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833. Establishment and safety evaluation of a flexible test platform for the vertical-axis wind turbine

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Abstract. This work intends to construct and execute the safety evaluation of an test platform for the small vertical-axis wind turbine (VAWT), which is mounted on the rooftop of a 60 m-height building. The experiment platform designed here is flexible and suitable for carrying out the systematic performance evaluation on different types of VAWT. The wind turbine performance measurement is conducted by utilizing the data acquisition system. All environmental information and power data from sensors and generator on this platform are recorded and transferred to the computer automatically. Later, these analog signals are transformed to digital format for transmitting into computer. Also, with the aids of a visual software programming within the framework of LabVIEW, the real-time monitoring on the input/output parameters of generator and the wind condition can be accomplished simultaneously. Afterwards the data processing and in-depth analysis on the experimental outcomes are carried out via the established computer program. Consequently, the on-site performance of the wind turbine generator system is attained in an automatic and systematic manner. Moreover, to ensure for providing sufficient data and its accuracy, statistic concept is enforced to judge whether the test data are qualified or not in the data-processing procedure. Regarding the safety evaluation of wind turbine on this test platform, the numerical models of wind turbine and platform are analyzed via ANSYS Workbench to obtain the forces exerting on the main shaft and blades. This force distribution can be analyzed for checking if they can stand and meet the safety criterion under various wind speeds. Furthermore, a 2 m-diameter, multi-blade vertical-axis wind turbine (MVAWT) is introduced as a demonstrating case of the entire procedural test. Firstly atmospheric parameter, such as wind velocity, wind direction, air temperature, and air pressure is measured based on IEC 61400-12 standard on the rooftop of building for one year range measurement time. By collecting and observing the wind parameter data, such as mean wind velocity and wind direction distribution, the wind energy estimation of this MVAWT can be analyzed quantitatively. In summary, together with the data-acquisition software programmed under the framework of LabVIEW, this experimental system can provide the capability for monitoring, recording, and filtering these test data in an rigor manner, and is appropriate for executing the R&D and performance evaluation on different VAWTs.

Keywords: vertical-axis wind turbine, flexible, test platform, Labview, data acquisition system.

Introduction

Due to environmental concerns, the renewable energy industry is attracting more R&D attentions from researchers all over the world, especially in the wind energy development. It becomes one of the promising energy sources candidates in gaining zero carbon content for future applications. From the gigantic-size horizontal-axis wind turbine (HAWT) to small-size VAWT for home utility are offered by manufacturers to fulfill the alternative energy demand. Within this decade, due to the increasing demand, Taiwan's wind turbine industry is growing exponentially [1, 2], and several VAWT companies also are founded to intend filling the niche market of small size wind turbine. VAWT owns a great potential as an energy harvester since it is suitable in urban population city due to several considerations, such as an omni-directional wind turbine, rotating on low wind speed, unsteady wind conditions, low acoustic noise, and

can be mounted on the building [3, 4]. These reasons motivate the wind turbine companies to introduce their cutting edge of VAWT technologies such as innovative design, light-weight material, and intelligent controller to consumers. However, it needs verification and quality certified process to be conducted in a systematic test platform [5], before the new technology implements to the consumer. Therefore an experimental setup of test platform for the VAWT system is built to support the Taiwan VAWT development in this research. Note that the test platform designed here is flexible and suitable for executing the systematic performance evaluation on different VAWTs in an automatic and 24-hour-operation manner.

In order to capture the maximum wind energy from the building, this experimental platform is installed on the rooftop of an approximate 60 m-height building. The wind turbine platform is designed with a swivel-motion experimental shaft system and an adjustable gear-chain system to accommodate the performance measurement for various wind turbine designs. The detailed specification of platform is listed in Table 1. Platform is equipped with data acquisition system for recording the meteorological properties (wind speed, wind direction, air temperature, atmospheric pressure) [3, 6], and wind turbine operational properties (electric power output, torque, rotor speed). With the aids of the visual programming language LabVIEW [7, 8], all metrology data and wind turbine operational properties are recorded and analyzed automatically via using the statistic method. The schematic of VAWT measurement platform can be seen on Fig. 1.

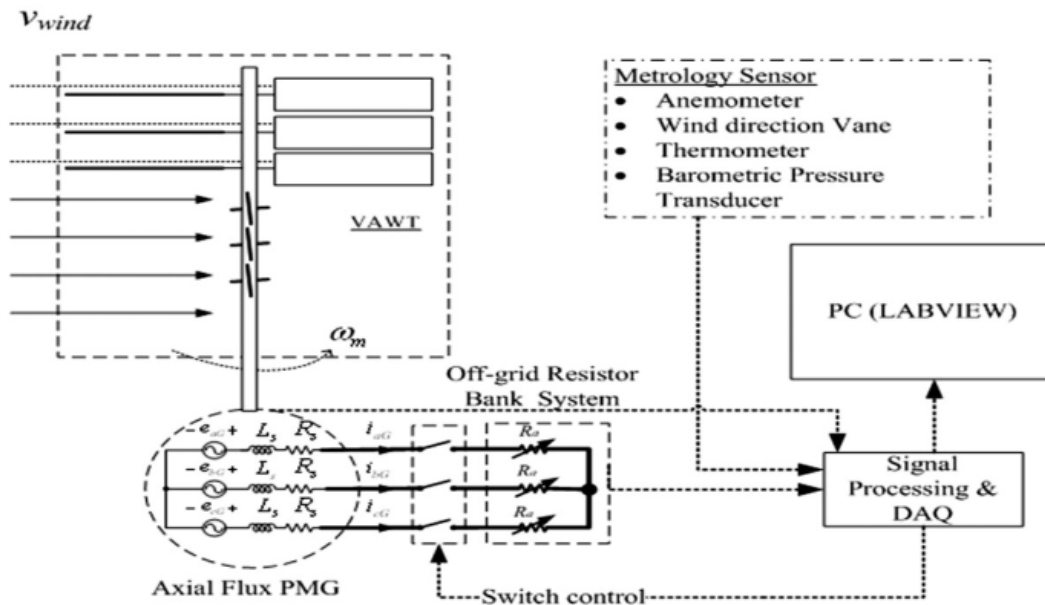


Fig. 1. The schematics of VAWT measurement platform

It is well known that the structure-induced vibration and strength are the critical concern on safety operation of wind turbine and test platform. Thus, for ensuring the operating safety of a wind turbine test system, a numerical model of wind turbine and platform are constructed via the commercial code Solidworks. It follows that this model is inserted into ANSYS Workbench [9, 10], which is the commercial finite element software, to simulate the force exerting on the main shaft and the blade. The calculated result will yield essential knowledge and accurate prediction about the structural behaviors and the safety criterion of wind turbine during operation. The major objectives of this work are to build up a systematic procedure of data

collecting and performance analysis in investigating different wind turbines' characteristics. Develop a safety evaluation numerical tool for the structure analysis of various VAWT designs.

Consequently, this study intends to support the VAWT's research and development via a combined effort of the integrated measurement platform and the structural evaluation system to assess its actual aerodynamic performance, such as the generator power output and the power curve determination, in a secure manner.

Descriptions of vertical axis wind turbine and test platform

The measurement platform is located on the roof top of a 15-story building. As indicated in Fig. 1, the platform consists of a wind turbine rotor, tower, and metrology tower. In this study, a 400 W, multi-blade, drag-type VAWT [11] is chosen as the wind turbine test sample. This selection primarily results from this VAWT's economic advantages, such as low manufacturing cost and the ability to rotate at low wind speed condition. It possesses great economic potential to be manufactured easily and cheaply as a wind energy product for under-developed countries.

This VAWT consists of 6 sets of blades with crossed configuration. Each set of blades contains two identical blades installed oppositely with 90° difference from blade's axis. This 90° difference configuration causes the down-wind-direction blade faces the wind direction while the up-wind-direction blade lays along the wind direction for each level. When the wind turbine rotates around the vertical rotor-axis, blades will be pushed by drag force dominantly. Until a certain rotation angle where the blade set is aligned with the wind direction, an auto-flap mechanism will be occurred by a counter-balance force between these two blades. This mechanism may decrease the negative torque from the down-wind-direction blade.

This VAWT is estimated to produce a 400 Watt rated power at 12 m/s, which is listed in Table 1. This 2 m-radius blade is made of a corrugated plastic (35 cm × 190 cm with 5 mm thickness) and is strengthened with the square stainless-steel frame (2.5 cm × 2.5 cm) as the blade's axis. The total dimension of VAWT is 195 cm × 400cm (height × diameter). Since the rated speed of this wind turbine is rather low, a sprocket-chain transmission system with a speed ratio 1:6 is linked with an axial permanent magnet synchronous generator (PMSG) to produce electric power. A variable resistor bank is implemented as the loading system, in which the PMSG's electric output goes through, and thus to furnish this off-grid VAWT generator system.

Table 1. Specifications of the experimental platform for the VAWT generator system

Wind Turbine	Vertical axis wind turbine
Blade type	Multi-blade drag type
Blade number	12 blades
Blade profile	flat plate, 5-mm-thick corrugated plastic, strengthen with 2.5 cm x 2.5 cm square profile stainless steel.
Blade Dimension	length: 200 cm, chord length: 35 cm.
Height	215 cm
Rotor diameter	400 cm
Swept area	8.60 m ² (height x rotor diameter)
Rotational Speed	90 rpm (max)
Base	Concrete with 4 x M15 bolts
Tower	L-shape steel structure with a swivel shaft system
Dimension	height = 2.15 m , shaft length = 1.3 m
Transmission sys.	Adjustable sprocket-chain system with speed ratio 1:6
Generator	3φ 1.5 kW Axial PMSG
Sensor	Wind speed, wind direction, temperature, air pressure, rotation speed, electric power measurement device
Control System	Off-grid LabVIEW based DAQ system

In order to collect the meteorological properties properly, the anemometer, wind direction vane, barometric sensor, and temperature sensor were installed on the meteorological station at the same height as the wind turbine's hub. It was mounted at 7 meters away from the center of wind turbine. This distance is more than 2.5 times of the wind turbine's diameter in order to prevent the uncertain test result caused by wind turbine blade's turbulence. Also, it meets the terms stated in IEC 1400-21 wind turbine power quality measurement standard [12].

To develop a reliable data recording system, NI USB-6210 DAQ-card is selected as a PC-based data acquisition system. With 16 analog input channel (16 bit, 250 kS/s), all the analog measuring signals, which come from climatic observatory and generator outputs, will be converted into ± 5 VDC signal before entering the DAQ-card. Also, with the aids of a visual software programming within the framework of Labview, the real-time monitoring on the input/output parameters of generator and the climatic condition on the rooftop can be accomplished simultaneously. Afterwards, the data processing and in-depth analysis on the experimental outcomes are carried out via the established computer program. Consequently, the actual performance of the wind turbine generator system is attained easily in an automatic and systematic manner. Moreover, for providing sufficient data and its accuracy, statistic concept is enforced to judge whether the test data are qualified or not in the data-processing procedure.

Data processing and performance analysis

Using a visual programming constructed within the framework of software Labview, all collected ± 5 VDC analog signals are converted into 16 bit digital signal for further calculation and analysis process. The sampling rate of the DAQ-card is set to 100 Hz / channel, which represents in one second there are 100 samples per channel transmitted to the data acquisition system. Then, records in each channel will be averaged statistically for every second to monitor the fluctuation of wind turbine's power measurement, and to save into a data bin for every 10 minutes. The structure of DAQ process is depicted on Fig. 2.

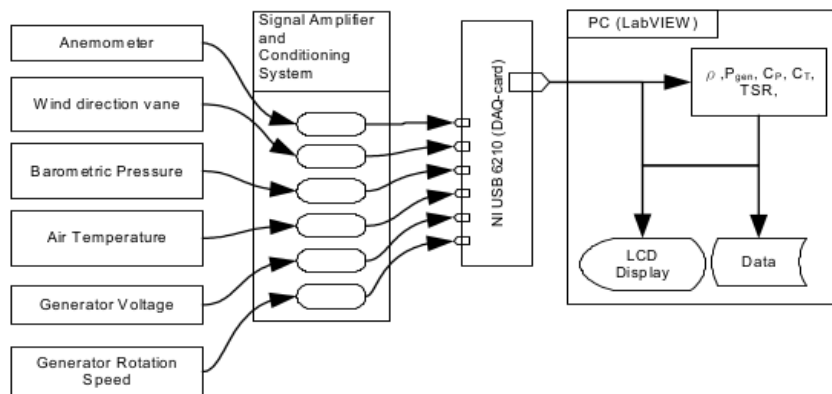


Fig. 2. Structure of data acquisition system

Several calculations are conducted to obtain the additional parameters, such as air density, tip speed ratio, electric power, power coefficient, and torque coefficient, as shown in below:

$$\rho = \frac{P}{RT} \quad (1)$$

$$TSR = \frac{\omega \cdot r}{V_{in}} \quad (2)$$

$$P_{gen} = \frac{V_{ac}^2}{R_s} \quad (3)$$

$$C_p = \frac{P_{gen}}{\frac{1}{2} \rho V_{in}^3 A} \quad (4)$$

$$C_T = \frac{T_i}{\frac{1}{2} \rho V_{in}^2 AR} \quad (5)$$

In order to acquire a reliable and stable data during measurement, all test data will be recorded when the wind speed exceeds 4 m/s for preventing the unstable starting operation of wind turbine. This action is taken to diminish the fluctuating data caused by starting up condition. Note that axial axis wind turbine is operating under the start-up and low-acceleration condition for the wind speed ranging from 2 to 4 m/s. Also, incorporated with the variable load system, the control system utilizes a similar strategy such that the loading will be applied only for the wind speed higher than 4 m/s. By removing the loading system, this small wind turbine should rotate to pass the start-up and low-acceleration stage more quickly and easily. In addition, this approach may help the wind turbine sustaining its rotation speed and keep rotating during the low-wind-speed situation.

After the measurement data are stored in sequential data files, wind distribution graph, wind speed data filtering, statistical study of every wind speed data, and wind turbine performance chart are analyzed and conducted. By using WAsP software from RISØ National Laboratory, wind properties within a certain time interval is analyzed statistically using Weibull distribution [13, 14], as plotted on Fig. 3. Figure 4 graphed the wind direction and wind speed distribution which is recorded from March 2009 to October 2009.

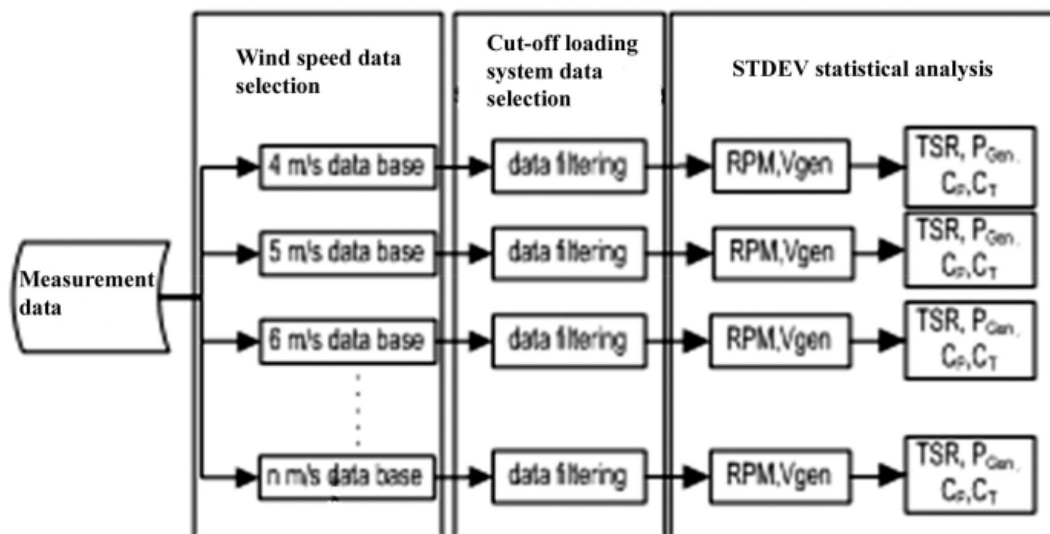


Fig. 3. Data processing and statistic analyses

Since controlling resistor bank in off-grid system may create the fluctuating results during the power measurement, so the filtering process and statistic analysis are introduced to attain the steady and reliable data. By proceeding in spreadsheet software, all experimental data will be separated and sorted according to the wind speed with 1 m/s interval database. Every wind speed database includes wind speed, wind direction, barometric pressure, air temperature,

rotational speed, generator outputs, and loading resistor. Thereafter, all data are averaged to find the mean value and standard deviation (σ) of each data distribution. By enforcing the 95 % confidence level from approximately 2000 data points, the confidence interval is obtained within ± 0.954 , which is illustrated in Fig. 5. Figure 5 shows the distribution of rotation speed. It is found that rotational speed is 8.99 ± 0.954 rpm for a 6 m/s wind speed. Overall speaking, most of the data can be analyzed with the similar confidence criterion, except for the cases of 4–6 m/s wind speed. Since wind turbine is entering the cut-in speed at 4–6 m/s, the transition situation for adding loading on generator frequently make the rotational speed falling to near 0 rpm, as indicated in Fig. 5. Even this kind of influence will gradually reduce for wind speed higher than 6 m/s; it might cause unexpected result for the data distribution. Moreover, for ensure the test reliability, the data collecting for the rotational speed ranging between 0~1 rpm is neglected completely in this work.

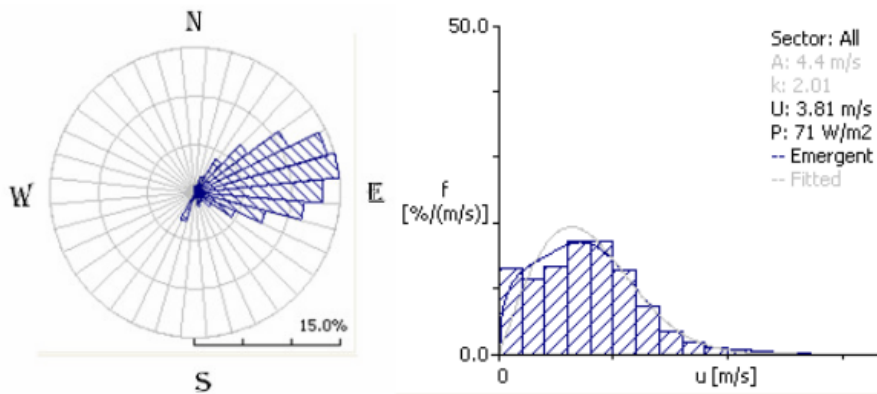


Fig. 4. The wind distribution at this VAWT test platform

Average wind speed 6.47m/s

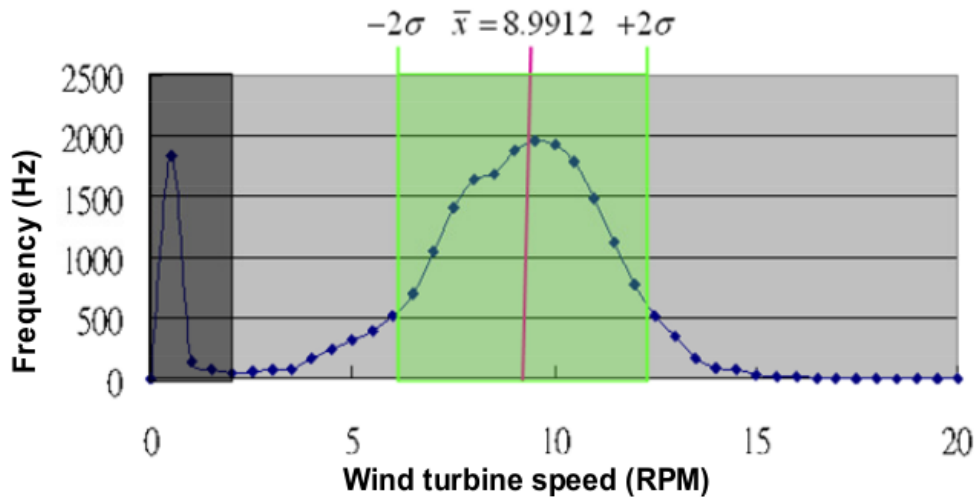
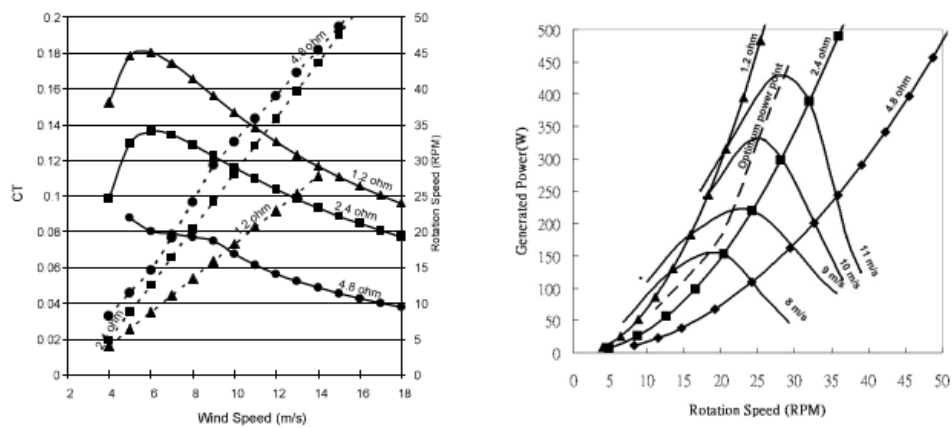


Fig. 5. Rotating speed distribution at wind speed 6 m/s

After all the data are analyzed, the aerodynamic characteristics of wind turbine are 16 strated by plotting wind speed to rotational speed at various loading conditions, such as 1.2 ohm, 2.4 ohm and 4.8 ohm. These loading amounts represent low, medium and high loading

conditions. Figure 6a shows the relationship between coefficients of torque distribution and rotation speed distribution at different wind speeds. The straight line symbolizes the torque coefficient curve at different wind speeds, while the dash line represents the relationship between rotational speed and wind speed with various loading conditions. By carefully observing the torque curve, it is found that wind turbine tends to have torque optimum at low wind speed, which is in accordance to the aerodynamic characteristics of drag type VAWT. Also, there exists a linear relationship between wind speed and rotation speed. Besides, the generated power of wind turbine is illustrated in Fig. 6b for different wind speeds and loadings. Clearly, the power characteristic curve of a wind turbine can be determined by connecting various loading condition at the same wind speed. With this systematic and lengthy process, the performance of VAWT can be determined in a rigorous manner. Consequently, these measurement data are considered as a reliable outcome after imposing the statistic analysis on all the raw data.



(a) Rotation speed and torque coefficient at various wind speeds (b) Generated power to rotation speed at different wind speeds

Fig. 6. The experimental performance characteristics of the VAWT under various loadings

Safety analysis of the wind turbine design

With the intention to establish the integrated on-site wind turbine test platform in a safe manner, the safety analysis is taken numerically to make sure the qualified structure design of wind turbine. This checking step offers a brief illustration about the wind turbine structural strength during a practical measurement, and some information about safety concerns, such as rotor brake wind speed and survival wind speed. Beforehand the wind turbine design is analyzed in ANSYS, the complexity of the geometry is simplified in CAD software SolidWorks, which is depicted on Fig. 7a. Since the blade system and the shaft system are recognized as the crucial part for safety concerns, one set of blade and a set of shaft system are used as the analysis object, as illustrated on Figs. 7b and 7c. Several assumptions, such as constant wind speed and neglecting friction, are imposed during the calculation procedure.

At first, 2 CAD files for blade set and shaft system are transferred and fed into the ANSYS. Since most of loading applied on system came from wind pressure during the normal rotating condition; thus there are a torque produce by drag force, and a moment of bending produce by wind pressure force. The drag force, torque, and safety factor can be figured out via the following equations:

$$F_d = \frac{1}{2} \rho U^2 C_D A \quad (6)$$

$$T_i = F_d r \quad (7)$$

$$SF = \frac{\sigma_{\max}}{\sigma_{\text{real}}} \quad (8)$$

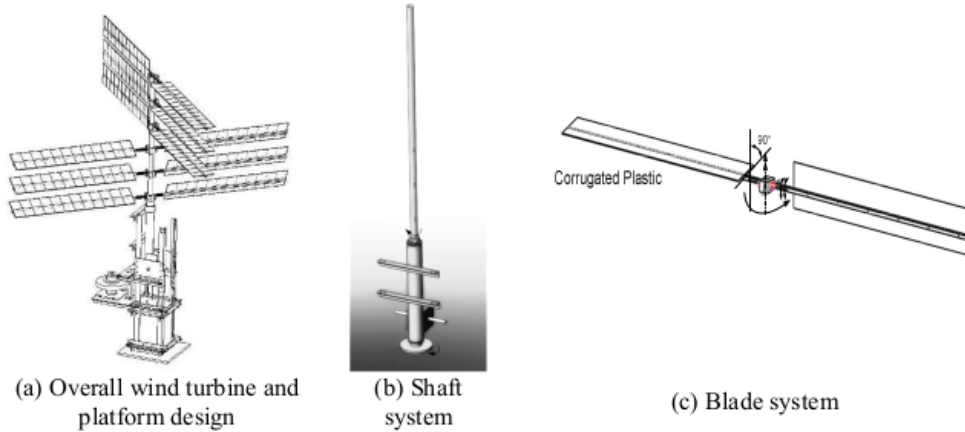


Fig. 7. Platform design of the multi-blade VAWT

Therefore, the blade and shaft system are loaded with calculated force as listed on Table 2. With this force estimation, the torque and any exerting force apply on the wind turbine system can be predicted. With these calculated data of equivalent stress and safety factor (SF) [15], the critical safety point of wind turbine system can be identified. Table 3 lists the maximum loading and safety factor occurred on the shaft system and the blade system. On Table 3 and Fig. 8b, it shows that the minimum safety factor on the shaft system is 1.93. This calculated result may deliver security information to engineers that the shaft system will not break down while running under the high wind speed in a short operation period; nevertheless, the maintenance procedure should be scheduled since the heavy loading is applied on the shaft's bearing. Most of bending moment applied on the bearing and this moment might cause vibration or wear out during the VATW's operation.

Table 2. An averaged force applied on the blade at various wind speeds

Wind speed (m/s)	Averaged force applied on blade (N)
8	44.2
10	63.3
12	82.3
14	128.4
16	98.4
18	124.6

Regards the safety analysis of blade system, the blade only may withstand a condition of wind speed below 14 m/s. As indicated in Table 2b, it will not survive or probably failed if the operation condition is exceeding wind speed 14 m/s. A drag force dominantly exerts on the blade system and causes a big bending moment on the blade axis near the hub/rotor junction. As seen in Fig. 8, the blade axis has an inadequate shape profile to endure the possible bending moment caused during the VAWT's operation.

This flawed structure design is presented as a demonstrating case to describe the capability for this integrated work in establishing a removable experiment platform for VAWT. Not only

it helps the engineer to measure and analyze the performance of different VAWTs, also it may identify and assist the engineer to estimate the structural strength of wind turbine. This estimated safety factor can serve as a warning parameter for engineer before the real on-site test takes action to conduct a safety test operation. Several safety messages might come out to prevent the wind turbine broke down. For example, we can brake up the VAWT when wind speed is exceeding the critical speed, or completely stop the wind turbine or even uninstall wind turbine when typhoon came.

Table 3. Loading conditions applied on shaft system and blades

Wind speed (m/s)	Max tensile strength (MPa)	Min. SF
8	35.4	5.85
10	50.4	4.11
12	66.4	3.12
14	107.5	1.93
16	82.3	2.52
18	100.3	2.06

(a) Shaft system

Wind speed (m/s)	Max tensile strength (MPa)	Min. SF
8	128.1	3.28
10	217.3	1.71
12	250.2	1.32
14	331.8	0.85
16	278.2	1.10
18	324.5	0.88

(b) Blade system

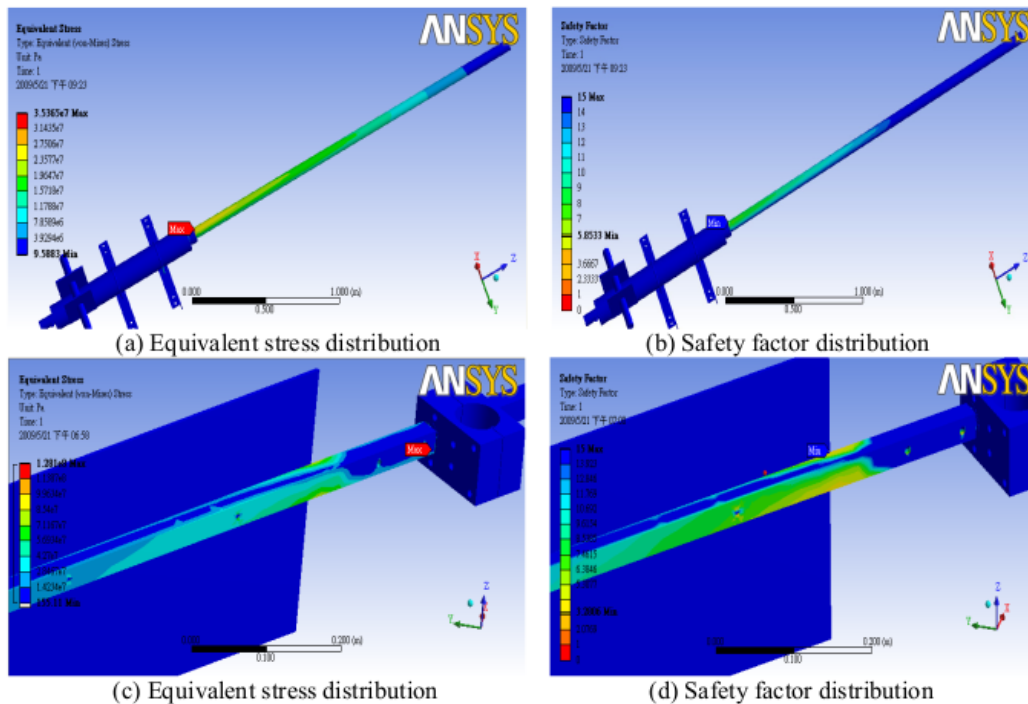


Fig. 8. Numerical calculations of the shaft system

Concluding remarks

A safety evaluation of a removable experiment platform for VAWT was conducted in this integrated numerical and experimental research. It is started with developing an adaptable platform which may conduct the performance evaluation for different VAWTs. Then, together with the data-acquisition software programmed under the framework of Labview; it can provide the capability for monitoring, recording, and filtering these test data in a real-time and systematic manner. This flexible and automatic test platform is appropriate for executing the R&D and the on-site performance evaluation on various VAWTs. Moreover, to ensure for providing sufficient data and its accuracy, statistic concept is enforced to judge whether the test data are qualified or not in the data-processing procedure. Consequently, the actual performance of the wind turbine generator system is attained conveniently in an automatic and rigor manner.

Furthermore, a safety analysis of the wind turbine design is performed numerically with the aids of ANSYS. Therefore, not only this investigation can assist engineer to measure and analyze the performance of VAWT, also it may identify and assist the engineer to estimate the structural strength of wind turbine. This estimated safety factor can serve as a warning parameter for engineer before the real on-site measurement takes action. In summary, this integrated research successfully combines the experimental, data collecting and analyzing scheme, and numerical technique together to provide the capability to automatically conduct the R&D and performance evaluation on different VAWTs in a rigor and safe manner.

Nomenclatures

A	= Wind turbine sweep area, m ² .
C_p	= Power coefficient.
C_T	= Torque coefficient.
C_d	= Drag coefficient.
ρ	= Air density, kg·m ⁻³ .
σ	= Standard deviation.
σ_{max}	= Ultimate strength of material, MPa.
σ_{real}	= Ultimate loading, MPa.
ω	= Rotation speed, rad·s ⁻¹ .
F_d	= Drag force, N.
P	= Barometric air pressure, kPa.
P^{gen}	= Generator power, Watt.
R	= Radius of wind turbine, m.
R_s	= Loading, ohm.
T_{SR}	= Tip speed ratio.
T	= Air temperature, K.
T_i	= Torque, N·m.
V_{ac}	= Single phase voltage, Volt.
V_{in}	= Wind speed, m·s ⁻¹ .

Acknowledgments

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