Simulation Based Approach to Predict Vertical Axis Wind Turbine Faults using Computational Fluid Dynamics

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ABSTRACT
Use of on-line fault detection techniques is integral to successful operation and maintenance of a wind turbine installation. The deployment of condition monitoring systems needs to be structured and sensitive to likely faults that may occur. In this work effects of blade faults have been simulated to understand sensitivity of blade faults on torque output. It is expected that this will help in developing a blade related condition monitoring strategy for a wind turbine system. It has been seen that instantaneous torque is a strong function of any blade imbalance and the torque output can be used successfully to identify initiation of blade imbalance related effects.

KEYWORDS
Condition Monitoring, Computational Fluid Dynamics, Sliding Mesh, Vertical Axis Wind Turbines

1 INTRODUCTION

Simulations [1-3] play a key role in understanding dynamics of different wind turbine systems. Such simulations are essential to predict power yield as well as design and off design performance characteristics of such systems. These simulations can also provide vital information about prognosis and diagnosis of different faults that may occur during the operational life of systems [4-7]. Integration of simulations in condition monitoring strategy may drastically reduce field data requirement as well as number of sensors needed. This will also make the condition monitoring system adaptive, more intelligent and cost effective. This paper investigates the use of simulations in developing condition monitoring strategy for wind turbine applications. This study uses computational fluid dynamics to simulate effects of blade deformation on torque characteristics of such systems through accurate flow mapping. This work provides results that are part of wide ranging initiatives being undertaken in developing a coherent condition monitoring strategy for wind turbine farms.

2 COMPUTATIONAL MODELLING

A vertical axis wind turbine developed in-house has been modelled computationally to predict its performance characteristics under different operating conditions. This turbine is made up of a combination of stator and rotor blades. The stator blades are designed to smoothly allow flow to impinge on rotor blades at the design velocity. The turbine used in present investigation consists of 12 rotor and stator blades each. The overall diameter of the turbine is 2m and the height of the turbine is 1m. The vertical axis wind turbines offer many advantages because they are directionally insensitive and do not require any yaw mechanism for alignment purposes. Figure 1 shows the schematic of the vertical axis wind turbine used

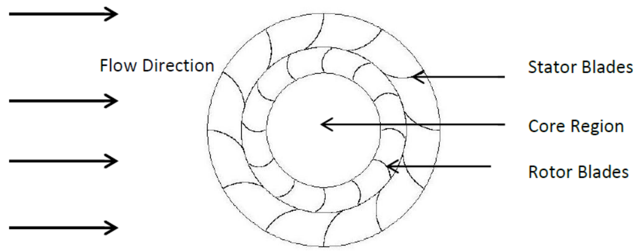

Figure 1: Schematic of the Vertical Axis Wind Turbine (VAWT).

In the present investigation, faults have been incorporated by deforming a rotor blade from its original position. The angular deformations of the rotor blade considered in the present study are shown in figure 2. In order to effectively use CFD as a condition monitoring tool for VAWTs, three different angular deformations of the blade have been used to represent a wide range of fault severity conditions in the wind turbine. The first set of simulations was carried out on baseline model, in which the blades of the VAWT are in their original shape and positions. The second and the third set of simulations were carried out on wind turbine model with angular deformation in a specified rotor blade by a magnitude of 5° and 10° respectively.

The details of all the configurations are summarised in table 1.

VAWT's Condition	Blade's Angular Deformation
Baseline Model	N/A
5° Blade Angle	5°
10° Blade Angle	10°

Table 1: Geometric details of the faults in VAWTs being analysed.

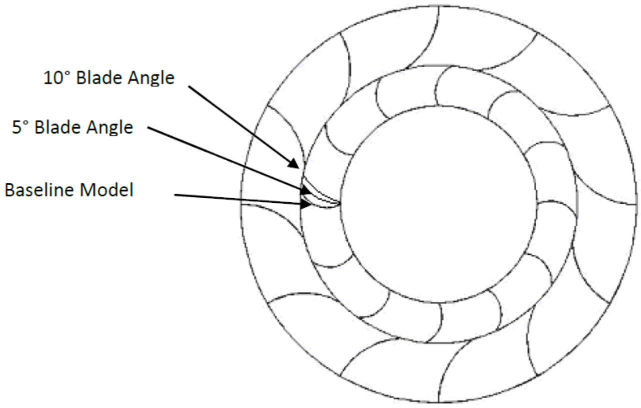

Figure 2 : Varions configurations of the rotor blade used in the analysis.

In the present investigation it has been assumed that flow does not change in vertical direction and hence a two dimensional analysis has been carried out. This also helps in reducing memory requirements and increasing speed of convergence. The shaft in the wind turbine is placed below the blades and does not affect the flow field and hence has not been included in the CFD model. Following are the details of the numerical scheme used in present investigation:

- To simulate wind turbine interaction transient Navier-Stokes equations have been solved numerically for the air flow corresponding to tip speed ratios of 0.1, 0.5 and 1. The tip speed ratio has been defined as:

$$\lambda = (r*\omega) / V \quad (1)$$

- The realizable k-ε turbulence model has been shown [4-6] to predict the performance characteristics of a vertical axis wind turbine with reasonable accuracy and hence has been used in the current analysis.

- The Sliding Mesh technique is used in order to simulate the rotation of the blades. The equations are solved using iterative method such that each time step corresponds to 3º rotation of the rotor blades.

- Second order spatial and temporal schemes have been specified with SIMPLE pressure-velocity coupling in the solver.

- The torque output of the VAWT is monitored throughout the iterative process. For transient models, the solution needs to become statistically steady in order to obtain the results with reasonable accuracy. In this investigation, it has been found that the model becomes statistically steady after four revolutions of the VAWT. The torque outputs from the VAWT are collected corresponding to the fifth revolution, which indicate that the solution instabilities have died out.

The computational model should incorporate time and length scale parameters that are reasonably small to pick-up geometry and time related effects. Computational grid resolution is a significant factor that affects the accuracy and computational time required for each simulation. In this investigation a hybrid mesh (figure 3) has been used to facilitate accurate mapping of the complex wind turbine geometry whilst providing a structured hexagonal/quadratic mesh in the outer flow domain. To allow for hybrid mesh creation the boundaries at which triangular and quadratic cells meet, a uniform mesh nodal spacing has been used such that the mesh quality can be maintained. Four different meshes were taken into consideration for mesh independence testing of the vertical axis wind turbine. These meshes had 45,000, 90,000, 180,000 and 500,000 mesh elements. The results revealed that the model with 90,000 mesh elements is fairly accurate and hence it was chosen for analysis.

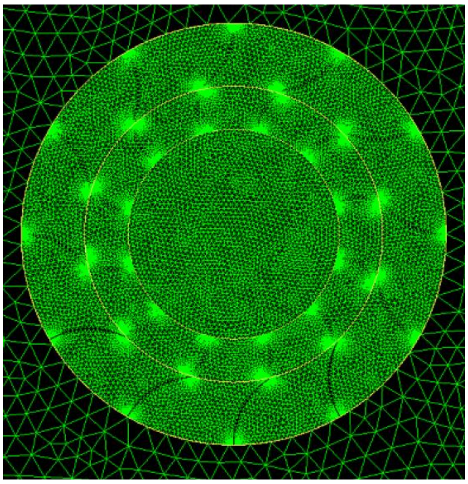

Figure 3: Mesh in and around the VAWT.

3 RESULTS

The performance characteristics of the vertical axis wind turbine used in present investigation were obtained computationally and are presented below.

3.1 Flow Field Analysis

Figure 4 shows the pressure contours for the baseline model in operation. It can be seen that pressure is higher on the front blades and lower on the rear blades. Furthermore, near the top and bottom of the stator blades the pressure is seen to decrease. Globally, as expected, pressure field is highly non-uniform. The rotor blades also show mixed trends. Rotor blades in the lower region seem to have more high pressure passages than on the top. To further visualise the flow pattern the velocity contours have been drawn as shown in figure 5. It shows the movement of air particles through the wind turbine space. It can be seen that near the stator blades the velocities are very small because of no-slip condition. Within the stator passages however the velocities increase.

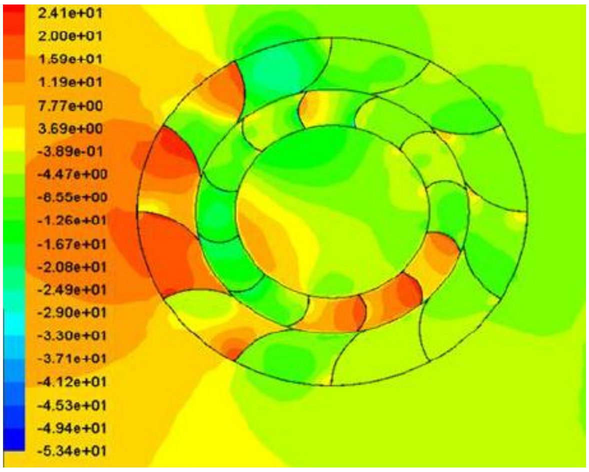

Figure 4: Pressure field around Baseline Model at a tip speed ratio of 0.1.

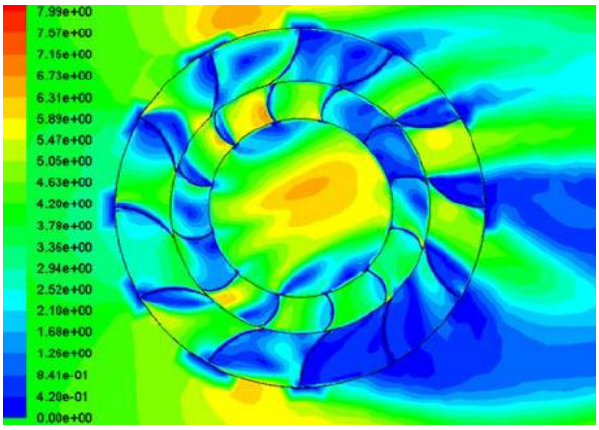

Figure 5: Velocity field around Baseline Model at a tip speed ratio of 0.1.

Within rotor passages the velocity field is found to be non-uniform. On the rear of the wind turbine, velocities are much smaller as compared to the front end. It can further be seen that the areas of high pressure in figure 4 correspond to the areas of low velocity in figure 5. The discussion has clearly indicated that the pressure and velocity fields in the vicinity of the turbine are highly non-uniform.

Examination of the flow through angularly deformed blade shows higher pressure in its vicinity (figure 6). Furthermore, it seems to affect the pressure values in the downstream blades considerably. This aspect can be seen more clearly in the velocity contours shown in figure 7. The flow velocities within stator blades are remarkably similar however below the faulty blade and on the downstream side flow features look completely changed. Hence, effect of any geometric fault in the turbine is seen to be fairly well captured by the flow field around it.

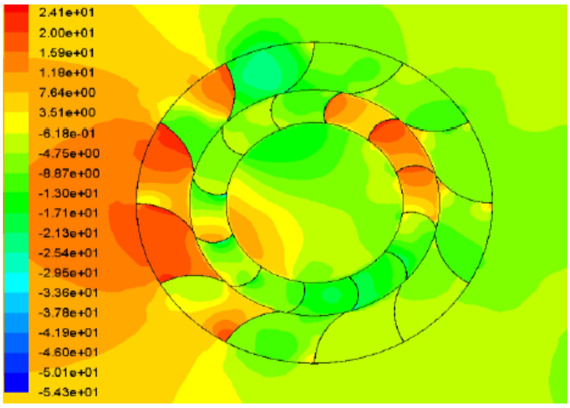

Figure 6: Pressure field around 5° Blade Angle configuration at a tip speed ratio of 0.1.

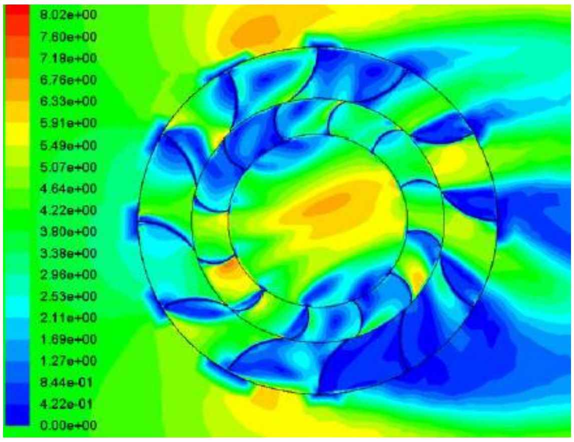

Figure 7: Velocity field around 5° Blade Angle configuration at a tip speed ratio of 0.1.

To investigate effect of deformation more in depth, the blade was moved by 10° and its effect on flow characteristics was simulated. Figure 8 shows pressure contours for such a flow condition. It can be seen that the pressure near the displaced blade has increased further. The pressure field on downstream side looks changed as well. Figure 9 shows the velocity contours for this flow condition. The velocity contours show strong non-uniformity and show strong similarity with figure 8. From the above it can be concluded that although the fault induced effects on flow fields can be seen, it would be difficult to isolate fault severity effects through flow field analysis. Keeping this in view, torque which can be directly measured in a machine, has been used as a parameter to isolate fault severity effects.

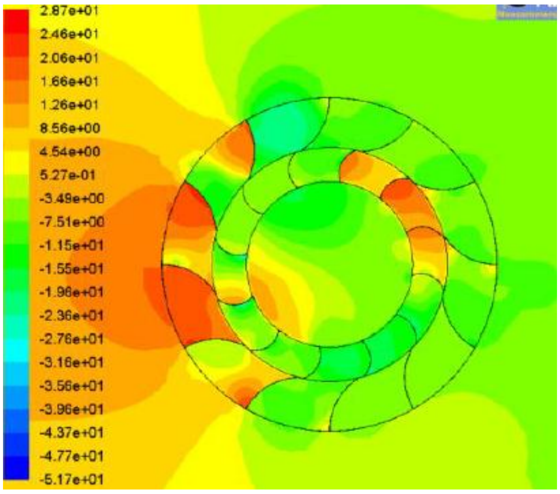

Figure 8: Pressure field around 10° Blade Angle configuration at a tip speed ratio of 0.1.

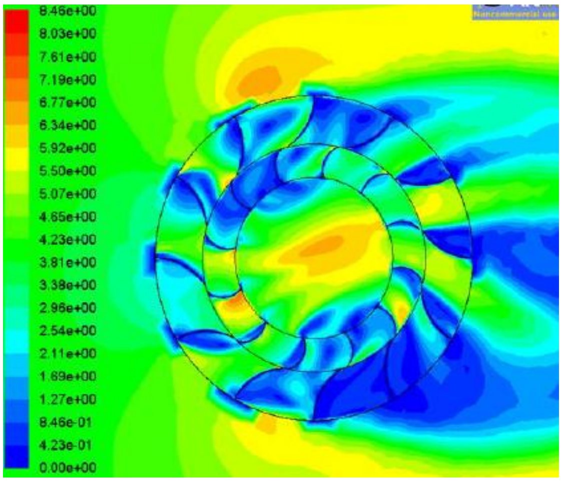

Figure 9: Velocity field around 10° Blade Angle configuration at a tip speed ratio of 0.1.

3.2 Effect of Tip Speed Ratio on Torque Output

Torque output of a wind turbine depends on tip speed ratio of the turbine. It can be clearly seen (figure 10) that as the tip speed ratio increases, the torque output increases for the baseline turbine. As the rotor blades move with respect to stator blades a cyclic variation in flow phenomenon results and hence the torque output is observed to be cyclic as well. It can further be seen that at lower tip speed ratio the variation in peak to minimum torque is much smaller as compared to the values at high tip speed ratios. It can be further seen that the amplitude of the curve representing tip speed ratio of 1 is much higher than for tip speed ratio of 0.1 and 0.5.

Instantaneous torque outputs at a tip speed ratios of 0.1, 0.5 and 1 of the VAWT for 5° Blade Angle and 10° Blade Angle configurations are shown in figures 11 and 12. The curves seem to represent same effect as seen for healthy turbine. A closer examination however reveals of subtle changes in torque output patterns (circles indicated in the figures). The peak and minimum torque values seem to be considerably different for faulty turbines as compared to healthy turbine.

In order to analyse the effects of the faults near design velocity the torque output from the VAWTs have been compared. The tip speed ratio 0.1 corresponds to design operating speed of this turbine. Figure 13 shows the variations in the instantaneous torques for the three geometric models of the VAWT under consideration. The results depict that three torque signatures are considerably different. This figure clearly shows the difference between peak torque and minimum torque over a cycle.

To quantify these effects the ratio of peak to minimum torque was computed for this tip speed ratio. It was found that this ratio is 1.18 for healthy turbine, 1.20 for 5 degree dislocation and 1.24 for 10 degree dislocation. It clearly indicates that this parameter can potentially be used for isolating blade related effects. These effects seem to minimise at higher `tip-speed ratios when churning effects become predominant.

The above discussion has clearly indicated that the geometric imperfections in the wind turbine are clearly felt in the flow field as well as in the torque signature of wind turbine. This information can potentially be very important in fault diagnostics of such systems. Ideally it is expected that it will be possible to simulate a real life wind turbine system very accurately and a comparison of real life wind turbine system with virtual system running on computers will provide us information for diagnosis and prognosis of a wind farm. This would greatly help in ensuring reliable power supply from such farms. Present work has clearly highlighted that simulation of energy transfer between the wind and the turbine can be carried out reasonably accurately and in particular any fault effects can be satisfactorily modelled.

4. CONCLUSIONS

Computational fluid dynamic simulations of healthy and faulty wind turbine have clearly highlighted that both the pressure and velocity fields show effects of any blade faults present in the wind turbine system very clearly. Any fault present seems to affect energy transfer process considerably and these effects are clearly seen in torque outputs of such turbines. It has been seen that the severity of faults affects ratio of peak torque to minimum torque over one cycle. This effect seems to reduce at higher velocities.

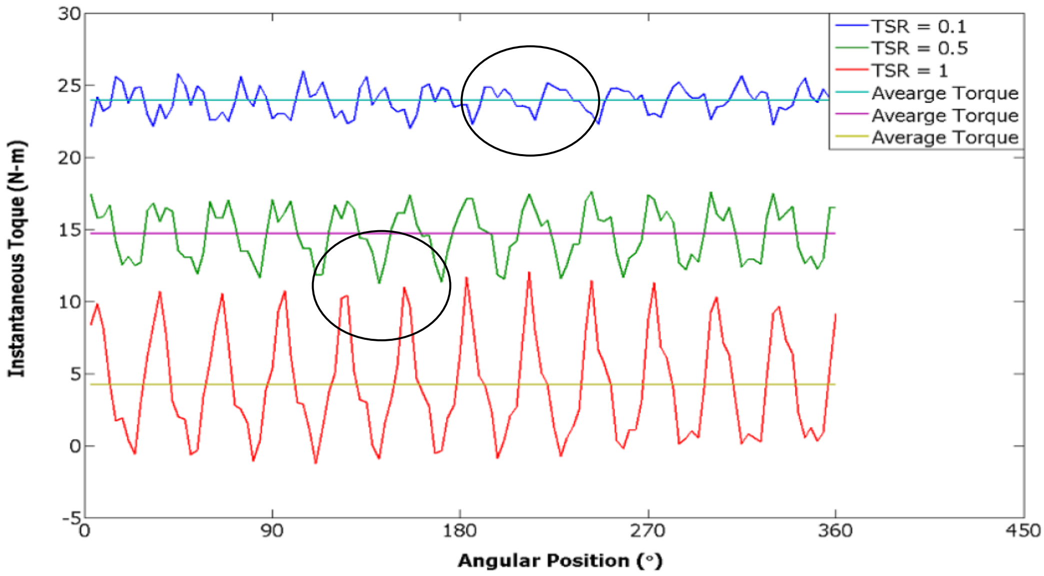

Figure 10: Instantaneous Torque output from the Baseline Model of the VAWT.

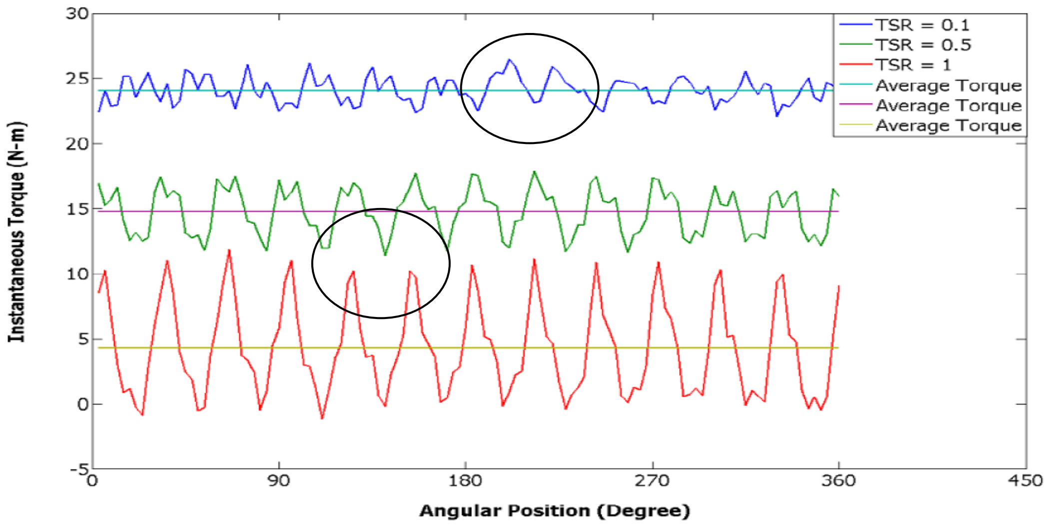

Figure 11: Instantaneous Torque output from 5° Blade Angle configuration of the VAWT.

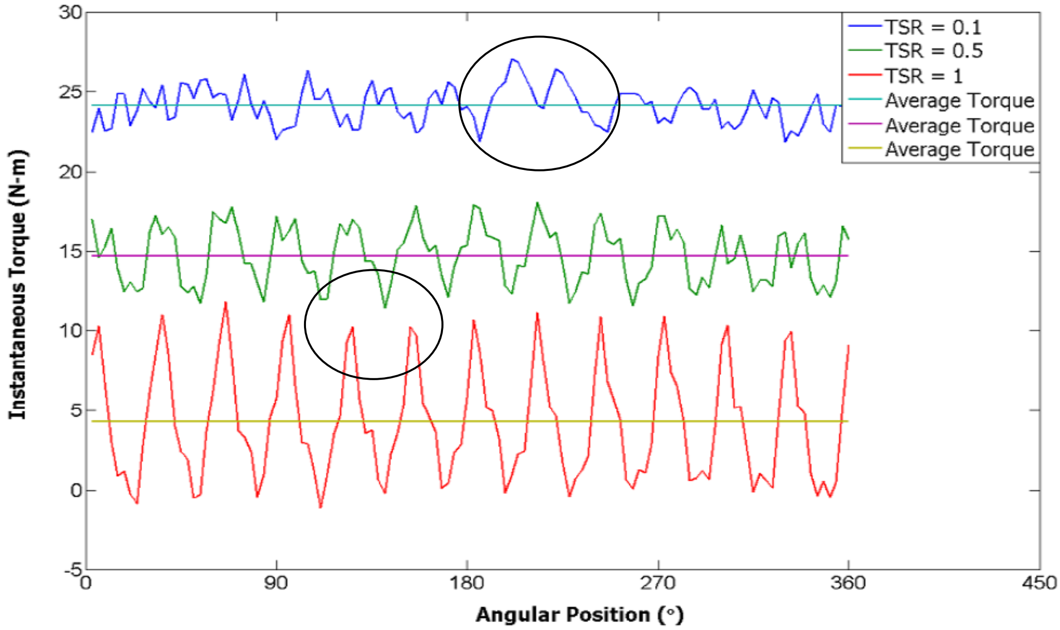

Figure 12: Instantaneous Torque output from 10° Blade Angle configuration of the VAWT.

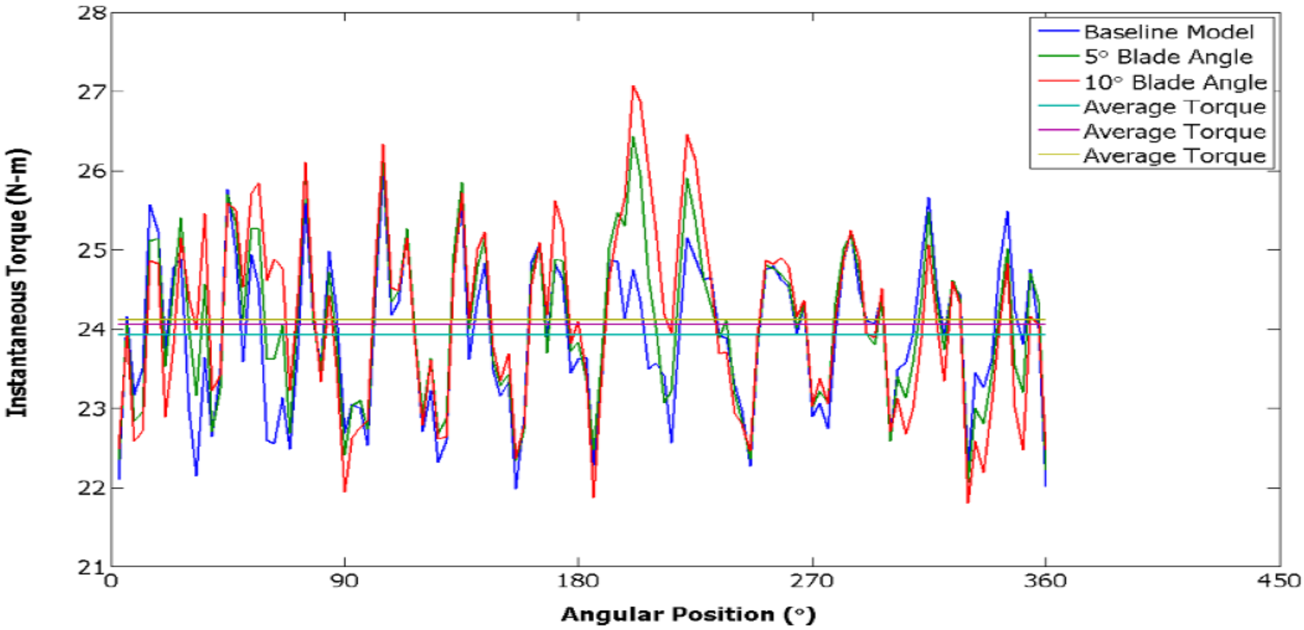

Figure 13 : Instantaneous Torque output for Tip Speed Ratio of 0.1.

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