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Vertical axis wind turbine types, efficiencies, and structural stability – A Review

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Abstract. Much advancement has been made in wind power due to modern technological developments. The wind energy technology is the world's fastest-growing energy option. More power can be generated from wind energy by the use of new design and techniques of wind energy machines. The geographical areas with suitable wind speed are more favorable and preferred for wind power deployment over other sources of energy generation. Today's wind turbines are mainly the horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). HAWTs are commercially available in various sizes starting from a few kilowatts to multi-megawatts and are suitable for almost all applications, including both onshore and offshore deployment. On the other hand, VAWTs finds their places in small and residential wind applications. The objective of the present work is to review the technological development, available sizes, efficiencies, structural types, and structural stability of VAWTs. Structural stability and efficiencies of the VAWTS are found to be dependent on the structural shape and size.

Keywords: vertical axis wind turbines; structural stability; advantages; disadvantages; optimization tools; blade failures

1. Introduction

The focus on the utilization of renewable and clean sources of energy has increased significantly because of the growing environmental concerns, fast depletion of primary energy resources, escalating energy costs, and adverse climatic changes. The renewable sources of energy mainly include wind, solar photovoltaic, solar thermal, large and small hydro, geothermal, biomass, and wave; to name some. Of these sources of clean energy, wind and solar are commercially accepted and economically at par with the conventional means and are being used currently worldwide. Wind energy has been proven to be an economically acceptable and reliable source of energy (Aslam *et al.* 2012). The generation of power through wind has an edge over other renewable energy technologies because of its simple infrastructure, technological maturity, and relatively low-cost energy generation. Furthermore, the ease of installation and maintenance, long life of wind turbines, minimal time requirement for the installation and operation after site assessment have led to the fast growth of regional and global wind power. The use of wind energy is expected to play an important role in the future national energy scenario worldwide (Fung *et al.* 1981, Sesto and Casale 1998) in meeting the load demands.

The global wind power installed capacities are increasing every year due to the fast technological development in the field wind power extraction, availability of efficient multi-megawatt-sized wind turbines, ease of maintenance, and short time requirement in the realization of a wind farm. As stated by Baker (1983) and Ponta *et al.*, (2007), wind power is the fastest growing source of renewable energy on a global scale. The cumulative annual growth of wind power installed capacities is shown in Fig. 1 between 2000 and 2017 (Weblink1 2018). It is evident from this figure that the capacity addition is increasing almost linearly from year 2010 onwards. In years 2015, 2016, and 2017, the annually added capacities are 63.6 GW, 54.6 GW, and 52.6 GW, respectively (Fig. 2, Weblink1 2018) i.e., a percent increase of 17%, 13% and 11%; respectively. Hence, with these facts, it is convincing to say that wind power is the fastest growing source of energy and is a commercially and technologically acceptable option. Visible price reductions for both onshore and offshore wind power deployment continue (Weblink2 2018). Markets in Morocco, India, Mexico and Canada range in the area of US$0.03/kWh, with a recent Mexican tender coming in with prices well below US$0.02/kWh (Weblink2 2018). Wind penetration levels also continue to increase rapidly. Denmark got 44% of its electricity from wind in 2017, and Uruguay more than 30%. In 2017, wind supplied 11.6% of the EU's power, led by Denmark, Portugal and Ireland at 24% and by Spain and Germany just under 20%. Four US states get more than 30% of their electricity from wind, as does the state of South Australia, and a number of states in Germany.

The Kingdom of Saudi Arabia has embarked on restructuring its energy mix portfolio by supplementing the existing capacity through wind power and solar photovoltaic. With respect to wind power, the Kingdom is expecting to develop around 450 MW of capacity in the

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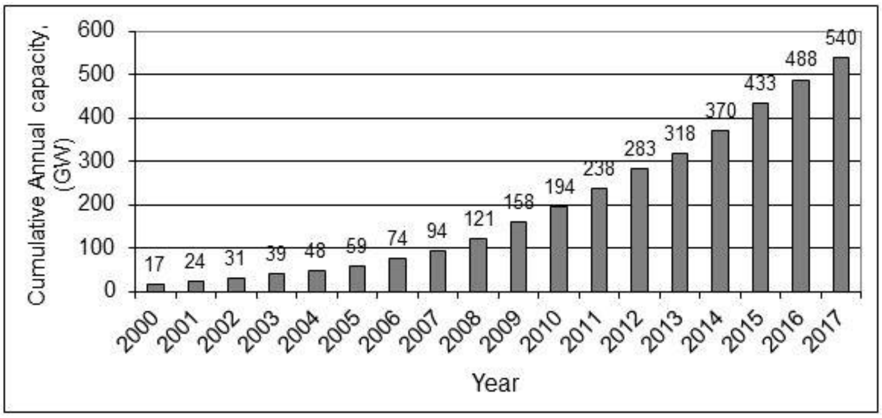

Fig. 1 Annual cumulative global wind power installed capacity

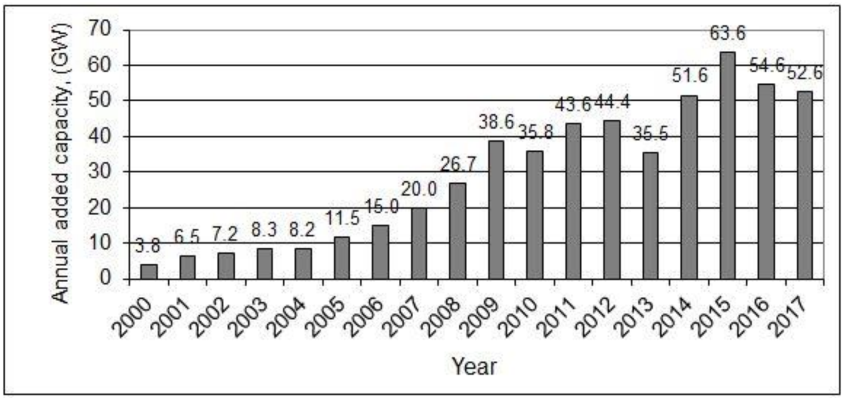

Fig. 2 Annually added wind power capacity on global scale

near future. Hence, as a consequence of it, large wind turbines of capacities ranging from 2 to 3.5 MW and even more will be installed in different operating areas of the Kingdom. Such large wind turbines are expected to have rotor diameters ranging from 80 to 120 meters and hub heights of 80 to 120 meters. This is the time that the researchers and the utility engineers come together and understand the physics and engineering behind holding and sustaining such huge infrastructure in the local environmental conditions. However, in the last 10 years, a great deal of research initiatives has been undertaken on wind power related topics such as (i) understanding of the wind speed behavior and its prediction using artificial neural network and other techniques (Shoaib *et al.* 2017, Islam *et al.* 2017, Mohandes and Rehman 2016, Mohandes and Rehman 2014, Mohandes *et al.* 2011), (ii) wind turbine selection and wind farm layout design using fuzzy logic and multi-criteria methodologies (Rehman and Khan 2017, Rehman *et al.* 2016, Rehman and Khan 2016, Khan and Rehman 2013), and (iii) wind power resource assessment, wind characteristics and feasibility (Zheng *et al.* 2017, Alam *et al.* 2014, Baseer *et al.* 2017, Himri *et al.* 2016, Himri *et al.* 2012, Bagiorgas *et al.* 2013, Rehman *et al.* 2016a, Rehman *et al.* 2016b, Baseer *et al.* 2016, Rehman *et al.* 2015, Baseer *et al.* 2015, Bassyouni *et al.* 2015, Rehman 2014, Rehman *et al.* 2013, Rehman 2013, Rehman *et al.* 2012a, Rehman *et al.* 2012b, Bagiorgas *et al.* 2012a, Bagiorgas *et al.* 2012b, McVicar *et al.* 2011, Bagiorgas *et al.* 2011, and Alam *et al.* 2011).

The objective of the present work is to review the VAWT technological development, available sizes, efficiencies, structural stability issues, and applications and identify and recommend suitable vertical axis wind turbines in Saudi Arabia and areas with similar meteorological conditions.

2. Types of wind turbines

The wind turbines are categorized by the orientation of the rotor and direction of the rotation axis of the blades. These are known as horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) used for electricity generation from wind. The blades of a HAWT look like a propeller and rotate around the horizontal axis as shown in Fig. 3, while those of a VAWT rotate around the vertical axis as illustrated in Fig. 4. The rotor of a HAWT always faces the upwind direction while a VAWT does not need to be pointed into the incoming wind direction. A comparison of both configurations is summarized in Table 1 (Aslam *et al.* 2012). As stated in Table 1, small towers are required in the case of VAWTs while very high in the case of HAWTs.

Table 1 Merits of vertical axis wind turbines over horizontal axis wind turbines

Parameter description	Vertical axis wind turbine (VAWT)	Horizontal axis wind turbine (HAWT)
Tower sway	Small	Large
Yaw mechanism	No	Yes
Self-starting	No	Yes
Overall formation	Simple	Complex
Generator location	On ground	Not on ground
Height from ground	Small	Large
Blade's operation space	Small	Large
Noise produced	Less	Relatively high
Wind direction	Independent	Dependent
Obstruction for birds	Less	High
Ideal efficiency	More than 70%	50–60%

Fig. 3 Horizontal axis wind turbine (HAWT). Source: http://www.turbinesinfo.com/

Fig. 4 Vertical axis wind turbine (VAWT). Source: http://www.indepthinfo.com/

Today's modern HAWTs have tower heights as high as 120 m and more for offshore wind turbines. Additionally, no yam mechanism and self-starting system are required in the case of VAWTs while these are needed in the case of HAWTs which adds to the complexity, involvement of skilled manpower, and at the same time the increased cost. A large blade operational area is required in the case of HAWT's while a relatively smaller and simpler for VAWTs. The VAWTs are independent of the wind direction and produce less noise compared to the HAWTs.

Extensive research activities have been carried out to develop different designs for VAWTs based on several aerodynamic computational models. These models are used

Table 2 Summary of relative merits and demerits of different optimization methodologies

	Tools/Techniques	Merits	Demerits
Software tools	HOMER	-	Cannot enable users to intuitively select appropriate system components
	HOGA	Involving genetic algorithms, and mono or multi-objective	-
	HYBRIDS	Comprehensive in terms of optimization variables and requiring higher level knowledge of system configurations	Only simulate one configuration at a time
Optimization techniques	Graphic construction method	-	Only two parameters can be included in the optimization process
	Probabilistic approach	Eliminate the need for time-series data	Cannot represent the dynamic changing performance of the system
	Iterative technique	-	Usually, requiring increased computational efforts and suboptimal solutions
	Artificial intelligence methods	Find the global optimum system configuration with relative computational simplicity	-
	Multi-objective design	Can optimize simultaneously at least two conflict objectives	-

for identifying the optimum design of wind turbine configurations. Table 2 shows a summary of the relative merits and demerits of different optimization software and techniques for better identification (Zhou *et al.* 2010). Homer Pro is the state of art hybrid power system design and optimization tool. It is capable of designing any combination of multiple power sources like wind-diesel, wind-pv-diesel, pv-diesel, including hydro and biomass with and without battery backup system. There may be more power source combinations. It allows multiple diesel generations and wind turbine types for optimization purposes. The other tools like HOGA and HYBRIDS are also being used but have limited capabilities compared to HOMER Pro which is now industry standard.

A vertical axis wind turbine works on a simple principle in which the airfoils are secured to the hub, and the hub is attached to a generator shaft. The air passing over the wind turbine blades causes the rotation of the rotor which spins the generator and produces electricity. VAWTs were the first to be used to convert the wind power into electricity. Omnidirectional property is one of the major advantages of the VAWTs (Chaichana and Chaitep 2010). Several efforts have been made to resolve different problems related to VAWTs but more need to be done to make this technology more efficient and commercially acceptable (Homicz 1989, Loth 1985). The usage of VAWTs in a large scale is not an economical option but offers a solution to provide energy to remote areas which are far away from the grid and where large wind turbines cannot be installed due to environmental and other concerns (Bishop and Amaratunga 2008). Due to economical drawbacks of large-scale VAWTs, mass installation of small-scale wind turbines has started to make the technology more feasible (Islam *et al.* 2004).

Different technologies and analysis have been utilized by researchers, engineers, and scientists for the development of different configurations of VAWTs by determining optimum working conditions. In this way, this technology gets more access to the market as an alternative source of energy. In this paper, different configurations of VAWTs are discussed, including techniques and performance. A comparison of VAWTs with HAWTs is also presented. A number of advantages and promising features are offered by VAWTs. It is needed to exploit these advantages in a better way to make it a better alternative as compared to other technologies.

Recent findings have shown that VAWTs can be packed significantly closer than HAWTs with no significant loss in the overall efficiency. This makes them much better suited for wind farms development (Brownstein *et al.* 2016), especially in the countries where there is land scarcity. Kinzel *et al.* (2012) conducted an experimental study and showed the wind speed recovery of up to 95% of the far-field wind speed within 6 times of the rotor diameter. Although individual VAWTs are less efficient than HAWTs, the tighter spacing of counter-rotating turbines allows VAWT based wind farms to have higher power densities. According to Dabiri (2011), a modern HAWT based farms can produce 2-3 W per square meter while field experiments with VAWT farms have shown a potential of production of up to 30 W per square meter. Hence utilization of VAWTs can address a major drawback that wind farms can be developed with much lesser land area compared to HAWTs based wind farms.

As a result of the advantages, VAWTs need lesser area for wind farm development. The wind farm developers are now showing interest to use VAWTs for offshore wind farm deployment (Sutherland 2012, Troutman 2016). Furthermore, in the case of VAWTs the heavy machinery like gearbox and generator is located at a much lower height above the ground level, unlike HAWTs where this heavy equipment is placed on the top of the tower behind the rotor. Hence, this makes the operation and maintenance of VAWTs much easier and cost-effective and also improves the stability of the complete setup. Furthermore, the symmetry of the VAWTs becomes additionally advantageous, independent of the wind direction.

Table 3 Advantages and disadvantages of VAWT's

Advantages	**Disadvantages**
They can produce electricity in any wind direction.	The design is less likely to be damaged by gusty wind conditions, but is more likely to stall out and stop spinning.
Strong supporting tower is not needed because generator, gearbox and other components are placed on the ground.	These turbines aren't typically well suited for areas of high wind speeds.
Low production cost as compared to horizontal axis wind turbines.	The blades tend to flex and twist as the rotor assembly spins faster and faster.
As there is no need of pointing turbine in wind direction to be efficient, so yaw drive and pitch mechanism are not needed.	The centrifugal force generated by the spinning blades causes stress and fatigue on some blade designs that occasionally results in them breaking apart.
Easy installation as compared to other wind turbines.	Blades do not produce torque at the same time, which limits the efficiency of VAWTs.
Easy to transport from one place to another.	VAWT blades experience more drag when rotating.
Low maintenance costs.	Low starting torque and dynamic stability problems can limit the functionality of VAWTs.
They can be installed in urban areas.	VAWTs are installed near the ground, so do not harness the higher wind speeds often found at higher levels.
Low risk to human and birds because blades move at relatively low speeds.	Air flow at ground level can increase turbulence and can increase vibrations.
They are particularly suitable for areas with extreme weather conditions, like on/around the mountains where they can supply electricity to mountain huts.	Due to increased vibrations and turbulence, maintenance cost may be more.

Fig. 5 Savonius wind turbine (Savonius 1931)

Fig. 6 The H-rotor placed in Marsta (Bahaj 2007)

3.1 Savonius wind turbine

Savonius wind turbine is a drag force driven type of turbine, comprising of a number of aerofoils mounted vertically on a rotating framework. This turbine was invented in 1929 by Savonius (1931). Savonius turbines are used in the cases of high reliability such as providing power for anemometers and ventilation. These turbines are efficient, self-starting, and effective in turbulent windy areas. A Savonius turbine has two cups or half cylinders fixed to a rotating shaft at the center, as shown in Fig. 5. The drag force acting on the cups generates the torque required for power generation (Islam *et al.* 2007).

This type of turbine is generally used for low power applications, being less efficient (<30%) than a Darrieus turbine (Kirke 1998, Gorelov and Krivospitsky 2008, Mohamed *et al.* 2011).

3.2 H-Rotors

The wind turbine development allowed wind energy to provide clean and environmental friendly electric power production. The development of this technology enhanced the use of small-scale VAWTs for power generation (Bahaj 2007). The H-rotors, as shown in Fig. 6, were developed in the UK in 1970–1980s. The H-rotor turbine is self-regulating at all wind speeds, and therefore it reaches its optimal rotational speed shortly.

Many studies have been carried out to enhance the performance of H-rotor turbines (Mohamed 2012, 2013, 2014, Mohamed *et al.* 2015). Mohamed (2012) investigated the effect of drag and lift to enhance the self-starting capability of an H-rotor turbine for efficient conversion of wind energy. The results of numerical and experimental studies indicated improvements in the self-starting performance. Mohamed (2013, 2014) and Mohamed *et al.* (2015) improved the design of H-rotor for increased and efficient wind energy conversion. The authors using two-dimensional numerical simulation examined different symmetric and asymmetric airfoils to improve the design performance of an H-rotor. They introduced new shapes for this wind turbine with a high efficiency.

3.3 Darrieus wind turbines

The first design for Darrieus wind turbine was patented in 1931 by a French engineer George Jeans Mary Darrieus (Darrieus 1931). This type of VAWTs having a low starting torque has a higher efficiency than the other VAWTs (Fig. 7). This is an aerodynamic-lift-force driven turbine which consists of two or more aerofoil-shaped blades attached to the central rotating shaft. The small-scale Darius turbines are available in the market, but large-scale development is yet limited to the research stage. However, the use of these turbines for small-scale power generation applications is more cost effective (Drees 1978).

3.4 Eggbeater type Darrieus wind turbine

The design of this turbine is like an eggbeater. Two or more blades are arranged as arms of an eggbeater as shown in Fig. 8. These turbines can operate with a higher efficiency, but have poor reliability due to more cyclic stress on the tower. The airflow around the wind turbine is unsteady and pulsating which produces a thrust force (Gorelov 2009, Gorelov and Krivospitsky 2008). This design is more effective for large-scale power generation, but has a high cost due to a complex configuration of the blades and hence has a limited production (Eriksson *et al.* 2008). This design has a self-starting problem because of a low starting torque produced, but provides minimum bending stresses in the blades (Islam *et al*. 2008).

Many authors have contributed towards the optimization of the eggbeater design of VAWTs (Brahimi and Paraschivoiu 1995, Marini *et al*. 1992, Rosen and Abramovich 1985, Schienbein and Malcolm 1983). Marini *et al.* (1992) carried out an aerodynamic analysis of eggbeater Darius models. Brahimi and Paraschivoiu (1995) theoretically calculated structural loads on the Darrieus rotor wings in turbulent flow conditions. Whereas, Shienbein and Malcolm (1983) studied 50 kW and 500 kW models of Darrieus wind turbines and presented their findings on mechanical and control systems of the turbines as well as their economic and performance analysis. Rosen and Abramovich (1985) theoretically and experimentally studied the blade structure to analyze the behavior of the blades under various loading configurations. Bergeles *et al.* (1991) experimentally studied the wake effect of blades rotors by carrying out flow field study.

3.5 Giromill (straight bladed type Darrieus wind) turbine

The giromill Darius turbine is an attractive and cost-effective option for small-scale power generation because of straight blades and simple design (Fig. 9). This type of turbine is sometimes also called as cyclo-turbine and can be in variable or fixed pitch configuration (Kirke 1998). The rotor can consist of any number of blades, but five-bladed configurations are commercially most available. Two- and three-bladed configurations are also commonly available. A two-bladed configuration of giromill turbine with fixed or variable pitch will form H-rotor which is discussed in previous sections (Gorelov and Krivospitsky 2008, Howell *et al.* 2010, Mertens *et al.* 2003).

Giromill turbine has a high conversion performance and a potential to overcome starting torque issues because of its variable pitch option (Howell *et al.* 2010). The efficiency of this configuration can be further enhanced by varying the attack angle of the blades in a sinusoidal pattern (Staelens *et al.* 2003). Siota *et al.* (2010) used Control Circuit (CC)-Less generation system for Giromill turbine to enhance the electrical performance associated with it. The results indicated that the CC-Less system for this straight bladed VAWT enhances the system performance. Relatively low initial cost is also an added advantage for this type of VAWT. Vandenberghe and Dick (1987) and Wilhelm *et al.* (2009) contributed towards the efficient design and optimization of Giromill turbine by conducting aerodynamic analysis and using circulation control

Fig. 7 A 55 kW rated power Darrius wind turbine model

Fig. 8 Egg-beater type Darrieus rotor. Source: Harvistor (Gorelov 2009)

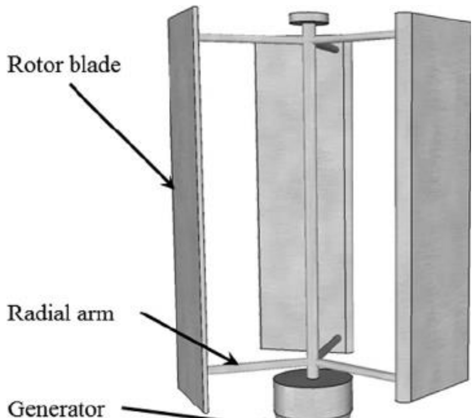

Fig. 9 Giromill (straight bladed type Darrius wind) turbine (Kirke 1998)

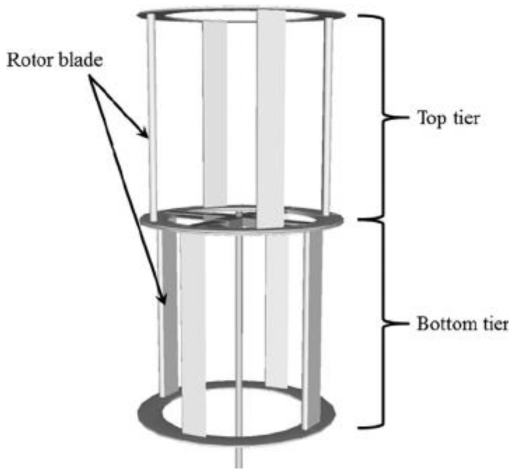

Fig. 10 Variable geometry oval trajectory (VGOT) Darrieus turbine

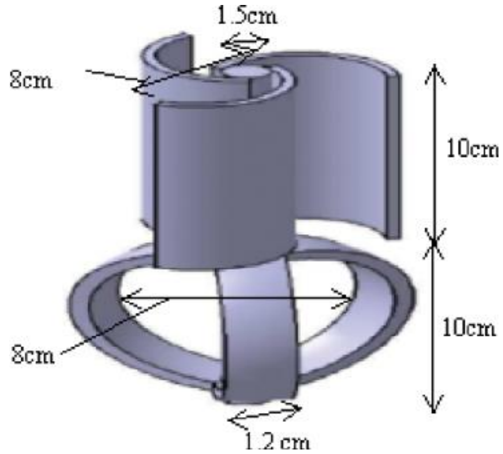

Fig. 11 Twisted three bladed Darrieus rotor

methods. Islam *et al.* (2007), Graham *et al.* (2009) and Takao *et al.* (2009) also carried out different analysis for this straight bladed VAWT to enhance and optimize its performance.

3.6 Variable geometry oval trajectory (VGOT) Darrieus turbine

Most of the configuration for Darrieus rotor have a low rotor speed, only suitable for small-scale applications. Ponta *et al.* (2007) presented a new configuration of Darius turbine suitable for large-scale applications. This configuration (Fig. 10) consists of an elevated rail track instead of a rotor on which the blades move. This movement of the blades on rail track generates electricity through a coupled electrical system. This configuration combines the characteristics of VAWT with high stability, high efficiency (about 57%) and low starting torque. The design still has to prove its capabilities through applications because the advantages presented are theoretical since no prototype is yet available. This configuration is not favorable for small-scale applications because of its complex design.

3.7 Darrieus–Masgrowe (two-tier) rotor

Gorelov and Krivospitsky (2008) suggested a two-tier configuration for straight bladed Darrieus rotor called Darrieus–Masgrowe rotor. This turbine consists of two or three blades in each tier. The two tiers are shifted by an angle of 90°. The two-tier configuration allows the turbine to self-start at low wind speeds. Variable pitch rotor is thus not required to overcome starting torque problems.

3.8 Twisted three-bladed Darrieus rotor

Twisted three-bladed rotor is another possible configuration of Darrieus rotor to overcome different issues related to VAWTs. In this configuration, the blades of Darrieus rotor are twisted at the trailing edge (Gupta and Biswas 2010). The rotor has the advantage of high efficiency and can self-start at a low speed with any auxiliary mechanism for starting. The configuration of this rotor is complex because of twisted blades. This increases the manufacturing cost and overall size of the turbine. Further, studies are required to optimize the performance of this configuration for efficient conversion of wind energy.

Fig. 12 Combined Savonius and Darrieus rotor

Table 4 Comparison between Darrius and Savonius VAWTs

	Advantages	Disadvantages
Darrieus wind turbine	1. High speed with low torque machine. 2. Generally requires manual push from external power source to start turning as the starting torque is very low. 3. Generator can be placed on the ground. 4. Easily integrated into buildings.	1. Difficult to self-starting. 2. Need multiple wires.
Savonius wind turbine	1. Slow rotating with high torque machine. 2. Shaft of the generator can be placed nearer to the ground. 3. Starts at low wind speed. 4. Low-noise system. 5. Work with any wind direction.	1. Low efficiency.

3.9 Cross flex wind turbine

The usage of VAWTs is limited by their structural design requirements and architectural aesthetics. An innovative idea of "true building integrated wind turbine" was given by Sharpe and Proven (2010). This idea suggested installing and combining several conventional Darrieus rotors within a frame. The introduction of low inertial mass design improves the efficiency of this design. The bending stresses and vibrations are reduced due to the use of flexible blades and strong supporting frame. This wind turbine can be installed at any location suitable for wind energy conversion. Prototypes of cross-flex wind turbines are already manufactured and are available. One of these turbines is installed at Newberry tower in Glasgow, Scotland.

3.10 Combined Savonius and Darrieus rotor

As discussed in the previous sections, Savonius and Darrieus turbines (Fig. 12) have advantages and disadvantages. Darrieus rotors give low starting torque as compared to Savonius whereas Darrieus rotors have higher efficiency compared to Savonius rotors (Debnath *et al.* 2009). A comparison of Darrius and Savonius vertical axis wind turbines is presented in Table 4.

Different studies combine both configurations for a better performance (Gavaldà *et al.* 1990, Gupta and Biswas 2010, Wakui *et al.* 2000). Gavalda *et al.* (1990) and Gupta and Biswas (2010) found a high f power coefficient and starting torque by combining both types of rotors. Further, the combination of both rotors makes the use of VAWTs more feasible for large-scale applications as well. Wakui *et al.* (2000) suggested that a custom system should be designed to suit each turbine configuration and wind flow conditions.

3.11 Two-leaf semi-rotary VAWT

The idea of two-leaf semi-rotary VAWTs was presented by Zhang *et al.* (2010). In this design, the two blades are arranged at an angle of 90° with each other. This turbine has a better self-starting capability and a uniform movement of wind along the blades, resulting in a high energy utilization factor. This VAWT is cost-effective and easy to install for off-grid applications due to its simple design. However, the

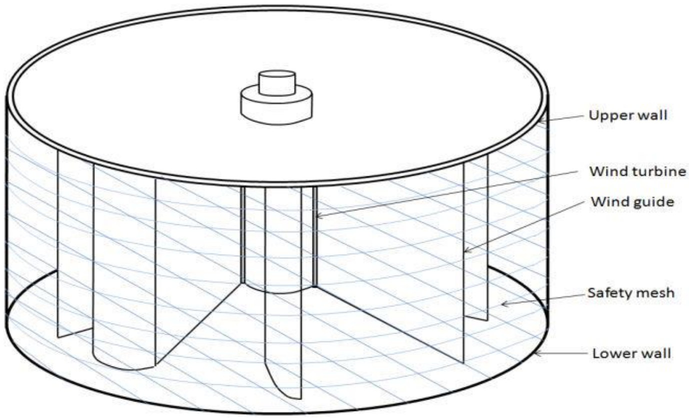

Fig. 13 Structure of a Sistan type wind turbine rotor

Table 5 Advantages and disadvantages of various types of VAWTs

	Advantages	Disadvantages
Ducted Wind Turbine	1. Less visual impact on building architecture than traditional HAWTs or VAWTs. 2. Make use of unused roof space in cities. 3. Allows energy need to be met on-site avoiding transmission losses associated with centralized energy generation. 4. Easy to maintain. 5. Most effective at mesas, hilltops, ridgelines and passes. 6. Lower construction and transportation costs.	1. Not directional
Vertical axis wind turbine (lift type)	1. Suitable for urban environments, but not households (only effective on urban high-rise buildings) 2. Much more research and development are needed. Research in this field is growing as people become more interested in urban wind generation 3. Research has to be conducted to determine energy production potential	1. Blades constantly spinning back into the wind causing drag. 2. Less efficient. 3. Operate in lower, more turbulent wind. 4. Low starting torque produced and may require energy to start turning. 5. Unidirectional. Fixed position and are dependent upon wind blowing in the correct direction.
Darrieus Wind Turbine	1. The rotor shaft is vertical. Therefore, it is possible to place, like a generator or a centrifugal pump at ground level. As the generator housing is not rotating, the cable to the load is not twisted and no brushes are required for large twisting angles. 2. The rotor can take wind from every direction. 3. The visual acceptance of placing VAWTs a building might be more than that for a HAWT. 4. Easily integrated into buildings.	1. Difficult start, unlike the Savonius wind turbine. 2. Low efficiency.
Savonius wind turbine	1. Having a vertical axis, the Savonius turbine continues to work effectively even if the wind changes its direction. 2. Because the Savonius design works well even at low wind speeds, there's no need for a tower or other expensive structure to hold it in place, greatly reducing the initial setup cost. 3. The device is quiet, easy to build, and relatively small. 4. Because the turbine is close to the ground, maintenance is easy.	1. The scoop system used to capture the wind's energy is half as efficient as a conventional turbine, resulting in less power generation.
Giromill Darrieus Wind Turbines	1. This turbine should self-start due to the drag aspect; 2. Has high efficiency due to the airfoils creating lift. 3. This turbine has an enclosure to direct the wind and increase its velocity. 4. The shroud helps to keep foreign objects out of the turbine	1. It has many moving parts which could result in vibrations, noise, and low mechanical reliability. 2. There is also a loss of efficiency due to friction in the cam and rotation of the blades from the lift to the drag position.

Fig. 14 Zephyr vertical axis wind turbine type

poor structural stability of blades at high wind speeds is a drawback of this design which needs to be studied more to make it a better option for wind power harnessing.

3.12 Sistan type windmill

This is one of the earliest wind turbines (Fig. 13) used for the conversion of wind energy. The name Sistan is given because it was firstly used in areas of Sistan and Khorasan, Iran (Hassan 1986). It is driven by drag force and can be easily integrated into the buildings. Muller *et al.* (2009) studied and suggested improvements in this turbine for a better performance. This design has the ability of self-start because of its drag type nature.

3.13 Zephyr turbine

The Zephyr turbine (Fig. 14) uses stator vanes with reversed winglets. The stator vanes are used in order to have a less aerodynamic loading on the blades. The flow leaves at a particular angle after entering the stationary stator blades. Then it strikes the rotor blades where power is extracted. This design has a good mechanical stability but the conversion performance is low and currently not acceptable for commercial scale. More research is needed to enhance the performance and to make commercial (Pope *et al.* 2010). The advantages and disadvantages of various types of VAWTs are summarized in Table 5, which may be helpful in selecting a particular type of wind turbine for a specific application.

4. Wind turbine sizes of VAWTS and optimization techniques

The turbine sizes have increased with the passage of time. The turbine sizes of up to 100 kW were commonly used till mid-80s, which increased to 100–500 kW by early 1990s. In the mid-1990s, 750–1000 kW turbines were typically used followed by 2500 kW in the late 90s. Now, turbines are available for power generation with a capacity of up to 3500 kW.

An increased time and effort is required with the increase in optimization variables and simulation numbers. That is why it is very important for designers to select a more feasible technique for better design using less effort and money. The mostly used optimization techniques in the literature are probabilistic approaches, graphic construction methods, iterative technique, multi-objective design, and artificial intelligence methods. The details of these methods can be found in the literature (Giraud and Salameh 2001, Yang *et al.* 2007).

5. VAWT blade failure issues and remedial measures

Most current VAWTs have three major problems:

- Low power generation performance
- Work in a narrow range of wind speeds and brake frequently, thus reducing power output
- Poor stability which reduces the turbine life

One of the major outstanding challenges the VAWT technology faces is dynamic stall of the blades as the angle of attack varies rapidly (Buchner *et al.* 2015, 2018). The blades of a VAWT are fatigue-prone due to the wide variation in applied forces in one rotation cycle. This can be overcome by the use of modern composite materials and improvements in design, including the use of aerodynamic wing tips that cause the spreader wing connections to have a static load. The vertically oriented blades can twist and bend during each turn, causing them to break apart. Earlier designs of VAWTs were proved to be less reliable than HAWTs although modern designs of VAWTs have overcome many of the issues associated with old designs (Ashwill *et al.* 2012).

A good VAWT has to remain stable while spinning. If not, the turbine will shake its head during the rotation and undergo a reduced service life, generating other problems such as noise and mechanical wear. The best solution to this problem is to use a coaxial structure for the rotor and

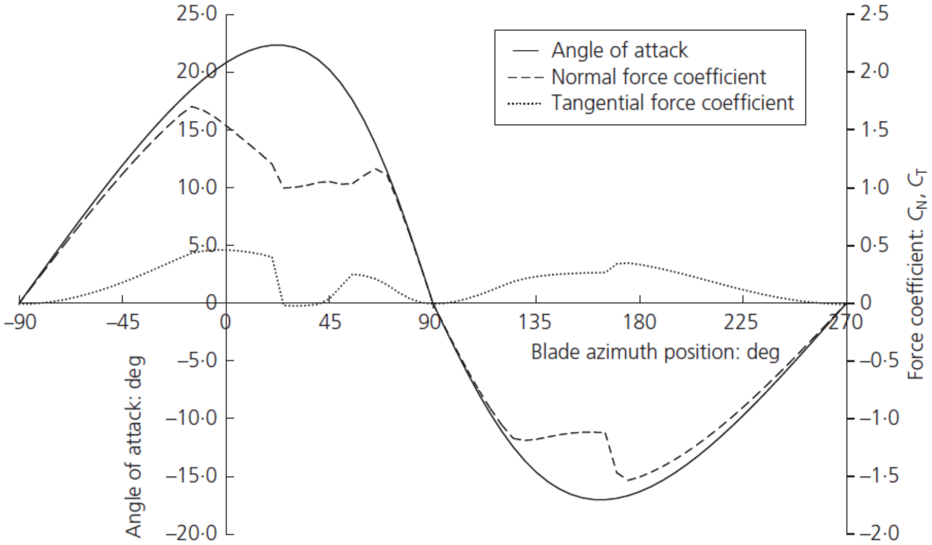

Fig. 15 Variations of angle of attack and loads with blade azimuth position (Shires 2012)

Fig. 16 Savonius wind turbine with a couple of 4 scoops, used for pumping water (Lack 2010)

generator, which ensures a reliable seal, safety and stability, free of mechanical noise, and long service life. Damage may occur to wind turbines when the wind speed exceeds 25 m/s. To overcome this problem, a vertical axis wind turbine needs an automatic brake system. As a wind turbine starts to brake, it must overcome the rotational inertia and the driving force from the wind. A good design calculates the torque in the rotor at survival wind speed and chooses a suitable disk brake. It is well known that a VAWT is quiet and safe, and does not need a tall tower. However, hardly any commercialized large VAWTs have been launched despite the efforts of countless engineers. The reasons are obvious: the problems of aerodynamic efficiency, self-starting, structural stability, and safe braking remain unsolved. The problems have to be solved.

The cost-effective energy yield from a VAWT or HAWT depends on the fact that the high initial cost of the turbine will be offset by low-cost operation over a long operational life. The fatigue life of major components, such as the blades, must be adequate to allow production of enough energy to overcome the initial investment. Oscillating stresses are inherent in VAWT operation. The two main reasons are the blade cycling through up-wind and down-wind orientations and the aerodynamic forces changing as the induced angle of attack of the blades changes. The magnitudes of these vibratory stresses in the blades can be reduced by analysing the resonant modes and frequencies of the operating turbine and judicious design to keep the inherent periodic loads from exciting any resonance. However, the vibratory stresses can never be removed completely. The effect of these oscillating stresses on blade life must be assessed before a wind turbine can be labeled cost-effective and projected to last for a specified amount of time.

The VAWTs use symmetrical aerofoils having a lower lift-to-drag ratio, with relatively more wake losses, compared to HAWTs. Mechanically a VAWT operates at a lower rpm and have in a greater machine weight and cost

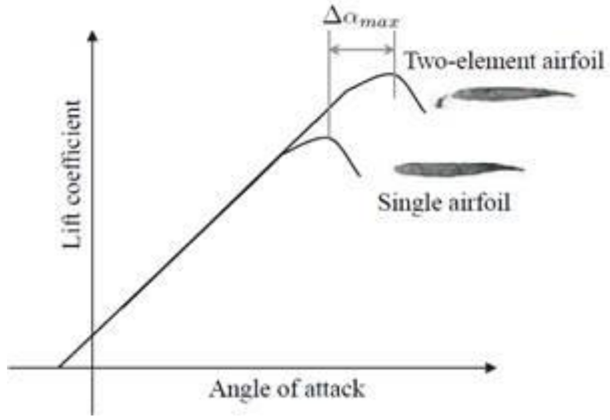

Fig. 17 Lift coefficient for a single and a double-element airfoil (Chougle 2015)

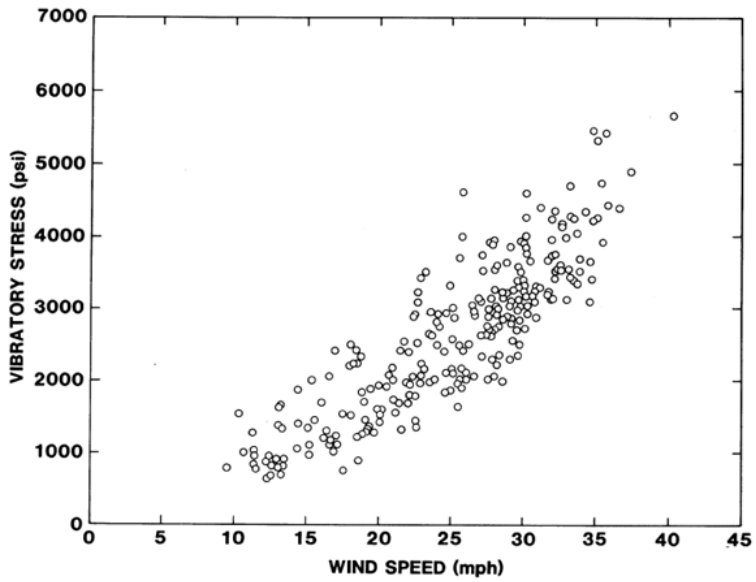

Fig. 18 Maximum vibratory stresses in 5-second interval vs wind speed (Veers 1981)

(Tangler 2000). The alternating stress loads are the main cause of VAWT blade failures. The original Darrieus turbines suffered from violent vibrations leading to fatigue blade failures. A high noise level with low efficiency has the major hurdles behind its limited success. Flexing of the wind turbine blades sometimes leads to premature failure of the blades due to the fatigue of the blade material.

In order to minimize the risk of failure, it is suggested to design a VAWT with high tensile wires running through all of its components. Shires's (2012) work on the aerodynamic optimization of a 10-MW rated power VAWT rotor offers a low-stress design to minimize manufacturing and maintenance costs of the complete turbine assembly including the supporting structure and foundations. The aero-generator of a VAWT is self-supporting so does not require a supporting tower. This provides a low Centre of gravity and results in significantly lower aerodynamic over-turning moments. Shires (2012) provided a numerical optimization procedure to minimize the aero-generator weight while imposing aerodynamic, mechanical and structural constraints. At azimuth positions of -90°and +90°, the blade chord remains parallel (Shires 2012) with the local flow direction while between -90° and +90° positions the blade passes through the upwind cycle of rotation and through the downwind cycle between +90° and +270° positions (Fig. 15). A reduction in the maximum angle of attack was observed over the downwind cycle due to the induced velocity field. However, the normal force coefficient of the element shown in Fig. 15 tracks the attack angle for attack angle of <17°. Above this value, the blade element stalls and normal force was reduced (Shires 2012).

Savonius turbines are simple and aerodynamically drag-type, consisting of two or more scoops (Lack 2010) as shown in Fig. 16. The curvature nature of the scoop results in less drag when moving against the wind than when moving with the wind. This type of arch of the rotor blades follows a funicular curve and hence is not exposed to bending moment under the centrifugal force. This type of turbine, though exerting a quiet negligible drag, produces large torque ripples and cyclic stress on the tower which

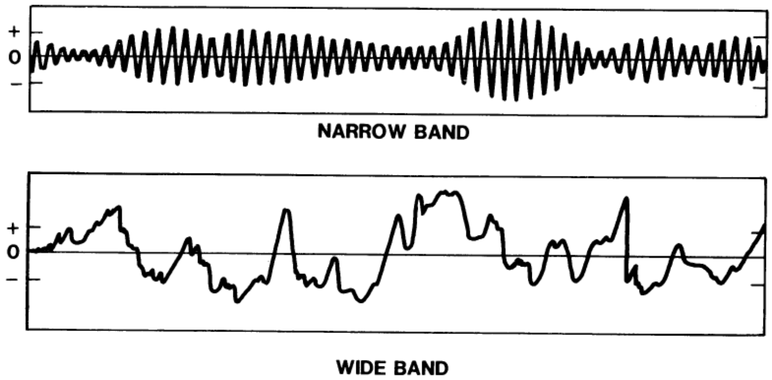

Fig. 19 Gaussian signals (Veers 1981)

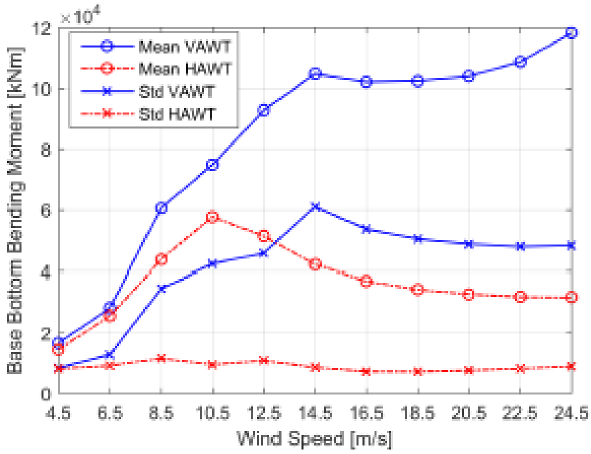

Fig. 20 Turbine base bending moment as a function of wind speed for vertical and horizontal axis wind turbines (Galinos *et al.* 2016)

degrades the reliability. However, the torque ripple is reduced by using three or more blades which results in a higher solidity for the rotor (Lack 2010).

Cheung (2011) used Atmel microcontrollers to monitor the blade vibration frequency by sampling a data set of 128 acceleration measurements and employed an integer version of Fast Fourier Transform to analyse the data. The proposed procedure can run for more than 30 years with lithium batteries if the accelerometer on the microcontroller board is replaced. The system has been tested on a vibration shaker, and it is also tested in a single disturbance with wood and aluminium beams. Brown and Brooks (2016) analysed the thermoplastic composite sandwich structure blade of a 5-kW VAWT to prove-out the one-step vacuum moulding process and validated the finite element methodology. The bending test simulation results showed a good correlation with test results for force-displacement and major damage modes. A modal analysis of the full-scale blade showed its fundamental frequency to be sufficiently high to avoid oscillation coupling with the rotational frequency (Brown and Brooks 2016).

Wind tunnel testing of a double-element airfoil (Fig. 17 provides details of the typical lift coefficients for a single and two-element airfoil) showed that aerodynamic characteristics of the airfoil increased considerably by delaying the stall angle (Chougle 2015). These two facts are very suitable for a VAWT since they operate in a larger range of attack angle, ±40°. In this configuration, the performance parameters are almost doubled compared to the traditional straight-bladed VAWTs. The reliability prediction and analysis of VAWTs require identifying the critical components, increasing the operating time, and minimizing failure rate and maintenance costs (Dumitrascu *et al.* 2015). The Monte Carlo simulation model enables to estimate the probability of minimum and maximum parameters. Furthermore, the experimental works consist of estimating the reliability and unreliability functions and hazard rate of the turbines.

Analysis of the stress history of wind turbine blades indicates that a single stress level at each wind speed does not adequately describe the blade stress history. The complete stress history of the turbine blades can be traced if the root-mean-square stress levels are known for all wind speeds (Veers 1981). It is clear from Fig. 18 that a single stress level at a wind speed cannot describe the stress history. A statistical distribution of stress levels can provide an accurate picture of the stress history. For a narrow band process (Fig. 19), the distributions of peaks and excursions

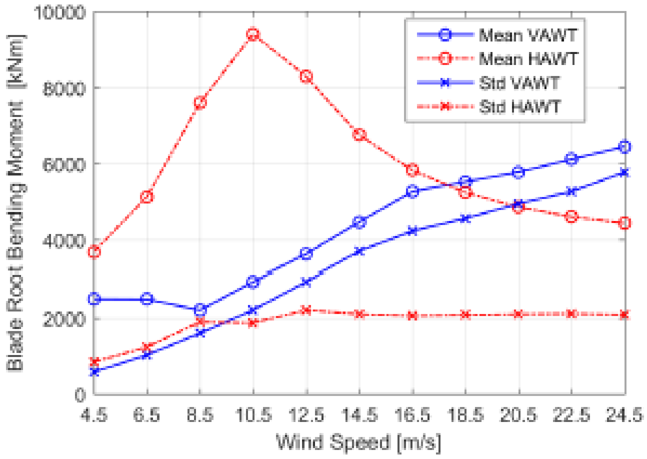

Fig. 21 Blade root (low root for VAWT) bending moment as a function of wind speed for vertical and horizontal axis wind turbines (Galinos *et al.* 2016)

are roughly equivalent because each peak is followed by a valley of about equal magnitude producing an excursion equal to twice the peak. With a wideband process (Fig. 19), this equivalence does not exist. Therefore, the peak distribution is a useful measure of fatigue damage for a narrow band Gaussian process, but not for a wideband process (Veers 1981).

VAWT's base and blade root edgewise fatigue loads (Fig. 20) are much higher compared to the HAWT's (Galinos *et al.* 2016). This leads to blade instabilities while extreme wind shear and wind direction changes are not critical in terms of loading of the VAWT structure. Additionally, under extreme operating gust wind conditions, the emerging loads depend on the combination of the rotor orientation and time stamp that the frontal passage of gust goes through the rotor plane (Galinos *et al.* 2016). The base mean bending moment (Fig. 21) for the VAWT is close to one of the HAWT at low wind speeds but becomes larger at high wind speeds. This is because the thrust on the HAWT is decreased after reaching the rated power due to blade pitching and consequently the base bottom moments are also reduced (Galinos *et al.* 2016).

6. Conclusions

- An advantage of VAWTs is that they can catch the wind from all directions without the need of yaw mechanism. Requiring a low starting torque, these turbines can be built at smaller heights and can withstand much harsher environment. Because of the low noise generation, less visibility, and small height, VAWTs are suitable for residential buildings, and can also be located near residential areas without adverse environmental issues. The usage of VAWTs on a large scale is not an economical option but offers a solution to provide energy to remote areas where large wind turbines cannot be installed due to environmental and other concerns.
- The VAWT produces a wake which becomes beneficial to the next wind turbine if placed correctly.
- VAWTs need lesser area for wind farm development, hence can be used for offshore wind farm deployment. Furthermore, the heavy equipment, like gearbox and generator, is located at a much lower height above ground level in the case of VAWTs unlike HAWTs where this heavy equipment is placed on the top of the tower behind the rotor. This advantage further makes the operation and maintenance of VAWTs much easier and cost-effective and also improves the stability of the complete setup.
- For sure VAWTs are less efficient, having capacity factors ranging from 10% to 15% compared to HAWTs attaining 25% - 50% efficiencies.
- The complete stress history of the turbine blades can only be traced if the root-mean-square stress levels are known for all wind speeds. The blades of a VAWT experience varied angle of attack in every rotation cycle, thus more prone to fatigue failure. The use of modern composite materials and improvements in design (e.g., use of aerodynamic wing tips) may improve the service life.

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