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Straight-Bladed Vertical Axis Wind Turbines: History, Performance, and Applications

Yan Li

Abstract

Wind turbine is a kind of rotating machinery. Although the horizontal axis wind turbine (HAWT) is the most popular wind turbine, the vertical axis wind turbine (VAWT) with the main advantages of smart design, novel structure, and wind direction independence receives more and more attention in small-scale wind power market. The straight-bladed VAWT (SB-VAWT) is one of the most researched and studied VAWTs. In this chapter, the historical development of the SB-VAWT will be briefly reviewed firstly. Then the aerodynamic models for the turbine design and performance analysis will be introduced. Finally, the types of traditional and new SB-VAWT and their characteristics and main utilizations will be introduced.

Keywords: vertical axis wind turbine, straight-bladed, aerodynamics performance, wind tunnel test, numerical simulation, application

1. Introduction

Wind turbine is a kind of rotating machine which can convert wind energy to mechanical energy, thermal energy, or electrical energy. With the years of research and development, many kinds of wind turbine were proposed and invented. There are some ways to classify different kinds of wind turbines. Generally, wind turbines can be classified by application, capacity, blade number, relative position of rotor shaft to ground, type of aerodynamic forces generated by blade, and so on. Among them, the relative position of rotor shaft to the ground and the aerodynamic forces of blade are the two main ways for classification of wind turbine. According to the relative position of rotor to ground, wind turbines can be classified into horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). According to the force type of the blade, wind turbines can be classified into lift-type wind turbines and drag-type wind turbines. The main kinds of wind turbines are shown in **Figure 1** [1].

Based on the progress of aerodynamic theory of aircraft, the propeller-type HAWT becomes the most popular lift-type wind turbine in the world. Nevertheless, the VAWT has not been paid so much attention in the past. In this modern time, benefiting from the rapid progress of large-scale wind turbine and wind farm, the small-scale wind turbine which can be used for distributed generation and off-grid wind power market has also received more and more attention. However, there are some disadvantages of small-scale wind turbine comparing with the large-scale

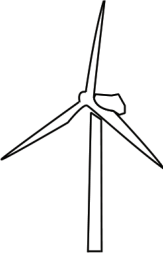
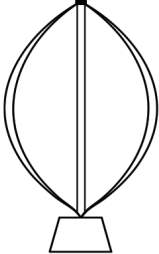
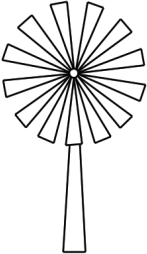
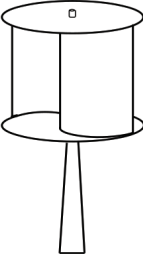
	HAWT	VAWT
Lift Type		
Drag Type		

Figure 1.
Main categories of wind turbine [1].

one, such as small swept area of rotor, difficulty of starting at low wind speed, and getting affected easily by wind speed and direction. For HAWT, the rotor should always face the wind direction. Therefore, a yaw system must be equipped. However, the VAWT can receive wind from any direction and does not need a yaw system. This is the biggest difference between the HAWT and VAWT. Due to its characteristics of independence from wind direction comparing with the HAWT, the VAWT can be thought as a good choice for the small- and middle-scale wind power market [2].

Although there are some types of VAWT, the straight-bladed vertical axis wind turbine (SB-VAWT) as a kind of lift-type VAWT with the main advantages of simple design, low cost, and good efficiency becomes one of the most researched and studied VAWTs. The SB-VAWT can be thought as a good choice for serving to the off-grid small-scale energy system which is one of the most important renewable energy resources for the people in urban area and countryside [2].

In this chapter, the historical development of the SB-VAWT will be briefly reviewed firstly. Then the aerodynamic models for the turbine design and performance analysis will be introduced. The research methods including wind tunnel test, visualization test, and numerical simulation are also introduced. Finally, the main utilizations and applications are introduced briefly.

2. Brief history of the development of SB-VAWT

2.1 The development of VAWT

Wind energy has been used for centuries for mankind. The earliest practical wind machines which could be found in documentary records were the vertical axis windmills [1]. These windmills were almost drag type with a multibladed rotor operating at very low tip-speed ratios (much less than unity), which explains their poor efficiency. In spite of the simple design, these types of wind turbines need large amounts of material, are not able to withstand high wind loads, and thus have not proven cost-effective. At the end of the nineteenth century, there were more than 30,000 wind mills in Europe, used primarily for the milling of grain and water pumping [3].

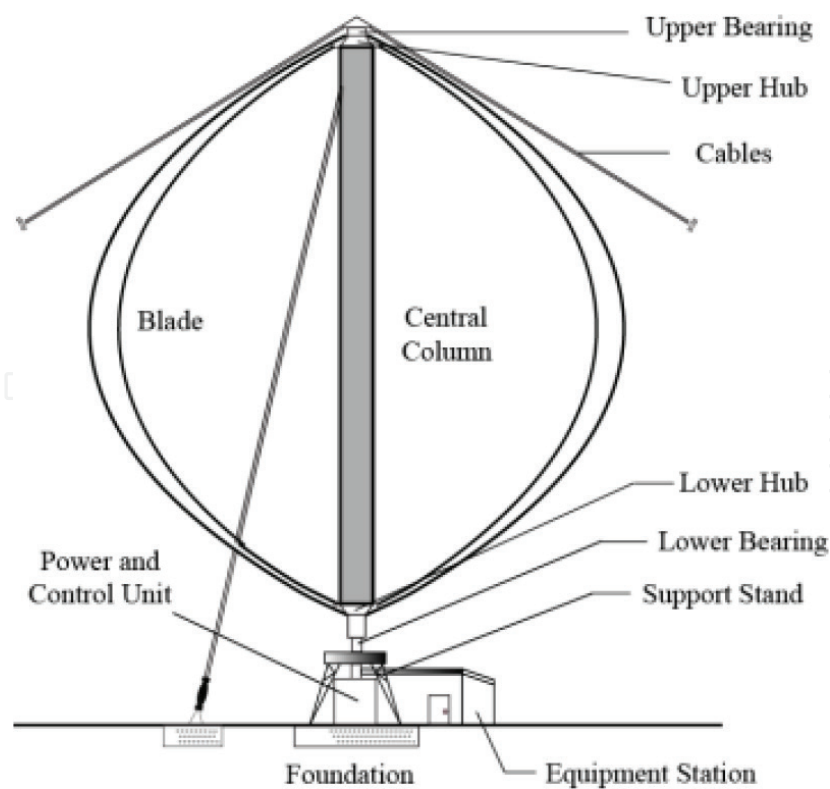


Figure 2.
Darrieus-type VAWT [3].

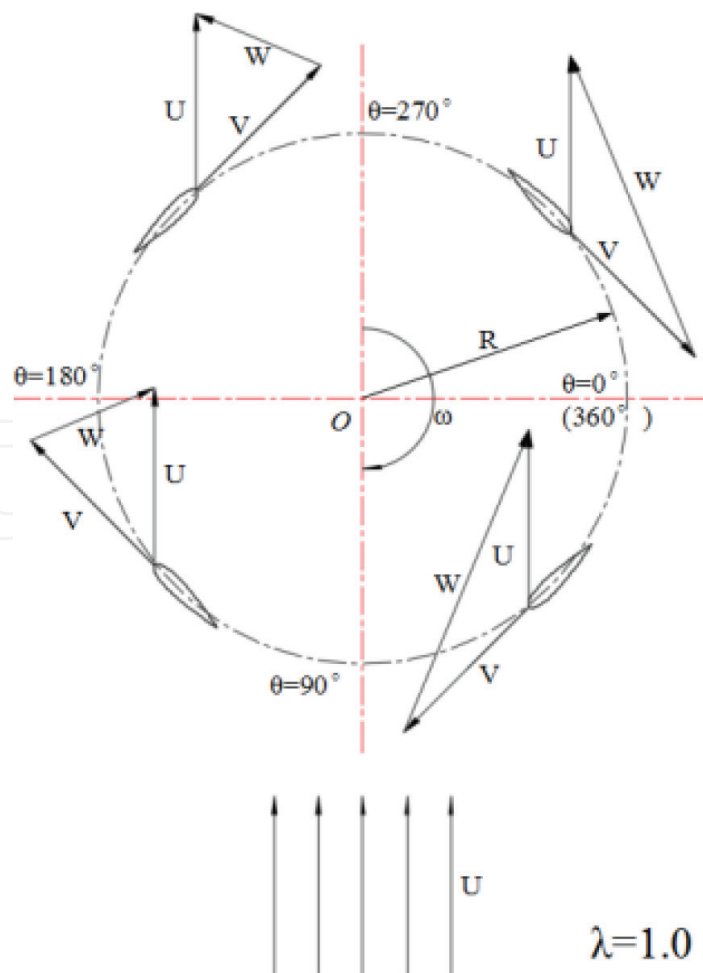


Figure 3.
Blade local relative velocities at different rotating angles (where U is wind speed, V is rotational speed of blade, and W is relative speed).

There was a golden development period of VAWT in 20 ~ 30s of the 20th century. At that time, some typical VAWTs were proposed and researched, mainly including Savonius rotor, Madaras rotor, Darrieus VAWT, and so on. The Darrieus VAWT is the most important one [3].

The Darrieus VAWT was invented in 1931 by a French engineer named George Jeans Marie Darrieus [4]. In the patent he proposed, there were two kinds of rotors included both the “curved blade” and “straight-bladed.” Usually, the wind turbine with curved blade is just called as Darrieus VAWT. The turbine rotor with straight blade is called straight-bladed Darrieus-type VAWT, or straight-bladed VAWT simply. The Darrieus VAWT is basically a lift-type wind turbine. The rotor consists of two or more airfoil-shaped blades which are attached to a rotating vertical shaft. **Figure 2** shows a typical Darrieus VAWT according to the book written by Prof Ion Para [3]. The Troposkien curve is often selected for the curved blade shape, which can minimize the bending stress in the blades. The changes of local relative velocity of blade during a revolution are shown in **Figure 3**. Darrieus VAWT was commercially deployed in the USA and Canada in the past.

2.2 The SB-VAWT

The SB-VAWT can be thought as a kind of Darrieus VAWT whose curved blades are replaced by straight blades [3]. Therefore, it always was called as H-Rotor for its rotor outlook. Compared with the Darrieus VAWT, the rotor structure of SB-VAWT is simpler, and the cost of manufacture is cheaper. **Figure 4** shows the structure of a typical SB-VAWT. Generally, a normal SB-VAWT usually has 2–6 blades. The NACA series symmetrical airfoils are often adopted for blades.

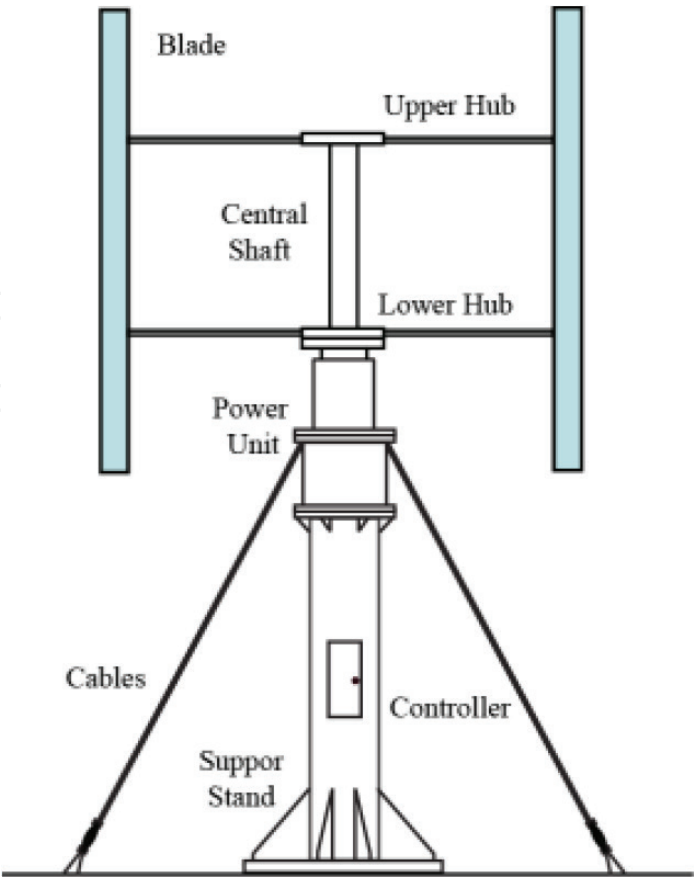


Figure 4.
Straight-bladed VAWT.

3. Aerodynamic characteristics: research methods

3.1 Aerodynamic computational methods

As a kind of wind turbine, the research methods of aerodynamic characteristics for wind turbines are all suitable for SB-VAWT. There are two main kinds of research ways including theoretical method and experimental method. The theoretical method includes aerodynamic computational models and numerical simulation [5, 6]. The experimental method mainly includes wind tunnel test, visualization test, and field test.

Although the structure of SB-VAWT is relatively simple comparing with HAWT, the aerodynamic characteristics are rather complex. **Figure 5** shows the main theoretical methods which are divided into two main categories. There are three typically aerodynamic models including momentum model, vortex model, and cascade model [6]. The first two methods are frequently used. These models are very important for deducing optimum design parameters and also for predicting the performance of SB-VAWT. The momentum theory is the most important method for analyzing the aerodynamic characteristics of blade both for HAWT and VAWT. It has three kinds of theory including momentum model, blade element model, and blade element momentum (BEM) model. The BEM model is the most widely used method even now. Based on the BEM model, an aerodynamic computational model, streamtube model, just used for Darrieus-type VAWT, was proposed. In 1974, Templin [7] proposed the single streamtube model firstly for the aerodynamic performance of Darrieus VAWT. This method is the simplest streamtube model. In the same year, an improved model, multiple streamtube model, was proposed by Wilson and Lissaman [8]. From then on, some other streamtube models were proposed [9–11]. The most important streamtube model, double-multiple streamtube model, was proposed by Ion Paraschivoiu in 1981 [12]. This model is one of the most widely used methods for analyzing the aerodynamic characteristics of Darrieus-type VAWT. The detailed information can be found in the book written by Ion Paraschivoiu [3]. The schematics

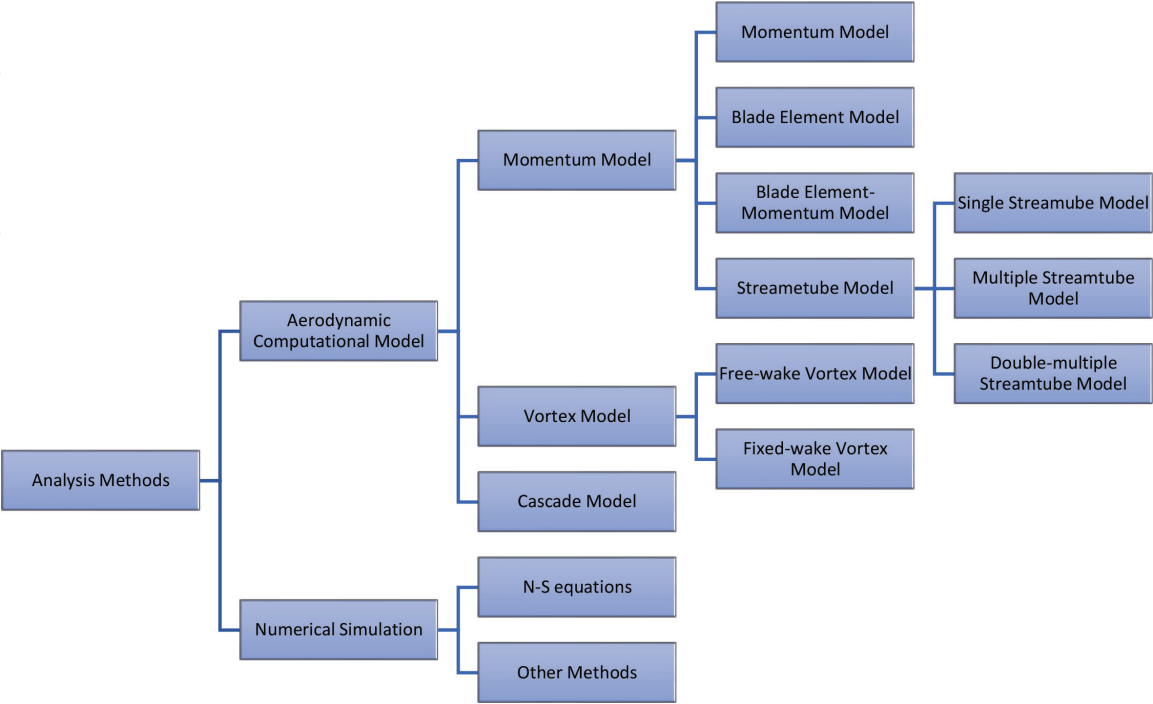


Figure 5.
Main theoretical methods for SB-VAWT.

of three kinds of streamtube model are shown in **Figure 6**. In **Figure 6(a)**, V is the wind velocity, V_a is the induced velocity, and V_w is the wake velocity in downstream side. For **Figure 6(b)**, the V_1 , V_2 , and V_3 are the wind velocities in different stream tubes; the V_{a1} , V_{a2} , and V_{a3} are the induced velocities in different stream tubes; and V_{w1} , V_{w2} , and V_{w3} are the wake velocities in different stream tubes.

The streamtube models equate the forces on the rotor blades to a change in streamwise momentum through the wind turbine rotor. Therefore, the momentum model can predict well the overall performance of the wind turbine when the loads on rotor blades are light and the tip-speed ratios are relatively low. However, for the condition of high tip-speed ratios and high rotor solidities, the momentum model is inadequate. Therefore, another aerodynamic model, the vortex model, was proposed and developed based on vorticity equations [13]. The vortex models

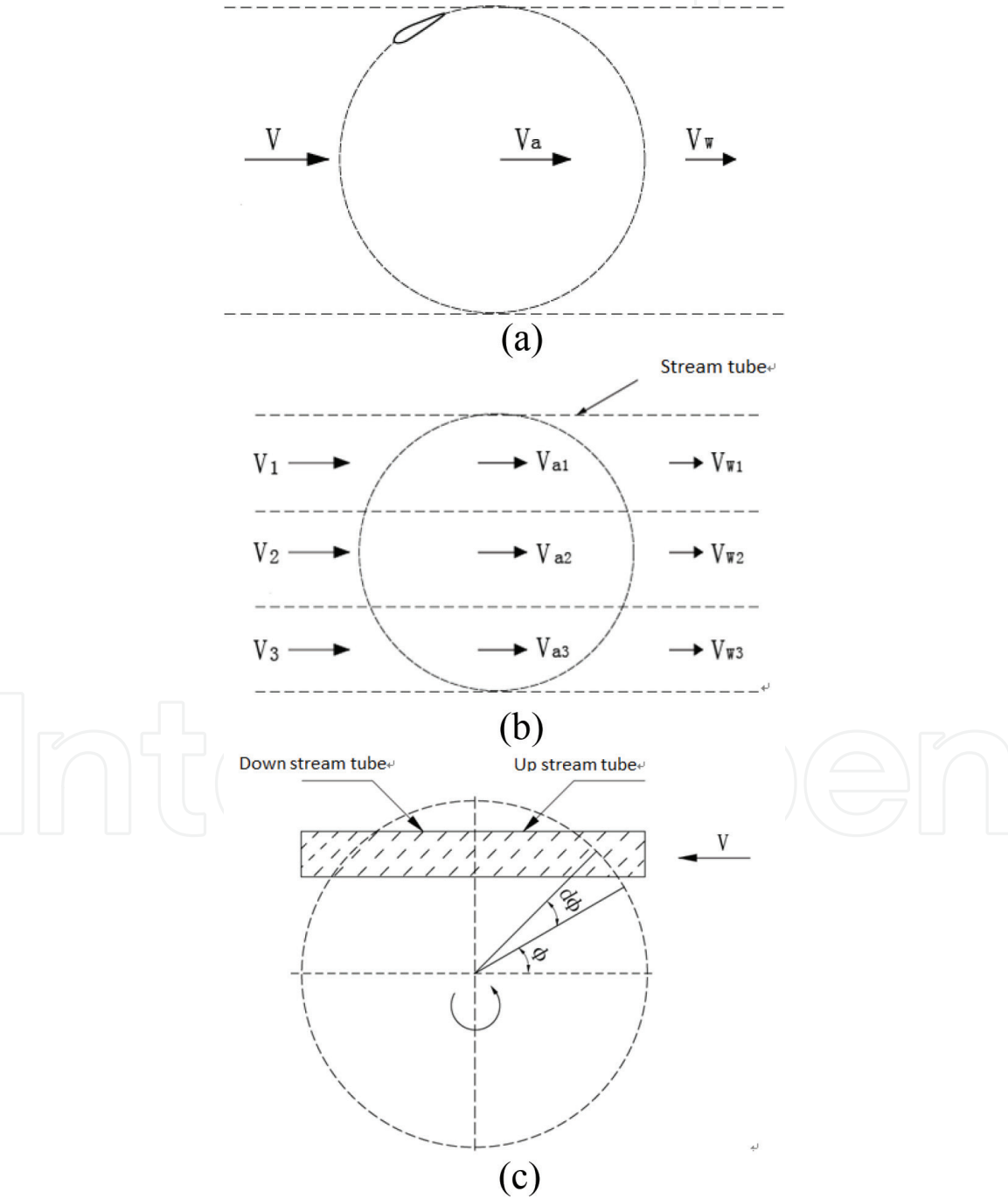


Figure 6. Schematic of three kinds of streamtube models [6]. (a) Single Streamtube Model, (b) Multiple Streamtube model, (c) Double-Multiple Streamtube model.

are basically potential flow models based on the calculation of the velocity field of the turbine through the influence of vorticity in the wake of the blades. The vortex model includes two kinds, free wake model and fixed wake model. The detailed information can be found in the relative references [6].

Numerical simulation based on computational fluid dynamics (CFD) is another important research method developed rapidly in recent years. With the fast development of computer science and technology, numerical simulation has become a main method for analysis and design of SB-VAWT. More and more researchers begin to use this way to develop a new type of SB-VAWT. In the modern time, the researchers have tried to combine these models together to simulate the aerodynamic performance of SB-VAWT [14–17]. Because the blade of SB-VAWT is straight, the blade section along span direction is the same. Therefore, two-dimensional simulation is often used. Of course, it can be thought that the three-dimensional simulation may have better accuracy. The time and cost for simulation will be higher on the contrary. **Figure 7** shows an example of two-dimensional meshing around the blades of a three-bladed SB-VAWT and the 3D flow field around rotor.

3.2 Experimental methods

Experimental methods can be thought as the most direct and effective method if the tests are well done. Usually, for wind turbine aerodynamic performance, the experiments can be categorized as wind tunnel test, visualization test, and field test. The following introduction of experimental methods is based on the author's research works in Northeast Agricultural University (NEAU) of China [18–20].

3.2.1 Wind tunnel test

Usually, the wind tunnel can be categorized as closed layout type and open jet type. Both of them can be used for aerodynamic characteristics test of wind turbines. Furthermore, according to the section shape of test part, it can be divided into round shape section and square shape section. For SB-VAWT, the wind tunnel with square shape section can be thought as more suitable. **Figure 8** shows a wind tunnel experimental system in NEAU. Considering the blockage effect, blockage ration defined as ration of the swept area of rotor against section area of wind tunnel should be less than 35%. Usually, the power can be obtained by measuring the torque and revolution of rotor. The aerodynamic performance evaluation indicators include power coefficient (C_p), torque coefficient (C_t), and tip-speed ratio (λ) defined as the equations shown below.

$$C_t = \frac{T}{\frac{1}{2}\rho A R U^2} \quad (1)$$

$$C_p = \frac{T\omega}{\frac{1}{2}\rho A U^3} = \frac{P}{\frac{1}{2}\rho A U^3} \quad (2)$$

$$\lambda = TSR = \frac{\omega R}{U} = \frac{\pi D n}{30U} \quad (3)$$

Where ρ (kg/m³) is air density, U (m/s) is the incoming flow velocity, R (m) is rotor radius, D (m) is rotor diameter, A (m²) is the cross-sectional area of the rotor, ω (rad/s) is angular velocity of the rotor, n (RPM) is the rotational speed of rotor, T (N•m) is the rotor torque, and P (m/s) is output power (W).

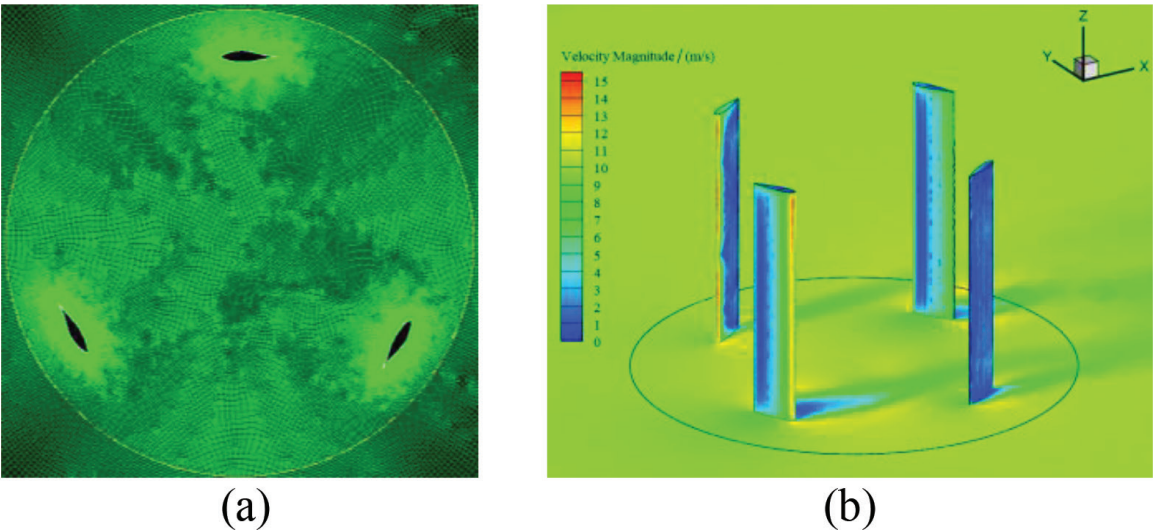


Figure 7.
Examples of numerical simulations for SB-VAWT. (a) 2D meshing and (b) 3D flow field.

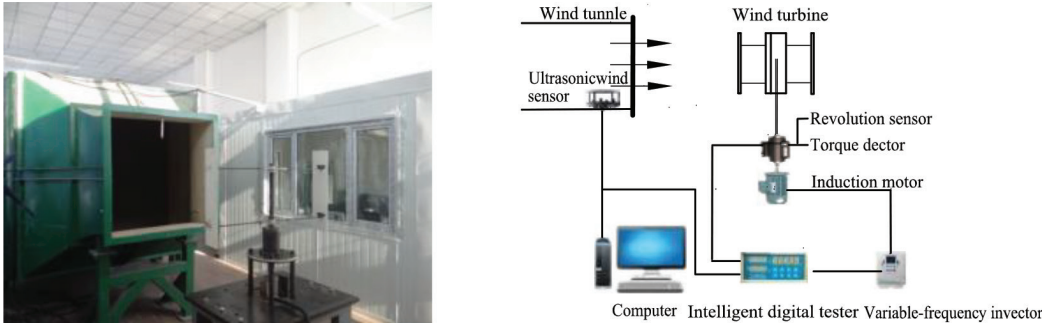


Figure 8.
Wind tunnel test system in NEAU for SB-VAWT.

3.2.2 Visualization test

The flow fields around wind turbine rotor are very complex. To investigate the performance, the flow mechanism should be researched. The visualization tests on flow fields around rotor are an important way. Benefiting from the visual technology, many methods were proposed, such as smoke-wire method, laser method, PIV, PTV, etc.

Figure 9 shows a schematic diagram of the visual experiment system in NEAU by smoke-wire way and the photo of flow field around a three-bladed SB-VAWT rotor obtained in the test. The test model was placed at the same center of the wind tunnel outlet and downstream from the outlet. The smoke-wire generator was set up at the center of the outlet of wind tunnel, and its volt was controlled to generate smoke wire. A CCD camera was placed above the test model to take photo. Visual photos of the flow path lines in and around the rotor were obtained and can be processed by image software in computer.

Recently, the particle image velocimetry (PIV) technology becomes more and more popular. PIV is an optical method of flow visualization used to obtain instantaneous velocity measurements and related properties in fluids. The sufficiently small particles named tracer particles are input into fluid, and their motion can be captured by CCD camera. Based on the relative function and computational methods, the velocity field of the flow can be obtained. Furthermore, the vorticity and pressure distributions around wind turbine blades can be also calculated. **Figure 10** shows an example of PIV system experimental system in NEAU and the flow fields around blade of SB-VAWTs at different azimuth angles.

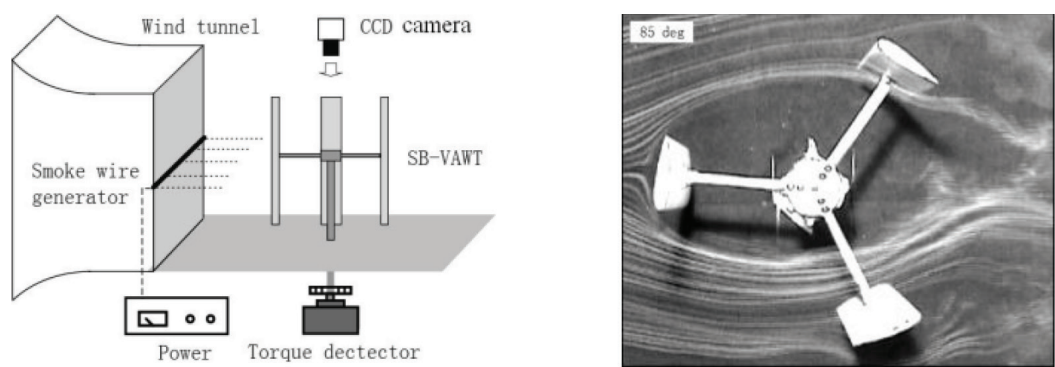


Figure 9.
Schematic diagram of the visual experiment system.

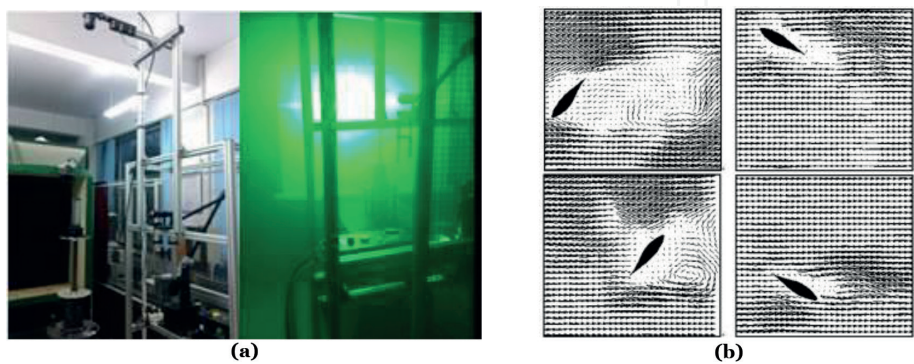


Figure 10.
An example of PIV experimental system for VAWT. (a) PIV system for VAWT and (b) flow fields obtained by PIV test.



Figure 11.
A prototype SB-VAWT for field test in NEAU.

3.2.3 Field test

To obtain the true and reliable aerodynamic performance of VAWT, sometimes, the field tests will be carried out after theoretical research or even wind tunnel tests. A prototype wind turbine, not the rotor only, should be designed

and fabricated. The turbine should be located in the area with good wind speed conditions. Continuous power performance measuring and testing are required for a long period of time. **Figure 11** shows a prototype SB-VAWT for field test in NEAU. Because the wind in nature is always changed both the wind speed and direction. The situation is different with the lab. Therefore, the results of field tests are often lower than that obtained by lab test.

4. Aerodynamic performance improvement researches

Since the SB-VAWT was proposed, many efforts have been made to study the ways on its performance improvement. The aerodynamic performance of SB-VAWT has gradually become more and more clear. However, there are still some disadvantages that should be improved comparing with the propeller-type HAWTs. The power performance of SB-VAWT is rather lower than the propeller-type HAWT, and the starting performance under low wind speed is not so good. To improve these disadvantages, investigations have been carried out, and the research methods can be summarized as mainly three ways [21]:

1. By developing new rotor structure or blade airfoil
2. By combining drag-type VAWT rotor
3. By adding additional device

4.1 Blade and rotor structure researches

In the early stage, there was no special airfoil for the blade of SB-VAWT. The blade airfoil for aircraft or HAWT was often adopted, such as NACA series. Prof. Seki from Tokai University in Japan took up the research on blade airfoils for SB-VAWT from 1976 year [22]. **Figure 12** shows a specialized TWT airfoil for SB-VAWT which was exploited in Tokai University. In recent years, more and more airfoils have been researched for the utilization of SB-VAWT. **Figure 13** shows the aerodynamic performance researches of SB-VAWT with 20 kinds of airfoil [23].

Figure 14 shows the main rotor structure types of SB-VAWT. The (a), (b), and (c) in the figure are the most basic types. The others are the improved types for increasing some performance, starting performance, decreasing blade tip loss and rotor structure strength performance, etc. As an example, to tilt the blade at certain angles shown in **Figure 14(d)–(f)** may improve the starting performance. By making the blade bend at certain angles, the loss of blade tip may be decreased as shown in **Figure 14(g)** and **(h)**. For the rotor with long blade, dividing one blade to several stages can reduce blade manufacture cost.

4.2 Combining drag-type VAWT rotor

For the researches on combining with drag-type rotor, as the most famous drag-type VAWT, Savonius rotor is often used to be added in the rotor of SB-VAWT



Figure 12.
TWT airfoil [22].

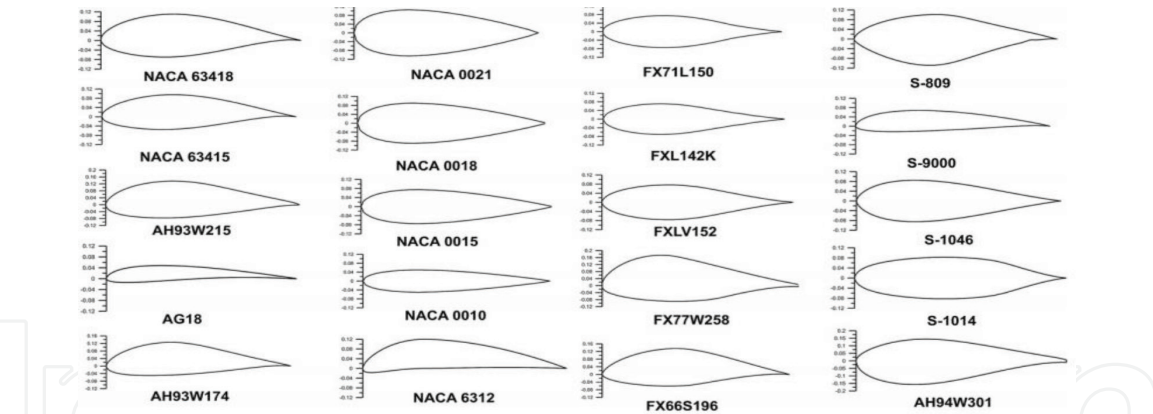


Figure 13.
Twenty kinds of airfoil research for SB-VAWT [23].

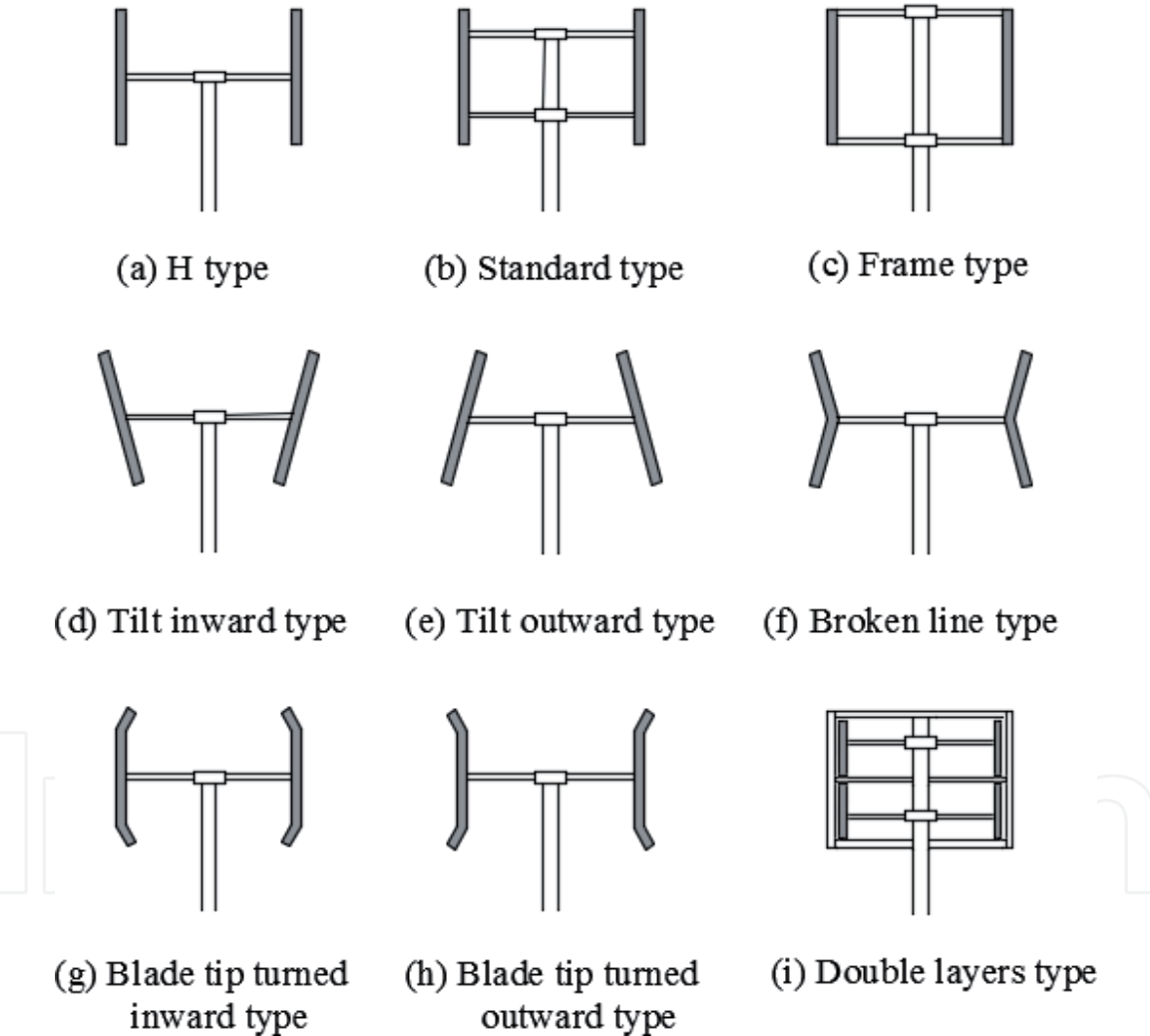


Figure 14.
Main rotor structures of SB-VAWT.

to increase its starting performance [21]. This method is firstly used for increasing the starting performance of Darrieus VAWT because the Darrieus VAWT can start rotation itself as shown in **Figure 15** [24]. **Figure 16** shows some examples of this kind of lift-drag combined-type VAWTs.

Although the improvement of starting performance by adding Savonius rotor is obvious, the power performance at high rotational speed is greatly affected. The reason is mainly because the Savonius rotor will be turned into a load when its

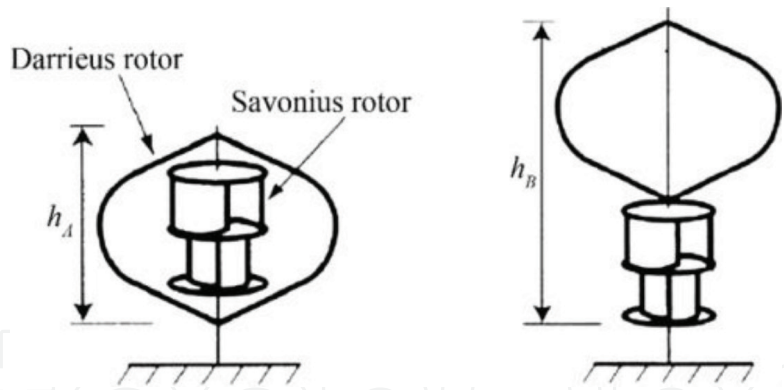


Figure 15.
Savonius-Darrieus combined-type VAWT [24].

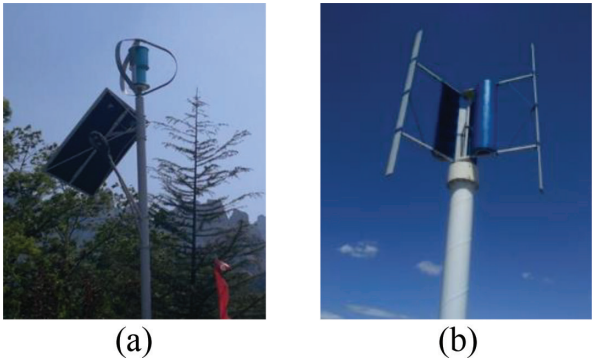


Figure 16.
Lift-drag combined-type VAWTs. (a) Street lamp and (b) wind turbine.

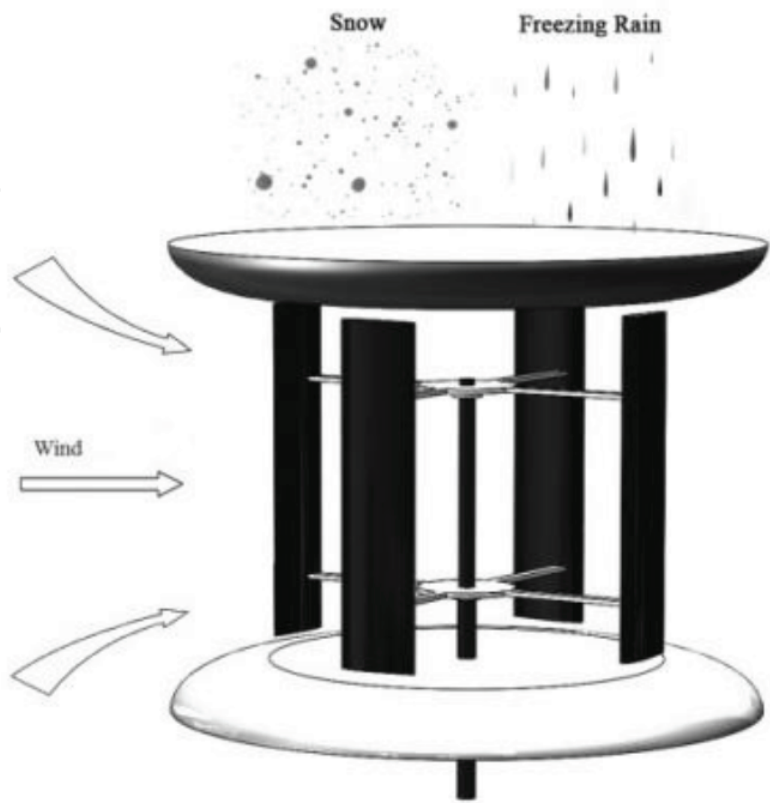


Figure 17.
SB-VAWT with WGD up and down of the rotor.

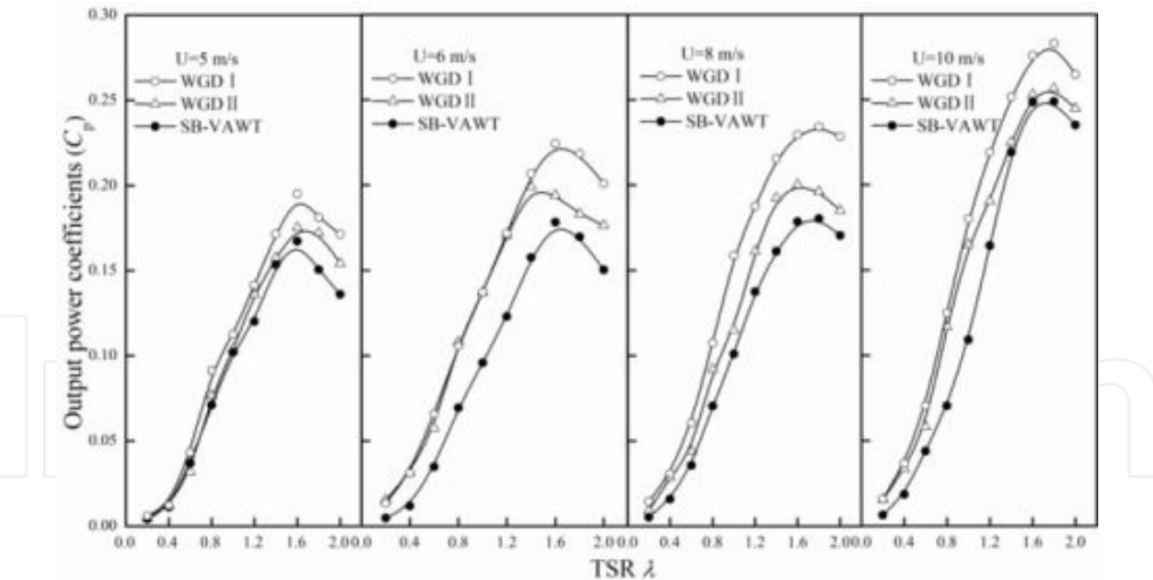


Figure 18.
 C_p of SB-VAWT with and without WGD by wind tunnel test [21].

tip-speed ratio becomes larger than unit. Therefore, the combination factors should be deeply researched such as their rotor diameter, combine angle, aspect ratio, etc.

4.3 Adding wind-gathering device

Some researches were carried out on setting additional devices around or up and down the rotor of SB-VAWT to increase its performance. These devices can be called as wind-gathering device (WGD). For the researches on adding WGD, most of researchers set up some different kinds of guide vanes around the rotor along with the wind direction [25]. Another way is to set the WGD up and down the rotor as shown in **Figure 17**. This type of WGD was proposed by Prof. Li from NEAU of China [21]. It is designed as a truncated cone-shaped structure installed up and down of the rotor. The main advantage of this WGD is that it can increase the wind speed from all wind directions. It will not need to take space along the wind direction so that the whole rotor structure will not be suffering from huge thrust and drag force. Furthermore, the WGD can play a certain role in preventing rain, snow, and ice on blades. According to the results of numerical simulation and wind tunnel tests, the power coefficients of the rotor with this WGD were much higher than the rotor without WGD (**Figure 18**).

5. Applications

Wind power generation is mainly including grid-connected and off-grid wind power generation. The large-scale wind turbine is often used for grid-connected power generation. The middle- and small-scale wind turbines are usually for off-grid power generation. For SB-VAWT, at the current stage, it is mainly used for small-scale off-grid wind power generation [26, 27].

5.1 Electrical generation

Figure 19 shows an example of off-grid electrical generation system based on SB-VAWT. The electrical generation system mainly includes SB-VAWT, control device, storage battery, and inverter. It is usually used in the power supply of street lamp, home lighting, etc.

Because the wind in nature is not stable, the wind energy is often used together with other kinds of renewable energy, such as solar energy, biomass energy, water energy, etc. This type of energy system is called hybrid energy system. The SB-VAWT also can be used as this type system. The most popular type of hybrid energy system for SB-VAWT is to be used together with solar energy. **Figure 20** shows the schematic diagram of an example of this system.

5.2 Other applications

There are many other applications for SB-VAWT excepted for electrical power generation. From the point of energy conversion, wind power can be transferred to

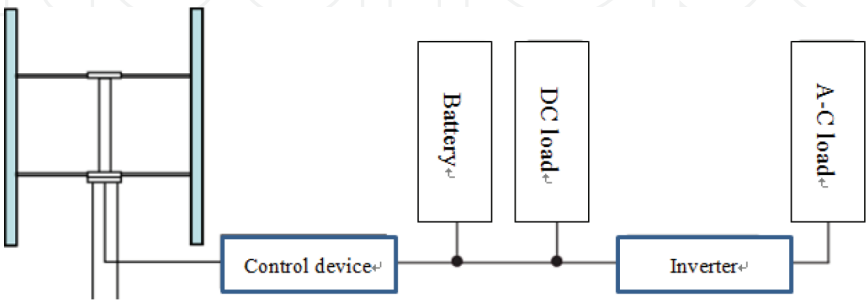


Figure 19.
Schematic diagram of an electrical generation system with SB-VAWT.

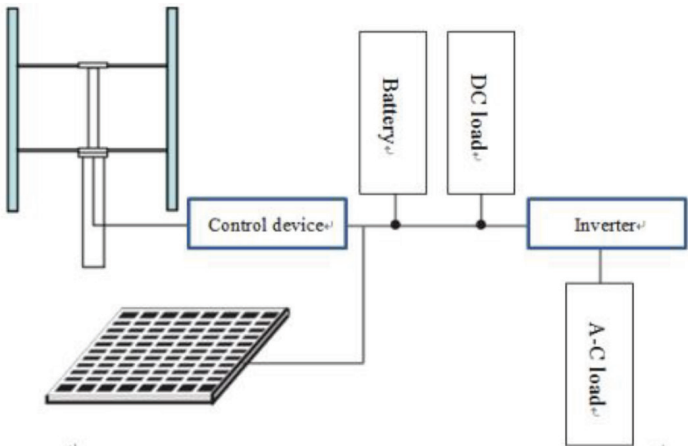


Figure 20.
Solar wind hybrid energy system.

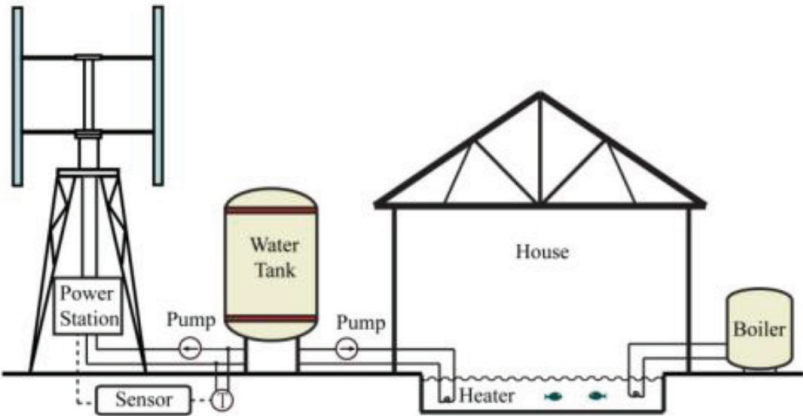


Figure 21.
Concept of fishpond heating system by SB-VAWT.

mechanical energy and heat energy. Therefore, the SB-VAWT energy system can be also used for water pumping, heating or cooling, etc. **Figure 21** shows a concept of fishpond heating system by wind power with SB-VAWT.

6. Summary

More and more attentions have been paid to the research on straight-bladed vertical axis wind. Many methods have been proposed for improving the aerodynamic performance. As the rotor becomes larger and larger, the utilization fields of SB-VAWT will become wider and wider in the future.

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