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A Multi-Step on-off Blade Vertical Rotor for Harnessing Wind Energy

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Abstract. A multi-step on-off blade vertical wind turbine is developed and experimented. Unlike Savonius rotors which rotate by an action of differential drag, the proposed design configuration makes the rotor rotates only by positive drag. The proposed rotor comprises four vertically arranged (layers) steps and in each step there are two rectangular blades aligned at 180 degree-angle around a vertical shaft in the same vertical plane. Geometrically, the four vertical planes which enclose the blades in the four layers make a spatial 45 degree-angle with each other, successively, from the topmost step to the bottommost step. A total of eight blades two in each step form the basic configuration of the rotor. The rotor steps are separated by circular endplates where each two blades are hinged to the upper endplate in their own step. During any moment of operation, only four of the eight blades are in the "on" position while the other four blades will be in the "off" position. The "on-off" positions of blades are automatically took place as a result of wind pressure without need for a special mechanism. Theoretical analysis, based on an irrotational flow, is simultaneously developed to compute the generated torque and power coefficients. Both theoretical and experimental results are compared. The main interesting result which was justified theoretically and experimentally is that the maximum power coefficient of the proposed rotor occurs at a speed ratio of 0.6 with wind speed of 8 m/s. This makes the proposed rotor liable for application in a lot of areas around the world where the recorded average speed is around 8 m/s. Also, this type of turbines is found to be competitive to classical vertical wind turbines like Savonius turbine. It provides power coefficient higher than that of the classical Savonius rotor while the later offers larger speed ratios for operation. The results of the potential-flow theory regarding the duplication of the number of blades, which consequently duplicates the height of the rotor, are very encouraging in terms of the offered power coefficients and generated torques.

Keywords: Wind energy, Savonius turbine, On-off bladed rotor, Multi-Step rotor, Theoretical analysis, Experimentation

1. Introduction

The majority of rural and arid regions, whenever reasonable wind exists, are considered as suitable areas for installation of large-, medium- and small-size wind turbines. The large-size Horizontal Axis Wind Turbines (HAWT) is located in these areas without having hazards of the rotating machinery on the human being. The situation is more complicated when HAWT are designed for urban areas. HAWTs sit atop a large tower where its large blades are fixed to a horizontal shaft that is mostly parallel to the direction of wind. HAWTs deliver more power than Vertical Axis Wind Turbines (VAWT). The VAWT have become under the focus of intensive research because of their many advantages. They can be located at ground level, they capture wind from any direction, they are easy to maintain and they are more suitable for small-scale domestic applications.

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On the top of list of VAWTs there are two important ones. The first one is the Darrieus turbine and the second one is the Savonius turbine. These two turbines have been under a lot of studies and investigations in the past two decades [1-3]. Darrieus turbine offers more power and speed ratios than the Savonius turbine. It is more suitable for generating electricity than Savonius one. The Darrieus wind turbine rotates around a central axis due to the lift caused by the rotating airfoils, whereas a Savonius turbine rotates due to the differential drag created by its leading and returning blades. A hybrid turbine, which combines Darrieus and Savonius designs in one configuration that has been proposed by many researchers [4, 5].

A computational study was introduced for optimizing the airfoil cross-section of a VAWT [6]. The main design constraints such as the tip speed ratio, solidity and blade profile were considered to enhance the generated torque. Such study was important because it introduced the first step towards the development of the VAWT utilizing an optimized blade cross-section. The study of [6] suggested further research and development in such field. An experimental study of Savonius turbines with different overlap ratios and shift angles under different wind speeds was performed in [7]. The results showed that a higher overlap ratio has an effect on improving the starting characteristics of the Savonius turbine than any phase shift angle changes. The power coefficient is found to be significantly increased at a specific phase shift angle at a specific air velocity. A twisted blade was a simple method to reduce the negative torque and the self-starting characteristics in a three bladed rotor system of Savonius turbine [8, 9]. The experiments were performed at a low speed wind tunnel on the basis of starting torque, power output and rotational speed. The investigation showed higher performance of the twisted bladed rotor compared with that of the conventional semicircular bladed rotor. The measurements also indicated that there is an optimized twisted angle. Artificial neural networks corresponding to different available experimental data on six blades with different wind speed were done in [10, 11]. The power coefficient was obtained at different angles of blade in proportion to blowing wind in a complete rotation. A comparison of the obtained results with the corresponding experiments showed that the simulation is able to provide reasonable computations for the maximum power of rotors and maximizing the efficiency of Savonius wind turbines. It was also found that, increasing tip speed ratio leads to a higher power ratio and torque.

An effort for improving the power coefficient of the conventional and modified Savonius rotors with and without central shaft was done in [12]. The results on modified Savonius rotor with the central shaft satisfied a maximum power coefficient of 0.32. Multi-bladed and multi-stage (multi-S) Savonius rotors for capturing and storing wind energy were developed and tested in [13, 14]. A solution for the wind and load fluctuation problems was suggested. The power coefficients of the new multi-S as well as the standard Savonius rotors were presented in view of measurements and new theoretical analysis [14]. A new geometrical parameter was found to play an important role for improving the performance of the turbine. Effects of guide plates with either flat or curved forms shielding the returning blade were optimized [15]. A relative increase of the power coefficient was registered in that research with the highest performance satisfied by the curved plate. An experimental study was done in [16] to investigate the design and development of a micro VAWT-Savonius type, while experimental and computational analysis on a micro wind turbine for urban environment was presented in [17]. The results of these researches showed that VAWT provide operational abilities at lower speeds at which the horizontal Axis Wind Turbines (HAWT) do not have a practical application due to high wind speed requirement.

Experimental and two-dimensional CFD studies using Fluent 6.2 software; were introduced in [18] on an airfoil shaped two bladed H-Darrieus rotor. A comparative study between experimental and computational works was carried out and found to be quite encouraging. More attentions are recently directed to the straight-bladed vertical axis wind turbine (SB-VAWT) because of its simplicity of construction and low costs [19, 20]. To improve the performance, the cycloidal blade system and the individual active blade control system were adopted. Aerodynamic analysis is carried out for cycloidal wind turbine by changing pitch angle and phase angle based on the cycloidal motion according to the change of wind speed and wind direction. It was found that the generated electrical power is about 30% higher than wind turbines which use fixed pitch angle configuration. Additionally, aerodynamic analysis showed performance improvement of 60% as reported in [19]. However, the starting performance of the straight-bladed vertical axis wind turbine (SB-VAWT) was found to be poor by investigators in [20]. Alternatively, Savonius rotor was combined to the SB-VAWT in order to increase its starting torque since Savonius rotor has much better starting torque characteristics. The simulation results of [20] showed that the starting and dynamic torque measures of the hybrid Savonius-SB-VAWT have been improved.

Some rotor designs have sought to eliminate the negative drag that acts on the blades acting upwind in a Savonius rotor [21,22]. Usually, they implement slatted or swinging blades that are designed to trap wind during their downwind travel. But swing freely in order to eliminate negative drag during their upwind travel. Dynamic-torque tests [22] were performed for Savonius wind rotor with hinged blades to improve the performance of the slatted-blade rotor that was originally proposed in [21]. This design provided slightly higher torque than the classical Savonius design at low wind speeds, but it reaches only a maximum of 0.05 power coefficient, compared to 0.18 for a typical Savonius turbine.

In this article, an on-off blade vertical wind turbine is designed and investigated. It looks like a vertical tower of four (steps) stories where each story has a circular floor and a circular roof. The detailed design is presented in Section 2 and its experimental set up is explained in Section 3. Theoretical and experimental results are presented and discussed in Section 4 and conclusions are extracted in Section 5.

2. Turbine Design and Power Calculations

The schematic diagram of the proposed multi-step on-off blade vertical wind turbine is shown in Fig. 1. It comprises four vertically arranged (steps) stages. Five circular end plates, installed to a vertical shaft, are used to separate the (steps) stages from each other such that each stage is formed by one upper end plate and one lower end plate. In each stage there is one advancing blade of squared shape and one returning blade of same shape and dimensions and both are lying in the same vertical plane, i.e., they are aligned such that they make an 1800-angle away of each other. The four vertical planes of blades in the four steps are spatially arranged such that they make a 450-angle with each other successively from the top step to the bottom one as indicated in Fig. 3. During operation, when every two blades in the same (step) stage are perpendicular to the flow of air, one of them will be totally open and the other one will be totally closed. The "on" position means that the blade is totally open for receiving air and the "off" position means that the blade is not receiving air at all and closed. In other words, each blade in every step is totally open along a180-degree angle of operation and is totally closed along the other 180-degree angle of operation. Hinges are used to install the on-off blades in each step to its upper end plate. Blade stops in each step are installed to its lower end plate. These stops keep the blades exactly in a vertical plane during its "on" position which consumes 180-degree active angle of operation. At the end of this active angle of operation the blade is turned off by action of air pushing its back to settle in a horizontal plane and it stays in this off position for a 180-degree inactive angle of operation. With hinges and blade stops used as shown in Fig. 2, the on-off positions of blades are performed by the action of air flow itself. In the schematic top-view diagram shown in Fig. 3, it is obvious that there are only four active blades which are in the "on" positions at any moment of operation. The other four blades are totally switched off and are not receiving air at all. So, according to Fig. 3, blades 1 and 2 are in the topmost step, and all the time of operation we will have one of them active and the other will be inactive. Same thing goes for blades 3 and 4 in the second step, blades 5 and 6 in the third step and blades 7 and 8 in the (fourth) bottommost step. Also from Fig. 3, the axis AB is the axis at which blades begins to switch "on" and "off" because it is parallel to the direction of air flow. The "on" position is obtained at point A and the "off" position is obtained at Point B. The axis CD represents the position at which the projected area of any open blade will equal the real area of the blade itself. Unlike Savonius rotors which rotate by an action of differential drag, our proposed design configuration makes the rotor rotates by an absolute positive drag. The important dimensions of stator and rotor are shown in Fig.2. These dimensions are the ones which were used to make the experimental set up.

In the present theoretical analysis, the air is assumed to be irrotational at any instant and it remains irrotational thereafter. Of course, the assumption of zero viscosity, and the absence of boundary layer effects, is never perfectly correct. It's obviously possible to introduce or remove vorticity due to real-world boundary layer effects. Nevertheless, in a large class of realistic situations the assumption of irrotational flow is valid [14].

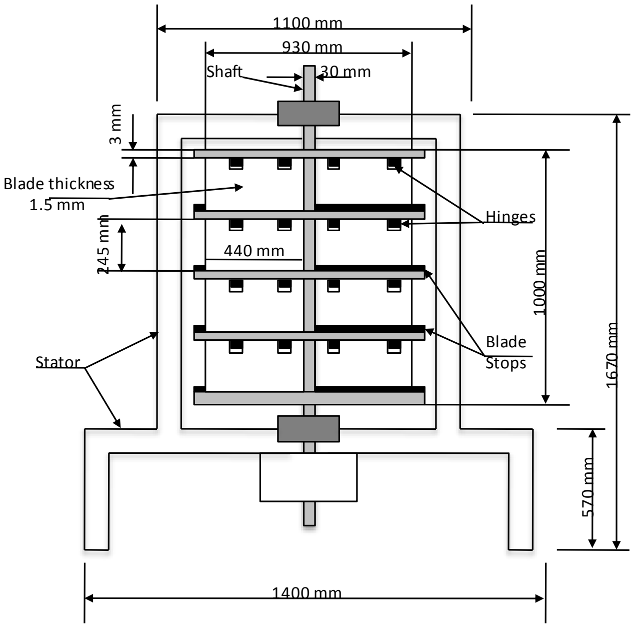

Fig. 1: Schematics of the proposed on-off blade turbine.

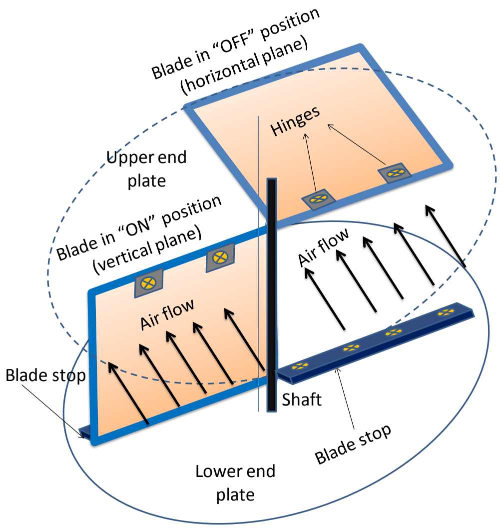

Fig. 2: Blades during operation in one step.

Under these conditions there exists a momentum force created by the velocity component normal to blades ($U_\infty \sin\theta$). Because of the rotation of the blade with angular velocity ω, the relative velocity is considered in computation of the momentum force acting on one blade as follows, see Fig. 3:

$$F = \rho R_c L(U_\infty \sin\theta - \omega R_c / 2)^2 \tag{1}$$

where L is the height of the blade and R_c is the length of the blade. The instantaneous generated torque and power coefficients C_p of a blade are then computed from:

$$T = \frac{F \times R_c}{2} = \frac{1}{2}\rho R_c^2 L(U_\infty \sin\theta - \omega R_c / 2)^2 \tag{2}$$

$$C_p = \frac{T \times \omega}{\rho U_\infty^3 R_c L} = \frac{= \frac{1}{2}\rho R_c^2 L(U_\infty \sin\theta - \omega R_c / 2)^2 \times \omega}{\rho U_\infty^3 R_c L} \tag{3}$$

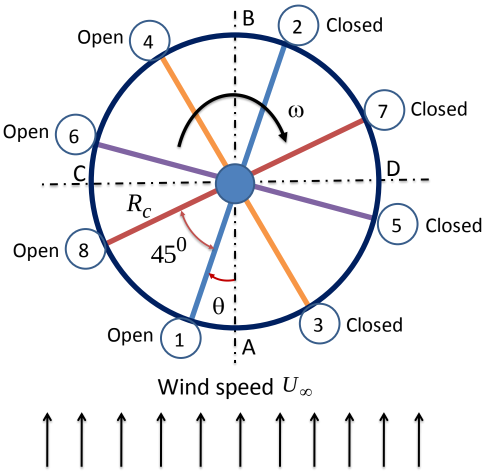

Fig. 3: A top view of the on-off multi-step rotor.

Fig. 4: Two different views of the experimental test rig.

Introducing the definition of the speed ratio $\lambda = \omega R_c / U_\infty$, it gives the power coefficient of the blade as:

$$C_p = \frac{1}{2}\lambda\left(\frac{\lambda^2}{4} - \lambda \sin\theta + \sin^2\theta\right) \tag{4}$$

The instantaneous total torque and power coefficients can be computed by summing the contributions made by the instantaneously four active blades in the different four steps. Referring to Fig. 3, and at any moment of operation, there are only four active blades which receives air one in each step. The mean value can simply be computed by integration over the active angle of operation from $\theta = 0$ to $\theta = \pi$.

3. Experimentation

The experimental set up of the proposed on-off blade rotor is shown in Fig. 4. It is in the form of two main parts. The first part is the stator part which consists of the supporting base and the carrying frame. The other part is the (rotor) dynamic part which consists of a 30-mm diameter shaft with five circular endplates fixed to it. The five circular endplates are of equal dimensions. Every two endplates enclose one step with two blades aligned at a 180-degree angle around the shaft. The four steps are of the same height and the eight blades are of equal dimensions. Fig. 5 reveals the philosophy of operation of the suggested rotor in which only four active blades receive air at any moment of operation with the other four blades switched off as explained before.

Precautions were made in manufacturing and assembling of the rotating parts of the turbine for avoiding effects of misalignment and unbalance. The paddles are hinged to the upper endplates in their own steps. A maximum of 90-degree angle of blade openings are achieved by using blade stops fixed to the lower endplate in their own steps. The shaft is supported by two types of bearing: thrust bearing joined to the supporting base near its bottom and radial bearing joined to the carrying frame near its top. It is also noted that the endplates are made of steel of 3 mm thickness and the paddles were made of galvanized steel sheets of thickness 2 mm. These endplate, blade and bearing designs and selections were capable of handling all the static and dynamic loads in all directions during experimentation. The overall dimensions of the suggested rotor are shown in Fig. 1.

In all experiments, the main flow is produced by a 1.48 kilowatt-5 blades rotating blower of 1 m diameter and it is covered by a steel grid in order to generate uniform flow. It can provide a wind-like speed up to 14 m/s. Wind velocity is measured by Windmeter (Hand Held Anemometer) which provides the speed measurements in the range of 0.2-30 m/s with an accuracy of ±5%. Wind velocity is adjusted according to a given Reynolds number and the rotor is allowed to rotate from no load speed. Rotational speed of the rotor is recorded by a digital tachometer called Smart Sensor model AR925. The features of this type of tachometer are such that: speed range of 0.5 – 19999 rpm with an accuracy range of ±0.05% and resolution of 0.1 rpm. We adapted the procedure used by Kamoji et al. [12] for measuring the static torque. This measuring system is called brake-drum instrumentation. It employs a portable digital scale HD-F01 of Huida with capacity of 30 kilogram and minimum scale division of 10 grams. The rotor is loaded gradually to record spring balance reading, weights and rotational speed of the rotor. At a given wind velocity, the rotor is loaded to prevent it from rotation at a given rotor angle. The values of load and spring balance reading are recorded to calculate the static torque at a given rotor angle. This process is repeated several times for calculating the average torque value.

4. Results and Discussions

A theoretical study is made to investigate effects of the number of blades on the performance potentials of the proposed on-off blade rotor. Three different rotor design configurations which comprise 4, 8 and 16 blades are considered. The chosen numbers of blades make it possible to investigate effects of doubling the number of blades on the torque and power coefficients. According to the design criterion that is thoroughly presented in Section 2, with the height of all blades kept constant, doubling the number of blades means doubling the total height of the rotor. The theoretical study is performed on the basis of an experiment investigation which showed that the peak of the power coefficient which corresponds to a freestream velocity, U_∞ = 8 m/sec, occurs at speed ratio λ = 0.6. This fact will be discussed later on.

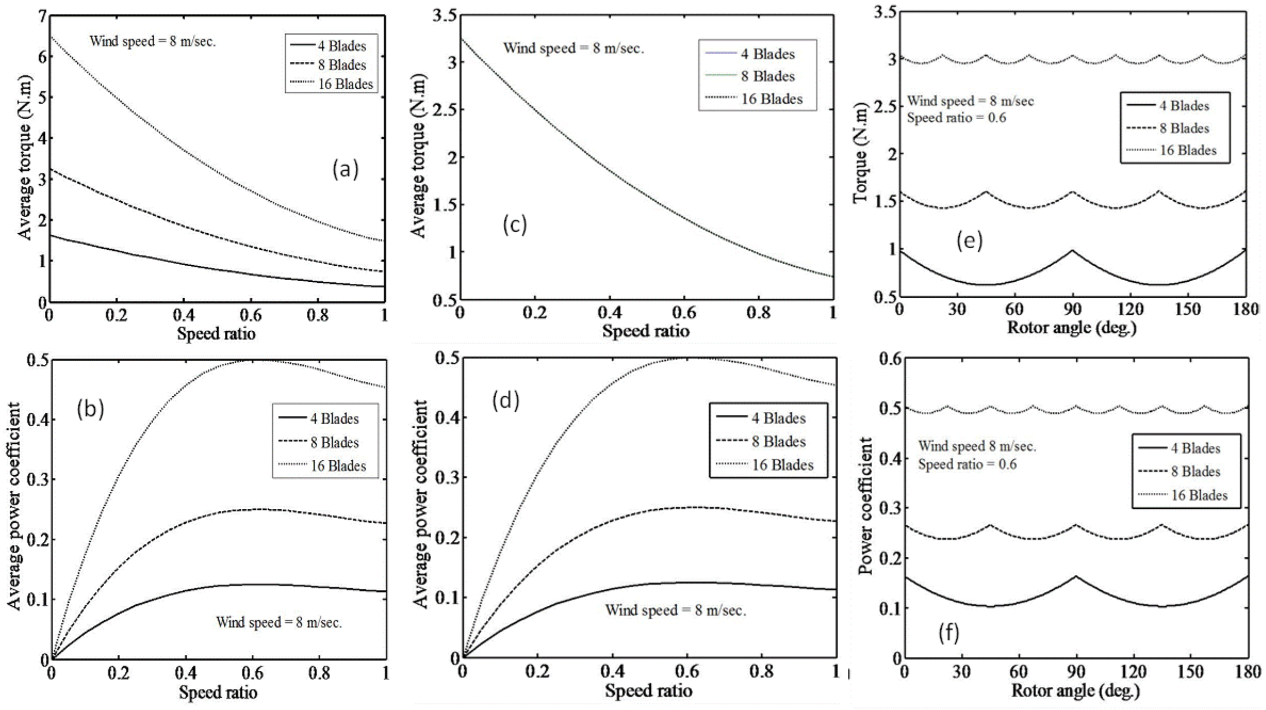

Fig. 5: Theoretical torque and power coefficient for the proposed rotor.

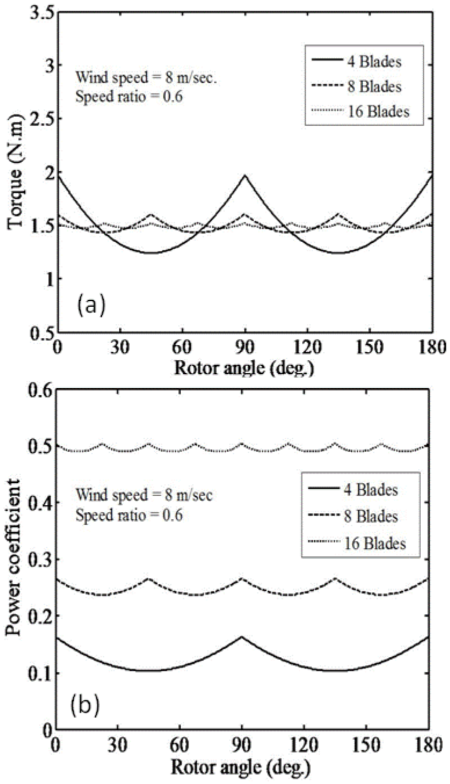

Fig. 6: Theoretical torque and power coefficient for the proposed rotor.

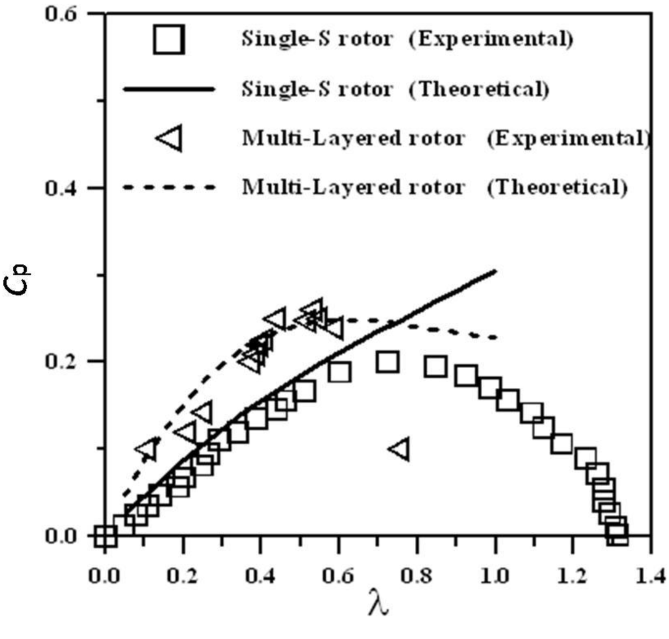

Fig. 7: Comparison of the proposed rotor to the Savonius rotor: (The power coefficient vs. the speed ratio).

The variations of mean values of the torque and power coefficients with the speed ratio, λ, at wind speed of 8 m/sec for the three different rotors with the rotor height duplicates as the number of blades duplicates are shown in Fig. 5(a,b). Generally, as the number of blades increases the mean torque and the mean power coefficient increase. The generated torque is going to be lower as the speed ratio increases, because of the reduction of the generated momentum force. The power coefficient on the other hand has a $3rd$ degree curve with its peak located at the same value of speed ratio ($\lambda = 0.6$) and the peak value increases with increasing the number of blades. The distribution of the mean torque and the mean power coefficients against the variation of the speed ratio when doubling the number of blades with the heights of all rotor remain the same as the height of the 8-blade rotor is shown in Fig. 5(c,d). This means that the heights of blades in the 16-blades rotor are decreased to half the height of the 8-blades rotor and the heights of blades of the 4-blades rotor are increased to duplicate the height of blade of the 8-blade rotor.

It is interesting to see that there are not any variations of the mean torque for the three rotors, while the quantitative forms of the power coefficients of the different rotors remain as before in Fig. 5(a) when the height of rotors were different. Now, we will investigate effects of doubling the number of blades on variations of the generated torque and power coefficient against variations of the local positions of all active blades along the 180-degree active angle of operation. The results are shown in Fig. 5(e,f). The fluctuations of the torque and hence the power are associated with variation of the imposed momentum force. The motivation behind most total torque studies generated by different (steps) stages is related to the need for better understanding of the mechanisms which are responsible for induced structural vibrations in vertical wind turbines. These vibrations can lead to radiated acoustical noise or structural damage if the oscillations are large. This issue will be of future research investigation of the current authors. From the angular position history of the torque and power coefficient in Fig. 5(e,f), increasing of blade stages leads to smoothening of the generated torque and power with noticed reduction of the cycle period. The period can be estimated by measuring the angle between two neighboring peaks; this reads: 90, 45 and 22.5 degrees which are corresponding to the 4-, 8- and 16-blades rotors, respectively. It is also noticed from Fig. 5(e,f) that the mean generated torque and power coefficient are duplicated with duplication of the number of (steps) stages which duplicates the number of blades. This is, of course, a theoretical study results based on an ideal flow theory; but it opens the door for further future experimental studies taking into consideration the overall size of the resulting turbine design and other complications like the produced noise and structural vibrations. The same theoretical study is performed for the three rotors except that the overall heights of the three rotors are kept constant and all equal the height of the 8-blade rotor. This means that the heights of blades of the 16-blades rotor are decreased to half the height of the 8-blades rotor and the heights of blades of the 4-blades rotor are increased to duplicate the height of blade of the 8-blade rotor. The periodical torque and power coefficient distributions are plotted in Fig. 6(a,b). It is noticed from Fig. 6(a) that the mean value of the torque is not affected by the variation of the number of blades as long as the overall heights of the rotors are the same. The behavior of the power coefficient does not vary when compared to Fig. 5(f) because, as was expected, the power coefficient is a dimensionless value and will not be affected by the variations of blades height.

A theoretical and experimental comparison between the power coefficients of the proposed multi-step 8-blade rotor and that of classical Savonius rotor are performed and the results are plotted in Fig. 7. The experimental data for the Savonius rotor were adapted from reference [14]. It can be deduced from Fig. 7 that the proposed multi-step rotor can produce higher power coefficient than that of Savonius turbine in the range of $\lambda \leq 0.7$ after which a strong drop of the power coefficient is clearly visible. This is due to the power lost in the mechanical vibration generated by the intensive rotation of the rotor. In view of the aerodynamic analysis, the high speed leads to a strong oscillated wake behind the blades causing also a large lost energy.

5. Conclusions

This article proposed, studied and investigated the relative performance potentials of a newly designed on-off blade vertical wind turbine. It looks like a vertical tower of four (steps) stories where each story has a (lower endplate) circular floor and a (upper endplate) circular roof with two blades installed and aligned at a180-degree angle around the shaft of the rotor. The main advantage of such design is that there no need for a special or complicated mechanism for opening and closing the blades. It opens and closes by action of the air flow with the aid of simple hinges and blade stops. For the 8-blade rotor configuration, a peripheral arrangement of each two blades in each story is made such that they successively make 45-degree angle from the topmost story the bottommost story. This configuration guarantees that 4 blades out of the 8 blades will be (active) open for receiving air while the other four ones will be inactive. Both theoretical and experimental investigations are performed and compared. The main interesting result which was justified theoretically and experimentally is that the maximum power coefficient of the proposed rotor takes place at a speed ratio of 0.6 with wind speed of 8 m/s. This makes the proposed rotor liable for application in a lot of areas around the world where the recorded average speed is around 8 m/s. It provides power coefficient higher than that of the classical Savonius rotor while the later offers wider speed ratios. Also, the Savonius rotor provides its maximum power coefficient, which is lower than that of the proposed rotor, at a higher speed ratio than that of the proposed rotor. The results of the theoretical investigations regarding the duplication of the number of blades, which consequently duplicates the height of the rotor, are very encouraging in terms of the offered power coefficients and generated torques.

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