the flicker produced is higher than two bladed wind turbines. In three bladed wind turbine because of 3p effect the flicker produced is more. As in three bladed wind turbine there is a three time jerk to the blades in one revolution. One jerk for each blade, in one revolution is produced when, the blade coincides with the tower.

**Table 2**
**Equations For Sixth Order Flicker Model For Different Number Of Blades**

| *Number of blades* | *Equations by curve fitting for different wind turbine blades* |
|---|---|
| 2 | *y* = -0.0002x4 + 0.0021x3 - 0.0067x2 + 0.009x - 0.0043 |
| 3 | *y* = -4E-05x4 + 0.0003x3 - 0.0008x2 + 0.0009x - 8E-05 |

**Table 3**
**Constant in sixth order flicker model for different number of blades**

| *Constants* | *Order of Vshr* | *Number of blades of wind turbine* | |
|---|---|---|---|
| | | 2 | 3 |
| A | 6 | 0 | 0 |
| B | 5 | 0 | 0 |
| C | 4 | -0.0002 | -4E-05 |
| D | 3 | + 0.0021 | + 0.0003 |
| E | 2 | - 0.0067 | - 0.0008 |
| F | 1 | + 0.009 | + 0.0009 |
| G | 0 | - 0.0043 | - 8E-05 |

## 7. PROPOSED SIXTH ORDER MODELS FOR DIFFERENT BLADE MATERIAL

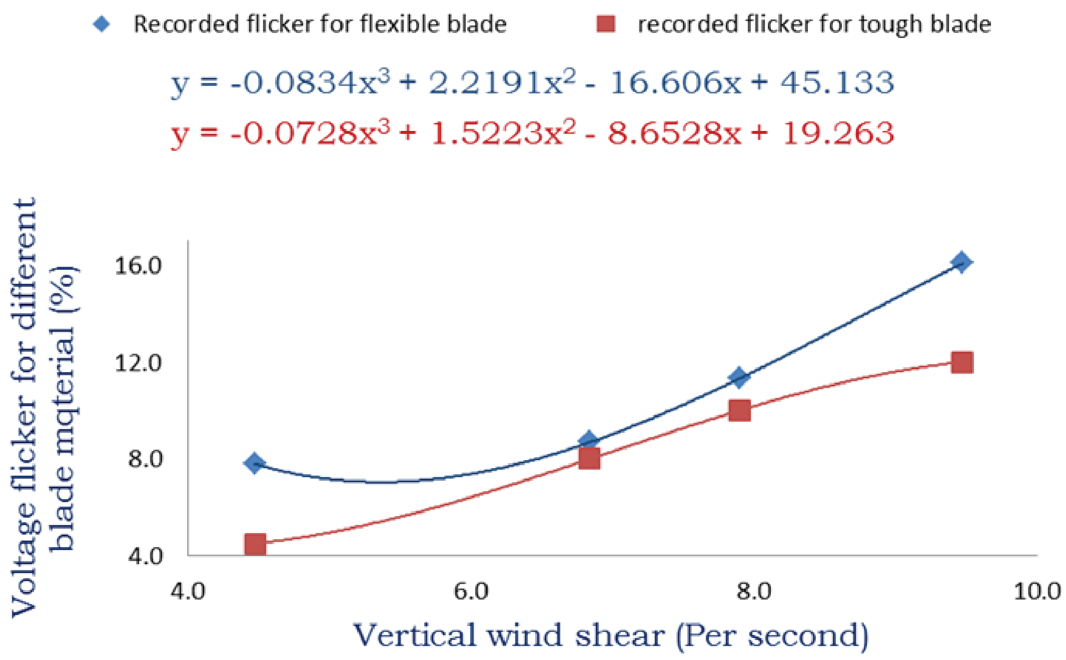

**Figure 4 : Comparison of flicker initiated by different blade materials**

**Table 4**
**Equations for sixth order flicker model for different blade materials**

| *Blade material* | *Equations by curve fitting for different blade materials* |
|---|---|
| Flexible | $y = -0.0834x^3 + 2.2191x^2 - 16.606x + 45.133$ |
| Tough | $y = -0.0728x^3 + 1.5223x^2 - 8.6528x + 19.263$ |

**Table 5**
**Constant in sixth order flicker model for different blade materials**

| *Constants* | *Order of vshr* | *Blade material of wind turbine model* | |
|---|---|---|---|
| | | Flexible | Tough |
| A | 6 | 0 | 0 |
| B | 5 | 0 | 0 |
| C | 4 | 0 | 0 |
| D | 3 | - 0.0834 | - 0.0728 |
| E | 2 | 2.2191 | 1.5223 |
| F | 1 | - 16.606 | - 8.6528 |
| G | 0 | 45.133 | 19.263 |

## 8. PROPOSED SIXTH ORDER MODELS FOR DIFFERENT BLADE LENGTHS

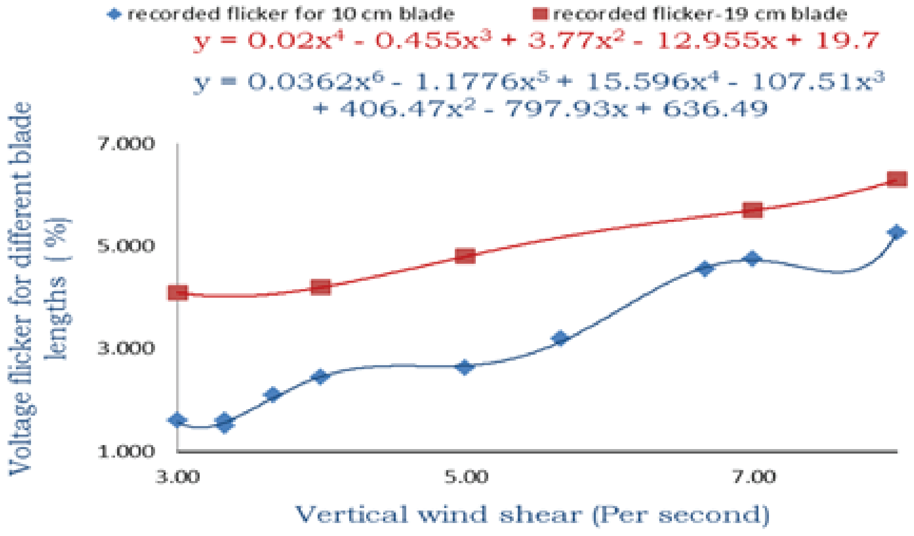

**Figure 5: Comparison of flicker initiated by different blade length**

**Table 6**
**Equations For Sixth Order Flicker Model For Different Blade Length**

| *Blade length* | *Equations by curve fitting for different blade lengths* |
|---|---|
| 10 | $y = 0.0362x^6 - 1.1776x^5 + 15.596x^4 - 107.51x^3 + 406.47x^2 - 797.93x + 636.49$ |
| 19 | $y = 0.02x^4 - 0.455x^3 + 3.77x^2 - 12.955x + 19.7$ |

**Tabe 7**
**Constant In Sixth Order Flicker Model For Different Blade Lengths**

| *Constants* | *Order of Vshr* | *Blade length of wind turbine model* | |
|---|---|---|---|
| | | 10 cm | 19 cm |
| A | 6 | 0.0362 | 0 |
| B | 5 | - 1.1776 | 0 |
| C | 4 | + 15.596 | 0.02 |
| D | 3 | - 107.51 | - 0.455 |
| E | 2 | + 406.47 | 3.77 |
| F | 1 | - 797.93 | - 12.955 |
| G | 0 | + 636.49 | + 19.7 |

## 9. PROPOSED SIXTH ORDER MODELS FOR DIFFERENT BLADE WIDTH

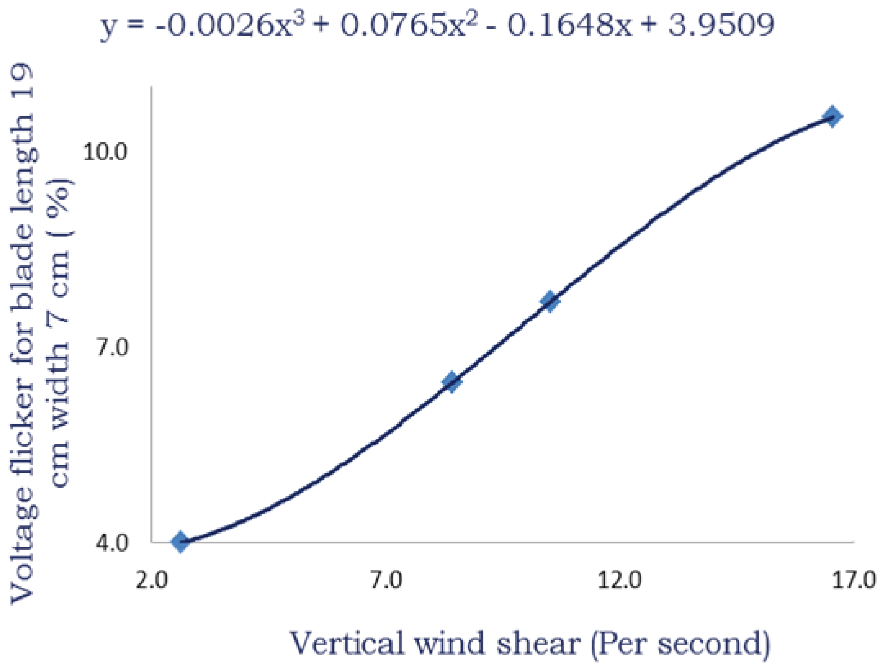

**Figure 6: Vertical wind shear for blade length 19 cm width 7 cm**

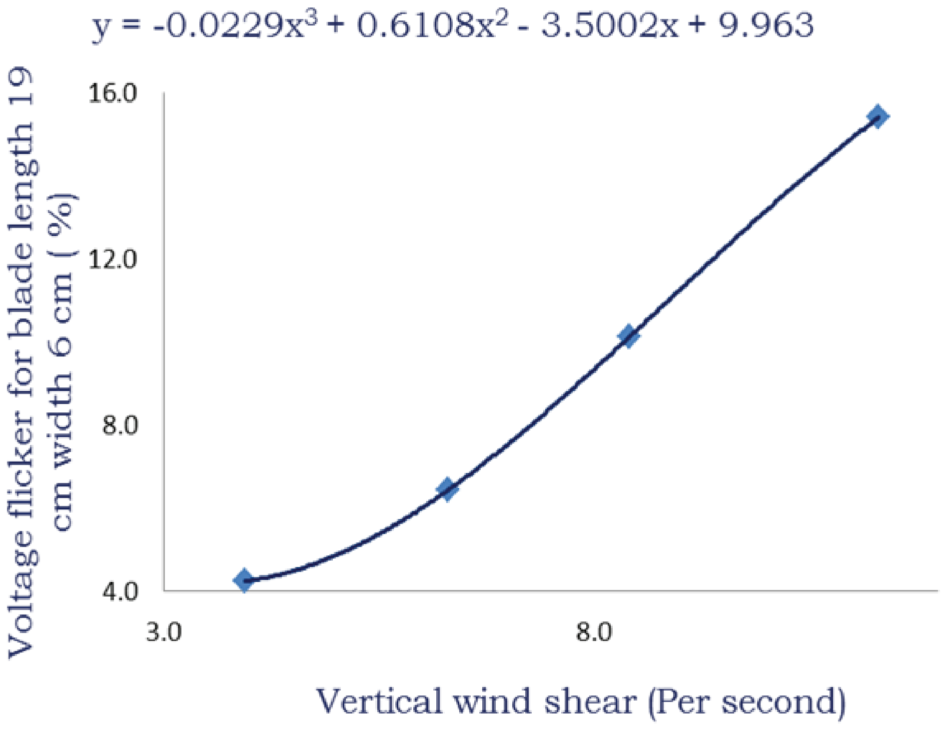

**Figure 7: Vertical wind shear for blade length 19 cm width 6 cm**

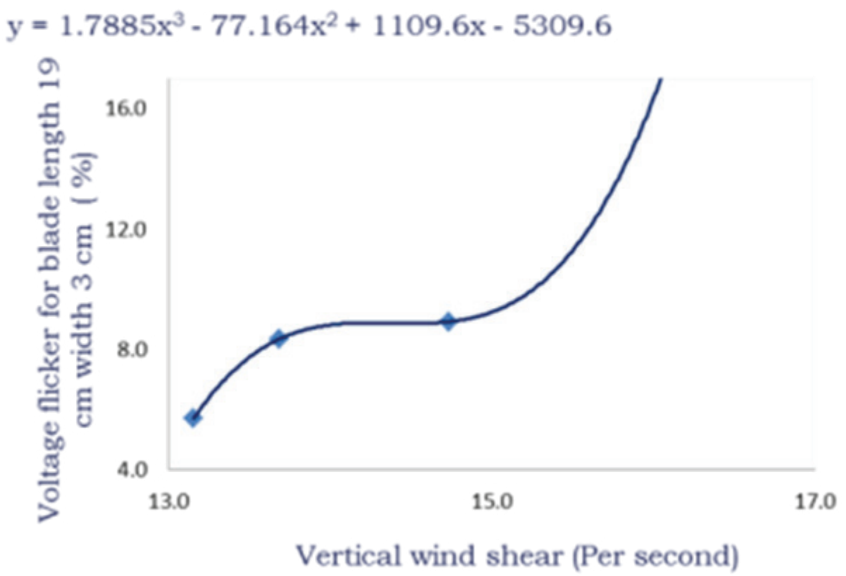

**Figure 8: Vertical wind shear for blade length 19 cm width 3 cm**

**Table 8**
**Sixth Order Equations For Different Chord Lengths I.e. Width Of Blades**

| *Blade width (cm)* | *Equations for different blade width. Blade length 19 cm* |
|---|---|
| 7 | $y = -0.0026x^3 + 0.0765x^2 - 0.1648x + 3.9509$ |
| 6 | $y = -0.0229x^3 + 0.6108x^2 - 3.5002x + 9.963$ |
| 3 | $y = 1.7885x^3 - 77.164x^2 + 1109.6x - 5309.6$ |

**Table 9**
**Constant in Sixth Order Flicker Model For Different Chord Lengths *i.e.* Width of Blades**

| *Constants* | *Order of vshr* | *Fixed blade length 19 cm, Blade width as given below* | | |
|---|---|---|---|---|
| | | 7 cm | 6 cm | 3 cm |
| A | 6 | 0 | 0 | 0 |
| B | 5 | 0 | 0 | 0 |
| C | 4 | 0 | 0 | 0 |
| D | 3 | - 0.0026 | 0.0229 | 1.7885 |
| E | 2 | + 0.0765 | + 0.6108 | - 77.164 |
| F | 1 | - 0.1648 | - 3.5002 | + 1109.6 |
| G | 0 | + 3.9509 | + 9.963 | - 5309.6 |

**Table 10**
**Comparison Of Constants Of Sixth Order Equations For Various Parameters of Wind Energy**

| | *Constants* | *A* | *B* | *C* | *D* | *E* | *F* | *G* |
|---|---|---|---|---|---|---|---|---|
| Parameters | | | | | | | | |
| Blade length | 10 cm | 0.03 | - 1.17 | 15.59 | - 107 | 406.4 | - 797 | 636.4 |
| | 19 cm | 0 | 0 | 0.02 | - 0.45 | 3.77 | - 12.9 | 19.7 |
| Blade width | 7 cm | 0 | 0 | 0 | - 0.00 | 0.07 | - 0.16 | 3.95 |
| | 6 cm | 0 | 0 | 0 | 0.02 | 0.61 | - 3.50 | 9.963 |
| | 3 cm | 0 | 0 | 0 | 1.78 | - 77.1 | 1109 | - 5309 |
| Number of blades | 2 | 0 | 0 | -0.0 | + 0.00 | - 0.00 | 0.0 | - 0.00 |
| Number of blades | 3 | 0 | 0 | -0.00 | + 0.0 | - 0.00 | 0.0 | - 0.00 |
| Type Of Blade | Flexible | 0 | 0 | 0 | - 0.0 | 2.21 | - 16 | 45.1 |
| | tough | 0 | 0 | 0 | - 0.0 | 1.52 | - 8.65 | 19.2 |

## 10. BOUNDARY CONDITIONS OF THE PROPOSED EMPIRICAL MODELS

In this section various boundary conditions of the voltage flicker models developed are given. These developed models are for horizontal axis upwind turbine.

1. Useful for horizontal axis wind turbine, as vertical axis wind turbine is installed at a ground level and there is no question of tower height.
2. Suitable for three bladed turbines. Experiment is carried out on three bladed wind turbines as most of the turbines have three blades. Two blade turbines are rarely used.
3. Suitable for fixed speed wind turbine. In variable speed wind turbine normally doubly fed induction generator along with convertor is incorporated. Most of the power quality issues are dealt over there but harmonics are initiated in the system because of electronic power devices.
4. Suitable for large wind turbines with longer blades. For smaller blades the wind speed on each blade is almost equal and wind shear effect is less.

In this section various boundary conditions of voltage flicker models are given.

Sixth order model is the best suited model. Assumptions during development of model and boundary conditions of developed voltage flicker model.

**Table 11**
**Sixth Order Model of Voltage Flicker**

| *Type of Voltage flicker Model* | *Constant* | *Mathematical model* |
|---|---|---|
| Curve fitting | With constant | $\mathrm{Pst} = 0.0544\ \mathrm{Vshr}^6 - 1.7039\ \mathrm{Vshr}^5 + 21.835\ \mathrm{Vshr}^4 - 146.18\ \mathrm{Vshr}^3 + 538.61\ \mathrm{Vshr}^2 - 1034\ \mathrm{Vshr} + 809.02$ |

In the fig. 9 graphs of voltage flicker verses vertical wind shear for various order models are given. The curve fitting sixth order model is shown by dotted lines. Curve fitting model is the best fitted model.

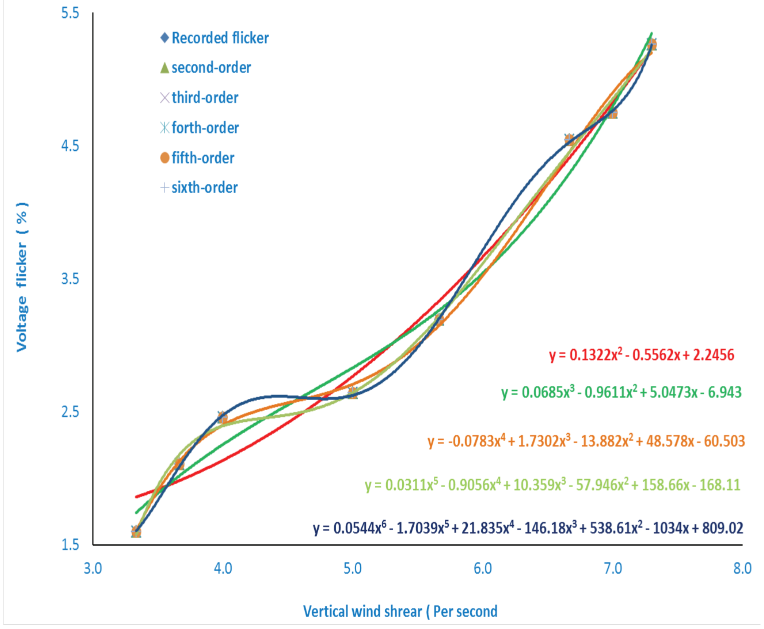

**Figure 9: Comparison of various order graphs with sixth order graph**

The graph of second order, third, fourth order, fifth order and sixth order are given. The sixth order model is the best fitted model. The models are obtained by curve fitting technique. The equations of the graphs re also obtained.

From the recorded RMS voltage, average voltage is computed. The change in the voltage is computed as well. The ratio of change in the voltage to the average voltage is multiplied by hundred to get percentage voltage flicker.

Table 12 shows sample calculation for computation of vertical wind shear from recorded values of wind speed at the top and bottom sided blade of the wind turbine.

**Table 2**
**Computation Of Vertical Wind Shear**

| *Speed at top sided blade of wind turbine (m/s)* | *Speed at bottom sided blade of wind turbine (m/s)* | *Average wind speed (m/s) Refer equation 4.1* | *Change in the wind speed Refer equation 4.2* | *Vertical wind shear (per second) Refer equation 4.3* |
|---|---|---|---|---|
| 6.8 | 5.9 | 6.35 | 0.9 | 3.0 |
| 5.4 | 4.4 | 4.9 | 1.0 | 3.3 |
| 6.6 | 5.6 | 6.1 | 1.0 | 3.3 |
| 5.3 | 4.2 | 4.75 | 1.1 | 3.7 |

## 11. CONCLUSIONS

In this paper various models are developed. Second order, third order, forth order, fifth order and sixth order model of flicker are developed. Out of these models sixth order models is the best suited model for computation of flicker.

## 12. ACKNOWLEDGMENT

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