A Brief Review on the Performances of Two-Bladed and Three-Bladed H-Darrieus Rotors

R. Medda, D. Gope, A. Chakraborty, N. Debnath, S. Das, and A. R. Sengupta

Abstract In recent times, the demand for renewable energy has increased very rapidly. Among all the renewable energy sources, wind energy is one of the most reliable options due to its high energy generation and zero CO_2 outflows to the climate. Wind turbines are a type of device which produces energy from the wind. Wind turbines are primarily categorized into two types, horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). HAWTs are popular to use commercially, but the development and research on the VAWTs are increasing gradually nowadays. In this present work, a brief review of the performances of two-bladed and three-bladed H-Darrieus rotors has been done considering different performance parameters like tip speed ratio, solidity, and power coefficient. It is seen that a two-bladed H-Darrieus rotor having a NACA0018 profile with a solidity of 0.12, tip speed ratio (TSR) of 4.5 showed the optimum power coefficient compared to the other investigations of similar rotors. Again, for the three-bladed H-Darrieus rotor, the highest power coefficient is achieved by the LS-0413 blade at a TSR of four which is higher than the NACA0018 blade for the same rotor. This study deals with the research progress of two-bladed rotor and three-bladed H-Darrieus rotor which can be helpful for future researchers to further improve the designs and performances of the same.

Keywords H-Darrieus rotor · Power coefficient · Tip speed ratio · Solidity · Wind turbine

1 Introduction

Energy has a significant role in the social and economic evolution and prosperity of humanity. The energy demands every year are growing exponentially all over the globe. Mostly, the demand for the energy required is, as electricity, to make this up: addressing renewable energy is one of the vital approaches for the development and

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the environment. We have been using conventional resources of energy since finding their application of these resources. As these resources have a limited amount in nature, so it's exhausting rapidly day by day. Also, it creates an excessive amount of greenhouse gases which caused global warming. Because of these issues, the uses and applications of renewable energy are extensively grown. It has increased the research and development activities in the field in the past few years. In a comparison of fossil fuels to renewable energy resources, renewable resources do not emit any harmful greenhouse gases into the atmosphere. There are several renewable sources are available for instance solar, wind, wave, biofuels, geothermal, and others. Among these renewable resources, wind is available abundantly in nature, even harvesting wind energy from the wind is easy to compare with others; the wind energy is economically suitable to generate and supply. A wind turbine is a kind of device which transforms kinetic energy into mechanical energy. Wind turbines could be installed in both distant areas and urban areas as well. Wind energy accomplished one-fourth of the total produced renewable energy every year, and it is growing over time. So, renewable is the future of the energy system, and wind energy is a part of it [1].

Wind energy is pretty convenient in terms of power generation, which is increasing over time. In 2020, the total electricity generation from renewable energy has raised by approximately 6.6% following the completion of approximately 462 TWh than the previous year. The electricity generated by wind in 2020 is around 12%, which is 177.8 TWh greater than the last year following. It is visible from the data that almost 40% of total renewable energy is generated from wind only [2].

1.1 Classification of Wind Turbines

Wind turbine extracts the power from wind and converts mechanical energy into electrical energy; wind turbines are primarily characterized into two classes: Horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) can be seen in Fig. 1. HAWT is the most common type of wind turbine (shown in Fig. 1a) which generates power by aerodynamic lift. The main advantage of HAWT is, it provides high power output as compare to others, and they are more likely to operate at higher wind speed.

On the other hand, VAWT can be easily mounted as compared to other wind turbines. It is portable, can run at low wind speed, is less expensive, creates less noise, and most importantly, it is omnidirectional. It can run in extreme weather, with variable wind speed. VAWTs can be divided into two categories: (a) Savonius rotor and (b) Darrieus rotor. The drag-type Savonius turbines (shown in Fig. 1b) rotate relatively slowly but yields a high torque compared to Darrieus turbines. On the contrary, in the lift-type Darrieus turbine, multiple blades are attached to a shaft that rotates, which is also categorized by its blade shapes, like Troposkien and H-Darrieus rotor. Several other kinds of VAWTs can be seen out there such as hybrid

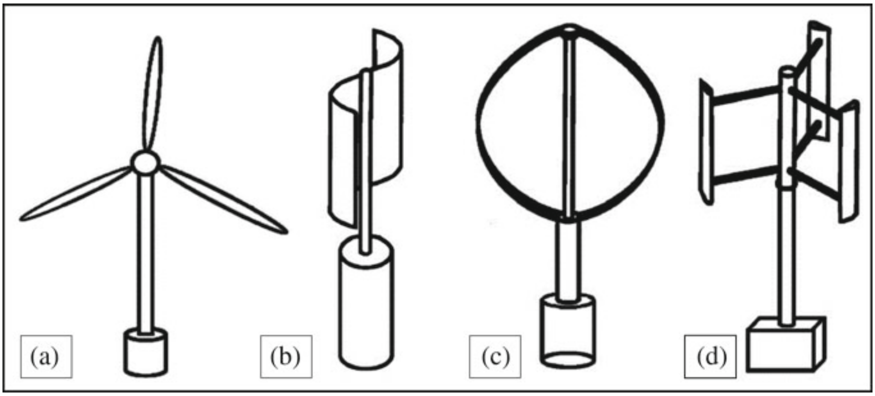


Fig. 1 **a** Horizontal axis wind turbine, **b** Savonius turbine, **c** Darrieus turbine, **d** H-Darrieus turbine [3]

Darrieus-Savonius, multistage rotor, augmented rotor, helical rotor, multi-bladed rotor, and V-type rotor [4].

2 Purpose of the Present Study

VAWT research has been accelerated over, past few decades both through experimental and numerical simulation. However, our awareness of certain key factors influencing their performance is still lacking. An enormous amount of work has been done on the three-bladed H-Darrieus rotor, but very less work has been done on the two-bladed H-Darrieus rotor in terms of their improvement of performance. The objective of this present investigation is to review the effects on the performance by the number of blades, different shaped airfoils, solidity, turbulence models, TSR range, wind velocity.

3 Comparative Study on the VAWTs

3.1 On Two-Bladed H-Darrieus Rotors

Over the years, various researches have been performed on the improvement of the performance of two-bladed H-Darrieus rotor in terms of modifying the design, the number of blades, types of airfoils, augmentation, dimension, etc. Some of the important researches are summarized below.

Lei et al. [5] have performed a computational study over the IDDES turbulence model, and compared the results with the experimental and validated data of the SST

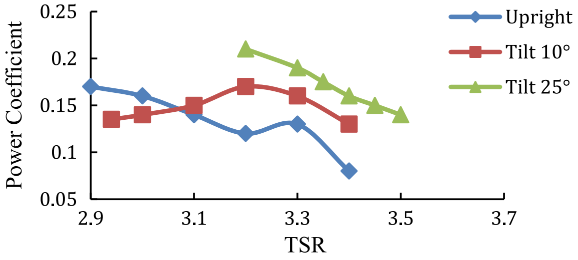


Fig. 2 Cp versus TSR graph in upright, 10° tilted, and 25° tilted position [7]

$k-\omega$ turbulence model at TSR range between 1.450 and 2.478. In the IDDES model, the power coefficient value is near around to the experimental data than the SST $k-\omega$ model. The optimum C_P is about 0.18 at a TSR of 2.23. Buchner et al. [6] have studied the dynamic stall of the two-bladed H-Darrieus VAWT; a 2D URANS model was used followed by a wind tunnel test to validate the simulation performance. Chowdhury et al. [7] have carried out a CFD study based on the inclination of the rotor shaft; three cases are carried out through the study, upright, 10° tilted and 25° tilted with the Y-axis. They have also concluded that the SST $k-\omega$ model shows better performance compared to other turbulence models. The VAWT, with a 25° tilted rotor axis, has produced a maximum C_P of 0.21 at TSR 3.2 which is shown in Fig. 2.

Bedon et al. [8] have investigated the aerodynamic characteristics of the H-Darrieus rotor with the newly developed WUP1615-shaped airfoil and compared it with NACA 0018 airfoil. The CFD study revealed that at a positive angle of attack, the lift coefficient (C_L) of the WUP1615 rotor is increased, but at a negative angle of attack, the values of the lift coefficient (C_L) are similar to the NACA 0018 bladed rotor. Biswas and Gupta [9] studied the effect of the different blade profiles, aspect ratios, and the twist at the trailing edge to improve the unsteadiness of the rotor at a low Reynolds number. They noticed that a 30% blade twist at the trailing edge of an airfoil helps to enhance the performance of a two-bladed rotor at a low Reynolds number. The velocity contour plot is shown in Fig. 3 where the wake structures past

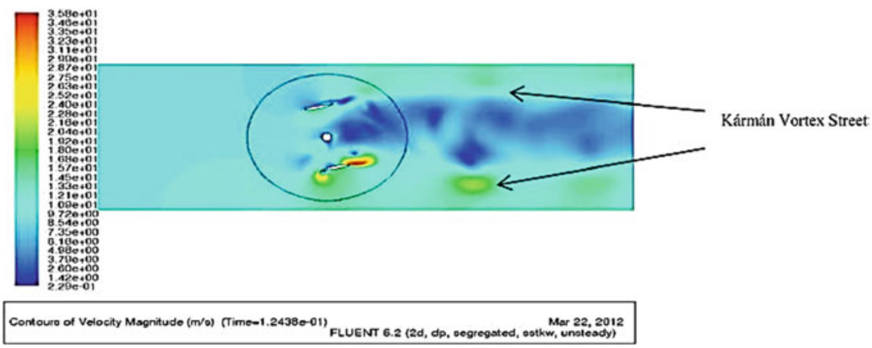


Fig. 3 Velocity contour in a quasi-periodic period [9]

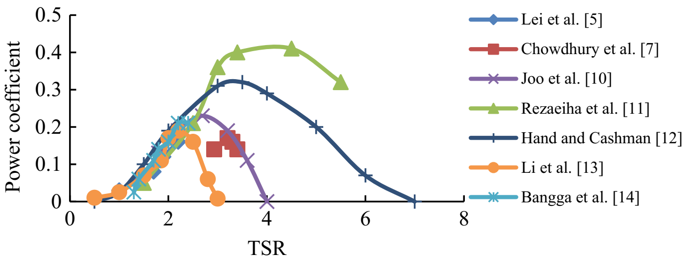


Fig. 4 Power coefficient (C_p) versus TSR of two-bladed literature

the rotor along with the Karman vortex street layers can be seen. The difference of velocity between the upstream and downstream sides of the rotor helps to determine the lift generated by the rotor blades. Joo et al. [10] have performed a computational study on the aerodynamic characteristics of two-bladed H-Darrieus rotors at several rotating speeds and solidities, with a moving framework. They have found that the maximum efficiency (C_p) of 0.23 at a solidity of 0.5 and TSR of 2.69. Rezaeiha et al. [11] in their numerical studies found that NACA0018 two-bladed H-Darrieus turbine having a solidity value of 0.12 and 4.5, TSR was able to display the highest power coefficient of 0.41.

Hand and Cashman [12] have investigated different parameters like solidity, aspect ratio, blade number, and TSR. They also found that the two-bladed turbine has shown a maximum C_p of 0.32 with the corresponding TSR of 3.14 at a wind velocity of 13 m/s. Li et al. [13] have experimented on the two-bladed H-Darrieus rotor having NACA0021 airfoils. It was noticed that the optimum performance of the rotor was achieved at a TSR 2, and the speed of wind ranges between 6 and 7 m/s. Bangga et al. [14] have carried out a 2D CFD analysis on a two-bladed H-Darrieus turbine at a wind velocity of 8 m/s having NACA0021 airfoils and found an optimum C_P of 0.2 at TSR 2.6 for the same. A comparative analysis of power coefficient values for the two-bladed H-Darrieus rotor obtained by various researchers is shown in Fig. 4.

The above literature covered up the effect of different geometrical and aerodynamic parameters like solidity, TSR, the angle of attack, aspect ratio, wind speed, turbulence model, blade shape in CFD, and many others. The important findings are mentioned in the conclusion section.

3.2 On Three-Bladed H-Darrieus Rotors.

In the recent past, researchers have performed various investigations on several parameters of three-bladed H-Darrieus rotors to improve their performance; among which, some important findings are discussed below.

Sengupta et al. [15] have investigated three blade profiles; among them, one is symmetrical (NACA0018) blade, and the other two chambered (EN0005 and S815)

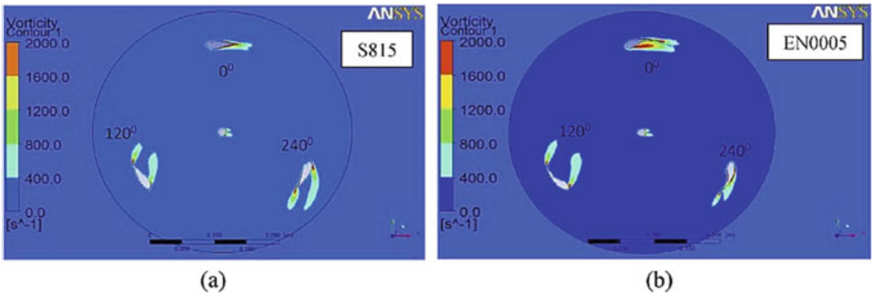
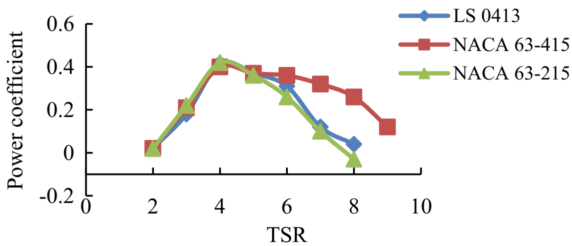


Fig. 5 Generation of vortices at wind velocity 6 m/s for unsymmetrical blade H-Darrieus rotors [16]

blades. They found that the maximum C_p of 0.19 for S815 and 0.17 for NACA 0018 airfoils at a flow velocity of 6 m/s. Again, Sengupta et al. [16] have emphasized the effect of the curvature and camber of the unsymmetrical airfoils to improve the performance of the turbine at low wind speeds. Result showed that in the power stroke, due to higher curvature in the suction side of the S815 airfoil, better performance is achieved. But, in the return stroke, the EN0005 airfoil with higher camber and lesser curvature shows better performance. The vorticity formation contour plots for these two blades are reproduced in Fig. 5 where the comparison has been done of rotor performances for different azimuthal angle positions in terms of vorticity generation.

Mohamed et al. [17] have investigated 25 different airfoil shapes in a broad TSR range with rotor solidity of 0.1. They found that LS-0413 airfoil delivered the highest power coefficient (C_P) of 0.415 at TSR 4, with an expansion of 10% compared to NACA 0018. They have also noticed that NACA 63-415 has the widest operating speed ratio range, and the maximum power coefficient (C_P) is 0.40 at TSR 4. The C_p versus TSR plot is shown in Fig. 6. Rezaeiha et al. [18] have attempted a computational study, which is based on the three different sets of VAWTs with different characteristics and extended range of operational conditions in seven different turbulence models, namely the Spalart–Allmaras (S–A), RNG $k-\varepsilon$, realizable $k-\varepsilon$, SST $k-\omega$, intermittency transition model (SSTI), $k-k_l-\omega$ transition model, and transition SST $k-\omega$ (TSST). The results showed only three turbulence models (TSST, SST $k-\omega$, and SSTI); out of those, seven can be used to achieve approximately accurate

Fig. 6 Power coefficient (C_P) versus TSR for the best three blade sections in Mohamed et al. [17]



aerodynamic performance. The highest C_p of 0.369 at TSR of 3.29 in TSST among the accurate turbulence model and TSST turbulence has the minimum overall deviation of 18.6% from the experimental data of Castelli et al. [19]. Balduzzi et al. [20] have performed CFD analysis with the H-Darrieus VAWT to find the most precise simulation setup and found that the best turbulence model is SST $k-\omega$ for simulating Darrieus rotors. Their study revealed that the highest power coefficient (C_P) of 0.31 was found at a TSR of 2.25 for the considered operating conditions.

Mohamed [21] again investigated the major problem of being able to self-start Darrieus turbines, to improve this downside. The impact of solidity and the utilization of a hybrid system which is a combination of both Savonius and H-Darrieus turbines have been investigated numerically and experimentally. It was found that enhancing the solidity of the turbine does improve its self-starting ability at low TSR. The hybrid system shows a better static torque coefficient which configures the self-starting ability, but the performance of the turbine is decreased in exchange. The rotor obtained the highest static torque at a solidity of 0.25, in which case the maximum (C_P) of 0.38 is produced by the rotor at TSR 4. Kumar et al. [22] have performed a CFD analysis on the performance improvement of the H-Darrieus rotor with cavities on the pressure side of the airfoils. The result has shown that the overall performance has been increased due to the suppression of the free stream boundary layer around the airfoil surface near the cavities. There is a significant improvement in self-starting capability; the optimum power coefficient (C_P) of 0.16 is achieved at TSR 1.3. Two unsymmetrical (S815 and EN0005) and one symmetrical (NACA 0018) blades are considered by Sengupta et al. [23, 24] to compare the performance of these three rotors by experimental analysis. The rotors have shown their optimum performance at the solidity of 0.51 and aspect ratio (H/D) of 1. The maximum power coefficient (C_P) is found at 0.19 for the S815 bladed rotor. It was concluded that high solidity unsymmetrical-bladed rotor has better dynamic and static torque coefficient and power coefficient values compared to the low-solidity blade rotors. Subramanian et al. [25] have attempted to find the performance of AIR 001, NACA 0015, NACA 0012, and NACA 0030 for H-Darrieus turbines. The TSR (λ) range was considered in between 1 and 2.5 with an incoming wind speed of 10 m/s. They concluded that the NACA0030 blade shape showed the optimum power coefficient at a low TSR of 1.8 considering the wind speed of 10 m/s. In Table 1, some important results of three-bladed H-Darrieus turbines for different parameters are mentioned.

Martinez et al. [26] performed the CFD simulation over four various thicknesses of NREL S815 airfoils to increase the performance of VAWT at wind speed conditions

Table 1 Results of the three-bladed H-Darrieus turbines

Literature	TSR	Solidity	Flow velocity (m/s)	Aspect ratio	Maximum Cp
Mohamed et al. [17]	1.0	0.1	5	1.0	0.41
Rezaeiha et al. [18]	3.29	0.25	9	1.0	0.36
Sengupta et al. [24]	1.43	0.24	8	1.4	0.19
Martinez et al. [26]	1.7	0.51	8	1.0	0.32

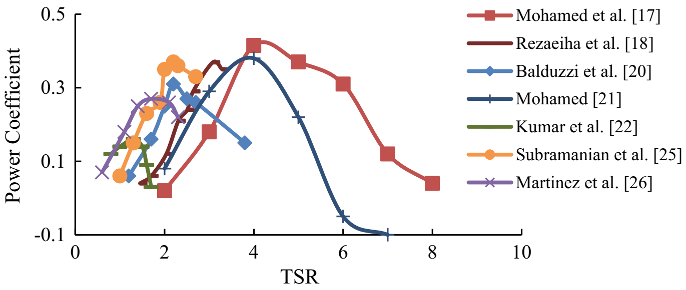


Fig. 7 Power coefficient versus TSR

of 6 and 8 m/s. The range of the TSR in this study was considered from 0.6 to 2.25. It was noticed that along with the increment of the thickness and TSR values, the performance of the rotor also increased until it has reached the optimum point (19.2% thickness). The highest C_P of 0.32 is achieved at a TSR of 1.725 in 8 m/s which is higher as compared to C_P of 0.28 at the same TSR in 6 m/s wind speed. In Fig. 7, C_p versus TSR graph for two-bladed H-Darrieus rotors obtained by various researchers is plotted.

On three-bladed H-Darrieus rotors, a lot of research works have been done and are being continued. Among those studies, some of the important literature on three-bladed H-Darrieus rotors have been presented here considering several performance parameters.

4 Conclusion

This review shows a brief overview of the performance of two and three-bladed H-Darrieus rotors considering several performance parameters. From this present study, some vital outcomes are listed below:

- Two-bladed H-Darrieus rotor having NACA0018 profile with a solidity of 0.12, TSR of 4.5, and an angular time step of 0.1° to 0.5° showed the optimum power coefficient of 0.41 for the considered operating conditions.
- The most accurate turbulence model is SST k-ω for the two-bladed rotor, and in the three-bladed rotor, the TSST $k-\omega$ shows the most accurate result compared to the SST $k-\omega$ and SSTI $k-\omega$ turbulence model. TSST $k-\omega$ turbulence model is able to capture the stall vortices around the blade surface in low Reynolds number.
- From the literature, optimal C_P is obtained for both two-bladed and three-bladed rotors at low solidity of around 0.1 in the moderate TSR range. If the solidity is increased at low TSR, the three-bladed rotor exhibits more power coefficient than the two-bladed rotor. But, in a high TSR range, a two-bladed rotor needs low solidity to display higher performance.

- For the three-bladed H-Darrieus rotor, the highest C_P of 0.415 is acquired by LS-0413 blade at TSR of four with a rise of 10% compared to NACA 0018 for the considered operating conditions.
- With an increase of the airfoil thickness, the performance is increased for the unsymmetrical S815 three-blade H-Darrieus rotor, but after the optimal thickness percentage (19.2% of the chord length), the performance is dropped down.

This investigation has gathered some valuable information regarding the performance of the two-bladed and three-bladed H-Darrieus rotor systems. This current study can be referred by future researchers to work in this field for comparative analysis in between two and three-bladed H-Darrieus rotors.

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