Simulating the response of a small horizontal-axis wind turbine during wind gust using FAST

M I Rakib, S P Evans and P D Clausen

1 School of Engineering, Faculty of Engineering and Built Environment, The University of Newcastle, Callaghan, NSW 2308, Australia
2 Diffuse Energy, Building E, 1 Technology Place, Williamtown, NSW 2318, Australia

*muhammadiftekharul.rakib@uon.edu.au

Abstract. Small wind turbines are often erected close to their load and in urban environments where the mean velocity is lower than ideal, and the turbulence level is high. Urban environments experience wind gust events with published results indicating the number of gust events greatly exceeding the number of events assumed in International Electrotechnical Commission (IEC) standard IEC 61400.2-2013. The work presented in this paper has analysed detailed wind measurements from a site in an urban environment to identify wind gust events and has used these wind gust events as an input into a FAST model of a 5 kW horizontal-axis wind turbine. The FAST model predicted the turbine power extracted from the measured gusts are lower than the power extracted during the assumed IEC gust. The maximum energy extracted by the turbine during a gust is at least 36% lower for a measured gust event than for the assumed ideal gust event.

1. Introduction

The International Electrotechnical Commission (IEC) standard IEC 61400.2-2013, defines a small wind turbine as a machine with a swept area of less than 200 m$^2$ and a power output of less than 50 kW [1]. These turbines are mainly used to supply power to remote homesteads or small communities and are often erected in suboptimal wind sites. These sites often have less-than-ideal mean wind speeds, and high levels of turbulence [2, 3]. Furthermore, these sites are likely to experience more gust events than turbines sited on open terrain; the terrain which forms the basis of the wind conditions used in IEC 61400.2-2013 [4].

One challenge that is faced by the small wind turbine designer is that there is little guidance in IEC61400.2 – 2013 for urban wind conditions. Anup et al. (2020) [5] found that the normal turbulence models used in IEC61400.2 – 2013 were inadequate for the design of small wind turbines subject to urban wind conditions. They found the wind conditions at two urban sites resulted in high damage equivalent loading leading to a shorter predicted blade life compared to the life predicted using the IEC assumed loading.

Rakib et al. (2020) [4] undertook detailed wind measurements on the Callaghan campus of The University of Newcastle, Australia to study gust events experienced at an urban wind site. They found that gust events that conform to the IEC 61400.2-2013 gust definition occurred 100 times during a 12-month period. This is significantly greater than the single event assumed by the IEC standard. The gust factor at this site was determined to be 1.76, some 23% higher than that the factor assumed by IEC
Given the high prevalence of gust events in the urban environment, an interesting question is raised: how much energy is available in a wind gust, and how much of this energy can be captured by a small wind turbine?

The work described in this paper investigates both of these questions. An array of ultrasonic anemometers has been erected in the urban environment and used to identify and quantify the wind velocity during gust events. Important aspects of the anemometer system and measurement campaigns are detailed in the methodology section of this paper. A FAST model of a 5 kW horizontal-axis wind turbine has been developed to predict the performance of the turbine during both measured gust events and the IEC 61400.2-2013 assumed gust. Important inputs to the FAST model are documented in this paper. The maximum and predicted turbine power output as a function of time for both the measured and ideal gusts have been determined allowing the energy capture to be calculated.

2. Methodology

2.1. Measuring the urban wind resources:
The Wind Energy Research Group at The University of Newcastle, Australia has a 5 kW Aerogenesis wind turbine installed on Callaghan campus for research purposes. This turbine is installed on an 18 m high galvanized steel, octagonal cross section monopole tower [6]. The turbine is surrounded by a complex terrain that includes buildings, undulating topography, trees, open fields, a car park, and a rail line easement (Figure 1). Wind resource measurement campaign undertaken at this site will bring valuable information to any application of renewable energy or structures located in complex urban terrain. Three 3D ultrasonic WindMaster anemometers are mounted at a height of 15 m above ground level on the wind turbine tower; see figure 1. The anemometers are placed equispaced at 120° around the tower and measuring continuously wind speed and direction at a rate of 20 Hz with data logged by a computer using WindView software and ATEN-UC4854 USB-hub data logging system. The computer is housed in a control room located approximately 30 m from the turbine. Wind monitoring at this site is ongoing.

![Figure 1. Location and overview of the 5 kW Aerogenesis turbine. The red circle is the turbine location and a 200 meters radius surrounding the turbine is indicated in black circle (Google Maps, 2019)](image_url)
2.2. Identifying gust events in urban region:
All the data collected by the anemometers are processed and analysed by code written in Matlab software. Reference [1, 7] defines the gust amplitude as the maximum value of a gust during a given period that is the scalar difference between a gust peak wind speed and the adjacent lull wind speed. There are two magnitudes associated with each gust event: one for the lull before the peak, one for the lull following the peak. The rise-and-fall time is defined as the time difference between lulls before and after the peak [4]. The approach used in this study for identifying gusts is described in Rakib et al. (2020) [4]. For this study, $V_{hub}$ was considered as $5 \text{ms}^{-1}$, and $V_{gust}$ was calculated as $6.9 \text{ms}^{-1}$ based on the IEC extreme operating gust model. The algorithm used in Matlab codes consisted of the following steps:

- Identify maximum wind speeds $9 \leq v \leq 11 \text{ms}^{-1}$
- Select the subset of these wind events which have an amplitude (prominence) $\geq 6.9 \text{ms}^{-1}$ as $V_{gust} = 6.9 \text{ms}^{-1}$ for this case.
- Select the subset of these events that have a rise-and-fall time $3 \leq t \leq 5.6 \text{second}$.

Figure 2. Identifying the measured wind gusts.

2.3. Aeroelastic modelling using FAST:
FAST wind turbine simulation tool, developed and maintained by the U.S. Department of Energy and National Renewable Energy Laboratory, is widely utilized for modelling wind turbines. An aeroelastic model of the 5 kW Aerogenesis wind turbine has been previously developed using FAST v7.02.00 [8]. The model had the initial turbine rotational speed set to 180 rpm, the rated wind speed set to $10.5 \text{ms}^{-1}$ and rated power output set at 5 kW. The nacelle inertia about the yaw axis was 105 kgm$^2$, based on data from a 3D solid model of the 5 kW Aerogenesis wind turbine. The turbine blades have a constant SD7062 aerofoil profile along the blade’s twisted aerodynamic working section, with this information added as an input through AeroDyn software. The physical turbine also has a passive yaw control system using a delta-wing tail fin; performance data of the delta-wing tail fin was also inputted through AeroDyn software. The mechanical properties of the 18.3 m high octagonal tower were added to the model via AeroDyn. Measured wind gusts data and IEC defined wind gust model were used as input wind data in this study. In order to avoid complexity of the model at this stage, wind direction was considered as unchanged during the wind gust period. The Aerogenesis turbine has a variable speed generator with the rotor speed generator control parameters consisting of experimentally determined speed verse torque calibration data; this data was used to form the model of the generator. Models for all the turbine components were compiled into a comprehensive and detailed FAST model of the whole turbine.

The FAST model will be used in this study to predict wind turbine rotor performance for an IEC prescribed open terrain gust event and wind gust events from measured wind data. The model provides arrays of output data including aerodynamic (power coefficient, local blade velocities, angle of attack, Coefficient of lift, Coefficient of drag), structural (including blade deflections and loadings and tower deflections and loadings), generator (including output electrical power, generator speed and torque), and general turbine performance (including rotor and torque, tip speed ratio, yaw alignment and yaw rate).

The focus of this study is to use this model is predicting the maximum aerodynamic energy available in a wind gust, and the amount of this energy captured by the rotor. Integrating the wind power and rotor
power output over a time period of 14 seconds, the time period for a prescribed gust in the IEC gust model, determines the availability of maximum aerodynamic energy and energy capture by the rotor respectively. Figure 3 shows example of this.

![Graph depicting aerodynamic power and gust energy](image1)

**Figure 3.** Calculating the availability of aerodynamic energy of a wind gust (23.4 kJ) and maximum energy extraction by the rotor from the gust (9.3 kJ).

### 2.4. Measuring the effect of gust:

For measuring the response of a blade during the turbine operation in wind gust, nine uniaxial strain gauges are installed on one of the turbine blades. Seven strain gauges are located on the pressure surface and two are located at the suction surface. The first gauge is located 350 mm from the blade root and rest of the six gauges at suction surface are spaced at an incremental distance of 250 mm. The uniaxial gauges at suction surface are located direction opposite side of the pressure surface first and third gauges. The location were chosen based on analysis of a finite element model of the blade.
Blade strain gauges are shielded in order to reduce the interference of grid frequency, which is 50 Hz. A magnetic reed switch pulse is used for measuring the rotor rotational speed. An optical encoder is used for measuring the turbine yaw angle. An accelerometer is installed on the tower just below the nacelle to monitor tower vibration. All these instrumentations are set to provide data at 500 Hz. Using an Xbee module enabled us to record data from all these instruments remotely in a computer. Figure 4 shows the wind turbine instrumented with the instrumentations. At this stage, the wind turbine was run in a gusty day for approximately three hours and data provided by anemometers and all the above mentioned instruments have been recorded simultaneously. The experimental works are ongoing.

![Wind turbine instrumentations](image)

**Figure 4.** Wind turbine instrumentations.

3. Results

3.1. *FAST simulation results of measured wind gusts:*

Analysis of gusts events at the Callaghan site clearly indicate gust events are not regular and symmetric in shape as assumed in IEC standard [4]. From the acquired wind data, 34 EOG events have been identified at the Callaghan site. Figure 5 shows two measured gust events plotted against the ideal gust event from the IEC standard. The measured gust events follow the generic shape of the ideal gust, however, with significant wind speed fluctuation throughout and a lack of symmetry in the gust.
Figure 5. IEC prescribed EOG and measured EOG at Callaghan site.

Figure 6 shows a comparison between the maximum available energy during an IEC prescribed gust and the measured gusts. As it is can be clearly seen, the measured gusts have less energy than the ideal gust. The ideal gust has an energy of 38 kJ, whereas usually the measured gust has energy less than 25 kJ in this study, due in part to the cap on the maximum velocity and the gust amplitude of the measured gust being higher than the IEC standard gust. Figure 7 shows a comparison of rotor performance during an ideal gust and measured gust events. The maximum rotor power predicted during an ideal gust was about 4.5 kW, whereas for a measured gust, the maximum about 3 kW. Figure 8 presents the predicted energy capture by the rotor during the measured gust events and the ideal gust. For the measured gusts, the rotor is predicted to capture less energy than the ideal gust. For an ideal gust, the rotor can extract 14.7 kJ of energy and for most of the measured gusts, the rotor was predicted to be extract less than 10 kJ. The average percentage of energy extracted by rotor from the available energy in the measured gust was found to be 35%, and for the ideal case, 39%.
Figure 6. Maximum available energy in measured gust and ideal gust.

Figure 7. Power captured by rotor during the measured and ideal gust.
3.2. Measuring effect of gust:

Figure 9 shows a measured gust event at the test site, and blade root bending moment, tip deflection, rotor rotational speed and turbine yaw angle were monitored and recorded simultaneously during the gust event in order to quantify the turbine’s structural response during wind gust. The measured wind gust also used in the FAST model and outputs were compared with the experimental results (Figure 10–13). At this stage, the FAST model shows reasonable similarities with the experimental results. This model was also experimentally verified in a previous study [9]. Figure 10 shows that the rotor rotational speed was well responsive due to wind gust, when it increased from 150 rpm to 178 rpm. Frequent formation of high root bending moment (304 Nm) and high blade tip deflection (22 mm) were also observed as mentioned in Figure 11 and 12, which may have impact on the turbine fatigue loading. The yaw inertia of the turbine is shown in Figure 13, which ensures the turbine is operating at a yaw error during the gust. It, therefore, causes reducing the energy capture, which is mentioned in Figure 8.
Figure 9. Measured wind gust event at Callaghan site

Figure 10. Rotor rotational speed during the wind gust
Figure 11. Blade root bending moment during the gust event

Figure 12. Blade tip deflection during the measured wind gust
Figure 13. Turbine yaw and measured wind speed during the measured wind gust

4. Discussion and Conclusions

This study has presented measurements of gust events in an urban built-environment and the results of FAST simulation undertaken to predict the performance of a 5 kW horizontal-axis Aerogenesis wind turbine, located on the Callaghan campus of the University of Newcastle, Australia, during wind gust events. The IEC standard prescribed an extreme operating gust (EOG) model, which is based on open terrain geographies that are free from significant obstructions and irregular topographic features. The IEC prescribed EOG model was also utilized in this study for predicting the turbine performance during gust events. The ideal gust model and measured gust data were input into the FAST model of the turbine, with the predicted turbine performance used to determine the energy capture of the turbine during these gust events.

The following conclusions can be drawn from this study:

1. An analysis of 34 measured wind gust events at the Callaghan site shows the energy content is between 24 kJ and 10.7 kJ, whereas the IEC prescribed ideal gust energy content was predicted as 38 kJ. The difference in available energy is due to the turbulent nature of the measured wind and the lower wind velocity before and after the gust peak when compared with the IEC gust event that has the same maximum gust wind velocity.

2. Rotor is predicted to extract 14.7 kJ of energy from an ideal gust and for all the measured gusts, the predicted energy extracted was less than 10 kJ. Annually, about 97 MJ of energy can be extracted from the wind gusts, which is less than 2% of total annual energy production of the wind turbine. The difference in energy extracted by the rotor is due to in part to issues raised in conclusion 1, and possibly the likelihood of lower aerodynamic performance of an aerofoil operating in turbulent flow.

3. The turbine rotor is predicted to extract on average 35% of energy available during a measured gust event compared to 39% for the IEC gust event.
As mentioned previously, these predictions were based on the wind direction not changing through the gust event. Our measurements indicate that the wind direction does change through gust events, so our energy capture predictions here are will be an upper bound. The yaw inertia of the turbine will ensure the turbine is operating at a yaw error during at least part of the gust, thereby reducing the energy capture. In addition, further work needs to be undertaken to quantify fatigue load due to the urban wind gusts.

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