Performance Characterization of EEEC (Eolic Energy Unit) for Horizontal Axis Wind Turbine

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Abstract. Wind energy is one of the fastest-growing forms of renewable energy which can be extracted using a wind turbines such as the Horizontal Axis Wind Turbines (HAWTs). All HAWT systems must go through experimental characterization for performance assessments. For this purpose, highly specialized wind units are employed. In this research a testing procedure has been evolved for characterizing the various HAWT configurations under variable operating conditions by using the Eolic Energy Units (EEEC). This research aims at developing comparative performance characterization curves for the EEEC unit by using the design of experiment (DoE) approach applied to HAWT system. The experiments for characterization have been conducted under different load and no-load conditions. The input parameters that include blade angles, the number of blades, and wind speeds have also been varied. Moreover, the results have been verified and validated through analytical calculations by using the Blade Element and Momentum (BEM) theory and computational analysis on ANSYS CFX. Substantial number of performance characteristic curves have been developed with good conformance of results.

Keywords: Third Keyword Eolic energy unit (EEEC), Horizontal Axis Wind Turbine (HAWT), Experimental Analysis, Load conditions, Design of Experiment (DoE), CFX, BEM

1 Introduction

As the world is facing multiple challenges such as climate change, which is raising the chance of floods, famines, etc. Understanding the situation, 195 countries signed an agreement in which they agreed to work for sustainable and prosperous world . Subsequently, the United Nations Organization has defined 17 sustainable development goals, which are interconnected with each other, for the sustainability of the Earth. However, the achievement of UN SDGs 7 and 13 mainly depends on producing clean and efficient energy to meet the world's requirements [1]. There are many sources of renewable energy that include wind, solar, hydro, geothermal energy, etc. Wind energy has substantial potential to meet a major part of the world's energy requirements. Wind energy is expected to meet almost 35 percent of the world's energy requirements by the year 2050 [2]. There are many advantages of using wind energy such as the production of eco-friendly and cheaper power.

The machines which extract wind energy from wind are known as wind turbines. There are many types of wind turbines such as VAWTs, HAWTs, CAWTs, et cetera that are used for extracting energy from wind. VAWTs are generally used for small-scale energy production, whereas HAWTs are one of the most efficient wind turbines for large-scale energy production. This is because HAWTs are more efficient, and they have more power coefficient with Betz's limit of 0.59 as compared to VAWT which has 0.34. Despite having great potential for power production, most of the HAWTs are unable to extract the expected 59.6% of energy from the wind because of the losses incurred.

To evaluate and design efficient HAWTs system an Eolic Energy Unit (EEEC) [3] installed at IC Engine and Power Plant Lab of DMAE (IAA), Air University Islamabad. EEEC is an apparatus of EDIBON for analyzing the conversion of the kinetic energy of wind into electrical energy.

1.1 Problem Statement

This research is used for characterization and performance of Eolic Energy Unit using Design of Experiment (DoE) approach under specific conditions, three different parameters have been selected which include blade angle, wind speed, and the number of blades with different load conditions. Experiments have been performed on different load conditions. Analytical and computational analyses have also been performed to establish the veracity of experimental results. Analytical calculations have been done by using Blade Element and Momentum (BEM) theory. Furthermore, for validation of experimental test results, computational analysis has been done on HAWT using ANSYS CFX for the case of turbulent flows. The qualitative and quantitative results of characteristic curves of EEEC unit are verifiable through alternate analysis. All the results have been verified and validated.

2 Design of Experiment and Eolic Energy Unit

2.1 DOE

First, DOE is established, then experimentations are performed on the basis of DOE. The results of experiments have been verified and validated through analytical calculations by using the Blade Element and Momentum (BEM) theory and computational analysis on ANSYS CFX. Experiments have been performed with both load and with no load condition. In no load conditions, our variables include blade pitch angle, number of blades, and wind velocity as input, while power as output. In load conditions, we need to analyse the effect of load resistance on turbine power. In DOE, thirty-six experiments in total have been designed and power has been calculated by changing blade angles 5˚, 10˚, and 20˚, however, the number of blades configuration were 2, 3, and 6 at four different wind speeds that are 3, 6, 9 and 12 m/s. Blade angle and number of blades are taken on the right side of the DOE because their variations are the most difficult one and time taking while wind speed has been put on the rightest side because their variations are easily controllable.

2.2 Experiment Test Unit

The EEEC unit is a scale-designed laboratory designed to study the effect of different parameters on the performance of wind turbines. The EEEC unit consists of a fan, rotor with six blades, anemometer, speed sensor, voltage probe (Wattmeter), current probe (Wattmeter), load module, temperature sensor, J-type thermocouple, and a regulator and control system (SCADA). Fig. 2 shows the complete EEEC unit setup.

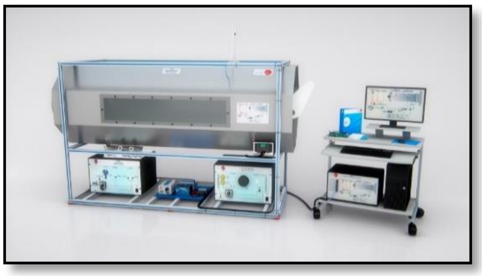


Fig. 1. Eolic energy unit (EEEC) [3].

2.3 Mathematical Model

For analytical calculations, BEM theory has been used. Power has been calculated using local forces like lift and drag forces on each section of the blade. For calculation, the flow has been considered steady, inviscid, and incompressible. From Fig. 7, it can be observed that two forces act on the blade which are lift force and drag force. The resultant force "R" is contributing to the positive power output. It can be seen from the Fig. 2 that force per of unit blade length is in the direction of the motion.

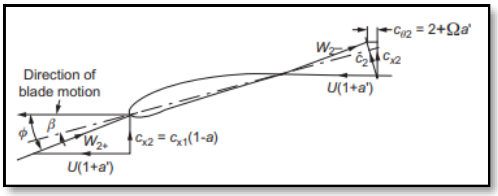


Fig. 2. Blade element at radius r showing various velocity [4].

Resultant of relative velocity immediately upstream of the blades is

$$w = \left[{C_{x_1}}^2(1-a)^2 + (\Omega r)^2(1+a')^2\right]^{0.5}$$

$$\tan \emptyset = \frac{C_{x_2}}{\Omega r} * \frac{(1-a)}{(1+a')}$$

For blade loading coefficient

$$\lambda = ZlC_L/8\pi r$$

For flow angle

$$\tan\ \phi = \frac{R}{rJ}\left(\frac{1-a}{1+a'}\right)$$

Considering Prandtl correction factor axial and tangential factors can be calculated by

$$\frac{a}{1-a} = \frac{\lambda(\cos\emptyset\ + \varepsilon\sin\emptyset)}{F\sin^2\emptyset}$$

$$\frac{a'}{1+a'} = \frac{\lambda(\sin\emptyset\ - \varepsilon\cos\emptyset)}{F\ sin\,\emptyset\ cos\emptyset}$$

$$F = \left(\frac{2}{\pi}\right)\cos^{-1}\left[\exp\left(-\frac{\pi d}{s}\right)\right]$$

$$\pi d/s = \frac{1}{2}Z(1-r/R)(1+J^2)^{0.5}$$

Torque can be calculated by using following formula:

$$d\tau = \frac{1}{2}\rho c \mathrm{Z}\mathrm{l}\Omega^2 R^4 [\frac{1+a'}{cos\emptyset}]^2 (\frac{r}{R})^3 Clsin\emptyset\Delta(\frac{\mathrm{r}}{\mathrm{R}})$$

Generated power is:

$$d\tau = \frac{1}{2}\rho c \mathrm{Z}\mathrm{l}\Omega^2 R^4 [\frac{1+a'}{cos\emptyset}]^2 (\frac{r}{R})^3 Clsin\emptyset\Delta(\frac{\mathrm{r}}{\mathrm{R}})$$

$P = \tau\Omega$

The application of BEM theory, which is an iterative scheme. Here the first value of axial and tangential induction factor is assumed as zero, and the other parameters are calculated. For using BEM theory MS Excel code has been developed to calculate our desired outputs.

2.4 Computational Analysis

Computational Fluid Dynamics (CFD). For CFD ANSYS-CFX has been utilized. All the steps involved starting from meshing, setup, and results have been computed using ANSYS-CFX. For the purpose of analysis, a simplified CAD model has also been considered for the turbine as shown in Fig. 4. For computational analysis, two domains have been created, one rotating domain which included a zone around the turbine inclusive of turbine blades and hub. This rotating domain had a diameter of 1.1 D with height kept at 0.2 D, the domain was placed right in the center of the stationary domain.

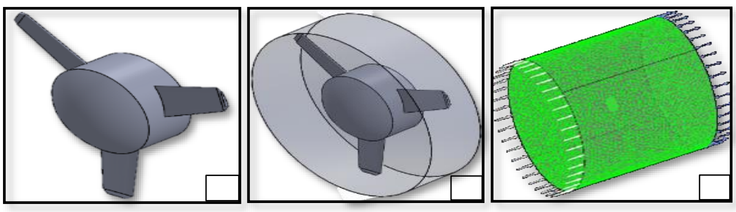


Fig. 3. Represents CAD Model and Domains for CFD Analysis (A) Simplified Model, (B) Rotary Domain and (C) Stationary Domain.

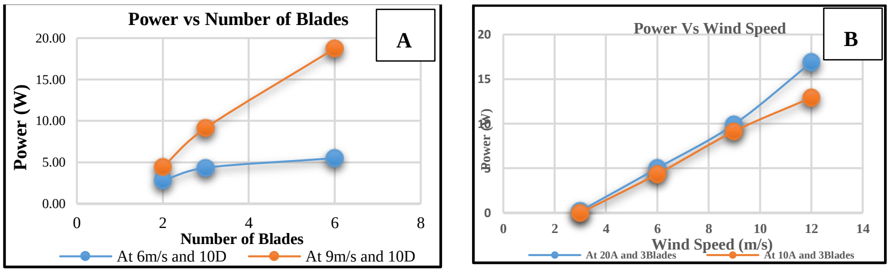
Meshing. Before setting up the CFD simulation, the meshing process was conducted, resulting in a tetrahedral mesh comprising 150,514 nodes and 952,163 elements. The average orthogonal quality of the mesh is 0.79, indicating a reasonable level of orthogonality. The average aspect ratio is 1.8, suggesting a moderate level of elongation in the elements. Furthermore, the element quality is 0.84, indicating a good overall quality of the elements in the mesh.

CFD Setup. After meshing has been done on the turbine model, the mesh has been then imported into ANSYS-CFX and steady state analysis has been performed with input wind speed to 3,6,9 and 12 m/s and outlet pressure 1 atm. Pressure based solver and steady state solution have been considered for the required solution. The Shear Stress Transport (SST) model has also been used to ensure better results for near wall and around flow separation. After the solution for the problem, which has been mostly converged around 1200 iterations, torque for each case can be displayed in postprocessor; and hence the power for each case could be calculated using the value of the computational torque and experimental RPM.

3 Results

3.1 Experimental

The Fig. 5(A) shows that with the increase in wind velocity, power increases to a certain limit. Here maximum wind velocity has been limited to 12 m/s. Power increases with the increase in wind velocity because with the increase in velocity, kinetic energy also increases which causes the blade to rotate faster hence power increases. Turbine power is directly proportional to cube of wind speed. So, the power of the turbine has been greatly influenced by the variation of wind speed.



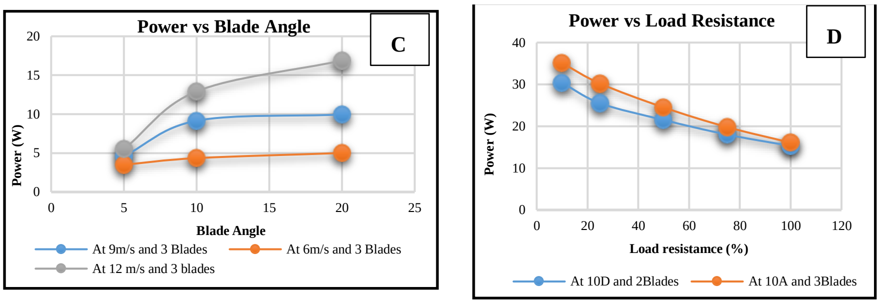


Figure 4: Experimental Results (A) Relationship between Power and Number of Blades (B) Relationship between Power and Wind Velocity (C) Relationship between Power and Blade Angle (D) Relationship between Power and Load Resistance

The Fig. 5(B) shows the relationship between the number of blades and turbine power. Here, it has been observed that an increase in the number of blades increases the turbine power. But the increase in the number of blades also increases the wind resistance and cut-in speed (the speed required to start the turbine). This has been the drawback in a turbine with a larger number of blades because they only work when there is high wind velocity which is mostly unavailable. The Fig. 5 (C) shows the effect of blade angle on turbine power generation. Here it has been noticed that with an increase in blade angle turbine power increases because with the increase in blade angle, lift force also increases, which causes the turbine to rotate faster and produce more power. As in the design of the experiment, we limit the blade angle to 20º. At this angle, it has been observed that power increases with an increase in blade angle, but this trend is not valid for all blade angles. Power increases to a certain limit of blade angle, after which the lift force will start decreasing, and drag force will start increasing, and eventually, turbine power will approach its minimum or zero value. The Fig. 5 (D) shows the effect of variation of load resistance on the power generation. It has been observed that with the increase in load resistance, the power generation decreases. The main aim should be to limit the generator resistance so that we can extract maximum power.

3.2 Verification and Validation

The simulations have been carried out on ANSYS CFX and results have been obtained using the ANSYS post processing menu. Simulations have been performed on all thirty-six cases but here only the results of two cases have been displayed. Results at 8 m/s with 3 number of blades and 2 number of blades have been displayed. Through computational analysis, torque has been calculated then using torque and angular velocity power generation is calculated. Fig. 12 (A) shows the pressure contours on model with velocity inlet 9 m/s, blade angle 20˚, and number of blades three. In the Fig. 12 (A) maximum pressure has a pressure with the value of 101.8 kPa has been represented by red spots and on the upper side, there has been low pressure region shown in green colour. Due to the high pressure at the lower region and low pressure at the upper region clockwise torque produces that causes the turbine to rotate in the clockwise direction.

Fig. 9(B) shows the pressure contour at the YZ plane, where it can be seen that pressure is reliving at the backside of turbine. Pressure is maximum at the front side of the turbine, and it is decreased at the backside of turbine. Fig. 9(C) shows the velocity contour at the YZ plane, here it is seen that velocity is low at the backside of turbine with respect to the front side. Similarly, Fig. 9 (D) shows the pressure contours at turbine. Fig. 9 (E) show the pressure contour at the YZ plane and Fig. 9 (F) shows the velocity contour at the YZ plane.

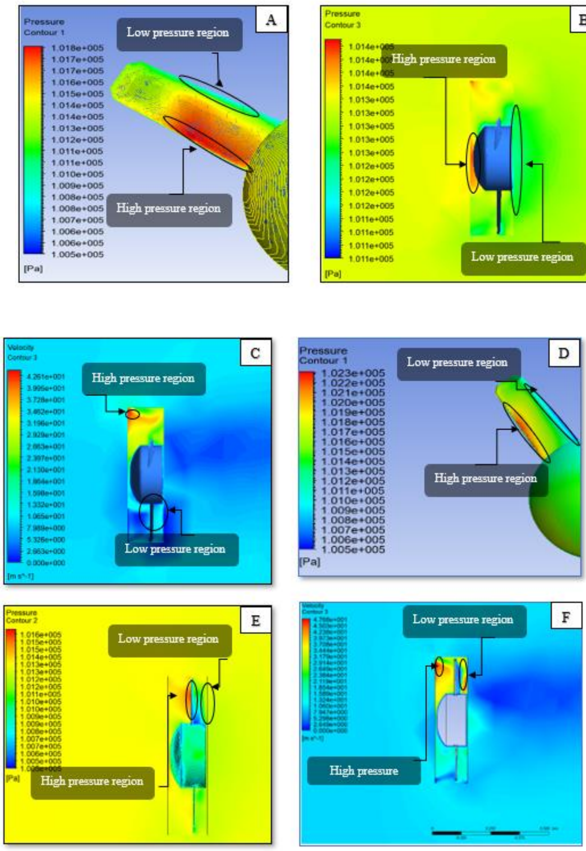


Fig. 5. Representation of Pressure Contours for (A) Blade with 9 m/s, 3 Number of Blades and 20-degree Blade Angle, (B) YZ plane with 9 m/s, 3 Number of Blades and 20-Degree Blade Angle, (C) YZ Plane with 9 m/s, 3 Number of Blades and 20-Degree Blade Angle, (D)

The results at 10˚ pitch angle shows that the analytical power has also been calculated using BEM theory, computational power has been calculated by performing simulations on ANSYS CFX and experimental power has been calculated by performing experimentations on Eolic Energy Unit (EEC). Here maximum error between computational and experiment power has been 8.90% and the maximum error between theoretical and computational results has been 5.83%. Maximum power achieved at 10˚ blade

angle using six number of blades with wind velocity of 12 m/s has been 38 W. Maximum Coefficient of performance has been for six number of blades with the wind velocity of 9 m/s.
Results at 20^0 blade angle shows that the maximum error between computational and experiment power has been around 19.50% and the maximum error between theoretical and computational results is 8.69%. Maximum power achieved at 20^0 blade angle using six number of blades with the wind velocity of 12 m/s has been 40 W. Maximum Coefficient of performance has been for six number of blades with the wind velocity of 9 m/s.
Results at 5^0 blade angle shows that the maximum error between computational and experiment power has been 32.50% and maximum error between theoretical and computational results has been 5.36%. Maximum power achieved at 5o blade angle using six number of blades with wind velocity of 12 m/s has been 5.5 W. Maximum Coefficient of performance has been for six number of blades with wind velocity 6 m/s has been 0.26. At load conditions experiments have been performed at 10^0 blade angle only. Here maximum power has been achieved for three number of blades for load resistance 10% case.

4 Conclusion

EEEC successfully utilized for characterization of HAWT unit. A DoE Based approach has been used for this purpose. It has been found that an increase in wind velocity increases the power generation of the turbine because an increase in velocity also increases the kinetic energy which causes the blade to rotate faster hence, power generation has been maximum for 12 m/s wind velocity as this has been the uppermost limit of the velocity in DOE. Power generation for 20° pitch angle has been maximum among the other blade angles in DOE. The maximum power generation has been recorded for a six-bladed case at 12 m/s wind velocity. The power generated in the said case comes out to be 40 watts. Simulation data has been compared to theoretical and experimental data to both verify and validate the results.

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