Optimization of Power Generation by a HWT Using Diffuser Augmented System

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Abstract
Horizontal axis wind turbine undergoes aerodynamic inefficiencies in the blade area due to many non-aerodynamic constrain which includes bareness of the blade, the gear box frictions, and the turbine. These constrain lead to great loss of power output of the wind turbine. A novel diffuser augmented wind turbine (DAWT) concept is adapted in this work which aims at mitigating these losses. Even though power production by wind turbines falls short of the Betz limit, diffuser augmented wind turbine have power coefficient larger than the Betz standard maximum coefficient of performance which is 0.59. The wind turbine system and the adapted diffuser augmented system are modeled and simulated using the Simulink tool in MATLAB software. Simulation results confirmed the increase in energy capture potential of the diffuser augmented wind turbine with a maximum coefficient of performance of 0.64, an 8% improvement over the Betz limit.

Keywords: Optimization, Power Generation, Horizontal Wind Turbine, Diffuser Augmented System.

1.0 Introduction
The depletion of fossil conventional energy source, for example, coal, oil and gas and the need to limit their use due to environmental hazards created through carbonization has led to the research that will increase utilization of renewable energy sources to meet ever growing demand of electrical power (Raul, 2014). Wind is one of the most promising among other different types of available renewable energy sources (Vennell and Feijoo, 2013). In the past decade, considerable research has been carried out to improve on wind turbine design and control for increased power conversion, efficiency and availability. One of such research is the maximization of power captured in wind turbine using diffuser augmented system (DAWT). A Diffuser augmented wind turbine is a turbine that is modified with cone shaped object that houses the blades of turbine with small air inlet and large air out let. The air flow through the small hole forces itself out through the large hole thereby causing the blades of the turbine to rotate faster and constantly and thus increases the output of the turbine. The increase in the efficiency is possible due to the increase in the wind speed the diffuser provides.

Horizontal axis wind turbine has the ability to collect maximum amount of wind energy for time of the day and season, and their blades can be adjusted to avoid high wind storm. Wind turbines operate in two modes namely constant or variable speed. For a constant speed turbine, the rotor turns at a constant angular speed regardless of wind variations. One advantage of this mode is that it eliminates expensive power electronics such as inverters and converters. Its disadvantage however, is that it constrains rotor speed so that the turbine cannot operate at its peak efficiency in all wind speeds. For this reason a constant wind speed turbine produces less energy at low wind speeds than does a variable wind speed turbine which is designed to operate at a rotor speed proportional to the wind. The output power or torque of a wind turbine is determined by several factors. Among them are turbine speed, rotor blade tilt, rotor blade pitch angle, size and shape of turbine, rotor geometry and wind speed (Vennell and Feijoo, 2013).

Efficiency is one of the paramount aspects in determining the economic attractiveness on the application of wind turbine as a source of energy generation. The maximum efficiency of the conventional wind turbine (bare wind turbine) is 0.59; known as the Betz Limit (Kirtley, 2012). It is believed that this efficiency limit does not simply come from any design flaws. According to (John, 2011) the wind turbine cannot extract the entire energy available in the free stream (upstream), the turbine itself affects the flow field as it extracts the power from the wind. There is a pressure change on the upstream of the turbine, which in turn diverts some of the fluid away from it. The limited efficiency of the turbine is caused by braking of the wind from its upstream speed to its downstream speed, while allowing a continuation of the flow regime. The additional losses in efficiency for a practical wind turbine are caused by the viscous and pressure drag on the rotor blades, the swirl imparted to the air flow by the rotor, and the power losses in the transmission and electrical system. This work intends to improve on power captured in the wind turbine using diffuser augmented wind turbine thereby improving the power output.

2.0 Overview of the Diffuser Augmented Wind Turbine (DAWT)

Diffuser augmented wind turbine (DAWT) is a wind turbine with cone shaped wind diffuser that is used to increase the efficiency of converting wind power to electrical power. The increase in efficiency is possible due to the increased wind speed the diffuser provides. In normal bare wind turbines, the rotor blades are vertically mounted at the top of a support tower or shaft. In DAWT the rotor blades are mounted within the diffuser air terrain which is placed on the top of the support tower. Diffuser augmented system is therefore a system employed to enhance the easy and fast flow of wind through the hole of the diffuser object thereby increasing the power captured in a wind turbine as shown in figure 1.

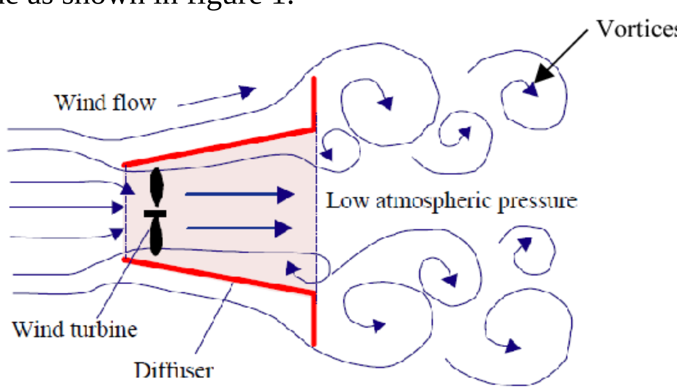


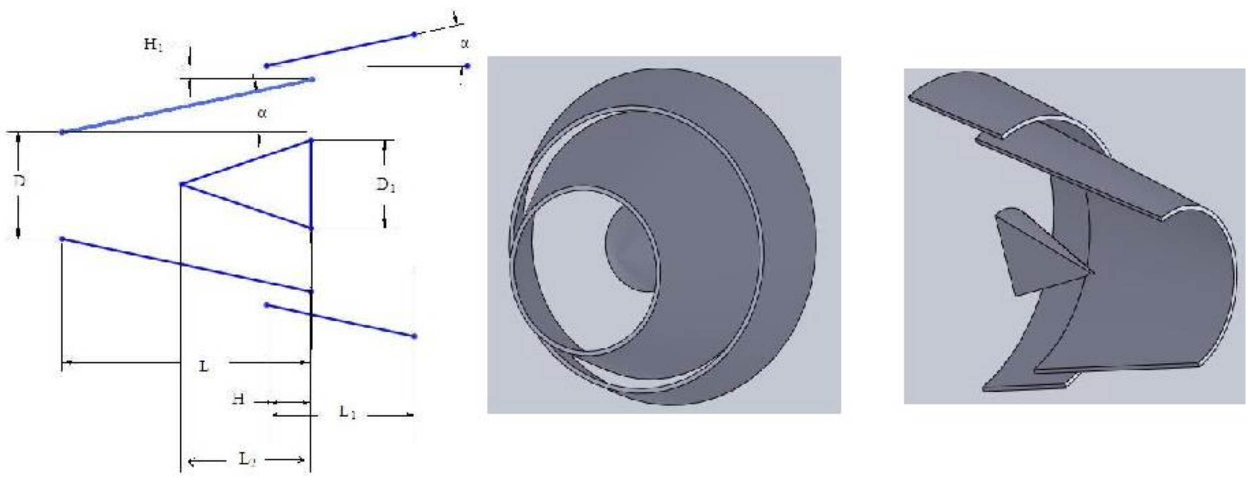
Figure 1: Operational Features of a Diffuser

The vortices are the air that strays away which if not checkmated will oppose the useful air that flows out of the diffuser which courses the blades of the turbine to rotate effectively, therefore the flanged design type of diffuser is preferred for augmentation system because the flange checkmates the vortices. With this arrangement, there is a constant wind within the air terrain along the walls of the diffuser to hit the blades of the turbine to rotate speedily and constantly, thereby increasing the efficiency and the reliability of power capturing in the wind turbine.

The characteristic performance of diffuser augmented wind turbine depends on the following parameters**:**

(1) The diffuser main body length (L)

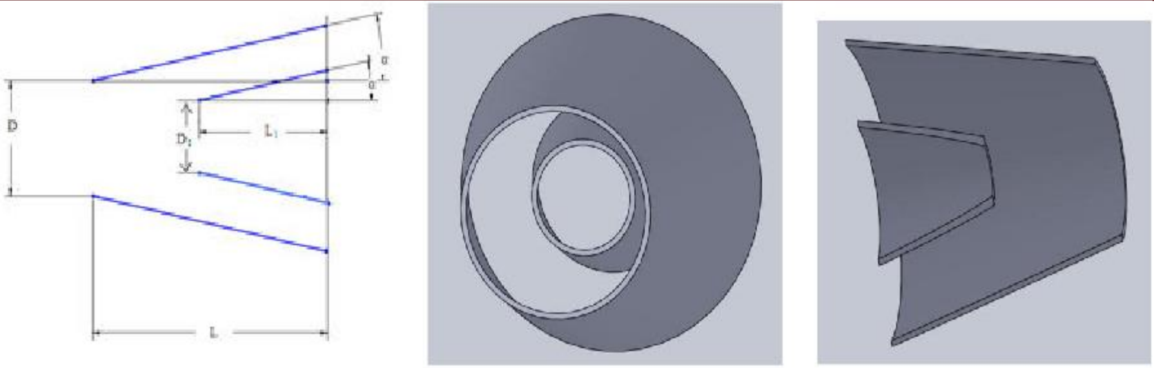
(2) The entrance diameter (D)
(3) The expansion or diffuser open angle (a).
(4) The flange length (h).
(5) The splitter open angle (a_1), as is shown in figure 2.



(a) Line Diagram **(b) Inflow Inlet** **(c) Sectional View**

Figure 2: Sectional Dimensions of a Diffuser.

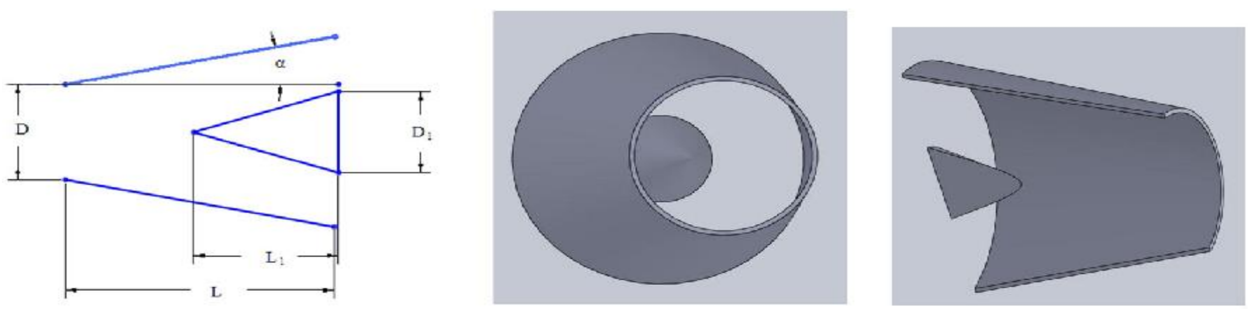
According to Abe and Ohya (2013) and Mohan and Robbins (2013), the performance of a flanged diffuser strongly depends on the loading coefficient (the volume of air allowed to enter the diffuser at a given time to hit the blades) as well as the opening angle. The loading coefficient for the best performance of a flanged diffuser was observed to be considerably smaller than that of the bare wind turbine. Since the flange is used in a diffuser augmented wind turbine, the little air that enters into the diffuser is more useful than the much air that flows around the bare wind turbine. With the use of the flange, the vortices (the opposing wind) is blocked, therefore the diffuser augmented system maximizes the power captured in the wind turbine and increases the power and torque outputs and the rotational speed of the turbine. The flanged diffuser shroud therefore plays a vital role of a device that collects and accelerates the approaching wind as shown in figure 3.



(a) Line diagram **(b) Inflow inlet** **(c) Sectional View**

Figure 3: Diffuser Design with Small Inner Diffuser Splitter.

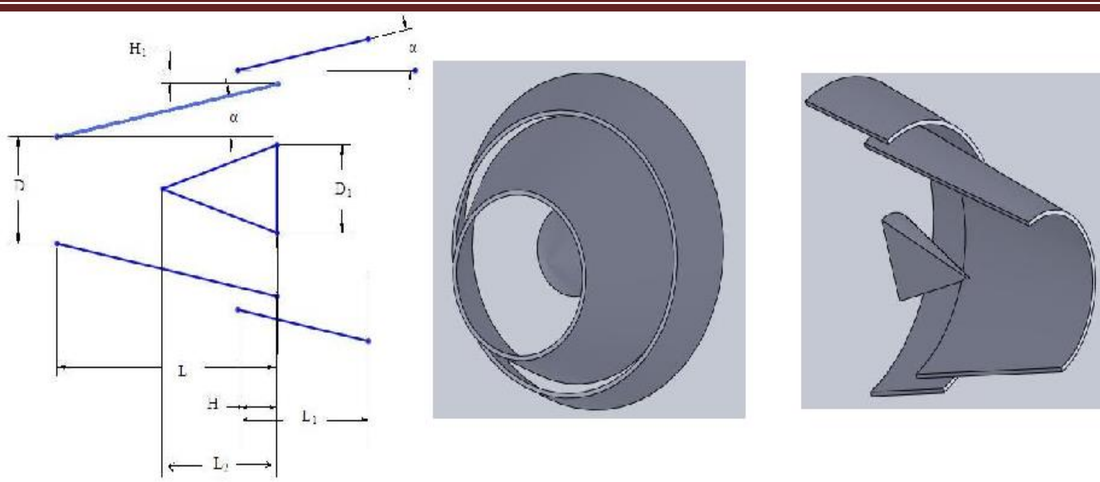
In this type of diffuser design, the splitter or separator is a smaller diffuser within the main diffuser (with a cone shape), added to the main diffuser system in order to optimize air pressure at the wake of the diffuser to minimize separation of air flow or vortices (back air flow) back into the main diffuser system. Another diffuser that is placed inside the main diffuser with splitter has the following enhancement characteristics; splitter angle a_1, splitter length L_1, and splitter diameter D_1 as can be seen in figure 3. This enables the main diffuser to direct and avoid separation of wind which would have caused vortex inside the diffuser walls.



(a) Line diagram **(b) Inflow inlet** **(c) Sectional View**

Figure 4: Diffuser Design with Cone Shaped Splitter

Most of the diffusers are cone shaped for the purpose of improving the velocity of the air as they enter the diffuser through the air terrain in order to turn the turbine blade fast. To achieve this, the exit hole of the diffuser is made larger than the entrance hole so that it will adequately diffuse the air. As the wind flows through the diffuser, it moves along the walls of the diffuser, this causing the air that is going out from the diffuser to form what is called vortices of wind (back wind flow or stray wind).



(a) Line Diagram (b) Inflow Inlet (c) Sectional View

Figure 5: Diffuser Design with Double Diffuser and with Cone Shaped Splitter

In this type of diffuser design, change in flow velocity of air occurs as a result of bigger diffuser and splitter that are inserted into the smaller diffuser, because the hole of the bigger diffuser is larger than the hole of the smaller diffuser at the exit end. It creates a vacuum that acts as air sucker which forces the exit wind to accelerate at a rate very suitable to rotate the wind turbine blade faster and constant, thereby increasing the output of the torque and power.

3.0 Implementation of the Wind Turbine System without Diffuser

The wind turbine system and controllers (figure 6) are modeled using the Simulink tool in MATLAB software. This simulation employs blocks from the Simulink Wind Turbine Block set 3.0. The blocks in the simulation can be broken up into six main subsystems: Wind Generator, Wind Turbine Rotor, Drive Train Dynamics, Robust Estimator Controller, Measurement Noise Generator, and the PI Controller. The simulation block diagram is as shown in figures 7a, 7b, 7c, 7d.

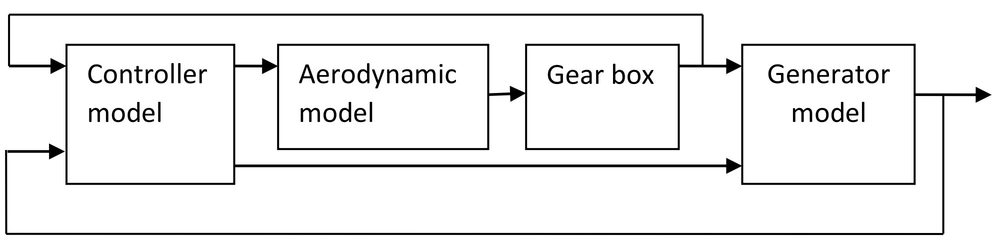


Figure 6: Block Diagram of the Proposed Wind Turbine System

The wind generator and the wind turbine rotor blocks come from the wind turbine block set. The simulation results show the modest improvements in the performance of the algorithm. The power output of a turbine is determined by the area of the rotor blades, wind speed and the power coefficient. The output power of the turbine can be varied by changing the area and flow conditions at the rotor system and this forms the basis of the control system. C_p (power coefficient), (value of efficient), this is the amount of wind captured by the wind turbine which is achieved at a particular λ *(*the angle tilt of the rotor), which is specific to the design of the turbine. The wind turbine simulation parameters are shown in table 1.

Table 1: Wind Turbine Simulation Requirements

Type description	1speedgenerator, watercooled
Annual average wind speed 8.5 m/s	8.5 m/s
Wind shear 0.20	0.2
Extreme wind speed	42.5 m/s (10 min. average)
Survival wind speed 59.5 m/s (3 sec. average)	59.5 m/s (3 sec. average)
Automatic stop limit 20 m/s (10 min. average)	20 m/s (10 min. average)
Re-cut in 18 m/s (10 min. average)	18 m/s (10 min. average)
Characteristic turbulence intensity	16% (including wind farmturbulence)
Maximum in-flow angle	8°
Rated power	1650 kW
Apparent power	1808 kVA
Rated current IN	1740 A
Max power at Class F PFma	1815 kW
Max current at Class F IFmax	1914 A
No load current	430 A
Reactive power consumption at rated power (tolerance. acc to IEC 60034-1)	740 kvar
Reactive power consumption at no load (tolerance. acc to IEC 60034-1)	447 kvar
Number of poles P	6
Synchronous rotation speed n_o	1200 rpm
Rotation speed at rated power N_n	1214 rpm
Slip at rated power N_s	0.0117
Voltage U_s	3 x 600 V
Frequency F	50 Hz
Coupling	Δ
Enclosure	IP54
Insulation class/ Temperature increase	F/B

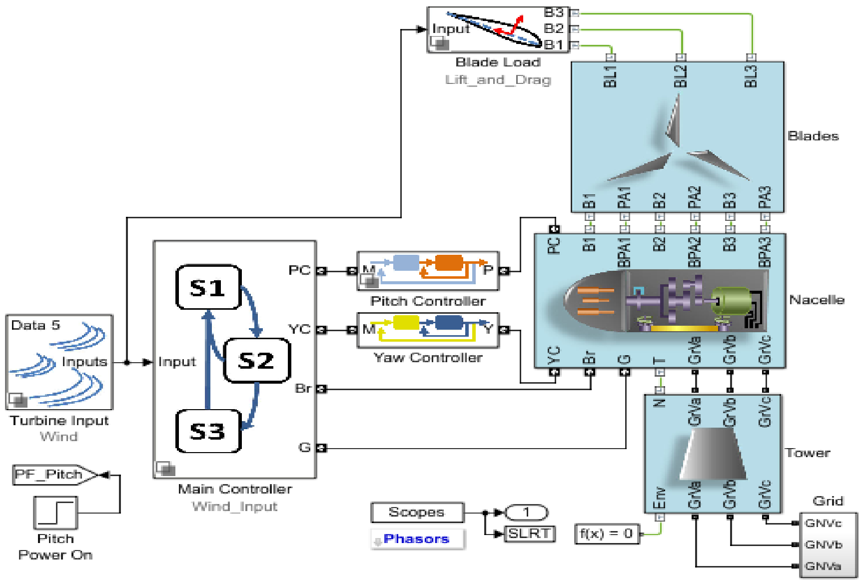


Figure 7a: Simulink Model of the HAWT without Diffuser and Simulation Block Diagram.

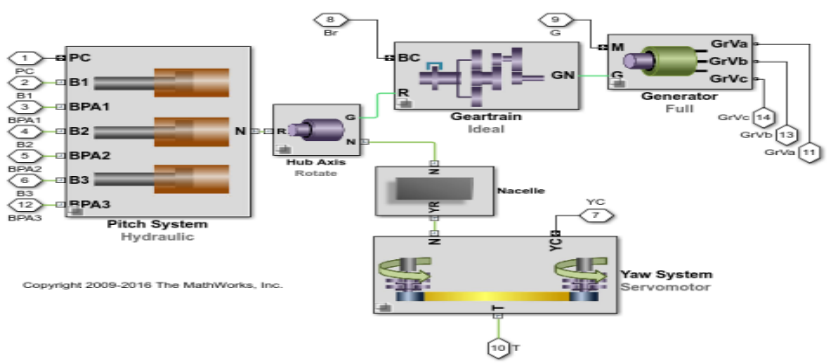


Figure 7b: Subsystem for Pitch and Yaw Controllers

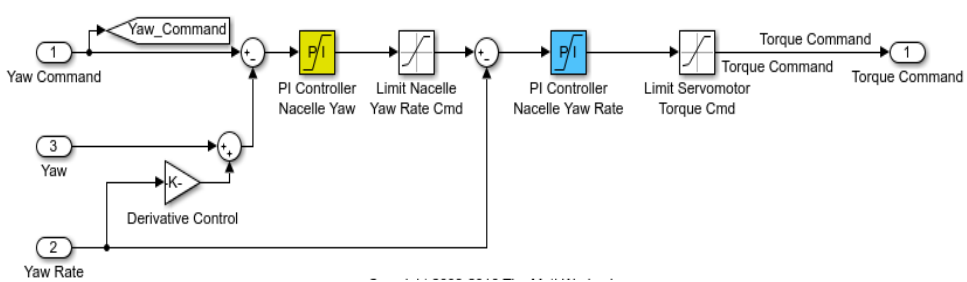


Figure 7c: Subsystem Showing PI Controller

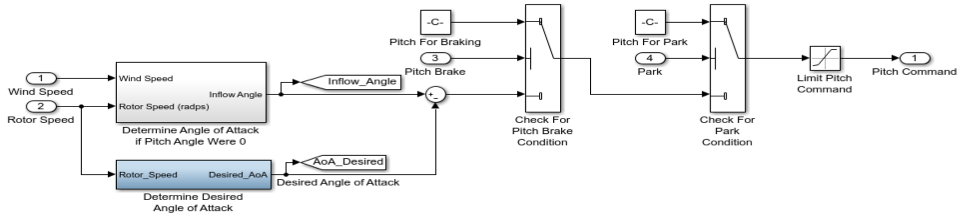


Figure 7d: Subsystem Showing the Pitch Command Control

It would also be interesting to develop a control system that adjusts the turbine, changes the angle of attack of the blade (pitch control) with changes in the wind power to control the power generated. Yaw control, generator torque and blade pitch strategies are used in the simulation model to shed excess power and limit the turbine's energy capture as well as to achieve other control objectives.

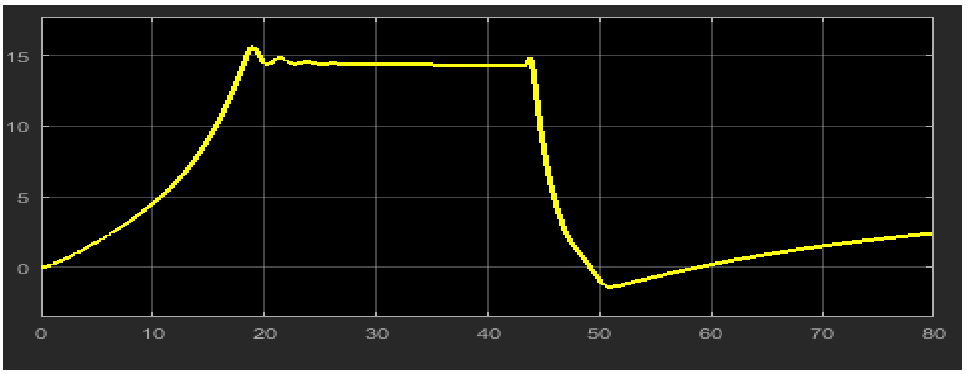


Figure 8a: Rotor Speed (RPM) (1,500)

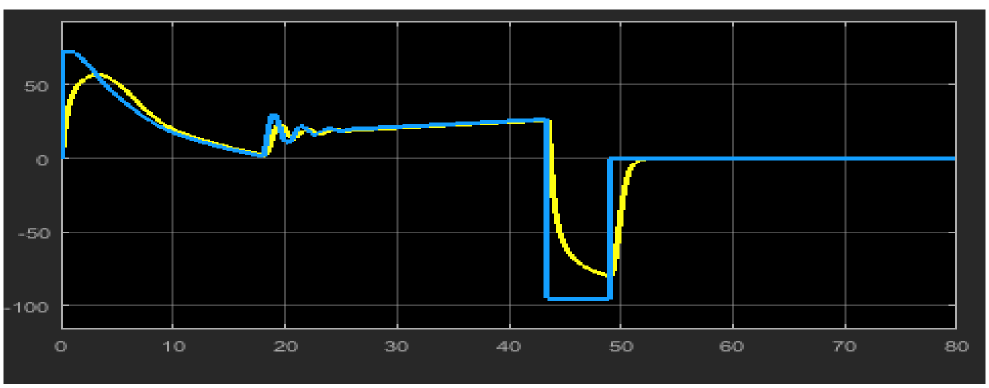


Figure 8b: Pitch Command and Angle

The maximum achievable power coefficient is 59.26 percent -- the Betz Limit. In practice however, obtainable values of the power coefficient center around 45 percent. This value that is below the theoretical limit is caused by the inefficiencies and losses attributed to different configurations, rotor blades profiles, finite wings, friction, and turbine designs. Maximum power extraction occurs at the optimal Tip Speed Ratio (TSR), where the difference between the actual TSR (blue curve) and the line defined by a constant TSR is the lowest. This difference represents the power in the wind that is not captured by the wind turbine. Tip Speed Ratio (Λ) for wind turbines - Tip speed ratio refers to the ratio between the wind speed and the speed of the tips of the wind turbine blades (figures 8a,b).

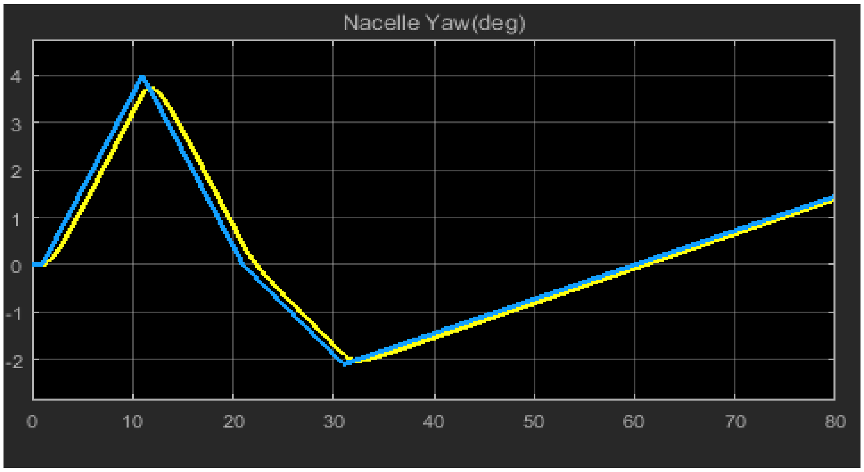


Figure 9: Nacelle Yaw Control Signals**.**

Figure 9 shows how Nacelle Yaw control signals operate; the power captured increases with wind speed till some value is attained and after that it decreases. The control system which is placed in the nacelle of the wind turbine provide safety for the turbine

3.1 The Incompressible and Steady Flow Simulation Graph

The graph of figure 10 shows the various diffuser angles (x - axis) and their corresponding wind energy conversion and power output in kilowatts (y–axis). The diffuser angles considered are 4^0 , 8^0 , 12^0 , 16^0 and 20^0 and it was noticed that the energy conversion started at a certain angle of about 4^0 and kept increasing until the angle of about 20^0 and it started decreasing as can be seen from the power output values of the graph.

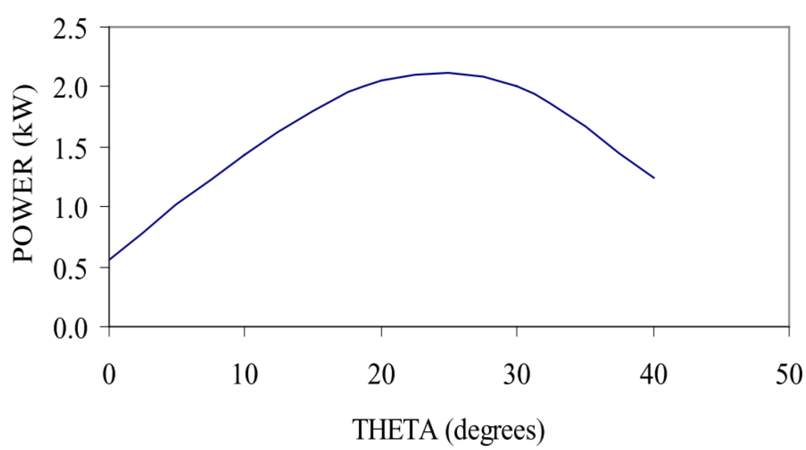


Figure 10: Showing the Effect of Increasing the Diffuser Angles

As the angles are increased the power output of the turbine also increases until it get to 20^0 then it begins to decline. Table 2 shows the maximized power captured in the wind turbine using diffuser augmented system at different angles. The table corresponds with the results from the graph. The angles of various diffusers were considered (diffuser opening angles, Dm). Wind velocity at the diffuser entrance (m/s) was also considered. Percentage increment of each angle was considered as well. It was discovered that as the velocity of the wind that flows through the diffuser increases, the speed of the wind turbine blade connected through a shaft to the gear box arrangement increases and with the aid of the gear transformation, the shaft connected from the gear box to the generator increases its speed thereby increasing the output of electricity generated.

Table 2: The effect of Diffuser Opening Angles, Wind Velocity at Entrance (m/s), % increment (initial velocity) (6m/s) and Power Output (kw)

Diffuser opening angles	4^0	8^0	12^0	16	20^0
Wind velocity at entrance (m/s)	7.2	7.38	7.62	7.92	8.22
% increment (initial velocity (6m/s)	20%	23%	27%	32%	38%
Power output (kw)	$1.115e^5$	$1.1201e^5$	$1.1345e^5$	$1.285e^5$	$1.328e^5$

From table 2, the wind velocity at diffuser inlet is proportional to the open angle. Diffuser with open angle 12° is seen to have high increment of wind velocity with economic recommendation because of low pressure inside the diffuser. Diffuser with open angles of 16^0 and 20^0 registered high increment. Diffuser with open angle α of 4° happens to have little decrement of 0.06%. It is assumed that the higher the open angle the greater the wind velocity.

Conclusion

A diffuser augmented wind turbine (DAWT) with a particular consideration of some of the design parameters has been modeled and simulated. The turbine operation exhibits a reasonable range of tip speed ratio and high efficiency. The proposed method suggests that an increase in C_P of 0.035 which is about 27%, for open angle of 12^0, 32% for open angle of 16^0 and 38% for open angle of 20^0, increase in aerodynamic efficiencies were attainable with the DAWT concept. This improvement is primarily due to efficient extraction of energy (wind) blowing near the hub of the main rotor, but in part also due to the addition of another energy extracting device -- the diffuser augmented system. Calculation of the developed model showed the possibility of a significant increase in the power and efficiency of a modernized turbine (diffuser augmented wind turbine) in comparison with a classical turbine (bare wind turbine). It is shown that the proposed modernization of the turbine increases the wind capture by 27%, 32% and 38%.

To verify the performance of the DAWT, the simulation results have been demonstrated on the virtual platform of Matlab/Simulink. A remarkable 7.62 m/s wind velocity with 27% augmentation was obtained using a 12^0 diffuser opening angle, 32% for open angle of 16^0 and 38% for open angle of 20^0. Similarly a remarkable power output of $1.328e^5$ kw was obtained at 20^0 opening angle. It was discovered that at 20^0 opening angle, the power output reaches the peak, however it is not economical to recommend a diffuser with an open angle of 20^0 because the cost is very high and is not proportional to captured power (power output). This is because the splitter, flange, separators needed to suspend the diffuser and other materials involved in maintaining a diffuser augmented system at this angle are very high. Once the angle of the diffuser is a little above 20^0, the diffuser angle tilt can no longer be capable of allowing air in. In this case, the wind will only hit the body of the diffuser and cannot produce any output.

Recommendations for Future Work

Further work is necessary to optimize the diffuser design in terms of power coefficients by considering momentum transfer to the turbine blade. Further development of the model must be done by spreading it onto a two-disk and multi-jet model needed to consider simulating the diffuser effect and the wind turbine model using the same software in order to improve efficiency.

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