# Cosine Model of Flicker Due to Vertical Wind Shear in a Wind Turbine Sited on a Building

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## Abstract

*Abstract* – “The global demand for wind power generation is increasing primarily because there are no $CO_2$ emissions. However harvesting the wind to generate electricity does present technical challenges. For example, vertical wind shear induces flicker in the output voltage of the wind turbine. This paper discusses the factors affecting the flicker. It also presents an analytical model to predict flicker that is based on turbine blade length and tower height. The model is based on a three bladed vertical axis upwind wind turbine

**Key words** :Flicker, shear, turbine, wind.

## 1. Introduction

In this section the work done by the previous researchers is described. Random or repetitive variations in the RMS voltage between 90 and 110% of nominal can produce a phenomenon known as "flicker" in lighting equipment. Wind turbine causes flicker in the output voltage. In the second section flicker emission severity is explained. In the third section linear model of flicker is developed. In the fourth section validation of the model is provided.

Horizontal wind shear affects flicker emission severity. But vertical wind shear has considerable impact on flicker emission severity which is observed while conducting trials on the wind turbine. Models are developed for a flicker produced in a wind generator under continuous operation of the wind turbine [1]. In some models short circuit ratio, flicker coefficient and grid impedance angle are considered for computation of flicker. Specific impact of vertical wind shear is considered in those models. In this paper impact of vertical wind shear on flicker emission is studied. Earlier researchers have given graphs of power versus wind speed for a pitch controlled wind turbine and stall regulated wind turbine. Flicker produced in doubly fed induction generator is studied by researchers [2]. PSCAD is used by them for development of the model of flicker. They developed a wind turbine model with double fed induction generator. They considered a vector control scheme for the doubly fed induction generator. Short circuit capacity ratio and grid impedance angle is considered by them for development of the model. Graph of short term flicker emission severity verses average wind speed is provided by them. Some researchers presented a direct method [3] to obtain a short term flicker emission severity by digital meter. Flicker propagated in grid by fixed speed wind turbine is studied in their paper. They developed with a case study of wind farm connected a three node network. In this paper flicker model is Fig.1 wind turbine mounted on a building developed with help of a wind tunnel. Validity of standard method [4] for computation of flicker is presented by some researchers. They considered fixed speed as well as variable speed wind turbine. They have dealt with standard method of computation of flicker and flicker type test. Site specific flicker is computed by them. Offshore wind farm is considered for their study. Some researchers developed a system for improving the power quality of wind turbine using ultra capacitors. Various power quality parameters [9] are given by some researchers. Various methods to measure flicker emission severity are also deliberated. Concept of short term flicker emission severity and long term flicker emission severity is presented as well. Generation of wind energy [5] is demonstrated by some resarchers. Impact of vertical wind shear on wind energy output is tudied by some researcher considering entire wind farm. Short term and long term flicker emission severity is also discussed by them. But in that paper blade lengh and tower height are not incorporated in the model developed by them. Ake Larsson [1] studied the power quality of the wind turbine. He studied the flicker produced from the wind turbine.

## 2. Flicker in Wind Turbines.

Flicker is caused by various reasons. Table I gives some reasons due to which flicker can occur.

TABLE I CAUSES OF FLICKER

| |
|---|
| Flicker due to continuous operation.<br>Vertical wind shear.<br>Horizontal wind shear.<br>Turbulence intensity.<br>Tower shadow effect.<br>Wake effect.<br>Wind gust. |
| Flicker due to switching operation.<br>Start up of generators of wind turbines.<br>Switching in and out of generators as wind speed cross cut in and cut out speed boundary.<br>Transition of winding in case of two speed, duel winding generators, from low speed winding, for lower wind speed to high speed winding for high speeds.<br>Switching of capacitor banks. |

## 3. Cosine Model to Compute Flicker

Short term flicker emission severity can be computed by the ratio of change in the output voltage to the average voltage expressed as percentage of the voltage. [9]

$$P_{st} = \frac{\begin{matrix}\text{Change in the output voltage} \\ \text{of the wind generator}\end{matrix}}{\begin{matrix}\text{Average output voltage} \\ \text{of the wind generator}\end{matrix}} \text{X } 100 \tag{1}$$

Short term flicker emission severity can be written in the abbreviation form as follows [9].

$$P_{st} = \frac{V_{max} - V_{min}}{\left(\frac{V_{max} + V_{min}}{2}\right)} \text{X } 100 \tag{2}$$

Further, simplifying the equation 2 above.

$$P_{st} = \frac{2(V_{max} - V_{min})}{V_{max} + V_{min}} \text{X } 100 \tag{3}$$

$$P_t = \frac{1}{2} A \rho V^3 C_p \tag{4}$$

Power generated by the wind turbine is given b equation (4). In equation (4) Pt is the power generated by wind turbine. A is the swept area of the wind turbine, ($m^2$), V is incoming wind speed (m/s), ρ is air mass density or mass per unit volume of earth's atmosphere (kg /$m^3$), $C_p$ is power coefficient which is the ratio of power extracted by the turbine $P_T$ to the total power contained in the wind resource $P_W$, The Betz limit is the maximum possible $C_p$ = 16/27. In order to increase the power generated by wind turbine the blade length is increased according to equation (4)

Now consider impact of area of the side of the building $A_b$on which turbine is sited. Short term Flicker emission severity increases with area of side of the building facing wind on which the turbine is mounted. If area of the building facing the wind is increased, it provides more obstruction to the wind. So the vertical wind shear is increased. Consequently the flicker in the output of the turbine is increased.

$$P_{st} \, \alpha \, A \tag{5}$$

Further impact of blade length of the wind turbine $B_L$ is discussed. In order to capture more energy from wind the turbine blade length is increased. Range of blade length is 10 m to 80 m. A is swept area of the wind turbine. Swept area is depends on the length of the turbine blade. If the length of the turbine blade is more the swept area is more and consequently the power generated by is turbine is increased. But with increase in the turbine blade length the voltage flicker initiated by wind turbine due to vertical wind shear is increased.

Short term Flicker emission severity increases with wind turbine blade length. If the blade length is more, then the magnitude of vibration of is more. Consequently the flicker emission severity in the output of the wind turbine is increased.

$$P_{st} \propto B_L \tag{6}$$

If we consider only one blade the effect of length of other blade is not considered, so the blade length is doubled to take into account effect of both the blades if there are two blades. In case of three blade turbine, diameter of the turbine can be considered or it approximated to twice the blade length.

$$P_{st} \propto 2B_L \tag{7}$$

Further, impact of tower height $T_h$ is depicted. In order to capture more energy from wind, the tower height is increased. Range of tower height is 50 m to 170 m. Short term Flicker emission severity decreases with height of the tower on which the turbine is mounted. If the tower height is increased, the turbine location moves away from the ground. If the distance of the turbine from the ground is increased, the vertical wind shear is reduced. The vertical wind shear reduced with height from the ground. If the vertical wind shear is reduced the flicker emission severity is also decreased. Consequently if the tower height is increased, the flicker emission severity is decreased.

$$P_{st} \propto \frac{1}{T_h} \tag{8}$$

Here impact of building height $B_h$ is echoed. Some turbines are erected on a building. Short term Flicker emission severity decreases with height of the building on which the turbine is sited. Vertical wind shear decreases with building height on which turbine is sited. If the vertical wind shear is decreased, the flicker emission severity is decreased. Consequently, if the building height is increased, the short term flicker emission severity is decreased.

$$P_{st} \propto \frac{1}{B_h} \tag{9}$$

Combining equations 7 and 8, new equation is formed.

$$P_{st} \propto \frac{1}{B_h + T_h} \tag{11}$$

Further, impact of vertical wind shear $V_{shr}$ is considered. Vertical wind shear is a change in the wind speed over a short distance with height in the atmosphere over a short span of time. It's unit is per second. Vertical wind shear can be computed by taking the ration of change in the speed to the change in the distance.[ 6 ]

$$V_{shr} = \frac{\text{wind speed at the tip of top sided blade} - \text{wind speed at the tip of bottom sided blade}}{\text{Diameter of the rotor of the wind turbine}} \tag{12}$$

Unit of vertical wind shear is per second. Vertical wind shear can be written in the abbreviation form as follows.

$$V_{shr} = \frac{V_{Top} - V_{Bottom}}{d_{bt}} \quad (13)$$

Here impact of vertical wind shear is reverberated. Short term flicker emission severity increases with vertical wind shear. If vertical wind shear is more, there is an uneven wind speed at the tip of the blades. So the vibration of the blades is increased with vertical wind shear. If the vibration of the blades is increased, the magnitude of the flicker emission severity is increased. Consequently, if the vertical wind shear is increased the flicker emission severity is also increased.

$$P_{st} \propto V_{shr} \quad (14)$$

Short term flicker emission severity decreases with average wind speed $V_a$ . If the wind speed is more, the wind turbine blades rotate at a high speed. If the rotational speed of the wind turbines is more, the magnitude of the vibration of the wind turbine blade is reduced and the frequency of vibration is increased. Consequently the magnitude of the flicker emission severity is decreased and the frequency if the flicker is increased. So, overall flicker emission is reduced. Subsequently if the wind speed is increased the flicker emission severity is decreased.

$$P_{st} \propto \frac{1}{V_a} \quad (15)$$

So ratio of vertical wind shear to average wind speed is considered

$$P_{st} \propto \frac{V_{shr}}{V_a} \quad (16)$$

From equation 6 and 13 new equation is formed as below

$$P_{st} \propto 2\, B_L \frac{V_{shr}}{V_a} \quad (17)$$

Short term Flicker emission severity increases with surface roughness of the terrain where the turbine is sited. [31]

$$P_{st} \propto Z_0 \quad (18)$$

Now consider impact of swept area of the turbine $S_A$. Short term flicker emission severity $P_{st}$ increases with the swept area of turbine. Swept area is the area swept by the turbine blades when the blades rotate. It is found by the area of the circle. $S_A = \pi r^2$ where r approximately equal to length of the one blade. $S_A$ is the sweep area of the wind turbine. Flicker emission severity increases with sweep area of the turbine. If the sweep area of the turbine is more, the turbines blades obstruct wind of larger area. So, more turbulence is produced in the air. Consequently vibration of blades is increased and the flicker emission severity in the output of the turbine is increased.

$$P_{st} \alpha \ S_A \qquad (19)$$

Further Cosine model of voltage flicker is developed

$$P_{st} = \frac{S_A}{T_h + B_h} \left(\frac{V_{shr}}{V_a}\right) \mathrm{Cos}\left( N \frac{V_{shr}}{V_a} + 1\right) + C \qquad (20)$$

In equation (20), $P_{st}$ is the short term flicker emission severity which is a dimensionless quantity. $T_h$ is tower height. $B_h$ ,is building height. $S_A$ is swept area of the turbine, $V_{shr}$ is vertical wind shear, $V_a$ is average wind speed. N is the number of wind turbine blades. Here a three bladed upwind wind turbine is used.

**4. Validation**

In the last section mathematical model of flicker is explained. In the current section validation of model is explained. Flicker is measured with change in the vertical wind shear. The test is carried out in a wind test set up. In this research initially readings on actual wind turbines were taken at different sites. The sites were Lohagaon, Talegaon Dhamadhere and Saswad in Pune district, India. However it was observed that it is impossible to control the environmental parameters like vertical wind shear, horizontal wind shear, turbulence intensity etc. of wind to study the impact of vertical wind shear on voltage flicker initiated in wind turbine. The wind is intermittent in nature. It was needed to wait for sufficient wind speed to conduct the trials. Secondly, other parameters horizontal wind shear and turbulence intensity were not constant. Secondly wind is intermittent in nature. Sometimes the wind speed is almost zero. At that speed it was difficult to test the wind turbine. So it was difficult find the impact of only vertical wind shear on voltage flicker which is main focus of this research project.

Hence, a small size wind tunnel was developed in a laboratory. It was developed with low cost raw materials. It was decided to conduct trials on a scaled down model of wind turbine and wind tower in the laboratory. To get an idea of wind tunnel some wind tunnels in Pune city were visited by the researcher of present research project along with a group of 5 students and an anemometer. Researcher visited Central Water and Power Research Station CWPRS, khadakwasala and Indian meteorological office, Shivajinagar to see wind tunnel to get an idea of wind tunnel. The fan of CWPRS wind tunnel was wooden. Some videos of National Aeronautics and Space Administration NASA USA, wind tunnel were also studied for getting an idea of wind tunnel. The wind tunnel facility is also available in Indian institute of technology, Kanpur. The visits enabled to decide size and shape of the wind tunnel. But in the developed wind tunnel, it was difficult to control the vertical wind shear as there was a single fan in the tunnel. Another difficulty is the conical shape of the tunnel at both the ends. Because of conical shape it was difficult to create vertical wind shear and horizontal wind shear. Due to conical shape the wind flow is concentrated toward test section and there is no separate control on the air flowing though top and bottom portion of the test section.

To overcome the drawback of production of vertical wind shear, it was decided to develop a wind turbine test set up. In wind turbine test set up, total five fans are fitted along with five regulators. In that wind turbine test set up, vertical wind shear, horizontal wind shear and turbulence intensity can be controlled by switching particular fans ON or OFF. The speed of the fans can be controlled by regulators as well. While checking impact of vertical wind shear, other wind parameters were kept constant.

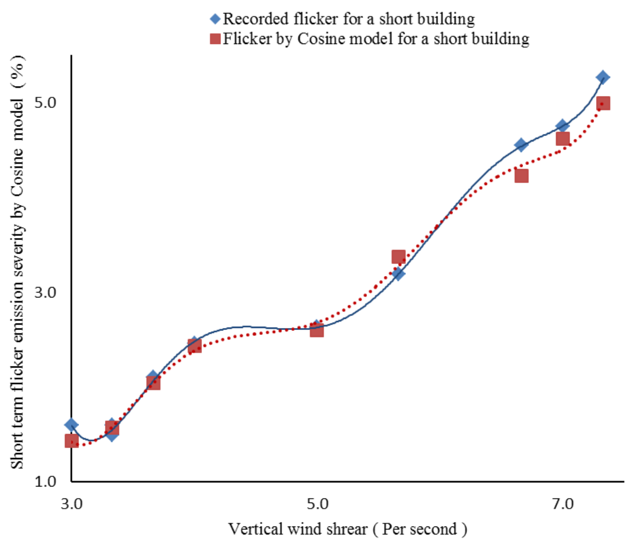


Fig 2. Impact vertical wind shear on flicker initiated in turbine mounted on a hill

## 5. Conclusion

It is concluded that the cosine model is closer to the actual flicker measured. If vertical wind shear is increased the flicker is also increased. The model utilises building height, tower height, average wind speed and vertical wind shear to compute voltage flicker.

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Appendix

| Abbreviation | Parameters |
|---|---|
| $B_H$ | Building height (m) |
| $B_L$ | Turbine blade length (m) |
| $N_T$ | Turbine speed (RPM ) |
| $N_B$ | Number of turbine blades |
| $P_{st}$ | Short term flicker emission severity (Dimensionless number) |
| $P_{lt}$ | Long term flicker emission severity (dimensionless number ) |
| T | Time ( second) |
| $T_H$ | Tower height (m) |
| $V_a$ | Average wind speed (m/s) |
| $V_{shr}$ | Vertical wind shear (per second) |

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