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Design and Analysis of Dimple Arrangement on a Small Wind Turbine Blade

Robin Johny K

Abstract**:** ***This article predominantly focuses on the performance estimation of a small wind turbine blade when a dimple arrangement is made along its upper surface. The dimple arrangement is grooved at two locations: 0.25c and 0.5c, where c is the chord length of the turbine blade. A CFD analysis using the k-ε turbulence model is carried out on the selected blade sections NREL S823 and S822. The continuity and momentum equations are solved using ANSYS Fluent Solver to assess the aerodynamic performance of the proposed design. The effect of introducing a dimple on the blade surface has shown to delay the flow separation, with the formation of vortices. Further, the overall performance of the blade is simulated using GH BLADED and the results acquired are discussed.***

Keywords**:** ***blade design, dimples, flow separation, wind turbine.***

I. INTRODUCTION

Renewable energy solves the sustainability problem associated with conventional fuels used for power generation as these sources are non-exhaustible, free and relatively clean. Much of rural India still waits for electricity. Although India has less than a fifth of the world's population, it has close to 40% of the world's population without access to electricity. This is because, India has a very weak power distribution system and many rural areas are far away from the power generating stations. This is where off-grid systems or stand-alone systems come in. Small wind turbines that can be used for residential purposes can be implemented in these rural areas to provide electricity for homes and small offices. The objective of this research it to analyse the performance of introducing a dimple groove along the surface of a small wind turbine blade, thereby reducing the cut-in wind speed of the turbine and achieve the rated power at lower wind speeds than conventional methods.

Robin Johny K et al. [9] has given a design and optimization model on a small wind turbine blade. The blade parameters, characteristics and airfoils are used in this research to further conduct studies by creating dimples along the blade surfaces. Xiongwei Liu et al. [4] presented an approach for the blade design optimization through linearization of both the chord and twist angle radial profiles for fixed pitch, fixed speed stall (FPFS) wind turbines. It was concluded that linearization of the chord and twist angle radial profiles with fixed values at the blade tip from a preliminary blade design offers a promising optimizing strategy for FPFS wind turbine blade design to improve power, performance and reduce both material and manufacturing cost. David Hartwanger et al. [3] presented the validation of CFD on 2D blade sections, which showed that using a high-resolution structure mesh, with advanced turbulence and transition models provides an excellent match with experimental data in the attached flow regime. However, the CFD and XFOIL panel code over-predicted peak lift and tends to underestimate stalled flow. Furthermore, utilizing the same high fidelity for a 3D case generates an extremely computationally demanding and expensive simulation, while John McCosker et al. [6] optimized the parameters that define a wind turbine blade using the momentum theory and blade section aerodynamic theory. For a residential wind turbine, it is imperative to maximize both blade radius and height, because from a cost-effective perspective, one is not optimizing fixed cost of building a wind turbine if it is not reaching the fastest wind or inscribing a large area. The final parametric study was conducted to determine if the airfoil had an appreciable effect on the efficiency of the wind turbine. Armin Ghoddoussi [1] completed a conceptual study of performance enhancing devices for an airfoil is performed using computational fluid dynamics. The dimples demonstrate the potential of lift to drag ratio improvement at higher angle of attack and Bhadri Rajasai et al. [7] is concerned with analysis of the turbulent flow over dimpled airfoil profiles. Dimples of varying aspect ratio were used to study the effects on the skin-friction drag and lift. An external flow study was performed using ANSYS FLUENT. Simulation for external flow configuration with and without dimples were carried out and analysed in detail. A pressure drop and reduction in drag were observed, leading to possibilities of better performance in wind turbines.

II. METHODOLOGY

The methodology followed to carry out this research:

1. Design of dimple arrangements on the blade using CATIA
2. Design of the optimized blade_1 with twist and without twist using CATIA
3. Flow Analysis over the blade using Ansys - Fluent and power estimation using GH Bladed
4. Comparison of the power production and performance of all the designs.

A. Design of Dimpled Blade

The airfoils NREL S823 and S822 is selected for the design based on the performance study by NREL [10].

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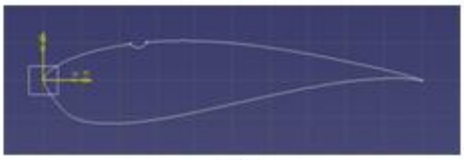
The dimples have a predefined diameter, depth and location on the airfoil blade which are designed in CATIA as seen in Table 1 and Fig. 1.

Table 1: Dimple configurations

	Dimple 1	Dimple 2
Diameter	0.05c	0.05c
Depth	0.025c	0.025c
Location from leading edge	0.5c	0.25c

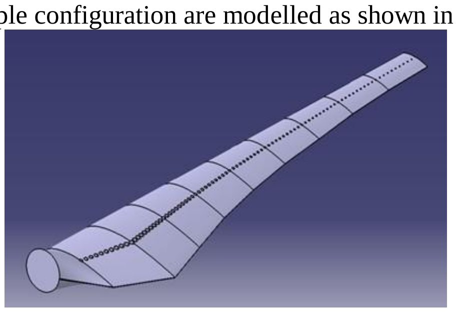

(a)


(b)


(c)


(d)

Fig. 1: (a) NREL S823 with Dimple 1 configuration, (b) NREL S823 with Dimple 2 configuration, (c) NREL S822 with Dimple 1 configuration, (d) NREL S822 with Dimple 2 configuration. Based on the Chord and Twist values optimized from [9], the 3-dimensional models of the blades with dimple configuration are modelled as shown in fig. 2.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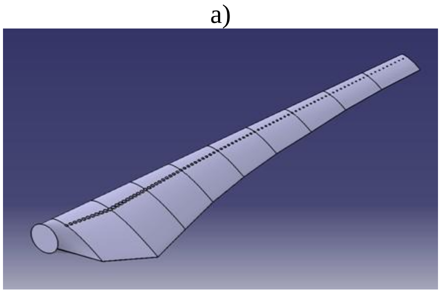
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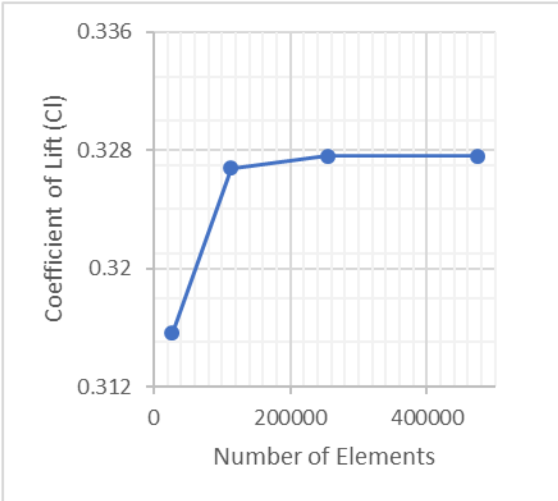
Fig. 2: (a) Wind turbine blade with Dimple 1 configuration, (b) Wind turbine blade with Dimple 2 configuration

III. DIMENSIONAL CFD ANALYSIS

The airfoils designed are analysed using a commercial numerical solver - Ansys CFD. A C-H shaped mesh is utilized here with an edge sizing of 100 divisions per edge and a biasing factor of 50, to create a uniform mesh. It was then solved using FLUENT, where the k-ε turbulent model with enhanced wall treatment was used. The SimpleC solution control is used while ignoring the higher order terms. Grid independence check was conducted on the NREL S823 airfoil as shown in Table 2 and Fig. 3, to validate the code.

Table 2: Grid Independence check for NREL S823

NREL S823		
Nodes	**Elements**	**C_l**
26866	26600	0.3156
106932	113091	0.3268
240198	254667	0.3276
447516	473940	0.32761



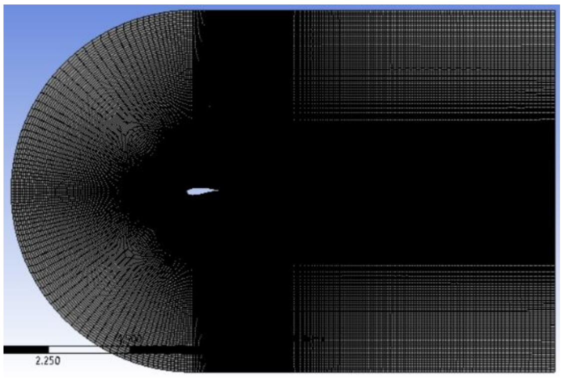


Fig. 3: Graphical representation of Grid Independence check on NREL S823 and refined mesh of airfoil

The analysis is validated with experimental data to extrapolate the simulation for other designs. The airfoil experimental data from [10] is compared with the CFD analysis. For the design Reynolds number of 4E+05 for NREL S823, the experimental and CFD analysis data of lift coefficient are compared as shown in the Fig. 4. The average deviation between the experimental results and the CFD results are around 3 %, which is under the acceptable tolerance.

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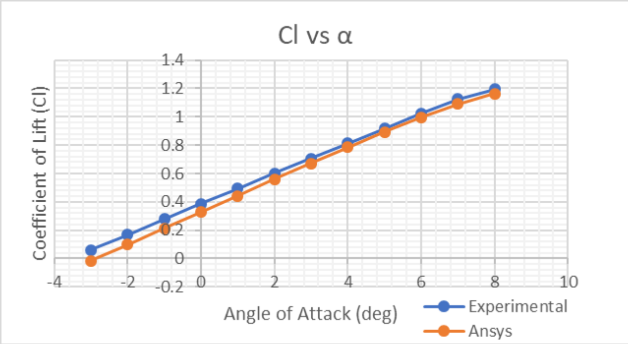


Fig. 4: Validation of CFD analysis with experimental data

The analysis is carried out for both the Dimple 1 and 2 configurations for varying Reynolds numbers from 2E+05 to 6E+05 for NREL S823 and Reynolds numbers from 4E+05 to 8E+05 for NREL S822 airfoils.

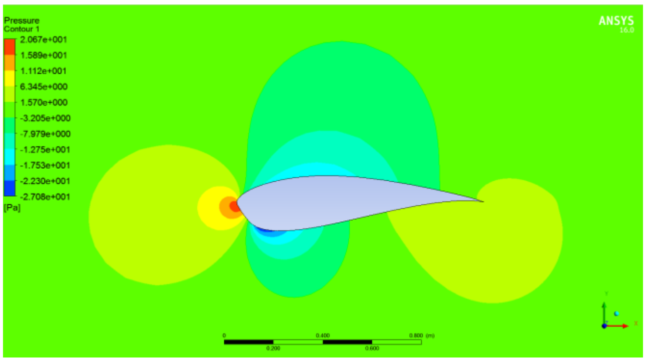
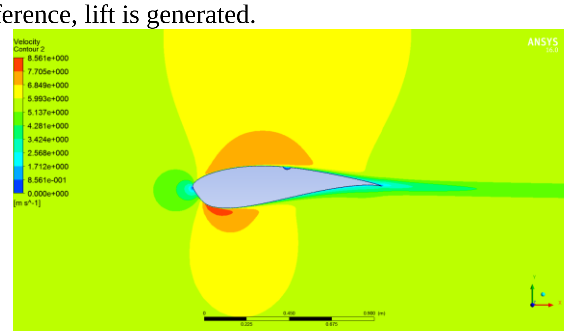


Fig. 5: Pressure contour of NREL S823 airfoil at 0 deg angle of attach and Re 4E+05

In the Fig. 5, a large area of low pressure is created on the top surface, whereas on the bottom surface of the airfoil, near the leading edge, high pressure is created. Due to this pressure difference, lift is generated.



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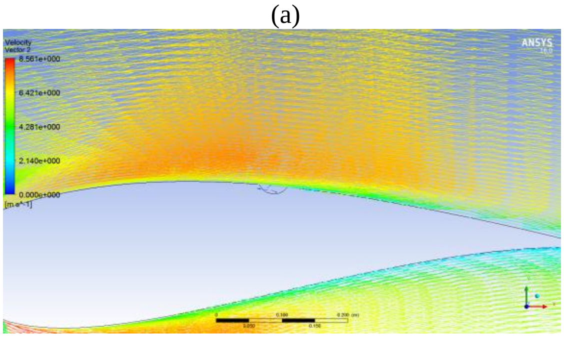
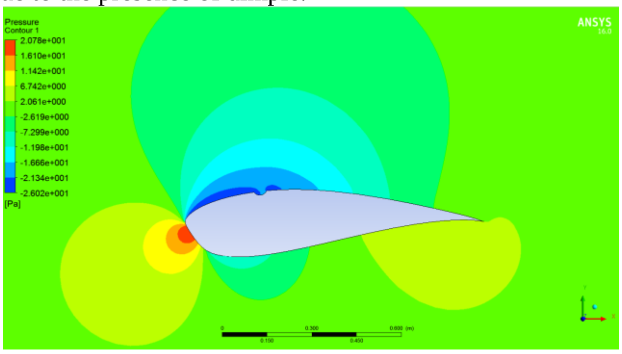


(b)

Fig. 6: (a) Velocity contour of NREL S823 dimple 1 airfoil at 0 deg angle of attack at Re 4E+05

(b) Velocity vector of NREL S823 dimple 1 airfoil at 0 deg angle of attack and Re 4E+05

In Fig. 6, the velocity contour and velocity vector are shown for the dimple 1 configuration of airfoil. The velocity is higher on the bottom surface of the airfoil than the top surface. Due to this a pressure difference is developed which contributes to the lift generation. The pressure and velocity contours along with streamlines and velocity vectors can be plotted using CFX in Ansys. This is mainly useful to understand the behaviour of the flow over the airfoil. For the Dimple 1 and Dimple 2 airfoils, from the velocity vector plots, Fig. 7, the effects of dimples can be understood. The flow over the dimple creates a circulation inside the dimple, which causes a vacuum effect that tends to suck the flow over the airfoil back to the surface of the airfoil. This process delays the flow separation on the airfoil surface. Since more surface area is in contact with air, more lift is produced with a consequence in drag. This is clearly visible in the vector plot, where the flow is attached to the airfoil for a larger distance due to the presence of dimple.



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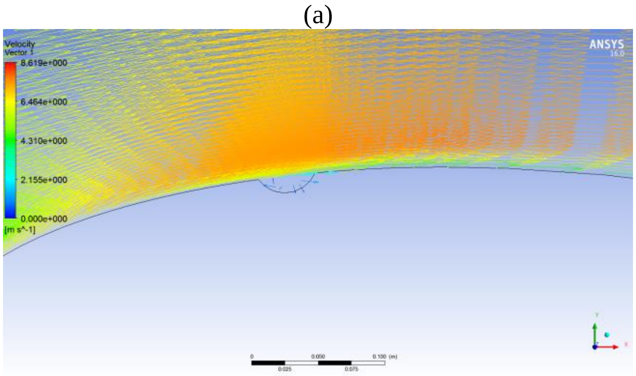

(b)

Fig. 7: (a) Velocity contour of NREL S823 dimple 2 airfoil at 10 deg angle of attack and Re 4E+05

(b) Velocity vector of NREL S823 dimple 2 airfoil at 10 deg angle of attack and Re 4E+05

The lift and drag coefficients gathered from all the analysis are tabulated in Table 3 and 4. It can be inferred that with the use of dimple 1 and dimple 2, lift has considerably increased for most regions of angles of attack. The important parameter to note is that the maximum lift coefficient has increased, which determines the power production of the blade. Also, in the dimple 2 design of both airfoils, it is seen that the maximum lift coefficient is achieved at a much lower angle of attack.

Table 3: Angle of attack Vs Coefficient of Lift for NREL S823

S823			S823			S823		
No Dimple			**Dimple 1**			**Dimple 2**		
Re = 4E+05			Re = 4E+05			Re = 4E+05		
AOA	**Cl**	**Cd**	**AOA**	**Cl**	**Cd**	**AOA**	**Cl**	**Cd**
-10	-0.723	0.04477	-10	-0.697	0.0404	-5	-0.2866	0.01403
-5	-0.2368	0.01391	-5	-0.284	0.01402	0	0.2736	0.01171
0	0.3276	0.01151	0	0.286	0.01187	5	0.806	0.01432
5	0.8921	0.01222	5	0.8869	0.01817	10	1.2725	0.02307
10	1.2369	0.02125	10	1.3112	0.02052	14	1.4532	0.03692
15	1.3242	0.05965	15	1.3759	0.05786	15	1.3645	0.09094
20	1.2751	0.13742	20	1.2591	0.14297	20	1.1709	0.17222

Table 4: Angle of attack Vs Coefficient of Lift for NREL S822

S822			S822			S822		
No Dimple			**Dimple 1**			**Dimple 2**		
Re = 6E+05			Re = 6E+05			Re = 6E+05		
AOA	**Cl**	**Cd**	**AOA**	**Cl**	**Cd**	**AOA**	**Cl**	**Cd**
-10	-0.6885	0.01551	-5	-0.3032	0.00857	-5	-0.3443	0.01097
-5	-0.2677	0.00914	0	0.2537	0.00679	0	0.1955	0.00968
0	0.2742	0.00779	5	0.7769	0.01435	5	0.7185	0.01733
5	0.8121	0.00798	10	1.2297	0.02181	10	1.1086	0.01997
10	1.0435	0.01992	14	1.3343	0.03656	14	1.3654	0.03435
15	1.2392	0.04696	15	1.1158	0.13297	15	1.3201	0.04491
20	0.8658	0.2619	20	0.8904	0.24027	20	0.8715	0.22226

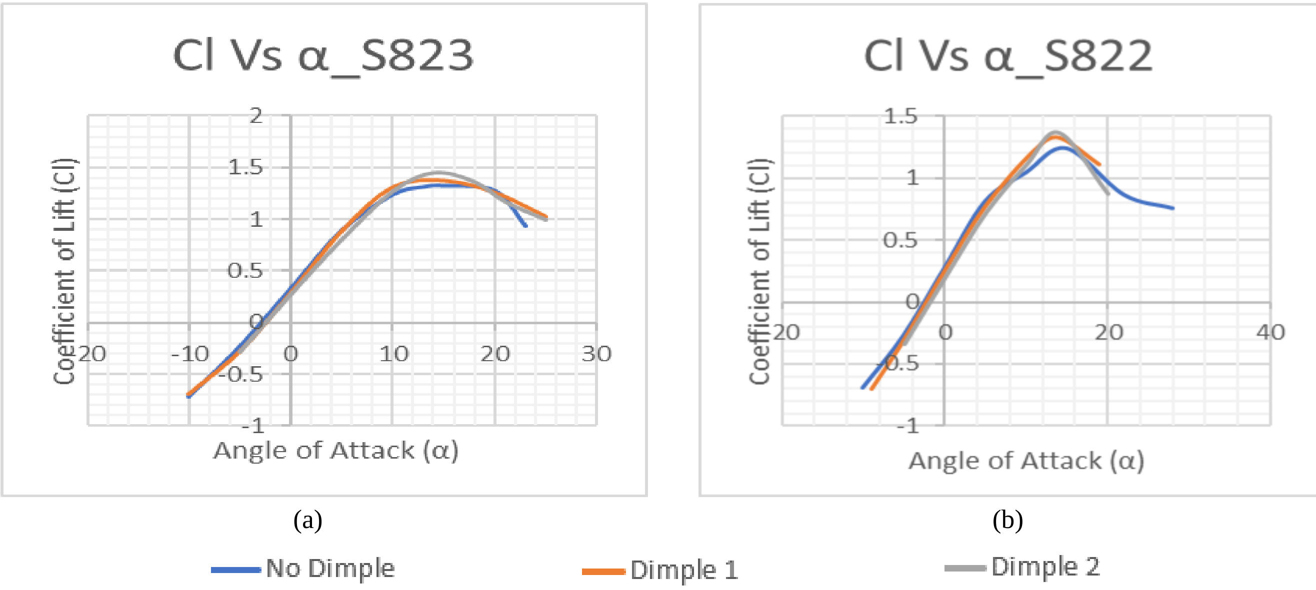

Fig. 8: (a) Coefficient of lift vs angle of attack for NREL S823 at Re 4E+05
(b) Coefficient of lift vs angle of attack for NREL S822 at Re 6E+05

IV. PERFORMANCE ANALYSIS OF WIND TURBINE

GH Bladed is the software used to estimate the power production and performance characteristics of a wind turbine. The blade geometry is first defined, along with the geometry for the rotor, hub design and tower geometry. The wind conditions in which the turbine is to be tested is defined for standard atmospheric conditions. The airfoil characteristics such as the coefficient of lift and coefficient of drag are fed as inputs.

The wind turbine blade geometry is defined in the blade properties window as shown in the Fig. 9, which is made up of parameters such as blade length, chord distribution and blade twist. All these parameters are taken from [9].

Fig. 9: Blade properties in GH Bladed

Since only the aerodynamical aspect of the wind turbine is analysed, there is no requirement to give inputs for the mass and stiffness of the rotor, hub and tower. The analysis is run for estimating the amount of power that can be extracted from the wind when an ideal generator is used. The software uses Blade Element Momentum (BEM) theory equations to calculate and produce results such as lift distribution, electrical power output, coefficient of power and tip speed ratio for various wind speeds. By using the airfoil characteristics of the newly designed airfoils, the performance of the wind turbine is calculated and compared. The analysis is run for wind speeds from 3 m/s to 25 m/s.

V. RESULTS

A. Lift Distribution

Table 5: Lift distribution along the blade length

-	No Dimple No Twist	No Dimple with Twist	Dimple 1	Dimple 2
Distance along blade [m]	Lift coefficient	Lift coefficient	Lift coefficient	Lift coefficient
0.24	0	0	0	0
0.34	0	0	0	0
0.397	0.755934	1.01644	0.910388	0.868452
0.712	0.876198	0.988943	1.10409	1.04746
1.027	1.28854	1.09014	1.28965	0.940058
1.342	1.29727	1.15322	1.38949	1.37975
1.657	1.29515	1.18461	1.35334	1.32741
1.972	1.25909	1.20124	1.31628	1.27826
2.287	1.06644	1.04045	1.16787	1.11989
2.602	0.999689	1.03269	1.10651	1.04325
2.917	0.919079	0.999033	1.0164	0.960144
3.232	1.04646	1.15713	1.17668	1.11315

3.1.2. Power Production

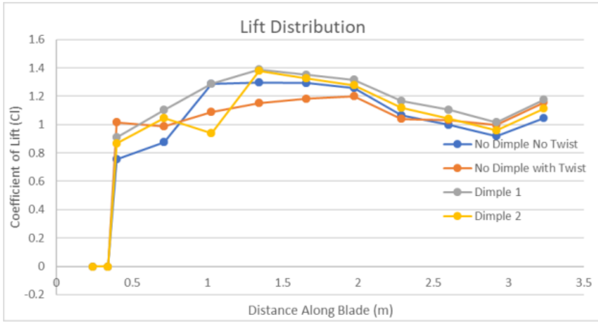

Fig. 10: Lift distribution along the blade length

The aerodynamic property which is more important is the lift distribution along the length of the blade. As shown in the Table 5 and Fig. 10, for the 3.2m blade, the lift distributed at various sections are presented. From the results, it can be seen that the 'no dimple with twist' configuration blade model had an overall lift distribution higher than the other three blade models and hence it can be concluded that the blade model with 'no dimple with twist' has the higher aerodynamic efficiency. The maximum lift coefficient plays a very important role in determining the power output of the wind turbine.

Table 6: Power production at various wind speeds

-	Genie [1]	No Dimple No Twist	No Dimple with Twist	Dimple 1	Dimple 2
Hub wind speed [m/s]	Electrical power [W]	Electrical power [W]	Electrical power [W]	Electrical power [W]	Electrical power [W]
4		9.01897	37.2818	43.7396	12.7886
5		547.266	647.386	561.224	544.814
6	499.029	1380.99	1549.65	1288.7	1303.37
7	1595.9	2552.14	2762.78	2421.97	2339.01
8	2962.07	3849.57	4217.61	3867.81	3716.48
9	4952.31	5281.51	5894.16	5543.02	5132.96
10	6416.29	6226.47	7568.85	6785.7	6460.96
11	8254.17	6702.62	9128.62	7478.69	7306.43
12	10003.4	7459.38	10477.8	8274.72	7558.25
13	11557.5	7234.1	11212.6	8246.86	7876.07
14	12652.4	6533.11	10485.2	7608.51	7162.83
15	13473.5	5992.52	8783.34	6927.86	6989.97
16	14183.7	5239.46	6696.98	6522.9	5815.3
17	14472.6	4517.34	5467.05	5816.33	5790.27
18	14669.4	3675.43	4573.3	5520.13	4238.25
19	14579.1	2833.38	4068.8	4731.57	4086.33
20	14322.6	2023.64	4056.05	4756.28	4300.65
21	14191.8	1910.54	4139.28	4911.28	4590.11
22	13985.5	1892.76	4311.26	5026.45	4873.07
23	13287.2	1815.44	4613.47	5163.61	5121.28
24	13252.4	1809.5	4952.27	5298.25	5369.89
25	13245.3	1901.04	5201.7	5418.15	5636.55

The power produced by the turbine at various wind speeds are shown in the Table 6 and Fig. 11. The design constraint was set to produce 5kW at a wind speed of 9 m/s.

As seen from the table, at 9 m/s, the 'Wind Genie' produced almost 5kW of power [9]. This confirms the validity of the analysis. The power produced by the 'no dimple with twist' configuration is very high at a higher wind speed. All other designs show almost the same power production. The generator used has a rated power of 5kW and hence, even if the power produced aerodynamically increases, the electrical power production will be maintained at 5kW.

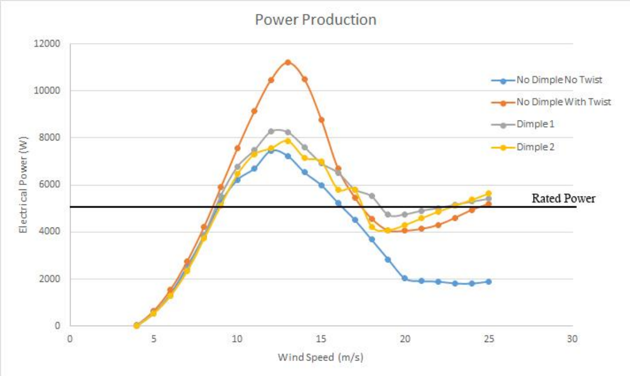

Fig. 11: Power curve

VI. CONCLUSION AND DISCUSSION

The aerodynamic analysis of the two dimple arrangements made along the surface of the blade and the optimized blade design is investigated. The power estimation for the optimized blade with twist, optimized blade with no twist, dimple 1 configuration, dimple 2 configuration blade models is done using GH Bladed. It was observed that the 'optimized blade with twist' achieved the rated power at a wind velocity slightly lower than the dimple 1 configuration. For the power estimation study, only the attainment of rated power at the lowest possible wind speed or the cut-in speed is considered as the assessing factor, and hence the power production at varying wind speeds are neglected in this research. The dimple and no twist configurations fared better than the original blade design, but they achieved the rated power at higher wind speeds compared to the other designs. Furthermore, the twisted blade design had the better power conversion of 43%. It can be inferred that the optimized blade with twist and dimple 1 configuration of wind turbine is best suited for residential areas, as it can produce the rated power of 5kW at lower wind speeds of 8 - 9 m/s.

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