Enhancement on Self-Starting Darrieus Bladed Wind Turbine Using J-Shape Airfoil

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ABSTRACT

Conventional Darrieus wind turbine faces a challenge to self-start in low wind speeds but their performance during operation is better than that of Savonius wind turbines which means that there is room for improvement for Darrieus wind turbine. In this paper, study has been focused to design and develop a modified-Darrieus wind turbine blade based on J-NACA0010, J-NACA0015 and J-NACA0018 airfoil profile. Performance study will be assessed in terms of its self-starting capability, tip speed ratio, angular speed and power output of the proposed system for all the above-mentioned modified airfoils. The J-shaped blade has a higher overall performance compared to the others because unlike the conventional Darrieus wind turbines which depends mostly on lift forces. The modification to the blades in cooperates drag forces is projected can produce better starting torque which solves the problem of self-starting in the conventional Darrieus wind turbines. From the experimental findings, it has been found that J-NACA0018 has recorded to achieve the largest power coefficient among the other airfoils with 0.558 as its (Cp) and generated power of approximately 40 mW, which is the highest among the rest. The J-NACA0018 also has the fastest recorded time for self-starting with 1.45 seconds. This is due to fact that the airfoil has a larger surface area in the blade which contributes to a larger drag force and thus contributed to the power generation and power coefficient. The highest torque coefficient was produced by J-NACA0015 at 0.714.

Keywords: J-shape, Darrieus, self-starting torque, wind turbine, airfoil.

1. Introduction

Energy is the most important resources compared to others; this is because energy itself is an essence to almost everything that we do in our daily lives. Malaysia has been very dependent on fossil fuels since the beginning of electrical usage in the country. As a developing country, the number of population and township development is bound to increase at an exponential rate hence increasing the demand of electricity. People of our current generation need to focus on the sustainability of energy for the survival of humankind. Energy and sustainability had become an important aspect and current issue around the globe. In terms of economy, energy is considered one of the most important pillars that drive a country's growth and development as it generates wealth.

Since our primary source of energy such as fossil fuels, coals, natural gas and etc are depleting resources; there is a need to find a suitable secondary source of energy to support or even take over the primary sources of energy. As stated by S.Mekhlief, et al. in [1], Malaysia is venturing into energies such as solar, wind, mini-hydro and biomass. Malaysia has the potential to utilize its natural resources just as well as other developed countries do but of course extensive research and adaptable renewable energy plant design must be taken into consideration. For example, our country can't possibly use the 70 meter in radius horizontal axis wind turbine because those are designed for higher wind speed capturing and it is rare that our country wind speeds are above 5 m/s. As stated by Lip-Wah Ho, the wind speeds are ranged between 1.9 m/s to 4.0 m/s at 50 meter above sea level, which indicates low on shore wind speeds [2].

Location also plays a vital role in wind power generation. There is also much to consider such as sizing of the wind turbine, type of material to be used and most importantly the cost to implement the system. Setting up a renewable energy system will indeed require a high amount of investment and capital to begin with but one article has mentioned that wind energy is cheaper than “dirty” energy even without government subsidiaries [3]. This in turn will result in cheaper electricity bills and greener environment [4].

As of 2012, World Wind Energy Association has shown that 100 countries are using electricity generated by wind turbines. These statistics are enough to convince everyone that wind energy is undoubtedly one of the most mainstream renewable energy sources and is still gaining reputation by more and more countries looking to adapt into renewable energy.

For a wind turbine to work, the most essential part is the wind itself. By converting the kinetic energy from the air flow to rotate the rotors of the wind turbine, a connecting shaft will rotate the generator shaft to produce electricity. In the wind power industry, there are two well-known types of wind turbine to generate electricity. First is the horizontal axis wind turbine (HAWT) and second one is vertical axis wind turbine (VAWT). It can be said that generally, HAWT would seem to be a better choice to invest in but since Malaysia has low wind speeds, VAWT would be a more viable choice to be implemented in Malaysia. Looking deeper in VAWT, there are two main types of VAWT which are the Savonius and the Darrieus wind turbines.

From the literature, it has been mentioned that Darrieus has higher power coefficient than Savonius. Darrieus yields much better performance than Savonius because it uses the lift force to rotate but then is held back by its inability to self-start. Therefore, as mentioned by N. C. Batista et al. in [5] that drag forces must be taken advantage to self-start. There are several factors that affect the self-starting capabilities of Darrieus wind turbines which are the blade airfoil profile and the blade configuration. By manipulating the two factors, the Darrieus wind turbine will be capable of self-starting in low wind speeds. Hence, improving performance of the wind turbine and possibly improving the power coefficient.

Blade airfoil profile plays an important role when it comes to a wind turbine. According to research conducted by I. Hashem and M. H. Mohamed [6], a modified airfoil could possibly increase the efficiency by 10% as compared to regular airfoil shapes as well as keeping the pitch angle at zero degree is the most optimal configuration [7]. In [8] and [9], authors also confirmed that the modified aorfoil may give better performance compared to the plan surface blade. Since Malaysia’s wind speed is relatively low, the VAWT designed must be designed in such a way that it can make use of the low wind speed.

The blade airfoil along with the configuration must be appropriate such that it gives the drag forces value to aid the Darrieus wind turbine to be self-starting. Besides that, since it a small-scale wind turbine, it would be a very useful asset to have as a backup energy supplier. One the most essential features of the Darrieus is also its ability to face wind from any direction and also its low building cost according to I. Hashem and M. H. Mohamed [7]. In-cooperating a suitable blade airfoil would give the wind turbine a much better performance especially for locations with low wind speeds, a suitable blade applied to the vertical axis wind turbine (VAWT) has claimed to be suitable for small electrical generations according to N Rosmin et al [1].

Looking at a global scale, the most used VAWT are the Savonius wind turbines, invented by a Finnish engineer Sigurd Johannes Savonius in the year 1922. The reason why Savonius gained more popularity than Darrieus is because of its ability to self-start even in low wind speeds which made the Savonius much more reliable than the Darrieus wind turbine despite its power coefficient being less than Darrieus [9]. A typical Darrieus wind turbine doesn’t have a good self-starting ability hence leading to its unfavored application in the real world. Therefore, it would be a vital task to design a blade which can exhibit self-starting capabilities so that the Darrieus can function at its maximum potential. The best strategy to improve the self-starting capabilities of the Darrieus wind turbine is to consider combination of both lift and drag forces exerted on the blades which gives a better starting torque due to the inclusion of drag forces [9-13] lacking in the Darrieus’ original design.

Hence, in this study, research has been focused to design and develop a modified-Darrieus wind turbine blade based on J-NACA0010, J-NACA0015 and J-NACA0018 airfoil profile. Performance study will be assessed in terms of its self-starting capability, tip speed ratio, angular speed and power output of the proposed system for all the above-mentioned modified airfoils.

2. Research Method

In the designing phase, there are a few processes which will receive paramount attention for this project. Firstly, blade geometry configuration is considered where the airfoils, modification of the airfoil and rotor design is planned out for implementation. Next is to obtain a suitable generator for a wind turbine. Next, the tower design phase which consists of materials and method to construct a sturdy tower for the wind turbine. Once these are done, assembling the three parts will be the next challenge as to enable them to work together as a unit. Then only the testing phase can be conducted.

2.1 Blade Geometry Configuration

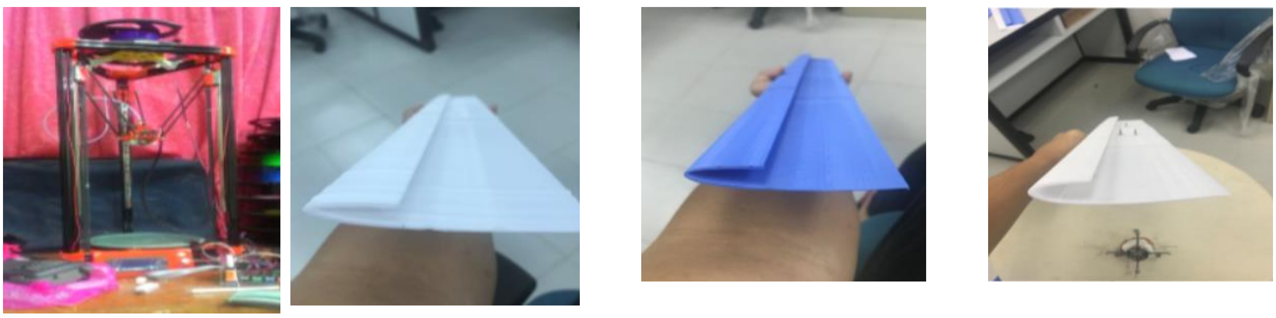
The determination of the blade geometry configuration is summarized in Table 1.

Table 1. Summary of Blade Rotor Design

No	Airfoil	The airfoil used will be NACA 0015 where the power coefficient of this airfoil recorded by I. Hashem and M. H. Mohamed is 0.3243 [6]. This power coefficient is the conventional airfoil power coefficient before applying any modifications to the blade. Airfoil NACA 0018 and NACA0010 will also be tested for the purpose of comparisons between the three airfoils. The solid work design for these airfoils is shown in Figure. 1. Meanwhile, the 3D printer, which was used to fabricate the blades and the built such airfoils are shown in Figure. 2. Materials used was polyactic acid (PLA). This has a heat resistance up to 150-degree Celcius.
1	J-shape modification	The J-shape modification will be done on the blade to enhance the self-starting characteristic as it in cooperate drag a force along with lift forces to create a better starting torque at all angles of attacks as well as improves the overall performance by 20% [13][14][15].
2	Blade thickness	The blade's airfoil profile makes it have different thickness around the blades but since the 3 types of airfoils are used.
3	Shaft design	The shaft is designed with a diameter of 1.5 cm to be connected to the generator shaft. The shaft used is of solid construction as it is easier to construct. The connecting shaft used a washing machine connector.
4	Blade material	Polyactic acid (PLA) is used as the material for the blades as it possesses several key characteristics. One of them includes that it has a high melting point of 150°C.
5	Airfoil	The airfoil used will be NACA 0015 where the power coefficient of this airfoil recorded by I. Hashem and M. H. Mohamed is 0.3243 [7]. This power coefficient is the conventional airfoil power coefficient before applying any modifications to the blade. Airfoil NACA 0018 and NACA0010 will also be tested for the purpose of comparisons between the three airfoils. The solid work design for these airfoils is shown in Figure. 1. Meanwhile, the 3D printer, which was used to fabricate the blades and the built such airfoils are shown in Figure. 2. Materials used was polyactic acid (PLA). This has a heat resistance up to 150-degree Celcius.

(a) NACA0010 (b) NACA0015 (c) NACA0018

Figure. 1. The Solid Work Design for the Considered Airfoils



(a) 3D Printer (b) NACA0010 (c) NACA0015 (d) NACA0018

Figure. 2. The Built Airfoils

2.2 Blade Fabrication

The blades are first designed using SolidWorks to obtain the desired 3.3J cutting position. The 3.3J indicates that the end trail of the J is at the maximum thickness of the airfoil. The SolidWorks design for the 3 airfoils is as shown in Figure. 3. The coordinates are first obtained then altered as required by the size of the blade then plotted into the SolidWorks. Figure.3(a) to Figureure.3(b) show a snippet of the modified and unmodified coordinates for each of the airfoils. The fewer the number of blades, the higher the performance of the rotor [4]. The use of double blades of solo Darrieus rotor makes the turbine lower in performance [19][20]. Hence, in this study, 3-bladed rotor was chosen to be examined.

NACA 0010		NACA0010 modified size	
1.0000	0.00105	0.10000	0.000105
0.9500	0.00672	[illegible]	0.000672
0.9000	0.01207	0.09000	0.001207
0.8000	0.02187	0.08000	0.002187
0.7000	0.03053	0.07000	0.003053
0.6000	0.03803	0.06000	0.003803
0.5000	0.04412	0.05000	0.004412
0.4000	0.04837	0.04000	0.004837
0.3000	0.05002	0.03000	0.005002
0.2500	0.04952	0.02500	[illegible]
0.2000	0.04782	0.02000	0.004782
0.1500	0.04455	0.01500	0.004455
0.1000	0.03902	0.01000	0.003902
0.0750	0.03500	0.00750	0.003500
0.0500	0.02962	0.00500	0.002962
0.0250	0.02178	0.00250	0.002178
0.0125	0.01578	0.00125	0.001578
0.0000	0.00000	0.00000	0.00000

(a) Coordinates for NACA0010

NACA 0015		NACA0015 modified size	
1.0000	0.00158	0.10000	0.000158
0.9500	0.01008	[illegible]	0.001008
0.9000	0.01810	0.09000	0.001810
0.8000	0.03279	0.08000	0.003279
0.7000	0.04580	0.07000	0.004580
0.6000	0.05704	0.06000	0.005704
0.5000	0.06617	0.05000	0.006617
0.4000	0.07254	0.04000	0.007254
0.3000	0.07502	0.03000	0.007502
0.2500	0.07427	0.02500	[illegible]
0.2000	0.07172	0.02000	0.007172
0.1500	0.06682	0.01500	0.006682
0.1000	0.05853	0.01000	0.005853
0.0750	0.05250	0.00750	0.005250
0.0500	0.04443	0.00500	0.004443
0.0250	0.03268	0.00250	0.003268
0.0125	0.02367	0.00125	0.002367
0.0000	0.00000	0.00000	0.000000
		0.00125	-0.002367

(b) Coordinates for NACA0015

NACA 0018		NACA0018 modified size	
1.0000	0.00189	0.10000	0.000189
0.9500	0.01210	[illegible]	0.001210
0.9000	0.02172	0.09000	0.002172
0.8000	0.03935	0.08000	0.003935
0.7000	0.05496	0.07000	0.005496
0.6000	0.06845	0.06000	0.006845
0.5000	0.07941	0.05000	0.007941
0.4000	0.08705	0.04000	[illegible]
0.3000	0.09003	0.03000	0.009003
0.2500	0.08912	0.02500	[illegible]
0.2000	0.08606	0.02000	0.0086060
0.1500	0.08018	0.01500	0.0080180
0.1000	0.07024	0.01000	0.0070240
0.0750	0.06300	0.00750	0.0063000
0.0500	0.05332	0.00500	0.005332
0.0250	0.03922	0.00250	0.003922
0.0125	0.02841	0.00125	0.002841
0.0000	0.00000	0.00000	0.00000
		0.00125	-0.002841

(c) Coordinates for NACA0018

Max length | Max thickness

Figure. 3. Snippet of the modified and unmodified coordinates for each of the airfoils

2.3 Generator Selection

The chosen generator should work with a maximum capacity of 35Watts. The chosen generator is an OEM product made in Taiwan. The model's name for the chosen generator is GM-2480 DC12V-24V 80RPM Large Torque Metal Gearbox. The generator has a rated voltage of 24VDC at 60 rpm with the gearbox on. The no load current is 220 mA and has an operating voltage between DC 6V to 24V. The image of the generator is shown in Figure. 4(a).

(a) 24 VDC Generator (b) Tower (c) Rotor hub (d) Wind speed test

Figure. 4. Main Components

2.4 Tower Design

The tower height is designed to be 1.5 meters tall including the blades. The tower has four poles supporting each other, made from wood and at the top a circle cut cone is glued to position the 4 poles vertical. The bottom base is made by a wood joinery to ensure the base is firm on the ground. The constructed tower with the height of 1 meter is shown in Figure. 4(b) while in Figure. 4(c), constructed rotor hub with a radius of 43 cm can be depicted. The blades and rotor hub are held together using a bookshelf L bracket.

2.5 Wind Speed Source

The wind speed is varied by using the three wind speeds (4, 5 and 6 m/s) of an industrial fan. The position of the tower from the industrial fan is placed approximately 1 meter apart. The industrial fan (wind source) is located approximately 1 meter away from the tower for this test, as depicted in Figure. 4(d).

3. Results and Analysis

In this section, results will be discussed based on three categories: 1- power performance, 2- starting time and TSR performance, and power and torque coefficient performance.

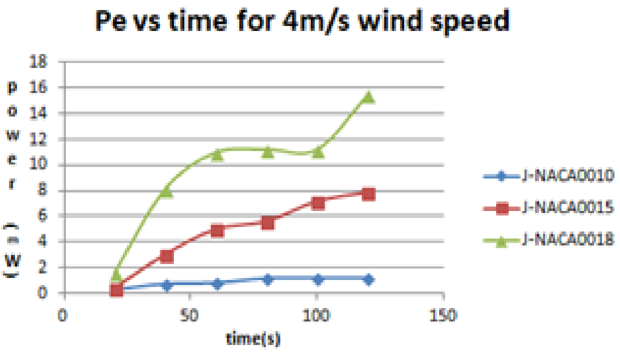
3.1 Power Performance

Figure. 5(a) shows the performance of output power when all airfoils are tested at wind speeds of 4, 5 and 6 m/s. The readings are taken at a 20-second interval for a total of 2 minutes. From the Figure, it can be seen that as time increases, the electrical production by the generator increases as well. All blades were exposed to wind speeds of 4 m/s and the highest power producing blade is by J-NACA0018. The 18-series blade experiences an exponential incline in power between 20 and 60 seconds and then stays constant until 100 seconds and continues to rise to a maximum of approximately 16 mW at 120 seconds. The power after 2 minutes is observed to be approximately constant until the wind source is switched off. The J-NACA0015 airfoil has a constant increment throughout the 2 minutes in power but only managed to produce 50% of the 18-series. The J-NACA0010 on the other hand shows a very small increment of power.

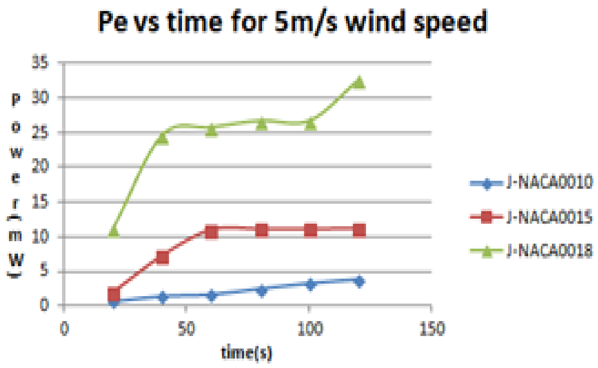
In Figure. 5(b), the performance of the modified airfoils when exposed to 5 m/s of wind speed is plotted. As predicted, the power outputs of the blades are better than when they are subjected to 4 m/s wind speed. The maximum output of the J-NACA0018 at 5 m/s has shown an increment of 200% when compared to the output during 4 m/s. For J-NACA0015, the output at 5 m/s has experience an increment up to 125% compared to 4 m/s. Finally, J-NACA0010 has shown an increase of approximately 300%. This explains that, even the slightest change in wind speed is able to change the output of the wind turbine. For wind speed of 6 m/s as shown in Figure. 5(c), it can be observed that even at the first interval at 20 seconds, the blades are able to produce a decent amount of power. The power increases gradually at a steady rate for all the tested airfoils. Summing up the test, the nature of power increment is the same for J-NACA0018 at all wind speeds, which is the 18-series increases exponentially at the beginning and has a moment of constant output and then continues to increase which is capped at the 2nd minute. The J-NACA0015 and J-NACA0010 on the other hand experiences a gradual increase throughout the 2 minutes. These results are in line with the theoretical equation where power is increased exponentially with wind speed increment.

3.2 Starting Time and TSR Performance

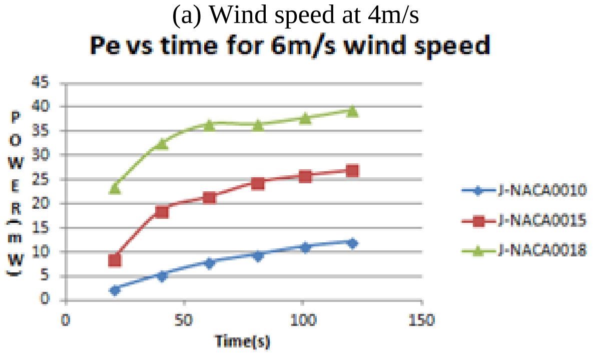
In Figure. 6(a) to Figure. 6(c), the correlation between wind speed, power output and tip speed ratio for J-NACA0010, J-NACA0015 and J-NACA0018 are shown respectively. For J-NACA0010 as depicted in Figure. 6(a), TSR is calculated to be approximately 0.4 and the recorded power output is approximately 8mW at 4 m/s. Both the power output and TSR shows a steady increase as the wind speed increases.



(a) Wind speed at 4m/s



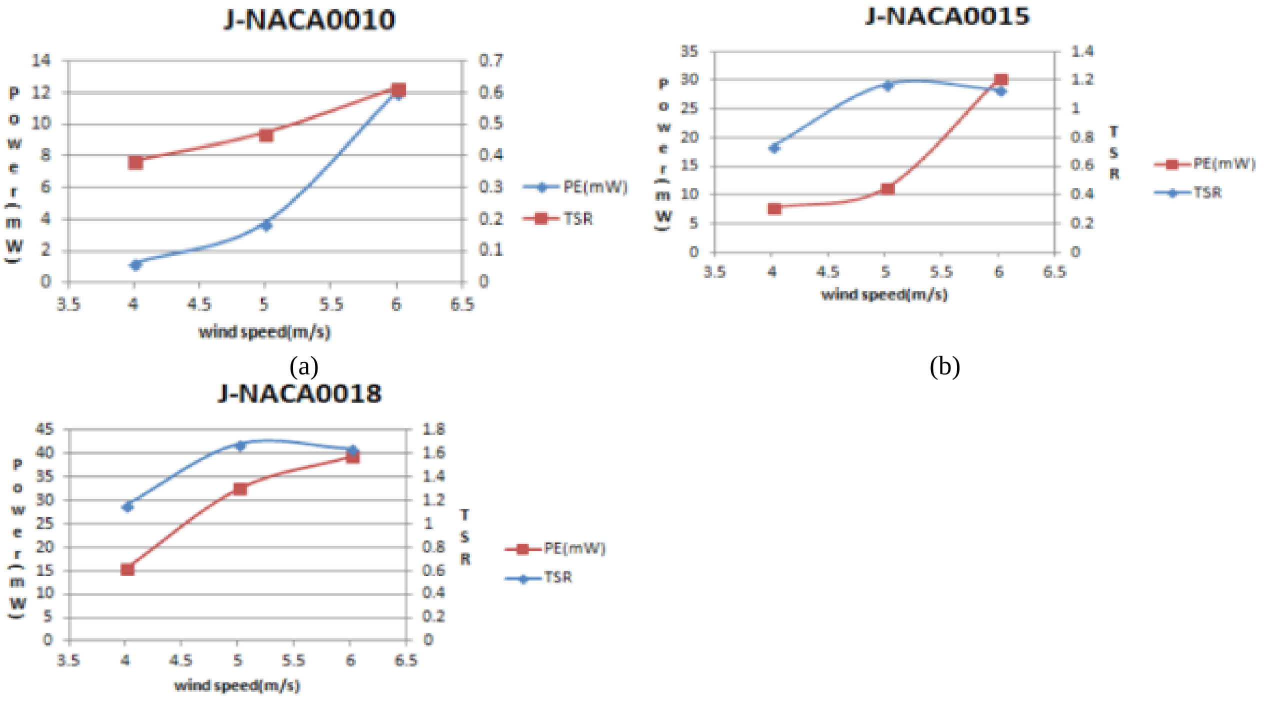
(b) Wind speed at 5m/s



(c) Wind speed at 6m/s

Figure. 5. Power Response

For J-NACA0015 as shown in Figure. 6(b), the TSR peaked at 1.2 when exposed to wind speed of 5 m/s but the power output was only around 10mW. As the wind speed was increased to 6 m/s, the TSR experienced a minor drop but power output increased exponentially. Meanwhile, for J-NACA0018 as depicted in Figure. 6(c), the TSR also peaked when exposed to 5 m/s at 1.64. The output power of the system shows a steady increment throughout the wind exposure levels where the maximum produced is about 40mW. From overall observation, both the J-NACA0015 and J-NACA0018 share a similar nature in terms of TSR which is both their respective TSRs experience a drop for wind speeds more than 5 m/s. In power production term, the generated power increases as the wind speed increases.

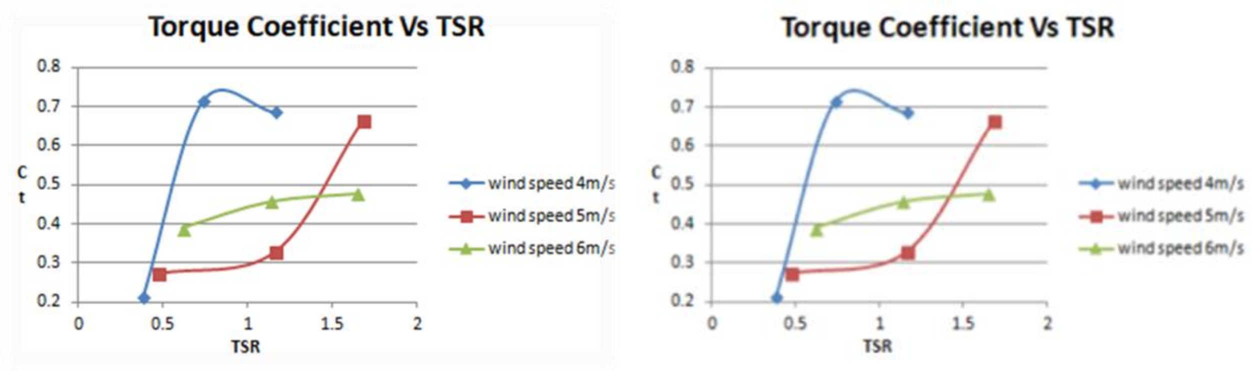


(a) (b) (c)

Figure. 6. Electrical Power and TSR Response

3.3 Power and Torque Coefficient Performance

Figure. 7(a) shows that the torque coefficient produced is highest when 4 m/s of wind is being blowed to the blades, followed by 5 m/s, and then 6 m/s. Although 6 m/s has a much higher starting torque at lower TSR, the increase in torque coefficient is small compared to the rest. The highest torque coefficient is produced by 6 m/s wind is 0.478 (referring to Table 1) which is produced by J-NACA0018 but when exposed to 5 m/s, the blade is able to obtain a coefficient of 0.663 which is the highest for that particular wind speed. The highest torque coefficient obtained was 0.714 which was produced by J-NACA0015 at 4 m/s but eventually decreases as the TSR increases. All in all, the smallest increment in torque coefficient is by 6 m/s. 5m/s wind recorded to have a steady incline of torque coefficient along the increment of TSR and 4 m/s wind speed had the highest torque coefficient in lower TSR ranges.



(a) (b)

Figure. 7. Torque Response

In Figure. 7(b), it shows that the power coefficient reaches a maximum of 0.558 when using the J-NACA0018 (referring to Table 1) when being exposed to wind speed of 5 m/s. In Figure. 7(a) and In Figure. 7(b), as the TSR increases, the torque and power coefficient show a steady increase too. Wind speeds at 4 m/s gives a linear increment of power coefficient at TSR less than 1. Surprisingly, the highest wind speed of 6 m/s didn't provide the highest power coefficient where it only achieved a power coefficient of 0.392 by the J-NACA0018 at 6 m/s. A conclusion is able to be made by this graph, which is that, as the TSR increases, the power coefficient will also increase accordingly.

3.4 Performance Comparison among All Airfoils

The blades basically have different thickness as the coordinates suggests in Figure. 3(a) to Figure. 3(b). This has effect on how much drag force is being in-cooperated with lift forces. For example, the Savonius has a large area to "capture" wind; therefore, it is called a drag type wind turbine. On the other hand, the proposed design in this project has enabled the Darriues to take advantage of the drag forces which is produced by the "captured" wind. The summary of performances is given in Table 1. From Table 1, it is obvious that J-NACA0018 has the best performance in terms of electrical generation with a recorded power output of 39.508mW. This is due to the fact that the blade enables the wind turbine to have a higher rpm compared to the other blade airfoil. Each blade has different characteristic due to the geometry of the blade. Since the electrical power of the J-NACA0018 is the highest, this also reflects to the power coefficient of the J-NACA0018. Difference between the blades are the thickness therefore, a conclusion that the thicker the blades (blade's inner gap) profile, the higher the achievable power coefficient hence, the larger the electrical power output.

Table 1. Comparison between all Airfoils

Airfoil Type	Fastest/slowest Starting time (s)		Max/min power coefficient		Max/min torque coefficient		Electrical Power(mW)
J-NACA0010	2.75	3.59	0.120	0.041	0.388	0.214	12.060
J-NACA0015	1.89	2.70	0.300	0.193	0.714	0.329	27.075
J-NACA0018	1.45	2.46	0.558	0.392	0.686	0.478	39.508

4. Conclusion

The main objective of this project was to develop a modified Darrieus wind turbine blade using airfoils NACA0010, NACA0015 and NACA0018 and to undergo performance testing on its self-starting capability, tip speed ratio, angular speed and power output of the proposed system for all the above-mentioned modified airfoils. The airfoils were successfully modified so that it could self-start without any external help from mechanical parts. Therefore, the wind turbine is able to be used in areas with low wind speeds. The blades were fabricated with a Flsun 3D printer using Polyactic acid (PLA) as its main component which light, durable and has high heat resistance. The wooden constructed tower was also successfully built which acted as the foundation for the rotor hubs. The analysis was also successfully conducted to determine their power coefficient and torque coefficient. This includes having to measure the rpm and torque of the wind turbine.

In conclusion, J-NACA0018 has recorded to achieve the largest power coefficient among the other airfoils with 0.558 as its (Cp) and generated power of approximately 40 mW, which is the highest among the rest. The J-NACA0018 also has the fastest recorded time for self-starting with 1.45 seconds. This is due to fact that the airfoil has a larger surface area in the blade which contributes to a larger drag force and thus contributed to the power generation and power coefficient. The highest torque coefficient was produced by J-NACA0015 at 0.714.

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References

[1] Saad Mekhilef, Meghdad Barimani, Azadeh Safari, Zainal Salam (2014), Malaysia's Renewable energy policies and programs with green aspects. Renewable and sustainable energy reviews 40, 497-504.

[2] Lip-Wah Ho (2016). Wind energy in Malaysia: Past, present and future. Renewable and sustainable energy reviews 53, 279-295.

[3] Zachary Shahan (2016). Low cost of solar power and wind power crush coal, crush nuclear and beat natural gas. Retrieved from https://cleantechnica.com/2016/12/25/cost-of-solar-power-vs-cost-of-wind-power-coal-nuclear-natural-gas/ .

[4] Marco Pellegrini, Alessandro Guzzini ND Cesare Saccani (2021). Experimental measurements of the performance of a micro-wind turbine located in an urban area. Energy Reports (7), 3922-3934.

[5] N.C. Batista, R. Melício,, J.C.O. Matias, J.P.S. Catalão (2011). Self-Start Evaluation in Lift-Type Vertical Axis Wind Turbines: Methodology and Computational Tool Applied to Asymmetrical Airfoils. Proceedings of the 2011 International Conference on Power Engineering, Energy and Electrical Drives. PowerEng 2011 (technically co-sponsored by IEEE), at Malaga, Spain, May 11013.2011.

[6] M.H. Mohamed (2012). Performance investigation of H-rotor Darriues turbine with new airfoil shapes. Energy 53 (1), November 2012, 522-530.

[7] Hashem, M.H. Mohamed (2018). Aerodynamic performance enhancement of H-rotor Darrieus Wind turbine. Energy 142, 531-545.

[8] Mahadi Masud, Naim Ul Hasan, Amit Arefin, Mohammad U.H.Joardder (2016). Design Modification of Airfoil by Integrating Sinusoidal Leading Edge and Dimpled Surface. AIP Conference Proceedings on 7th BSME International conference on Thermal Engineering, Bangladesh 2016.

[9] Salih N.Akour, Mohammed Al-Heymari, Talha Ahmed, Kamel AliKhalil (2018).Experimental and theoretical investigation of micro wind turbine for low wind speed regions. Renewable Energy (116), 215-223.

[10] Giovanni Gerardo Muscolo, Rezia Molfino (2014). From Savonius to Bronzinus: a comparison among vertical wind turbines. The International Conference on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES14. Energy Procedia, 50, 10 – 18.

[11] M. Zamani, S. Nazari, S.A, Moshizi, M.J. Maghrebi (2016). Three dimensional simulation of J-shaped Darrieus vertical axis wind turbine. Energy (116), 1243-1255.

[12] A.A Al-Aqel, B.K.Lim, E.E.Mohd. Noor, T.C Yap, S.A.Alkaff (2016). Potentiality of small wind turbine along highway in Malaysia. International Conference on Robotics, Automation and Sciences (ICORAS), 5-6 Nov. 2016.

[13] The Renewable Energy Website. Darrieus Wind turbine. Retrived from http://www.reuk.co.uk/wordpress/wind/darrieus-wind-turbines/ .

[14] Christopher W. Gabrys(2011). Self Starting darrieus wind turbine. U.S. patent PCT/US2008/013586 issued February 10, 2011.

[15] Zamani, M.J. Maghrebi,S.R.Varedi (2016). Starting torque improvement using J-shaped straight bladed Darrieus vertical axis wind turbine by means of numerical simulation. Renewable Energy 95,109-126.