Renewable Energy 42 (2012) 140–144

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Effects of design parameters on aerodynamic performance of a counter-rotating wind turbine

Seungmin Lee[a,1], Hogeon Kim[a,2], Eunkuk Son[a,2], Soogab Lee[b,*]

[a] Department of Mechanical and Aerospace Engineering, Seoul National University, South Korea
[b] Department of Mechanical and Aerospace Engineering and Institute of Advanced Aerospace Technology, Seoul National University, South Korea

ARTICLE INFO

Article history:
Received 8 March 2011
Accepted 22 August 2011
Available online 6 October 2011

Keywords:
Wind turbine
Counter-rotating
Blade element momentum theory
Power coefficient
Tip speed ratio

ABSTRACT

This study investigates the effects of design parameters on the aerodynamic performance of a counter-rotating wind turbine. The counter-rotating wind turbine has two rotors rotating in opposite directions on the same axis. It has been proposed on the basis of the theory which states that a configuration of two rotors having the same swept area on the same axis has a higher maximum power coefficient than a conventional configuration of a wind turbine having a single rotor. More design parameters are involved in the description of the counter-rotating wind turbine than of a wind turbine using a single rotor because of the complex phenomenon arising from the aerodynamic interaction between its two rotors, but influences of these parameters is yet to be fully understood. In this study, a modified blade element momentum theory for the counter-rotating wind turbine is developed to investigate the effects of these design parameters such as the combinations of the pitch angles, rotating speeds and rotors' radii on the aerodynamic performance of the counter-rotating wind turbine.

1. Introduction

Wind is one of the clean energy resources and it can meet more than two hundred times the annual requirement of world energy consumption [1]. It is very important to use this wind resource to reduce fossil fuel dependency and promote sustainable development. A wind turbine converts the energy of the wind to mechanical energy by the rotation of its rotor. Worldwide installation of wind turbines has shown a high growth rate because power generation through a wind turbine is lower cost and has higher technology maturation than that through other means of renewable energy resources [2].

In order to reduce the cost of wind energy further and maintain continued growth of wind power, the energy conversion efficiency of a wind turbine needs to be improved. The energy conversion efficiency of a wind turbine is usually characterized by its power coefficient, which is the ratio of the power extracted from the wind to the power available in the wind. Based on classical momentum theory, the maximum power coefficient of a wind turbine having an ideal single rotor without any losses is about 59%, which is known as the Betz limit [3]. In practice, the maximum power coefficient of conventional horizontal axis wind turbines having a single rotor is about 40–50% due to some losses such as viscous loss, three-dimensional loss, and transmission loss. Over the past few decades, many different concepts and blade designs of a wind turbine have been proposed to improve the maximum power coefficient [4].

A counter-rotating wind turbine having two rotors rotating in opposite direction on the same axis has been proposed as a new concept to enhance the maximum power coefficient of the wind turbine. Using classical momentum theory, Newman found that the maximum power coefficient of a wind turbine having two rotors without any losses increased to about 64% [5]. Recently, based on this result, the counter-rotating wind turbine has been studied extensively to obtain more power from the wind than that obtainable from a conventional wind turbine having a single rotor [6–11].

Despite these efforts, it has been still difficult to optimize the aerodynamics of the rotors to obtain the maximum power coefficient. This is because complex phenomena are induced by the aerodynamic interactions of the two rotors in the counter-rotating wind turbine, unlike in a conventional wind turbine having a single

* Corresponding author. Present address: Rm. 105, Bldg. 311, Seoul National University, Seoul 151-744, South Korea. Tel.: +82 2 880 7384; fax: +82 2 875 4360.
E-mail address: solee@snu.ac.kr (S. Lee).
[1] Present address: Rm. 105, Bldg. 311, Seoul National University, Seoul 151-744, South Korea. Tel.: +82 2880 7384.
[2] Present address: Rm. 318, Bldg. 313, Seoul National University, Seoul 151-744, South Korea. Tel.: +82 2880 7545.

0960-1481/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2011.08.046

rotor. In addition to the design parameters of a single rotor, design parameters such as the differences of pitch angles, rotational speeds and radii of the two rotors need to be considered to improve the aerodynamic performance of the counter-rotating wind turbine. Furthermore, the effects of these additional design parameters on the aerodynamic performance of the counter-rotating wind turbine have yet to be fully understood, so the design becomes more complicated. Therefore, a preliminary study investigates the effects of design parameters on the aerodynamic performance of the counter-rotating wind turbine to obtain the optimized design of the counter-rotating wind turbine yielding the maximum power coefficient and compares the optimized design with that of a conventional wind turbine having a single rotor.

In this paper, the effects of design parameters on the aerodynamic performance of the counter-rotating wind turbine are investigated. The design parameters used in this study are the combinations of pitch angles, rotating speeds and radii of the two rotors of the counter-rotating wind turbine. For the parametric study, the modified blade element momentum theory (BEMT) is developed, and this theory is applied to the inflow model of a rear rotor of the counter-rotating wind turbine. By using this method, the power coefficient characteristics of the counter-rotating wind turbine according to the design parameters are investigated.

2. Numerical method

The blade element momentum theory (BEMT) combines the momentum theory and blade element theory for the analysis of a rotor. The momentum theory is a control volume theory based on the conservation of linear and angular momentum and the blade element theory is a theory about the forces determined solely by the lift and drag characteristics of the airfoil shape of the blade sections based on the assumption of no aerodynamic interaction between section elements. By BEMT, the inflow on each blade section can be solved by equating the forces from the two theories [12]. BEMT is a reliable and effective theory for rotor design because it is based on solid physical principles and has a remarkably low computing cost.

The flow model for the counter-rotating wind turbine is shown in Fig. 1. It is assumed that the rear rotor operates inside the fully developed stream tube of the front rotor. The downstream velocity fully reduced by the front rotor in the stream tube acts as an inflow velocity for the rear rotor. It is also assumed that the wake from the front rotor leads to flow interference into the rear rotor, but the wake from the rear rotor does not affect the flow of the front rotor. Flow visualization has revealed that in practice, the wake from the front rotor expands quickly [13], so the assumption of a fully developed stream tube is valid in most cases except in cases of very closely spaced rotors.

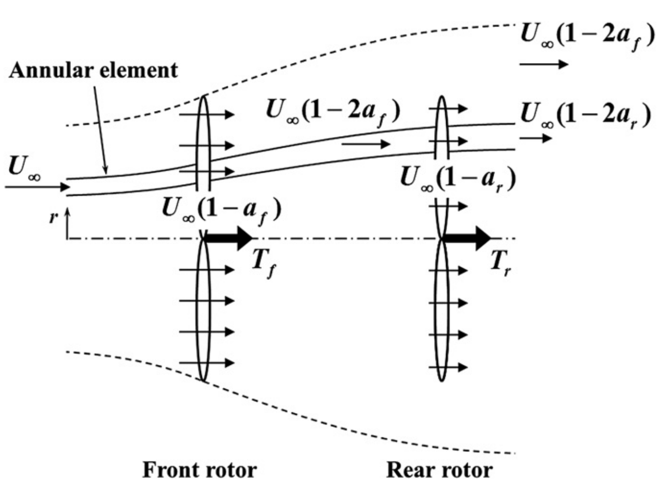

Fig. 1. Flow model of the BEMT for a counter-rotating wind turbine with the rear rotor operating inside the stream tube of the front rotor.

First, for the front rotor, the axial momentum conservation and the Bernoulli equation are applied on the rotor annulus, then the incremental thrust is

$$\mathrm{d}T_f = \rho \mathrm{d}A\left(U_\infty^2 - U_{far}^2\right)\Big/2 \tag{1}$$

where ρ is the air density, dA is the rotor annulus area, U is the air velocity and the subscripts f, ∞ and far indicate the front rotor, the free stream and the far downstream velocity, respectively. If the axial induction factor, a_f, is defined as the fractional decrease in wind velocity, then the incremental thrust can be written as

$$\mathrm{d}T_f = 4\rho\, U_\infty^2 a_f\left(1-a_f\right)\pi r\mathrm{d}r \tag{2}$$

where r is the blade span-wise position and dr is the increment of r.

Applying the angular momentum conservation on the front rotor disk and using the angular induction factor, a_f', which is defined as the ratio of the angular velocity at the rotor induced by wake rotation to the rotational velocity of the rotor, Ω_f, the torque exerted on the rotor annulus is

$$\mathrm{d}Q_f = 4\ a_f'\left(1-a_f\right)\rho\, U_\infty \pi r^3 \Omega_f \mathrm{d}r \tag{3}$$

The tip-loss effect in the blade root and tip region is accounted by the Prandtl's tip-loss function [12]. This effect is expressed in terms of the Prandtl's correction factor, F, as

$$\begin{aligned} F &= F_{root} \times F_{tip} \\ &= 2\cos^{-1}(\exp.(-f_{root}))/\pi \times 2\cos^{-1}\left(\exp.\left(-f_{tip}\right)\right)\Big/\pi \end{aligned} \tag{4}$$

where f_{root} and f_{tip} are given by

$$f_{root} = N_b \times (r/R - r_{hub}/R)/(2r/R \times \sin\varphi) \tag{5}$$

and

$$f_{tip} = N_b \times (1 - r/R)/(2r/R \times \sin\varphi) \tag{6}$$

where N_b is the number of blades, R is the radius of the rotor, r_{hub} is the hub radius and φ is the angle of the relative wind defined by the geometric relation as

$$\varphi = \tan^{-1}\left\{U_\infty\left(1-a_f\right)/\left[\Omega_f r\left(1+a_f'\right)\right]\right\} \tag{7}$$

The Prandtl's correction factor is introduced to the forces derived above, and then the incremental thrust and torque are modified to

$$\mathrm{d}T_f = 4F\rho\, U_\infty^2 a_f\left(1-a_f\right)\pi r\mathrm{d}r \tag{8}$$

and

$$\mathrm{d}Q_f = 4Fa_f'\left(1-a_f\right)\rho\, U_\infty \pi r^3 \Omega_f \mathrm{d}r \tag{9}$$

Now, using the blade element theory, the incremental thrust and torque on the annulus area of the rotor disk is

$$\begin{aligned} \mathrm{d}T_f &= N_b \rho\, U_{rel}^2 (c_l \cos\varphi + c_d \sin\varphi) c\,\mathrm{d}r/2 \\ &= \sigma' \pi \rho \left[U_\infty \left(1 - a_f\right)/\sin\varphi\right]^2 (c_l \cos\varphi + c_d \sin\varphi) r\,\mathrm{d}r \end{aligned} \tag{10}$$

and

$$\begin{aligned} dQ_f &= N_b \rho\, U_{rel}^2 (c_l \sin\varphi - c_d \cos\varphi) c r\,dr/2 \\ &= \sigma' \pi \rho \left[\mathrm{U}_\infty \left(1 - a_f\right)/\sin\varphi\right]^2 (c_l \sin\varphi - c_d \cos\varphi) r^2 \mathrm{d}r \end{aligned} \tag{11}$$

where σ′ is the local solidity, and it is defined as

$$\sigma' = N_b c/(2\pi r) \tag{12}$$

By equating the thrust equations and torque equations from the momentum theory and blade element theory, the inflow conditions that are expressed by a_f and a_f' on each blade section are determined. Because the equations cannot be solved directly, the solution is obtained by an iterative numerical approach. Rapid convergence is obtained with three or four iterations in most cases.

Once the inflow solution is obtained, the total thrust and torque are calculated by integrating the equations

$$T_f = \int \mathrm{d}T_f = \int 4F\rho\, U_\infty^2 a_f \left(1 - a_f\right) \pi r \mathrm{d}r \tag{13}$$

and

$$Q_f = \int \mathrm{d}Q_f = \int 4\ a_f' \left(1 - a_f\right) \rho\, U_\infty \pi \mathrm{r}^3 \Omega_f \mathrm{d}r \tag{14}$$

Once the total torque is obtained, the power coefficient of the front rotor is determined by

$$C_{p,f} = \Omega_f Q_f / \left(\rho \pi R^2 U^3/2\right) \tag{15}$$

In order to simulate the three-dimensional stall delay effects, the stall delay model developed by Du and Selig [14] is used for the calculation of two-dimensional aerodynamic coefficients. In addition, for the turbulent wake state in which a_f is larger than 0.5 and the thrust determined by momentum theory is invalid, the empirical relationship of the axial induction factor and the thrust coefficient developed by Glauert [15] is applied to the solution determined by the BEMT.

The same mathematical principles are used to analyze the rear rotor of the counter-rotating wind turbine. However, it is assumed that the rear rotor operates inside the fully developed stream tube of the front rotor. The inflow velocity on the plane of the rear rotor is determined by the axial induction factor of the front rotor as follows.

$$U_{\infty,r} = U_\infty \left(1 - 2a_f\right) \tag{16}$$

where the subscripts r indicates the rear rotor.

The radial expansion radius of the fully developed stream tube of the front rotor, R_e, is determined by the mass conservation of the flow on the rotor plane and far downstream of the front rotor. After algebraic manipulations, the radial expansion radius is derived as

$$R_e = R_f \times sqrt\left[\left(1 - a_f\right) / \left(1 - 2a_f\right)\right] \tag{17}$$

If there are some positions of the rear rotor outside the radial expansion radius of the fully developed stream tube of the front rotor due to the difference of the rotor sizes, the inflow velocity at those positions that are unaffected by the wake from the front rotor is set to be the free stream wind velocity, U_∞.

3. Results and discussion

The parametric study for the counter-rotating wind turbine is performed by using the BEMT which is developed based on solid physical principles and reasonable assumptions. To consider the characteristics of the counter-rotating wind turbine having two rotors, pitch angles, rotating speed ratios and radius differences of two rotors and their combinations are chosen as design parameters in this study.

The baseline rotor used for the parametric study has a relatively simple blade geometry, which allows easy comparisons of results according to the design parameters. The rotor has three rectangular blades whose the chord length is constant with span-wise positions. The rotor solidity is 0.05 and NACA0012 airfoil is used for the blade section. For an efficient operation of the rotor, the blades have an ideal blade twist, $\theta_{twist}(r) = \theta_{tip}/r$,, where θ_{tip} is the tip pitch angle. Then the blade sectional pitch angle is defined as $\theta(r) = \theta_0 + \theta_{twist}(r)$, where θ_0 is the blade pitch angle. The tip speed ratio (TSR) is defined as the ratio of the blade tip speed to the free stream wind speed, and TSR at which a maximum power coefficient is obtained is set to 8.0, which is in the range of the conventional design TSR. For this design TSR, θ_0 and θ_{tip} is set to 0.0 and 0.3°, respectively.

Performance results from the BEMT for the baseline single rotor are shown in Fig. 2. The power coefficient at the design TSR of the rotor in an ideal condition without any losses reached the Betz limit. However, in the case with tip loss and viscous losses like drag and stall, the maximum power coefficient is reduced to 0.448. In the parametric study of the counter-rotating wind turbine, the baseline single rotor with losses is used for the front and rear rotors.

3.1. Combination of pitch angles

To investigate the effect of combinations of the pitch angles on performance, the same baseline rotor described above is used for each rotor of the counter-rotating wind turbine. The rotating speed of each rotor is set equal each other, and that means the TSR of each rotor is fixed to the design TSR, 8.0.

The variation of power coefficient versus pitch difference between the two rotors as a set of curves for increasing values of the front rotor pitch is shown in Fig. 3. The maximum power coefficient

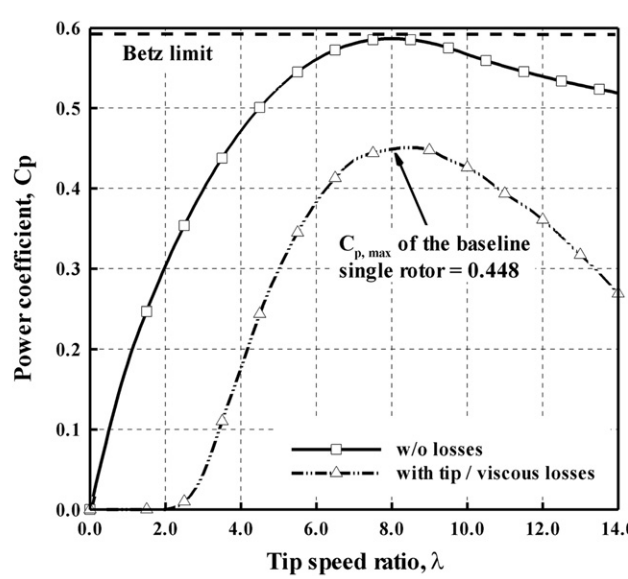

Fig. 2. Power coefficient versus tip speed ratio of the baseline single rotor with design TSR of 8.0 ($\sigma = 0.05$, $\theta_0 = 0.0$ deg., $\theta_{tip} = 0.3$ deg.).

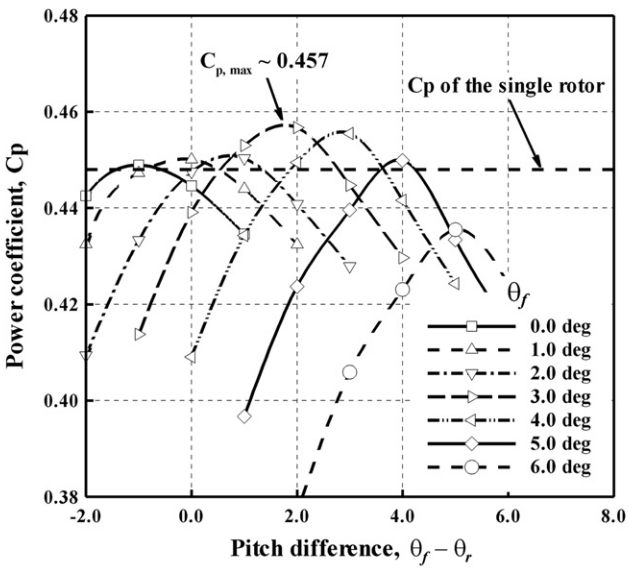

Fig. 3. Power coefficient versus pitch difference between two rotors as a set of curves for increasing values of the front rotor pitch ($R_f = R_r$, $\Omega_f = \Omega_r$, $TSR_f = TSR_r = 8.0$).

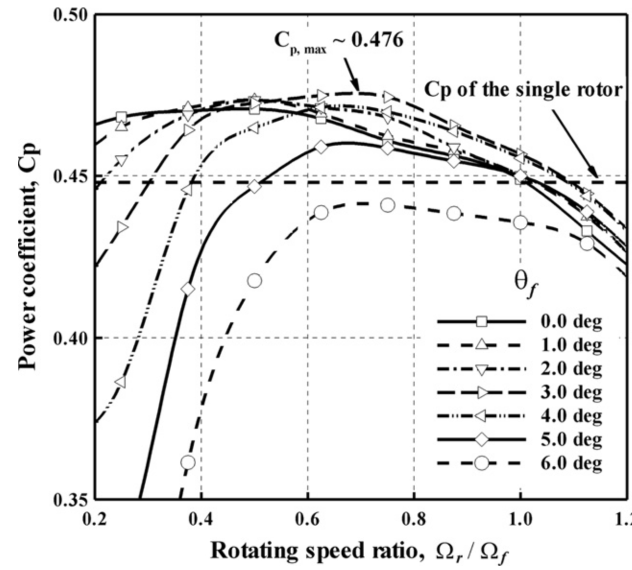

Fig. 4. Power coefficient versus rotating speed ratio of the two rotors as a set of curves for increasing values of the front rotor pitch ($R_f = R_r$, $TSR_f = 8.0$, $\theta_r = 0.0$ deg.).

of the counter-rotating wind turbine is obtained when the front rotor pitch is 3.0° while that of the baseline rotor is obtained at 0.0°. As the front rotor pitch increases, the operation condition of the front rotor moves away from the design condition of the baseline rotor, and the power coefficient of the front rotor decreases. In contrast, because the interference of the front rotor on the rear rotor is reduced, the power coefficient of the rear rotor increases. For that reason, the maximum power coefficient is obtained when each rotor shares the total power, not when the front rotor extracts the maximum power from the wind. In addition, because the interference of the front rotor induces the decrease of inflow velocity on the rear rotor, the pitch of the rear rotor needs to be smaller than that of the front rotor for maximum power coefficient. In the case of this study, the maximum value is obtained when the pitch angles of the front and rear rotors are 3.0 and 1.0°, respectively.

3.2. Rotating speed ratio

Fig. 4 shows the variation of power coefficient versus rotating speed ratio of the two rotors as a set of curves for increasing values of the front rotor pitch. To compare performance according to only the rotating speed ratio, the radius of each rotor is set equal each other, and the pitch of the rear rotor and TSR of the front rotor are set to 0.0° and 8.0, respectively.

As shown in Fig. 4, the maximum power coefficient for each pitch setting of the front rotor is obtained below the rotating speed ratio of 1.0, which means that two rotors have the same rotating speed. At the same rotating speed, due to decrease of the inflow velocity on the rear rotor, the angle of the relative wind on the rear rotor becomes smaller than that on the baseline rotor having maximum performance, so the power coefficient of the rear rotor decreases. Therefore, the maximum power coefficient is obtained when rotating speed of the rear rotor is reduced to recover the angle of the relative wind for maximum performance of the rear rotor.

3.3. Radius difference

The variation of power coefficient versus radius difference between the two rotors for various pitch combinations is shown in Fig. 5. A reference radius to evaluate power coefficient is the bigger radius of the two radii of the two rotors and the radius difference is non-dimensionalized by this reference radius. The negative value of the non-dimensional difference of radii means that the radius of the front rotor is smaller than that of the rear rotor, and zero means that the two radii are equal. In this parametric study, even if the rotor radius is changed, the TSR and σ are fixed to 8.0 and 0.05.

Fig. 5 shows that power coefficient decreases when non-dimensional difference of radii moves away from zero except below about −0.2. Because the power from the wind is proportional to the area swept by the rotor, power coefficient decreases when one of the rotor radii decreases. However, power coefficient increases again when the non-dimensional difference of radii decreases below about −0.2, despite the decrease of the front rotor radius. This explains that the outer parts of the rear rotor blades recover the wind velocity as the radial expansion radius of the fully developed stream tube of the front rotor becomes smaller than the radius of the rear rotor.

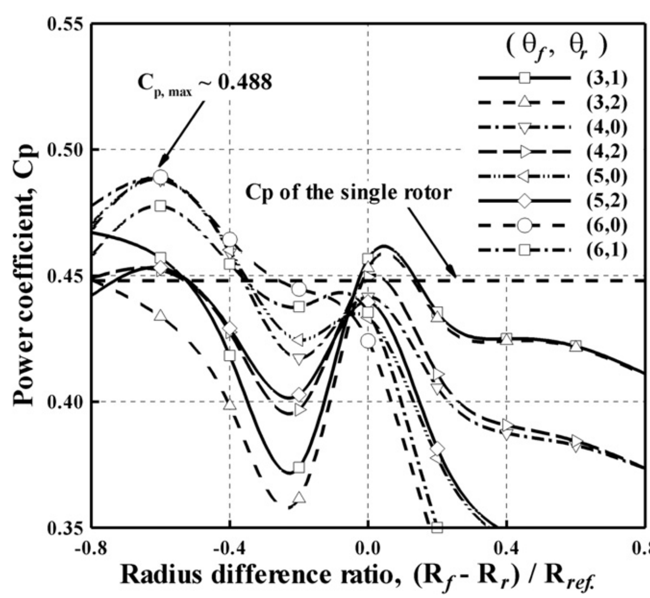

Fig. 5. Power coefficient versus radius difference between two rotors for various pitch combinations ($\sigma = 0.05$, $TSR_f = TSR_r = 8.0$).

4. Conclusion

The effects of design parameters on the aerodynamic performance of the counter-rotating wind turbine were investigated. For the parametric study, the blade element momentum theory for the counter-rotating wind turbine was established. It was assumed that the rear rotor operated inside the fully developed stream tube of the front rotor. The velocity fully reduced by the front rotor in the stream tube acted as the inflow on the rear rotor.

To consider the characteristics of the counter-rotating wind turbine having two rotors, the combinations of pitch angles, rotating speed ratios and radius differences of the two rotors were chosen as design parameters. Regarding the effect of the combinations of pitch angles on performance, the power coefficient increased when each rotor shared the total power, not when the front rotor extracted the maximum power from the wind. Moreover, the power coefficient increased when the rotating speed of the rear rotor was reduced to recover the angle of the relative wind for the maximum performance of the rear rotor. In addition, the power coefficient increased when the non-dimensional difference of radii decreased below about -0.2, despite the decrease of the front rotor radius. This explained that the outer parts of the rear rotor blades recovered the wind velocity as the radial expansion of the fully developed stream tube of the front rotor became smaller than the radius of the rear rotor. Consequently, it was demonstrated that the aerodynamic performance of the counter-rotating wind turbine can be improved by varying the combinations of pitch angles, the rotating speed ratio, and the radius difference of the two rotors.

Acknowledgement

This work was supported by the Human Resources Development and the New and Renewable Energy of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy (No. 20094020100060 & 20104010100490).

References

[1] Jongh JA, Raghavan K, van Hulle FJL. Power for the world - A common concept, study 1. ECN-C–95–037. ECN; 1996.
[2] World wind energy report 2009. WWEA (World Wind Energy Association); 2010.
[3] Betz A. Schraubenpropeller mit geringstem energieverlust. Germany: Gottinger Nachr.; 1919.
[4] Hau Erich. Wind turbines: fundamentals, technologies, application, economics. New York: Springer; 2000. pp.67–80.
[5] Newman BG. Actuator-disc theory for vertical-axis wind turbines. Journal of Wind Engineering and Industrial Aerodynamics 1983;15:pp. 347–355.
[6] Appa K. Energy innovations small grant (EISG) program (counter rotating wind turbine system). EISG Final Report, California, US; 2002.
[7] Jung S, No T, Ryu K. Aerodynamic performance prediction of a 30kW counter-rotating wind turbine system. Renewable Energy 2005;30:pp. 631–644.
[8] Kanemoto Toshiaki, Galal Ahmed Mohamed. Development of intelligent wind turbine generator with tandem wind rotors and double rotational armatures. JSME International Journal, Series B 2006;49(No. 2):pp.450–457.
[9] Shen WZ, Zakkam VAK, Sorensen JN, Appa K. Analysis of counter-rotating wind turbines. Journal of Physics, Conference Series 2007;75.
[10] Jang TJ, Heo HK. Study on the development of wind power system using mutually opposite rotation of dual rotors. Proceedings of the Renewable Energy; 2008. 2008.
[11] Lee S, Kim H, Lee S. Analysis of aerodynamic characteristics on a counter-rotating wind turbine. Current Applied Physics 2010;10:S339–42.
[12] Gordon Leishman J. Principles of helicopter aerodynamics. New York: Cambridge University Press; 2006. pp. 727–747.
[13] Vermeer LJ. A review of wind turbine wake research at TU Delft. 2001 ASME Wind Energy Symposium Technical Papers. New York: ASME; 2001. pp. 103–113.
[14] Du Z, Selig M. A 3-D stall-delay model for horizontal axis wind turbine performance prediction. AIAA-98–0021, January; 1998.
[15] Glauert H. The analysis of experimental results in the windmill break and vortex ring states of an airscrew. Technical Report No. 1026; 1926.