Parametric Sensitivity Analysis of Vertical Axis Wind Turbine

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***Abstract*—Renewable energy has a huge potential in the upcoming era due to the scarcity of fossil fuels. Taking this into account a 2D numerical simulation has been carried out to predict the performance of a five-bladed Darrieus H-type vertical axis wind turbine (VAWT). To this aim, a computational setup is built on a finite-volume method discretization of two-dimensional unsteady Reynolds-averaged Navier–Stokes equations (RANS), with k-ε turbulence modelling. The analysis is carried out adopting sliding mesh technique and validated against the experimental results. Using this approach the proposed model is solved to predict the lift and drag coefficients, the torque generated, the power coefficients at different tip speed ratios (TSR). Finally, the investigation concludes by validating the overall performance and the power output of the five-blade (NACA 0018) vertical axis wind turbine in freestream condition. The performance efficiency of the current analysis is compared with experimental three bladed (NACA 0018) wind turbine. The turbine achieves a maximum peak power coefficient (C_p) at higher wind speed and tip speed ranging from 2.5 to 3.5. This research advances on understanding the design optimization of small or medium scale VAWT with associated power rating.**

***Index Terms*—wind energy, performance analysis, vertical axis wind turbine, static and dynamic condition**

I. Introduction

Vertical Axis wind turbine gathers its attentions as there will be a scarcity of fossil fuels in near future, hence the planet will liberally depend on renewable energy. Vertical Axis wind turbine doesn't require any yaw mechanism and accumulates air from all directions which leads to a simple design of the turbine system. In early 1980's a free wake method had been carried out to figure the performance and unsteady load on the vertical axis wind turbine. The method incorporates coupling of vortex flow generated by the turbine with three-dimensional unsteady aerodynamics. By computing the strength of bounded vortex (Γ) caused by induced flow [1]. Later a comparative case study on three different turbines, Savonius rotor, Darrieus turbine and the H-rotor was presented. The study validates the mechanical behavior, structural dynamics, aerodynamic performance, constructions and cost of the three different turbines. The case study figures out the desirable feature of vertical axis wind turbine over horizontal axis wind turbine, also envisages that the H-rotor is technically more advantageous over the Darrieus turbine [2]. The H-type turbine blades are uniform with no taper or twist making it a very intelligible device for manufacturing, Research on comparing the aerodynamic efficiency of both vertical axis and horizontal axis wind turbines has been made an excellent argument in parameters such as tip speed ratio (λ), effects of Reynolds number (Re), torque characteristics (τ), effects of airfoil shape, effects of solidity (σ), and effects of Wind Shear. Reynolds number notably affects the C_L, C_D and the accuracy of the numerical analysis results. Also, variable blade pitching angle promotes complex flow around the turbine with unsteady C_L and C_D [3]. A small scale power generating vertical axis wind turbine was modelled and tested in a large scale wind tunnel using both open and closed type configuration. The three-dimensional flow field around the turbine was derived using hot-wire measurements. The upstream velocity correction (V') depend on the wind tunnels blockage ratio (B), these velocity corrections may decrease the thrust coefficient (C_T) [4]. Furthermore, both the 2D and 3D analysis of a three bladed vertical axis wind turbine were performed with transient computation and mesh deformation technique, with inner and outer domain [5]. Late 2013, An analytic approach to accurately predict the coefficient of power using double multiple stream tube model (DMST) which allows modelling velocity variation in both upwind and downwind part of the turbine. In which the induced flow in the upwind and the downwind of the turbine is calculated separately [6]. When it comes to airfoil thickness NACA 0018 performed well and generated a maximum peak power coefficient (C_p) for different tip speed ratio (λ), compared to other airfoils. The performance of the turbine increases with the increase in turbine blades (N) resulting in a high power coefficient for different tip speed ratios [7].

II. Theoretical Background

A. Static Analysis

In this research, a five bladed vertical axis wind turbine is probed with each blade kept at an angle of 72 º. The blades in the turbine are exposed to an immense range of angle of attack at the startup. Also, the induced flow over each blade influences the other parallel blade when it passes by. To examine this effect a static flow

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analysis is accomplished to interpret the aerodynamic forces around each blade at the startup and its impact over the other blade. The blades experience both lift and drag force, Lift (L) force acts perpendicular to the direction of relative wind flow and drag (D) in the direction of the flow of wind. So the normalized lift and drag coefficients on each blade are given by

$$C_L = \frac{L}{\frac{1}{2}\rho A V^2} \quad (1)$$

$$C_D = \frac{D}{\frac{1}{2}\rho A V^2}. \quad (2)$$

The tangential force drives along the turbine blades but the normal force acts normal to the blades propelling it away from the shaft, the tangential and normal coefficients which act on the blades are defined as

$$C_t = C_L \sin(\alpha) - C_D \cos(\alpha), \quad (3)$$

$$C_n = C_L \cos(\alpha) - C_D \sin(\alpha). \quad (4)$$

B. Dynamic Analysis

The pressure, velocity and torque generated by the turbine are then analyzed. This analysis gives a finer picture of the load on blades while producing power (P). The efficiency of the wind turbine amount to power coefficient (C_p) relay on the tip speed ratio (λ), designated as

$$C_p = \frac{P}{\frac{1}{2}\rho A V^3} \quad (5)$$

V is the wind velocity, ρ is the density of the air, and A is the swept area of the turbine

$$\lambda = \frac{\omega R}{V} \quad (6)$$

R is the radius of the turbine.

III. Methodology

A. Model Geometry and Mesh Generation

Two-Dimensional five bladed vertical axis wind turbine is modelled in SolidWorks and the flow analysis is carried out in ANSYS Fluent (academic). The turbine is a lift-based, with NACA 0018 symmetrical airfoils, chord length (c) of 0.2 m, turbine diameter (D) of 2.5m with an aspect ratio of 12.5 has been taken into account [8]. The geometry is divided into two domains, a circular interface and a rectangular outer domain. The circular interface is of 3m diameter mounts the turbine blades, while the outer rectangular domain has dimensions of 50 × 20m contains the inlet, outlet and specified shear wall boundary conditions. Using ANSYS mesh generation 2D grids were built with 4.5×10^5 elements, with fine structured mesh for the outer rectangular domain and linear triangular mesh in the circular interface domain with a growth ratio of 1.1. Edge sizing is done for both the interface and the airfoil which were the area of concentration. In order to compute the unsteady flow physics around the rotor, sliding mesh technique has been performed for the dynamic analysis, this technique is time-periodic which accurately predicts the unsteady flows in a moving frame of reference.

B. Aerodynamic Simulation Parameters

The numerical calculation is performed for both the static and sliding mesh technique with the freestream wind velocity (V) ranging from 5, 10 and 15m/s and TSR from 2.5 to 4.5 with an increment of 0.5 for dynamic analysis. The air density and viscosity are set to 1.23 kg/m^3 and 1.78×10^{-5} kg/m-s, which remains the same for all the cases. A 2D, transient, pressure based, coupled, incompressible solver setting has been adopted for the investigation. No-slip condition is imposed on the surface of the blade walls and specified shear wall condition for the outer wall region and pressure outlet boundary condition (Δp=0) for the outlet. Both the continuity and unsteady Reynolds-averaged Naiver-Stokes equation governs the flow field.

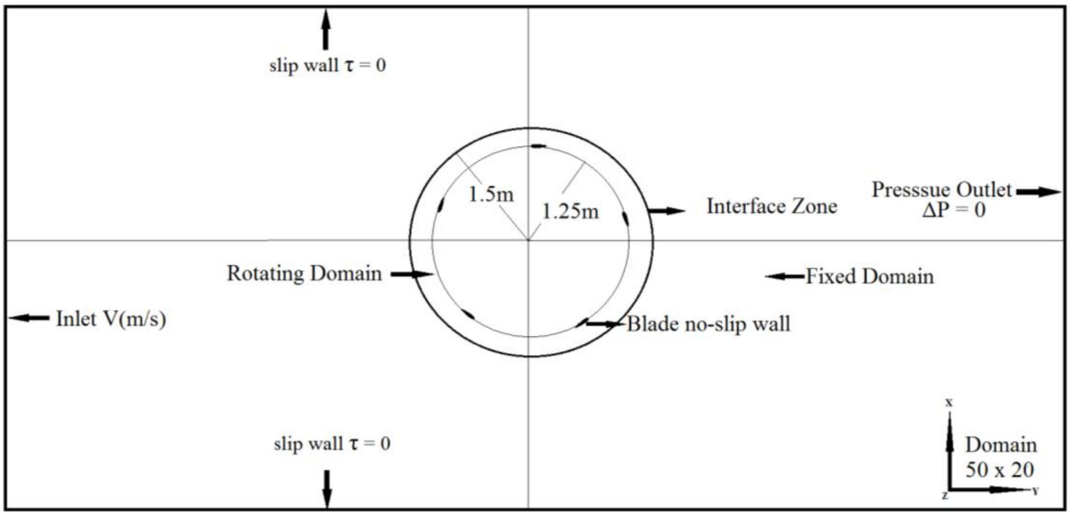

Figure 1. Computational wind tunnel domain dimensions and boundary conditions.

C. Turbulence Modelling

For both static and sliding mesh simulation Realizable k-ε turbulence modelling has been chosen to solve the Reynolds stresses with enhanced wall treatment with the turbulence intensity of 0.5% and turbulence viscosity ratio of 5%. The RANS equation is solved using least square cell based with second order accuracy for the gradients, pressure, momentum and turbulent length scale. Finally, the time-step is set to 1 $\times 10^{-3}$s for the aerodynamics static computation and 1$\times 10^{-5}$s for the dynamic computation. The choice of Realizable k-ε turbulence model is that the model resolves flow field with large boundary layer separation more accurately.

IV. Result and Discussion

A. Static Analysis

To study the startup performance of a vertical axis wind turbine, it is much needed to analyze lift and drag on the surface of individual airfoil. Taking this in reckon a static analysis on the five blades vertical axis wind turbine is formulated to characterize the lift and drag around each airfoil at a different angle of attack. The five blades incidence range from 0 º, 72 º, 144 º, 216 º and 288 º which defines that each blade pose different angle of attack during the startup. Also, such data is very scant for NACA 0018 airfoil, which has high aerodynamic efficiency when compared to other airfoils [7]. The aerodynamic lift and drag coefficient results for three different Reynolds number has been collected and compared with experimental results of Alessandro Bianchini et al [9]. The graph plotted for numerical results of both drag and lift coefficients is in close agreement to that of the experiment's data, which are plotted and shown in Fig. 3 & Fig. 4.The drag coefficient graph maintains a symmetrical drag curve with the same axis while the lift curve remains asymmetrical. From the lift curve it is noted that there is a surge in the lift coefficient, the formations of wake from the leading and trailing edge of the blade affects the next parallel blade. This phenomenon will affect the performance of the turbine predominantly during startup. The blade at 144 º achieved a peak range for all the above velocities with a peak lift coefficient of 1.25 for 10m/s, higher order of lift coefficients are due to the deferral stall angle. The compared results led to visualize how induced flow past one blade prevail the flow behavior and affects the flow field of the adjacent blade, sympathize that the startup lift force is contributed only by blades positioned at an angle 0 º, 144 º, and 288 º , But the remaining two blades shows a divergence in the lift curve. All the three simulation blades at an angle 72 º and 216 º pose a high drag due to the detached flow, which leads to a pressure differential at the leading and trailing edge of the blades reducing lift, with a peak drag coefficient of 1.75 at 5m/s. These phenomena can be viewed from the pressure contour plot at Fig. 2, which shows how the wakes are created and disturbs the flow pattern of the other blades. Hence the static simulation enables to understand the startup physics of the five-bladed vertical axis wind turbine by modelling the aerodynamic parameters.

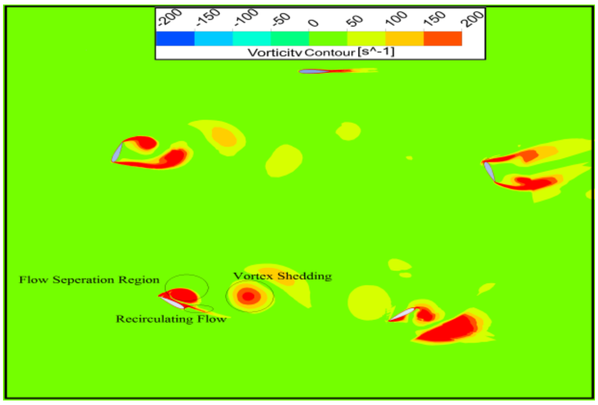

Figure 2. Predicted vorticity field for static analysis at 15m/s.

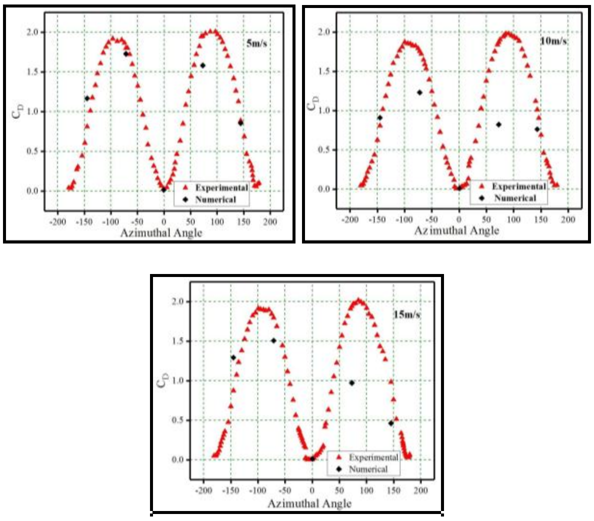

Figure 3. Comparisoin of experimental and numerical static analysis drag plot on each airfoil at different azhimuthal angle.

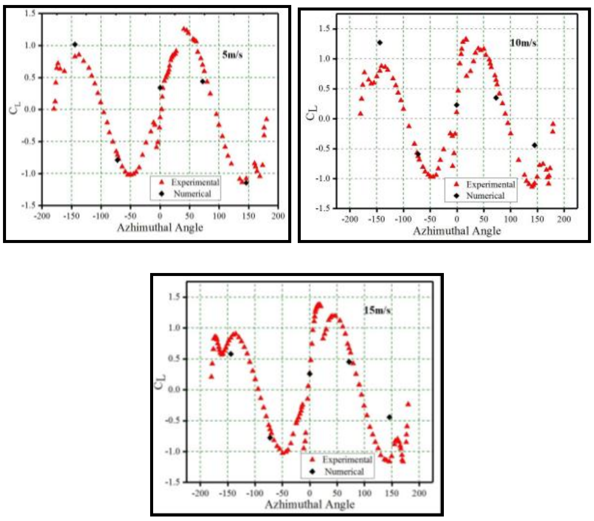

Figure 4. Comparisoin of experimental and numerical static analysis lift plot on each airfoil at different azhimuthal angle.

TABLE I. FLOW POSTURE FOR THE DYNAMIC ANALYSIS

Velocity (m/s)	Appearance			
	λ = 2.5	λ = 3	λ = 3.5	λ = 4
	Rotational Velocity (ω) rad/s			
5	10	12	14	16
10	20	24	28	32
15	30	36	42	48

B. *Dynamic Analysis*

1) Validation with three bladed NACA 0018 airfoil turbine.

In order to probe the performance of five bladed NACA 0018 vertical axis wind turbine, a validation analysis is performed with three bladed NACA 0018 turbine performed by Firdaus et al. [10].The validation of three-bladed turbine is performed in such a way that geometry and boundary conditions are same as that of the five-bladed turbine, with an inlet velocity of 8m/s and rotational speed from 3.2 to 25.6 with an increment of 3.2, making a set of eight simulations. There may be a slight shift in the result of comparison as the computational domain parameters and boundary conditions used for the current analysis differ from that of the experimental setup, the solver settings and other parameters is same as that of five bladed. The analysis is performed and compared to the fixed pitch blades α = 0º. The compared results of both numerical 2D simulation and experimental are shown in Fig. 5. The C_p value for the three bladed experimental is about 0.18 between 1 to 1.5 tip speed ratio but for the numerical 2D analysis peak of about 0.06 at 2.5 tip speed ratio. This variation also shows that C_p varies with the diameter of the turbine, bigger the turbine higher C_p will be obtained at higher tip speed ratio. This comparison is made mainly to check that the current model follows the trend as that of the experimental setup hence righteous for validation, despite the shift in C_p. Eventually, the performance of the five-bladed NACA 0018 will be compared with NACA 0018 three-bladed turbine.

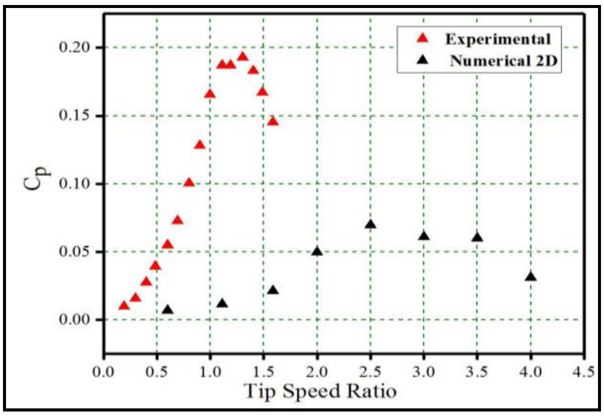

Figure 5. Performance curve of three bladed H-Darrieus turbine versus TSR with experimental data.

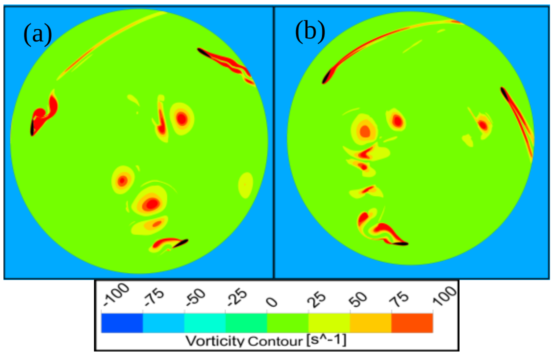

Figure 6. Predicted Vorticity field for the three bladed rotor computed using Realizable k-ε model with (a) 9.6 rad/s and (b) 12.8 rad/s with a velocity 8 m/s.

2) Analysis on five bladed NACA 0018 airfoil vertical axis wind turbine

The dynamic analysis carries through three different velocities and four different tip speed ratio with different rotational speed as shown in table 1. Boundary condition remains the same as that for the static analysis with a slight division of the model into two interfaces, one for the domain and one for the rotor. The mesh motion depends on the rotational velocity, which is calculated as per the tip speed ratio. The numerical results are compared with an experimental study done by Firdaus et al [10], which the author has studied the overall performance of three straight blades NACA 0018 vertical axis wind turbine. Due to the inadequacy of data regarding a five bladed NACA0018 vertical axis wind turbine. The curve starts with a positive torque at 2.5 tip speed ratio for all the three velocities with a sudden transit by reaching a peak. Higher C_p value of 0.41 is obtained at 15m/s at TSR=3, has seen in Fig. 7. After reaching the peak the curve starts to dip down, the turbine generates a negative or minimum C_p at TSR=4, which shows that there won't be any positive torque generated by the turbine if it is set to higher tip speed. Between TSR=2.5 to TSR=3.5, the work done by the turbine is very sensible but further increase in Tip speed forms an increase in pressure drag and drop in lift due to detached flow from low aspect ratio wind turbine blades.

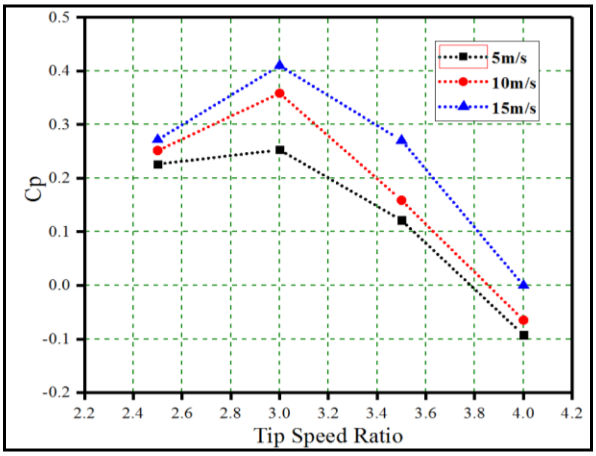

Figure 7. Performance curve of five bladed H-Darrieus turbine versus TSR with experimental data.

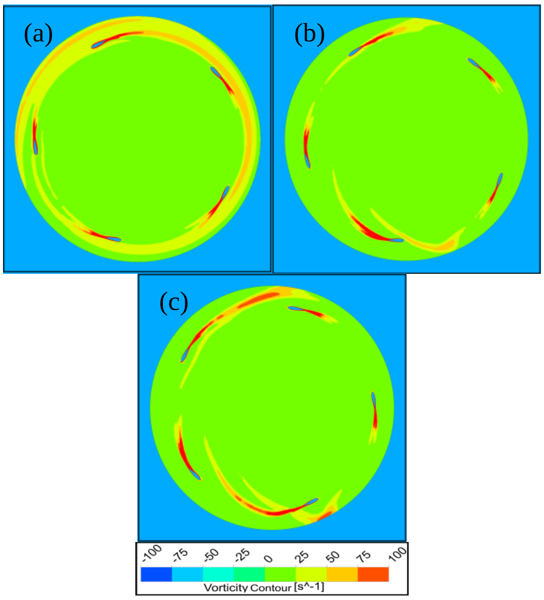

Figure 8. Predicted Vorticity field for the five bladed rotor computed using Realizable k-ε model with (a) 12rad/s at 5m/s, (b) 24rad/s at 10 m/s and (c) 36 rad/s at 15m/s

Fig. 9 Shows the torque generated by each blade at 10m/s with a TSR=3, the graph is highly fluctuating for single rotation of the turbine. Initial startup torque is enormously contributed by blade four and five, subsequently followed by blade three and two. The blades produce torque periodically and it ranges from values close to 60 Nm to -10 Nm. But, the net torque throughout the cycle remains positive. Fig. 10 shows the variation of torque with respect to azimuthal angle. The graph depicts the comparison of the torque generated by the turbine at different tip speed ratios within one rotation at a wind speed of 10m/s. Net torque remains in the positive note with two peaks from TSR=2.5 and TSR=3.5, the curve remains fluctuating with positive torque at each revolution for all the tip speed ratios. Which concludes that at lower tip speed ratio the torque will be minimum or negative torque.

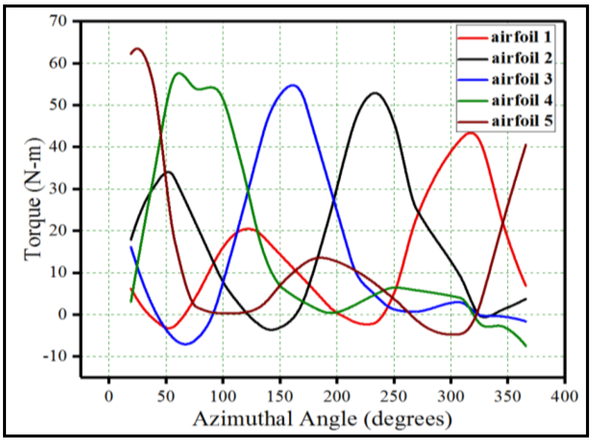

Figure 9. Predicted Torque generated by each airfoil at 10m/s with 28 rad/s

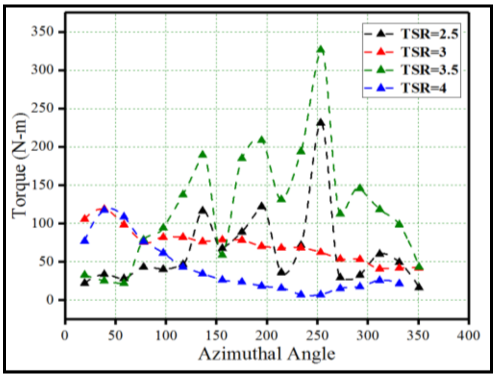

Figure 10. Predicted Torque versus Tip at speed ratio at 10 m/s

3) *Mesh adaptation*

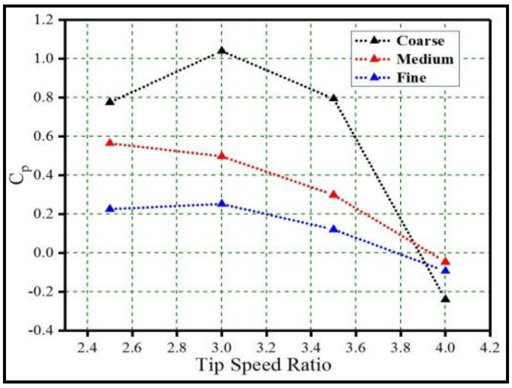

Figure 11. Mesh adaptation plot for power coefficient verses TSR with 2.5, 3.5 and 4.5 million elements at 5m/s

Three different types of the mesh have been made to perform the grid adaptation with 2.5, 3.5 and 4.5 million elements for 5m/s as shown in the Fig. 11, with more refinement on the surface of blades to obtain more accurate result. From the curve, it is observed that fine grids figures out more accurate and peak C_p value while the medium and coarse grids under predicts the turbine performance. The reasonable trend is predicted in all the three cases expect with fine mesh which measures the accurate peak C_p.

V. Conclusion

The analysis is characterized using Realizable k-ε turbulence modelling, which predicted the performance of the turbine more accurately with that of experimental result. Static analysis demonstrates the starting performance or the initial torque generation of the turbine from the lift and drag curve obtained. The maximum peak value is obtained at higher tip speed ratio, implies that NACA 0018 doesn't self-start at low tip speed with the lift is highly contributed by any two blades in a complete rotation. Gradually degrade in C_p value is observed as the tip speed is increased but a steady drop is seen with that of three bladed with an increase in tip speed. Eventually, remarkably positive torque will be maintained throughout each rotation of a five bladed turbines between 2.5 to 4 tip speed ratios also defines that the turbine performs well ahead of the three-bladed turbines.

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