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A systematic comparison among different passive flow control strategies to enhance the aerodynamic performance of wind turbines

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Abstract

The world is facing an energy crisis as the sources of conventional energy are being depleted at an alarming rate. To meet this rapid energy demand, wind turbines have the potential to play a vital role. To harness the maximum power from wind energy in countries like Bangladesh, where the wind speed is very low, conventional wind turbines can be modified in several ways to maximize performance. These include active method, passive method or changing the shape of the turbine airfoil to create more turbulence flow, incorporation of flow augmentation device, various blade optimization strategies and biomimetic (inspired by nature) approach. The aim of this research is to provide a comparative analysis among different passive flow control strategies and find out the best possible turbine modification for low wind-speed regions like Bangladesh. Vortex Generators (VGs) have the potential to increase the power coefficient by 13% in a wind turbine, offering one of the highest power improvements among different passive control strategies. Gurney flaps, strategically placed at the trailing edge, have further demonstrated their capability to improve power coefficient by 21.32%. This comparative analysis will be beneficial for the researchers to select the best modification or best sets of modifications to conventional turbines to maximize their performance in low wind-speed regions.

Keywords: Wind Turbines, Passive Flow Control, Vortex Generator, Gurney Flaps, Power Coefficient.

1. Introduction

The urgent need for the cleanest form of energy is increasing to reduce the higher dependency on the polluted conventional resources of energy. The world is heavily dependent on conventional sources of energy, like (fossil fuels) coal, natural gas, and oil, which are being diminished due to the huge demand for energy consumption. At our current global rate of energy consumption and production, there are hardly any conventional sources of energy that will last us only a few decades or a century [1]. Renewable sources of energy like solar, wind, hydro, bioenergy, and geothermal energy are the most environmentally friendly and more sustainable. Wind turbines have the huge potential to make the proper use of this renewable source of energy. Bangladesh experiences low to moderate wind speeds due to the tropical monsoon climate. Coastal microsites like Charfashion and Monpura in Bangladesh offer promising wind speeds reaching 7.3 m/s at 100 m above ground level, making them potential sites for wind energy production. [2]. Since the output power of a wind turbine is proportional to the cube of wind speed, turbine performance enhancement is needed to harness the maximum power from wind energy in lower wind speed regions like Bangladesh. There are many performance enhancement methods to maximize the energy output from the turbines, including the optimization method, passive method, and active method. The optimization method includes optimized aerodynamic designs to enhance the power output of a turbine. Passive methods include geometrical shaping and grooving or using fixed mechanical structures, incorporating flow augmentation devices to control pressure gradients for enhancing the aerodynamic performance and control the flow [3]. The active method employs sensors and microprocessors distribution along the turbine blades to capture the local variations in the flow conditions and the related blade loading and apply integrated control algorithms by processing the sensor output to enhance system response [4].

The discovery of different passive control strategies, i.e., Vortex generators (VG), Gurney flaps (GF), Tubercles, Sinusoidal leading edge, and so on, has become a matter of concern to the researchers to compare the power outputs of each modification in wind turbines. A study investigated the output torque of a wind turbine with VGs raised by 3.73%, 8.74%, and 10.82% at wind speeds of 10, 13, and 15 m/s, respectively [5]. Another research study found that, the power coefficient was increased by 21.3% at (Tip-Speed Ratio) TSR = 2.4, when the GF was applied on the inner side of the airfoils [6]. In addition to these studies, there is no systematic, up-to-date review of all the passive control strategies of a wind turbine. Overall, the objective of this study is to make a

comparative review of different passive control strategies that will enhance the aerodynamic performance of a wind turbine and to find out the most effective one for wind turbine applications.

2. Factors affecting the aerodynamic performance of a wind turbine

There are a lot of factors that affect the overall aerodynamic performance of a wind turbine, such as turbine blade length, number of blades, wind speed, temperature, turbine swept area, density of air, and height of the tower. The factors that significantly affect the aerodynamic performance of the wind turbines are briefly discussed as follows:

Wind speed: The output aerodynamic performance of a wind turbine increases with the increase in wind speed. Due to some wind speed loss in the turbine blades, the theoretical total power from the wind energy cannot be extracted. The mechanical power $P(KW)$ that can be extracted from the wind turbine is calculated from the following equations:

$$P = C_p P_{wind} \tag{1}$$

That means,

$$P = \frac{1}{2} C_p \rho A v^3 \tag{2}$$

Where, C_p defines the Power coefficient of a wind turbine, $A(m^2)$ defines the air swept area by the turbine, $\rho(kg/m^3)$ defines the density of air, $v\ (m/s)$ defines the wind speed. [7]

From the equation (2), the power extracted from the wind has a cubic proportionality with wind speed. Fig. 1(a) highlights the power output till the saturation level along different wind speeds. The air speed increases rapidly with the increase in the tower height of a wind turbine.

Turbine swept area: From equation (2), it is conceded that the power output is directly proportional to the swept area. The increase in this area certainly increases the aerodynamic performance of a turbine.

Density of air: Density of air ρ is one of the most crucial factors which affects the power output of a wind turbine. The higher the density the higher the power generation which can be seen in the Fig. 1(c). According to the gas laws $'\rho'$ depends on the pressure and temperature of air .[7]

$$\rho = \frac{p}{RT} \tag{3}$$

Temperature: From the equation (3) it can be said that density is inversely proportional to temperature. Fig. 1(b) demonstrates the power output at different temperatures. That's why the power output for a wind turbine at a given wind speed decreases when the temperature is increased [7].

Blade length and Number of Blades: The blade has direct contact with the wind. That's why it is one of the most important components of a wind turbine. To utilize the wind turbine properly, the aerodynamic performance of the blades must be increased. The blade length must be optimal to tolerate the ultimate strength developed.

The aerodynamic performance increases with the increase in number of blades of a wind turbine. For the Horizontal axis wind turbine, the optimal number of blades is three. But in small scale wind turbines, the optimal number of blades is two. [8]

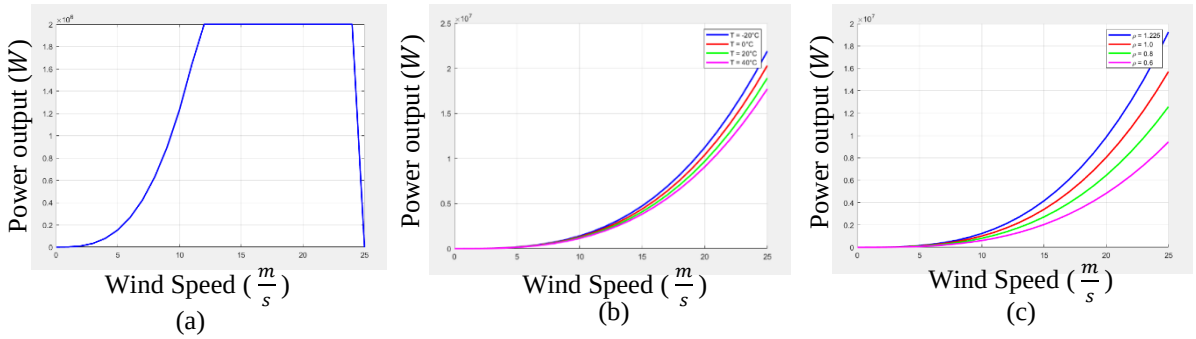


Fig. 1. Wind turbine power output across different wind speeds (a) to the saturation level, (b) at different temperatures and (c) at different densities of air.

3. Different Passive Flow Control Technics

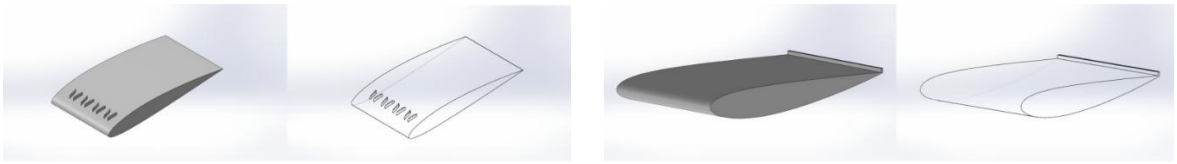
Vortex Generator

The vortex generator is a small aerodynamic device which is attached to the surface of the wind turbine blade. It was first promoted and applied to the aircraft wings by Taylor in the middle of the last century [9]. A VG can transfer the momentum from the flow outside the boundary layer into it, which increases the momentum [10].

Vortex generators have been used successfully in many aeronautical applications for the reduction of separation in both internal and external flows. An experiment showed that in wind turbine blade, without VG, the coefficient of lift was 0.3269 and with VG, the coefficient of lift is 0.4539 [11]. Fig. 2(a) demonstrates a VG.

Gurney Flaps

Gurney flaps (GF) are passive devices used to enhance lift, consisting of a small plate located at the trailing edge perpendicular to the trailing edge of the airfoil. GF was developed and applied to race cars by Robert Liebeck and Dan Gurney in the 1960s [12]. Fig. 2(b) shows the diagram of GF in airfoil. GF is a configuration for effectively increasing airfoils' lift coefficient. GFs can distinctly raise the lift coefficient by increasing the equivalent back camber of airfoils and delaying the flow separation on suction surfaces [13]. An experiment showed that for SB-VAWT, the best configuration of GF can improve the overall power coefficient up to 21.32% [14].



(a) (b)

Fig. 2. (a) Vortex Generator (b) Gurney Flaps

Sinusoidal Leading Edge

A sinusoidal leading edge is a curve shape applied to the leading edge of a wind turbine blade to improve its aerodynamic performance and power efficiency. The main mechanisms of the leading-edge protuberances effective are focused on two aspects. Firstly, one mechanism is the zoning effect, which is like the function of a wing fence. Additionally, the protuberances act as VGs, producing vortices along the flow direction [15].
Computational investigations were performed and protrusions in the leading edge of the NACA 4415 airfoil were incorporated as a passive flow control measure on the wind turbine blades. This experiment resulted in 8.2% more power coefficient by using sinusoidal leading edge method [16]. Fig 3(a) shows a sinusoidal leading edge diagram.

Tubercles

Tubercles on wind turbine blades can improve the performance of the turbine by reducing flow separation, increasing lift, decreasing drag and reducing noise. The effect of using tubercles on wind turbine blades has been studied physically and numerically. The first and all other research performed, either physically or numerically, and considered Reynolds number of the order of $R_e = 10^5$ had almost similar results [17]. The tubercle affects the airfoil of the wind turbine by channeling flow over the airfoil into more narrow streams, creating higher velocities. Fig. 3(b) shows the diagram of tubercles in airfoil.



(a) (b)

Fig. 3. (a) Sinusoidal Leading Edge (b) Tubercles

Slots

The slotted airfoil of a wind turbine exhibits superior aerodynamic performance over moderate-to-high angles of attack ($\alpha > 6°$), with increased lift and enhanced glide ratio of up to 1.3×, 0.5×, and 3.7× respectively, compared to the baseline. [18]. The slotted airfoil was initially introduced by Handley Page (Inventor and Parker, 1920) in Britain and Lachmann in Germany but the first detailed study was performed by Weick (1933) [19]. The performance of a wind turbine with slotted blades can decrease if the slotted gap is too wide [20].

Split Winglet

A split winglet on a wind turbine blade is designed to reduce backflow at the tip of the blade and improve the turbine's performance. Winglets (WLs) have recently been used to improve the performance of HAWT. The WL geometry is a key parameter for diverging blade tip vortices away from turbine blades and reducing drag [21]. Fig. 4 shows the diagram of a split winglet in the airfoil.
Improving the aerodynamic performance of HAWTs is important and it is done by many passive control methods, among them, split winglet is one type of method. The primary purpose of a winglet on a wind turbine blade is to reduce the impact of wingtip vortices, which are a major source of induced drag and a reduction in lift force [22].



Fig. 4. Split Winglet

4. Recent Research on Different Passive Flow Control Technics

Table 1. provides a detailed overview of passive control methods applied to both Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). It highlights the modifications made to the wind turbine for better performance enhancements. Depending on the modifications, the efficiency gain can be 3-4% to up to 46% for tubercles. These passive control methods can play a vital role in optimizing energy capture and improving overall performance in a wind turbine. For example, the application of Gurney Flaps in a VAWT using the NACA 0021 airfoil resulted in a 17.92% increase in C_p while Vortex Generators improved C_p up to 13%. The use of Tubercles on wind turbine blades also showed an increase of C_p by 28%.

Table 1. Recent research on performance enhancement of wind turbines using passive flow control methods.

Published Year	**Passive Control Method**	**Turbine Type**	**Airfoil Type**	**Modification**	**Performance After Modification**	**Reference**
July 2023	Vortex Generator	SB-VAWT	NACA 0015	• Triangular High-Efficiency Vortex variation	• Highest power coefficient value experienced an increase of 13%.	[23]
January 2022	Vortex Generator	SB-VAWT	S809	• The Inverse blade element moment (IBEM) method is used to obtain the local angle of attack. • Relative velocity of the wind turbine blade.	• The output torques of the wind turbine with VGs are raised by 3.73%, 8.74% and 10.82% at 10, 13 and 15 m/s respectively.	[5]
March 2019	Gurney Flap	SB-VAWT	NACA0021	• The inboard, outboard, two-side Gurney flap (GF) and dimple-GF are applied in SB-VAWT	• Can increase the maximum power coefficient by 17.92%	[24]
March 2021	Gurney Flap	SB-VAWT	NACA0012, NACA0018	• The 0.75%-chord-length height is most appropriate for the straight-bladed VAWT	• An improvement of 21.32% in power coefficient was obtained	[25]
February 2023	Sinusoidal Leading Edge	HAWT	NACA 4415	• Protrusions in the leading edge of the NACA 4415 airfoil were incorporated.	• Exhibit 8.2% more power coefficient.	[16]
May 2016	Sinusoidal Leading Edge	HAWT	NACA 634-021	• To improve the aerodynamic performance of the HAWT, the sinusoidal shape is applied to the turbine blade.	• At (v = 6 m/s), two different models have averagely 17.5 % and 13.3 % higher power coefficients than the baseline model.	[26]
October 2022	Tubercles	VAWT	NACA0018	• The leading-edge geometry was	• The power coefficient increase was between 46% and 20% for wind	[27]

				subsequently tested in the wind tunnel.	velocities ranging from 5.5 m/s to 9 m/s, respectively.	
August 2022	Tubercles	VAWT	NACA 4412	• Four tubercle configurations on VAWT blades.	• showing a 28% increase in the C_P of VAWT.	[28]
July 2023	Slots	NREL Phase VI wind turbine	NACA 4412, NACA 63(4)-021	• The slot is engraved on the mid-chord region of the turbine blade.	• 21% increment in annual energy production.	[29]
January 2020	Slots	VAWT	NACA 0018	• The flow over the turbine was modeled using the ANSYS-FLUENT code.	• At TSR=2, the SA turbine calculated C_p= 0.3 which is approximately 3 times that of the BL turbine.	[30]
November 2020	Split Winglet	HAWT	NACA 4412, S809	• The effects of the radial position of a split are investigated using CFD simulation.	• The power generated by all the split blades at any TSR<3.5 is higher than the No-split blade.	[31]
Jun 2024	Split Winglet	HAWT	NACA 4418	• Investigated different pitch angles and TSR • Keeping a cant angle of 50° and a split-tip height equivalent to 6% of the rotor radius	• When the pitch angle was set at 0°, the symmetrical split tips exhibited an average torque increase of 9.61% • Asymmetrical split tips showed a torque increase of 6.95%.	[32]

5. Recommendation and Challenges

Based on the research, Tubercles and GF would be the best passive flow control method for Bangladesh. Both methods proved their ability to enhance lift, delaying the flow separation and increasing power output. Bangladesh is situated in coastal and rural regions. So, these methods can be both low cost and applicable to horizontal and vertical axis wind turbines. Fig. 5 represents the performance reflection of Table 1.
But there will also be some challenges. Among them, maintenance and lacking technical expertise can be vital. The wind conditions can also be a problem in Bangladesh as there are fluctuations in wind speed. However, by focusing on adoptable methods, Bangladesh can improve its renewable energy infrastructure and ensure more efficient energy production. Though Tubercles have the potential to increase the power output effectively in low wind speed regions, but the implementation of this method would be difficult for Bangladesh compared to GFs.

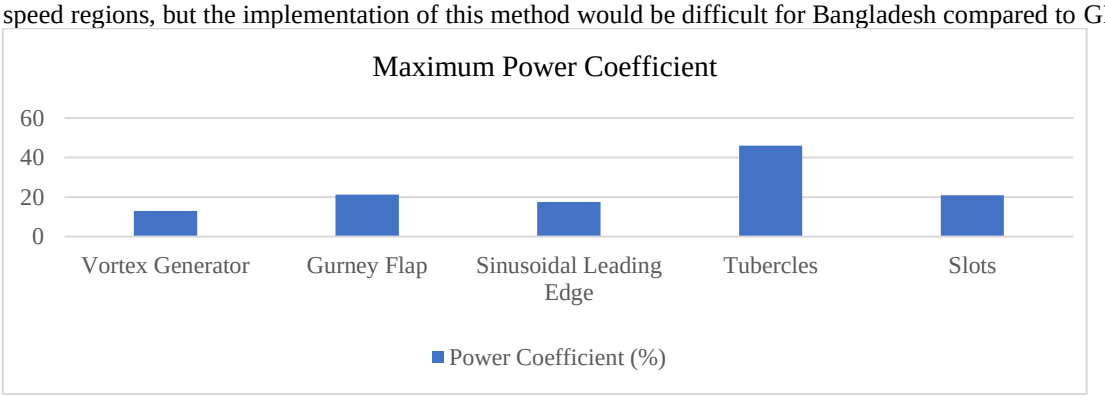


Fig. 5. Increase of power coefficient by passive control methods

6. Conclusion

This study examines different passive control methods and their comparison in increasing the aerodynamic performance of a wind turbine. Six different passive control methods were compared to find out the best modification for a wind turbine. The study started by analyzing several factors that affect the aerodynamic performance of a wind turbine, including wind speed, temperature, number of blades, swept area, blade length and air density. The requirement of performance enhancement leads us towards different passive control strategies including vortex generators, gurney flaps, sinusoidal leading edge, tubercles, slots, and split winglets. VG and GF demonstrated their potential of increasing the performance of a wind turbine effectively for Bangladesh perspective. The application of Gurney Flaps in a VAWT increase the C_p by 17.92%. The use of Vortex Generators improved torque by up to 10.82% and an increase of C_p of 13%. The other performance enhancement methods such as tubercles, sinusoidal leading edge, slots, and split winglets have shown significant potential in improving the aerodynamic performance of a wind turbine. For example, the use of Tubercles on wind turbine blades also showed an increase of C_p of 28%. However, these methods need further research and development to remove the implementation complexities in an infrastructure-limited country like Bangladesh.

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