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INVESTIGATING THE FLAPPED HORIZONTAL AXIAL WIND TURBINE EXPERIMENTALLY TO IMPROVE POWER COEFFICIENT AND STABILITY

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ABSTRACT

This paper investigates the potential of deploying flaps on wind turbine blades to enhance their efficiency and energy capture capabilities. The FX66-S-196V, FX63-137 S, and SG6043 supercritical airfoils were used and distributed along the blade radius. Flaps, situated 20% along the trailing edge of the blade chord, offer a means of actively controlling aerodynamic forces and optimizing blade performance under varying wind conditions. Through computational fluid dynamics (CFD) simulations and optimization techniques. The aerodynamic effects of flap deployment on wind turbine blades are analyzed. The study explores the impact of flap angle, position, and deployment strategy on key performance metrics such as power coefficient, lift-to-drag ratio, and energy extraction efficiency. Results demonstrate that judiciously deploying flaps can lead to significant improvements in turbine efficiency, with power output enhancements ranging from 2.5% to 4.6%, depending on operating conditions such as wind speed, tip speed ratio, angle of attack, and flap angle setting. Furthermore, sensitivity analysis reveals optimal flap configurations for different wind regimes, highlighting the importance of adaptive control strategies. This research contributes to the growing body of knowledge on active aerodynamic control techniques for wind turbine optimization and underscores the potential of flaps as a viable means of enhancing wind turbine blade efficiency in practical applications.

KEYWORDS

Wind turbine efficiency, High lift devices, Flap, Aerodynamic Enhancement, Aerodynamic control.

1. INTRODUCTION

Wind energy has emerged as a prominent source of renewable power, contributing significantly to global electricity generation (Olabi, A.G,et al, 2023) .Central to the effectiveness of wind energy conversion systems are wind turbine blades, which play a crucial role in capturing and converting wind energy into usable electricity (Batay, S,et al , 2024) .Maximizing the efficiency of wind turbine blades is paramount for enhancing overall system performance and reducing the cost of wind energy production (Speirs, J,et al , 2015) .Traditional wind turbine blades typically feature uniform airfoil profiles along their length, designed to optimize performance under specific wind conditions. However, advancements in aerodynamic design and control technologies have spurred interest in novel blade configurations to further enhance efficiency and adaptability to varying wind regimes (Herbert, G.J,et al , 2007) .One such innovation involves the integration of multi-section designs coupled with active aerodynamic control elements, such as flaps, along the blade span (Belamadi, Riyadh, et al, 2016) .The concept of multi-section wind turbine blades involves dividing the blade length into distinct sections , each with tailored aerodynamic characteristics optimized for specific operating conditions. This approach allows for greater flexibility in blade design, enabling finer control over aerodynamic performance across a wide range of wind speeds and directions. Concurrently, the incorporation of flaps along the trailing edge of each blade section provides an additional level of control over aerodynamic forces, further optimizing performance and energy capture efficiency (Qin, Zhiwen, et al, 2018) .In this paper, The concept of enhancing wind turbine blade efficiency through the integration of multi-section designs and flap deployment is explored. Through computational modeling, aerodynamic analysis, and optimization techniques, The synergistic effects of multi-section blade configurations and flap deployment on overall turbine performance are investigated. The objectives of this study are to assess the potential benefits of this innovative approach, identify optimal blade configurations, and elucidate the mechanisms underlying enhanced efficiency and energy capture. By elucidating the benefits and mechanisms of multi-section blade designs with flap deployment, this research aims to contribute to the ongoing efforts to advance wind turbine technology and accelerate the transition towards sustainable renewable energy sources. There were several studies investigating the multi-cross and leading, trialing edge devise (flap. and slat) of horizontal wind To improve its behavior and performance. (Amer H. Muheisen et al , 2023) studied and investigated the performance and behavior of a multi-section HAWT blade design with and without fencing. Supercritical airfoils were used and spread around the blade radius. A

NACA4412 blade with the same dimensions was also used to examine the overall behaviors and effectiveness of all the blades. The results showed that the multi-cross-section HAWT blades outperformed the single-cross-section blades, as the increase was 8% in the power factor (40 watts) for small wind turbines (diameter 127 cm, output power 500 watts). The gates were designed and installed on multi-section blades at experimentally determined locations. The fences worked effectively, boosting the overall power factor by 16% while maintaining excellent flutter stability. (Hussein Ali Hussein et al , 2018) suggested uses CFD code with Schmitz and Betz to optimize the twist angle and chord of windmill blades. The technical perspective on modifying the blade cross section using symmetry, unsymmetrical, and supercritical airfoils. The most effective optimization techniques were Schmitz chord modification and lift to drag for twist optimization, which raised Cp by 10.3% for Eppler 417, 9.5% for NACA 4412, and 16% for NACA 0012. (Raghad Majeed Rasheed et al ,2022) used the Proposed method to determine the appropriate range of values for the ratio (CL/CD) in order to maximize power coefficient and, therefore, the distribution of the air angle of attack for horizontal wind turbines. Three distinct cross-section airfoils symmetrical, unsymmetrical, and supercritical were selected for this purpose, and the values with the highest power factor were (NACA). These are 0.47, 0.49, and 0.48 for NACA 4412, Eppler, and 0012. The lift-to-drag ratio distribution's places provided the most precise way to determine the maximum power coefficient. (Muhammad A.R. Yass et al,2018) studied , a (HAWT) with symmetrical blade section type (NACA 0012) airfoil was designed, analyzed, improved, and manufactured. To obtain optimal wind turbine performance and behavior, some factors must be installed while others must be managed, The design data is analyzed and calculated using Fortran 90 computer programs, which are then compared to the findings of CFD code. The Scmitz, Betz, and (CL /CD) improvement methods were then utilized to optimize a wind turbine's chord and pitch angle. The findings were as follows, where the Cp=0.481 at TSR=7 before and after optimization, the best outcomes were as follows: Cp= 0.556 at Schmitz chord modification and lift/drag twist improvement, Also Cp= 0.53 at Betz chord adjustment and lift/drag twist optimization at same TSR .(Lei Xi and Lihua Zhao, 2022) used a set of airfoils from the NACA series and organized and distributed them based on the thickness and curvature of each airfoil and created a new blade that differed from the individual blades taken in the experiment. The german cod was used to evaluate and analyze the blades' aerodynamic performance. The final results reveal that the use of complex multi-airfoil modeling may increase The wind energy utilization factor of the wind turbine blade is from 0.46 to 0.49. (Vahid Akbari et al , 2022) divided the turbine blade into two parts, where the first section is in which the ratio is r/R<0.52

, or in which the majority of the turbine's energy is concentrated, as he increased the chord length and twist angle in it, and the second section is in which the ratio is r/R > 0.52 , is the section concentrated. In which the generation of starting torque kept it in its ideal condition, the results showed a decrease in the power factor by 1.5%, with this accompanying the rotation of the wind turbine at a speed of 4 m/s instead of 6 m/s.

2. THEORETICAL ANALYSIS

The fundamental theory of design and operation of wind turbines depends on the interactions between the rotor and wind. The theory is applied on both horizontal and vertical axis wind turbines. The power coefficient (Cp)of a wind turbine is defined and is related to the Betz Limit, (M. K. Chaudhary and A. Roy,2015).

$$Cp = \frac{P}{\frac{1}{2}\rho V^3 A} = \frac{power\ of\ Rotor}{power\ of\ Wind} \quad (1)$$

$$Cp = 4a(1-a)^2 \quad (2)$$

The maximum Cp is then calculated from the power coefficient derivative with respect to a

equated to $\frac{V_2}{V_1} = 1/3$ (3)

$$Cp_{max} = \frac{16}{27} = 0.5926$$

The wind speed upstream of the turbine (V_1) and the downstream wind speed (V_2) are the subjects of the Betz Equation. The wind braking from its upstream speed V_1 to its downstream speed, V_2 while the blade maintains the flow regime, is what causes a wind turbine's restricted efficiency. The rotor's swirling effect on air flow, the pressure and viscous drag on the blades, and power losses in the electrical and transmission systems account for the remaining efficiency losses for a realistic wind turbine (P. J. Schubel and R. J. Crossley,2012).as shown in Fig.1 shows Profile of a Wind turbine illustrating the path of air flow.

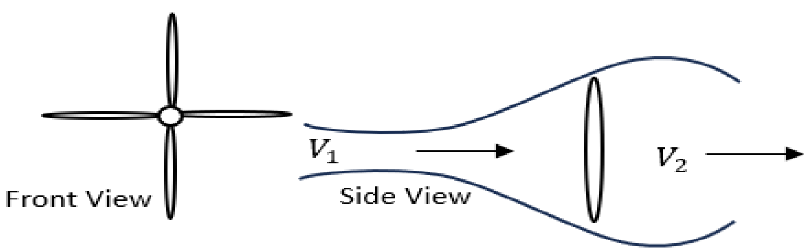

Fig .1. Profile of a Wind turbine illustrating the path of air flow (blackwood and Marisa , 2016)

2.1. Lift and Drag forces

The lift and drag forces are dependent on the lift coefficients (CL) and drag coefficients (CD), which are determined by the cross section of the blade being used and the angle α at which the wind strikes the blade. (Mamadaminov and U. M,2013).

$$\text{LIFT forces} = \text{CL}\ (\sigma/2)\text{A}\ \text{V}\mathbf{a^2} \tag{4}$$

$$\text{DRAG forces} = \text{CD}\ (\sigma/2)\text{A}\ \text{V}\mathbf{a^2} \tag{5}$$

Drag applies a force on the body in the direction of the relative flow, while lift applies a force perpendicular to the relative flow,(N. K. Kohli and E. Ahuja ,2014).

3. FLAPS

To raise the lift of a blade, the flow must be enhanced and separation prevented.The (circulation can be improved by raising and making the camber more positive in the vicinity of the T.E flap. This increase (and, to a lesser degree, an L.E flap) effectively increases the airfoil camber and circulation, leading in an increase in CL. As circulation increases, the angle for zero lift (α_{OL}) also improvement.Separation is avoided by lowering the unfavorable pressure gradient across the airfoil or by stabilizing the layer using suction or a blade. Trailing edge flaps work by adjusting the camber of the airfoil section.The camber is made more positive in the region of the trailing edge, which has a powerful influence on making α_{OL} more negative A camber change in the region of the leading edge has only a small influence on α_{OL}.
where α_{OL} is the angle between the unflapped section chord line and the free stream velocity. T.E flaps do not prevent flow separation; in fact, they aggravate flow separation slightly due to the increase in upwash at the leading edge due to increased circulation. Thus, trailing edge flaps become less effective as the blade sweeps (Leland M. Nicolai 1975).

3.1. Flaps CL_{max} Calculation Requirement

The finite blade increase in $CLmax$ due to a trailing edge flap is obtained from

$$\Delta CL_{MAX} = (\Delta CL_{MAX\ blade})\ (S_{WF}/S_W)(K) \tag{6}$$

($\Delta \text{CL}_{\text{MAX blade}}$) it can be measured experimentally in wind tunnels and area of the flaps (S_{Wf}) and (S_W)is total blade area . The $\Delta \text{CL}_{\text{MAX}}$ is added to the basic (unflapped) blade CL_{max} and the final flapped blade curve is drawn as illustrated by Fig. 2 shows Construction of Blade Lift Curves for Mechanical High Lift Device. The $\Delta\alpha_{\text{OL}}$for the flapped blade is the same as for the flapped airfoil section determined earlier. Notice that trailing edge flaps are not very effective on highly swept blades (Leland M. Nicolai 1975).

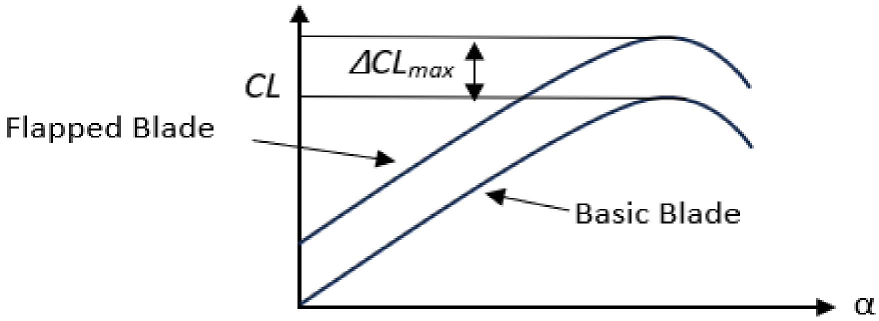

Fig. 2 Construction of Blade Lift Curves for Mechanical High Lift Device (Leland M. Nicolai 1975)

4. EXPERIMENTAL WORK

When it comes to torque and rotational frequency, the rotor of a wind turbine is regarded as a crucial component that transforms wind energy into mechanical power. The wind turbine had three blades. Fig.3 displays the measurements of the blade, which were 0.56 m in length and 0.1 m in chord at the base. Table 1 specifies the HAWT used, providing details of the small wind turbine model with three multi-cross-section blades, as shown in Fig. 4. Optimal values were determined for all aerodynamic and geometric designs to maximize the power generated by the wind turbine blade and the power absorbed from the free stream, resulting in a high operation power coefficient. For blade design and optimization, a rotor blade can be produced by a submodule where the number of sections can be variable. each segment of the blade geometry is specified by its location, chord, twist, and airfoil. The wind turbine blade's three-dimensional geometry is constructed using Fusion360 design tools, considering aerodynamics, and estimating an assumed inflow angle for each section to calculate the tip speed ratio. German cod is utilized to calculate the geometrical data. The wind turbine blades' three-dimensional structures are produced by a 3D printer using Polylactic acid (PLA) material, resulting in each blade weighing 200 grams. Referring to Fig.5, Multi Cross-Section Wind Turbine Blade With Flaps is shown, where the flaps are fitted on to blades with multiple cross-sections, and their placements are established through experimentation. Servo digital (Younkin and George,2002). with programming to regulate the flaps relative angle of attach (α) and placed on multi-cross-section blades.

Table 1. Specification of used HAWT

Rotor Diameter	1.251 m	Blade Span	0.56 m
Hup Diameter	0.13 m	Base Chord	0.113 m

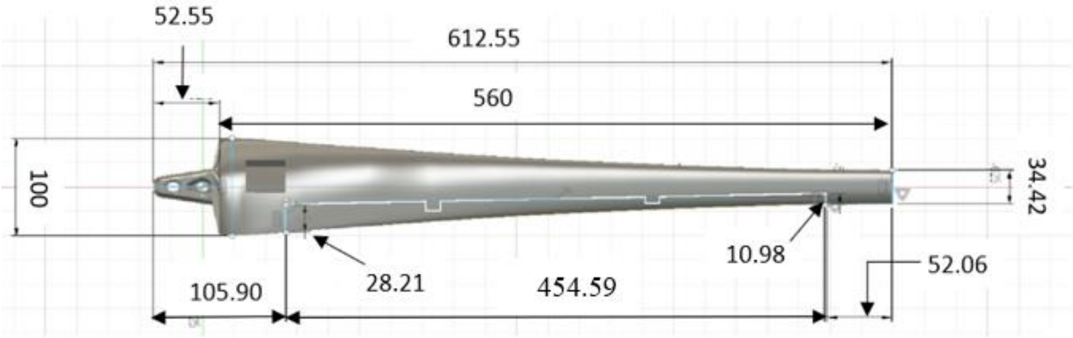

Fig 3. Dimension Multi Cross-Section Blade With Flaps (Al Dimension in mm)

Fig. 4 Multi Cross-Section Three Blade With Flaps Printed in 4D Printer.

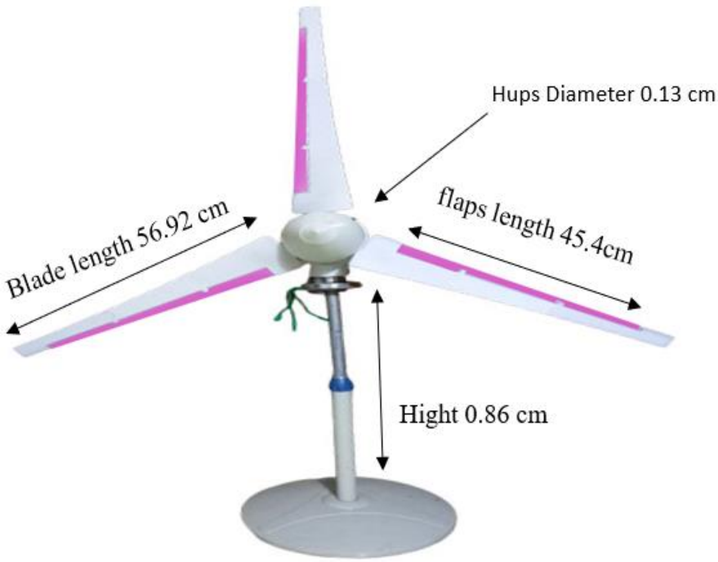

Fig.5 . Multi Cross-Section Wind Turbine Blade With Flaps

5. RESULT AND DISCUSSION.

The enhancement of efficiency and stability for multi-section wind turbine blades by using High Lift Devices presents promising results. Flaps, strategically placed along the blade's trailing edge, play a crucial role in improving aerodynamic performance. Through computational simulations and experimental validations, it was observed that the incorporation of flaps led to notable enhancements in turbine efficiency and stability. One significant finding is that flaps effectively manipulate the aerodynamic forces acting on the blade, resulting in increased lift and reduced drag. This optimization of airflow over the blade surface contributes to improved energy capture and overall turbine performance. Moreover, the study revealed that the effectiveness of flaps is influenced by various factors, including flap angle, position, and deployment strategy. Adjusting these parameters allows for fine-tuning of the turbine's aerodynamic behavior to maximize efficiency under different operating conditions. Furthermore, the addition of flaps was observed to mitigate issues related to flow separation and stall, thereby enhancing stability and reducing the risk of blade fatigue and structural damage. Fig.6 and Table 2 show the relation between lift coefficient (CL) and tip speed ratio (λ) with and without blades flaps as the lift coefficient increase (ΔCL_{max}=0.53 at λ=2.5). same behavior is shown in Fig.7 and Table 3 at angle of attack 19.5°. From Fig.8. and Table 4, it is clear that the drag coefficient gradually decreases when the rotation of wind turbine increases, and drag coefficient is at its maximum. Start the rotation of the wind turbine.

Table (2). Lift Coefficient (CL) Vers Tip Speed Ratio (λ) with and without flaps (flaps angle 5°)

Tip Speed Ratio (λ)	lift Coefficient without flaps	lift Coefficient with flaps
1	1.95	2.393865
1.5	2.12	2.60256
2	2.32	2.848085
2.5	2.34	2.872637
3	1.95	2.70077

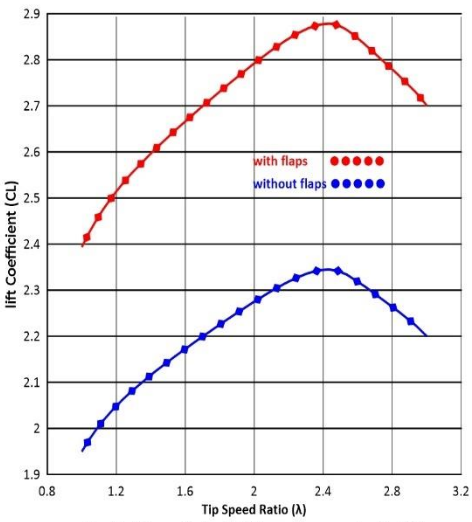

Fig. 6 . lift coefficient (CL) vers tip speed ratio (λ).

Table 3. Lift Coefficient (CL) Vers Angle of Attack with and without flaps (flaps angle 5°)

Angle of Attack (Alpha)	lift Coefficient without flaps	lift Coefficient with flaps
0.42°	0.94	1.153965
1.52°	1.06	1.30128
2.72°	1.2	1.473147
4.21°	1.35	1.657291
6.1°	1.55	1.902815
8.5°	1.77	2.172892
11.2°	2	2.455246
15°	2.2	2.70077
19.5°	2.34	2.872637
21°	2.32	2.848085

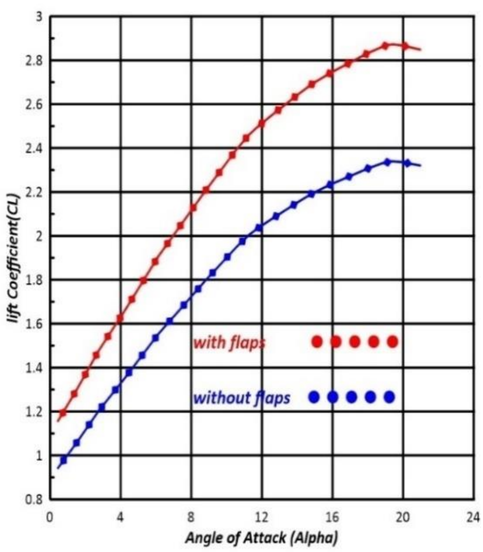

Fig.7. lift Coefficient vers Angle of Attack (Alpha)

Table (4) Drag Coefficient (CL) Vers Rotation Wind speed with and without flaps

Rotation Wind Speed in rpm	Drag Coefficient without flaps	Drag Coefficient with flaps
91.5385	0.978778	1.20157
137.308	0.72907	0.895023
183.077	0.505359	0.62039
228.846	0.32162	0.394828
274.616	0.137753	0.169109
320.385	0.0481927	0.059162
366.154	0.0256785	0.031524
411.923	0.0166524	0.020443
457.693	0.0116757	0.014333
503.462	0.00806251	0.009898
549.231	0.00632352	0.007763
595	0.0056094	0.006886
640.77	0.00592765	0.007277

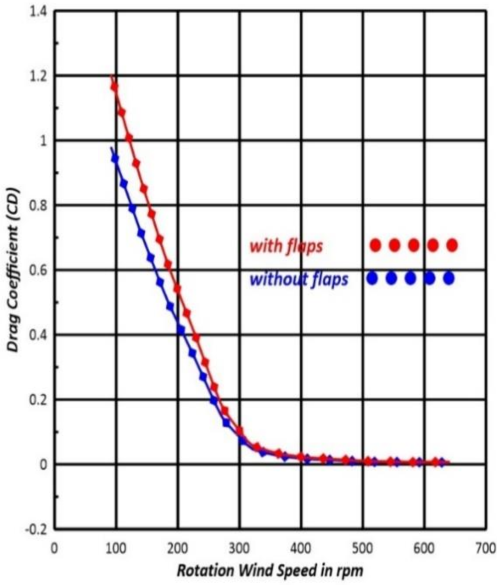

Figure .8.Rotation Wind Speed vers Drag Coefficient

CL/CD will rise due to increased lift created by the wind turbine blade. By deflecting the flap downward, the blade's effective camber rises, resulting in a larger lift coefficient (Cl). This enables the blade to absorb more wind energy and produce more rotational torque. as shown in Fig.9 and Table 5.

Table (5) (CL/CD) Vers Rotation Wind speed with and without flaps

Rotation Wind turbine Spees in rpm	CL/CD Without flaps	CL/CD With flaps
٩١,٥٣٨٥	1.9922	2.0535
١٣٧,٣٠٨	2.90781	2.9901
١٨٣,٠٧٧	4.5907	4.7095
٢٢٨,٨٤٦	7.24457	7.4311
٢٧٤,٦١٦	16.9869	17.4224
٣٢٠,٣٨٥	45.6500	46.8950
٣٦٦,١٥٤	77.1073	79.4438
٤١١,٩٢٣	106.891	110.4945
٤٥٧,٦٩٣	132.754	137.8932
٥٠٣,٤٦٢	168.681	176.1238
٥٤٩,٢٣١	189.767	199.2561
٥٩٥	188.9685	199.6648
٦٤٠,٧٧	160.265	170.3879

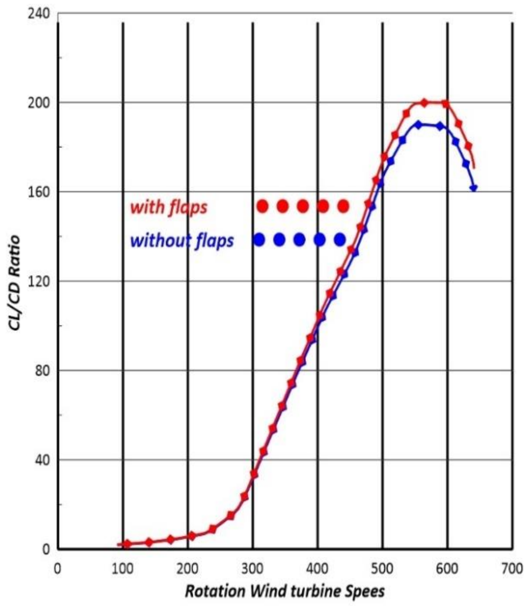

Fig .9 . CL/CD Ratio Vers Rotation Wind Speed

The results shows increase in power coefficient much higher at low rotation speed as shown in Fig.10 and experimental Tables (6,7 and 8) which can be noticed that at flap angle 20° , Flaps

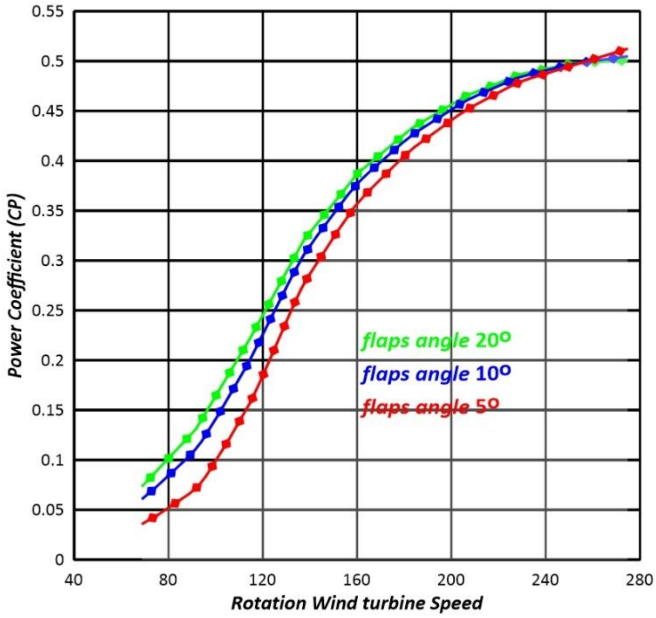

Fig .10. Rotation Wind Speed verses Power Coefficient

extracted give more increment in power coefficient than the low flaps extracted angle as shown in Table 9.

Table 6. rotational wind speed =343rpm , wind speed =3 and flaps angle =20°

Rotation Wind turbine Spees in rpm Without flaps	Power Coefficient (CP) Without flaps	Rotation Wind turbine Speed in rpm With flaps	Power Coefficient (CP) With flaps	Increase in Power Coefficient (CP)
45.7693	0.041005	68.7693	0.073424966	0.03242037
68.6539	0.073135	91.6539	0.13103541	0.05790011
91.5385	0.130578	114.5385	0.221784393	0.09120639
114.423	0.221285	137.423	0.320571356	0.09928636
137.308	0.320234	160.308	0.387593883	0.06735988
160.192	0.387365	183.192	0.432681864	0.04531686
183.077	0.43252	206.077	0.464840181	0.03232018
205.962	0.464731	228.962	0.486515114	0.02178411
228.846	0.486457	251.846	0.497937704	0.0114807
251.731	0.497922	274.731	0.500959443	0.00303744

Table 7. rotational wind speed =338rpm , wind speed =3 and flaps angle =10o

Rotation Wind turbine Spees in rpm Without flaps	Power Coefficient (CP) Without flaps	Rotation Wind turbine Spees in rpm With flaps	Power Coefficient (CP) With flaps	Increase in Power Coefficient (CP)
45.7693	0.041005	63.7693	0.060874452	0.01986985
68.6539	0.073135	86.6539	0.111216973	0.03808167
91.5385	0.130578	109.5385	0.200165647	0.06958765
114.423	0.221285	132.423	0.305903685	0.08461868
137.308	0.320234	155.308	0.37772825	0.05749425
160.192	0.387365	178.192	0.425644285	0.03827929
183.077	0.43252	201.077	0.460093196	0.0275732
205.962	0.464731	223.962	0.484010198	0.0192792
228.846	0.486457	246.846	0.497254942	0.01079794
251.731	0.497922	269.731	0.504766252	0.00684425

Table 8. rotational wind speed =328rpm , wind speed =3 and flaps angle =5°

Rotation Wind turbine Spees in rpm Without flaps	Power Coefficient (CP) Without flaps	Rotation Wind turbine Spees in rpm With flaps	Power Coefficient (CP) With flaps	Increase in Power Coefficient (CP)
45.7693	0.041005	53.7693	0.035773423	-------------
68.6539	0.073135	76.6539	0.071580101	--------------
91.5385	0.130578	99.5385	0.156928155	0.02635016
114.423	0.221285	122.423	0.276568341	0.05528334
137.308	0.320234	145.308	0.357996985	0.03776299
160.192	0.387365	168.192	0.411569127	0.02420413
183.077	0.43252	191.077	0.450599226	0.01807923
205.962	0.464731	213.962	0.479000366	0.01426937
228.846	0.486457	236.846	0.495889419	0.00943242
251.731	0.497922	259.731	0.512379868	0.01445787

Table 9. Experimental Results Data shows increase in Power coefficient

Flaps Angle	Area Under Curve of CP	RPM	Increase in Cp
5°	73.69776731	328	2.5%
10°	77.74427914	338	3.7%
20°	79.65311004	343	4.6%

The essence of the idea of installing flaps on wind turbine blades was the starting speed of rotation normally wind turbine blades start at 3 m/s wind speed with flaps which start rotation at 1.4 m/s which is beneficial to place such wind turbines at low wind speed area. In comparison to (Zhang,Dahai,et al ,2024, Rahnamay Bahambary,2024 and Gall,Mihnea,Ion Mălăel,and Dragos Preda's,2022) They enhanced turbine performance at wind speeds between 5 and 13 m/according to our findings, in the current investigation used a novel way to enhance performance at 3 m/represented by utilizing flaps.

6. CONCLUSION

the utilization of flaps for enhancing the performance of horizontal wind turbine blades presents a promising avenue for improving efficiency and power generation. By strategically deploying flaps along the blade's surface, it becomes possible to actively control aerodynamic forces, optimize lift-to-drag ratios, and minimize the risk of stalling. Through computational simulations and experimental testing, it has been demonstrated that flaps can lead to significant improvements in power coefficient and overall turbine efficiency. Flaps offer flexibility in adapting to changing wind conditions, allowing for better energy extraction and increased turbine performance. Overall, the integration of flaps represents a valuable strategy for optimizing horizontal wind turbine blade performance and advancing the capabilities of renewable energy technologies. In the present work leads to the following findings.

1- The flaps on wind turbine blades primarily effect its lift to drag ratio (CL/CD) by altering the blades lift and drag characteristic.

2- Torque increase at low-speed rotation.

3- as the extending flaps angle increase the power coefficient at low-speed rotation.

4-Multiple airfoils with flaps can increase lift force by (7.1 N) compared with it at same environment and conditions at without flaps

5- Multiple airfoils with flaps can also increase Drag force by (3 N) compared with it at same environment and conditions at without flaps.

6- Flaps can increase the lift of the blade, which allows the blade to start at lower speeds without Stalling.

7 -finally the efficiency of multi section wind turbine increased by add flaps on the blade Experimentally by 4.6% at flaps angle 20 degree, 3.7% at flaps angle 10 degree and 2.5% at flaps angle 5 degree compared without flaps at same environment and Conditions.

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