

Effect of Winglets on Improving Wind Turbine Performance

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Abstract – Indonesia, with the longest coastline in the world, has enormous potential to develop large-scale wind energy. In wind turbines, the formation of a wake behind the wind turbine can reduce efficiency. It is estimated that the formation of a vortex tip behind the wind turbine blade can be reduced by adding a winglet. The main function of winglets attached to the blade is to reduce the effect of the wingtip vortices which are generated due to 3D spanwise flow that occurs because of the pressure non-equalization between the upper and lower blade surfaces. This paper aims to summarize the results of research on the effect of adding winglets to wind turbines.

Keywords – wind turbine, winglet, tip vortices, alternative energy, wake

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1. Introduction

Energy supply in the future is a problem that must be concerned by all nations because the quality of human life is closely related to the quantity and quality of energy used. In line with the increase in development, especially development in the industrial sector, population and economic growth, energy demand will continue to increase.

The main energy source used in the world, including in Indonesia, is fossil energy. In the electricity sector, in Indonesia the installed capacity of power plants in 2018 mostly came from fossil energy generation, especially coal (50%), followed by natural gas (29%), fuel (7%) and renewable energy (14%)[1].

Power plants fueled by fossil energy cause problems, including pollution caused by coal fly ash, sulfur dioxide gas (SO₂) and greenhouse gases such as carbon dioxide (CO₂). The limitations of fossil energy in nature and price fluctuations often cause problems in the economic and political fields. Therefore, exploration of cheap, efficient and environmentally friendly renewable energy sources such as geothermal, solar and wind must be carried out more massively. There are still many potentials for renewable energy that have not been utilized because the price is not yet competitive compared to fossil energy. This is because technology has not been mastered and there is no government policy that encourages the development of renewable energy.

Among renewable energies, the development of wind energy in the world is quite fast due to its large potential and easy technology [2]. In addition, the required cost has also decreased and is currently at 0.03US \$ / kWh, even in Mexico it has reached 17.7US \$ / MWh [3]. Based on the REN 21 report in Renewables 2019 Status Report, the capacity of renewable energy in the world in 2018 is 2378 GW, which consists of water, wind, solar, geothermal, sea water, etc. The installed wind energy capacity is 591 GW or about 25% of the total installed energy capacity [4]. Meanwhile in Indonesia, the installed wind energy capacity has only reached 60.6 GW [1].

Indonesia, with the longest coastline in the world, has enormous potential to develop large-scale wind energy. The average wind speed that has the potential to be developed is above 4.16 m/s. The average wind speed in the coastal area is quite large, especially in the south of the equator ranging from 8 - 10 m/s or the potential wind energy on average between 300-400 W/m². Even around The Indian and Arafuru seas have wind speeds of up to 600 W/m² [5].

In wind turbines, the formation of a wake behind the wind turbine can reduce efficiency. It is estimated that the formation of a vortex tip behind the wind turbine blade can be reduced by adding a winglet. This paper aims to summarize the results of research on the effect of adding winglets to wind turbines.

2. Wind Turbine Performance

The wind speeds in different regions of the earth are not the same. Geographical location and conditions greatly affect the wind speed in an area, the higher the place, the higher the wind speed and the lower the turbulence. Therefore, to get the greatest wind energy, the wind turbine must be placed in a place that has the largest wind speed with a small level of turbulence. The amount of wind energy available in the wind can be formulated as below :

$$P_a = \frac{1}{2} \rho A v^3 \quad (1)$$

where ρ : density, A : swept area of the rotor and v : speed. Equation 1 is the theoretical power, while the actual power still has to be multiplied by the turbine efficiency which is usually called the C_p (coefficient of performance).

$$C_p = \frac{P_m}{P_a} \quad (2)$$

Where P_m is mechanical power and P_a is wind power. The maximum work efficiency or often called the Betz limit is 0.593. There has been a lot of research on wind turbines. The final goal to be achieved is to produce a wind turbine design that provides the highest C_p at low cost and is easy to manufacture and maintain [6]. Optimization of wind turbine aerodynamic performance depends on many things such as the number of blades, solidity, blade angle, angle between curved lines and rotating plane, etc. Many aspects in blade design affect wind turbine efficiency, including:

- Tip speed ratio
Tip speed ratio is the ratio of wind speed to blade tip speed. Tip speed ratio determines the width of the blade, the higher the tip speed ratio is chosen, then theoretically based on the momentum theory of the blade element, the C_p will be higher [7] and the blade will be slimmer and thinner.
- Shape of airfoil
An important criterion in selecting an airfoil is the ratio of the lift coefficient to drag (C_l / C_d), the greater the C_l / C_d , the better the rotor's performance. The choice of airfoil type is usually based on the Reynolds number. As average wind speeds in Indonesia are mostly not very high, the Reynolds number for wind turbine applications is usually low. For low Reynolds number (around 4000) the best performing airfoil characteristic is thin, sharp leading edge and about 5% curvature in the center [8].
- Number of blade
Based on the blade element momentum theory, each blade will provide additional power, but this addition is not linear. If the wind turbine is designed at a low tip speed ratio, the addition of the blade will increase the C_p . The initial torque is also better so that the turbine rotates easily at low wind speeds, but the increase in the number of blades also increases the rotor weight and

investment costs, especially for large-scale wind turbines.

- Blade geometry
The shape of the blade that provides optimal performance is hyperbolic, but for the sake of ease of manufacture it is often used a trapezoidal shape. Meanwhile, the thickness of the blade is greatly influenced by its strength to overcome external forces.
- Solidity
Blade solidity is the ratio between the area of the rotor blade with the swept area of the blade. Blade solidity will decrease with an increase in tip speed ratio. Solidity greatly affects the weight and cost of the rotor, aerodynamically, solidity should be as small as possible to minimize drag, but also must be able to withstand external forces. Based on numerical calculation, C_p will increase with increasing solidity [9][10].

3. Wind Turbine Wake and Winglet

The component that converts wind energy into mechanical energy is the rotor. The more optimal the rotor absorbs wind energy, then the energy produced is greater. In the rotor, the flow that occurs in the blades is a three-dimensional flow which results in a vortex tip at the end of the wind turbine blade. The formation of this vortex tip requires energy, as a result the energy generated by the wind turbine will be reduced. The energy transfer from the blade to the air is called induced drag, the amount of induced drag is inversely proportional to the square of the velocity. At high speeds the induced drag is small and at low speeds the induced drag is large [11].

Wind turbines are expected to reduce the induced drag, thereby increasing the energy produced. Theoretically based on the momentum theory of the blade element C_p , the maximum that can be achieved is 0.593, but in reality the C_p will be smaller, this is because the blade element momentum theory does not take into account the energy loss due to the wake. The wake behind the wind turbine is more complex than the wake behind the cylinder or disc, because the wind turbine also launches the vortex and root vortex tips [12]. Root vortices combine to form a single vortex at the center of the wake in the opposite direction to the rotation of the rotor.

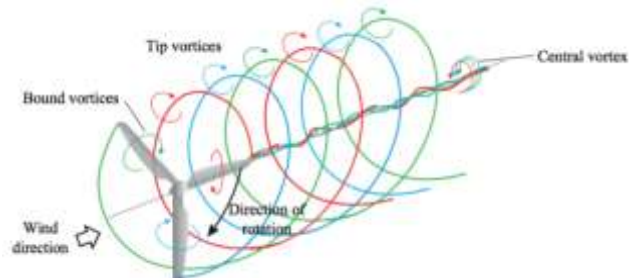
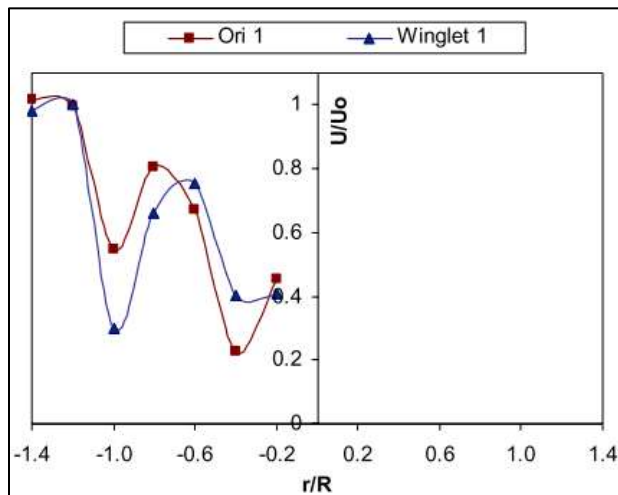


Figure 1. The formation of wind turbine vortex [13]

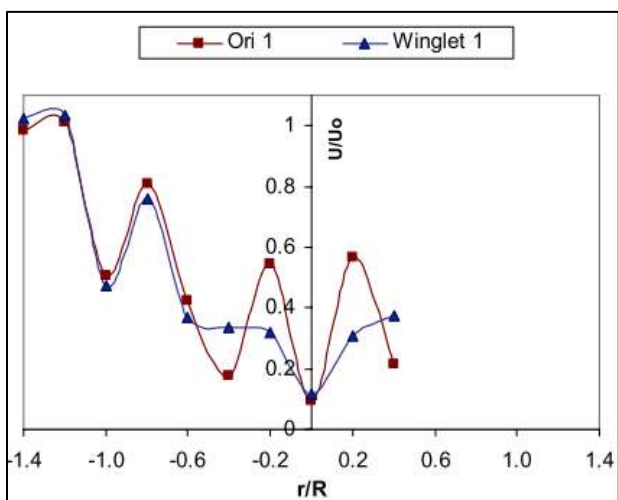
The existence of a vortex tip in the wind turbine rotor can also be seen from the visualization in the open jet wind tunnel in a study conducted by Vermeer (2001) using

a rotor model that has a radius of 0.6 m. In wind turbines, the formation of tip vortices reduces power which are often called blade tip losses. The greater the number of blades, the greater the blade tip losses [6].

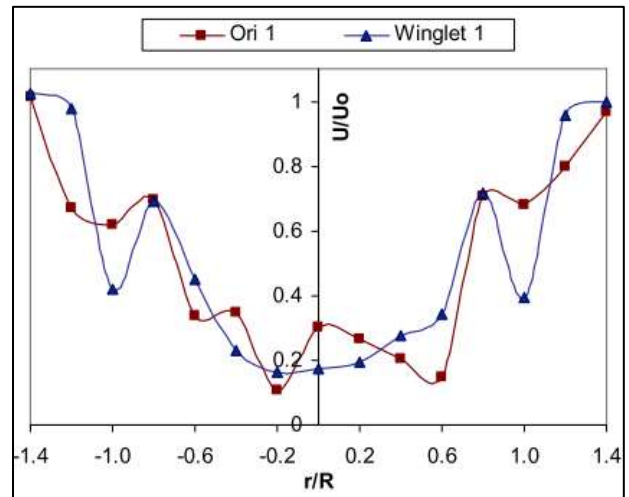
The existence of a vortex tip on the wind turbine blade is also evident from the research conducted by Handayani (2008) by measuring the velocity distribution of the flow behind the wind turbine using a five hole probe. From the measurement of the speed behind the wind turbine, it can be seen that there is a decrease in speed at the point $r/R = 1$, this velocity reduction decreased with increasing axial distance (Figure 2). The probe likely reaches the region within the tip vortex, resulting in a decrease in velocity. This can be explained by the vortex stretching as the wake expands. The power per unit length remains constant, but the diameter of the vortex spiral grows larger, resulting in a reduction in circulation per unit volume. The reduction ends in $Z/D=1$ for rotor model without winglet. [14].



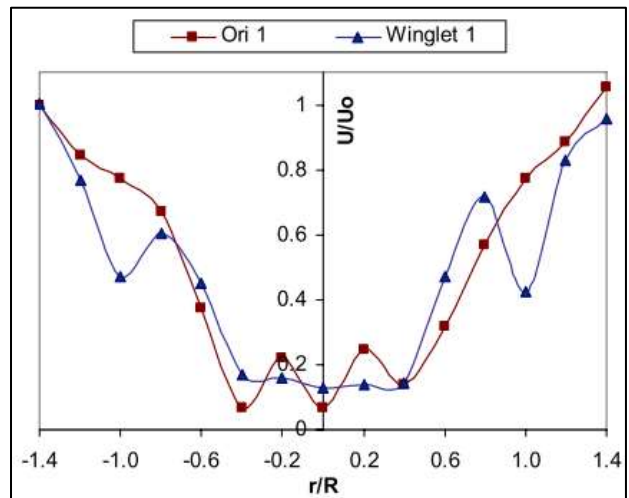
a. $Z/D=0,125$



b. $Z/D=0,25$



c. $Z/D=0,5$



d. $Z/D=1$

Figure 2. Axial velocity distribution behind wind turbine rotor[14]

Medici (2005) examined the wake in wind turbines and compared the theoretical CP and Cp achieved from a wind turbine with two blades with a diameter of 0.18. The results show that by minimizing the tip vortex loss and stall on the blade root, the maximum Cp will increase.

In aircraft the winglets at the wing tips are expected to produce a velocity field that interacts with the wing velocity field to reduce the amount of span wise flow. The addition of a winglet to the wind turbine blade can also have the same effect because in principle the wind turbine rotor is a rotated airplane wing. Johansen and Sorensen (2006) examined the numerical effect of winglet aerodynamics on wind turbines. The results show that there is an increase in power and thrust on blades with winglets at various speeds [15]. Adding a winglet to the wind turbine blade can give an increase of Cp, especially at speeds below 5 m/s [11].

In the numerical simulation conducted on a horizontal shaft wind turbine equipped with a winglet with a length of 1% to 7% at a 15° to 90° cant angle. The best

performance increase was 8.787% on a winglet with a length of 6.32. % and cant angle of 48.3° [16]. The existence of winglets is proven to increase the coefficient of power and thrust. At the same cant angle, the longer the winglet, the coefficient of power and thrust [16].

The effect of winglets on the performance of horizontal shaft wind turbines was also studied numerically with CFD, using airfoil types S809 and PSU94-097 [17]. The wind turbine with a rectangular shape, a winglet length of 15 cm and a cant angle of 45° provides the best performance. The winglet design is influenced by the turbine operating conditions such as Reynold number, turbulence and flow separation.

The effect of winglet modification on small wind turbine modification also studied by Papadopoulos et.al by using CFD computation. The flow pattern over the wing tip changes significantly, the performance and torque generation are increase from 1,5% to 11%. Winglet with cant angle 45° either in positive or negative direction were give the best performance from another cant angle [18].

5. Conclusion

There are many factors regarding designing blades that affect the efficiency of the wind turbine ie TSR, airfoil section, number of blades, geometry and blade solidity. Wake formed behind the wind turbine can reduce efficiency. The addition of winglet on wind turbine blades can reduce the wake effect on the wind turbine and increase the wind turbine performance.

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