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Increasing Wind Turbine Efficiency

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Abstract: This research is constraining on wind power, particularly studying the horizontal wind turbine and its efficiency. The wind turbine is considered an important method to convert wind's kinetic energy to electric power for humankind's benefit. An ordinary wind turbine has a design point which means that the turbine will not achieve its best efficiency until the wind velocity reaches the designed point. In other words, the turbine will not be able to convert a maximum amount of wind energy if the wind velocity lower or higher than the design point. However, wind turbines cost a lot, and the outcome does not make this cost reasonable. This research is searching for untraditional solutions to increase wind turbine efficiency. The smart wind turbine blade concept with the changeable surface model is a new method to increase wind turbine efficiency. Two smart blade models have been analyzed during this research, and the results show that both blade models can increase power extracted from the wind. Using smart blade models with the changeable surface will create a new path of increasing wind turbine efficiency.

Keywords: *Wind turbine, efficiency, smart blade, aerodynamics, renewable energy*

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I. INTRODUCTION

Humanity started utilizing wind energy to propel boats along the Nile River as early as 5,000 BC. Old nations used windmills to grind corn, grind flour, and pump water [1]. The first modern wind turbine generating electricity as it known nowadays was established in July 1887 by Scottish Academic [2].

Wind turbine is considering as an important renewable energy sources in the new century, the continues consumable of power sources by humanity will lead to a lack of available sources for the new generations in addition to the harm caused to the environment, however, humanity should search for new sources able to cover the increasing of demand of power. The renewable energy is one of the alternative sources of energy which naturally occurring, the theoretically inexhaustible source of energy [3, 4]. Man tried to exploit the natural energy sources a thousand years before Christ, later on, people depend on other energy sources, but due to the uncontrolled consuming of these resources all of these resources will be finished, in another word during the upcoming hundreds years humanity will not be able to utilize any of these sources, however, people go back to history and took lessons which led them to depend on the renewable energy instead of relay on the consumable energy resources [5, 6].

The main goal of designing a wind turbine and designer is to maximize the aerodynamic efficiency or power extracted from wind, the places of fixing the wind turbine. Wind turbine is a machine which is catching wind kinetic energy to produce electricity by converting this energy to rotational energy, wind turbine is working by opposite of fan which using electricity to work, offshore and onshore wind turbines have the same work principles, however the wind energy rotates wind blades around the rotor which is connected to the main shaft "low-speed shaft" as the produced rotation isn't enough to produce power (Overview of design chapter). The drivetrain contains the gears which responsible for increasing the rotational speed "high- speed shaft" this shaft is connected to a

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generator which creates electricity. The Planform is with the span of 9.8 m and an aspect ratio of 6.8. The lift to drag ratio (glide ratio) has been estimated to be about five [7]. According to Rankine-Froude theory, the generated power (P) by a known wind turbine calculated by the following equation:

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

Where ρ is air density, sweep area is, wind velocity is V and Power coefficient is C_p which is constant and equal to 0.4 (Betz limit) [8].

In general, WT can be classified in two main types horizontal axis WT and vertical axis WT, HAWT called like this. Because its shaft is parallel to ground while VAWT shaft is perpendicular to ground, both types have advantages and disadvantages, any way HAWT is still more common and there are many designs of it available in the commercial markets.

Fig. 1. Horizontal axis wind turbine

The ordinary wind turbine as it is known nowadays consisting of 16 parts, each of it has a precise and clear rule with power production process [9].

TABLE 1
WIND TURBINE COMPONENTS

1. Nacelle	9. Wind vane
2. Blade	10. Anemometer
3. Hub	11. Low speed shaft
4. Pitch system	12. Break
5. Main shaft	13. Yaw drive
6. Gear box	14. Yaw motor
7. Generator	15. Tower
8. Controller	16. Rotor

Blades are the parts which catch the kinetic energy of the wind and transfer it to rotational energy, blades are fixed on a specific bearing, which enable the blades to pitch "to change their angle relative to the hub while they are still in the rotor plane". The angle of attack of the blades (relative of the wind) can accordingly be optimized, so blades make the maximum lift for different wind velocity without stalling. Blades are feathered to maintain the rated power when wind velocity gets high, while fast pitching of the blades to zero degrees provides an effective means to stop [10]. Early wind turbine blade depends on airplane wing airfoil, same aerodynamics forces control both blades work [11]. Manufacturing wind turbine blades forming 15-20% of the total cost, the aerodynamics profiles of wind turbine blades have a crucial influence of wind turbine [12].

The blade has an airfoil shape different along the blade length from root up to the tip, and the most common wind turbine has a blade with a length of 16-19 meter with three blades. Early blades were flat which were very common, flat blades were used in the windmills, when wind turbine design developed, blade shape change, and curved blades appear. The curved blades are very similar to airplane wings where lifting forces cause blades rotation, as it causing airplane taking off. Similar principles control both systems, lift and drag forces, different pressure on both faces of the blade, however, we can say that the wind turbine blade simulate airplane wing. For purposes of efficiency, control, fuss, and aesthetics the modernistic wind turbine market is dominated by the horizontally mounted three blade designs, with the utilize of yaw and pitch, for survive and work under different wind velocities ability [13]. An international supply chain has evolved around this design, which is now the industry leader and will remain so soon. Usually manufacturers aiming greater cost efficiency have exploited the ability to scale the design, while the latest models reaching 164 m in diameter [14].

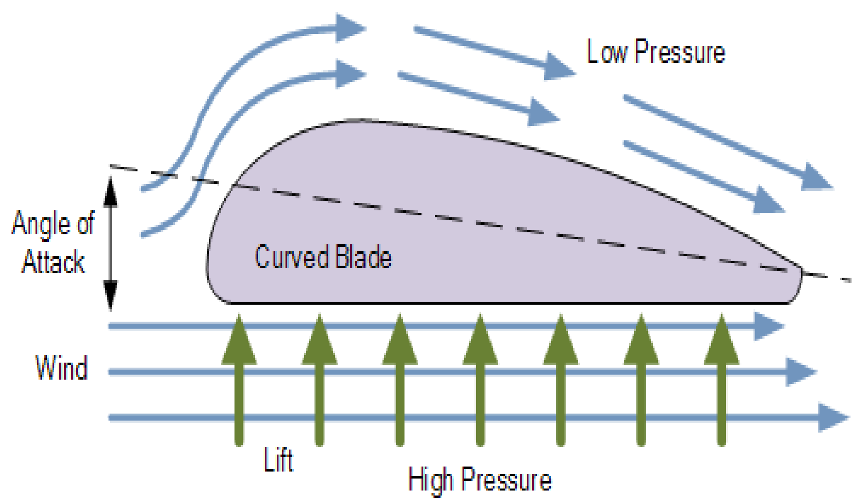


Fig. 2. Wind turbine blade airfoil

II. LITERATURE REVIEW

If we look at wind turbine before ten years ago and a close look on it nowadays we can recognize the dramatically increase of development of it in the rotors, controls, electronics, and gearboxes but the advancing technology used in wind power production has always aimed for the same goal: making wind power a better choice for power generation. Hence, improving wind turbine efficiency and reduce cost.

Increasing wind turbine efficiency can be achieved by different concepts [15], such as constraining on developing the gearbox, increase the rotor size, examine intelligent control systems [16, 17], blades number, size and shapes and pitches. Ordinary wind turbine blades subjected to many attempts to develop the structural design, manufacturing materials and developing the rotor control system of the blade. Some other attempts seek to reduce the cost of producing power by wind turbine by increasing the size of the wind turbine to increase the efficiency [18, 19].

In 2008, a scientific research conducted a comparing between flat and curved blade and how curved blades give better efficiency because curved blade has air flowing around the blade with the air moving over the curved top faster than it does under the flat side of the blade which create a lower pressure area on top, hence, as a result, is subjected to aerodynamic lifting forces which create movement. These lifting forces are always perpendicular to the curved blade's upper surface which led to the blade to move rotating around the central hub. The faster the wind blows, the more lift would produce on the blade, and therefore the faster the rotation. The advantages of a curved rotor blade compared to a flat blade is that lift forces enable the blade tips of a wind turbine to move faster than the wind is moving to generate more power and higher efficiencies. As a result, lift based wind turbine blades are becoming more common now. In 2014 some scientific papers addressed a problem of poor performance of small WT which working at low wind velocity due to laminar separation and laminar separation bubbles on the blades, this can be defined due to the low Reynolds number (Re) as a result of low wind velocity and small rotor size, however, the utilize of specially designed low Re airfoil permits start up at lower wind velocity, increasing the start-up torque and thus improving the overall performance of the WT. Other attempts seek to study and understand the turbulent loading effect on wind turbine performance, In the past, the effect of turbulence has been considered in many domains such as heat transfer, combustion, and aerodynamics. The study of turbulence of aerodynamics phenomena related to wind turbines is rapidly becoming one of the major issues of interest within the wind energy community, this research used experimental approaches to study the influence of turbulent flow on the performance of the WT and loading of a scale-representation of a three-bladed wind turbine. A miniature turbine with a rotor diameter of 384mm was developed and tested within a wind tunnel of 0.9m×0.9m cross-section. To predict the performance of the wind turbine, the lift and drag coefficients of a 2-D foil have been measured over a range of Reynolds numbers and angle of incidences. The measurements have been carried out downstream of the turbulent flows which were simulated in the wind tunnel to be the representative of an atmospheric boundary layer with turbulent intensities ranging from 0.5% to 23% and length scales ranging from zero to 210mm. This range of turbulence characteristics was developed using vortex generators, barrier wall and bed-mounted cubes and the grid turbulence generator. It was observed that when the vortex generators with the barrier wall and the groups of cubes generated the background air flow, the level of turbulent intensity was up to 23% at 150mm from the ground and 6% at 450mm with a range of integral length scales from 210mm at the level of 150mm to 150mm at the level of 450mm. Meanwhile, the grid turbulence generator could not sustain greater than a 35mm length scale; however, it can maintain a higher level for the turbulent intensity (16%) at a cross section five mesh sizes downstream.

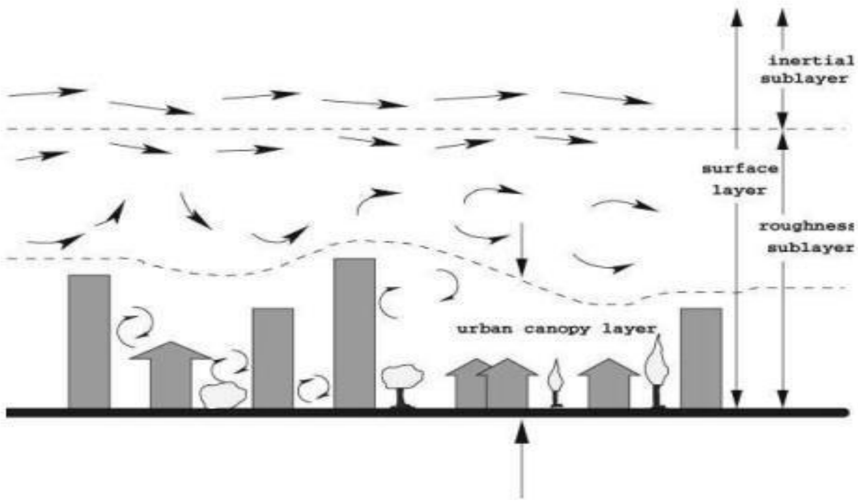


Fig. 3. Sub-layers within the urban boundary layer

In Germany 2014, 19 wind turbines in four farms subjected to non-convex efficiency analysis to determine losses, then in a second stage regression, they adapt the linear regression results of Kneip, Simar, and Wilson (2014) to explain electricity losses by means of a bias-corrected truncated regression analysis. The results show that electricity losses amount to 27% of the maximal producible electricity. Most of these losses are from changing wind conditions, while 6% are from turbine errors. Other attempts seek to reduce the establishment cost of the wind turbine to increase the benefit of the wind turbine. However, in 2001 the tallest wind turbine tower with more than 65 m, but the cost was huge, as an alternative solution to this huge cost an attempt in 2002 and 2003 started to build the wind turbine in the construction site, and still under study but to build a wind turbine with a tower of 100 m to increase wind turbine efficiency. Later new methodology of developing wind turbine blades created which is modeling the smart structure of wind turbine, this study highlighted how developed load control techniques has induced the interest in aerodynamic control systems with built-in intelligence on the blades, this study shows the structure of blade vibration protection using piezoelectric materials is suggested. The blades modeling is completed, the embedded construction of piezoelectric materials is designed, the analysis of deformation displacement and stress of piezoelectric material which proved that the glass fiber composite with piezoelectric materials can be used for the blades active vibration control with Algor software. Blade modeling and finite element analysis of piezoelectric structures are contributed to analyzing the problem of wind turbine blades aeroelastic and lay a foundation for blades stability [20].

III. METHODS AND MATERIALS

To achieve a theoretical evidence of improving wind turbine work conditions two types of the smart blade "using Solidworks software" have been drawn and examined at a different angle of attacks while wind velocity took different values, the study implemented at wind speeds of 5 m/sec and 8 m/sec. This research discussing the two scenarios. The smart blade has a changeable airfoil which give the blade the ability to change the contact surface with the wind according to wind velocity. All loads on both surfaces of the blade have been considered in the study, the purpose of the study is searching for the best angle of attack for the assumed wind velocity which is accompanied by a certain value of the angle between both blade parts to prove that each wind speed has its own optimum angle of attack besides a special angle between the two parts of the blade where the efficiency of the turbine is maximum. The airfoil of A NACA 4705 has been used in the modeling.

A. *First Smart Blade Model*

The first model is a smart blade with changeable surface able to take different positions according to wind velocity. The blade is consisting of two parts fixed to each other from the middle with special rubber joints, this model shows the ability of the smart blade wind turbine to cross over the cutting of the torque when velocity achieved the maximum value where wind turbine still able to produce torque.

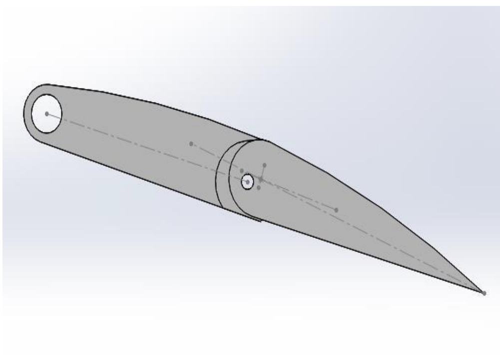


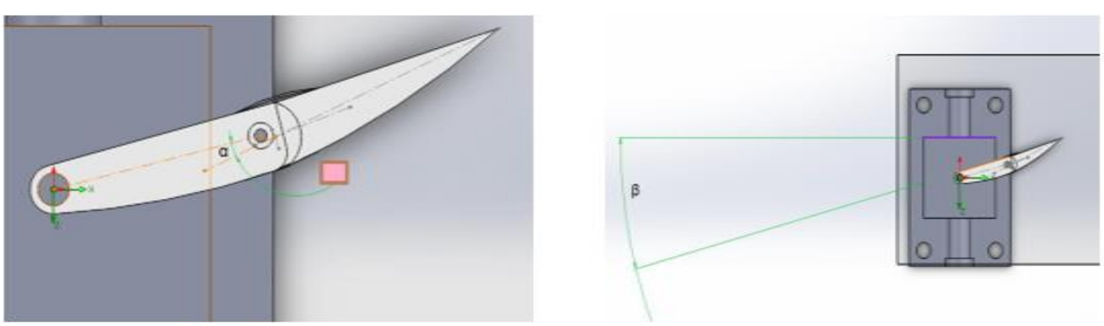
Fig. 4. First smart blade model

Let's define study parameters, α is the angle between the both parts of the blade this angle will take different values in another word, we are going to change this angle until we achieve the best outcome moment *M*, this torque will be responsible of rotating the blade, hence, more of torque means more of electricity. The following values of α will be tested α = (7°, 11°, 15°, 17.5°, 20°) Fig 5a. While, β is the angle of attack which means the angle between the relative wind velocity and blade cord Fig 5b. During our experiment we will give β different values as the following β = (10°, 13°, 15°, 16°, 17°), as a first step we will fix α at 7° which consider the zero point for our study and changing β according to the previous values, this step will enabling us from determining the best angle of attack for wind speed of 5 m/s, then we will start to repeat the study but with fixed β and changing α to previous values. When we start applying the flow pressures on both faces created with different values, however values and pressure distribution are explained in figures and table for each case of the study. Area of both faces isn't fixed because the front face is curved while the back face isn't, we can recognize that each part of the blade area subjected to different values of pressure and that what appears in pressure analyzing Fig 6. During the calculation we used the percentage of each area subjected to certain pressure as % the measurement unit is mm^2. Then the forces (Kg) applied on each area calculated using equation (2) where A (mm^2) is the area affected by a certain amount of pressure according to the analysis, applied forced on the front face have been gathered and same for forces applied on the back face, the difference between the two forces used to determine *Fa* the force affecting the blade, this force and according to applied angle of attack will support our calculation to discover *F* the force which cause the moment and calculated according to equation (3), where γ in the complementary angle of the incident angle, however, the last produced moment calculated according to equation (4) where *b* is the length of rotating arm (the space defined as the distance between the rotating center and the middle of the blade length) $b = 320 * 10^{-3} m$.

$$Fa = P^{*}A \tag{2}$$

$$F = Fa^{*}cos\gamma \tag{3}$$

$$M = F^{*}B \tag{4}$$

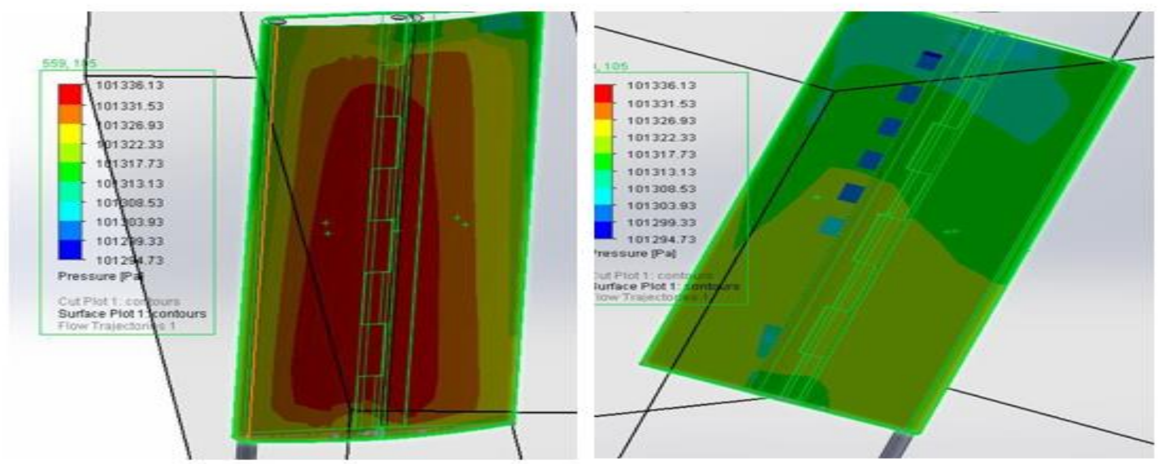


a b

Fig. 5. The angle between both blade parts and the angle of attack

In the first case we fixed the angle between the two blades at $\alpha = 7°$ which consider the zero angle between both parts because we negotiate a concept of curved blade with an angle between the two parts, and move the whole blade in many different values of angle of attack as the following $\beta = (10°,13°,15°,16°,17°,20°,25°,30°,35°,45°)$, during this test we will try to discover the ideal angle of attack to move to the next phase of the experiment which will test different angle between the two blades according to the optimum angle of attack, in other word, from the first test we will determine best angle of attack for the 7° which is the basic state between the two blade parts then we will try to determine the best angle between both parts of the blade depending on the discovered the best angle of attack. Then, we will move to the second step of our test which considering the best angle of attack equal to 15°. Then we will start changing the angle between the both parts of the blade to take different values as the following: $\alpha = (7°,11°,15°,17.5°,20°)$, this step aims to determine the best angle between both blade parts when wind velocity is 5 m/s. Calculation were done similar to calculation of the previous experiment when $\alpha = 7°$ and $\beta = 15°$ already earlier. we repeat the study with wind velocity of 8 m/sec. The angle between both blade parts is fix $\alpha = 7°$ and we change the angle of attack according to the following values: $\beta = (10°,13°,16°,17°,20°,24°,25°,26°,27°,30°,35°)$ to determine the best angle of attack for this blade model when wind velocity became 8 m/sec.

The following figure is an example of pressure distribution on blade surfaces and one table of results is listed as well for the first study case ($\alpha = 7°$ & $\beta = 10°$), all cases has figure and table of results.



a. Pressure on the front face of the blade   b. Pressure on the back face of the blade

Fig. 6. Pressure distribution on blade faces where $\beta = 10°$ and $\alpha = 7°$

TABLE 2
THE PRODUCED FORCES WHEN $\beta = 10°$ AND $\alpha = 7°$

Blade Faces	Pressure/Pa	Pressure Kg/mm^2	Area mm^2	Area %	Area subjected to pressure/mm^2	Force/Kg
Front face	101357.03	0.010335376	48463.9	25	12115.9625	125.223
	101349.64	0.010334623	48463.9	30	14539.155	150.2567
	101342.24	0.010333868	48463.9	25	12115.9625	125.2048
	101334.85	0.010333115	48463.9	15	7269.5775	75.11738
	101327.46	0.010332361	48463.9	5	2423.1925	25.0373
	101349.64	0.010334623	46433.8	3	1393.0137	14.39627
Back face	101334.85	0.010333115	46433.8	2	928.6758	9.596114
	101327.46	0.010332361	46433.8	60	27860.274	287.8624
	101320.06	0.010331607	46433.8	30	13930.137	143.9207
	101305.27	0.010330098	46433.8	5	2321.6895	23.98328

B. Second Smart Blade Model

The second model is a smart blade with a changeable surface able to take different areas according to wind velocity. The blade is consisting of two parts fixed to each other from the root with special joints, figure 6 shows the second model.   is the angle between the both parts of the blade. This angle will take different values in another world we are going to change this angle until we achieve the best outcome moment, as the following α = (0°, 3°, 6°), while wind speed is equal to 8 m/s, besides reaching the best angle of attack for this model we will see how the area affecting wind turbine performance. During the experiment, the area of the blade will change three times. However, wind will face different areas in three cases, a new calculation method has been used in this section, while the inputs enabling the Solid works program from calculating the forces on the X-axis, this force is responsible for rotating the blade, however, same equations have been used.

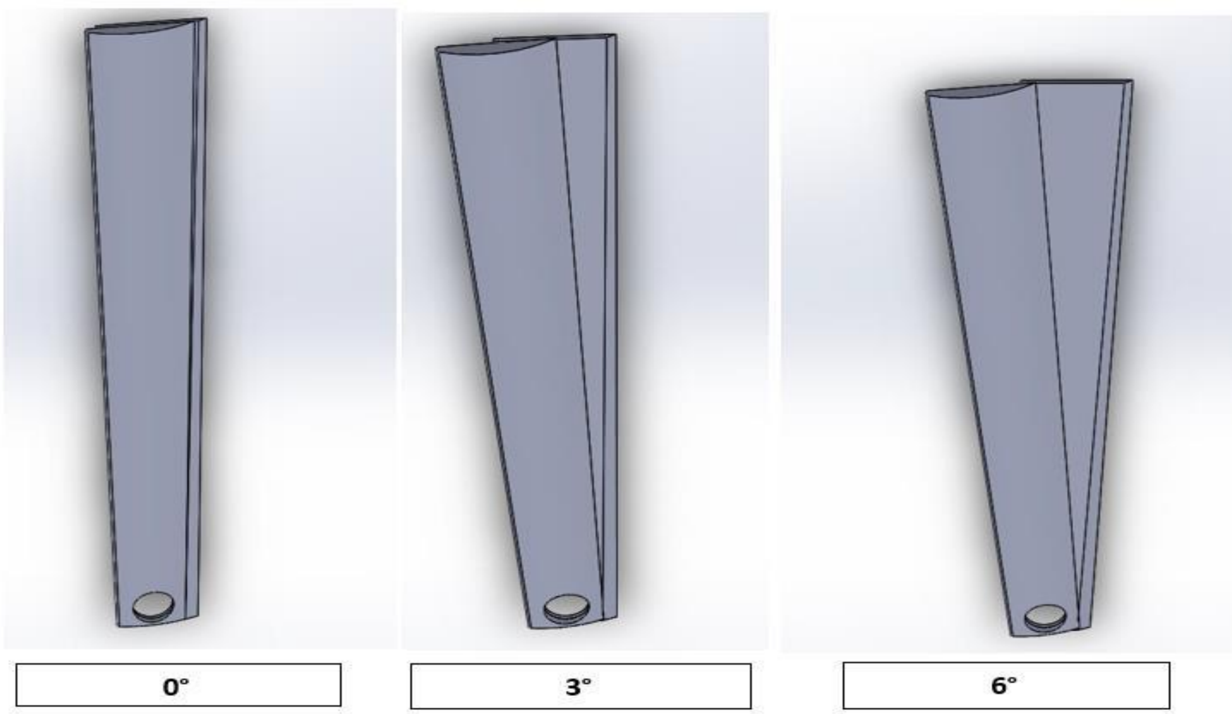


Fig. 7. Second smart blade model

1) First case: The angel between both parts equal to 0° the first case: The first case examined an angle between the two slides of the blade equal to Zero, area subjected to wind attack is 125811.45 mm^2, the rotating arm is $b = 472.41^{*}10^{-3}m$, the following table explains forces formed on X and Y axises.

TABLE 3
FORCES FORMED ON X AND Y AXISES WHEN α = 0°

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value
GG Normal Force 1	[N]	6.76278712	6.740381596	6.72728914	6.76342059
GG Normal Force (X) 1	[N]	-1.06832198	-1.037381215	-1.068686824	-0.97861949
GG Force (X) 1	[N]	-1.06536145	-1.033007795	-1.065361453	-0.974511285
GG Force (Y) 1	[N]	6.69014766	6.672385174	6.659227885	6.690788981

Normal force (X) is F, the force causing blade rotation, using equation (3) moment will be calculated,

$$M = 1.068^{*}472.41^{*}10^{-3} \rightarrow M = 0.5N.m.$$

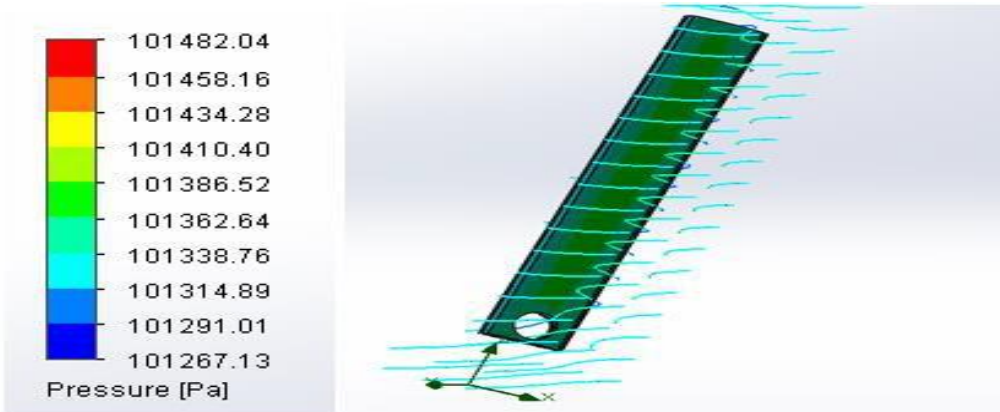


Fig. 8. Pressure distribution on the blade faces when the angle between both blades is 0°

2) Second case: The angel between both parts equal to 3° the second case: The second case examined an angle between the two slides of the blade equal to 3°, area subjected to wind flow is 150554.09 mm^2, same steps in section 4.3.2.2 has been followed.

TABLE 4
FORCES FORMED ON X AND Y AXISES WHEN α = 3°

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value
GG Normal Force 1	[N]	9.73167765	9.658144925	9.568219517	9.992341621
GG Normal Force (X) 1	[N]	-1.37333301	-1.355220781	-1.381295481	-1.332227623
GG Force (X) 1	[N]	-1.37317147	-1.355055271	-1.380342724	-1.331705824
GG Force (Y) 1	[N]	9.64404643	9.572289365	9.484727085	9.906612994

$M = 1.37{*}472.41{*}10^{-3} \rightarrow M = 0.64 N.m.$

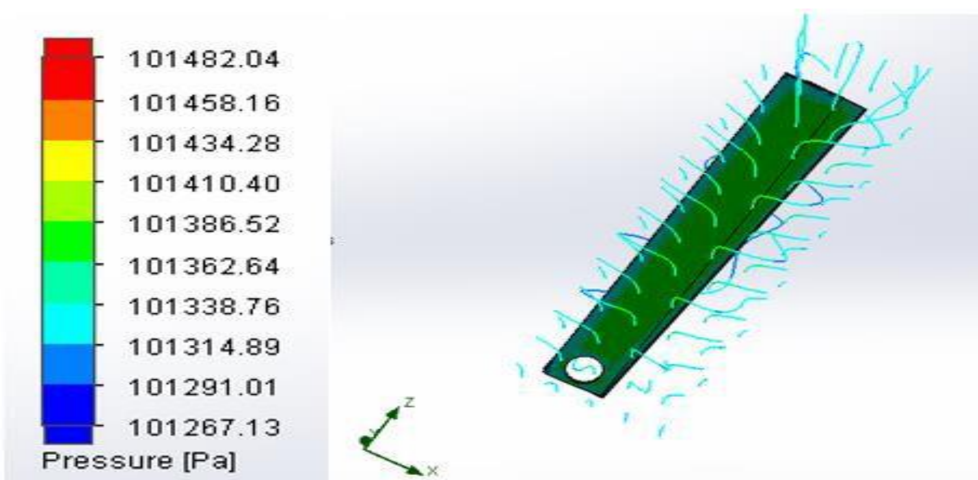


Fig. 9. Pressure distribution and wind forces on the front faces of the blade from Y-axis when α = 3°

3) Third case: The angel between both parts equal to 6° the third case: The third case examined an angle between the two slides of the blade equal to 6°, area subjected to wind attack is 175282.29 mm^2, same steps mentioned previously has been followed.

TABLE 5
FORCES FORMED ON X AND Y AXISES WHEN $\alpha = 6°$

Goal Name	Unit	Value	Averaged Value	Minimum Value	Maximum Value
GG Normal Force 1	[N]	11.9897873	12.0948466	11.89761326	12.5663019
GG Normal Force (X) 1	[N]	-1.66360071	-1.656347594	-1.741572334	-1.637479103
GG Force (X) 1	[N]	-1.65427211	-1.645544276	-1.731181822	-1.626966062
GG Force (Y) 1	[N]	11.8801593	11.98721329	11.78980987	12.45214811

$$M = 1.66^{*}472.41^{*}10^{-3} \rightarrow M = 0.78N.m$$

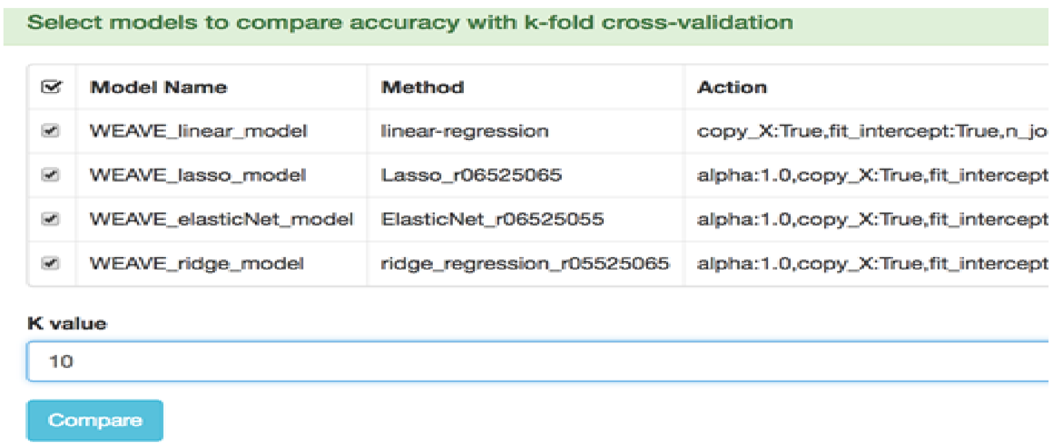


Fig. 10. Pressure distribution and wind forces on the front faces of the blade from Y-axis when $\alpha = 6°$

TABLE 6
PRODUCED MOMENT WITH DIFFERENT ANGLE BETWEEN BOTH BLADE FACES WHEN WIND VELOCITY IS 8 M/SEC

Angle	Area	Moment
0°	125811.45 mm^2	0.5
3°	150554.09 mm^2	0.64
6°	175282.29 mm^2	0.78

IV. FINDINGS AND DISCUSSION

A. *First Smart Blade Model*

From the first model, we can recognize that we fixed the angle between the two parts of the blade at 7°, which consider the zero point of the model, an airfoil of A NACA 4705 wind turbine blade has been used for the first model. The blade subjected to steady wind velocity 5 m/sec. The wind hits the two blade faces and different pressures formed on the both faces, logically the first face which is the curved face subjected to higher pressure than the back face, the aerodynamic forces have been calculated and we assume that the force which hit the front face is *Fa* from this force and depending on the complementary angle of the incident angle we calculated *F* which is the force produce moment or torque which causes blade rotation. Increasing the produced moment meaning increasing the power produced by the wind turbine as simple as it. When $\alpha = 7°$ we change the angle of attack to discover at which value the produced moment is maximum, the following values have been applied and results recorded $\beta = (10°,13°,15°,16°,17°,20°,25°,30°,35°,45°)$, Fig 1, 2, 3, 4, 5, 6, 8, 9, 10 and 11 are demonstrating the pressure distribution on the front face of the blade when wind come from the Z-axis with different angle of attack.

Produced moment has been calculated according to the different angle of attack values as explained before and the following curve appeared.

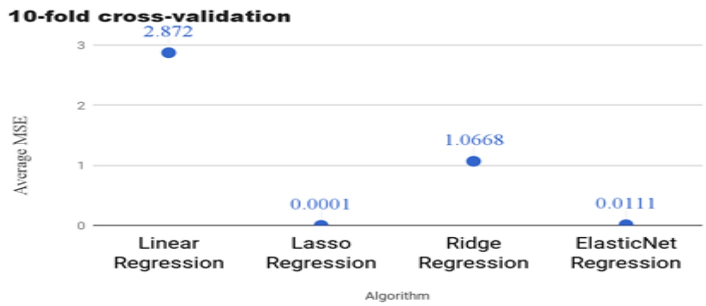


Fig. 11. Produced moment and the angle of attack with fixed $\alpha = 7°$

Easley, we can recognize that the best moment has been achieved with the value of angle of attack equal to 15°. Now, we have the optimum angle of attack, hence, we can search for the best angle between the two parts of the blade, as mentioned, by this way we can reach the best performance of the wind turbine at the given wind velocity. Back to our concept, we assume $\beta = 15°$, and α= 7°, 11°, 15°, 17.5°, 20°.

Produced moment calculated by the same approach and the results that lead us to the best angle between the two parts of the blade, results are showed in Fig 10.

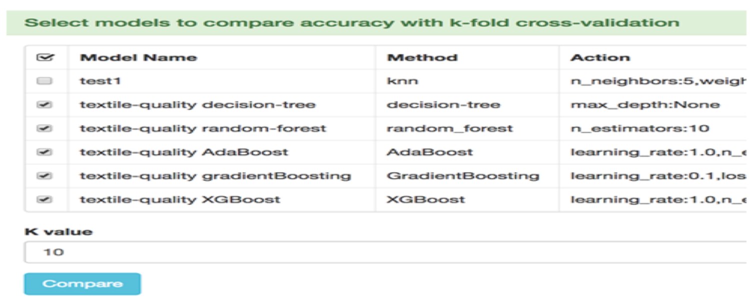


Fig. 12. Produced moment with different values of α

We repeat the same process fixing the angle between both parts ($\alpha = 7°$) of the blade and change the angle of attack but the wind velocity of 8 m/sec, the results support the previous inclusion where the maximum torque appears with an angle of attack equal to 24° as Fig 11 shows.

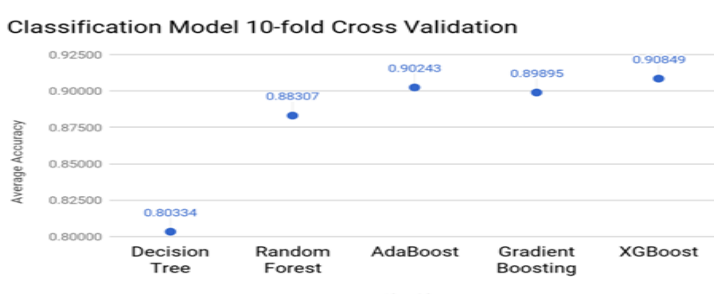


Fig. 13. Produced moment and the angle of attack with fixed β

The previous chart supports our idea that each wind velocity has an optimum angle of attack.

B. *Second Smart Blade Model*

After calculation of the produced moment addressed, we will create a chart which gives the relation between surface area change and produced moment Fig 12 explains the results.

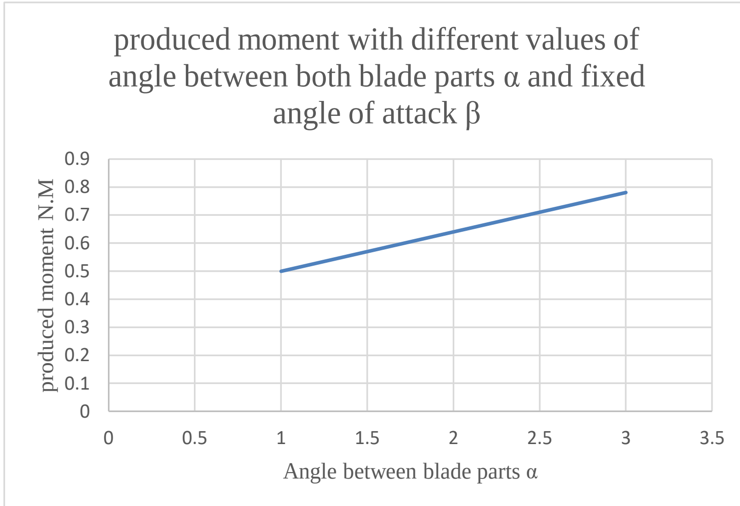


Fig. 14. Produced moment at wind speed 8m/s with different values of α

From the previous chart, we can recognize that when we increase the area of the wind turbine blade which facing the wind the produced moment increased. Changing the angle from 0° to 3° caused moment increase with 28% and that can be acceptable due to the incidence increasing with area. But when we moved to 6° produced moment increased up to 21%, this still theoretical results but it can be an indicator to which extent increasing the blade surface could increase wind turbine efficiency, however, this angle is the best angle because of high pressure and moment transfer.

V. CONCLUSION AND RECOMMENDATIONS

Increasing wind turbine performance or increasing wind turbine efficiency can be achieved by other methods away from using a smart rotator, special control systems, increasing tower height, blade with special flaps or increasing the size of the wind turbine which will lead to massive increase with the cost.

The previous results can be used as tangible evidence that the smart blade model is able to be used in the future of wind turbine manufacturing and able to become a real model, as well as the results agreed that this smart model affect the performance of the wind turbine positively when it accomplished with a live control system.

Now we can move forward with the concept of the smart blades with changeable surfaces facing the wind. To maximize the benefit from winds blow through a wind turbine farm we can create multiple farm consisting of ordinary horizontal axis wind turbine and wind turbine with smart blades from both models.

This research will be participating within the development of the wind turbine manufacturing and facing the variable wind conditions in different locations, in another hand, increasing power produced from wind energy will have a positive impact on the economic situation of the country and the environment.

Declaration of Conflicting Interests

There are no competing interests.

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