Experimental Investigation of Augmented Horizontal Axis Wind Turbine

Abiyu Mersha Tefera[1](✉), Abdulkadir Aman[2], and Muluken Temesgen Tigabu[3]

[1] Faculty of Mechanical and Industrial Engineering, Bahir Dar Institute of Technology, Bahir Dar University, P.O. BOX 26, Bahirdar, Ethiopia
abiyumu.16@gmail.com

[2] School of Mechanical and Industrial Engineering, Addis Ababa Institute of Technology (AAiT), Addis Ababa University, Addis Ababa, Ethiopia
abdiaman2004@yahoo.com

[3] Faculty of Mechanical and Industrial Engineering, Bahirdar Energy Center, Bahir Dar Institute of Technology, Bahir Dar University, P.O. BOX 26, Bahirdar, Ethiopia
mulhtemz@gmail.com

Abstract. An augmented wind turbine has been an interesting concept of wind energy conversion, due to the system capability to increase the performance of wind turbine relative to bare wind turbine with a similar size. Different capsulated wind energy systems have been studied to improve the performance of wind rotors by increasing the energy density of the wind. One of them is the nozzle-diffuser capsulated system. However, more studies concerned on the influence of the concentrator (nozzle) while little research has been done concerning on the diffuser influence and there is still a need to carry out experiment investigation. Therefore, this paper investigates the effect of the concentrator, diffuser and combined augmentation at different wind speed. In this paper, the main objective involves design and an experiment testing of the augmented wind turbine. Blade Element Momentum theory was used to design the blade. Glass fiber and thin sheet were used to manufacture non-twisted NACA 4412 blade and augmentation respectively. The tunnel wind speed was used in this experiment at 3 m/s, 4 m/s, 5 m/s, and 6 m/s. AC fan motor was used as a generator and direct measurement were performed for performance investigation. The result shows that all augmentation increases the power output. The average percentage of power variation between a bare wind turbine and augmented wind turbine was 33.8% for a diffuser, 88% for the nozzle and 81.6% for nozzle-diffuser combination. Also, augmentation is a capable of affecting the cut in speed.

Keywords: Diffuser · Nozzle · Nozzle-diffuser combined augmentation · Blade · Wind speed

N. G. Habtu et al. (Eds.): ICAST 2019, LNICST 308, pp. 566–575, 2020.
https://doi.org/10.1007/978-3-030-43690-2_42

1 Introduction

Wind turbine systems are among the most useful renewable energy resource in the world. To improve the aerodynamic efficiency of wind turbines under steady-state flow conditions both optimal design of wind turbine blade and integration with the electricity generation system are essential parameters [1]. There are two types of wind turbine system, horizontal axis wind turbines and vertical-axis wind turbines [2]. The criterion for maximum power extraction is called Betz criterion (Cp = 16/27). In practical operation, a commercial wind turbine may have a maximum power coefficient of about 0.4 [3]. Due to low density of air large system is require for conversion. Wind energy conversion can be improved by introducing non-rotating capsulation to rotating blade, like diffuser, nozzle, converging-diverging. A capsulated wind turbine has been an attractive concepts of wind energy conversion. Due to the system capability to increase the power performance relative to bare wind turbine with the similar size.

There is an extensive literature on augmented horizontal axis wind turbine system. Bontempo and Manna [4], analyze the performance of open and ducted wind turbines. The authors clearly conclude that with the same rotor size the capsulated wind turbine can produce a higher mass flow rate than the open wind turbine. Asl et al. [5] presents the effect of blade number and design for a ducted wind turbine. Khamlaj et al. [6] investigates the shape of the augmentation model and, although they did not carry out any experiment investigation. Rio et al. [7] studied what happen if the blade element momentum method applied to diffuser capsulated wind turbines. The results show that the power coefficient significantly influenced by the presence of the diffuser capsulation, this justify that the use of diffusers as a technology to improve performance of a wind energy system. More evidence, Vaz and Wood [8] performed a study on aerodynamic optimization of the blade of diffuser augmented horizontal wind turbines. This study was seeking a new approach to the aerodynamic optimization of a wind turbine with a diffuser. As a result, the diffuser speedup ratio was significantly influenced by an aerodynamic improvement of wind turbine geometry. In order to evaluate the proposed approach, a comparison with the classical Glauert optimization was performed for a flanged diffuser, which increased the efficiency by 35%. Pambudi et al. [9] investigated wind turbine using nozzle augmentation at lower wind speed situation. The Artificial of low wind speed have been used in this experiment at 2.4 m/s, 3.5 m/s and 4.5 m/s. This paper shows that the nozzle augmentation improves the performance of wind energy. The tip speed ratio of the turbine blade is directly proportional with nozzle diameter. The investigation shows difference number of blades, the three blades turbine consistently generates the highest power output compared to two blades and four blades turbines. The researchers, based on experimental evidence, conclude that the performance of wind energy can be improved by the combination of three blade and nozzle augmentation in areas where wind speed is low. Different capsulated wind energy system has been studied to improve the performance of wind rotor by increases the energy density of wind. One of them is nozzle-diffuser augmented wind energy system [10–12]. However, more studies concerned on the influence of nozzle augmentation and numerical investigation while little researchers have been done concerning on diffuser augmentation influence and the combination of bot. there is still a need to investigate in experiment. Therefore, this paper investigates the effect of the concentrator, diffuser and combined augmentation experimentally. Local fabrication turbine blade is also at early stage and this research has a particular ambition to analyze the aerodynamic performance of wind turbine blade that is fabricated by local available materials. To do this, the research focus on design analysis, modeling, fabrication and testing of the prototype model.

2 Materials and Methods

2.1 Design and Fabrication

The design procedures of a horizontal axis wind turbine start by determining forces in which lift forces on airfoils are the driving forces. The design of a wind rotor composed of two steps: first the choice of basic parameters such as the number of blades, the radius of the rotor, the type of airfoil shape and design tip speed ratio, and second the estimation of the blade twist angle and the chord distribution at a number of segments along with the blade. In order to produce optimum performance at a specific tip speed ratio by each segment of the blade. Calculation of blade chord and blade setting angles were done based on Blade Element Theory and by using Eqs. 1–3.

$$\phi = \frac{2}{3}\tan^{-1}(1/\lambda_r) \tag{1}$$

$$C = \frac{8\pi r}{NC_{ld}(1 - \cos\phi)} \tag{2}$$

$$\mathrm{C} = 2.5(\mathrm{C}_{0.9} - \mathrm{C}_{0.5})\frac{r}{R} + 2.25C_{0.5} - 1.25C_{0.9} \tag{3}$$

Where;
ϕ is twist angle
λ_r is local tip speed ratio
C is chord
R is segment radius of rotor
N is number of blades
C_{ld} is design lift coefficient
$C_{0.9}$ is chord at 90% of radius
$C_{0.5}$ is chord at 50% of radius
R is radius of rotor

The blade was divided at equal segments based on medium density fiber wood which maximum thickness of (22 mm) and the chord values were calculated and presented in Fig. 1.

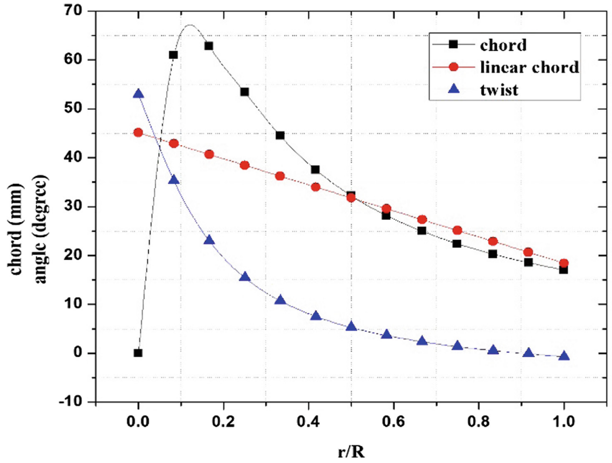

Fig. 1. Chord and twist angle distribution

The blade geometry profile of NACA 4412 taken as; root chord length 43 mm, tip chord length 15 mm, hub diameter 40 mm, length of blade 316 mm, and root cut-out 30 mm. The NACA 4412 is selected due to its suitability for power generation using three blades. As a result, the blade profile was formed by medium density fiber wood using the NACA 4412 airfoil shape. A medium density fiber wood was used because it is easy to form airfoils by using files mechanical tool. After the profile was done the mold formed by applying wax over the prepared profile. Then glass fiber was laminating over the mold with polyester resign. The polyester resign was mixed with 0.39 g hardener for hardening the fiber. After applied the resign the blade was allowed to dry for about 3 h. as show in the Figs. 2 and 3.

In order to increase the electrical power performance of the wind turbine, various augmentation system have been studied. One of them is converging diverging encapsulated wind turbine system. And step to construct the shape is presented as follow;

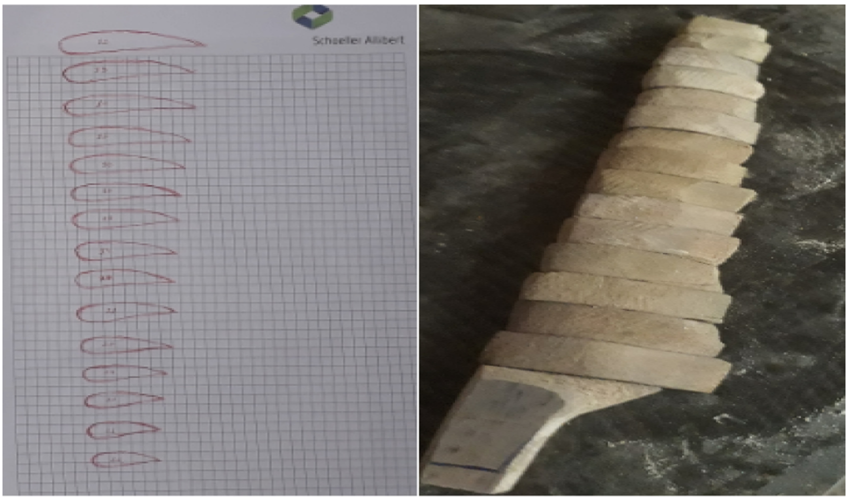

Fig. 2. Blade draft stage

Fig. 3. Finished blade manufactured

- Draw the layout over sheet metal
- Cutting was performed in line with layout drawing
- Attaching the separate sheet metal by bending at the end of sheet metal with the dimension of 20 mm, the right and lift the end of sheet metal bent in reverse direction. Rivet bolt was used to strengthen the attachments
- Round 6 mm diameter metal was used to strengthen the augmentation and place at the right and lift end of all augmentation
- Finally, the painting was performed as shown in Figs. 4 and 5.

Fig. 4. First stage of augmentations manufacturing

Fig. 5. Final stage of augmentations manufacturing

2.2 Wind Tunnel Testing

The experiment was carried out in open wind tunnel with the capacity of 25 m/s wind speed. During the experimental work different measuring instruments, digital multimeter, digital tachometer, and digital cup anemometer were used. The experimental procedure was started with ensuring the uniformity of the up-coming freestream velocity at any point of the inlet of augmentation. Wind tunnel air velocity was measured directly by a digital cup anemometer, which was placed in front of the augmentation at different locations and velocity was measured directly. The aluminum paper was stick on at the back side of the generator shaft to measure the revolution per minute. A digital tachometer was used to measure the shaft revolution per minute at different operating condition. The hub and angle plate have been made to provide blade angle and permit to displaced (change) the blade angle. Hub was made from plastic and blade was made from fiber. The connection between hub and blade were by 6 mm bolt and nut as shown in Fig. 6. The assembled hub and blade mounted on the AC generator and the clamp was used to mount all this on the metal bar. Metal bar frame with 1.20×1.20 m was used to place the augmentation. The height of the frame was equal to the height of the tunnel in order to get the good free stream velocity. The frame and metal bar with all accessories placed in front of a wind tunnel. Digital Multimeter was used to measure current and voltage for each operating condition. The series connection was used for current measurement and a parallel connection was used for voltage measurement as well.

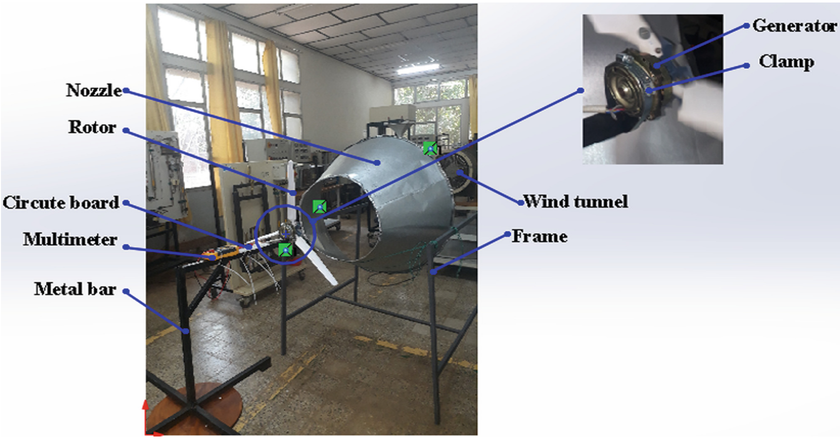

Fig. 6. Experimental set up

3 Results and Discussion

The experimental tests were conducted at wind tunnel on a diffuser, nozzle, nozzle-diffuser combination and bare at blade angle of 15. The wind speed was varying from 3–6 m/s. The wind speed limited 6 m/s because of experimental difficulties. It was not possible to measure the power for 7 m/s and above. The result obtained in this work were also compared with other data publish in literature obtained by Pambudi et al. [9], where the wind speed 2.5 m/s, 3.5 m/s and 4.5 m/s were made. To obtain the corresponding value of power with 3 m/s, 4 m/s, 5 m/s and 6 m/s we were use third order interpolation for better comparison as shown in Figs. 7 and 8. As can be seen from Figs. 7 and 8 a clear behavior of the power curve of this work and Pambudi et al. [9] power curve is presented. In our case the power curve is in the same behavior with those obtained on Pambudi et al. [9]. Due to design in different blade radius and nozzle diameter the value not expected to be agree.

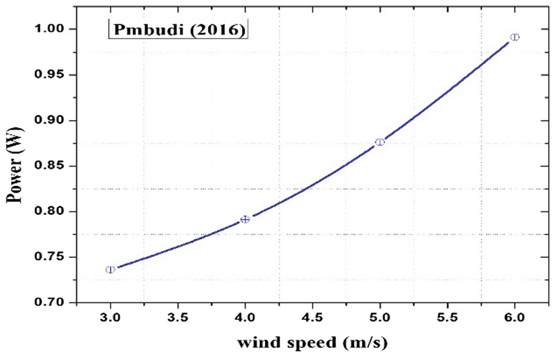

Fig. 7. Comparison used Pambudi result

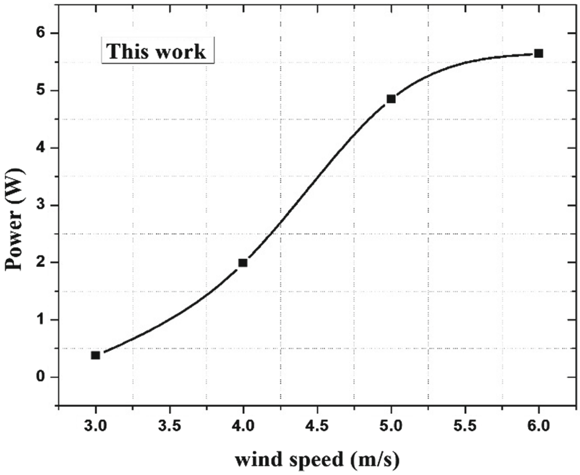

Fig. 8. Comparison of result this work result

The result from different augmentation and wind speed presented in the as shown in Fig. 12. There was no significant power difference between open and diffuser, but significant power recorded in nozzle and combined augmented wind turbine. Figures 9, 10, 11, and 12 gives the variation pf power between bare condition and augmented condition. Regarding to the variation relative to bare the maximum variation of approximately 68% was obtained with diffuser, 92% was obtained with nozzle and 88% was obtained with combined at 4 m/s wind speed. The average percentage of power variation between bare wind turbine and augmented wind turbine were 33.8% for diffuser, 88% for nozzle and 81.6% for nozzle-diffuser combination. The current study does not support previous research in this area. In fact, we found that the power curve increases gradually with increase of wind speed. Although, the curve shares the curve trained of existing wind power curve. Figure 12, is a plot of power versus wind speed for different capsulation. The cut in speed for nozzle and combination (converging and diverging) was 3 m/s. For diffuser and bare condition 4 m/s and almost 5 m/s were the cut in speeds respectively. As can be seen from the plot the diffuser and bare conditions do not show significant difference. The main objective of diffuser capsulation is to generate significant improvements in production output, as can be seen from Fig. 10, this goal was not achieved. In fact, diffuser capsulation can produce an enhancement in electric power, caused by the reducing the wake effect on the air ow that surrounding wind turbine. Nozzle and combined capsulation can effectively produce increments in air ow velocity resulting in a somewhat improved power output. Significant power variations were seen in the nozzle and combined capsulated condition.

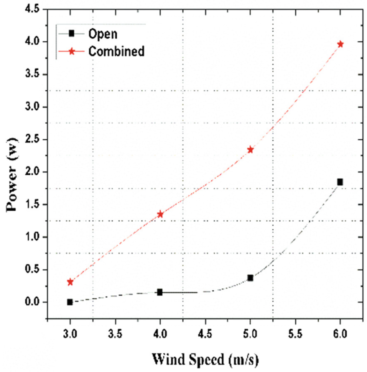

Fig. 9. Power curve of open vs combined

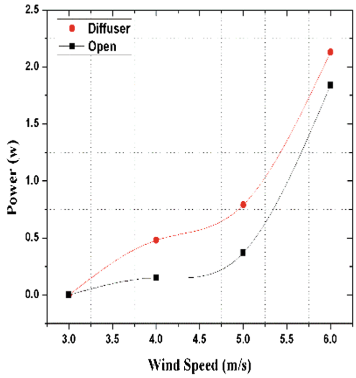

Fig. 10. Power curve of open vs diffuser

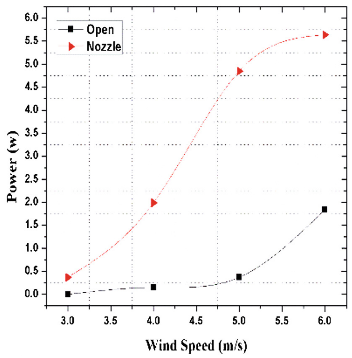

Fig. 11. Power curve of open vs nozzle

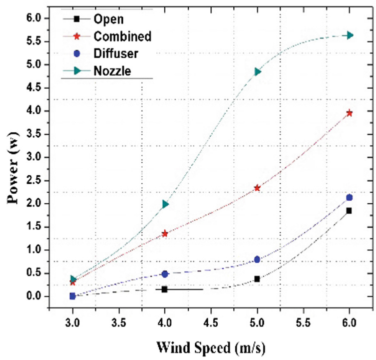

Fig. 12. Power curve of all conditions

4 Conclusions

In order to increase the performance of wind turbine different power augmentation systems have been studied and one of them is the ducted augmentation system. An augmented wind turbine has been an interesting concept of wind energy conversion, due to the system ability to increase the power generated relative to bare turbine with the similar size. We have found maximum power 5.64 W from nozzle augmented at 6 m/s wind speed. A resistor of 1000 Ω was used to determine electric power at different wind speed. A wind speed of 6 m/s gave the highest of 1.84 W with bare condition, 2.13 W with diffuser, 5.64 W nozzle and 3.96 W combined augmentation wind turbine. Although, the cut in speed for nozzle and converging and diverging augmented wind turbine was 3 m/s, while diffuser augmented and bare 4 m/s and almost 5 m/s were the cut in speed respectively.

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