International Journal of Modern Engineering Research (IJMER)
www.ijmer.com Vol. 3, Issue. 5, Sep - Oct. 2013 pp-2978-2986 ISSN: 2249-6645

Experimental Comparison Study for Savonius Wind Turbine of Two & Three Blades At Low Wind Speed

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ABSTRACT: *In this project, experimental comparison and investigations were carried out to study the performance and to make a comparison between two and three blades Savonius wind turbine.*
For this purpose, two models of two and three blades were designed and fabricated from Aluminum sheet, each of them has an aspect ratio of (A_s = H/D =1), the dimension is (H = 200 mm height and diameter D = 200 mm) and the blades were made of semi – cylindrical half of diameter (d = 100 mm). The two models were assembled to have (overlap e = 0 and a separation gap e' = 0).

These two models were tested and investigated by using a subsonic wind tunnel that was fabricated for this purpose under a low wind speed due to many reason mostly that the savonius wind turbine has its maximum performance at (λ = TSR = 1) and a high starting torque at low wind speed.

It was observed from the measured and calculated results that the two blades savonius wind turbine is more efficient, it has higher power coefficient under the same test condition than that of three blades savonius wind turbine.
The reason is that increasing the number of blades will increase the drag surfaces against the wind air flow and causes to increase the reverse torque and leads to decrease the net torque working on the blades of savonius wind turbine.

I. INTRODUCTION:

The renewable energy is considered as a new technology and an alternating energy source to be used instead of fossil fuel, its continuous rising cost of it and due to growing concern to reduce the effects of climate change, such as global warming, generated by extensive and deliberate use of fossil fuels, mainly in the electric power generating plants and transport.

Global warming will continue unless dependence on fossil is reduced, thus the Wind power has a key role in reducing greenhouse gas emissions [ref. 1].

Today, the most commonly used wind turbine is the Horizontal Axis Wind Turbine (HAWT), where the axis of rotation is parallel to the ground. However, there exist other types of wind turbines, one of which will be the primary focus of this paper, the Vertical Axis Wind Turbine (VAWT). These devices can operate in flows coming from any direction, and take up much less space than a traditional HAWT [ref. 2], and VAWT are definitely a credible source of energy for the future [ref. 1].

VAWTs have a number of advantages over HAWTs, such as [ref. 3]:
1) Simple construction, they can be made from oil barrels cut in two halves.
2) Extremely (low cost), simplicity reduces cost of construction, and aids installation.
3) They can accept wind from any direction, thus eliminating the need for re-orienting towards the wind.

VAWTs work well in places with relatively low wind strength, and constant winds, VAWTs include both a drag-type configuration, such as the Savonius rotor, and a lift-type configuration, such as the Darrieus rotor [ref. 4].

II. PRINCIPLES OF SAVONIUS ROTOR WIND TURBINE:

Savonius turbines are one of the simplest turbines. Aerodynamically, they are drag-type devices, consisting of two or three blades (vertical – half cylinders). A two blades savonius wind turbine would look like an "S" letter shape in cross section (figure 1).

The savonius wind turbine works due to the difference in forces exert on each blade. The lower blade (the concave half to the wind direction) caught the air wind and forces the blade to rotate around its central vertical shaft. Whereas, the upper blade (the convex half to wind direction) hits the blade and causes the air wind to be deflected sideway around it.

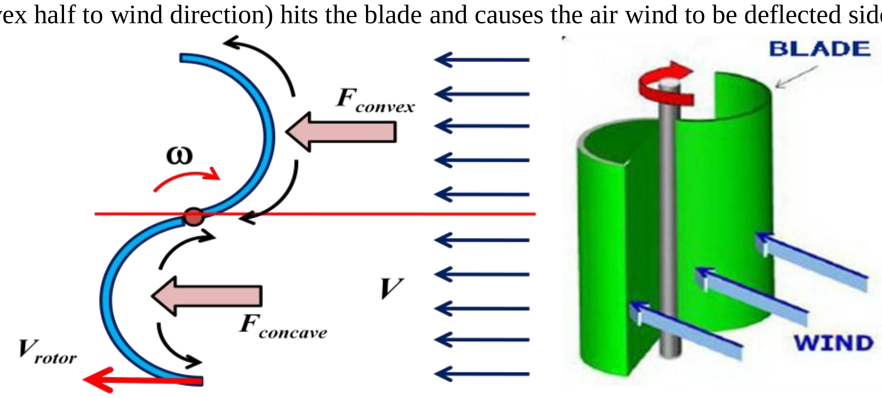

Figure (1): Schematic drawing showing the drag forces exert on two blade Savonius.

Because of the blades curvature, the blades experience less drag force (F_{convex}) when moving against the wind than the blades when moving with the wind ($F_{concave}$). Hence, the half cylinder with concave side facing the wind will experience more drag force than the other cylinder, thus forcing the rotor to rotate. The differential drag causes the Savonius turbine to spin. For this reason, Savonius turbines extract much less of the wind's power than other similarly sized lift type turbines because much of the power that might be captured has used up pushing the convex half, so savonius wind turbine has a lower efficiency.

Similarly, the three blade savonius wind turbine is constructed from three half cylinders, they are arranged at (120^o) relative to each other as shown in figure (2).

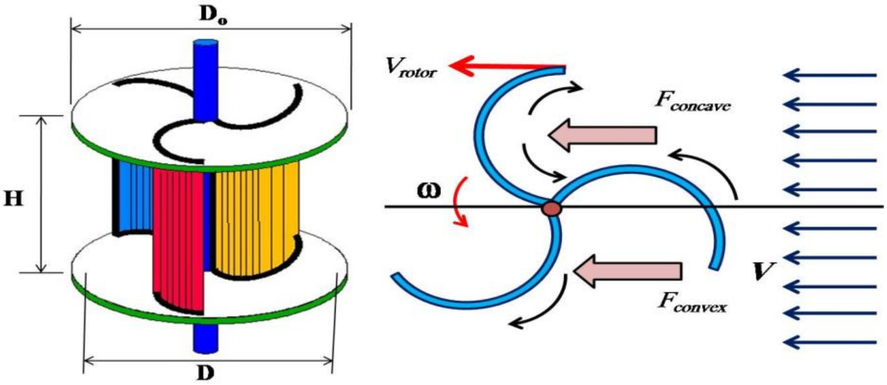

Figure (2): Schematic drawing showing the drag forces exert on three blade Savonius.

III. THE RESEARCH GOAL:

The goal of this research is to carry out a study and make a comparison in performance between two and three blades savonius wind turbine at low wind speed, the reasons to study them at low speed are:

1. In many areas in the world apart from coastal region, the average wind speed is relatively low and varies appreciably with seasons. It is around 20 km/h.
2. A Savonius rotor requires (30 times) more surface for the same power as a conventional rotor blade wind turbine. Therefore it is only useful and economical for small power requirements [ref. 5].
3. It has a high starting torque; a Savonius rotor can theoretically produce energy at low wind velocities [ref. 6].
4. It is difficult to protect them from extreme winds [ref. 7].
5. The peak power coefficient for any Savonius rotor occurs at a tip speed ratio (less than 1) [ref. 7].
6. Lower wind speeds found at lower heights, thus VAWT like savonius can be installed close to the ground without an extended post with the generator and the driven train mounting at the base near the ground level which makes these components easier to service and repair.

IV. EXPERIMENTAL RIG DESIGN:

The Wind Tunnel:

A subsonic wind tunnel was designed and fabricated for the experimental part of this research as shown in the schematic drawing and the experimental rig construction [figure 3]. The wind tunnel was designed using plywood modeling and fabricated at laboratory workshop. The wind tunnel is (250 cm) long which consists of fan section (with circular mouth entry), rectangle section, converging section and square exit section with straightener section.

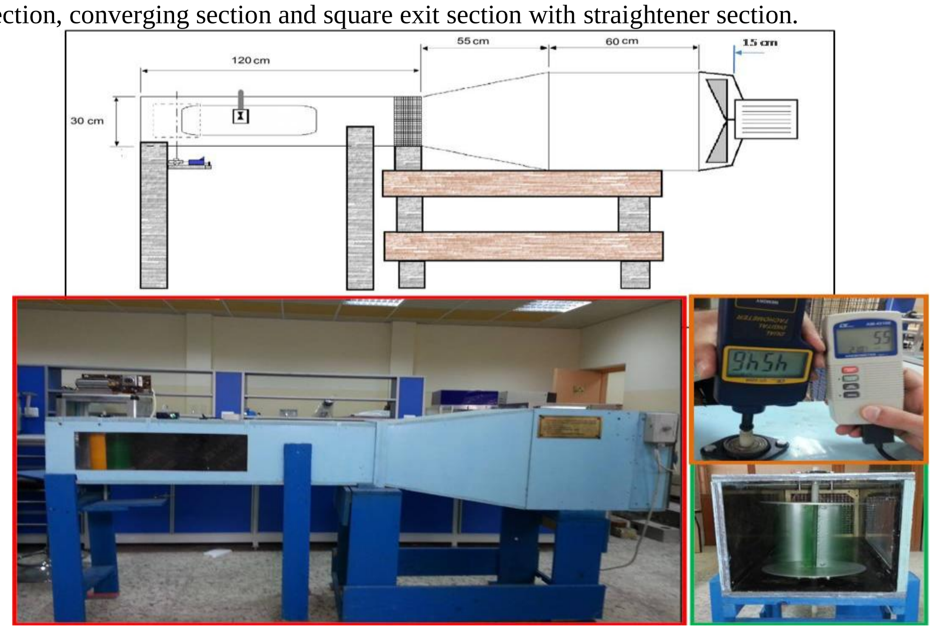

Figure (3): Schematic drawing & the Experimental rig with Savonius blade model.

a) The Fan section – The axial flow fan is mounted and encased in a circular mouth casing. The capacity of the fan is 4500 m^3/hour at 1500 rpm. The fan is driven by a single phase 0.5 kW motor.
b) The Rectangular section – it is made of plywood to make the entry of the air blowing from the fan into the diverging section and to decay turbulence.
c) The Diverging section – it is a contraction zone made of plywood to produce a uniform velocity distribution with weak turbulence in Straightener section.
d) The Straightener section – it is at the entrance of the test section to break the large scale disturbances and eddies. The Straightener comprises a number of plastic sheet meshed together to form a square cells shape to straighten the air flow and their axis parallel with the direction axis of the tunnel.
e) Test Section - it has four sides made of plywood. One of the vertical sides has a window with glass plate for seeing the testing models. Part of the upper side can be opened to change the testing models. There is a hole in the upper plate for inserting a wind speed instrument. The four sides make square section of dimension (30 cm X 30 cm) with a length of (120 cm).
f) The Air Speed Regulator – it used to control the air speed flowing through the wind tunnel to represent a change in wind speed.

The Savonius rotor blades:

The savonius rotor blades (the model) was designed and fabricated. The model was tested in the wind tunnel for various air flow speed conditions.
The material choice to fabricate such models for two and three savonius wind turbine depends mainly on many criterions. Aluminum is the best choice due to its light weight, corrosion resistance, rigidity, recyclable materials, easy to construct and low cost [ref. 8].
The dimensions of these rotors were selected to have an aspect ratio (A_a = H / D = 1), thus the blades (scoops) were made of semi-cylindrical scoops of diameter (d = 100 mm), height of (H = 200 mm) and thickness of (0.079 mm).
These blades were assembled and mounted on two Aluminium disc sheets (End plates) of diameter (D_o = 210 mm) and thickness of (1.59 mm) to obtain a better performance (figure 4). Both the semi- cylindrical blades and the two end plates were assembled to a central shaft.

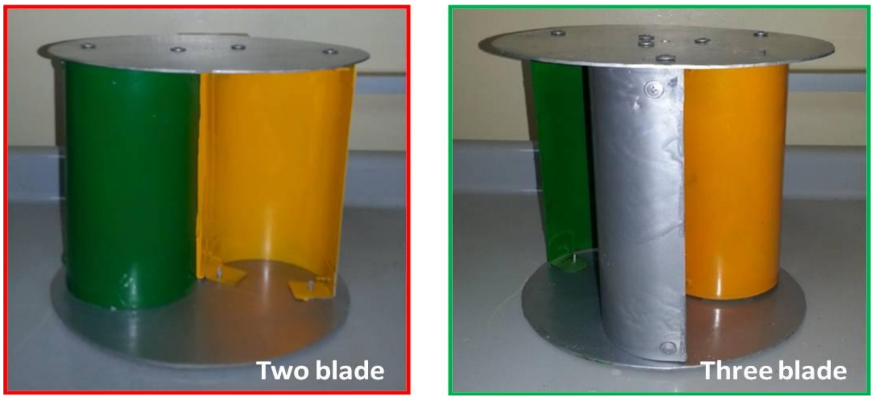

Figure (4): The fabricated models of two & three blades Savonius wind turbine.

The measuring instruments:

The experiment was carried out at different wind speeds [V = 2 m/s, to V = 6 m/s] and data was recorded at room temperature.
Different digital instruments were used to measure and record the required data. The rotational speed (N) of the rotor blade speed was measured using a photo - contact tachometer (model: DT-2268). The rotational speed was measure by using a digital tachmeter to calculate the angular velocity (□) and then the rotor tip velocity (V_{rotor}). The wind speed (V) was determined using the digital Thermo – Anemometer (model: AM-4210E). The anemometer vane was mounted and fixed in the wind tunnel - test section between the straightener and the testing savonius wind turbine.
The static torque was measured by measuring the tangential force exerted on the savonius rotor shaft by digital electronic force meter (*WeiHeng* model).

V. THE BASIC CONCEPTS:

The performance of savonius wind turbine can be explained according to the following three basic rules that are still applicable [ref. 7]:

1. The speed of the blade tips is ideally proportional to the speed of wind.
2. The maximum torque is proportional to the speed of wind squared.
3. The maximum power is proportional to the speed of wind cubed.

The performance of any kind of wind turbine can be expressed in the form of torque coefficient (C_t) and the coefficient of power (C_p) versus the tip speed ratio ( ).

The swept area (A_s):

As the rotor turns, its blades generate an imaginary surface whose projection on a vertical plane to wind direction is called the *swept area* [ref. 9].

The amount of energy produced by a wind turbine primarily depends on the rotor area, also referred to as cross-sectional area, swept area, or intercept area.

The swept area for Savonius wind turbine can be calculated from the dimensions of the rotor (Figure 5).

Savonius area = The swept area = $A_s = H * D$

Where: H = the rotor height (m).

D = the rotor diameter (m).

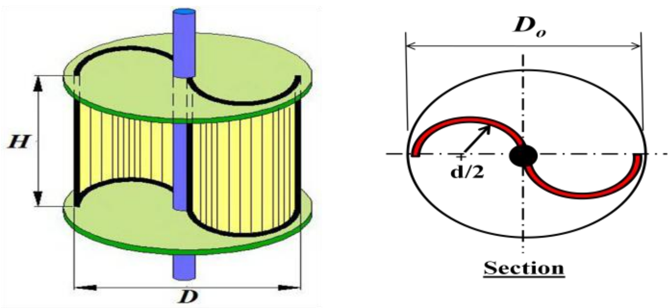

Figure (5): Schematic diagram of Savonius rotor wind turbine.

The Tip speed ratio ( ):

The tip speed ratio is the ratio of the product of blade radius and angular speed of the rotor to the wind velocity [ref. 10]. The tip peripheral velocity of the rotor (V_{rotor}) is defined as (Figure 6):

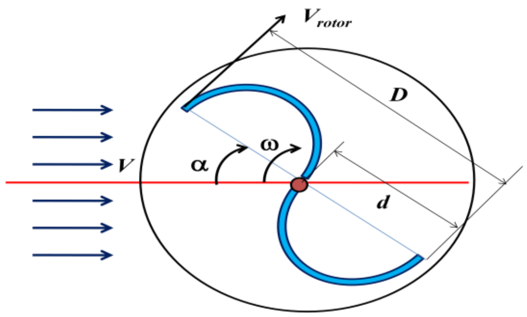

Figure (6): Scheme of a Savonius rotor showing the tip velocity of the rotor.

$$V_{rotor} = \omega * d$$

Where: V_{rotor} = the tip speed (the peripheral velocity of Savonius rotor) (m/sec)

ω = the angular velocity of Savonius rotor (rad/sec).

d = the diameter of the semi-cylindrical Savonius rotor (m).

Now the Tip Speed Ratio (TSR) of a turbine is expressed as:

$$\textit{The tip speed ratio } (TSR) = \lambda = \frac{V_{rotor}}{V} = \frac{\omega * d}{V}$$

Where: V = the wind speed (m/sec)

The Torque Coefficient (C_t):

It is defined as the ratio between the actual torque developed by the rotor (T) and the theoretical torque available in the wind (T_w) [ref. 11], thus the torque coefficient (C_t) is given by:

$$C_t = \frac{\textit{the rotor Torque}}{\textit{the wind Torque}} = \frac{T}{T_w} = \frac{T}{\frac{1}{4}\rho * A_s * d * V^2}$$

Where: C_t = the torque coefficient

T = the rotor torque (N . m)

T_w = the wind available torque (N . m)

ρ = the air density (kg/m^3)

Another concept that can used to measure the wind turbine performance is the static torque (T_s), which measures the self-starting capability of the turbine. Static torque is defined as a maximum value of the torque when rotor is blocked i.e. without ability to rotate [ref. 12]. So, the static torque coefficient is given by:

$$C_{ts} = = \frac{T_s}{T_w} = \frac{T_s}{\frac{1}{4}\rho * A_s * d * V^2}$$

Where: C_{ts} = the static torque coefficient

T_s = the rotor static torque (N . m)

The static torque of different angle of attack (α) relative to the wind direction was measured at every (30^o) to (360^o). Figure (7) shows the angle of attack (α) for both two and three blades savonius wind turbine.

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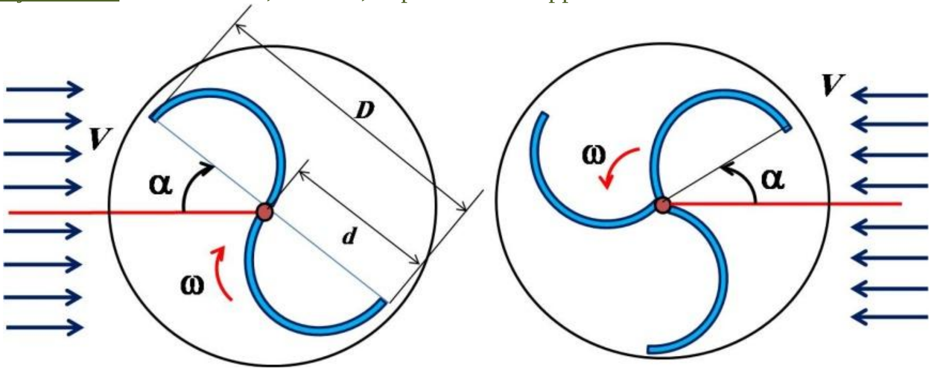


Figure (7): Scheme of a Savonius rotor showing the angle of attack ( ).

The torque is defined as the force acting tangentially over the rotor blade, operating at a distance of rotor radius (*d*) from the centre, it is given as:

$$T = I \,.\, \alpha$$

Where: *I* = the rotor moment of inertia [(kg . m^2) or (N . m . s^2)]

□ = the rotor angular acceleration (1 / s^2)

The moment of inertia tells us "how much energy is stored in a rotating shaft or about how much energy it will take to accelerate the shaft to a particular velocity. This is called the second moment or moment of inertia" and it is equal to [ref. 13]:

$$dI = r^2 * dm$$

Referring to (figure 8), the moment of inertia for a semi-circular blade shape can be calculated according to the following equation:

$$I_b = \int r^2 \,.\, dm$$

Where: *r* = the radius (the distance of the infinitesimal element of mass from the origin) (m)

$= d * cos\emptyset$

dm = the infinitesimal element of mass (kg)

$= \rho \,.\, H \,.\, t \,.\, d \,.\, cos\emptyset \; d\emptyset$

t = the blade thickness (m)

Therefore, the moment of inertia for one blade (I_{1b}) becomes equal to:

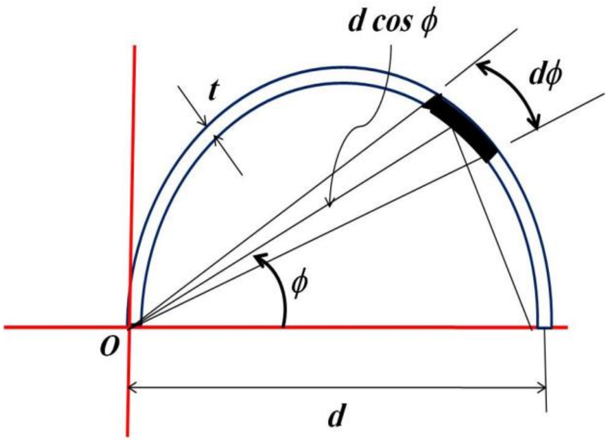


Figure (8): Schematic drawing for a semi-circular shape for moment of inertia calculation.

$$I_{1b} = \int_0^{\pi/2} \rho \,.\, H \,.\, t \,.\, d^3 . cos^3\emptyset \,.\, d\emptyset = \rho \,.\, H \,.\, t \,.\, d^3 \int_0^{\pi/2} cos^3\emptyset \,.\, d\emptyset$$

$$I_{1b} = \frac{2}{\pi}\, m \,.\, d^2 \int_0^{\frac{\pi}{2}} cos^3\emptyset \,.\, d\emptyset = \frac{4}{3\pi}\, m \,.\, d^2$$

Where: $m = \frac{\pi}{2}\, \rho . H . t . d$ (kg)

Thus, the moment of inertia for two and three blades of savonius becomes:

$$I_{2b} = \frac{8}{3\pi}\, m \,.\, d^2 \qquad and \qquad I_{3b} = \frac{4}{\pi}\, m \,.\, d^2$$

Referring to figure (9), the total moment of inertia for the savonius wind turbine is equal to:

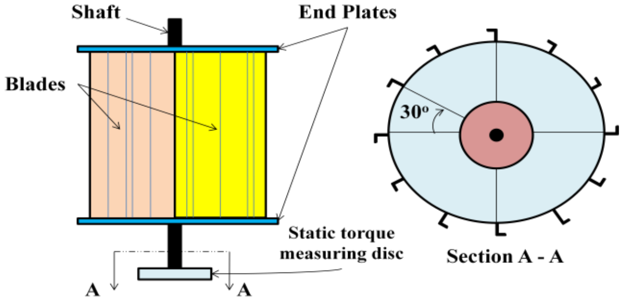


Figure (9): Schematic drawing for a semi-circular shape for moment of inertia calculation.

$$I = I_b + 2\,I_p + I_s + I_d$$

Where: I_b = the two or three blades moment of inertia (kg. m^2)
I_p = the end plates moment of inertia (kg. m^2)
I_s = the shaft moment of inertia (kg. m^2)
I_d = the torque measuring disc moment of inertia (kg. m^2)

The angular acceleration (□), is given as:

$$\omega_2 = \omega_1 + \alpha\,.\,\tau$$

$$\alpha = \frac{\omega_2 - \omega_1}{\tau} \quad \rightarrow \quad \alpha = \frac{\omega_2}{\tau} \quad when\ \omega_1 = 0$$

Where: τ = the time (sec.)
ω_1 = the initial angular velocity (1/ s)
ω_2 = the final angular velocity (1/ s)

Power Coefficient (C_p) Analysis:

Power coefficient, (C_p) of a wind turbine is the ratio of maximum power obtained from the wind to the total power available in the wind [ref. 14].

This hypothesis shows the relationship between the power coefficient (C_p) and the wind speed (V), which expresses the basic theory of the Savonius wind turbine. Principally the power that the savonius rotor can extract from the wind (P_w) is less than the actual available from the wind power (P_a).

The available power (P_a), which is also the kinetic energy (KE) of the wind, can be defined as:

$$K_E = P_a = \frac{1}{2}\,m_a\,.\,V^2 \qquad \text{(Watt)}$$

$$P_a = \frac{1}{2}\,\rho\,.\,A_s\,.\,V^3$$

Where: m_a = wind mass flow rate striking the swept area of the wind turbine (kg/sec).
$= \rho\,.\,A_s\,.\,V$

But, the swept area ($A_s = H * D$), therefore the actual power becomes:

$$P_a = \frac{1}{2}\,\rho\,.\,H\,.\,D\,.\,V^3$$

The power that the rotor extracts from the wind is:

$$P_w = T * \omega \qquad \text{(Watt)}$$

Where: P_w = the power that the rotor extracts from the wind (Watt).

The power coefficient (C_p) is given by:

$$C_p = \frac{the\ extracted\ power\ from\ the\ wind}{the\ available\ power\ of\ the\ wind} = \frac{P_w}{P_a}$$

VI. RESULTS & DISCUSSION:

The experiment's procedure was carried out and tested in the wind tunnel and the required measurement were obtained to study the performance of the two blades and three blades savonius wind turbine and makes the comparison between them to see which one is better in performance than the other.

The performance [the dimensionless parameters torque coefficient (C_t) and power coefficient (C_p)] was evaluated as function of the dimensionless parameter the tip speed ratio (λ) at low wind speeds in terms of starting acceleration and maximum no-load speed.

Figure (10) shows the plot between the wind (air) speed and the rotor revolution (rpm) for both two and three blades savonius wind turbine, it appears that as the wind speed increases from [(0 m/s) upto (3 m/s)] where the savonius wind turbine is initiated and starts to move. At this wind velocity where the wind turbine starts to move, the wind velocity is called the cut in speed, the low cut-in speed for this type of wind turbine which is about (2.5 m/s) and two blades savonius is a little bit lesser than three blades.

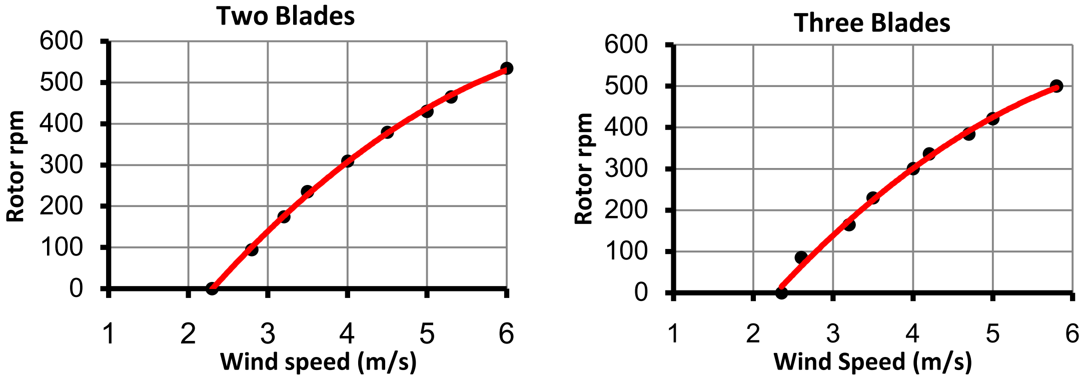


Figure (10): The graph showing the rotor rpm versus wind speed for two & three blade.

Figure (10) shows high rotational speed, the cause is that slim rotor with small diameter can get higher rotational speed but lower torque**,** and vice versa rotor with bigger rotational diameter produces a bigger torque but a lower rotational speed.

It is observed from figure (11) that static torque for two blade savonius wind turbine varies with the angle of attack [angle of rotation (α)] for a wind speed of (V = 5.3 m/s) , the static torque was measured at every (30^o to 360^o), it appears the torque that can be produced during each revolution is an oscillatory torque.

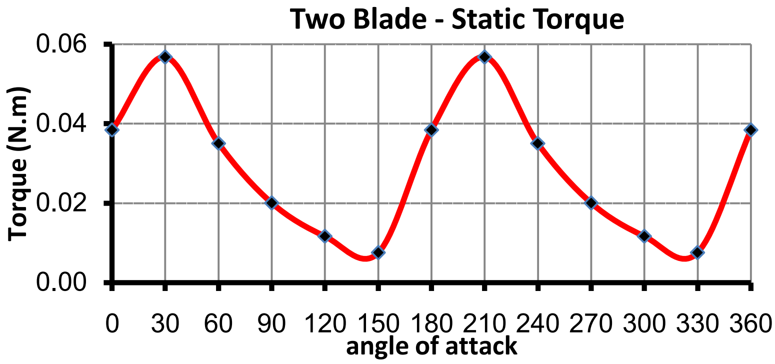


Figure (11): The static torque variation with angle of rotation for two blade savonius wind turbine.

Figure (12) shows the static torque coefficient for two blade savonius wind turbine for different wind speed (5.3 & 4.6 m/s), the static torque coefficient varies with increasing the angle of rotation, it starts to increase from (0^o to 30^0) to reach its maximum value of (0.83 & 0.65) respectively and then goes down to decrease from (30^o to 150^o) to reach it lowest value of (0.11 & 0). It is noticeable that torque values are yielding the symmetry for flow angles higher than (180° to 360^o). At angle of (150^o and 330^o), the static torque coefficient has it lowest value and for lower wind speed it may has a negative torque.

Figure (12): The static torque coefficient variation with angle of rotation for two blade savonius wind turbine at different wind speed.

Figure (13) shows the static torque coefficient for three blade savonius wind turbine for (5 m/s) wind speed, the static torque coefficient varies with increasing the angle of rotation, it starts to increase from (0^o to 60^0) and then goes down to decrease from (60^o to 120^o), It is noticeable that torque values are yielding the symmetry for flow angles higher than (120°) from (120^o to 210^o) and (240^o to 330^o).

The static torque for both two and three blade is found to be positive at any angle, high enough to obtain self-starting conditions.

Figure (14) shows the torque coefficient for two and three blades savonius wind turbine, it appears that the torque coefficient for two blades has a noticeable increasing values than the three blades.

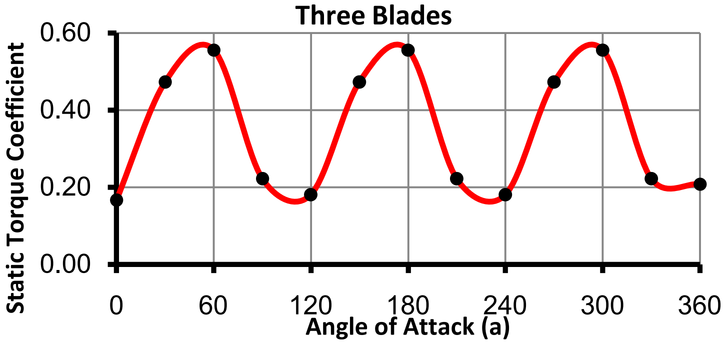


Figure (13): The static torque coefficient variation with angle of rotation for three blade savonius wind turbine.

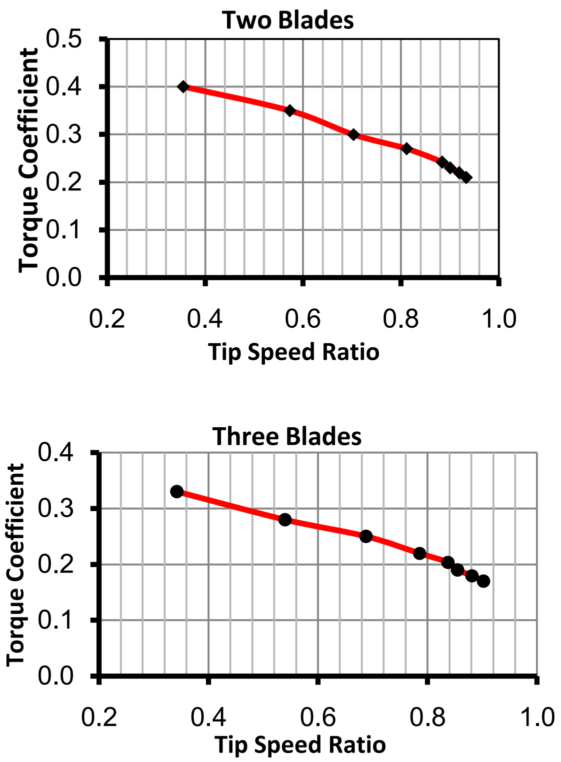
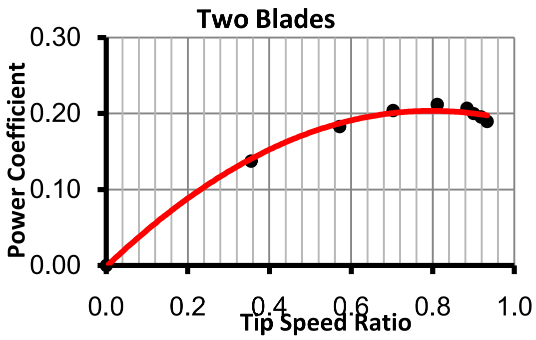


Figure (14): The torque coefficient variation with the tip speed ratio for two & three blades savonius wind turbine.

The reason is that increasing the number of blades will increase the drag surfaces against the wind air flow and causes to increase the reverse torque that leads to decrease the net torque working on the blades of savonius wind turbine.

Figure (15) shows the power coefficient for both two and three blades savonius wind turbine, it appears that the power coefficient for two blades has a noticeable increasing values than the three blades. It appears that the two blades savonius wind turbine has it highest value of (0.21) at the tip speed ratio of (0.8), the three blades has a value of (0.17) at the tip speed ratio of (0.8).



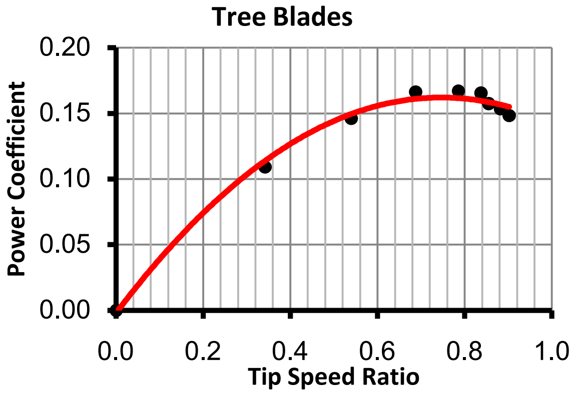


Figure (15): The power coefficient variation with the tip speed ratio for two & three blades savonius wind turbine.

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