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Effect of Closing the Blade Tip on Downwind Thai Sail Windmill

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Abstract: Thai sail windmill has been a traditional wind turbine of Thailand, which is a type of horizontal axis wind turbine and now used for pumping the seawater into the salt farms widely in the Samut-Songkhram province for the sea salt production. Currently, the efficiency of the conventional Thai sail windmill is typically quite low that is only approximately 10 percent. Actually, the efficiency of wind turbines depends on many parameters such as blade shape, pitch angle, solidity, wind speed, tip loss, etc. However, this study focused on the tip loss reduction by using technique of closing the blade tip in order to be a guideline for enhancing efficiency. The objective of this study was to investigate the effect of employing technique of closing the blade tip on the efficiency of Thai sail windmill in the fashion of downwind rotor. For experiments, the small scale of 4-blade and 6-blade rotor in the pattern of downwind Thai sail windmill was built and used as a prototype to experiment by using the tow testing method. As a result, the use of technique of closing the blade tip could help the 4-blade rotor increase maximum efficiency from 17 percent into 22 percent at the tip speed ratio of 2.2 and help the 6-blade rotor increase maximum efficiency from 25 percent into 35 percent at the tip speed ratio of 2.0.

Keywords: Thai sail windmill; Wind turbine efficiency; Downwind rotor; Closing the blade tip

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1. Introduction

Conventional Thai sail windmill (CTSW) has been used widely in Samut Songkhram province for pumping the seawater into the salt farms for sea salt production. The CTSW is a kind of a horizontal axis wind turbine, which is a lift type. Referring to Mukhia [1] reports, the actual rotor size of CTSW was about 6-8 meters with 6 blades in triangular shape made of either canvas or woven mat. The tip side area of the CTSW blades was larger than the root side area as showing in Fig.1 [2, 3]. Due to the big size at the tip blades, the tip loss could be happened enormously and inevitably; which leads to that the CTSW had low efficiency. Ronnakorn [4] reported that the average efficiency of the CTSW was only about 10 percent. However, if able to reduce the tip loss at the blade tip, the efficiency of the CTSW could be improved.

Fig.1 Conventional Thai sail windmill [2, 3]

In recent years, Teerawat *et al.* [5] improved the CTSW to have more efficiency in terms of finding the optimum tip pitch angle including the changing rotor from an upwind type into a downwind type, which was the so-called “downwind Thai sail windmill (DTSW)” as shown in Fig.2 to take advantages in being a passive yaw control similar to the experiment of Kress *et al.* [6]. The optimum tip pitch angle of DTSW was in the range of 5-10 degrees. Spera [7] described the method for wind turbine testing that there were three main techniques able to perform as follows: (i) wind tunnel testing, (ii) tow testing, and (iii) field testing. This study used the tow testing method. The tow testing was the technique that was to install the prototype on a moving vehicle, such as a pick-up truck, that was moving at a constant speed. For example, this technique was also performed in the study of Maughmer [8] and Song [9].

Fig.2 Downwind Thai sail windmill [3]

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For this research, the rotors were consisted of two manners, namely 4-blade, and 6-blade rotor in the fashion of DTSW but scale down the rotor diameter from 8.0 meters into 1.0 meter in order to be more suitable and practical to experiment. The tip pitch angle was used by the two angles, namely 5 and 10 degrees due to being the range of optimum pitch angle referring to the previous study [5]. This article focused on the reduction of the tip loss, especially for DTSW. This study aimed to investigate the effect of employing technique of closing the blade tip on DTSW efficiency to be a guideline for enhancing efficiency.

Fig.3 Tip pitch angle setting [3]

2. Materials and Methods

2.1 Basic Information of the CTSW

The actual rotor size of CTSW was about 6-8 meters placed in the upwind position. The manner of blades was the triangular shape made of either canvas or woven mat; whereby the blades were located on that the bigger side was placed at the rim of the rotor. The tip pitch angle was typically in the range of about 5-20 degrees as showing in Fig.3. The solidity of the rotor was in the range of approximately 15-60 percent [4]; whereby the solidity meant that the ratio between the projected area of all blades and the swept area of rotor.

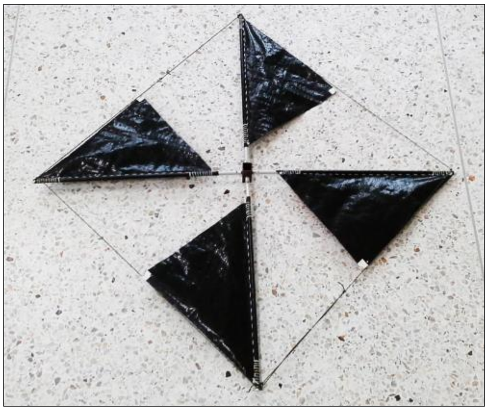

Fig.4 The opened-tip DTSW on the 4-blade rotor

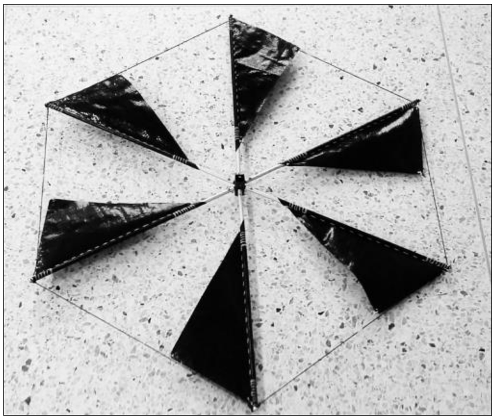

Fig.5 The opened-tip DTSW on the 6-blade rotor

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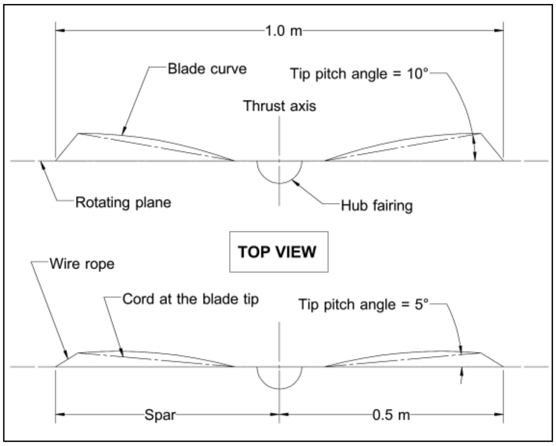

Fig.6 Tip pitch angle setting

2.2 Prototype and Closing the Blade Tip

The DTSW, which was developed from the CTSW, had the blade tip opened independently off the rotor rim (Opened-tip DTSW) as showing in Fig.4 and Fig.5, which the optimum tip pitch angle was in the range of approximate 5-10 degrees. In the top view, Fig.6 presented the relation of the tip pitch angle of the DTSW between the rotor plane and the cord line at the blade tip. With this appearance, the blade tip would affect the wind turbine to create enormously the tip loss especially at the blade tip that was large and long as explained by Prandtl [10]. This was the reason why the efficiency of CTSW including the opened-tip DTSW was quite low. Consequently, the technique of closing the blade tip was implemented for this study to help reducing the tip loss so that the efficiency of DTSW might be enhanced. The technique of closing the blade tip was to extend the blade tip area to the rotor rim of DTSW and sew tightly together with setting the required tip pitch angle as showing in Fig.7 and Fig.8.

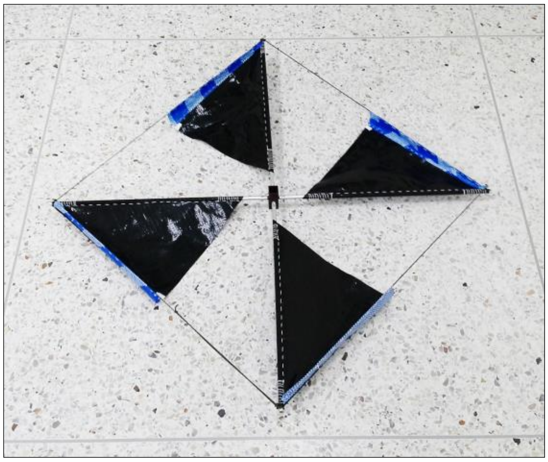

Fig.7 The 4-blade rotor by using the technique of closing the blade tip (Closed-tip DTSW)

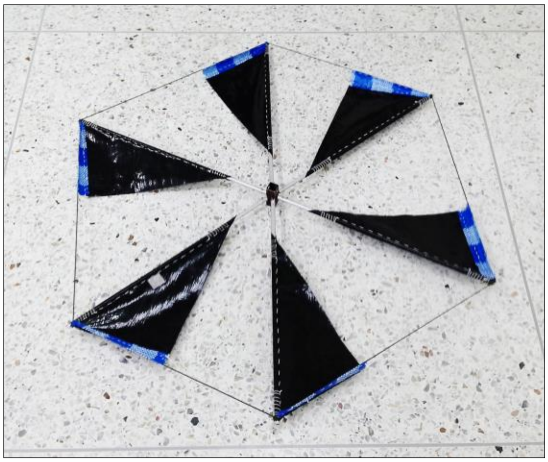

Fig.8 The 6-blade rotor by using the technique of closing the blade tip (Closed-tip DTSW)

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The prototype was fabricated by scaling down from 6-8 meters into 1.0 meter. The rotor was built in only two manners, namely 4-blade and 6-blade rotor with the same solidity of about 28 percent. The tip pitch angle was employed only two optimum angles, namely 5 and 10 degrees as mentioned by a previous study [5]. The rotor orientation of the prototype was placed in the downwind position, which was called the downwind Thai sail windmill (DTSW), to take advantage of being passive yaw controlled. The 4-blade and 6-blade rotor with the opened-tip DTSW and the blades using the technique of closing the blade tip (Closed-tip DTSW) were used as prototypes for the experiment in order to investigate the effect of the use of technique of closing the blade tip on DTSW efficiency.

2.3 Testing Procedure

Referring to that the tow testing was one effective method able to use for wind turbine testing as explained by Spera [7]. Thus, it was performed in this study owing to the suitable and available tools and equipment. This method was to equip the prototype on a moving vehicle such as a pick-up truck moving at a constant speed. Similar experiments for wind turbine testing were performed and reported by Maughmer [8] and Song [9]. However, it should be noted that the vehicle speed was actually the same as inlet wind velocity by wind tunnel testing method;

Fig.9 Carbon steel rack, prototypes, and measurement accessories installation: tension spring, optical rotational speed sensor, and anemometer [3]

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which the prototype was stationary in the test section. For this study, the carbon steel racks were installed on a pick-up truck to facilitate in fastening the prototypes and all measurement accessories such as tension spring, optical rotational speed sensor, and anemometer. The rotor was installed 2.5 meters away from a vehicle's roof to avoid the turbulent disturbance or wake from the boundary layer effect as reported by Hucho *et al.* [11]. The anemometer was placed in front of the rotor plane about 1.0 meter. The tested velocity was approximate 20 kilometers per hour.

The procedure of the tow testing method was as follows;

1) Install completely a carbon steel rack, prototypes, and all measurement accessories on a pick-up truck as showing in Fig.9 and Fig.10.

2) Examine the interference from the local wind at that time; whereby the pick-up truck could start moving only if the local wind did not exceed 5 percent from the tested speed in order to avoid the non-uniform flow of tested velocity of air from the local wind interference.

3) Move the pick-up truck forward with a constant speed of 20 kilometers per hour to tow the prototype on the route, which must be straight and must not be sloping as showing in Fig.11.

4) Give the rotor shaft the more resistance load by adjusting the turnbuckle screw to measure the torque and rotor speed happening as showing in Fig.9.

5) Measure the F1 and F2 by tension springs and measure the rotor speed by optical rotating speed sensor as showing in Fig.9 when the system was fully in steady-state.

Fig.10 Prototype on the pick-up truck

Fig.11 Straight route for the tow testing

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6) Provide more the resistance load and measure the F1, F2, and the rotor speed again as the previous step until the rotor speed stops rotating.

3. Theory

3.1 Tip Loss

The tip loss was a thing that was inevitably happened in all types of horizontal axis wind turbine due to having the finite span of wind turbine blades and having the rotating blades as explained by Branlard *et al.* [12]. The tip loss mainly occurred at the tip of the blade span or the blade tip. This tip loss caused a part of lift force, torque, and gained power that was created by wind turbine blades to decrease enormously. The tip loss was the dimensionless coefficient, which was in the range between 0-1. For example, the tip loss factor that was equal to 0.9 meant that the wind turbine power was lost 10 percent from the mechanical power that should be totally deserved 100 percent. Presently, there were many the tip loss models used for the wind turbine simulation especially by the blade element momentum theory (BEM) [2, 13, 14]; such as Glauert's BEM, Vortex Code, and New BEM Code [12] as showing in Fig.12. For Fig.12, it was obvious that the tip loss was mainly happened in the area of the blade tip especially in the range of r/R=0.8-1.0 as showing that the tip loss was decreased rapidly.

Even though the tip loss was a thing that could not eliminate totally, it could be reduced by using some auxiliary devices; such as tip fins [15, 16], winglets [17], shroud [18], etc. For this study, the technique of closing the blade tip was performed to reduce the tip loss for the DTSW.

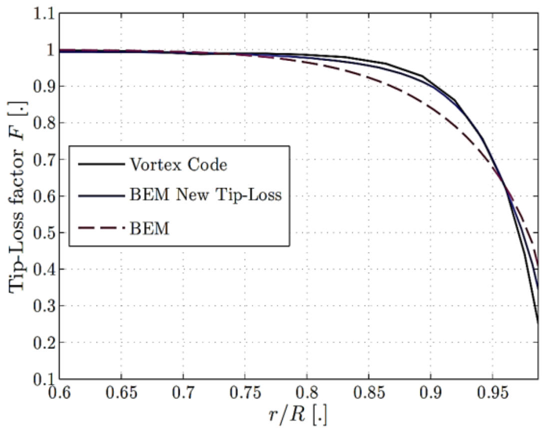

Fig.12 Tip loss factor from Glauert's BEM, Vortex Code, and New BEM Code [12]

3.2 Wind Turbine Efficiency

Mostly, the wind turbine efficiency would be presented in terms of power coefficient (C_p), which is the dimensionless parameter. The C_p was the ratio between the gained power from the wind turbine (P_t); which was a mechanical power or shaft power, and the wind power (P_w). Consequently, the power coefficient of the wind turbine could be expressed as Eq. (1) [19].

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$$C_p = \frac{P_t}{P_w} = \frac{T \cdot \omega}{0.5 \rho \pi R^2 U_0^3} \quad (1)$$

where *T* was the shaft torque ($N \cdot m$), which was converted from the aerodynamic loads: lift and drag of the wind turbine blades. ρ was the density of air (kg/m^3). *R* was the rotor radius of the wind turbine (m). U_0 was the wind velocity (m/s). ω was the angular velocity of the rotor (rad/s), which could be calculated by Eq.(2) [19].

$$\omega = \frac{2\pi N}{60} \quad (2)$$

where *N* was the rotor speed (RPM). However, it should be noted that the wind turbine efficiency could be explained in terms of the power coefficient multiplied by 100 percent as presented in Eq.(3).

$$\eta_{tb} = C_p \times 100\% \quad (3)$$

whereby η_{tb} was the wind turbine efficiency, which was the energy conversion efficiencies [20]. According to the free body diagram of the torque acting on the pulley that was equipped on the rotor shaft of the prototype as showing in Fig. 13, the shaft torque could be measured by using the equilibrium of forces and torques; which is the basic principle of mechanics (Newton's first law of motion).

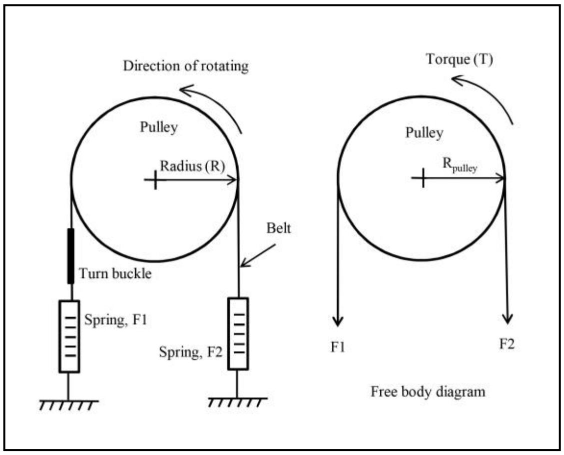

Fig.13 Free body diagram of the torque acting on the pulley [3]

When the system is in equilibrium, the sum of all forces and the sum of all torques acting on the system must be zero. Hence, the shaft torque could be shown in Eq.(4) [5].

$$T = R_p (F_2 - F_1) \quad (4)$$

where R_p was the radius of pulley. F_1 and F_2 were the forces acting on the tension springs as showing in the free body diagram. Tip speed ratio (λ) was the ratio between the tangent velocity at the blade tip and the wind velocity, which could be presented in Eq.(5) [19].

$$\lambda = \frac{\omega R}{U_0} \quad (5)$$

where R represented the radius of the blade tip. It should be noted that the power coefficient and the tip speed ratio would be dimensionless.

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4. Results and Discussion

When all prototypes were completely tested by the tow testing method with a tested speed of 20 kilometers per hour, the results showed that;

Fig.14 showed the comparison between the opened-tip and the closed-tip rotor of DTSW of the 4-blade rotor at the tip pitch setting of 5 degrees and. It was obvious that the closed-tip rotor provided maximum efficiency more than the opened-tip rotor. The closed-tip rotor had the utmost efficiency of about 22 percent at the optimum tip speed ratio of 2.2; while the opened-tip had 17 percent at the tip speed ratio of 2.0. Hence, the efficiency could be enhanced 5 percent, which was considered fairly high. In addition, it should be noted that; mostly, the stall was occurred at the lower tip speed ratio (the left side of the curve) due to a very high angle of attack. Thus, the C_p for this area could not measure because the rotor would stop rotating immediately.

Fig.15 showed the comparison between the opened-tip and the closed-tip rotor of DTSW of the 4-blade rotor at the tip pitch setting of 10 degrees. Like the 5 degree of tip pitch angle, the closed-tip rotor provided maximum efficiency more than the opened-tip rotor. The closed-tip rotor had the utmost efficiency of approximately 22 percent at the optimum tip speed ratio of about 2.0; while the opened-tip rotor had only 16 percent at the optimum tip speed ratio of 2.0. It can be seen that; the maximum efficiency obtained by the tip pitch angle of 10 degrees was not very different from 5 degrees.

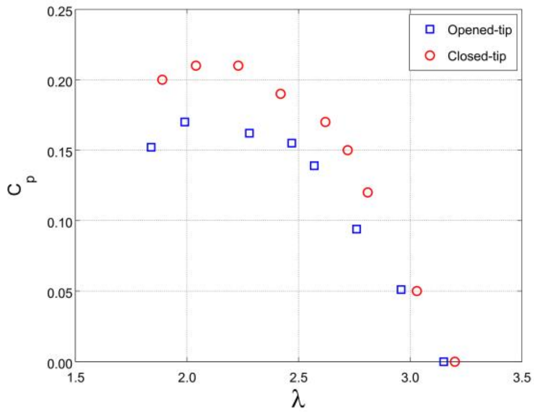

Fig. 14 Experimental results of the 4-blade rotor at the tip pitch of 5 degrees in the fashion of opened-tip and closed-tip DTSW

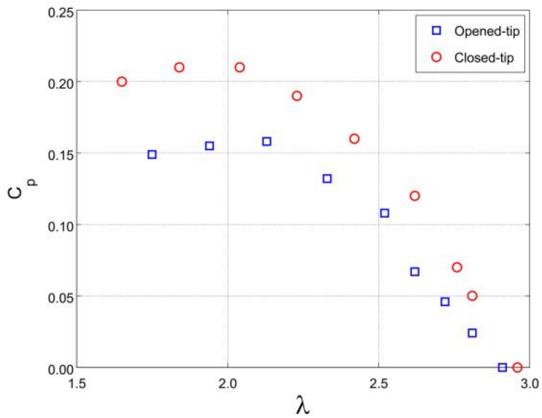

Fig. 15 Experimental results of the 4-blade rotor at the tip pitch of 10 degrees in the fashion of opened-tip and closed-tip DTSW

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Fig.16 illustrated the comparing results of the 6-blade rotor at the tip pitch setting of 5 degrees between the opened-tip and the closed-tip rotor of DTSW. It was apparent that the closed-tip rotor could provide the utmost efficiency more than the opened-tip rotor including more than the rotor in the fashion of 4-blade DTSW. The closed-tip rotor with the 6-blade manner could provide the maximum efficiency of approximately 28 percent at the optimum tip speed ratio of about 2.7; while the opened-tip rotor had the utmost efficiency only about 22 percent at the optimum tip speed ratio of 2.7. Thus, it can be seen that; the efficiency could be augmented by approximately 6 percent from the opened-tip rotor and increased approximately 6 percent from the 4-blade rotor together with the use of closing the blade tip technique at the tip pitch angle of 5 degrees.

Fig.17 illustrated the comparing results of the 6-blade rotor at the tip pitch setting of 10 degrees between the opened-tip and the closed-tip rotor of DTSW. It was very clear that the closed-tip rotor could provide the utmost efficiency more than the opened-tip rotor tremendously. the closed-tip rotor had maximum efficiency of approximately 35 percent at the optimum tip speed ratio of approximately 2; while the opened-tip rotor had a maximum efficiency of about 25 percent at the optimum tip speed ratio of about 2.2. Consequently, it was obviously that; when

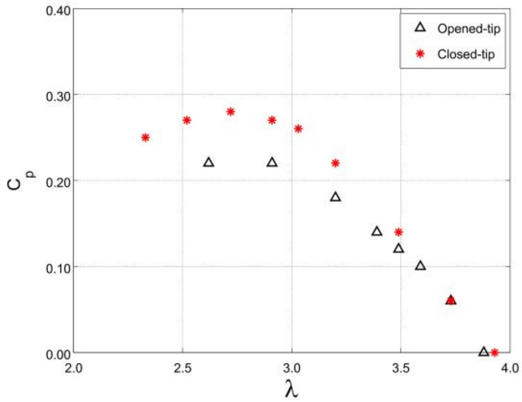

Fig. 16 Experimental results of the 6-blade rotor at the tip pitch of 5 degrees in the fashion of opened-tip and closed-tip DTSW

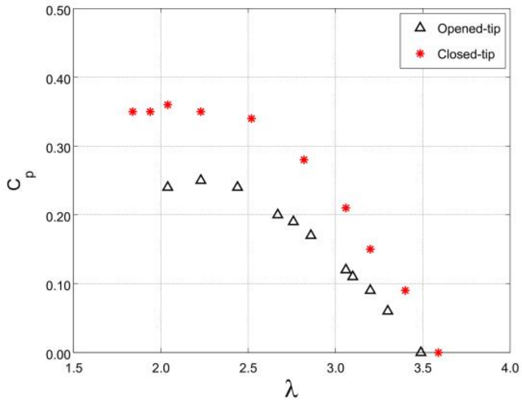

Fig. 17 Experimental results of the 6-blade rotor at the tip pitch of 10 degrees in the fashion of opened-tip and closed-tip DTSW

employing the technique of closing the blade tip for the 6-blade rotor for DTSW, the efficiency could be enhanced approximate 10 percent from the conventionally opened-tip rotor, which was considered as relatively high. Additionally,

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if comparing with the closed-tip rotor for the 4-blade rotor, the efficiency could be enhanced approximate 13 percent.

5. Conclusions

This study aimed to investigate the effect of employing the technique of closing the blade tip on the efficiency of the downwind Thai sail windmill to be a guideline for enhancing efficiency. The results showed that;

The 4-blade rotor which was using the technique of closing the blade tip provided maximum efficiency of approximately 22 percent at the tip pitch angle of both 5 and 10 degrees at the optimum tip speed ratio of about 2.2. Thus, the efficiency increased 5 percent from the opened-tip rotor.

The 6-blade DTSW which was using the technique of closing the blade tip provided maximum efficiency of 35 percent at the tip pitch angle of 10 degrees at the optimum tip speed ratio of 2.0. So, the efficiency increased 10 percent from the opened-tip rotor, which was considered relatively high. Additionally, if comparing the closed-tip rotor for the 4-blade rotor, the efficiency was enhanced 13 percent. the 6-blade rotor for DTSW which was using the technique of closing the blade tip provided maximum efficiency more than the 4-blade rotor because this technique was able to help DTSW to change a part of the tip loss into the power gain simultaneously, which was considered as a double benefit in efficiency enhancement. Consequently, with the higher number of blades, the total torque would be more obtained as a result of the number of blades as showing in the equation of $T = B\int_{root}^{tip} dF_T r$ [19]; whereby B was the number of blades and dF_T was the differential relative force in tangent direction at any radius from the blade root to tip.

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