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Study of a Vertical Axis Wind Turbine for Low Speed Regions in Saudi Arabia

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Abstract – There are number of sources for generation of power but in the recent years wind energy shown its potential as the clean source of energy and contributing to the high-energy demands of the world. Vertical axis wind turbine (VAWT) is the best option for the area, which are under load sheading. Thus, in this paper, VAWT blades for low average wind speed regions like Al Khobar in Saudi arabia is designed and implemented. Performance and power produced are investigated and utilized in the design and the economic analysis. An experimental and theoretical review on the performance of Savonius VAWT is presented. The turbine was made of Aluminium alloy with a blade angle of 160 degree and maximum coefficient of power, Cp, of 0.286. The results of this current study showed that the power output, with speed of minimum speed of 12-15 m/s generate 40-80 watts with an efficiency of 31~35%.

***Keywords*:** Vertical Axis Wind Turbines, Wind Speed, Power Generation, Efficiency And Performance.

1. Introduction

Wind energy represents one of the most promising sector of renewable energy. Harvesting energy from low average wind speed profile regions such as the Saudi Arabia is a challenge. Due to the low average of wind speeds in Saudi Arabia, use of large and medium size conventional wind turbines is not economically feasible. These conventional turbines are designed for high rated wind speeds in range of 15 m/s to 20 m/s. However, the average wind speed in the Saudi Arabia specially in Al Khobar city is in range of 10 m/s to 15 m/s maximum. The intent of this study is to design a Savonius small Vertical Axis Wind Turbine (VAWT) that fits the low average wind speed regions. Al Khobar city in Saudi Arabia has become one of the busiest cities with more buildings under construction. The nearby city of Dammam has the second-largest port in Saudi Arabia and embodies the administrative departments of the Eastern region. The current electricity peak demand in the Kingdom of Saudi Arabia (KSA) is about 55 Gigawatts (GW) out of which 72% is used for Heat Ventilation and Air conditioning system (HVAC). The peak demand is expected to reach 120 GW by the year 2032. The Saudi Government initiated a 2030 vision that involved massive program for alternative energy [1]. These programs involve renewable energy and nuclear as an alternatives to the existing power plant.

Al Khobar city in Saudi Arabia is chosen as sample site for experimental and theoretical investigation the VAWT for low wind speed regions [2]. The majority of sites fulfilling these requirements are situated along the two coastlines, for example, Yanbu in the West and Juaymah and Dammam/Al Khobar/Dhahran in the East [3]. With existing wind measurements limited to location of meteorological stations only, additional attractive sites can be expected in unchartered regions.

Wind turbines that are most efficient had been designed by Cole Gustafson from Dakota State University [4]. In his research, he showed that the horizontal axis wind turbine machines was more efficient than vertical axis one. Moreover, the blade span of horizontal wind turbines used was larger than vertical axis machines which limited the placement confined spaces.

VAWT was not as commonly used as the Horizontal Axis Wind Turbine. The reason behind that was that VAWT is less efficient than HAWT when considered as a power plant generator. However, for the small scales like homes, parks, or offices VAWT was more efficient. In general, vertical axis turbines are powered by wind coming from all 360 degrees even though some turbines are powered when the wind blows from top to bottom. Because of this versatility, vertical axis wind turbines were thought to be ideal for installations where wind conditions were not consistent, or due to public ordinances the turbine cannot be placed high enough to benefit from steady wind [5].

The most important parameter in studying the performance of a VAWT is the the efficiency. In fact, as proved in [6] and [7], the efficiency of Savonius model in varying wind conditions was compared to the traditional horizontal axis wind turbine. The results showed that at low angles of attack the lift force had major contribution to the overall torque generation. The Savonius rotor was not a solely drag-driven machine but a combination of a drag-driven and lift-driven device. Therefore, it can go beyond the limit of Maximum power coefficient Cp established for the purely drag-driven machines. A research article published by Advances in Mechanical Engineering (AIME) focused on how to improve the efficiency of the turbine by selecting the best blade angle [8].

The effect of the blade arc angle on the performance of a typical two-bladed Savonius wind turbine is investigated with a transient computational fluid dynamics method [9]. Simulations were based on the Reynolds Averaged Navier–Stokes equations, and the renormalization group turbulent model was utilized. The numerical method was validated with existing experimental data [10]. The results of this article indicate that the turbine with a blade arc angle of 160° generates the maximum power coefficient Cp is equal to 0.2836, which is the highest that gain from the experiment. The article provided the below Table 1, which shows the maximum coefficient of power for different cases. In addition, Figure 1 shows the blade dynamic torque coefficient for different blade arc angles.

Table 1: Maximum coefficient of power for different cases [9].

Case	Blade angle	$C_{P\,max}$	C_P gain percentage (relative to *case 4*)
1	150	0.2687	2.67%
2	160	0.2836	8.37%
3	170	0.2835	8.33%
4	180	0.2617	0.00%
5	190	0.2521	−3.67%
6	200	0.2271	−13.22%

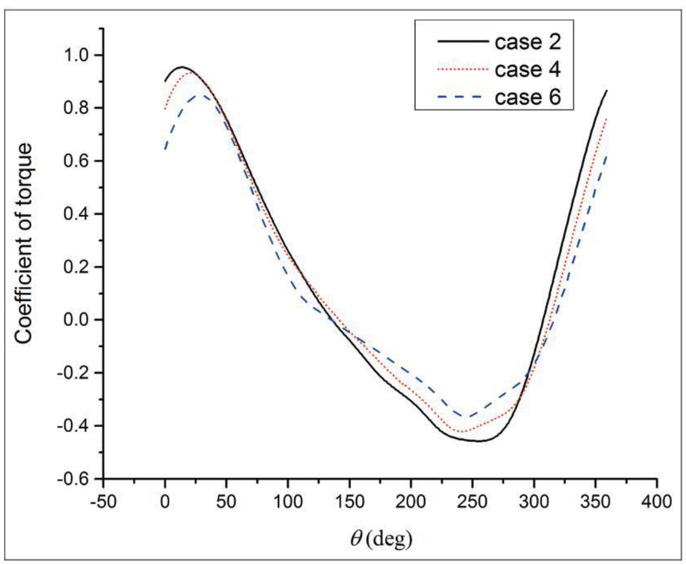

Fig. 1: Blade dynamic torque coefficient for different blade arc angles [9].

The key part in designing wind turbines is the blade. Generally, the main goal in designing a wind turbine blade is maximizing the power coefficient. In case of VAWT, the starting time (cut-in speed) and economic feasibility are very important in optimizing the final design of VAWT blade. The starting time optimization carried out by Pourrajabian et al. have shown that the starting time of micro wind turbine can be reduced by increasing the number of blades which would also increase the power coefficient, Cp [11]. Increasing the number of blades increases the overall energy of the system, but it increases the overall cost of the system.

The main objective of the current study is to design an efficient VAWT employing low Reynolds number airfoils, i.e. low wind speed airfoil. It is proven by Refs. [12] and [13] that Reynolds number has considerable effect on turbine blades performance that employ such airfoil and this will be confirmed by theoretical and experimental results.

2. Theoretical Modeling

Theoretical analysis is conducted for the calculus of the theoretical power generation. In f act, wind power depends on the velocity and the mass flow rate

$$P = \frac{1}{2}\dot{m}v^2 = \frac{1}{2}\rho A v^3 \quad (1)$$

Taking in consideration the turbine Power coefficient, power in the wind is calculated using the following equation:

$$P = \frac{1}{2}\rho A v^3 C_p \quad (2)$$

Where:

P: Power in watts

ρ: Air density "At sea level 'air density' is approximately 1.2 $\frac{kg}{m^3}$

A: Turbine area in m^2 , which can be calculated from the length of turbine blades. In this study, the turbine high is 0.9 m and width is 1.25m. Therefore, area is $A = 1.125\ m$

v^3: wind speed, which is the velocity of the wind in $\frac{m}{s}$.

C_p: Power coefficient, usually varies according to wind turbine design, ranging between 0.05 and 0.45. In this case, from Table 1. We choose $C_p = 0.2836$ based on the selected angle 160°.

The only variable in this equation is the wind speed. Table 2 and Figure 2 show the theoretical gained power at different wind speeds.

Table 2: Theoretical gained power calculation.

Theoretical Gained Power Calculation						
Density ρ	A =h*w= 1.125m		Wind Wpeed V	Power coefficient Cp	Power P	Power (2) Turbines P
	h=0.9m	w=1.25m				
1.2	1.125		1	0.2836	0	0
			2		2	3
			3		5	10
			4		12	25
			5		24	48
			6		41	83
			7		66	131

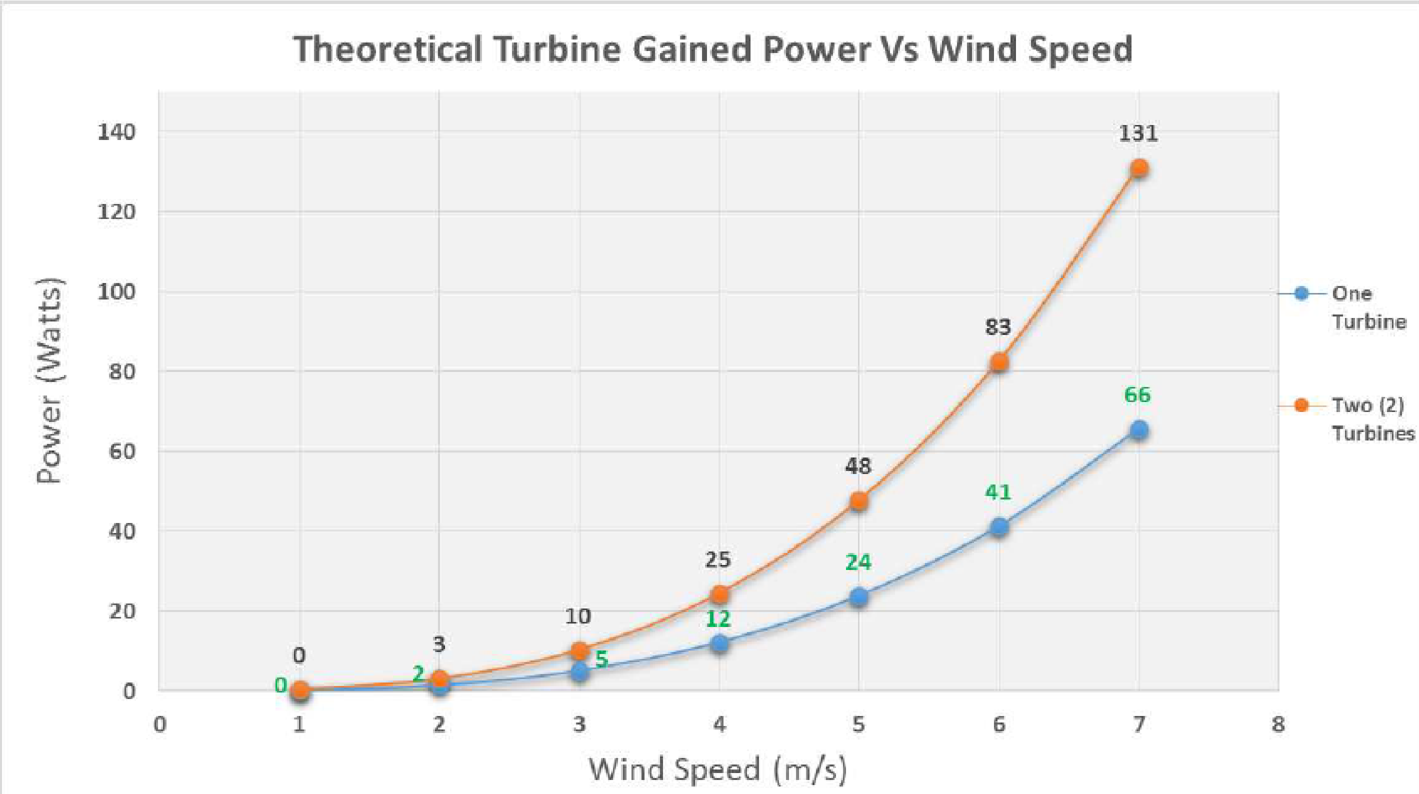

Fig. 2: Theoretical Turbine Gained Power vs. Wind Speed.

3. Design

The methodology applied to this project can be divided into six phases. These phases are information gathering, concept generation, model generation, model analysis and refinement, concept selection, and verification; these phases are shown in Figure 3.

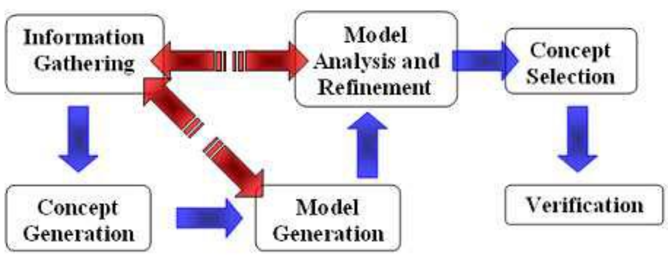

Fig. 3: Applied Phases of used Methodology.

The objective of this study is to design a vertical axis wind turbine (VAWT) that could generate power under relatively low wind velocities.

3.1. Rotor Blades And Shaft

Savonius blades are a crucial and basic part of a wind turbine shown in Figure 4. They are mainly made of aluminum, fiber glass or carbon fiber. We selected the aluminum alloy as recommended because they provide better strength to weight ratio.

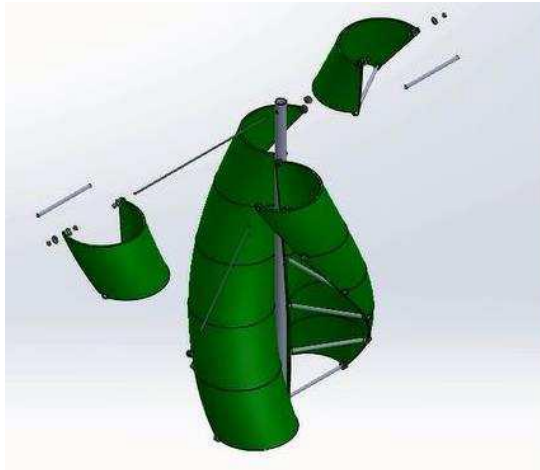

Fig. 4: Sketch for Turbine Blade and Shaft Design.

The design of the individual blades also affects the overall design of the rotor. Rotor blades take the energy out of the wind; they capture the wind and convert its kinetic energy into the rotation of the hub. The arc angle was designed at an angle of 160°. The shaft is the part that should be turned by the turbine blades as is shown in Figure 3.

3.2. Radial & Thrust Bearings

The bearing is integral part of the overall system. The lubricant and sealing elements also play a crucial role. To enhance bearing effectiveness in the system, the right type should be selected. Based on theoretical study on [14] and [15], we opted for two ball bearing 6004R. This choice can carry out the static load rating and dynamic load rating 5 KN and 9 KN respectively.

3.3. Tree Model

This design starting from defining the high and width of the tree to be 2.8 meter high to achieve as much wind as possible and a width equal to 2 m. A goal for defining a tree branches was to have the most popular design and material that would be able to provide realistic results. Initially, we tried to use aluminum material for the tree branches, but this material will not hold the turbines easily. Thus, a carbon steel galvanizing materials (Pipe, flanges & blade) for the tree would satisfy our requirements. Figure 5 shows initial tree design and the turbine fabrication.

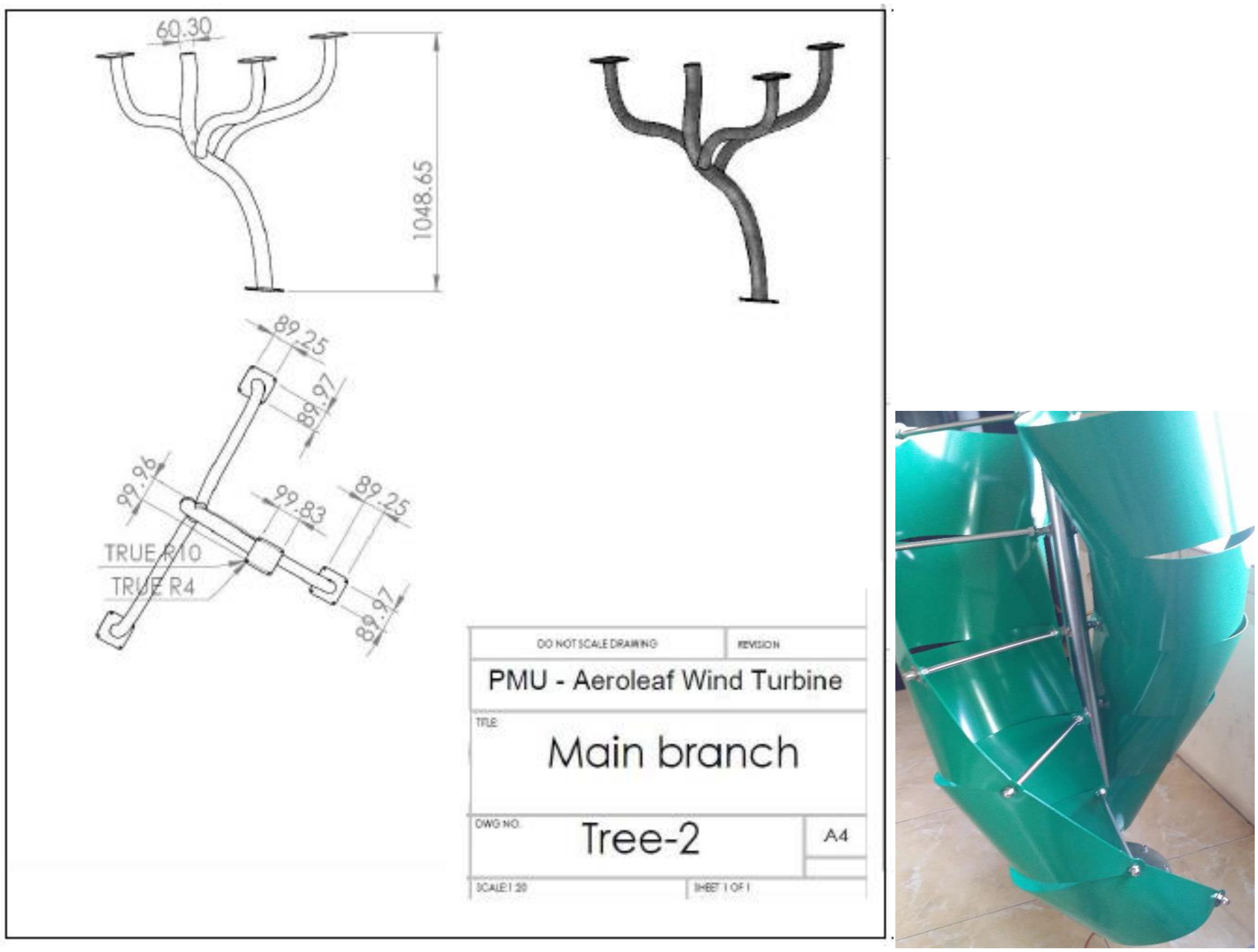

Fig. 5: Initial Tree Design and turbine fabrication.

4. Experimental Work

Experiment is conducted to validate the model designed. We created the experimental set-ups required to test the prototypes and structures. In order to determine the effectiveness of the products that were manufactured, we performed tests to evaluate them. We also tested the power output of the turbine blades and evaluated how the vibrations from the turbine affect the stress on the tree structure.

Two experiments have been conducted based on the wind speed value. The procedure of calculating the power is counting the voltage and the current that feeding the battery. The power gained can be calculated using the below equation.

$$P = I \times V \tag{3}$$

where I: the current in Ampere and V is the voltage.

Below are the results that we got from the experiments. Table 3 and Figure 6 are for experiment# 1, Table 4 and Figure 7 are for experiment# 2.

Table 3: Experiment# 1 reading.

Experimental Readings					
Experiment# 1 Normal weather					
Time	Wind Speed m/S	Voltage (V)	Current (I)	Power (Watt)	Power (2) Trubines (Watt)
21:00	0.7	8.6	0.05	0	1
18:00	1.6	10.6	0.15	2	3
15:00	3.4	12.3	0.24	3	6
12:00	4.3	13.7	0.43	6	12
9:00	5.2	14.2	0.52	7	15

* Sorted by increasing in wind speed

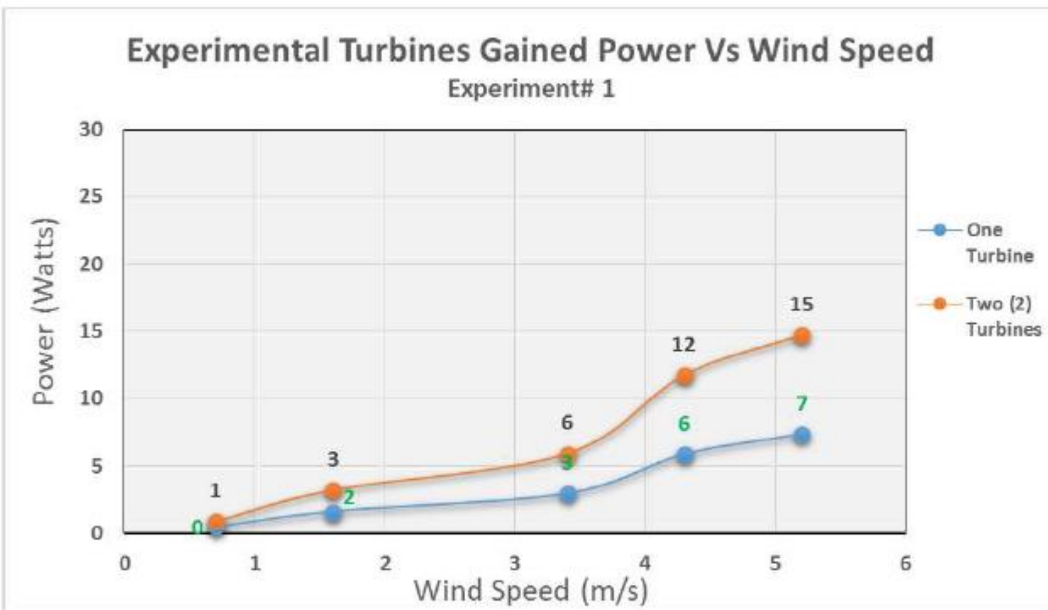

Fig. 6: Curves of the power vs the wind speed for Experiment# 1.

Table 4: Experiment# 2 reading.

Experimental Readings					
Experiment# 2 Windy Day					
Time	Wind Speed m/S	Voltage (V)	Current (I)	Power (Watt)	Power (2) Turbines (Watt)
21:00	6.2	15.8	0.51	8	16
18:00	6.6	16.5	0.57	9	19
15:00	7.1	17.2	0.84	14	29
12:00	7.5	17.7	1.2	21	42
9:00	8.4	18.4	1.9	35	70

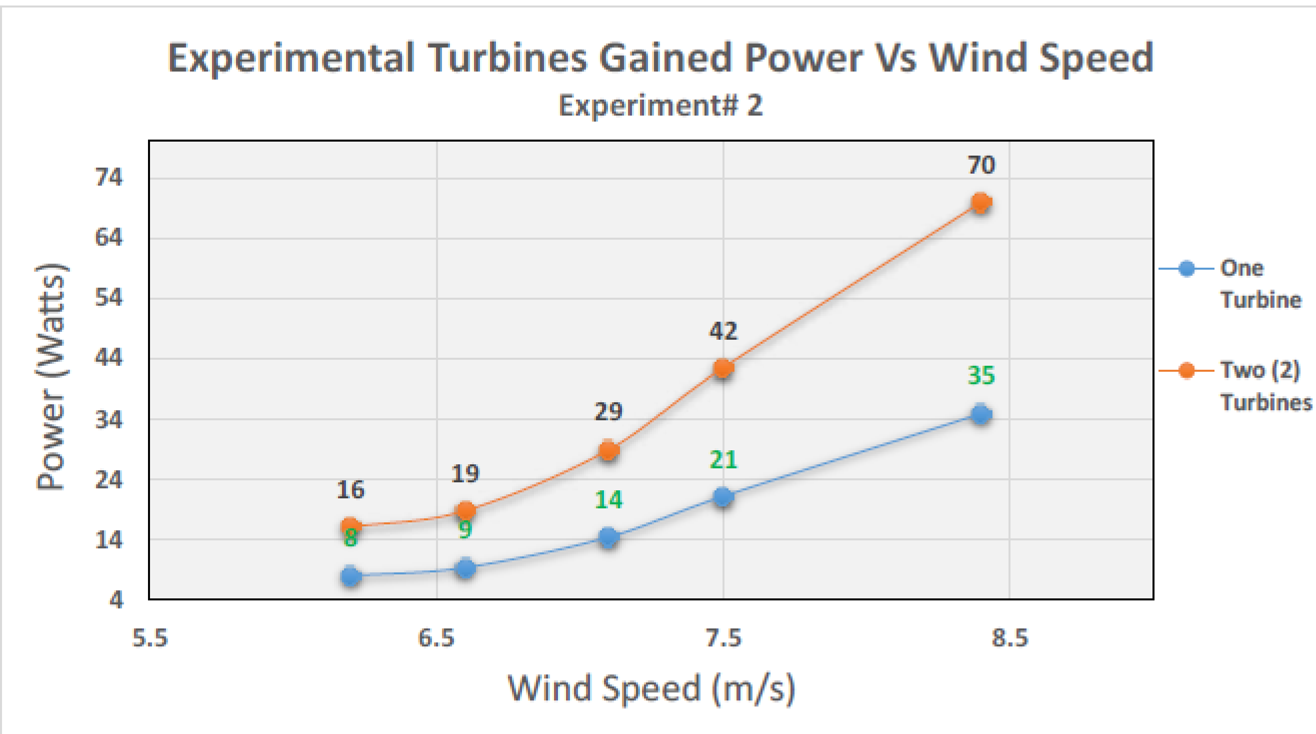

Fig. 7: Curves of the power vs the wind speed for Experiment# 2.

5. Results and Discussion

As a result, this study (experimentally and theoretically) present a review on the performance of Savonius wind turbines. It shows in the Figure 8 the gap between the actual and ideal output power, where a several factors have affected clearly on the actual performance, these factors are due to external factors, lack of resources, process, geometrically, or due to human error. These factor resulted in drop of 31~ 35% between the theoretical and experiment results.

The theoretical results in Figure 2 showed that for one turbine and at wind speed of 5 m/s, the turbine produced 24 watts compared to 48 watts for two turbines. In Figure 6, the experimental results showed that when two turbines were operated, the actual power increased to 15 watts at the same wind speed of 5 m/s. The difference between the theoretical single turbine and experimental two turbines was 33%. As the wind speed increased and more turbines were used, the more power were generated. Savonius rotor performance was affected by operational conditions such as instability and insufficient of wind speed. In addition, air flow direction was effected on torque and power coefficient, while assumed as average in the theoretical part. Moreover, to reduce the error between the actual and theoretical, and to improve the performance of the turbines, two areas have to be improved. First, future study has to be focused on the effect of blades surface friction and dust contamination that is common in the desert environment. In addition, losses were contributed to the friction in the rotating parts, bearings, rods, generator's shaft and controller panel wires; have to be reduced for better efficiencies. Second, in regards to the improvement of the geometry side of the turbine, the uniformity of the arc angle in each blade was difficult to obtain due to manufacturing difficulties. This no uniformity causes vibrational effect as the wind speed increase and thus affecting the performance of the Savonius turbine.

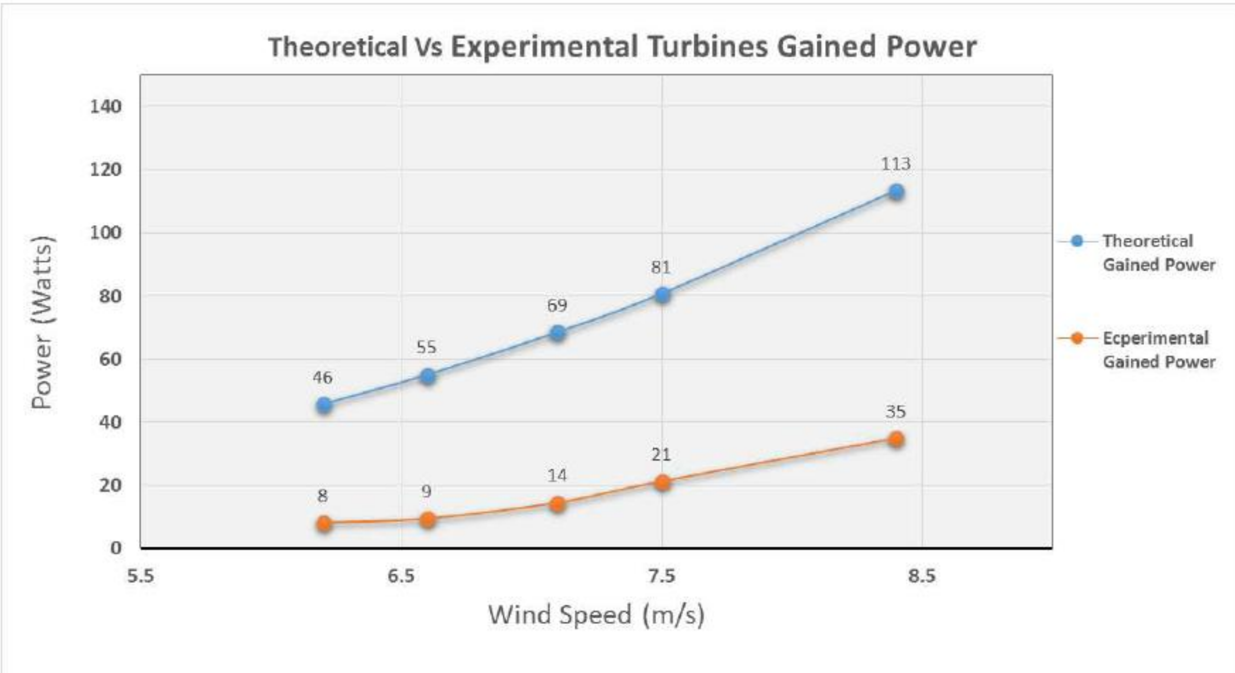

Fig. 8: Curves of theoretical vs Experimental studies.

4. Conclusion

We have presented in this paper a review on the performance of Savonius VAWT for low wind speed region in Saudi Arabia. The results showed that the power output, with speed of minimum speed of 12-15 m/s generate 40-80 watts with an efficiency of 31~35% between theoretical and experimental results. Inefficient wind speed was the huge impact getting the required power output, minimum speed of 12 m/s is required to have acceptable output power. Further research based on new numerical methods in CFD methods are investigated in future work to confirm the experimental results and can be used to optimize the performance of the Savonius VAWT.

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