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# WindPACT 1.5 MW Wind Turbine Rotor Dynamic Loads Under the Effect of Atmospheric Turbulence

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**Abstract-** The increasing demand for energy in the modern world, and the environmental effects of conventional energy sources, necessitate the need for renewable energy. Among the renewable energy sources, wind energy provides a clean and sustainable source of energy. Since the wind is of turbulent nature, the dynamic behavior of wind turbines is highly affected by the turbulence intensity value. The study of dynamic loads and behavior of wind turbine components is of crucial importance to making decisions regarding a wind turbine's operation. In this work, the rotor dynamics of the WindPACT 1.5 MW wind turbine are studied under the influence of atmospheric turbulence. Four different wind fields with a mean wind speed value of 12 m/s, and turbulence intensities of 1%, 10%, 25%, and 50% are simulated for the study. Rotor thrust force and torque are evaluated for each turbulence intensity. It was found that as the turbulence intensity increased, the fluctuations of the load around the mean value increased severely. For the rotor thrust, although the mean value is nearly unchanged, the standard deviation increases by 325% for the 50% turbulence intensity compared to the 1% intensity. An enormous increase in the rotor torque's standard deviation occurs as well, for the 50% intensity compared to the 1% intensity, a 1300% increase occurs. The extremely high difference implies complications not only in the tower dynamics but also in the added cost of variable speed control continuously in operation. Continuous monitoring of wind speeds is highly recommended for the decision of putting the turbine into brake in such cases of severe turbulence.

**Keywords** Dynamic Loads; Renewable Energy; Rotor Dynamics; Turbulence; Wind Turbines.

## 1. Introduction

Renewable energy is the key to a sustainable future. With the fossil fuels sources draining, and the harmful emissions they produce in the environment, most governments are switching to renewable energy sources on the grid level, and on a regionalized scale [1]. Utilizing renewable energy is useful in smart cities to produce clean energy and cover all the residents' needs for energy for appliances and daily use [2], [3].

Many sources of renewable energy are being used and improved for better performance. Sources of renewable energy include solar [4], geothermal [5], wind [6], tidal [7], and wave energy [8]. In addition hybrid systems utilize more than one renewable energy source for increasing the efficiency of the system [9], [10].

Wind energy is gaining the attention of researchers for its sustainability and cleanliness. Innovations and new concepts of wind energy harvesting emerge every year, airborne wind energy for instance [11]. On a governmental level, new wind turbine installations are executed annually. Tremendous year-over-year growth is achieved in wind energy installations, with a current global wind power capacity of 837 GW [12]. On the urban scale as well, small wind turbines have been presented as a replacement for solar panels, for household energy needs [13].

Wind turbines are the most conventional and fastest-growing wind power harvesting systems. Intensive research is being made globally every year to optimize wind turbines' design and increase the efficiency of energy production. Optimization can be done in many aspects, mainly in the aerodynamic design of the blades, active and passive flow control, structural design and aeroelastic behavior of wind turbine components, and control algorithms for the generator and the turbine's main actuator systems [14]-[18].

However, to benefit from a wind turbine for as long as possible, it should be designed to last for a long lifetime. Typically, wind turbines are designed to have a lifetime of about 20 years in operation [19]. Due to the dynamic nature of wind, dynamic loads are the main reason for wind turbine failures. Severe dynamic loading can affect the lifetime of a wind turbine component.

For that reason, continuous forecasting for the wind velocities and directions is made to anticipate the structural behavior and aerodynamic performance of wind turbine components [20], [22]. As the wind velocity increases, the produced power increases proportionally to the cube of wind velocity. However, high fluctuations of wind velocities in highly turbulent regions or in regions subject to wind gusts and storms lead to structural complications and decrease the lifetime of a wind turbine.

The effect of turbulence intensity on the performance of a wind turbine has been studied by many researchers. Most of the research attempts are concerned with the power production performance of the wind turbine [23]-[26]. Other studies were concerned with the effect of turbulence intensities on the fatigue lifetime of wind turbine components [27]-[30]. It has been found that high turbulence intensities have a negative effect on the lifetime of a wind turbine. The effect of turbulence on the dynamic behavior of the blades has been studied by the author [31], high turbulence intensity leads to an enormous increase in the standard deviation of the blade deflections, and for high turbulence intensity, the danger of tower strike occurs.

The study of rotor dynamic loads solely is of high importance, it is the main factor affecting the dynamic loads on the tower, and hence the tower deflections and fatigue loading. Numerical methods like Computational Fluid Dynamics (CFD) techniques for such studies can provide promising results. However, the computational cost can make it a drawback specially in analytical problems where a wide range of simulations are performed [32]. On the other hand, deterministic models like Blade Element Momentum (BEM) for aerodynamic loads, and Euler Beam Theory for Structural behavior, provide a much less costly and time-efficient solution in such cases [33].

In this context, this paper presents a study of atmospheric turbulence on the dynamic loads of a wind turbine rotor. A simulation is performed on the WindPACT 1.5 MW wind turbine [34], with a mean wind speed of 12 m/s but with four different turbulence intensities with a low intensity of 1%, an intermediate intensity of 10%, a medium-high intensity of 25%, and a high intensity of 50%. While the turbulence intensity values are usually less than 50%, extreme values are presented for comparison with lower turbulence intensity values, and to simulate extreme conditions like gusts or typhoons. The importance of the study is to anticipate the tower's structural behavior under such dynamic loads.

In the following section, the turbine model, and the methodology followed for generating the wind field and for the simulations for evaluating the dynamic loads are introduced. Then the results of the simulation are shown and discussed, in addition to statistical measures to compare the results of different cases. Finally, the last section concludes the main findings of the current work and suggests recommendations for future work.

## 2. Turbine Model and Methodology

### 2.1. WindPACT 1.5 MW Turbine Definition

In a project made by the National Renewable Energy Laboratory (NREL), a wind turbine has been designed with available data for researchers to use. The result of this project is the WindPACT turbine with four different configurations of different capacities to study the scaling effect on the Cost of Energy (CoE). The 1.5 MW configuration has been chosen for the current study. It has a rotor diameter of 70 m, placed on a tower of 84 height, producing a rated wind power of 1.5 MW at a rated wind speed of 12.5 m/s. Figure 1 shows the WindPACT 1.5 MW turbine, and Table 1 shows the main features of the turbine under study.

**Fig. 1.** WindPACT 1.5 MW Wind Turbine [35]

**Table 1**. WindPACT 1.5 MW Main Features [34]

| Property | Value |
|---|---|
| Rotor Diameter (m) | 70 |
| Hub Height (m) | 84 |
| Rated Rotor Speed (rpm) | 20.5 |
| Rated Wind Speed (m/s) | 12.5 |
| Rated Power (MW) | 1.5 |
| Hub Overhang (m) | 3.3 |
| Tower Base Diameter (m) | 5.663 |

### 2.2. Methodology

In order to study the dynamics of the turbine, first, a turbulent wind field should be generated. Wind's turbulent nature can change on a short-time scale or on a long-time scale. It is a complex phenomenon that cannot be expressed mathematically, however, turbulence intensity is a good measure of wind velocity values over time. Turbulence intensity ($I$) can be defined as the standard deviation of wind velocities over a certain period of time ($\sigma$), divided by the mean wind velocity for the same time period ($U$) as defined in Equation 1 [36].

$$I = \frac{\sigma}{U} \tag{1}$$

Several models are used to simulate the turbulence intensities, whether based on a timescale like the models used in CFD simulations or based on spectral models like the models used in aeroelastic simulations based on deterministic methods. In the current work, the Kaimal spectral model is used to generate different wind fields since it best suits atmospheric turbulence [32].

The open-source software TurbSim [37] is used to generate four different wind fields. The main inputs to the software are the turbine dimensions, mean wind speed, spectral model, and desired turbulence intensities. The mean wind speed for all turbulent fields is 12 m/s, and four different turbulence intensities with values of 1%, 10%, 25%, and 50% are generated. The aim of generating the four fields with the same wind speed is to eliminate the effect of wind speed on the dynamic loads, and only observe the effect of turbulence intensity. Figure 2 shows the generated wind speeds at hub height for 40 seconds of physical time.

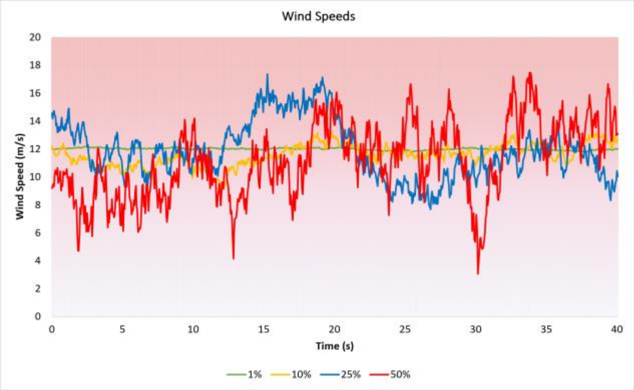

**Fig. 2.** Wind Speed at Hub Height

As the turbulence intensity increases, the fluctuations around the mean value of wind speed increase. For the 1% turbulence intensity, the wind velocity is almost constant at the mean value of 12 m/s, but for the 50% turbulence intensity, the wind speed oscillates dramatically around the mean value over a very short period of time.

The generated wind fields are then used as an input to the open-source software FAST (Fatigue, Aerodynamics, Structure, and Turbulence) [38]. A time series for the turbine loads and deflections is the result of the FAST simulation. The turbine geometry and aerodynamic properties are used as inputs as well. Figure 3 shows the flowchart of the FAST simulation's procedure.

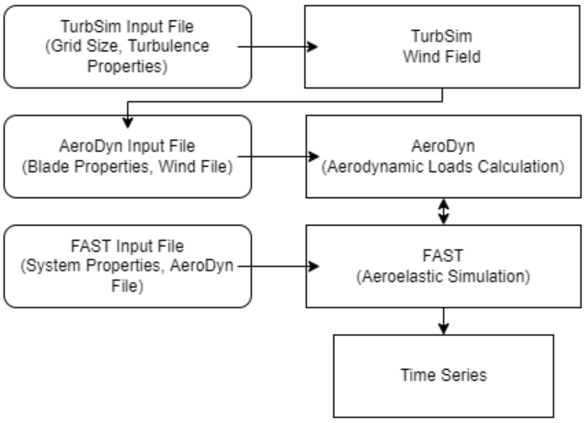

**Fig. 3.** FAST Simulation Procedure

The simulation is defined for 40 seconds of physical time. The main concern of this work is the rotor dynamic loads, namely the rotor thrust and rotor torque. In the next section, the results of the simulation are introduced and discussed.

## 3. Results and Discussion

### *3.1. Rotor Thrust*

Rotor Thrust is of high importance for the turbine's dynamic behavior. It is directed along the Low-Speed Shaft (LSS), to the High-Speed Shaft (HSS), then eventually to the tower top. The transmitted thrust is the main factor affecting the tower's fore-aft bending moments and deflections. Hence, is important to anticipate the dynamic nature of the tower dynamics.

FAST simulations are performed for the four different wind fields, and the thrust is shown as a time series over 40 seconds of simulation. Figures 4 to 7 show the rotor thrust for the turbulence intensities of 1%, 10%, 25%, and 50% respectively.

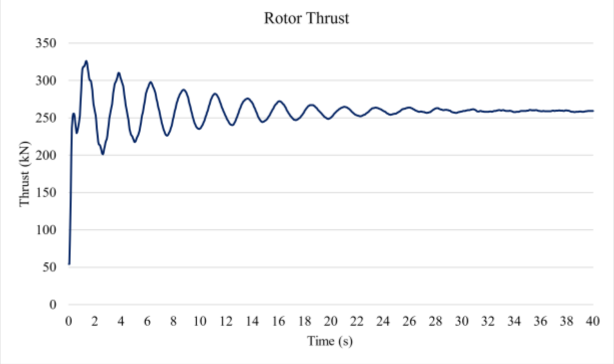

**Fig. 4.** Rotor Thrust - 1% Turbulence Intensity

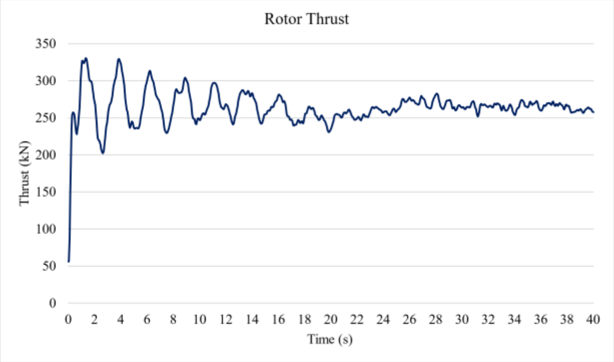

**Fig. 5.** Rotor Thrust - 10% Turbulence Intensity

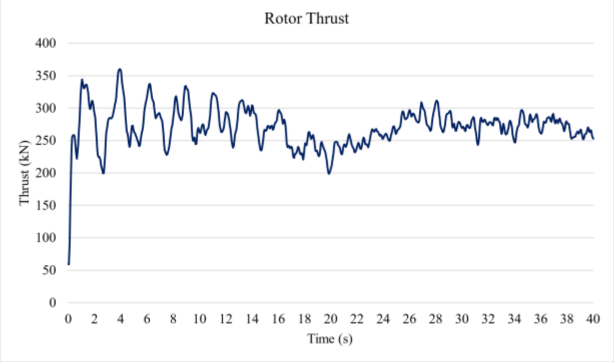

**Fig. 6.** Rotor Thrust - 25% Turbulence Intensity

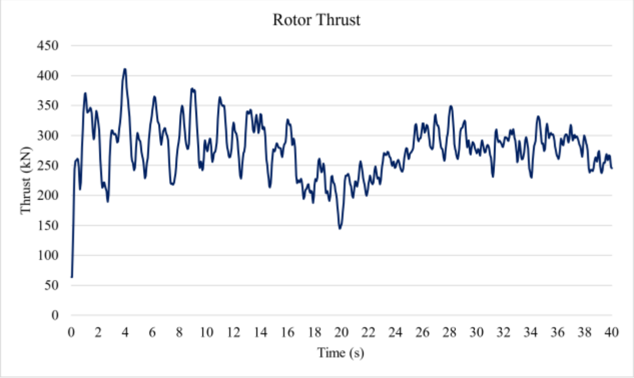

**Fig. 7.** Rotor Thrust - 50% Turbulence Intensity

The effect of turbulence intensity on the value of rotor thrust is severe. For the very low turbulence intensity of 1%, the thrust oscillates for the first 20 seconds of operation, then settles around a nearly constant value. As the turbulence intensity increases, the rotor thrust develops a dynamic behavior with a random nature.

For the 10% turbulence intensity, the rotor thrust does not settle after the first 20 seconds of operation, instead, it keeps fluctuating around the mean value of 260 kN. This fluctuation increases with the increase of turbulence intensity. It becomes extremely severe fluctuation for the highest turbulence intensity of the value of 50%.

As mentioned earlier, rotor thrust is the major factor affecting the tower's fore-aft dynamics. As the fluctuations increase, the fatigue loads on the tower as well as the tower top deflection increase. It is undesirable to have a severely fluctuating rotor thrust load, hence, in such cases of wind gusts or in severe storms, a wind turbine is advised to be put on the brake. In the next subsection, the second important aerodynamic load of a wind turbine's rotor, namely the rotor torque will be investigated under the turbulence effect.

### *3.2. Rotor Torque*

The second FAST output of interest in this work is the rotor torque. The importance of the rotor torque is not only for the structural behavior but also for the produced power of the wind turbine. The produced power is a result of the multiplication of the rotor torque and rotor rotational speed. It is also the main factor affecting the tower's side-side bending moments and deflections.

Rotor torque is calculated for the different wind fields of turbulence intensities and plotted against time. Figures 8 to 11 show the rotor torque for the turbulence intensity of 1%, 10%, 25%, and 50% respectively.

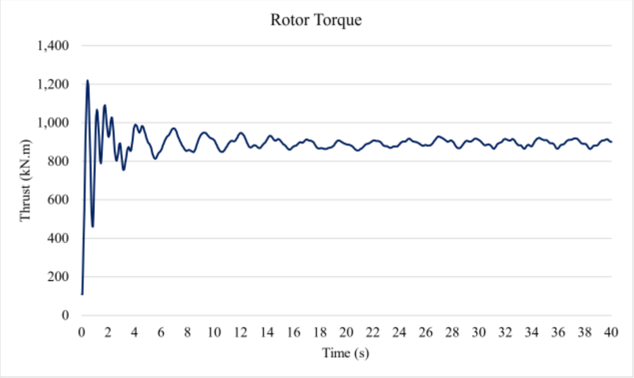

**Fig. 8.** Rotor Torque - 1% Turbulence Intensity

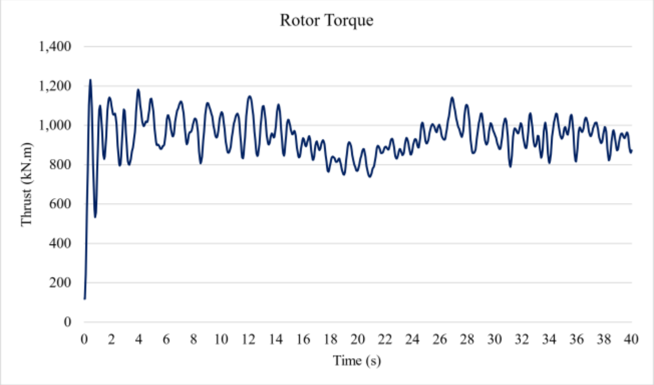

**Fig. 9.** Rotor Torque - 10% Turbulence Intensity

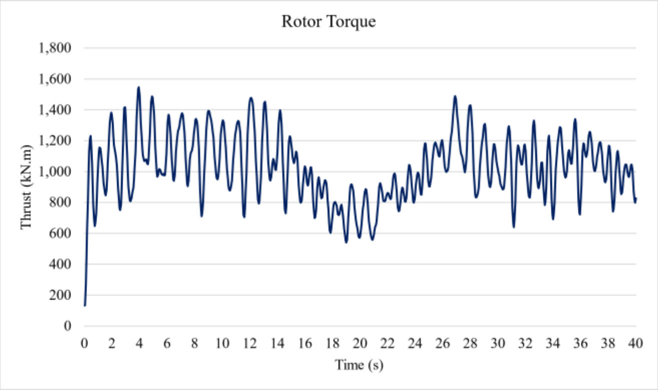

**Fig. 10.** Rotor Torque - 25% Turbulence Intensity

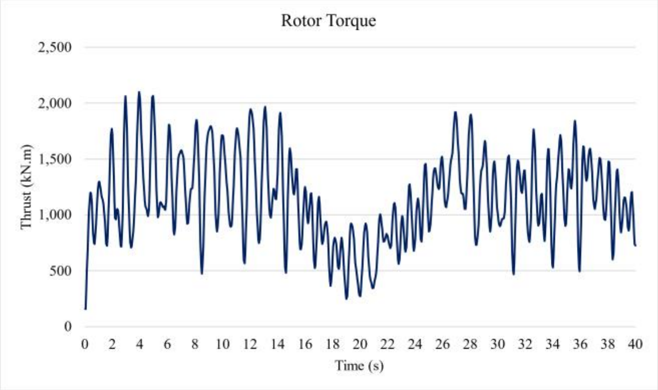

**Fig. 11.** Rotor Torque - 50% Turbulence Intensity

Similarly, the turbulence intensity effect on the rotor torque is a severe fluctuation around the mean value of the aerodynamic torque. The fluctuations have a mild value for the low turbulence intensity of 1% and it increases as the turbulence intensity increase until it becomes violent for the 50% turbulence intensity.

In addition to the effect of rotor torque on the tower side-side dynamics, the high-speed shaft of the generator needs a variable speed controller to manage the produced power. So, in addition to the negative effect on the tower's fatigue loads, a controller in operation during the whole time of the rotor's motion induces extra cost and hence increases the cost of energy.

The effect of high turbulence intensity on both the aerodynamic thrust and torque has been shown to be negative from structural and power performance points of view. For a better judgment of the turbulence effect, statistical measures can be of great importance. Aerodynamic loads and statistical measures are shown in the next subsection.

### 3.3. Results Summary

To have a better image of the differences in the aerodynamic loads with different turbulence intensities, the rotor thrust as well as the rotor torque are plotted for the four different turbulence intensities on the same plot. Figures 12 and 13 show the rotor thrust and torque respectively.

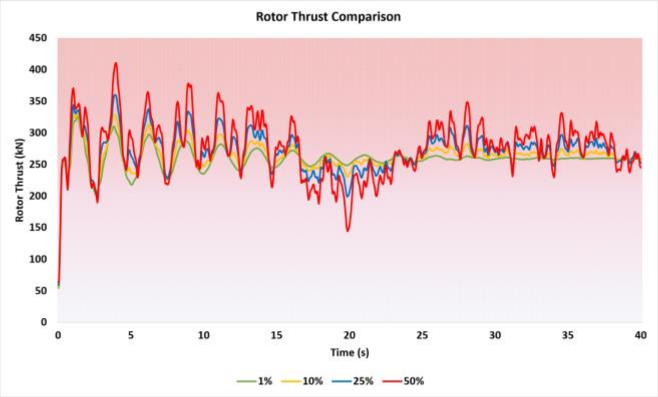

**Fig. 12.** Rotor Thrust Comparison - All Turbulence Intensities

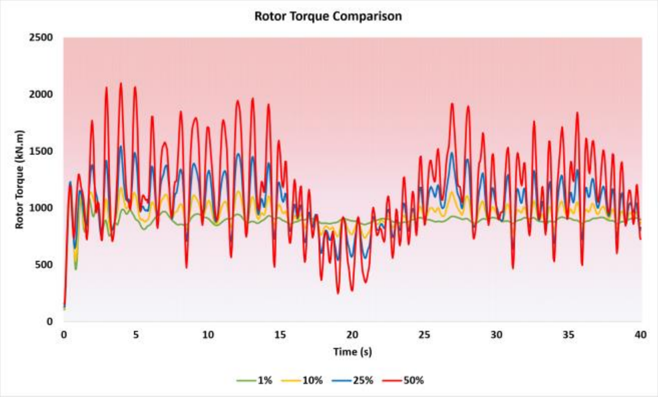

**Fig. 13.** Rotor Torque Comparison - All Turbulence Intensities

Plotting the rotor aerodynamics for the four different intensities on the same plot show a clearer image of the effect of turbulence on rotor dynamics. As the intensity of turbulence increases, the severity of load fluctuations increases. There is a vast difference between the rotor loads not only in the value but also in the range of values and the frequency of oscillation.

Statistical measures also give a better insight into the effect of turbulence. The main five measures that give a good judgment are the mean value, maximum value, minimum value, range of values, and standard deviation. Figure 14 shows the statistical measures for the rotor thrust in kN, while Figure 15 shows the statistical measures for the rotor torque in kN.m.

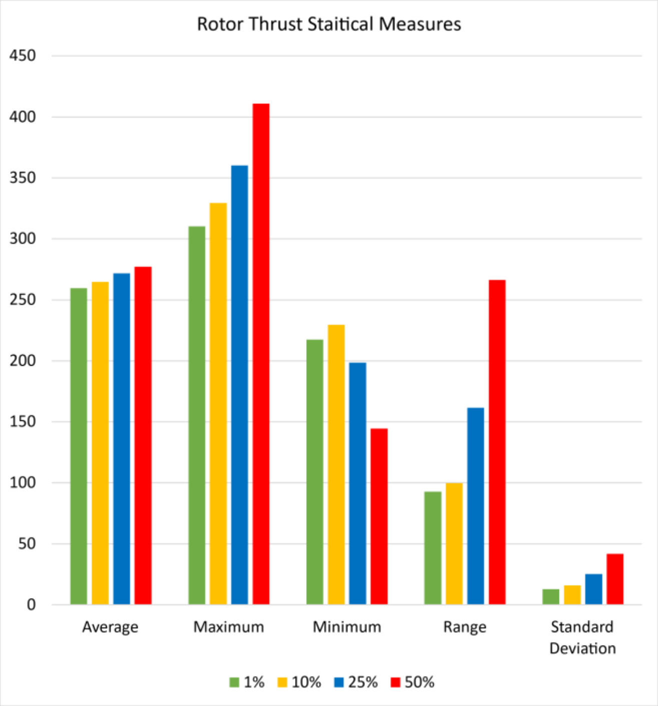

**Fig. 14.** Rotor Thrust Statistical Measures

For the thrust loads, it is observed that the average value is almost not changed, however, the maximum and minimum values for the thrust load vary severely. As a result, the range of values has an enormous increase, especially for the 50% turbulence intensity. This means that instead of fluctuating around the average value mildly, the dynamic load changes dramatically over a short period of time. This is also measured by the standard deviation. For instance, the 1% turbulence intensity has a standard deviation of 12.84 kN, while for the 50% turbulence intensity it has a value of 41.79 kN with a 325% increase. The severity of fluctuations is represented by the value of the standard deviation, and hence, fatigue loads in the tower fore-aft directions are affected strongly.

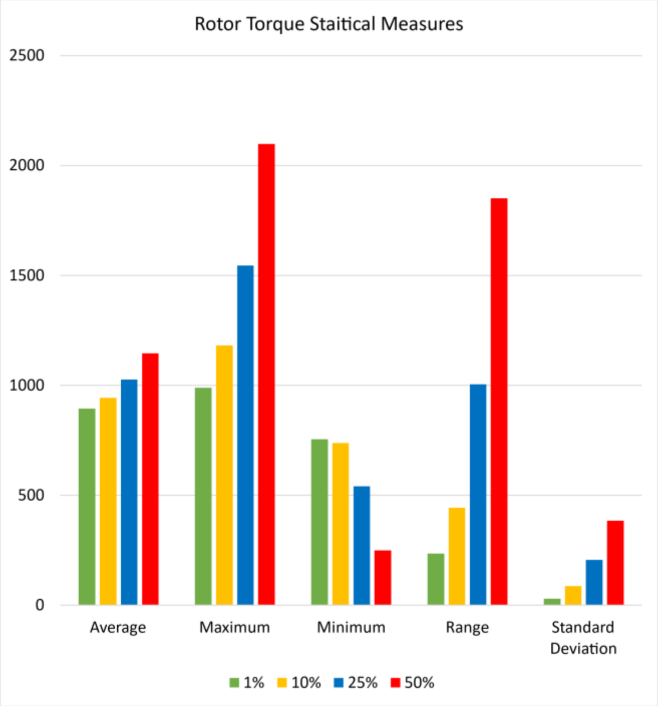

**Fig. 15.** Rotor Torque Statistical Measures

The rotor torque on the other hand, has a higher average value for the higher turbulence intensity. An increased torque implies higher rotor power for the same rotational speed; however, it has a bad influence on the tower's side-side dynamics. There is an obvious increase in the range of values and the standard deviation as well. Instead of fluctuating within a range of 235 kN.m for the 1% turbulence intensity, the rotor torque fluctuates within a range of 1850 kN.m for the 50% intensity. A huge difference in the range of values indicates that the rotor undergoes severe oscillations. Standard deviation increases as well from 28.84 kN/m for the 1% intensity, to a value of 383.87 kN.m for the 50% intensity. The value of standard deviation increases by 1300% for the highest turbulence intensity compared to the lowest one. In addition to the structural complications, this value means an added cost for a variable speed controller is included as well. It is highly recommended that the rotor is put onto brake when the turbulence intensities exceed such limits to avoid severe dynamics and added controller costs.

## 4. Conclusions

In this work, the rotor dynamics of the WindPACT 1.5 MW turbine are studied. Four different wind fields with a mean wind speed value of 12 m/s and turbulence intensities of 1%, 10%, 25%, and 50% respectively are generated. Rotor dynamic loads are evaluated based on deterministic models using the software tool FAST.

Rotor thrust was observed to have severer fluctuations around the average value which is almost the same for all turbulence intensity values. The higher turbulence intensities implied higher variation in the minimum, maximum, and range of values. The standard deviation of the rotor thrust for the 50% turbulence intensity is 325% of that for the 1% turbulence intensity. The severity of fluctuations indicates complications in the tower fore-aft dynamics.

In addition, rotor torque has shown similar behavior, but with much more severe fluctuations as the turbulence intensities. The standard deviation for instance increases as high as 1300% for the 50% intensity compared to the 1% intensity. Torque oscillation with a high frequency not only affects the tower's side-side dynamics but also requires continuous variable speed control which adds to the cost of energy.

It is highly recommended to have continuous forecasting and monitoring of wind conditions at a wind farm so that a decision is made for putting the wind turbine into brake if the turbulence intensities reach a high value. It is also recommended that the tower dynamic loads and deflections should be studied under the effect of different turbulence intensities for structural considerations.

## Acknowledgments

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## Nomenclature

| | |
|---|---|
| BEM | Blade Element Momentum |
| CFD | Computational Fluid Dynamics |
| CoE | Cost of Energy |
| FAST | Fatigue, Aerodynamics, Structure, and Turbulence |
| HSS | High-Speed Shaft |
| LSS | Low-Speed Shaft |
| NREL | National Renewable Energy Laboratory |
| $I$ | Turbulence Intensity (-) |
| $U$ | Mean Wind Speed (m/s) |
| $\sigma$ | Wind Speed's Standard Deviation (m/s) |

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