JREE: Vol. 4, No. 4, (Fall 2017) 49-56

Journal of Renewable Energy and Environment

Research Article

Journal Homepage: www.jree.ir

An Investigation on Performance of Shrouding a Small Wind Turbine with a Simple Ring in a Wind Tunnel

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PAPER INFO

Paper history:
Received 09 November 2018
Accepted in revised form 05 February 2019

Keywords:
Wind Turbine
Power Coefficient
Power Augmentation Duct
Starter
Flywheel

ABSTRACT

Ducted wind turbines are a kind of small wind turbine having a diffuser or any other shape around the rotor which increases the air flow through the blades and absorbs more power. In the present study, a small wind turbine was ducted with a relatively simple ring and its performance was investigated in a wind tunnel. The duct is shaped using rolling steel sheets on a sloping surface and finally fabricated in double-glazed surfaces. The turbine utilizes polyester resin glass fiber-armed composite hollow blades. Bare turbine produces 165 watts in its highest power generation mode which can reach 282 watts when it is ducted. The evaluation of the system in the wind tunnel showed that the power generation of the ducted system compared to a conventional turbine was 14 % higher on average. Furthermore, the rotor speed of the ducted turbine was 45 % higher than the bare one which increases the tip speed ratio (TSR). In this study, TSR increment raised the absorbed power in the developed wind turbine.

1. INTRODUCTION

Energy is the most important factor in the economic and social prosperity of any society. Iran is one of the richest countries in the world in terms of fossil energy sources and now being Iran as a strong point in global equations, nevertheless, the mortality and environmental problems associated with the consumption of these fuels in the near future will lead to a lot of problems. Many developed countries welcomed renewable energy sources such as the sun, wind, and biomass in order to diversify energy sources and sustainable development, secure energy and eliminate environmental problems. It is predictable that by increasing global warming trend, environmental problems and satiety of developed countries to fossil resources due to alternative energy sources development, soon there will be international conventions that will limit the use of fossil fuels. Of course, it is worthy to mention that by joining the Paris climate agreement, Iran is committing to reduce using the fossil fuels by 12 % until 2020. In the Iranian Ministry of Energy, installation of 5,000 megawatts of renewable energy has been targeted where 4,500 megawatts of that were considered for the wind energy. Thus, it can be supposed that in the next five years, there will be close to 4,000 megawatts of the market for the private sector in the wind energy development [1]. The program announced by the Ministry of Energy for various sources of energy production in the coming years is described in Figure 1.

The cost of energy from the wind turbines is higher than the conventional ones like oil and gas. The reason for this difference is the kinetic energy density of the wind stream relative to the potential energy found in fossil sources. Many researchers have been working several decades on all types of wind turbines, blade optimization, and development of power generators as well as ducted wind turbines to increase the energy density of the wind turbines. This research focuses on the horizontal axis small ducted wind turbines.

From the ancient times up to the present, the wind energy has been used only in one form; conversion of wind kinetic energy to mechanical one in a rotating shaft. In the past, wind energy has been used for grinding grain and draining water from aqueducts and wells. But now, it is used to generate electricity which is known as “wind turbine” [1].

A ducted wind turbine is equipped with a diffuser surrounding the rotor. In order for a ducted wind turbine to have an economic advantage, the following specifications should be included:

Improved performance, reduced the construction cost, significant life span, reliability, availability, easy maintenance, eco-compatibility, and functionality.

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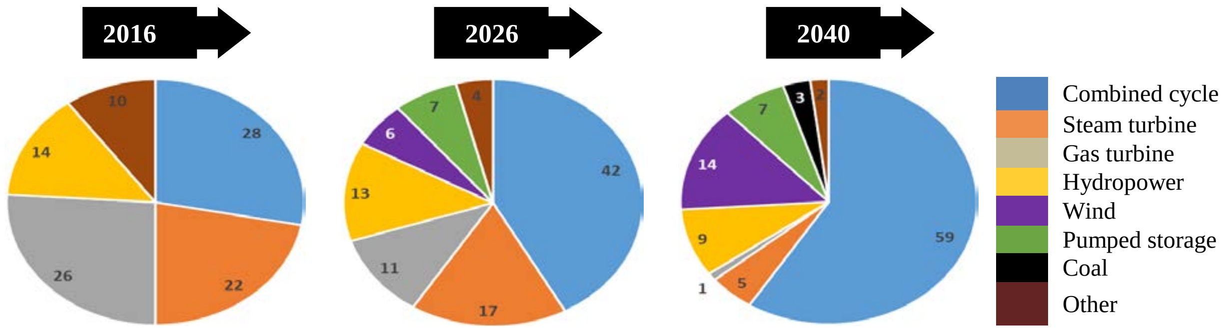

Figure 1. Future of Iranian energy sources percentage [1].

Ducted wind turbines have the following advantages than conventional ones:

- Increased output power per unit swept area.
- Power generation at low wind speeds.
- Rotor angular speed increment (which reduces the gearbox size).

Majority of reported works indicate that ducting a wind turbine will augment its power generation, but it also raises the fabrication cost and requires an ultra-heavy structure for it. Therefore, in this work, development of a simple lightweight duct was decided to reduce drag force acting on it. In the next section, some reported works are discussed to find out the ducted wind turbines performance.

Due to the moderate wind speed regimes in most parts of Iran, the development of a wind turbine that meets low power-density areas is vacant. The performance of a ducted wind turbine is such that by creating a relative vacuum behind the rotor, the air flow is sucked into the blades. Lots of studies have been shown that if the duct is properly designed, the wind flow velocity on the rotor will be doubled in average and continuous power production will exceed the Betz limit by 50 %.

The first steps were taken in ancient Iran to increase the wind turbine power coefficient. In the Sassanid period in eastern Iran, windmills were made with a vertical axis having a duct which greatly increased the power coefficient. Some of these wind wheels, which were used to grind the grain, are still working in great Khorasan.

The first study on a modern ducted wind turbine was carried out by *Lilley* and *Rainbord* in 1956 who has incorrectly shown that the ducting cannot cross the Betz limit. The study was mathematically investigated [2]. Several years later, a series of empirical studies have been conducted by *Kogan* [3]. The abundant and inexpensive oil provided no economic justification for these activities until the 1973 oil crisis. The boycott forced the countries which needed *Persian Gulf* oil to develop alternative sources. After the crisis, the first attempt was carried out by *Igra* at the University of Ben-Gurion of *Israel*. *Igra* has studied the ducted wind turbines theoretically and experimentally and evaluated different shapes for the duct. In his studies, he achieved a 2.4 times augmentation ratio [4-8]. In 1979, Gilbert and Foreman developed a series of studies at the Grumman aerospace company in New York that showed a 4-time increment in comparison with the Betz limit [9-15]. These groups also expanded a mathematical model to justify the results of its experiments, which, of course, was not able to justify all aspects of the results such as wake. *Igra* and *Foreman*'s efforts were opened a clear path to the researchers which have been continued to the present time. In 1981, *Fletcher* has presented a mathematical model based on BEM in terms of continuous wake vortex and effects of Reynolds number, which indicates that the efficiency of the duct and its output loss coefficient control the performance of the turbine [16]. The VORTEC 7 ducted Wind Turbine was built in the 70's and 80's based on previous studies in New Zealand. VORTEC 7 is one of the most successful plans in this field. The turbine has a multi-slot duct that creates more air intake and prevents from the separation phenomenon.

By time passing and technology upgrades, the cost of fabrication of the ducted wind turbines was justified. In 1994, *Phillips* has conducted a comprehensive study on the ducted wind turbines and formulated the turbine performance. Despite all the shortcomings of his method, the study opened up a distinct approach to the next researchers [17].

In 2000, *Hansen* has presented a 1-D mathematical model established upon an actuator disc and validated it using CFD analysis through the Navier-Stoks solver. The study has shown that using a duct can pass the Betz limit. But the amount of reinforcement will never be as much as flow velocity increment at the rotor's plain [18]. *The* experimental results obtained by Hansen showed that the magnitude of the enhancement is less than the predicted values in the mathematical model. The reason for this difference is the inability of the mathematical model to cover separation phenomenon. In 2007, *Van Bussel et al.* have proposed a mathematical model for the ducted wind turbines based on the energy conservation laws. The model indicates that augmentation of the ducting depends on the increment in the air flow rate through the rotor plane. Based on the theory of momentum conservation, *Van Bussel* also claims that the maximum power coefficient of a ducted wind turbine is 0.7 or slightly higher [19].

In 2013, *Kishore et al.* have designed and built a ducted wind turbine specialized for low wind regime. Numerical and laboratory analyses showed that the diffuser part of the ducting is more effective than its nozzle part [20]. In this study, the augmentation ratio was reported to be 1.4–1.6. It should be noted that the augmentation ratio is equal to actual ducted wind turbine power coefficient per Betz power coefficient which is equal to 0.59. In 2014, *Bontempo* and *Manna* have provided a linear semi-analytic method that could cover a non-linear behavior such as wake and velocity alterations in the radial direction [21]. The model has been verified by CFD assessment and has shown a satisfactory consistency. The research team have also presented a nonlinear model based on the momentum conservation to study the impact of the thrust force on ducted the wind turbine performance. The method has the advantage over linear methods that can cover wake rotation as well as interactions between the rotor and the duct, while the linear methods cannot [22].

2. MATERIALS AND METHODS

2.1. Bare wind turbine

When the wind turbine rotates, the rotor can be assumed as an actuator disc. The model is presented in Figure 2. However, simplifications are needed to get started:

- The entire process is considered in the small Mach number, where air density is considered constant.
- The wind flow is steady.
- Air is incompressible.
- There is no friction between any component.
- There is not any external force acting on control volume.

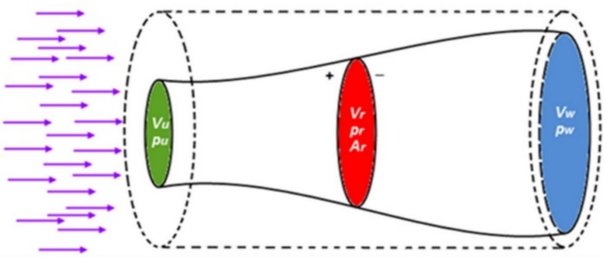

Figure 2. The control volume for the actuator disc instead of bare wind turbine.

As shown in Figure 2, the disc acts as a thrust on the wind flow and reduces the velocity from V_u to V_r. The pressure on the rotor plate is also extremely reduced. These changes in pressure and velocity at the front and back of the disc can be linked using Bernoulli's equations as Eq.1 and Eq.2 [23]:

$$p_u + \frac{1}{2}\rho V_u^2 = p_r^+ + \frac{1}{2}\rho V_r^2 \quad (1)$$

$$p_r^- + \frac{1}{2}\rho V_r^2 = p_u + \frac{1}{2}\rho V_w^2 \quad (2)$$

As mentioned earlier, while a wind turbine rotates, it turns into a disc and prevents wind flow and reduces its speed. Assuming that the velocity in the rotor plane is reduced by aV_u, so, axial flow induction factor (a) will be:

$$V_r = V_u - aV_u \quad \Rightarrow \quad a = 1 - \frac{V_r}{V_u} \quad (3)$$

Then, the absorbed power by a wind turbine is obtained as:

$$P = 2\rho A_r V_u^3 a(1-a)^2 \quad (4)$$

The power coefficient can be achieved by dividing Eq.4 to overall wind power:

$$C_P = \frac{2\rho A_r V_u^3 a(1-a)^2}{\frac{1}{2}\rho A_r V_r^3} = 4a(1-a)^2 \quad (5)$$

The derivative to "a" in Eq.5 is the maximum power coefficient which is known as Betz-Lanchester (Betz-Joukowsky) limit that can be obtained as:

$$C_{P_{optimum}} = \frac{16}{27} = 0.593 \quad (6)$$

2.2. Ducted wind turbine

According to Eq.6, any ideal wind turbine cannot catch more than 60 % of wind energy. As a result, scientists tried to exceed it by some innovative devices. Diffuser shrouds are one of the layouts that were developed to exceed the Betz limit.

With the same initial conditions as in the previous section, a one-dimensional model is presented for a disc that is located at the entrance of a diffuser ducted wind turbine. According to Figure 3, the Bernoulli equation is written as follows [17]:

$$p_u + \frac{1}{2}\rho V_u^2 = p_r^+ + \frac{1}{2}\rho V_r^2 \quad (7)$$

$$p_e + \frac{1}{2}\rho V_e^2 = p_u + \frac{1}{2}\rho V_w^2 \quad (8)$$

The Energy balance for the C.V can be also written as:

$$\frac{1}{2}\rho Q V_u^2 - \frac{1}{2}\rho Q V_w^2 = V_r F_r + Q\Delta p_d \quad (9)$$

Assuming some dimensionless parameters, a phrase for power and power coefficient can be written [17, 24, 25]:

$$\gamma = \frac{V_r}{V_u} \quad (10)$$

$$\beta = \frac{A_r}{A_e} = \frac{V_e}{V_r} \quad (11)$$

$$\eta_d = \frac{p_e - p_r^-}{\frac{1}{2}\rho(V_r^2 - V_e^2)} \quad (12)$$

$$Cp_e = \frac{p_e - p_u}{\frac{1}{2}\rho V_u^2} \quad (13)$$

Therefore, the power and power coefficient will be expressed as:

$$P = \frac{1}{2}\rho A_r V_u^3 \gamma[(1 - Cp_e + \gamma^2\beta^2) - \gamma^2(1 - \beta^2)(1 - \eta_d)] \quad (14)$$

$$C_P = \gamma[(1 - Cp_e + \gamma^2\beta^2) - \gamma^2(1 - \beta^2)(1 - \eta_d)] \quad (15)$$

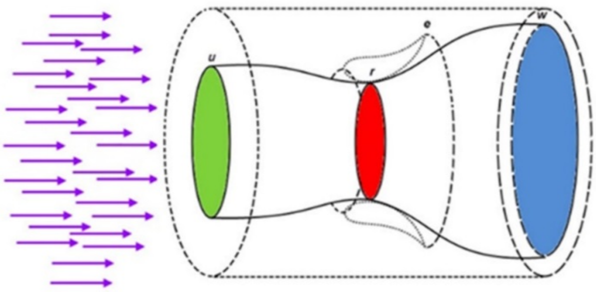

Figure 3. The control volume for the actuator disk instead of ducted wind turbine.

The cross section used for the duct is illustrated in Figure 4. It consists of a small nozzle as a collector and a short diffuser which can make air flow more accelerated in the rotor plane. Besides, a simple duct can improve the axial induction factor that could cause a strong suction in the blade plane. The duct is shaped by rolling 4 parts steel sheets and fabricated through welding. In Figure 5, the fabrication process is illustrated.

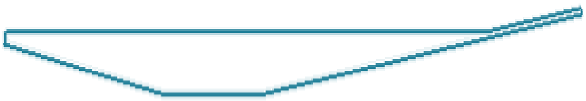

Figure 4. Ring duct cross section.

2.3. Rotor design and fabrication

The wind turbines are primarily designed based on the environmental variables such as wind speed regimes, atmospheric conditions, roughness and vegetation cover (vegetation and structure) as well as available power grids. For the turbine design, wind velocity is investigated in two different modes; Normal and Storm mode (or Consecutive wind direction alters). For the wind turbine design, the wind characteristics of the region are used in a semi-long period (from 2 to 50 years) and according to Table 1, the turbine class is determined. To determine the wind turbine class, the average wind speed of the region is extracted using the Weibull distribution [26].

Figure 5. Duct fabrication process.

The classification is just for the small wind turbines where their swept area is less than 200 m^2 (rotor diameter less than 16 m) or their power is less than 100 kilowatts. Class S, which is presented in Table 1, is based on the requirements of the specific conditions such as offshore, tropical areas, and dusty areas in order to give a release to the designer. In this study, we use the S class.

Table 1. Different winds classes in small wind turbines [26].

S	IV	III	II	I	class
Specify by designer	30	37.5	42.5	50	V_{ref}
	6	7.5	8.5	10	V_{ave}
	0.18	0.18	0.18	0.18	I_{15}
	2	2	2	2	a

Under normal circumstances, the probability of occurrence of V_{hub} at the hub height (rotor axis height) is calculated using Eq.16 which is known as the Rayleigh distribution [26]:

$$P_R(V_{hub}) = 1 - e^{(-\pi(V_0/2V_{ave})^2))} \quad (16)$$

In such a situation, the wind speed at any distance of earth surface will be discussed using Eq.17:

$$V(H) = V_{hub}(\frac{H}{H_{hub}})^{0.2} \quad (17)$$

After extracting the average wind speed of the region and identifying hub height, the design speed is considered to be 1.4 times by average speed at that height. According to the IEC 61400-2 standards, a small wind turbine design needs to consider ten different factors such as temperature range, humidity, and solar radiation. The design considering IEC 61400-2 standards will result in a safe performance.

Considering the simplified relations of standard and BEM theory, a small ducted wind turbine is designed and fabricated which is named TMWT[2]. TMWT is a 3-blade horizontal wind turbine which uses an SG6043 airfoil in blade main body and SG6040 airfoil in its root. The blade was designed using BEM method by considering *Snel* and *Prandtl* corrections. Finally, the blade chord and twist distribution along its radii are as illustrated in Figure 6. The blades were fabricated hollow with resin polyester reinforced by glass fiber.

TMWT is a laboratory turbine consisting of 75 machined parts, which can use up to 2kW rotor and PM generators, pitch angle adjustment, auxiliary start systems and any duct with any shape and size. Figure 7 illustrates TMWT installed in the TMU agriculture department yard. In this work, the simple ring duct (which is located just around the duct) effect on a wind turbine is investigated.

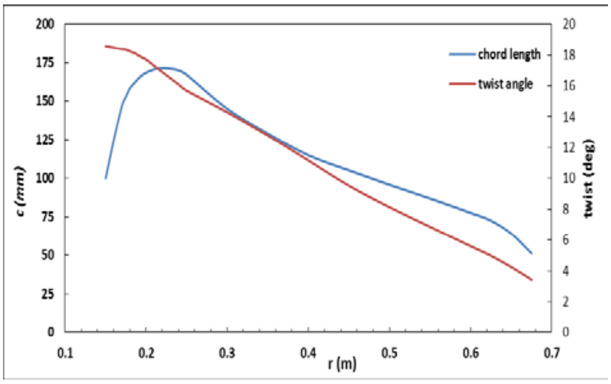

Figure 6. Calculated chord and twist distribution along TMWT blade radial length.

[2] **T**arbiat **M**odares University Multi-Slot Ducted **W**ind **T**urbine

Figure 7. Installed TMWT in agriculture department of TMU.

2.4. Wind tunnel

All performance evaluation of TMWT (in bare and a ring as duct) was done in a wind tunnel. The tunnel was equipped by a 6 phase, 1.2 megawatts synchronized electromotor with a 4.5 *m* diameter blowing fan. The dimension of the test section was 2.8*2.2 *m* where its maximum wind velocity could raise from 5 to 50 *m/s*. The tunnel was calibrated by one of the governmental organizations where its respective office reports that the flow turbulence in the test section is in excellent condition. The results showed that the velocity variation is less than 0.1 % from its mean value and flow turbulence in the center of the test section is less than 0.13 %.

The main test section dimensions were 2.8 *m* width and 2. 2 *m* height. Test section length was 4 *m* in open condition and 6.5 *m* in a closed state. The tunnel had a relaxation chamber with a contraction ratio of 9 to 1 which had two gauzes and a honeycomb sheet to uniform air flow. The blowing fan angular speed was controlled by a converter which can be controlled at a speed of 60 rpm to 560 rpm with a precision of 1 rpm. The fan parameters were controlled by the transmission of control and warning signals to the control room and the fan speed were controllable manually or automatically with the computer.

In order to evaluate the turbine performance in the wind tunnel, it was installed in the test section as shown in Figure 8. The tunnel air flow speed was changed from 5 to 13 m/s and the turbine power generation and its rotor speed were measured using a variable power consumer and a frequency meter, respectively. The measurements were done in two states: bare wind turbine and ducted wind turbine.

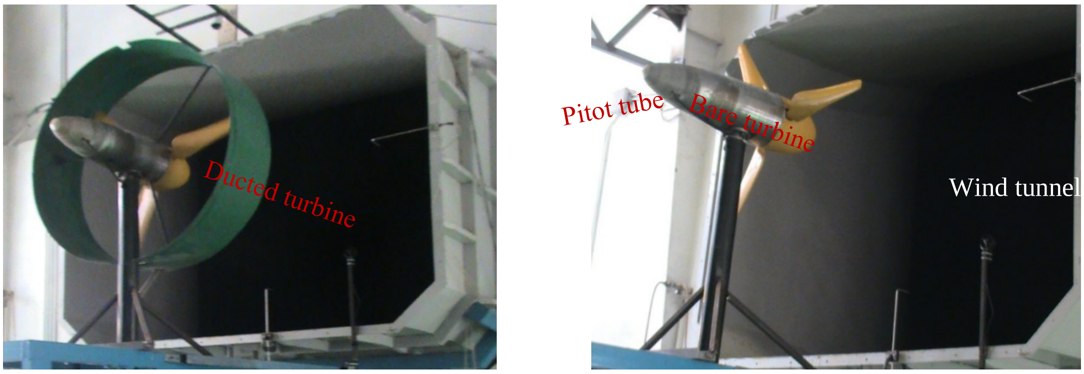

Figure 8. TMWT in the wind tunnel test section.

3. RESULTS AND DISCUSSION

The power generation of each treatment is illustrated in Figure 9. The Figure indicates duct positive effects on the turbine performance mainly in upper wind speed domains. This Figure also shows an average of 14 % increase in power output. Oyha's bare and flanged duct 500 w wind turbine also illustrated which power production from it shows a similar trend with this work results [27]. Since Oyha's wind turbine rotor is designed especially for a ducted turbine, so, its power generation is very low during its test as a bare turbine. If it is accepted that the same thing may happen to the current work, redesigning the rotor as specialized for a ducted turbine will extremely increase the power generation. Similarly, it is forecasted that redesigning the rotor may decrease the power generation of TMWT in the bare turbine. Oyha has used a brimmed duct with a power coefficient class that is higher than normal. Oyha's ducted wind turbine maximum power coefficient is reported as 1.4 [27].

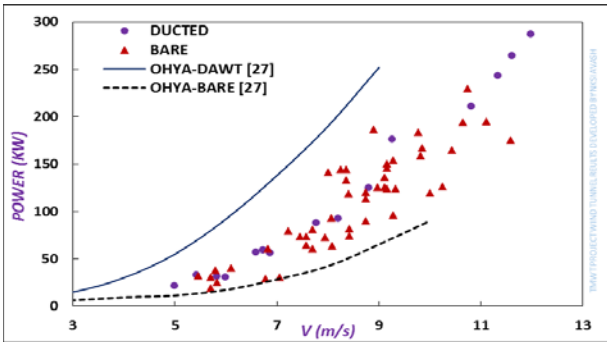

Figure 9. Power generation of TMWT in bare and a simple duct around the rotor in different wind velocity.

Accurate augmentation percent (AP) of the ducted turbine as a function of wind velocity is illustrated in Figure 10. It is clear that in all wind velocity domains, the ducted turbine produces more power, but the amount varies. In 6 to 8 m/s of wind speed, AP is descended and beyond 8 m/s of wind speeds, AP is ascended sharply up to the end of the evaluation domain.

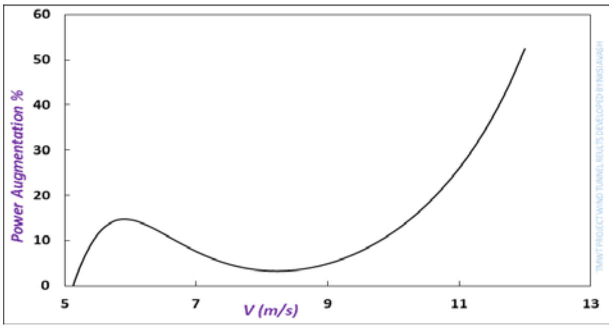

Figure 10. Power augmentation percent of TMWT using a simple duct against the bare.

Considering the airflow velocity in the rotor plain of a bare turbine and comparing the power, the estimated air flow speed-up ration in rotor plain can be obtained for the ducted turbines. However, it should be noted that the extracted ratio is a result of the negative Relative Pressure in the duct exit. The average pressure can be calculated using Eq.14 and Eq.15 in the duct exit.

The power production comparison at different rotational speeds of the rotor is shown in Figure 11. The maximum rotational speed of the ducted turbine rotor is 200 RPMs more than the bare turbine one. In the same rotor speed, the bare turbine has produced more power, so, its generated torque is less for corresponding power. Due to these characteristics, the ducted wind turbines can be called as high-speed turbines.

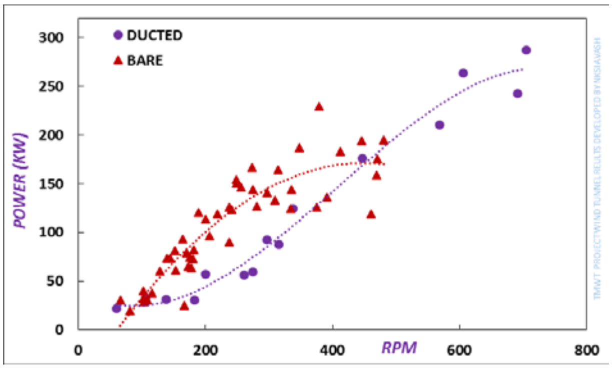

Figure 11. Power generation of TMWT in bare and a simple duct around the rotor in rotor speed.

In Figure 12, the rotor speed difference is shown for the ducted and bare TMWT. The ducted rotor is 45 % faster than the bare one. Higher speed for a rotor will carry some advantages and disadvantages as follows:

- **Advantages**
- TSR will rise and power generation will increase. It should be noted that the statement is just for a domain of TSR which TMWT works in.
- Rotor speed-up allows the turbine to eliminate the use of a gearbox or in worse condition makes the gearbox smaller.
- Corresponding torque will be decreased, so, the main shaft will be weaker and braking the shaft will be easier.
- **Disadvantages**
- Rotor speed-up will raise centrifugal force acting on rotating parts. Accordingly, the blade root (wrist) should be armed. For example, a 20 % rise in rotor speed will force the designer to augment the blade root to 45 %. Consequently, its weight and construction cost will raise.
- High speed also can bring more depreciation to the rotating parts especially bearings. The life of parts like bearings is determined by the number of their overall rotation. Therefore, it is obvious that the rotor will reach the end of its life faster than the bare rotor.
- Fatigue will be closer for loaded parts especially blade root and wrist.

Figure 13 illustrates the rotor speed-up percent more accurately in wind velocity domain. Using this Figure, the dependence between tip speed ratio and rotor speed-up can be obtained.

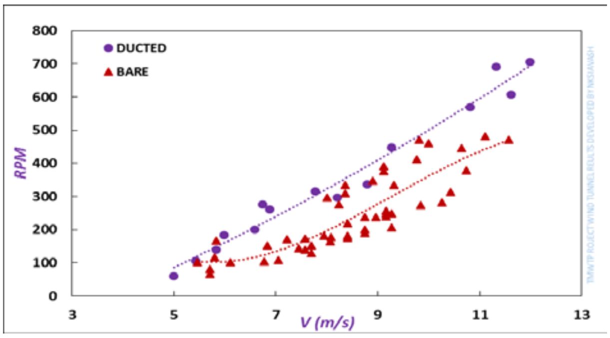

Figure 12. Rotor speed against wind velocity of TMWT in bare and simple duct.

4. CONCLUSIONS

In general, it can be summarized that the ducted wind turbine significantly increases the power output with a rotor which has been designed for a bare turbine. The duct also increases the rotor speed and enables the turbine to rotate 200 rpm faster than normal. Comparing the results obtained in this study with the pervious results, it is shown that the rotor must be designed and constructed according to the turbine shrouding. Majority of reported works have been utilized a complicated heavy diffuser duct that may use multi-slot layouts that are very heavy in weight and expensive in cost. But, in this work, a semi-simple light-weight duct was developed that can augment the turbine power generation by 14 % and its rotor angular speed by 45 %.

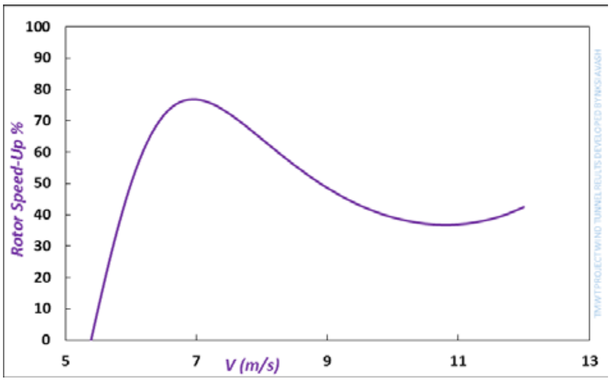

Figure 13. Rotor speed-up percent of TMWT using a simple duct against the bare.

It is technically preferable to provide a ducted wind turbine with a bare wind turbine. Choosing a ducted turbine in terms of price varies depending on its size. Therefore, the designer in addition to the technical calculations must also consider the cost remarks.

5. ACKNOWLEDGEMENT

The authors gratefully acknowledge the help of Mr. Ali Siasarani for his valuable comments in TMWT fabrication and providing raw materials. We also want to thanks Mr. Liu Tongie for his efforts to supply generators and power control units.

NOMENCLATURE

a	Axial flow induction factor
A_r	Swept area by rotor (m^2)
C_D	Lift coefficient
C_L	Drag coefficient
C_P	Power coefficient
Cp_e	Duct exit pressure coefficient
N	Number of blades
p_u	Upstream pressure (pa)
p_e	Duct outlet pressure
p_r^-	Pressure in front of the rotor (pa)
p_r^+	Pressure in back of the rotor (pa)
P	Power (Watt)
V_u	Wind speed (m/s)
V_e	Wind speed at the duct outlet (m/s)
V_w	Wind speed downstream (m/s)
V_r	Wind speed on rotor plate (m/s)
β	Rotor to duct exit area ratio
γ	Speed-up ratio
μ	Wind speed ratio in far wake
ρ	Air density (Kg/m^3)
η_d	Duct Efficiency

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