MODULAR-STACKABLE VERTICAL-AXIS WIND TURBINE APPLICABLE ON SHIPS, IN PORTS AND OFFSHORE

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ABSTRACT

Wind energy is attractive since it is a renewable energy resource. A wind turbine is a device to convert wind energy to electrical energy. There are two kinds of wind turbines: horizontal-axis wind turbine (HAWT) and vertical-axis wind turbine (VAWT). This paper presents the design, working principle, tests and application prospects of a green power tower (GPT) wind turbine. The GPT is a novel modular-stackable VAWT. Features of the GPT are that it does not require a tall tower as the HAWT does and does not have large turbine blades as the other VAWT designs have. The GPT is applicable to generate electricity used to drive auxiliary electric machineries on ships, such as pumps, heaters, cargo winches, winches, etc. and electric devices in ports and offshore, such as conveyers, lifters, cranes, etc. The novel GPT has no exposed moving turbine blades. The blades are covered completely in a round enclosure. Stackable modules of the GPT are prefabricated in factory. A single module is composed of one enclosure and one turbine, which form one level of the GPT. The GPT can be designed and installed to meet the required power load by using multiple level modules. The design of the novel modular-stackable GPT, comprising the turbine blade, enclosure, and wind flow channel, is described. In the paper, tests of scaled GPT prototypes in a wind tunnel and on site are described. The performance parameters of the wind turbine, such as power generation capacity, tip speed ratio (TSR), and power coefficient (C_p) are measured and calculated. Finally, the prospect application of the GPT on ships, in ports, and offshore is presented.
Keywords: wind energy, vertical-axis wind turbine (VAWT).

1 INTRODUCTION

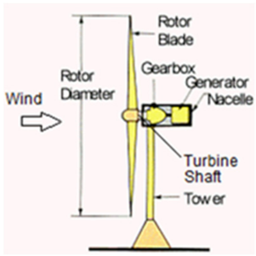
A wind turbine is a device to convert wind energy to electric power. There are two kinds of wind turbines: the horizontal-axis wind turbine (HAWT) and the vertical-axis wind turbine (VAWT). In a HAWT, the turbine shaft axis is parallel to the ground. In other words, the shaft axis is parallel to the wind flow direction. While in a VAWT, the turbine shaft axis is perpendicular to the ground [1], [2]. Sketches of the two types of wind turbines are shown in Fig. 1.

As wind is blowing to rotate the wind turbine blades, the kinetic energy of wind is converted to the mechanical energy of the wind turbine (the wind turbine shaft work). Then the wind turbine shaft drives a generator to generate electricity out.

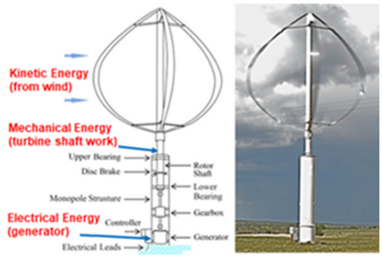
In the wind turbine's development history, the first wind turbine applied to generate electric power was a VAWT dated back to 19th century [3]. The VAWT was intended to generate power for the lighting in a cottage as shown in Fig. 2. The VAWT experienced long-time development and there have been various designs. Some of them are presented in Fig. 3.

Compared to the HAWT, the VAWT does not have a giant tower and huge blades and consequently does not need a large open area. The VAWT installation is convenient and its application is flexible [4], [5]. In 2010, two VAWTs were successfully installed on the Eiffel Tower, Paris. They were on the second tower level about 400 ft above ground as shown in Fig. 4 to supply 10,000 kWh of electricity each year [6]. It was an iconic application of the VAWT.

www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/ESUS230081



(a)



(b)

Figure 1: (a) HAWT; and (b) VAWT.

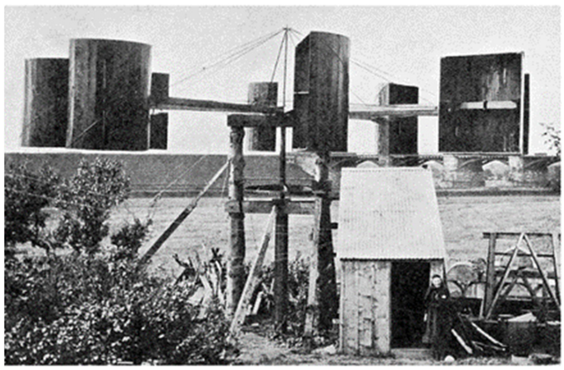


Figure 2: The first electric power wind turbine [3].

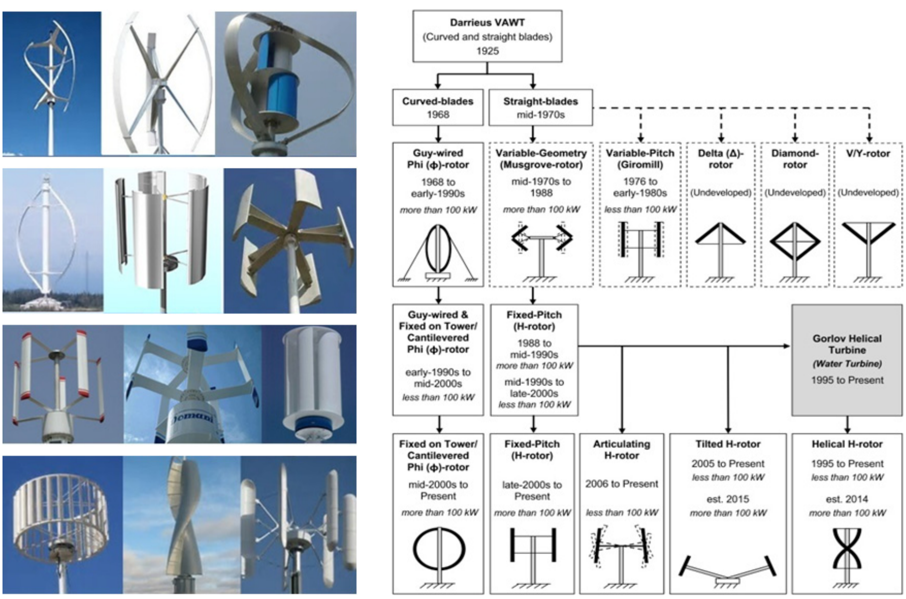


Figure 3: Various VAWT designs.

Figure 4: VAWTs on the Eiffel Tower, Paris [6].

In 2017, a novel modular-stackable VAWT, green power tower (GPT), was developed [7], [8]. The GPT does not have exposed moving components to surroundings. The moving components are completely covered in the round enclosures. Therefore, the GPT is safe and its operation is environmentally friendly. The GPT can be stacked up with multiple levels to meet the designed power load and future power load upgrade. The GPT is quite feasible for application on ships, in ports, and offshore.

2 OVERVIEW OF EQUIPMENT ON SHIPS, IN PORTS, AND OFFSHORE POWERED BY THE GPT

On ships, in ports, and offshore, there are considerable machineries and equipment driven by electric power. On a ship, many auxiliary machineries driven by electric power are needed to support the propulsion system and ship related services, such as pumps, heaters, refrigeration system, air conditioning machines, compressors, winches, and cranes, etc. Some of these machineries and equipment on the deck of a ship are shown in Fig. 5. In ports, many machines driven by electric power are needed to transport cargo and goods, such as pumps, cranes, compressors, and moving belt machines, etc. Some of these machines in the port are shown in Fig. 6. Fig. 7 shows an offshore platform on which many machines driven by electric power are needed to keep the platform in normal operation, such as pumps, cranes, compressors, etc. These machineries and equipment on the ships, in the ports, and offshore consume large quantity of electric power. The application of the GPT can substantially reduce the size of the conventional electric power generation system and the fuel cost of electric power generation. The economy of electric power generation can be improved.

3 THE NOVEL MODULAR-STACKABLE VAWT

The GPT, a novel modular-stackable VAWT, is a cylindrically shaped VAWT. It can generate electric power from 360° wind flow.

3.1 GPT working principle

Fig. 8 shows the configuration of the GPT. Air stream horizontally blows into the channels of the cylindrical enclosures. Air flows along the channels up to rotate the turbine blades nearly in perpendicular. After going through several levels, the air flows out at the top of the GPT. The turbine drives the shaft at the enclosure center. The shaft is connected to the

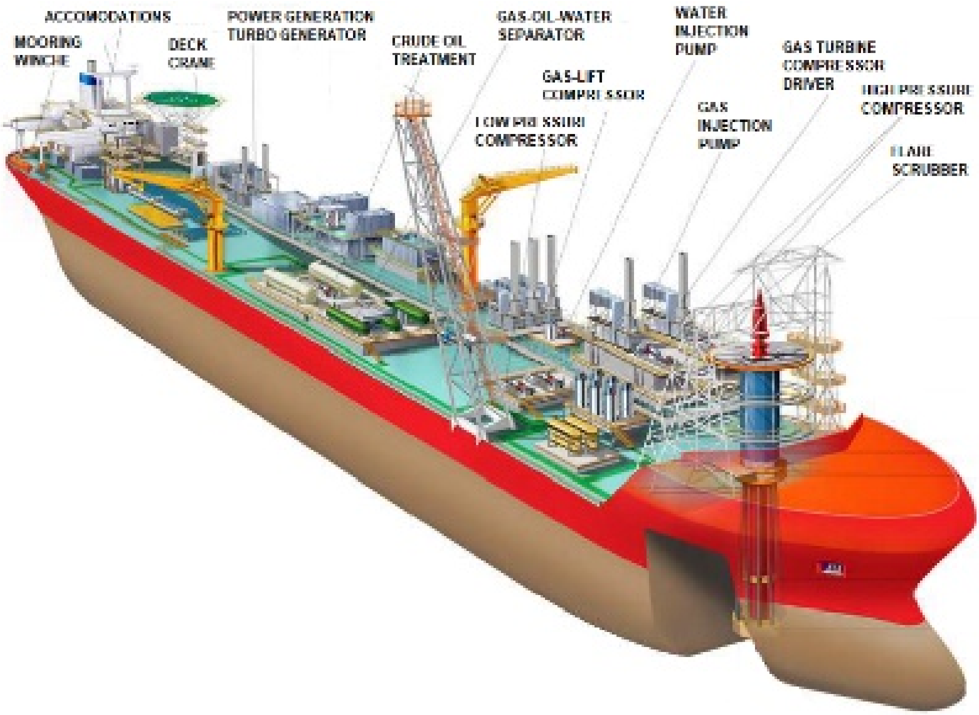


Figure 5: Equipment driven by electric power on a ship.

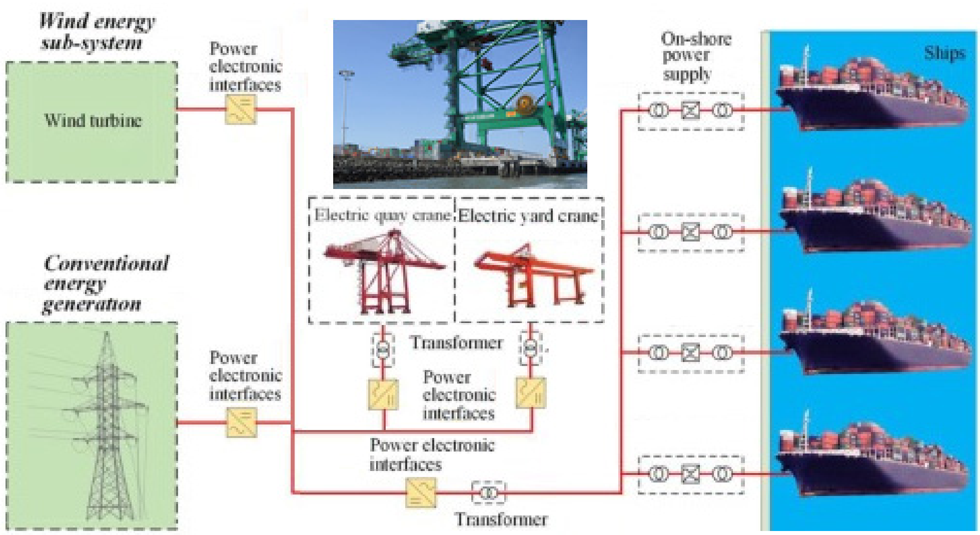


Figure 6: Equipment driven by electric power in a port.

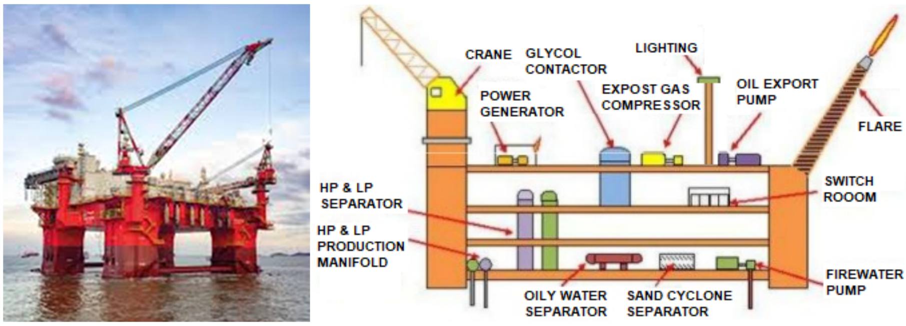


Figure 7: Equipment driven by electric power on an offshore platform.

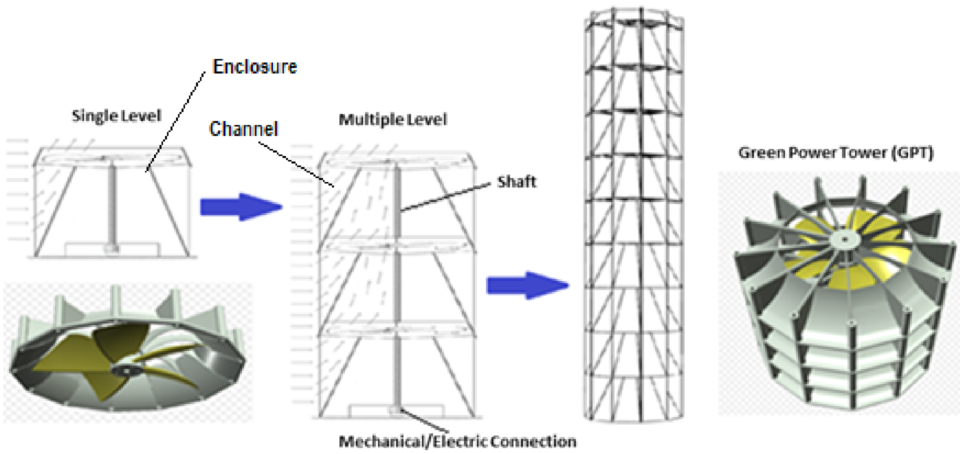


Figure 8: Green power tower (GPT).

generator located at the bottom (ground) to generate electricity out. In the GPT, all rotating components are covered in the enclosures and not exposed to surroundings. One level of the GPT modular is composed of one enclosure and one turbine. The modular is prefabricated in factory. The GPT can be stacked up in multiple levels to meet the designed power load.

3.2 Design consideration of the GPT

The GPT design is related to the knowledge of aerodynamics, dynamics, materials, mechanical engineering and electrical engineering, among others. In light of the working principle of the GPT, the important components are:

- turbine blade,
- enclosure and
- channel,

which are unique in the GPTs as shown in Fig. 9. The design of these components design is relatively complicated. The detailed design will be presented in separate papers. The general design consideration is described below.

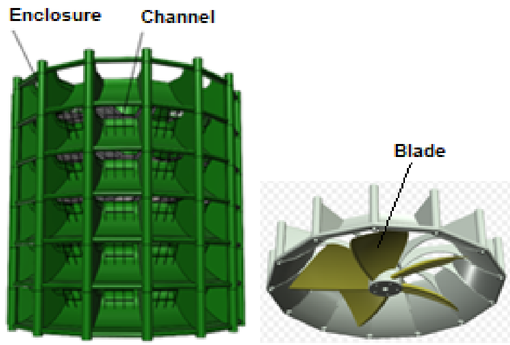


Figure 9: Unique components of the GPT.

3.2.1 Turbine blade

The blade design of the GPT is a very professional work which involves two aspects: one is the blade shape and another is the blade number. An efficient blade shape to maximize performance consists of several aero foil features, such as twist angle, chord length, and geometries, which are similar to those of the fan in a turbofan engine. From an aerodynamic point of view, it is not due to more blades, that more energy can be attracted from the blowing air. More blades also will cost more in construction. There should be an optimum blade number based on aerodynamics and economic analysis.

3.2.2 Enclosure

An important consideration in the enclosure design is to let the wind stream blow into the GPT with less energy loss and direct the stream towards turbine blades perpendicularly. The height and the partition of the enclosure should have a sufficient space and good shape. The enclosure height and diameter depend on the turbine size. The flow stagnation impact in the enclosure partition should be reduced. From a geometric and aerodynamic study, it is reasonable to divide an enclosure facing the wind flow into six partitions. Fig. 10 presents the enclosure partition of the GPT.

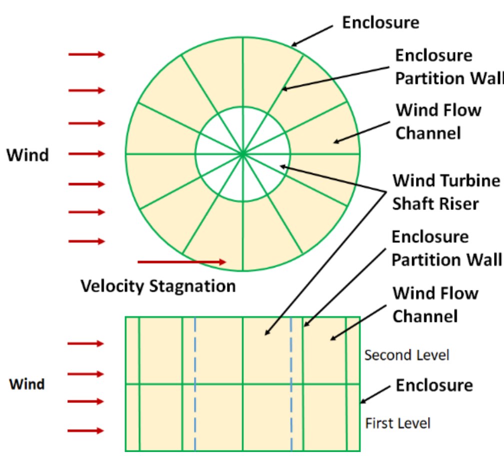


Figure 10: Enclosure partition of the GPT.

3.2.3 Channel

The wind channel design is critical because the channel in the GPT plays a function as a nozzle in which the kinetic energy of wind will be efficiently utilized to rotate the turbine blades. In the channel, the direction of wind flow is changing from horizontal to vertical by an inclined base-plate. From an aerodynamics point of view, the ideal inclined base-plate should function to lead the wind flow perpendicularly with the turbine blade. After comparing two types of channel base-plates shown in Fig. 11, the curved base-plate is applied in the design since it is more efficient in maximizing the energy conversion.

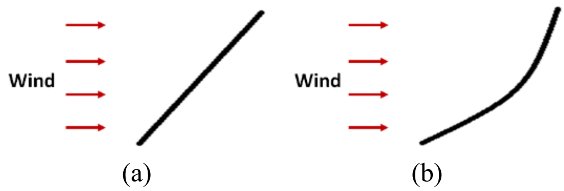


Figure 11: Inclined base-plate of the wind channel. (a) Straight; and (b) Curved.

3.3 GPT performance tests

To evaluate the performance of the GPT, scaled prototypes were tested with multiple levels in light of the above design consideration. Fig. 12 presents the test scenes conducted in the wind tunnel and at the site, respectively. At the site tests, the GPT was installed on top of a moving vehicle. The driving speed of the vehicle was the velocity of the wind blowing. In the tests, the performance of the GPT with one, two, and three levels were conducted. Table 1 shows the prototype and physical parameters in the tests.

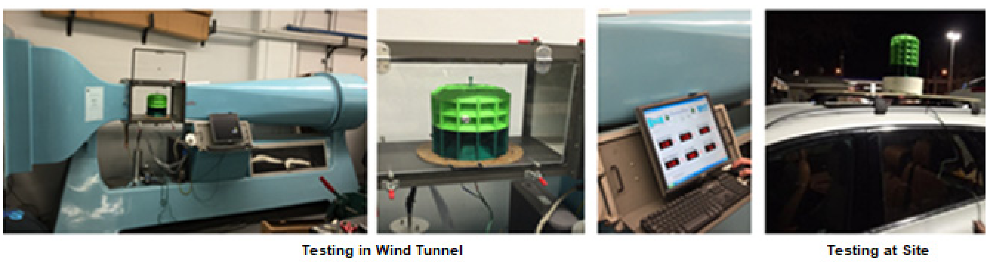
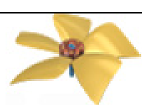


Figure 12: Performance testing.

Table 1: Test prototype parameters.

Prototype 	**GPT radius (length of blade) (cm)**	**Swept area (cm^2)**
GPT – one level	9	180
GPT – two levels	9	270
GPT – three levels	9	360

The power generation capacity, tip speed ratio (TSR), and power coefficient (C_p) of the GPT are measured and calculated. TSR and C_p are defined by [9]

$$\text{TSR} = \text{tip speed of blade/wind speed} = (2\pi r \times \text{RPM})/60v, \tag{1}$$

where r is the radius of wind blade. That is, the distance from wind shaft axis center to blade tip (m), RPM a revolution in per minute of wind blade, v the wind speed (m/s) and

$$C_p = P_{out}/P_{in} = (V \times I)/P_{in}, \tag{2}$$

where P_{out} is the power output from a wind turbine (kW), P_{in} the power of the wind (kW), $P_{in} = \rho \pi d^2 v^3/8$, ρ the air density (kg/m^3), d the diameter of wind turbine (m), V the electrical voltage generated by a wind turbine (V) and I the electrical current generated by a wind turbine (A). Some of the test results are shown in Fig. 13.

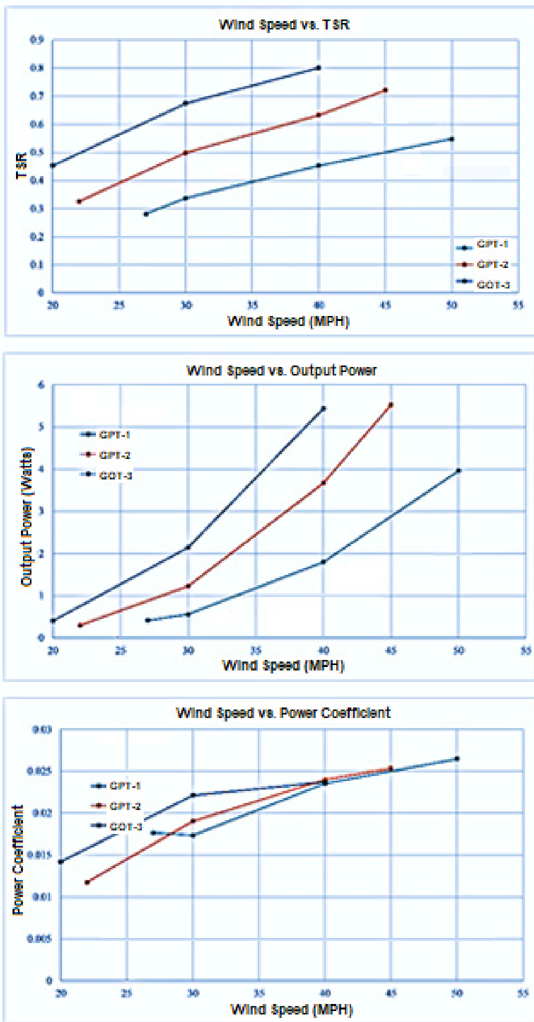


Figure 13: Testing results.

4 APPLICATION PERSPECTIVE OF THE GPT

The construction of the GPT is convenient since it does not have a giant tower and huge turbine blades. All electric and mechanical components sit on the ground without the need of extra supports. The GPT is modular-stackable. One module is one level of the GPT including one enclosure and one turbine. Each level of the GPT can be prefabricated in factory and assembled at site. The modules are stackable in multiple levels to meet the designed power load. At the installation site, only light work is required, such as the connections of enclosures, turbine shafts, and mechanical to electrical.

The GPT is safe and works environment friendly. The stackable feature can also make the GPT upgraded easily to the future power requirement. With these characteristics, the GPT is quite feasible to be applied on ships, in ports, and offshore. Some of these potential applications are illustrated in Fig. 14.

Figure 14: Potential applications of the GPT.

5 SUMMARY

Compared to the HAVT, the VAWT does not have a tall tower and giant turbine blades. A large open area is not required for a VAWT. The GPT, a novel modular-stackable VAWT, not only has all advantages of the VAWTs, but also has no exposed rotating components to surroundings. Therefore, the GPT is safe and works in an environmentally friendly manner.

The modular-stackable feature of the GPT makes VAWT to be constructed conveniently. The GPT can be prefabricated in factory and assembled at site. The modules can be stacked up in multiple levels to meet the designed power load and future power load upgrade. With these characteristics, the GPT is quite feasible in application on ships, in ports, and offshore to provide support to the machineries and equipment driven by electric power. The application of the GPT can reduce the size of the conventional electric power generation system and the fuel cost of electric power generation.

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