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Development of Flapping Type Wind Turbine System for 5 kW Class Hybrid Power Generation System

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Abstract

Even though the differential drag type machines of the vertical wind turbines are a bit less efficient than the lift type machines such as Darrieus type machines, they have an advantage of low starting torque. The flapping blade type wind turbine is a specific type of the differential drag machines, and it has no need for orientation as well as quite low starting torque. This work is to develop an innovative 5kW class flapping type vertical wind turbine system which will be applicable to a hybrid power generation system driven by the diesel engine and the wind turbine. The parametric study was carried out to decide an optimum aerodynamic configuration of the wind turbine blade. In order to evaluate the designed blade, the subscale wind tunnel test and the performance test were carried out, and their test results were compared with the analysis results.

Key words: Flapping Type Vertical Wind Turbine, Design, Analysis, Performance Test, Hybrid Power Generation System

1. Introduction

Several MW class large scale wind turbine systems have been developed in some countries. Even though the large scale wind turbine can effectively produce the electrical power, the small scale wind turbines have been continuously developed due some advantages, for instance, it can be easily built by low cost without any limitation of location, i.e. even in city, local area, etc. In case of small scale wind turbines, the vertical axis wind turbine (VAWT) is used in frequent wind direction changing region, even though it has a bit lower efficient than the horizontal axis wind turbine. Furthermore, most small scale wind turbine systems have been designed at the rated wind speed of around 12m/s, but they have a great reduction of aerodynamic efficiency in low wind speed region[1,2,3,4,7].

The differential drag type wind turbines have much lower staring torque than the lift type wind turbines like the Darrieus type wind turbine. In the differential drag machines, various types have been proposed, for instances, the cupped rotor using different drags between the concave side of hemisphere cup and the convex side id hemisphere cup, the Lafond turbine using differential impulse, reminiscent of centrifugal fans or Banki turbine, the Savonius rotor using two half cylinders whose axes are offset relative to one another, the screened machine using a movable screen by a downstream rudder and rotating vanes, the flapping blade machine using flapping blades and stoppers, and the tuning blade machine using rotating blades [5]. The flapping blade type wind turbine has much lower staring torque compared to other drag machines, and no need of orientation. However it has disadvantages such as fragility and noise caused by the impact of the blades o the stops once per revolution and wear caused by the blade movement. The flapping blade machines are divided into two types such as model with central ring and model with stoppers [5]. The model with stoppers is structurally stable relatively to the model with central ring.

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The some previous works on the flapping wind turbines are shown at You-tube, for instance, US patent 7780416 blinking sail windmill fast wind, etc. However it is only a conceptual device and not practical application [6].

Therefore this work proposes newly a 5kW class flapping-type VAWT system which is applicable to relatively low speed region, especially offshore fish farm. This wind turbine system is a low cost hybrid power supply system which is combined with the 5 kW class electrical generation system driven by diesel engine to supply continuously electrical power to the offshore farm which is independent from the grid line. The wind system adopts the flapping type which has a good starting capability at low wing speed.

2. Design procedure of flapping wind turbine system

The design procedure of the wind turbine setup firstly the system specification, then perform the aerodynamic design and the structural design[9]. In the aerodynamic design, the blade length, number of blades and tip speed ratio are firstly determined from the design requirements, and then the design is modified until meeting the target performance through the aerodynamic CFD analysis and subscale wind tunnel test.

After carrying out the aerodynamic design, the design loads are calculated from the load case analysis, and then the structural design is done based on the design loads. The structural design is modified by confirming the safety through structural analysis including static stress analysis, buckling analysis, vibration analysis and fatigue life analysis. After carrying out the structural design, the prototype structure is manufactured and the structural test carried out. The design is finalized through comparing the experimental performance test results with the analysis results. Figure 1 shows both aerodynamic and structural design procedure applied to this work.

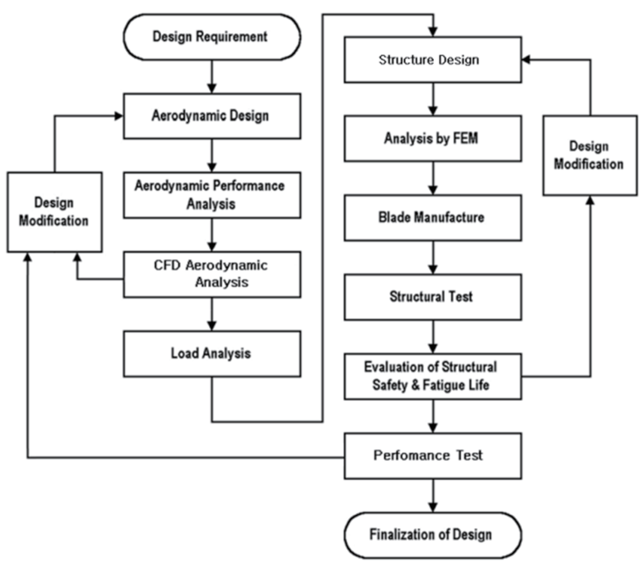


Fig. 1. Proposed aerodynamic and structural design Procedure

Table 1. Design requirements of the flapping wind turbine system.

Type	Flapping Type Vertical Axis Wind Turbine(VAWTS)
Rated power	5000W (electric power)
Rated wind speed	12m/s
Cut-out wind speed	20m/s
Maximum survival wind speed	55m/s
Rotor orientation	Anticlockwise

The proposed system is a hybrid electrical power generation system combined with the flapping type wind turbine system and the generation system driven by diesel engine to supply 5kW electrical power to offshore fish farm. This work is focused to design the 5kW class flapping type wind turbine system at the rated wind speed of 12m/s. Table 1 shows the design requirements of the flapping wind turbine system.

3. Aerodynamic Design

The flapping wind turbine can generated the torque by the differential wind drag acted on the flapping blades or fins. The flapping blades are stopped once per revolution at the stoppers. This system is no need of the wind orientation change. Figure 2 shows the arrangement of split flapping blades to produce the aerodynamic power by differential wind drag.

The following equations show how to size the optimal aerodynamic configuration of the flapper blades. The maximum power can be generated at the blade tip speed ratio λ_0 range of 0.2 to 0.6 according to references [4,5].

$$0.2 < \lambda_0 < 0.6 \tag{1}$$

$$\lambda_0 = \frac{R \cdot \omega}{V} = \frac{R \cdot 2\pi n}{V \cdot 60} \tag{2}$$

Where V is wind speed, R is radius of blade, l is blade width (or chord), and h is height (or span) of blade.

The drag force F and the power P of the flapper blade are calculated the following equations.

$$\mathrm{F} = \mathrm{C} \cdot \frac{1}{2} \cdot \rho \cdot \mathrm{V}^2 \cdot \mathrm{S} \quad (\text{plate: } \mathrm{C} \approx 2.3) \tag{3}$$

$$\mathrm{P} = \frac{1}{2} \cdot \rho \cdot \mathrm{S}[\mathrm{C}_1(\mathrm{V}-\mathrm{v})^2 - \mathrm{C}_2(\mathrm{V}+\mathrm{v})^2 \tag{4}$$

Where C is drag coefficient, C_1 is drag coefficient of downward moving flapping blade, C_2 is drag coefficient of upward moving flapping blade, and v is blade moving speed. If C_2 is assumed as zero, hence;

$$\mathrm{C}_2(\mathrm{V}+\mathrm{v})^2 \approx 0 \tag{5}$$

The v_{opt} for P_{max} can be obtained by the partial differential of the power, $\partial P/\partial v = 0$. Therefore vopt for P_{max} is V/3.

$$\frac{\partial \mathrm{P}}{\partial \mathrm{v}} = 0$$

$$= 2(\mathrm{V}-\mathrm{v})(-1) \cdot \mathrm{V} + (\mathrm{V}-\mathrm{v})^2 \cdot 1 \tag{6}$$

$$= 3\mathrm{v}^2 - 4\mathrm{Vv} + \mathrm{V}^2$$

$$\therefore \mathrm{v_{opt}} = {}^{\mathrm{V}}\!/_{3} \tag{7}$$

$$\lambda_0 = \frac{\mathrm{wR}}{\mathrm{V}} = \frac{\mathrm{v_{opt}}}{\mathrm{V}} = \frac{\mathrm{V}/3}{\mathrm{V}} = \frac{1}{3} = 0.333 \tag{8}$$

The maximum power of the proposed flapping type wind turbine expressed by equation (10) is a bit lower than the maximum power of the typical Darrieus type wind turbine expressed by equation (9).

$$\mathrm{P} = 0.25SV^3 (\text{Darrieus type wind turbine power}) \tag{9}$$

$$\mathrm{P}_{max} = \frac{2}{27} CbSV^3 = 0.213SV^3 \tag{10}$$

Generally when the flapping blade hits the stopper, impact occurs. Therefore if the flapper blade is divided into several pieces, the impact force of the small size flapper blade is reduced than one piece flapping blade. The split flapping blade is much safer in structural point of view. Therefore the optimal aerodynamic configuration is considered as the split type flapper blades shown as the Fig. 2. The power of the outer flapper blades and the inner flapper blades can be calculated by eq. (11) and eq. (12), respectively. If the area of the outer flapper blade is defined as S1 and the area of the inner flapper blade is defined as S2, the power is a function of radius R. Therefore the total power can be calculated by

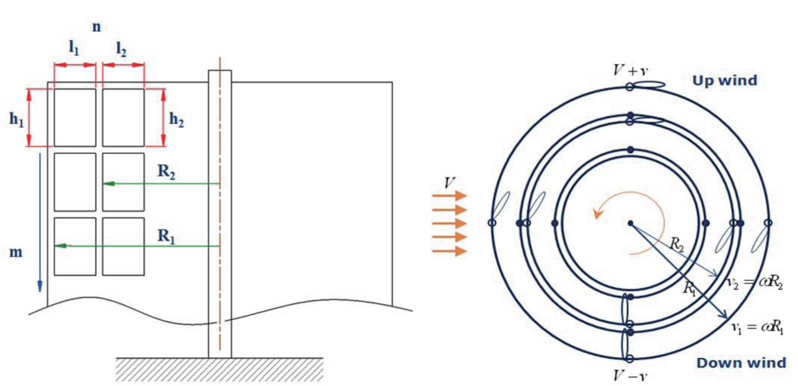


Fig. 2. Arrangement of split flapping blades with upward splits m by outward splits n

eq. (13).

$$P_{outer} = \frac{1}{2}\rho S_1 C_1 (V_{desing} - v_2)^2 v_1 \times m \quad (11)$$

where, w=n·2π, v_1=wR_1

$$P_{inner} = \frac{1}{2}\rho S_2 C_1 (V_{desing} - v_2)^2 v_2 \times m \quad (12)$$

where, w=n·2π, v_2=wR_2

$$\therefore P_{total} = P_{outer} + P_{inner} \quad (13)$$

Using the equations mentioned above, the power changes are calculated depending on several split cases such as m(upward) × n(inward), i.e., 2×2, 2×3, 2×4, 2×5, 2×6, 2×7, 2×8, 3×3, 4×4, 5×5.

Figure 3 shows the calculated power curve depending on inward split flapper blades while upward split is fixed as 2. All the split cases satisfy the target required rated power of 5kW. Among them the 2×8 split case has the lowest power but the lowest impact force, and the 2×2 split case has the highest power but the highest impact force. Therefore the 2×5 split case is selected as the optimum split case due to consideration of both appropriate power and impact force. Figure 4 shows the proposed aerodynamic configuration with the selected 2×5 split flapping blades. Figure 5 shows the estimated power of the 2×5 split case wind turbine.

4. Validation of Aerodynamic Design Results

4.1 Fluid flow analysis using CFD code

In order to evaluate the aerodynamic design results of the proposed flapping type wind turbine, the flow analysis is performed using commercial CFD code PHOENICS. Figure 6 shows 3-D numerical analysis mesh generation of the wind turbine model[8].

The assumed flow conditions of numerical analysis are 3-D turbulent, compressible, steady, isothermal flow conditions, etc. The grid generation for CFD analysis is performed from the CATIA model. Pressure distribution is calculated by

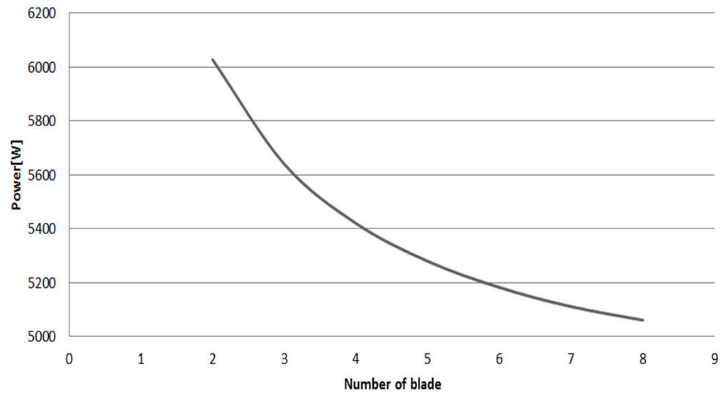
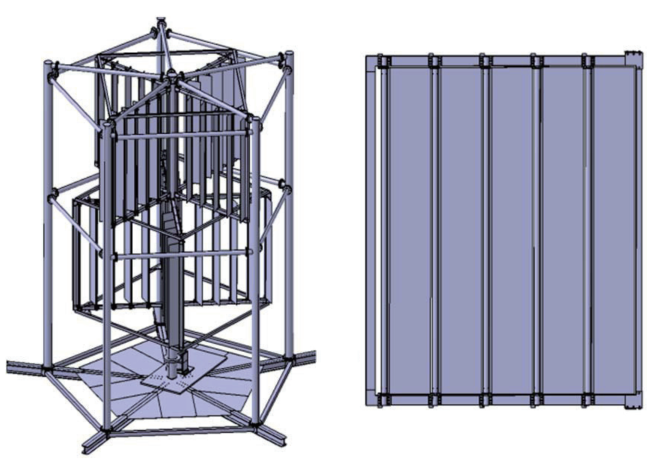


Fig. 3. Power versus number of inward split blades (upward split is fixed as 2)



(a) Assembly of wind turbine (b) flapper blades

Fig. 4. Aerodynamic configuration of designed flapper blades and its assembly

SIMPLE algorithm and the convection term calculation of standard κ-ε turbulent model is done by hybrid scheme. In the analysis, the upwind velocity is considered as 12m/s and the wind turbine rotational speed is assumed as 16rpm. Figure 7 shows the flow velocity distribution and Fig. 8 shows the pressure distribution on turbine blade. The calculated power based on flow and poser distribution is 5.4kW which is similar to the design result of 5.27 kW.

4.2 Subscale model performance test

The subscale model performance test is carried out to verify the theoretical aerodynamic design results. The proposed subscale is simplified due the complexity of the full wind turbine assembly, and the scale factor is about 14 with one upward split. Figure 9 shows schematic view and picture of subscale wind turbine model performance test setup, and Fig. 10 shows the subscale model of the flapping wind turbine rotor. The model is tested in the open type wind tunnel.

Rotational speed and torque are measured. The equivalent measured power is 4.62 kW which is a bit lower than the estimated design power due to simplification of the subscale model and differences from the real environment. Even though the model performance is a bit lower than the design result, the feasibility of the proposed wind turbine system is confirmed.

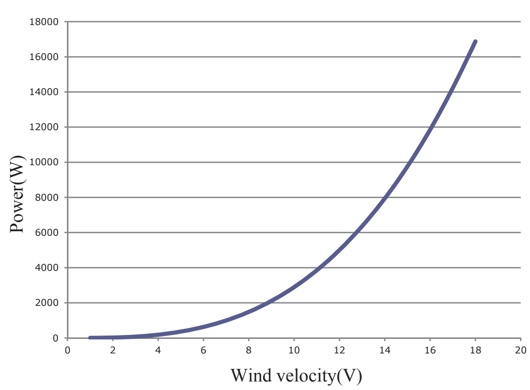


Fig. 5. Estimated power of the 2×5 split case wind turbine

5. Structural Design

The major structural parts of the flapping type wind turbine are the flapping blade and the stopper. The flapping blade must be light and stiff. Therefore the flapping blade's deflection δ_{blade} and the stopper's reaction force $R_{stopper}$ shown as Table 2 are calculated at several split cases considered in the aerodynamic design. The split flapper blade is made of stainless steel plate. As shown in Table 2 if the number of blades increases, both the blade's deflection and the stopper's reaction force decrease while the aerodynamic

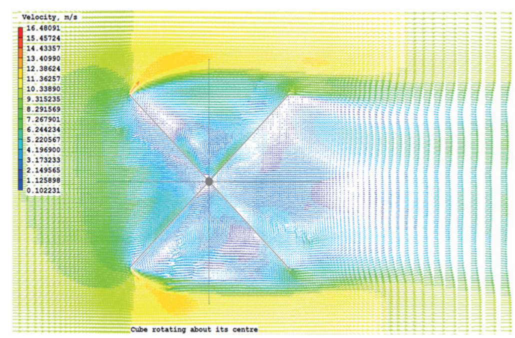


Fig. 7. Flow velocity distribution

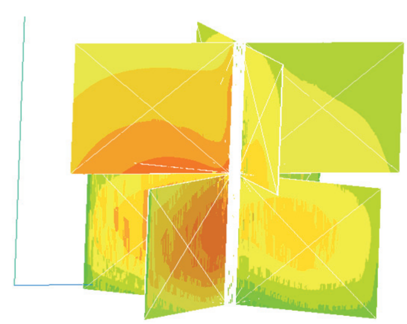
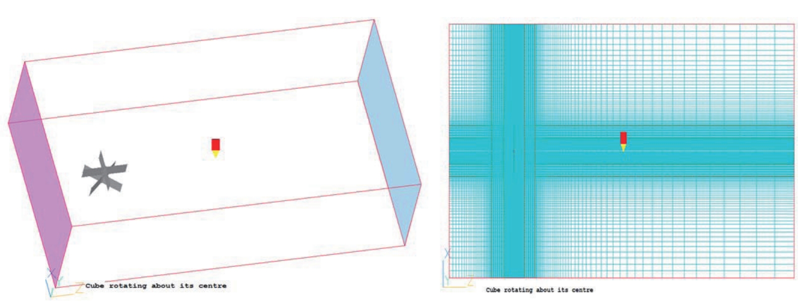


Fig. 8. Pressure distribution on turbine blade



(a) (b)

Fig. 6. Prospective view of wind turbine model (a) and3-D numerical analysis mesh generation of wind turbine model (b)

power decrease. Therefore as previously mentioned in the aerodynamic design, the final split case is selected as the 2×5 case through consideration of deflection, reaction and power. The final aerodynamic design configuration is shown as Fig. 4. The major structural design loads of wind turbine blade are aerodynamic load and centrifugal load. The detailed loading cases are shown in Table 3. In this study, the structural design of blade is performed considering on the most critical load case 3. The design summary of the proposed flapping type wind turbine system is shown as Table 4.

In order to confirm the structural safety, the designed structure is analyzed using a commercial FEM code NASTRAN. Used materials are the die-casting Al alloy ADC12 for hinge and stopper and stainless steel for flapping blade. According to stress analysis results are Von Mises max. stress of 74 MPa for hinge and Von Mises max. stress of 115 MPa for stopper shown as Fig. 11. The safety factor 1.5 for structural design is applied to this study. The stress of stopper is less than yielding strength at the maximum load case. Therefore the structural safety is confirmed that all the max. stresses are less than the yielding strength of 185 MPa.

The flapping blade's materials is a high strength stainless

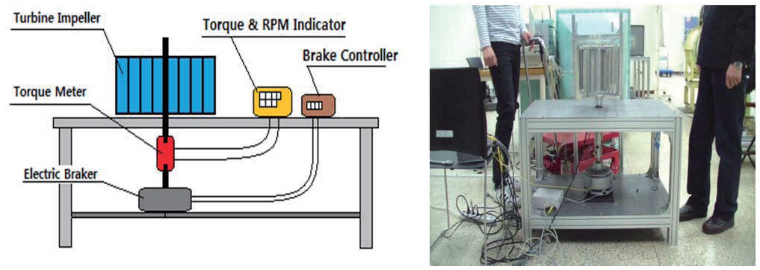


Fig. 9. Schematic view and picture of subscale wind turbine model performance test setup

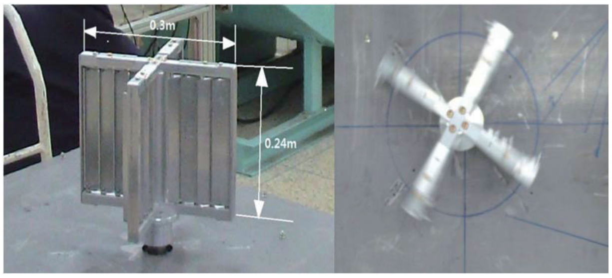


Fig. 10. Subscale model of the flapping wind turbine blade assembly

Table 2. Flapping blade's deflection and stopper's reaction force depending on flapper split cases

Split cases	S[m^2]	δ_{blade}[m]	$R_{stopper}$[kN]
5×5	0.72	4.33154E-06	1050.768
4×4	1.125	8.88266E-06	2565.351
3×3	2	2.20842E-05	8107.776
2×2	4.5	7.80996E-05	41045.616
2×3	3	9.81519E-06	12161.664
2×4	2.25	2.22066E-06	5130.702
2×5	1.8	6.93046E-07	2626.919
2×6	1.5	2.64981E-07	1520.208
2×7	1.28571	1.16505E-07	957.332
2×8	1.125	5.67161E-08	641.338

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Table 3. Load cases for structural design

Load Case	Case I	Case II	Case III
Reference wind speed	12.0 m/s	20.0 m/s	55.0 m/s
Gust condition (±20 m/s, ±40°)	Without gust	With gust	Storm condition
Rotational speed	17 rpm	24 rpm	Stop

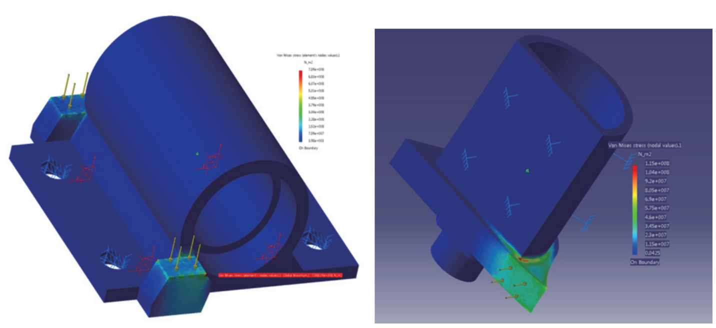
Table 4. Aerodynamic and structural design results of flapping type wind turbine

Rated power	5kW
Rated speed	12m/s
Rated RPM	16
Number of blades	8
Number of split blades	5
Radius	2.1m
Blade length	3m
Blade chord length	0.39m

steel having material properties of E=210 GPa, G=80 GPa, Poisson Ratio=0.3, t=0.8 mm, and yield strength=800 MPa. The Von Mises max. stress is 31.9 MPa and max. deflection is 3.5 mm due to cut-out condition wind load of 575 MPa. Therefore the structural safety is confirmed that all the maximum stresses are less than the yielding strength of 800 MPa.

6. Hybrid Electric Power Generation System

The hybrid electric power generation system is proposed for offshore fish farm and it is combined with diesel engine driven generator for main power and flapping wind turbine driven generator for auxiliary power, and independent from the grid line and low cost for operation[10]. Figure 13 shows the proposed hybrid electric power generation system which



(a) Hinge (b) Stopper

Fig. 11. Von-Mises stress distributions of hinge and stopper

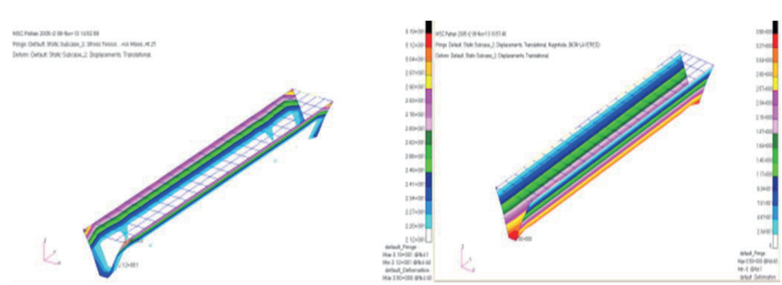


Fig. 12. Stress and deformation distribution

is composed of the flapping wind turbine power generation system, the diesel engine driven power generation system, integral controllers, wind turbine controller and battery set. The integral controller controls diesel generation system and wind turbine generation system by RS-485 serial data communication system, and monitors the system status by the GUI type real time monitoring system.

7. Performance Test

The performance test is carried out to verify the aerodynamic design results. For this purpose the specific prototype wind turbine system and the tower are manufactured. In order to avoid the ground effect, the wind turbine system is mounted on the 20 m test bed. The gear-up ratio of the wind turbine rotor to the electric generator is 1:13. The performance test is carried out during about 2 months, and the maximum wind speed is 16 m/s during the test. Figure 16 shows that the experiment performance test results are compared with the estimated aerodynamic performance. The measured performance results include mechanical loss, and the estimated performance results consider the assumed generator efficiency. It is confirmed that the measured performance results are well agreed with the estimated performance results.

8. Conclusion

This work is to propose the aerodynamic and structural design results of the 5 kW class flapping type wind turbine system for the hybrid electrical power generation system combined with the diesel engine driven power generation system to supply continuously electrical power to the offshore fish farm. In aerodynamic design, the parametric trade-off study such as several flapper blade splitting cases to get the optimal target rated power. The flow analysis is performed to estimate the target rated performance using CFD code PHEONICS. In the structural design, flapping blade's deflection and stopper's reaction force are considered. The structure analysis is performed to confirm the structural safety using FEM code NASTRAN. An optimal design result of the flapping type wind turbine is proposed. The estimated performance is confirmed through comparing with the CFD analysis and the subscale wind tunnel performance test. The prototype wind turbine system is manufactured and tested to confirm the target performance. Finally it is found that the estimated performance results of the designed wind turbine system are well agreed with the tested performance results of prototype.

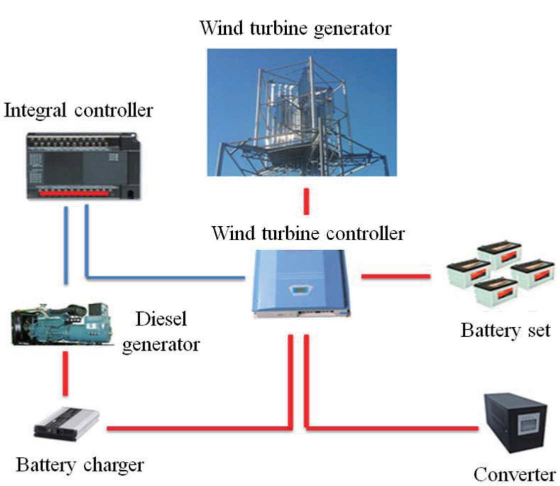


Fig. 13. Hybrid electric power generation system

Acknowledgement

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References

[1] Kong, C. and J, Kim., "Structural Design of Medium Scale Composite Wind Turbine Blade", *International Journal. of Aeronautical and Space Sciences*, Vol. 1, No. 1, 2000, pp. 92-102.

[2] Kong, C., Kim, T., Han, D. and Sugiyama, Y., "Investigation of Fatigue Life for a Medium Scale Composite Wind Turbine Blade", *International Journal. of Fatigue*, Vol. 28, No. 10, 2006, pp. 1382-1388.

[3] Kong, C., Choi, S. and Park, H., "Investigation on Design for a 500W Wind Turbine Composite Blade Considering Impact Damage", *Advanced Composite Materials*, Vol. 20, No. 2, 2011, pp. 105-123.

[4] Eggleston, D. M. and Stoddard, F., *Wind Turbine Engineering Design*, 1987.

[5] Le, G. D., *Wind Power Plants Theory and Design*, Pergamon Press, 1982.

[6] http://www.youtube.com/watch?v=c052h99VT_Y&list=PLEE6502E1E4645358.

[7] Ushiyama, I., "Introduction to Wind Turbine Engineering", Morikita Ltd., 2003.

[8] Templin R. J., "Aerodynamic Performance Theory for the NRC Vertical Axis Wind Turbine", LRT-LA160. National Research Council: Canada, 1974.

[9] IEC 61400-02. Part 2: Design requirements for small wind turbine, IEC, 2006.

[10] IEC 1400-1. Wind turbine generator system. Part I. Safety Requirement, 1st ed., IEC, 1994.