Experimental study of local pitch variations on electric power generated by counter rotating wind turbine with single generator without gearbox

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Abstract. Wind energy is one of the clean renewable energy that can be used as an alternative to reduce fossil fuel consumption. The aim of this research was to design and test the performance of counter-rotating wind turbine (CRWT) model corresponded with wind velocity and planned power output. The CRWT has two rotors with a diameter of 0.70 m comprised of NACA 4412 airfoils, which separated by axial distance of 0.3D and connected directly to each shaft of DC generator without a gearbox mechanism. In this research, local pitch (θp) of the rear rotor can be varied as followed (-10º, -5º, 0º, +5º and +10º). The data collection was done in a wind tunnel with a constant wind speed of 4 m/s, and given a load from bulb lamp started from 0 to 4.5 watt every 0.75 watts. The result shows that the local pitch +10º produced the highest rotation and electrical power generated. The highest electrical power generated at a local pitch +10º was at load 0.75 watt in amount of 1.057 watts or 23.55% higher than normal rotor (θp=0º). At the same load, the lowest electrical power generated was at the local pitch -10º which only produced 0.598 watts.

1. Introduction

Wind energy is one of the clean renewable energy that can be used as an alternative to reduce fossil fuel consumption. Utilization of wind energy is usually using a turbine or a windmill that functions to convert kinetic energy from wind into mechanical energy to rotate the electric generator. Research and technology of wind turbines also continue to develop according to location selection and wind characteristics. Counter Rotating Wind Turbine (CRWT) is one of the latest developments of horizontal axis wind turbines, consisting of two rotors (front rotor and rear rotor) which rotate in opposite directions on the same axis. Researchers found that Counter Rotating Wind Turbines (CRWT) could harness additional power, therefore increase overall power production. Appa [1] through his research explains that CRWT can extract an additional energy of 25% to 40% of the wind flow with the same sweeping area. Chantharasenawong [2] based on the axial momentum theory, an ideal dual wind turbine can convert wind energy up to 64%, or exceed the maximum power limit for a single rotor described in the momentum theory (Betz Limit) of 59.3%.

The wind turbine rotates by exploiting of wind kinetic energy which forces generated on the sections blades while the wind flows. The kind of forces are lifting force and dragging force. The lift force is
acting on the blade with the perpendicular direction of the wind flow, while the drag force is the force acting on the blade in the same direction of the wind flow. In general, horizontal turbines rotate by utilizing the lift force that arises on the rotor. To extract energy more efficiently, modern wind turbines use a blade in the form of airfoil.

\[ \theta_p \] is the local pitch of blade, the angle between the chord line and the rotation plane. The local pitch is a combination of pitch angle, \( \beta \) and twist of blade, \( \theta \), or can also be written \( \theta_p = \beta + \theta \), where the pitch angle is the angle between the end of chord and the plane of rotation. Rahmanlou [4] studied for optimization blades of horizontal wind turbines based on analytic methods leading to optimal torsion angle and hypotenuse length for each section of the turbine blade also founded that blades with NACA 4412 airfoil have the optimum power generation.

On a wind power plant, generator becomes one of the main components, as functions to convert mechanical energy into electrical energy. But in a fact found that a common failure of wind power plant is the neuralgic components such as gearbox and generator [5]. So, an idea to use a single generator and does not use a transmission system (gearbox) on Counter Rotating Wind Turbines (CRWT) becomes a solution to reduce construction and maintenance costs.

With an advanced of numerical studies, Lee [6] represented that the aerodynamic performance of counter-rotating wind turbine can be increased by combinations of the pitch angles, rotating speed ratio and radius differences of the two rotors. According to Buana et al [7] by numerical approach founded that CRWT with equal diameter size \( (D_1/D_2 = 1) \) produce maximum mechanical power. Irawan et al [8] also founded that CRWTs designed with close axial distance ranging 0.2 until 0.7 of the rotor diameter, produce higher mechanical power rather than longer axial distances.
2. Design of rotor
To calculate of rotor diameter is determined by the amount of power required to rotate the generator. Mathew [9] formulates the calculation of the rotor diameter using the equation:

\[ D = 2 \left[ \frac{2E_A}{\rho_s \cdot \eta_s \cdot \pi \cdot v_D^3} \right]^{1/2} \]  

(1)

With \( E_A \) [watt] power shaft design and \( v_D \) [m/s] wind velocity design.

The calculation of pitch angle (\( \beta \)) and chord length (\( c \)) depends on the distance \( r \) being determined, so it is generally expressed by the notations \( \beta(r) \) and \( c(r) \). Schmitz with the blade element theory momentum formulated [10]:

\[ \beta(r) = \arctan \left( \frac{2R}{3\lambda R} \right) - \alpha \]  

(2)

\[ c(r) = \frac{16\pi \cdot R^2}{9 \cdot \lambda^2 B} \]  

(3)

With \( \lambda \) tip speed ratio and \( B \) number of blade.

To reduce the size of the chord near the blade root (hub), the formula with the aim to reduce the production cost and because of this element was found to be less power contribution, then the linearization formula for the chord length of each element is formulated:

\[ c_i = c_{0.9R} - \left( \frac{c_{0.7R} - c_{0.9R}}{0.2R} \right) (r_i - 0.9R), \text{for } r_i > 0.9R \]  

(4)

\[ c_i = \left( \frac{c_{0.7R} - c_{0.9R}}{0.2R} \right) (0.9R - r_i) + c_{0.9R}, \text{for } r_i \leq 0.9R \]  

(5)

Figure 3. Result of blade design: a) initial b) linearization.

3. Experiment method
The method used in this research is quasi-experimental research, where the wind turbine is tested in a fixed position on a wind tunnel whose environmental condition can be determined. Wind tunnel used is an open type with a test chamber dimension of 1.85 m x 1.85 m, wind speed measurement by hot wire anemometer which placed 30 cm in front of the front rotor. In this study there are three variables, they are independent variables, dependent variables and controlled variables. The independent variables are local pitch of rear rotor and electric power load (bulb lamp). The amount of local pitch (\( \theta_p \)) is -10o, -5o, 0o, +5o and +10o by angle of attack design or equal to the front rotor attack angle, as shown in Fig. 4, while for the electric power load is 0 watts up to 4.5 watts with a doubling of load every 0.75 watts.
The dependent variable is the rotational speed of the rotor, electrical current and electrical voltage. The controlled variables in this study are wind velocity (4 m/s), number of blade (3), axial distance between rotor (L/D=0.3) and rotor diameter ratio (D1/D2 = 1).

![Figure 4. Local pitch angle variations of rear rotor.](image)

The front rotor and rear rotor are made of the same material that is ABS (Acrylonitrile Butadiene Styrene) by 3D Printing. The front and rear rotor specification used in the study are shown in Table 1.

| Specification     | Front Rotor | Rear Rotor |
|-------------------|-------------|------------|
| Diameter          | 0.70 m      | 0.70 m     |
| Number of blade   | 3           | 3          |
| Airfoil           | NACA 4412   | NACA 4412  |
| Angle of attack   | 8°          | 8°         |
| Local pitch       | 0°          | -10°,-5°,0°,+5°,+10° |
| Rotation          | CCW         | CW         |

Collecting data is done after rotors are rotated stably in constant conditions, and then to give an electric power load step by step, until multimeter will know the magnitude of electrical voltage and electrical current coming out of the generator. The test installations and sketch to collecting data are shown in Figure 5.

![Figure 5. Installation of the experimental object (a) and the sketch of collecting data (b).](image)
4. Result and discussion
Based on the design and experimental results, the final data are presented in the form of rotor rotational speed, electric power generated and percentage of power increased.

4.1. Characteristic of rotational speed
A relation between the electrical load and total rotational speed from two rotors showed in Figure 6. This show the highest rotational speed while without load is achieved by CRWT with the rear rotor which has a local pitch 0º, while the load increases, the rotational speed of two rotors tends to decrease.

![Figure 6. Relation of the electric load on rotation speed.](image)

This happens because of the magnetic field created between the conductor plate and the permanent magnet in the generator and produce an electromotive force (EMF) which must be passed to bulb lamp as an electric power load. Starting from the load of 1 lamp (0.75 watts), the magnitude of the magnetic field created is not capable of being resisted by the torque generated by the rear rotor, so that the rear rotor of the CRWT revolves and rotates following the armature rotation that is connected directly to the same axis to the front rotor. However, anomalies occur in CRWT with local pitch of rear rotor +10º and +5º, where with the addition of the load does not decrease the rotational speed significantly and tends to be constant in addition to the next load. Theoretically, this is due to the lifting force generated from a rear rotor with local pitch +10º able to resist the magnetic field on the generator more, and help to decrease of torque load on the front rotor.

4.2. Characteristic of electrical generation
In Figure 7, 8 and 9 we can see the relation of the electric power load on electric power generated, where the highest power is achieved when CRWT is loaded with 1 lamp (0.75 watts). The use of local pitch variation of the rear rotor has considerable influence on the performance of the CRWT, such as electrical voltage, electrical current and electrical power output.

Overall the best performance CRWT was generated on the rear rotor with local pitch +10º, the highest power is 1.057 watt at rotational speed 821 rpm, followed by rear rotor with local pitch 0º, +5º, -5º and the lowest performance occurred at local pitch of rear rotor -10º with electric power generated only 0.598 watts at rotational speed 609 rpm. Theoretically, this happens because of the stall phenomenon that occurs when airfoil NACA 4412 has the angle of attack is below 0º (α = -2º), so lift force of the airfoil to rotate the rotor will disappear and affected to rotational speed and electric power generation.
4.3. Increased power
The increased power is a comparison of the electrical power generated deviation between highest powers generated on variation local pitch with a normal pitch of the rear rotor (0°). The greatest increased power
occurs in the local pitch of rear rotor +10° with 23.55%, then 6.47% is increased power for local pitch +5°, and the others variation is decreased power, see Table 2.

Table 2. Comparison of highest power generation on variation local pitch on the rear rotor.

| Pitch   | Power Generation |
|---------|------------------|
| Pitch -10 | 0.598 watt       |
| Pitch -5  | 0.811 watt       |
| Pitch 0   | 0.856 watt       |
| Pitch +5  | 0.911 watt       |
| Pitch +10 | 1.057 watt       |

5. Conclusion
Based on data of experimental and the calculation result of effect local pitch variation on electric power generation from horizontal wind turbine counter-rotating model, hence can be taken some conclusion as follows:

- The use of local pitch variation of the rear rotor has considerable influence on the performance of the CRWT. It is because the variation of the local pitch of the rear rotor affects the wind energy absorbed by the front rotor.
- The highest electrical power generated at a local pitch +10° was at load 0.75 watt in amount of 1.057 watts or 23.55% higher than normal rotor (pitch 0°).

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