Optimization and Experimental Investigation of Savonius Wind Turbine Performance at Low Wind Speed Condition

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Abstract-- Many improvements have been researched for conventional Savonius wind turbines in the blade shape to amend the power efficiency. In the present study, the artificial neural network was used to predict the optimum blade shape design for an enhanced power coefficient value for Savonius wind turbine at low wind speed condition numerically with commercial code software ANSYS-CFX and MATLAB. The numerical and experimental work was done with a comparison between two models; conventional and an optimized blade shape. The simulations included the analysis of many models used to learn the artificial neural network to predict the optimum blade shape of Savonius wind turbine at a wind speed of (3 m/s) and a tip speed ratio (TSR) of (0.8). Two aspect ratios (1 and 0.77) were used depending on two and three blades numerically modelled at 3 m/s and TSR range (0.2-1.2) to select the best performance model for manufacturing and experimental test. From the experimental work, the torque and power coefficient were calculated based on a range of wind speed of (2.5 - 4 m/s) and an angular velocity range of (130 - 280 RPM) based on the meteorological statistics in Baghdad. The numerical results were compared with the experimental ones obtained from the wind tunnel test. The results manifested that the best model is the modified with two blades with AR =1, and the enhancement ratio of power coefficient is 46% numerically and 31% experimentally.

Index Term-- Savonius Wind Turbine, SWT, Optimization blade shape, CFX, Renewable Energy

Symbols and Abbreviations

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<tr>
<td>AR</td>
<td>Aspect ratio</td>
<td>r</td>
<td>Time in (sec)</td>
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<td>Cp</td>
<td>Power coefficient</td>
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<td>Ct</td>
<td>Torque coefficient</td>
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<td>Ib</td>
<td>The 2 or 3 blades moment of inertia (kg.m²)</td>
<td>TSR</td>
<td>Tip speed ratio</td>
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<td>Ip</td>
<td>The moment of inertia of end plates in (kg.m²)</td>
<td>HAWT</td>
<td>Horizontal axis wind turbine</td>
</tr>
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<td>Is</td>
<td>The moment of inertia of shaft in (kg.m²)</td>
<td>VAWT</td>
<td>Vertical axis wind turbine</td>
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<td>The moment of inertia of the torque measuring disc in (kg.m²)</td>
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1. INTRODUCTION

Savonius is a drag kind vertical axis wind turbine; it has a low cut-in speed and is able to work at a low speed of wind. It’s appropriate for a small-scale power generation like the distinct domestic installations [1]. The wind turbines utilization has increased quickly recently due to the prospective that they provide for the free carbon emission power generation. The two initial kinds of the lift-driven wind turbine are the horizontal-axis (HAWT) and the drag-driven (VAWT) turbines. The horizontal axis turbines are mostly evolved and utilized in the whole present larger-scale wind farms in addition to the many smaller-scale uses in the rural sites. The concept of (VAWT) is significantly less evolved. The (VAWT) possibly introduces some benefits over the highly familiar (HAWT): There is no need for yawing (turning for facing the wind), lowering the emission of sound owing to the running operation at lower ratios of tip speed, increasing performance in the skewed flow, and the cost of production for a big (VAWT) possesses the prospective to be less than that of an equivalent (HAWT) when the simpler straight blades of fixed cross section are used [2]. The cause of less efficiency principally rests upon the truth that a single bucket is moving versus the wind if the other bucket is moving in the wind direction. It’s mainly used to pump the water and supply the power of wind on a slight scale. For augmenting or controlling the rotor output power, it appears that the guide vanes or the coming flow appropriate tunnel will be needed. Within preceding investigations,
influences of no., or blades geometry, or the ratio of overlap between blades upon the rotor features with and without end plate [1] [3]. The result of simulation showed a strong capability for enhancement and estimation the maximum power according to the artificial neural network to increase the tip speed ratio which leads to a higher power ratio and torque [4]. So, many researchers studied how to make a trade-off to get the perfect design by optimizing the performance of wind turbine such as using an obstacle shielding the returning blade to improve the design by increasing the power with two or three blades. A novel profile design was presented by [5] for Savonius wind turbine through determining nine points on the surface of blade to create different polynomial shapes, and the best shape was found to enhance the power coefficient comparing with the traditional semi-circle blade. The method to optimize the geometrical dimensions of the semicircular blade of Savonius wind turbine by differential evaluation based on the inverse optimization methodology to improve the power coefficient [6]. The genetic algorithm is used to maximize the value of power coefficient by the optimization conventional Savonius to get the optimum S shape theoretically and then tested experimentally to compare the results for two and three conventional blade numbers with the optimum blade shapes. The power coefficient enhancement was about 28% [7]. In addition, the aerodynamic effect of the optimum blade numerically was studied, the results manifested that the optimum blade is better than semicircular at a wide TSR range (0.6-1.2). The improvement value in power coefficient reached to 33%, and it was noticed that the optimum blade is simple and low-cost manufacturing so it is suitable for urban area [8]. The aerodynamic effect of forces (Drag and lift coefficient) on the optimization of elliptic blade was studied on the 2D and 3D model [9]. Such automatic optimization was done via coupling an in-house optimization library (OPAL) with industrial flow code (ANSYS-FLUENT). For maximize the output power coefficient, the enhancement ratio was 27% at wind speed 10 m/s and tip speed ratio TSR=0.7 [10]. To develop and enhance the performance of SWT design newly, a two-blade SWT was experimented by wind tunnel [11]. Many experimental applications like lighting street system were studied [12]. The adapted shapes of rotor are the familiar technique for increasing the SWT performance. The variations in the shapes of rotor cause the variations in the coefficient of power. The outcomes elucidated that the coefficient of power was within the range (0.14-0.32) and enhanced by (6.64%) and (18.75%) in comparison with the traditional rotor [13]. The twisted shape of blade was also studied to show the effect on the performance. The numerical outcomes appeared that the increment of the greatest coefficient of power (Cpmax) increased with the angle of twist until ideal value (45°) and then decreased but for an angle of twist (135°) [14]. The aim of this article is to present numerically a new technique to optimize the blade shape of (SWT) at a low wind speed by ANN. Power coefficient will be simulated by ANSYS and MATLAB to obtain the optimum blade profile at a specific condition, and then a comparison between modified and conventional model will be carried out numerically and experimentally.

2. SCHEMATIC OF SWT

Conventional semi-circular and modified blade shape wind turbine was used in this study according to the optimization work (section 3). The rotor diameter was equal to 350 mm without a central shaft, the overlap was zero because it was reducing the torque [15]. Two values of aspect ratio (0.77 and 1) were used [15]. The model was fixed with a shaft by screw and nut in the end plate. Where, H is the rotor height, D₀ is the end plate diameter (1.1 D), and r is a half cylinder diameter of rotor, as depicted in figure (1).

![Fig. 1. Schematic diagram of SWT (rotor part)](image-url)
3. Parametric Optimization Process

Optimization issues regularly require the utilization of optimization methodologies that permit the minimization or maximization of certain objective functions, especially if the problem is not linear or polynomial [16]. Comprehensive reviews of ANN applications in energy systems in general and in renewable energy systems in particular are available [17,18]. Artificial neural network ANN was used previously for enhancing the power and torque coefficient by learning it with experimental data from different prototypes [4], but in the present work, it is learnt and utilized to optimize the edge shape for SWT by numerical result from CFX, as appeared in figure (2). Three variable points P1(x1, y1), P2(x2, y2) and P3(x3, y3) in conjunction with two fixed point focuses O (0, 0) and A (d, 0) which being utilized for characterizing the geometry of blade. The drawing with (6) coordinate design factors (x1, x2, x3, y1, y2, and y3), which is the blade line, can be interpolated employing a cubic spline curve. The optimization of shape process starting from the half cylinder shape to the optimum shape is performed. Furthermore, such design is created via removal of the shaft from the blade center. Additionally, the blade gets as a single unit for cancelling the vortex and the air division upon the blade. Such inventive design increases the power based on the exceedingly pressure discrepancies upon the sides of blade. These points are changed with x and y direction many times to generate a new blade profile in each tray. ANSYS- CFX software is used to find the power coefficient Cp for a different generated model, according to the input data to the ANNs code written in MATLAB for learning an ANNs and tested with many others models. Then, the optimum model is run and selected according to the maximum power coefficient value. The flow chart in figure (3) below shows the process of this work.

![Fig. 2. Schematic for turbine blade with variable points](image-url)
In the current study, eight rotor models were used, as shown in figure (4). The tested model geometry was built by SolidWorks, simulated and analyzed by commercial code ANSYS- CFX software to predict the performance of SWT numerically, and select the best performance to fabricate and experimentally test.

4. NUMERICAL SETUP

In the current study, eight rotor models were used, as shown in figure (4). The tested model geometry was built by SolidWorks, simulated and analyzed by commercial code ANSYS- CFX software to predict the performance of SWT numerically, and select the best performance to fabricate and experimentally test.
Fig. 4. SWT rotor models

4.1 Computational Domain and Boundary Conditions.

The domain of computation comprises two subdomains: rotating domain (rotor) and stationary domain (WTU). Size of the stationary domain was assumed to be 1400 mm, 1400 mm, and 2100 mm. The rotor fixed at distance 700 mm from the inlet and rotates around perpendicular axis with angular velocity. The technique of sliding mesh was utilized for the simulation with an interface between rotating and stationary domain, as illustrated in Figure (5a and b). There is no slip boundary condition was implemented at the rotating and stationary walls comprising blades. Uniform velocity (V=3 m/s) was assumed at the inlet domain, and the opening boundary condition was applied at the bottom and top sides of stationary domain. Pressure outlet of boundary condition was applied at the outlet stationary domain. In this study, 3D unsteady turbulent flow around SWT was simulated [19]. The flow around the rotor is turbulent, thus the CFD simulation around the rotor is very complex. Simulations of CFD were implemented for solving the cases according to the (3D) study finite volume incompressible Reynolds Averaged Navier-Stokes (RANS) equations[20], these equations in conservation form are:

\[
\frac{\partial u_i}{\partial x_i} = 0 \quad \text{............... (1)}
\]

\[
\frac{\partial}{\partial x_i} \left( \rho \bar{u}_i \bar{u}_j \right) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \tau_{ij} - \rho \bar{u}_i \bar{u}_j \right) + S_u \quad \text{............... (2)}
\]

Where

\[
S_u = -\rho \left[ 2\bar{\Omega} \times \bar{u} + \bar{\Omega} \times (\bar{\Omega} \times \bar{r}) \right] \quad \text{............... (3)}
\]

\[
\tau_{ij} = -\mu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad \text{............... (4)}
\]

Three-dimension transient simulation was conducted. The shear stress transport (sst-kw) turbulent model is utilized for calculating the terms of viscosity. This model has a good stability and a convergence ability to reveal more details of the flow, in additional to the ability to ensure the share stress transport flow accurately. This model provides exceedingly accurate expectations of stream separation under adverse pressure by un execution of the transport impact on formulation of the eddy viscosity [21].

4.2 Grid Generation

In rotating domain, an unstructured triangular mesh was adopted. Owing to the rotor intricate geometry, an important work was devoted to adjust the stated grid. The numerical grid generated by ANSYS ICEM CFD software package with (Tetra/mixed) mesh type was used. For a high mesh quality and to capture the forces on the blades surface, prismatic girds have
been applied on the couple side of blade. There are ten layers of boundary layer with growth rate equal to 1.3 away from the blade surface, as illustrate in figure (5-c). The side wall of the stator is defined as (opening). To achieve this, a proper simulation must take into consideration the grid of flow around the blade in the rotating and stationary domain. Figure (5) shows a numerical grid on the blade surface and surrounding for the rotational and stationary domains.

![Fig. 5. The grid on stator and rotational domain](image)

**4.3 Tests of Grid Independence**
These tests are presented for the SWT. Figure (6) depicts three sets of meshes, with the whole cell numbers from (4M) to (6M) cell, and the power coefficient value is slightly changed with increasing the number of elements, so it depends on the number of elements approximately with blade element size 0.003 m.

![Fig. 6. Mesh dependancy test](image)

5. **Experimental Set-up**
A low speed wind tunnel and a measuring devise in the aerodynamic lab were used for experimental set-up, the design model was fabricated in the workshop unit of university. The experimental study comprises the measurement of static torque created by the Savonius rotor models for diverse precise positions and different wind speeds. Subsequently, the torque will be procured with a force gauge. Additionally, a back structure will be fundamental to be designed in arrangement to hold the rotor submerged in air stream, since the bolsters of wind adjustment don’t permit the association between torque sensor and rotor shaft. The subsonic low wind speed open wind tunnel was used for the experimental test with total length 7.25 m and cross section 1.25 m x 1 m and electric motor drive 15 hp 1460 rpm 3 phases [22]. A centrifugal fan with a double butterfly valve was used to control the air flow, as shown in figure (7). The wind turbine model setup is located at the exit of wind tunnel. The rotor is associated to the steel shelter throughout its lower and upper end plates via a steel shaft of 20 mm diameter. Aluminum
was used to fabricate the rotor blades and the end plates. Two ball bearings being fixed within the steel shelter in arrange to permit easily rotating of the rotor [23]. The losses of bearing were neglected in the calculation of the coefficient of power, the bearing is fixed with the structure shelter, and the rotor is removed and replaced with another rotor. Figure (7) manifests the rig details with the measuring device. The flow around the blade was experimentally tested, as described in the following. AC drive was used to increase gradually the motor speed to the maximum rotating speed. The wind tunnel needs 15 min to reach the steady state conditions. The double butterfly valve was gradually opened until reaching the desire flow rate (i.e., desire air speed). The pressure and temperature were measured before carrying out the experiments.

\[ V = \sqrt{\frac{2(\Delta p)}{\rho}} \quad \text{........... (5)} \]

Where, \( \Delta p \) (\( p_o - p \)) is the relative total pressure recorded by of the pitot - static tube and pressure gauge as displayed in figure (8), and \( \rho \) is the air density.

The relative total pressure was measured with pressure gauge. The rotor rotating speed (RPM) was read with a digital laser tachometer (Model: DT-2259 Photo tachometer/STROBOSCOPE). The mechanical power generated and the aerodynamic
coefficient by the tested models were measured by determining the force effected on the rotating shaft by a digital force gauge (Model: HF-5) and the rotating speed at various values of the speed of wind speed and the repelling loads.

6. CALCULATION PROCEDURE

The immediate power produced by the rotor and torque are commonly used to present the $C_p$ and $C_t$ to predict the aerodynamic performance of rotor model, as depicted equation (6). The mechanical torque (N.m) that obtained from the measured force is given by:

$$T = Fr$$

Where, $r$ is the pulley radius, and $F$ is the force acting on the rotor shaft. The mechanical power ($P_m$) can be computed at every speed of speed as:

$$P_m = T \omega = T \left[ \frac{2\pi n}{60} \right]$$

Where, $\omega$ is angular velocity (rad/s), and $n$ is the shaft rotational speed in rpm. The wind power ($P_w$) can be obtained from,

$$P_w = 0.5 \rho A_s V^3$$

Where, $\rho$ is the density of air at room temperature (kg/m$^3$), $A$ is the projected area or a swept area for the rotor (m$^2$), and $V$ is the wind speed (m/s).

The tip speed ratio (TSR) is the ratio between the blade tip speed of rotor and the velocity of free stream and described via,

$$TSR = \frac{\omega d}{V}$$

Then, the power coefficient ($C_p$) is

$$C_p = \frac{P_m}{P_w}$$

And, the torque coefficient is

$$C_t = \frac{the \ rotor \ torque}{the \ wind \ Torque} = \frac{T}{0.25 \rho A_s \times d \times V^2} = \frac{C_p}{C_t}$$

The whole SWT moment of inertia is:

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

Where, the moment of inertia of rotating is

$$I_{solid \ shaft \ (s)} = \frac{1}{2}mr^2$$

$$I_{pulley \ and \ plat(p)} = \frac{1}{2}mr^2$$

$$I_{half \ cylinder(b)} = mr^2$$

When each one is known, the total moment of inertia is obtained. The angular acceleration ($\alpha$) is manifested in figure (9).

$$\alpha = \frac{\omega_2 - \omega_1}{t}$$
The mass of each part was read by the portable electron scale shown in figure (10), and the radius was known.

7. RESULTS AND DISCUSSION

7.1 Optimal Blade Shape Results

Using ANN as a new technique for the optimization blade shape profile of SWT has changed the coordinate of points in figure (2). The four points have been changed randomly to generate a new profile for each run according to their output function (high Cp). The optimization has executed fourteen shapes individually simulated in CFX and five shapes for tested learning ANN. Figure (11) evinced the samples of different models generated and simulated for indicating the best blade shape profile coordinate. A set of result was used as input to learn ANNs, the starting code run as in figure (12) displayed that the error between the actual and desired power coefficient is ±2.5% to predict a new profile point (Cp) that made from the results obtained in code, and it can be seen that the model no. 4 in figure (11) is the best one.
7.2 Numerical Results
The pressure distribution around the modified and conventional blade of SWT is presented in figure (13) with four positions for one cycle. The drawing nearer the stream to begin influences the curved surface of the returning edge and provides its energy to the blade front portion, which sequentially raises the pressure, as displayed in figure (13). The flow moves alongside the surface upper portion, the weight reduces in that zone. The air having lower vitality at that point strikes the progressing edge, which marginally increases the pressure upon its concave surface. The enhancement in the performance is clearly by the high value of pressure around the modified blade model, especially at \( \Theta = 90^\circ \) and \( \Theta = 120^\circ \). The contour of velocity for two various models at four various positions are compared in figure (14). As soon as the wind gets close to the rotor, the value of velocity begins to reduce. The velocity stays continuously the lowest around the blade. Beyond that, after the wind strikes the blade, the wind also creates a certain angular velocity and begins gaining the velocity once more. Generally, the zone of higher velocity is exhibited at the convex blade edge, particularly at the position (\( \Theta = 0^\circ \)) and (\( \Theta = 60^\circ \)). The rotor side back continuously produces a vacuum and stays at the lowest velocity. Figures (15 and 16) demonstrate the simulation result and compression between four different designs for the modified model to present the best performance with a high power and torque coefficient. Two AR (0.77 and 1) with three and two blades were used at velocity 3 m/s, and the TSR rang was (0.2-1.2) [25]. It is clearly seen that the performance of two blades wind turbine is better than three blades with some difference between the values depending on the AR difference. The same thing is with the figures (17 and 18) for the conventional model. The results evinced that the performance of two blades is better than three blades with AR =1. The model of the best performance with a higher value of the power coefficient was selected to manufacture from, and the experimental test was done.

7.3 Experimental Result
The performance of the two models of wind turbine was selected to test experimentally in wind tunnel with a range of wind speed (2-4) m/s. The first set of experimental result was done with wind speed 2.59 m/s at TSR rang (0.3-1.2) to evaluate the power and torque coefficient. The obtained result of power coefficient was compared with a numerical result and it showed the closeness between two curves as cleared in figure (19) for the modified and conventional models. Also, figure (20) illustrates the work under another wind speed (V= 3.26 m/s) utilized for predicting the wind turbine performance for the modified and conventional model. The result depicts that the performance of the modified wind turbine continuously increases as TSR is increased contrary to the conventional one. Figure (21) presents that the enhancement ratio of the modified model performance numerically is 46% at TSR equal (0.8) [26][27][28] and experimentally shown in figure (22) is 31% at TSR equal 0.8. The obvious result illustrated that the Cp of modified model continuously increases either TSR is increased until 1.1 or 1.2 or decreased in contrary to the conventional model; that means it is suitable for urban area and low wind speed application. The relationship between the rotational speed (N) and wind speed (u) for the SWT models is shows how the performance of modified blade is developed by get higher rotation speed with low wind speed as shown in figure (23) and that the main reason to develop SWT to be suitable for location have low wind energy like this study location.

Fig. 12. learning ANNs test and error value
Lastly, the enhancement ratio with TSR was presented for the experimental and numerical result to select the suitable condition for work and design for future research, as viewed in figure (24).

![Pressure contour for conventional and modified blade shape models at different positions](image1)

**Fig. 13.** Pressure contour for conventional and modified blade shape models at different positions

![Velocity contour for conventional and modified blade shape models at different positions](image2)

**Fig. 14.** Velocity contour for conventional and modified blade shape models at different positions
Fig. 15. Power coefficient for modified model with AR=1 and AR=0.77 at V=3 m/s

Fig. 16. Torque coefficient for modified model with AR=1 and AR=0.77 at V=3 m/s

Fig. 17. Power coefficient for conventional model with AR=1 and AR=0.77 at V=3 m/s

Fig. 18. Torque coefficient for conventional model with AR=1 and AR=0.77 at V=3 m/s

Fig. 19. Power coefficient with AR=1 and V_{exp.}= 2.59 m/s

Fig. 20. Compression of power coefficient with AR=1 and V_{exp.}= 3.26 m/s

Fig. 21. Numerical compression of power coefficient for conventional mode and modified model with AR=1 and V=3 m/s

Fig. 22. Experimental compression of power coefficient for conventional model and modified model with AR=1 and V_{exp.}= 3.26 m/s
8 CONCLUSIONS
The present investigation used ANN for the optimization of the conventional Savonius wind turbine for increasing the performance efficiency of SWT work in low wind energy location. The study was carried out at the similar experimental circumstances for comparing the performance of two turbine models. From the obtained results, the followings are the main conclusions can be drawn:

1. The optimum blade shape of wind turbine is better than the conventional wind turbine at low wind speed.
2. ANN is a smooth and good choice for optimization with simplicity and flexibility in work, and the error value does not exceed 2.5% between the learning and obtained values of the power coefficient result.
3. The numerical result with ANSYS-CFX for eight models with different AR values manifested the best performance at two blades with AR=1.
4. Self-starting velocity and rotational speed for modified blade is better than conventional blade as experimental result.
5. The enhancement is obtained by the optimization of the blade shape design, the improvement is to 46% at TSR= 0.8 comparing with the conventional SWT.
6. The optimal blade shape of Savonius wind turbine is better than semicircular blade at TSR range (0.6-1.2); that means it is more suitable for applying in the urban area environment where the complex conditions and low wind speed range.

7. The experimental test elucidated the enhancement ratio of the optimum blade shape 31% over conventional model at TSR =0.8

REFERENCES