Performance Exploration of Mixed Airfoil Small Scale Horizontal Axis Wind Turbine Blade by QBLADE and CFD

L. Rajib Kanti Monda, R. Gayathri, R. Mercy Shanthi

Abstract--- In this energy hungry world, energy efficient methods to increase the extraction of work from various sources of renewable energy is always appreciated. One such commonly used source is wind energy. Wind turbines and their aerodynamics are always subjected to constant research for increasing their efficiency which convert the abundant wind energy into usable electric energy. The current work is based on the comparative study between "Blade-Element- Momentum" (BEM) analysis and "Computational-Fluid-Dynamics" (CFD) analysis of mixed airfoil small-scale horizontal axis wind turbine blade which gives optimize torque, power and power coefficient. Then BEM was executed with the application of the open source wind turbine design and performance computation software Q-Blade v0.96. After that, CFD simulation was done by Ansys fluent version 14.5. Here, k omega Shear Stress Transport (SST) model was conducted. Blade was designed in creo parametric version 5.

Keywords--- Qblade, Mixed airfoil, Blade Element Momentum Method, Schmitz Optimization Method, CREO Parametric, HAWT.

I. INTRODUCTION

One of the biggest problems in developing countries is a problem of electricity. It is worth mentioning that about a fifth of the world's population lack access to electricity, especially those people who live in remote areas of the world. Researchers around the world have shown that global warming has been caused in part by the greenhouse effect which is largely due to the use of fossil fuels for transportation and electricity. So, the use of renewable energy sources such as geothermal, solar, wind and hydroelectric power needs to be increased to protect the environment. As a renewable energy, wind energy has taken an increasingly important place in energy policies at national and international level as a response to climate change.

II. DESIGN

Airfoil selection

Thick airfoils used at the root end of the blade to provide sufficient strength and thin at the tip portion to improve aerodynamic performance. Two airfoil have been selected according to their maximum L/D ratio. The selected airfoils are SG6040 and SG6043.SG6040 is a thick airfoil(thickness 16%) that used for root part of the blade and SG6040 is a thin airfoil(thickness 10%) that used for tip part of the blade.

Blade element momentum method

- Blade Element Momentum Theory equates two methods of examining how a wind turbine operates.
- The first method is to use a momentum balance on a rotating annular stream tube passing through a turbine.
- The second is to examine the forces generated by the aerofoil lift and drag coefficients at various sections along the blade.
- These two methods then give a series of equations that can be solved iteratively.

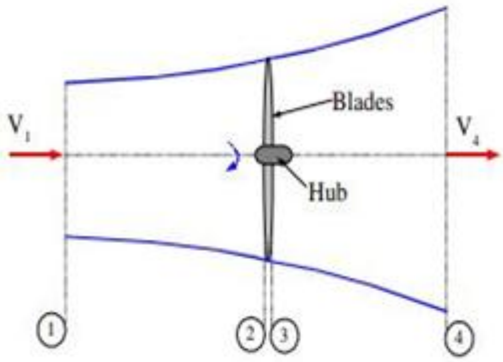

Figure 1: Axial stream tube around a wind turbine

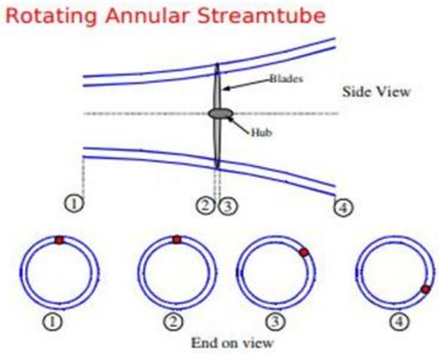

Figure 2: Rotating annular stream tube

- Assume $p_1 = p_4$ and $V_2=V_3$ and Bernouli eqn, $p_2-p_3=(½)\ \rho(V_1^2 - V_4^2)$
- Axial force, $dFx = (p_2 - p_3)dA$
- $dFx = (1/2)\ \rho(V_1^2 - V_4^2)dA$

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- Axial induction factor, $a = V_1 - V_2/V_1$ and $V_2 = V_1(1-a)$
- $V_4 = v_1(1-2a)$

So we get, Axial force, $dF_x = (1/2)\rho V_1^2 [4a(1-a)]2\pi r dr$.
Moment of Inertia of an annulus, $I = mr^2$

- Angular Moment, $L = I\omega$
- Torque, $T = dL/dt$
- $T = dI\omega/dt = d(mr^2\omega)/dt = dm'/dt(r^2\omega)$ and $dm' = \rho A V_2$
- $dT = \rho 2\pi r dr V_2 \omega r^2 = \rho V_2 \omega r^2 2\pi r dr$ and angular induction factor, $a' = \omega/2\Omega$
- $V_2 = V(1-a)$
  So we get, $dT = 4a'(1-a)\rho V \Omega r^3 \pi dr$

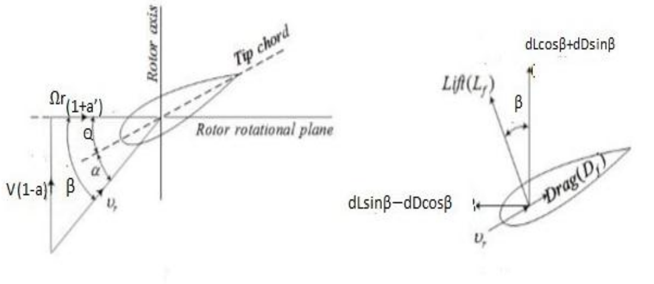

Figure 3: Aerodynamic Forces on a blade elemnt

From figure 3, $\tan\beta = v(1-a)/\Omega r(1+a')$ and Tip speed ratio, $\lambda r = (\Omega r/V)$

- $\tan\beta = (1-a)/\lambda r(1+a')$..assume $a=1/3$ and $a'=0$....we get inflow angle, $\beta=(2/3)\tan^{-1}(1/\lambda r)$
- Axial thrust on this blade element is the normal force acting on it and the torque exerted on this element is the tangential force times the radial distance r from the hub
- Blade element: $dT = dL\sin\beta - dD\cos\beta$ and $dF_x = dL\cos\beta + dD\sin\beta$
- $dL = C_L(1/2)\rho W^2 c dr$ and $dD = C_D(1/2)\rho W^2 c dr$
- $dF_x = B(1/2)\rho W^2(C_L\cos\beta + C_D\sin\beta)c dr$ and $dT = B(1/2)\rho W^2(C_L\sin\beta - C_D\cos\beta)c dr$
- So, from blade element we get, $dF_x = \sigma'\pi\rho\{V^2(1-a)^2/\sin^2\beta\}(C_L\cos\beta + C_D\sin\beta)r dr$ and $dT = \sigma'\pi\rho\{V^2(1-a)^2/\sin^2\beta\}(C_L\sin\beta - C_D\cos\beta)r^2 dr$..........(1)
- Solidity: $\sigma' = Bc/2\pi$
- Previously from momentum method we get, $dF_x = (1/2)\rho V^2[4a(1-a)]\pi r dr$ and $dT = 4a'(1-a)\rho V\Omega r^3 \pi r dr$.........(2) and comparing the eqn 1 and eqn 2 we get below,
- $a'/1-a = \sigma' C_L/(4\lambda r \sin\beta)$
- $a/1-a = \sigma' C_L\cos\beta/4\sin^2\beta$
- $a'/1-a' = \sigma' C_L/4\cos\beta$
- We get, Angular induction factor, $a' = 1/[\{4\cos\beta/\sigma' C_L\}-1]$ and axial induction factor, $a = 1/[1+4\sin^2\beta/\sigma' C_L\cos\beta]$
- Guess the axial and angular induction factors (a and a')
- Re-compute a and a'
- Compare the new a and a' with the ones obtained from previous iteration
- Continue iteration until converged
- Kinetic energy, $E_k=(1/2)mv^2$ and wind power, $p=E_K/t$
- $m=\rho Avt$
- So we get, Wind power, $P=(1/2)\rho Av^3$
- Power coefficient, C_p(Rotor power/wind power)= $P/((1/2)\rho Av^3)$
- Rotor power, $P=(1/2)C_p\eta\rho Av^3$
- The power out, P, is equal to the thrust times the velocity at the disc: $P=(1/2)\rho A_2(v_1^2-v_4^2)v_2=(1/2)\rho A_2 v^3 4a(1-a)^2$
- Power coefficient, $C_p=4a(1-a)^2$

Blade design procedure:

Power $P=(1/2)C_p\eta\rho Av^3$

Step-1: Design procedure begins with deciding power requirement. Where, C_P power coefficient, η efficiency (mechanical & electrical).

Step-2: Choose a tip speed ratio (λ) for the machine. For water pumping pick $1 < \lambda < 3$ (which gives a high torque) and for electrical power generation pick $4 < \lambda < 10$. Normally 6 or 7 TSR used for low wind speed region.

Step-3: Choose the number of blades (B), which is based on practical experience. Generally, 3 number of blades used due to structural and performance measure. Up to 3 blades power developed is good but after this power increase is not significant and expenditure increased too much. B=3 chosen for designing rotor blade.

Step-4: Select airfoil according to chosen TSR, for TSR<3 flat plates are used instead of airfoil shape. Two airfoils have been selected SG6040, SG6043.

Step-5: Obtain and examine lift & drag coefficient curves for the airfoil. Note that; different airfoil may be used at different span of the blade length; a thick airfoil may be selected for the hub to give greater strength. Two airfoils has been used to design rotor blade, thick airfoil is used at root portion and thin airfoil is used at tip section.

Step-6: Define chord and twist distribution along the blade length using optimized Schmitz theory which is given below, we can see in fig(a) twist angle, Q=(inflow angle-angle of attack).

$$Q = \frac{2}{3}\tan^{-1}\frac{1}{\lambda_r} - \alpha_D$$

$$c = \frac{16\pi r}{BC_L}\left(\sin\left(\frac{1}{3}\tan^{-1}1/\lambda r\right)\right)^2$$

Step-7: Divide whole blade length into N number of blades.

Step-8: To determine the Performance of the blade, initially we need to guess the values for axial induction factor at each blade element. Then using the equations from Blade element momentum theory by iterative method optimum axial induction factor can be calculated. Flow algorithm for calculation of induction factors has been developed which has been widely used by various wind Turbine industries. So, the initial guess is better to have zero i.e. a=0 & a'=0.

Step-9: Now modify the design as performance analysis is an iterative process.

III. QBLADE ANALYSIS

The software QBlade is developed as an open source framework for the simulation and design of wind turbines. QBlade utilizes the Blade Element Momentum (BEM) method for the simulation of horizontal axis wind turbine performance. For the design of custom airfoils and the computation of airfoil lift-and drag coefficient polars the viscous-inviscid coupled panel method code XFOIL is integrated within the graphical user interface of QBlade. Additionally, a module for the extrapolation of airfoil polars, beyond the stall point, for a 360° range of angles of attack is integrated. The resulting functionality allows the use of QBlade as a comprehensive tool for wind turbine design. QBlade is constantly being maintained, validated and advanced with new functionality.

We have done hand calculation, using the schmitz formula(STEP 6) for finding the chord and twist angle. Then we directly put the value in Qblade tool.

Firstly we have imported the airfoil in Qblade. Then we have to analyse it by giving Reynold number and strat-end angle. Secondly, we have done 360degree extrapolation for a smooth conversation and reasonable result. Thirdly, we have put the chord and twist angle directly in Qblade.

- Blade length with hub=1.4m
- Hub diameter=.2m
- Rotor diameter=2.9m
- Root part=sg6040 airfoil,angle of attack=9,Cl=1.3732
- Tip part=sg6043 airfoil,angle of attack=7,Cl=1.2061
- Tip speed ratio=7
- Velocity of air=6m/s
- Reynold number=100000

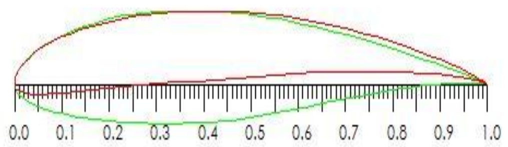

Figure 4: Importing airfoil in Qblade Xfoil

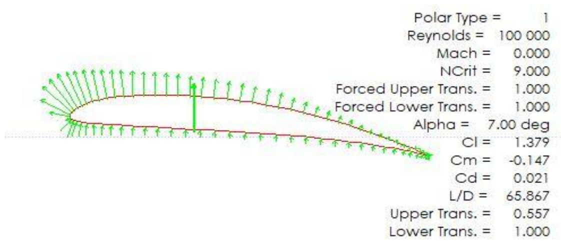

Figure 5: SG6043 Airfoil Analysis

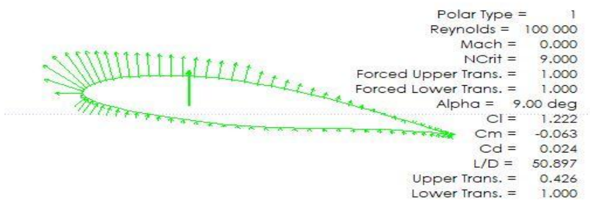

Figure 6: SG6040 Airfoil analysis

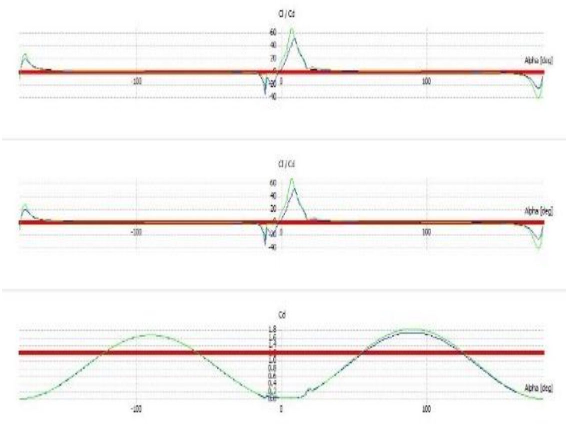

Figure 7: 360˚extrpolation

HAWT

3 blades and 0.20 m hub radius ☑ Blade Root Coordinates

	Pos (m)	Chord (m)	Twist	Foil
1	0	0.05	0	Circular Foil
2	0.05	0.05	0	Circular Foil
3	0.1	0.146327	8.96249	SG6040
4	0.2	0.121895	3.43495	SG6040
5	0.3	0.0835468	1.93142	SG6043
6	0.4	0.0717943	-0.471192	SG6043
7	0.5	0.0627253	-2.2157	SG6043
8	0.6	0.0555836	-3.53768	SG6043
9	0.7	0.049844	-4.57303	SG6043
10	0.8	0.0451454	-5.40536	SG6043
11	0.9	0.0412359	-6.08877	SG6043
12	1	0.0379366	-6.65981	SG6043
13	1.1	0.0351175	-7.14399	SG6043
14	1.2	0.0326826	-7.55967	SG6043

Fig. 8: Section wise Chord and twist angle distribution (Schmitz method)

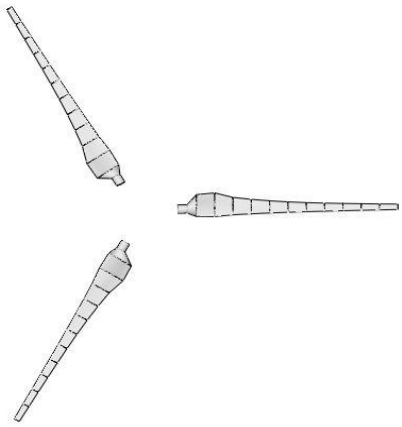

Figure 9: Qblade HAWT design

IV. DESIGN IN CREO PARAMETRIC VERSION 5

Since Ansys 14.5 does not support Qblade stl file, creo parametric version 5 is used.

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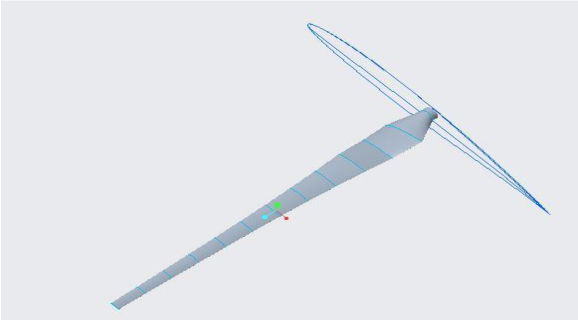

Figure 10: Design of single HAWT blade

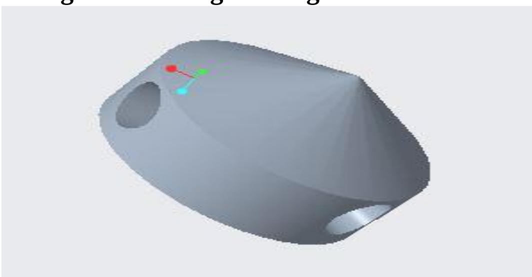

Figure 11: Design of Hub

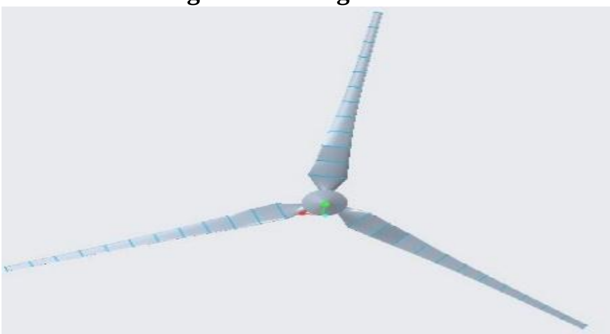

Figure 12: Assembly

As discussed above, Schmitz chord and twist angle formulae are used to find chord and twist angle and design was made in creo parametric version 5 which is similar to Qblade design.

V. CFD ANALYSIS

CFD analysis of full rotor is done using Ansys fluent version 14.5. k-omega sst model is preferred for more accuracy.

Domain 1:Rotor blade with hub

Domain 2:Wall 1.inlet 2.outlet 3.wall

Applying boundary condition:1.Inlet velocity inlet:6m/s 2.Rotor body smooth rotating at 30 rad/s or 286 rpm 3.Outlet:Pressure outlet 4.Wall:no slip wall: stationary.

It is pressure based, time steady, model viscous-sst k-omega, materials-air, domain 1 is using as a reference frame motion-rotational velocity 30 rad/s or 286 rpm, Reference frame- absolute, Reference :compute from inlet and area 6.15m². Mesh-Nodes:52525, Elements-285115,Hexdominant mesh with prism layer. Scheme-simple, Gradient-least square cell based, Pressure-standard, Momentum, turbulent kinetic energy, specific dissipation rate are taken as second order upwind. Solution initialization-standard initialization.

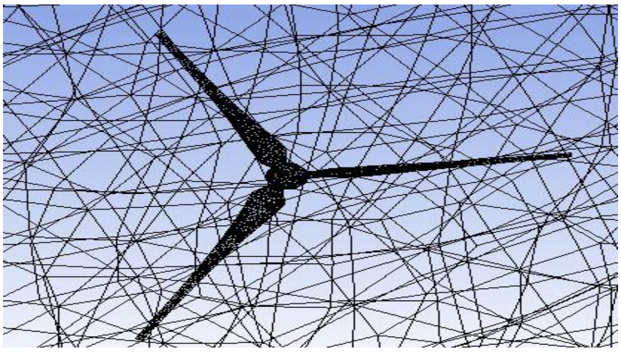

Figure 13: Meshing of HAWT

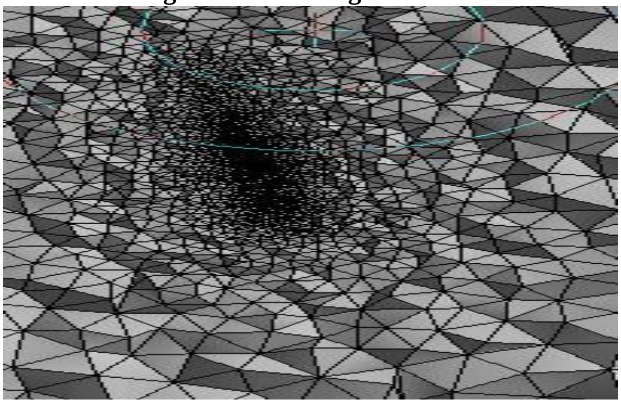

Figure 14: Prism layer

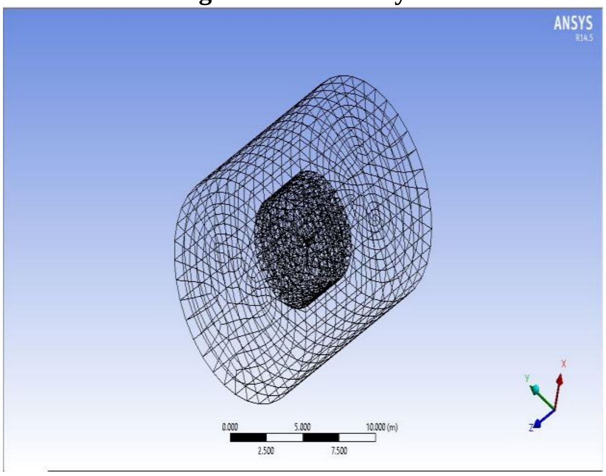

Figure 15: Cylindrical Domains at Z axis

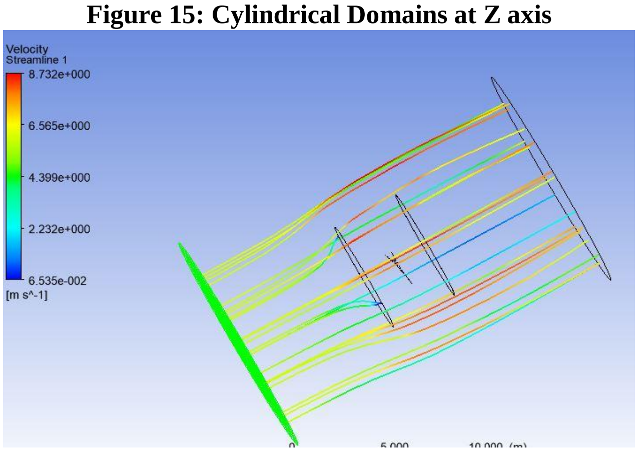

Figure 16: Velocity streamline

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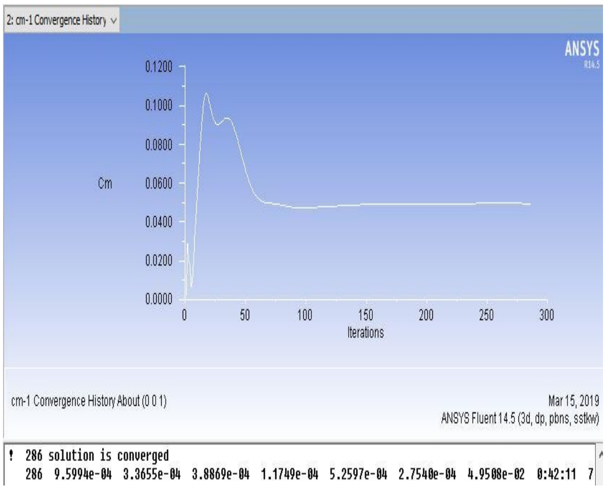

Figure 17: Torque coefficient

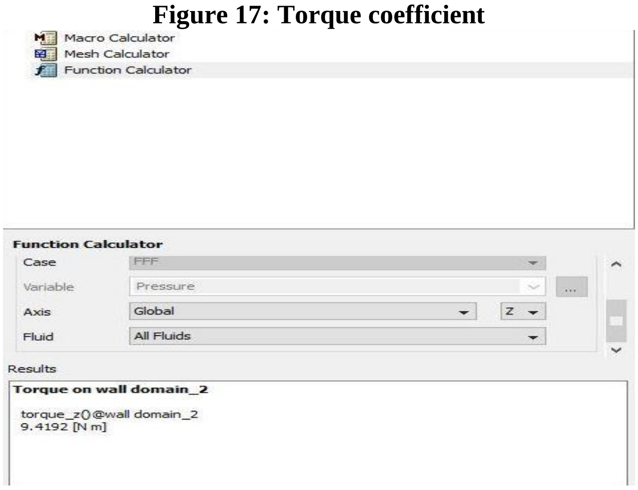

Figure 18: Torque value in CFD calculator

VI. RESULT AND DISCUSSION

Result from QBLADE

The Qblade results are as below.

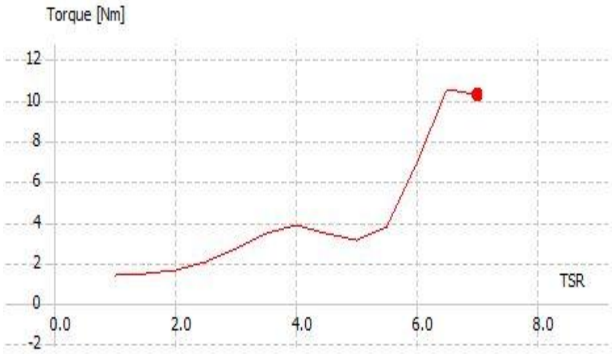

Figure 19: Torque vs Tip Speed Ratio

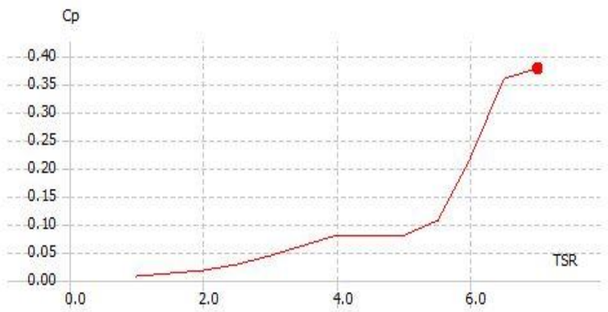

Figure 20: Power coefficient vs TSR

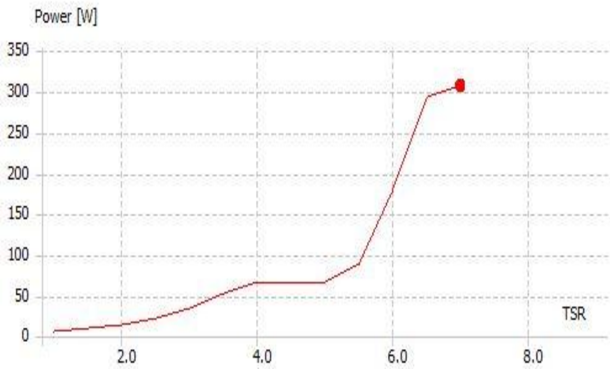

Figure 21: Power vs TSR

In the above graphs, the deep red point indicate the value of power coefficient, torque and power value at tip speed ratio 7. The values are as below.

Power coefficient = 0.38 , torque=10.2Nm and power = 305 W.

Result from the CFD

The CFD calculator results are shown in figure 18 and 19. The values are Torque=9.4192,torque coefficient Cm=.0496.

Similarly, Power coefficient Cp=Cm*TSR=0.0496*7=0.35 or 35%, Power, P=Torque * angular velocity =9.5*30=285W.

Table 1: Comparison between Qblade and CFD results

Software	Torque		Power coefficient	Power
Qblade	10.2 Nm		0.38 or 38%	305W
CFD	9.42 Nm		0.35 or 35%	285W

VII. CONCLUSION

By comparing Qblade and CFD results, it was found that Qblade results are almost similar to CFD results. The percentage of deviation is 6 % between these two softwares for this HAWT configuration. The power output from the

HAWT is 305 W for flow velocity 6m/s which helps to meet the daily needs.

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