Blade Shape Optimization of Savonius Wind Turbine at Low Wind Energy by Artificial Neural network

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Abstract. Recently, vertical axis wind turbine specially Savonius type due to their positive properties and capabilities have picked up a significant consideration. This article deals with the use of artificial neural network to predict optimum blade shape design for enhanced power coefficient value for savonius wind turbine at low wind speed numerically with commercial code software ANSYS- CFX. The simulations included the analysis of many models used to learn artificial neural network to predict the optimum blade shape of savonius wind turbine at wind speed 3m/s and tip speed ratio TSR of 0.8. The performance of optimal and conventional model is studied at wide range of TSR (0.2-1.2). The obtained enhancement ratio in power coefficient is 55%. The obtained results point out that optimal blade shape Savonius wind turbine is better than semicircular blade at rang of TSR (0.6-1.1) that mean is more suitable for applying in urban area environment where the complex condition and low wind speed range.

1. Introduction
The rising demand of energy with human civilization is growing up, a world is looking for alternative sources for energy. Continuous use of fossil fuel sources are depleted in future, in addition to increase greenhouse gasses especially CO2 and that lead to rising average global warming and global temperture in general. Renewable energy, especially the wind energy is very good option for this purpose. Among all renewable energies present in the word, the wind energy is known to have the highest potential and is environmentally friendly too. It has been roughly estimated that roughly 10 million MW of energy is continuously available from the earth's wind [1].

In Iraq, conventional energy sources are fully relied upon to generate electricity, although there is a shortage of processed energy reliance on clean energy such as wind is still limited. In general, the wind energy converted to electricity by wind turbine devise, the wind turbine classified into horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). The VAWT contain two types: drag driven (Savonius) and lift driven (Darrius) depending on pressure difference throw the blade surface. In spite of low cost, easy to manufacture, blade catch air from any direction and self-start for drag driven type than lift driven type, but it gives limited efficiency. Many aerodynamic theories have been applied to VAWT composed by airfoils like Darreius type but these theories are not suitable for Savonius. Since low efficiency leads many researchers to improve design by change or optimize in main characteristic parameters or blade shape [2]. Researchers have many ways to reach optimum design or a new method to predict power and torque coefficient, some of them predicted power and torque coefficient by depend on
experimental data that collected for seven VAWT prototype tested in wind tunnel. The simulation result shows a strong capability for enhancement and estimate maximum power according to artificial neural network to increasing tip speed ratio which leads to a higher power ratio and torque.[3]. Others, use thirty experimental data and find the number of layers is affected with error percentage in power coefficient (Cp) and torque coefficient (Ct) value predicted [4]. Many researchers studied how to make a trade-off to get the perfect design by optimize performance of wind turbine such as use obstacle shielding the returning blade to improv design by increasing the power with two or three blades. This automatic optimization is carried out by coupling an in-house optimization library (OPAL) with industrial flow code (ANSYS-FLUENT). For maximize output power coefficient, the enhancement ratio is 27% at wind speed 10 m/s and tip speed ratio TSR=0.7 [5]. Novel profile design presented by [6] for Savonius wind turbine throw determining nine point on the surface of blade to create different polynomial shape, he found best shape to enhanced power coefficient comparing with traditional semi-circle blade. The method to optimize geometry dimensions of semicircular blade Savonius wind turbine by differential evaluation based inverse optimization methodology to improved power coefficient [7]. The genetic algorithm uses to maximized value of power coefficient by optimization if conventional Savonius to get optimum S shape theoretically, and then tested experimentally to compare the results for two and three conventional blade number with optimum blade shape. The power coefficient enhancement about 28% [8]. In addition, was studied the aerodynamic effect of optimum blade numerically, the results show the optimum blade is better than semicircular at wide TSR rang (0.6-1.2). The improvement value in power coefficient reach to 33% and notice that optimum blade is simple and low-cost manufacturing so it is suitable for urban area.[9]. The aerodynamic effect of forces (Drag and lift coefficient) on optimized of elliptic blade had been studied on the 2D and 3D model [10].

The aim of this article is presents numerically new technique to optimize blade shape of (SWT) at low wind speed. Power coefficient simulated by ANSYS and MATLAB to obtain optimum blade profile at specific condition, then comparison between modified and conventional model is carried out.

2. Numerical validation work

One of the main steps to the achieve this study is the validation of the numerical method. The validation done by re-solve single Savonius rotor of previous published articles [11,13] with same dimensions (D= 0.210 m, H= 0.230 m, Do(1.1D= 0.231m, φ=1.095 and δ=0.2 d) where D,H, Do, φ, δ is a dimeter of rotor, high of rotor, outer dimeter, aspect ratio and overlap ratio respectively as shown in figure (1). The model is simulated by commercial code (ANSYS -CFX) and mesh done with identical element size (0.005m for rotation and stationary domain) and total element number is eight million with same setting condition V = 6 m/s and shear stress transport (SST) turbulence model. The obtained numerical results are compared with the experimental and numerical data in published article before start optimization process. Figure (1) present the tree dimensional model of conventional wind turbine. The results of this test shown in figure (2) where clearly seen the matching between obtained and published results with error 1.88%.

![Figure 1. Savonius wind turbine validation model](image-url)
3. Computational Description

3.1 Savonius Geometry

The most important geometric parameters for SWT shown in Fig. (3). The design has overlap ratio is zero because its reduces the torque [12]. The selected aspect ratio is \((H/D) =1\) and the dimeter \(D = 200\) mm with blade thickness \(t=1\)mm.

3.2 Performance parameters

Torque coefficient \(C_t\) and power coefficient \(C_p\) generated by the Savonius rotors are monitored and calculated as following:[12]

\[
C_t = \frac{T}{\frac{1}{4} \rho V^2 D} \quad (1)
\]

\[
C_p = \frac{P}{\frac{1}{2} \rho A_v V^3} \quad (2)
\]

where \(A_v\) is the swept area of the rotor , \(V\) is the free stream velocity of the wind and \(\rho\) is density of air at 25° C. \(T\) is the torque and \(P\) is the power produced. The power coefficient, \(C_p\) is used to evaluate the wind turbine performance. This coefficient represents the fraction of extracted power from the total available power in free stream of air flow velocity that runs through the projected area of rotor at the flow direction. Simulations have been conducted at different tip speed ratio expressed by

\[
TSR = \frac{R}{V} \quad (3)
\]

where \(R\) is the cord length of rotor and \(\omega\) is angular velocity . The TSR for maximum \(C_p\) is selected to be 0.8 because Savonius turbine will operate at TSR of around 1 and has a power coefficient of about 0.15 as shown in fig. (4) [12].

![Figure 2. Commercial code program validation result](attachment:image.png)
4. **Parametric Optimization Process**

Artificial neural network ANN is utilized to optimize the edge shape for SWT. The optimization issue is to maximize the power coefficient $C_p$. As appeared in Fig (5) three variable points $P1(x_1, y_1)$, $P2(x_2, y_2)$ and $P3(x_3, y_3)$ in conjunction with two fixed point focuses $O (0, 0)$ and $A (d, 0)$ which are used to characterize the blade geometry. The sketch with the six coordinate design factors ($x_1, x_2, x_3, y_1, y_2, y_3$) which is line of the blade can be interpolated employing a cubic spline curve. The optimization shape process start from the half cylinder shape to the optimum shape is conducted. Furthermore, this design is created by removing the shaft from the center of the blade. Additionally, the blade becomes as one unit to cancel the vortex and division of air on the blade. This inventive design increments the power according to the exceedingly pressure differences on the blade sides. These points are changed with $x$ and $y$ direction many times to generate new blade profile in each tray. ANSYS- CFX software is used to find power coefficient $C_p$ for a deferent generated model, according to the input data to the ANNs code wrote in MATLAB for learning an ANNs and tested with many others models. Then run and selected the optimum model according to maximum power coefficient value.
5. Numerical Simulation Aspects
In order to design and achieve a proper geometry for vertical axis wind rotor, an appropriate modelling procedure should be applied. In this article, unsteady turbulent flow around Savonius rotor has been simulated using commercial computational fluid dynamics software ANSYS-CFX. The conventional wind turbine and other tested model are generated in solid work with different blade shape model.

5.1 Turbulent Model
Three-dimensions transient simulation are conducted in ANSYS. The shear stress transport (SST-KW) turbulent model is employed to determine the viscosity terms. This model has good stability and convergence ability to reveal more details of the flow. In addition, ensure the shear 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. [15]

5.2 Grid Independence Test
The grid independence rests are conducted for the conventional Savonius wind with semicircular blade as shown in table (1). Three different grids on model with various component sizes are examined for comparable TSR 0.7. From this result the slight difference between test 2 and 3 in simulation the Cp value so two millions element are used for the rotor.

Table 1. Grid independence tests based on the conventional Savoniuse turbine.

| Test No. | Cp     | Total element for rotor | nodes   | Blade element size (m) |
|----------|--------|-------------------------|---------|------------------------|
| 1        | 0.1804 | 1750000                 | 667748  | 0.009                  |
| 2        | 0.1909 | 1692000                 | 653646  | 0.005                  |
| 3        | 0.1944 | 2570000                 | 809727  | 0.002                  |
5.3 Computational Domain and Mesh Generation
Computational grid domain consists of two parts separated by interface, stationary part represented by wind tunnel with dimensions (0.5 m, 0.5m, 0.7m). The rotating domain surround the blades represented by rotor (wind turbine). The rotor fixed at (0.3m) from the inlet and rotate around perpendicular axis with angular speed of the domain.

The boundary conditions of the computational model at the inlet face is the inlet velocity 3 m/s according to the local space of study in Baghdad city and atmospheric pressure in the outlet face. The numerical grid generated by ANSYS ICEM CFD software package is used, (Tetra/mixed) mesh type was adopted. For more accuracy, prismatic grids for flow in the boundary of rotor blade are applied on the couple side of blade to capture flow separation and refined mesh of boundary layer type over the blade surface [16]. There are ten layers of boundary layer with growth rate of 1.2 away from the blade surface. The side wall of stator defines as (opening) and the boundary condition of blade as (wall with non-slip smooth). To achieve a proper simulation grid of flow around the blade in rotating and stationary domain is taken into consideration fig. (6).

6. Results and Discussion
6.1 Optimal Blade Shape Results
The optimal shape is relying on ANNs code for optimize blade profile blade by changing coordinate of points in fig. (5). The four points which have been change randomly to generate new profile for each run
according to their output function (high Cp). The optimization is executed thirty shape individually simulated in CFX.

Fig. (7) shows samples of different models generated and the simulation result is shown in fig. (8) to which indicate the best blade shape profile coordinate to made set of result used as input to learn ANNs. Starting code run as in figure (9) shows the error between actual and desired power coefficient is ±2.5% to predict a new profile point and Cp value. From the results obtained in code, it can be seen that model no. 4 in fig.(7) is the best one.

![Figure 7. Ten samples of the model shape with Cp values](image7)

![Figure 8. CFX simulation](image8)
6.2 Tip Speed Ratio Effect (TSR)

The TSR effect on performance model of Savonius wind turbine is shown in fig. (10) with range (0.2-1.1). From this figure it can be seen that power coefficient for semi-circular model increasing with TSR increase only at TSR > 0.9. For optimal model blade shape increasing of TSR < 0.9-1.1 make a continuous increasing in Cp value. As a result of that the Savonius optimal shape working with wide range of TSR that made it more appropriated than semi-circular to working in real urban area environment examining the feasibility of applying it in urban area.

Figure (11) shows the analyses performance of optimal model and conventional model in CFX at TSR = 0.8 and wind velocity V=3 m/s.
6.3 Flow Field Analysis

Figure (12. a,b) shows the pressure contour at three positions 0°, 30°, 90° throw the cycle for optimum and conventional model. It can be seen that the optimized design improved the power and efficiency by the increase drag effect pointed by red color intensity. Figure (13. a,b) illustrates the velocity contour for optimum blade shape and conventional model at 0°, 30°, 90° rotor position angle. It can be notice that the wake generated behind the modified rotor is less than conventional rotor and decrease with increase rotation angle.

**Figure 11.** Run optimization at TSR=0.8
\[ \theta = 0^\circ, \theta = 30^\circ, \theta = 90^\circ \]

Figure 12. Pressure contour for (a) optimal blade shape model (b) conventional model at \( \theta = 0^\circ, 30^\circ, 90^\circ \)
Figure 13. velocity contour for (a) optimal blade shape model (b) conventional model at $\theta = 0^\circ, 30^\circ, 90^\circ$
7. Conclusion
The optimization of two-blade design SWT is evaluated using ANNs to improve the power coefficient. The main observations are summarized as follows:
1. The SWT was operated at constant TSR= 0.8 and Re = 0.3*10^5.
2. The 3D models simulated numerically to analyzed the results for generated model.
3. The enhancement is conducted with optimizing the blade shape design, the improvement is come to 55% comparing with conventional SWT.
4. The SST turbulence model use for more accuracy and mesh generation by ISEM.
5. The optimal blade shape Savonius wind turbine is better than semicircular blade at rang of TSR= (0.6-1.1) that mean is more suitable for applying in urban area environment where the complex conditions and low wind speed rang.

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