Novel Design of a Vertical Axis Hydrokinetic Turbine – Straight-Blade Cascaded (VAHT–SBC): Experimental and Numerical Simulation

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Abstract. A promising technology to reduce dependency on fossil fuels is hydrokinetic energy conversion using either turbine and non-turbine technology. Hydrokinetic turbine technology is penalized by low efficiency and lack of self-starting. This study involved experimental testing and numerical simulation of a novel hydrokinetic turbine design, called a Vertical Axis Hydrokinetic Turbine – Straight-Blade Cascaded (VAHT–SBC). Three configurations of the design were tested. Model 1 had 3 passive-pitch blades, while Model 2 and Model 3 had 6 and 9 blades respectively, where the outer blades were passive-pitch and the others fixed-blade. Both in the experimental test and in the numerical simulation Model 3 outperformed the other two models. The Cp of Model 3 was 0.42, which is very close to the theoretical Cp for VAHTs (0.45). It worked properly at low TSR. A CFD simulation based on the RANS solver was performed to gain supplementary information for performance investigation. This simulation confirmed that the torque changes because of the change in angle of attack as the turbine rotates. Because they have different numbers of blades, each model has different periodical torque fluctuation patterns. This study verified that utilization of cascaded blades and a passive-pitch mechanism is able to improve turbine performance.

Keywords: *cascaded blade; CFD; hydrokinetic; passive-pitch; turbine performance; vertical axis turbine.*

1 Introduction

Hydrokinetic energy conversion promises non-polluting alternative energy conversion to reduce dependence on fossil and nuclear energy in meeting energy demand. Hydrokinetic technology is a developing class of renewable energy technology, which can be deployed on many kinds of energy resources, such as rivers, tidal estuaries, marine currents and waves [1]. Conceptually it works the same way as a wind turbine system. Many studies have been conducted to improve the design of hydrokinetic energy conversion systems, especially to increase their efficiency. However, compared to fossil fuel and nuclear energy conversion, hydrokinetic energy conversion is still lagging behind.

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Turbines are the best option for hydrokinetic energy conversion systems. The vertical axis hydrokinetic turbine (VAHT) system is suitable for low current speed application, since it can generate power under low current speed, it is omni-directional (independent of current direction), it does not require a yaw mechanism, and it is easy to maintain [2-5]. Testing of vertical axis hydrokinetic turbines began in 1991 [6]. Since VAHT is penalized by low efficiency compared to horizontal axis systems and lack of self-starting [7], several hydrokinetic turbine researches have been conducted to improve VAHT performance. Some researchers have looked at the shape of the blades, proposing straight blades, helical blades, troposkein curved blades, helical twisted blades, including a Gorlov turbine with V-blades [8-13]. Other studies attempted to optimize the characteristics of the airfoil blade for VAHT, including pitch angle, airfoil section, chamber, solidity, and more [14-16]. The utilization of a passive-pitch mechanism is another method for improving turbine performance [17-19]. *Seven Energy Generation Systems* (2007) reports that the adjustment of pitch angle can increase the power output up to 8%. Hantoro, *et al.* employed a passive-pitch mechanism to minimize the stall effect and improve self-starting [20].

Lift devices such as VAHTs employ the airfoil-section of the blade to generate lift. For existing upstream and downstream VAHT blades, the aerodynamic analysis is more complex than for horizontal axis turbines (HAT). The flow characteristics of downstream blades, which create many vortexes, high turbulence intensity and the shedding wake of upstream blades affect the magnitude of the aerodynamic force they generate. The increasing decrement of downstream blade performance is a result of this phenomenon.

As the turbines rotates it experiences a change of angle of attack (AOA) and relative velocity. AOA is the angle between the cord line and local velocity, while relative velocity is defined as the resultant of freestream velocity and the turbine’s tangential velocity. Both the magnitude of AOA and the relative velocity change with the turbine’s azimuthal position, called the azimuth angle. At small non-zero AOA, the lift force has a tangential component in the direction of the turbine rotation [20].

VAHT blades frequently suffer from high AOA beyond the stall angle, especially when they operate at low tip speed ratio (TSR) ($\lambda < 4$) [21]. TSR is defined as the ratio between turbine tangential velocity (Ωr) and freestream velocity ($u\infty$). The relative velocity shown by each blade in VAHT is the vectoral addition of freestream velocity ($u\infty$) and tangential velocity (Ωr). Hence, the relative velocity encounters change in both magnitude of u_r and AOA α depending on the azimuthal position θ and the TSR. When the blade is in the upstream position (i.e. $0^\circ \leq \theta \leq 180^\circ$), u_r and AOA α can be estimated by

Eqs. (1)-(2). In the downstream position, the blades experience more complex flow due to the shedding wake of the upstream blades, which causes the determination of u_r and AOA to be more difficult [22].

$$u_r = u_\infty(1 + 2\lambda sin\theta + \lambda^2)^{1/2} \tag{1}$$

$$\alpha = tan^{-1}\left(\frac{cos\theta}{sin\theta+\lambda}\right) \tag{2}$$

Since a high AOA leads to stalling, many studies have been conducted to overcome this issue, such as the deployment of a passive-pitch mechanism that is able to adjust the AOA according to the azimuthal position of the blades. Jing, *et al.* investigated a vertical axis blade turbine with passive-pitch mechanism and 6 blades. The experimental result confirmed that the use of the passive-pitch mechanism did not significantly improve the Cp of the turbine, where the maximum Cp obtained was 0.25 [23]. However, the use of a passive-pitch mechanism is able to fix the turbine's self-starting issue [20].

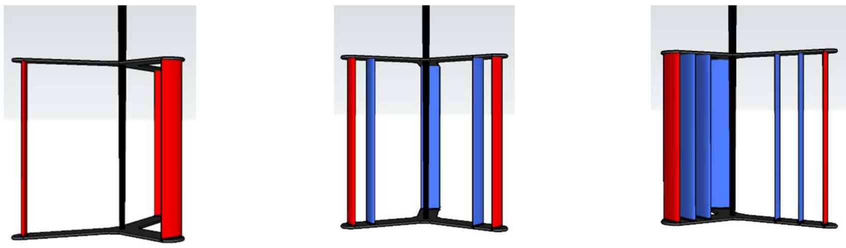
Theoretically, the Double Multiple Stream-tube (DMST) model has shown that the coefficient of performance of vertical axis turbines is 0.45, especially Darrieus turbines [24]. However, another reference states that the theoretical Cp of vertical axis turbines is 0.47, i.e. higher than that of Darrieus and H-rotor type turbines [25]. In 2007, Antheaume proposed the SANDIA turbine, a modified Darrieus turbine. Its maximum Cp is 0.3 at a TSR of around 5 [25]. In another study, a modified vertical axis tidal turbine, called the Hunter turbine, was tested. It was shown that its Cp is about 0.19 [26].

Various mechanisms that have been applied did not produce a significant increase in torque production. Another effort that can be done to increase torque production is by enlarging the swept area by magnifying the turbine dimensions. However, this can cause difficulties during installation and maintenance. This study proposes a novel VAHT design called the Vertical Axis Hydrokinetic Turbine – Straight-Blade Cascaded (VAHT–SBC). By employing cascaded blades and a passive-pitch mechanism, VAHT–SBC is capable of generating greater torque without increasing the turbine's dimensions.

2 Novel Design of Vertical Axis Hydrokinetic Turbine – Straight-Blade Cascaded (VAHT–SBC)

The VAHT–SBC was designed to solve the low efficiency and self-starting issues of ordinary vertical axis turbines. Generally, vertical axis turbines possess lower efficiency than horizontal axis turbines (HAT). Furthermore, VAHT's poor self-starting causes the turbine to start rotating only at higher freestream velocity.

Since VAHTs can rotate at low free stream velocity and capture currents from all directions (omni-directional), this turbine is a promising technology to accommodate energy demand in rural areas that have low potency of hydrokinetic energy. Well-performing turbines that are easy to install, operate and maintain should be developed. Hence, improvement of the conventional VAHT design should be carried out.



(a) (b) (c)

Figure 1 Turbine design: (a) Model 1, (b) Model 2, (c) Model 3.

The VAHT–SBC is a turbine consisting of three arms with more than one blade on each arm. Three different blade configurations of VAHT–SBC were designed, i.e. VAHT–SBC with 3 blades (Model 1), VAHT–SBC with 6 blades (Model 2), and VAHT–SBC with 9 blades (Model 3), as depicted in Figure 1. NACA 0018 was used as hydrofoil. All blades of Model 1 apply a passive-pitch mechanism. Meanwhile, in Model 2 and Model 3 the outer blades utilize a passive-pitch mechanism (red), whereas the others are fixed-blade (blue). The passive-pitch mechanism gives freedom to the blade to adjust its pitch angel in the range of $-20° \leq \beta \leq 20°$, where β is the pitch angle, as illustrated in Figure. 2. The dimensions of the turbines used in this study are listed in Table 1.

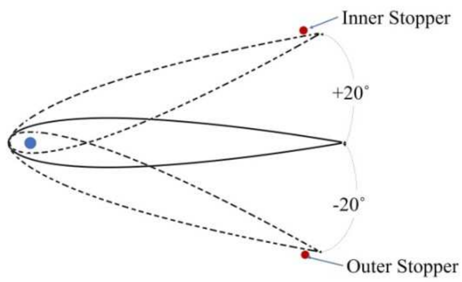


Figure 2 Passive-pitch mechanism.

Table 1 Dimension of darrieus straight-blade cascaded turbine.

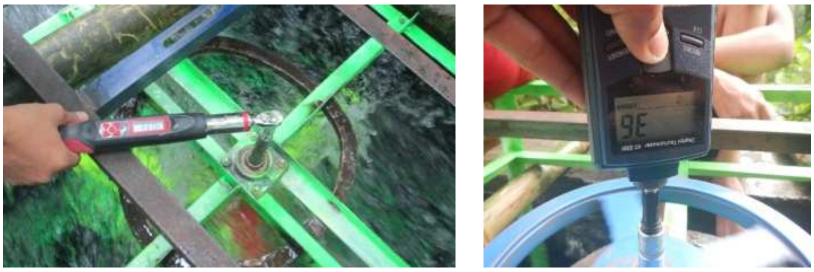
Parameter	VAHT–SBC
Number of blades (N)	Model 1: 3 blades Model 2: 6 blades Model 3: 9 blades
Blade Mechanism	Model 1: passive pitch Model 2: passive pitch & fix Model 3: passive pitch & fix
Cord length (c)	0.1 m
Span (H)	0.8 m
Diameter (D)	0.8 m
H/D	1
Aspect ratio (AR)	8
Hydrofoil	NACA 0018

3 Experimental Setup

Experimental testing was carried out to establish the performance of the turbine design. Its performance is influenced by several factors that arise when the turbine operates at the actual installation site, such as the bearing effect, channel blockage, freestream velocity fluctuation in the channel, and so on. Therefore, the characteristics of the channel used for turbine testing should be studied. It should have stale flow characteristics at a certain point and low turbulence intensity.

Three VAHT–SBC models were tested in an open canal. The design of the frame was adapted to the channel shape aiming to simplify the installation process. In the field test, the VAHT–SBC models were subjected to three current speeds, i.e. 1.1; 1.2 and 1.3 m/s, obtained from 3 different installation points (in the same channel). The measurement of the current speed was carried out at an upstream distance of 50 cm and a downstream distance of 50 cm, measured from the outer section of the turbine, using a CM-1BX Denta water current meter. The current speed was measured using the water current meter before the data of torque and rotational velocity were taken.

In the field test, rotational velocity was measured at the surface of the water using a tachometer that was mounted on the end of a shaft. Meanwhile, static torque was measured using a torque wrench at 5 different azimuths, i.e. 0°, 90°, 120°, 180°, and 240°, so the torque fluctuation during turbine rotation could be predicted. For every azimuth variation 10 torque data were collected and were averaged to get the torque per azimuth. The total static torque generated by the turbine models was calculated from the average torque for all azimuth angles measured. The standard deviation for torque and rotational velocity measurement were 0.8811 N.m and 1.13 rpm, respectively. Since the standard deviation was low, the experiment could be considered valid. The measurement process is illustrated in Figure 3. Rotational velocity and torque were measured for every current speed variation (1.1, 1.2 and 1.3 m/s) and every turbine model (Model 1, Model 2 and Model 3).



(a) (b)

Figure 3 Field testing: (a) torque measurement, (b) rotational velocity measurement.

4 Simulation Setup

A computational fluid dynamics (CFD) simulation based on the Reynold Average Navier-Stokes (RANS) solver was conducted to analyze the torque fluctuation of VAHT–SBC. This simulation was aimed at getting supplementary information about the characteristics of VAHT–SBC. The RANS solver is a coupled flow solver, where the momentum and continuity equation are solved simultaneously. This approach has a low number of iterations and does not required pressure correction to maintain mass conservation, leading to a more robust and accurate solver [26, 27].

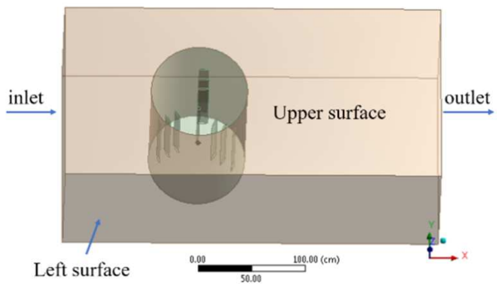


Figure 4 Geometry and boundary conditions for the simulation process.

Design Modeler Software was used to create the VAHT–SBC geometry, which consists of turbine domain, rotational domain and flow domain. Figure 4 depicts the turbine geometry and boundary conditions used in the numerical simulation. The choice of turbulence model affects the required computational resources and the computational results. This simulation process used the SST (shear stress transport) turbulence model, since this is generally used in vertical axis turbulence simulation. The conditions utilized in the simulation process are listed in Table 2.

Table 2 Dimension of darrieus straight-blade cascaded turbine.

Inlet	Normal speed (freestream velocity variation of 0.5, 1, 1.5 m/s)
Outlet	Opening
Left and right surface	Opening
Turbine (blades and shaft)	Rotating Wall – no slip
Lower surface	Wall – free slip
Upper surface	Wall – free slip

The simulation result was compared with the experimental data to know the data conformity (data verification). In the simulation process, the bearing effect was ignored. Moreover, several assumptions were made to avoid exceedingly massive computation. The simulation was an ideal calculation without considering power losses caused by nature. Due to the several assumptions that were made, the torque obtained from the numerical simulation was higher than in the experimental result, as depicted in Figure 5.

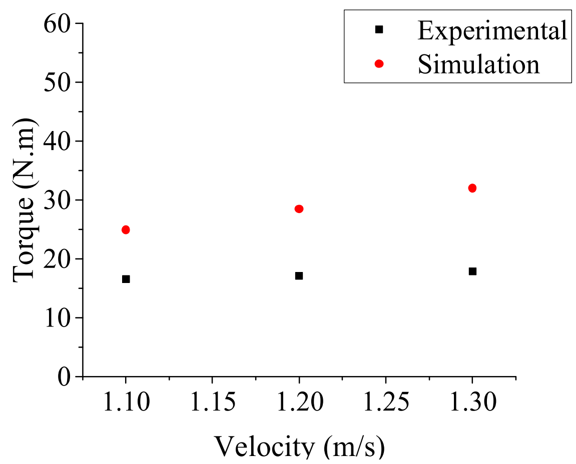


Figure 5 Data verification (Model 1).

5 Blade Dynamic Behavior

The VAHT–SBC is a modified VAHT that uses two pitching mechanism, i.e. a passive-pitch mechanism for the outer blades and a fixed-pitch mechanism for the other blades. The passive-pitch mechanism allows the outers blade to move within a certain pitch angle range. This study designed the VAHT–SBC with a pitch angle range of ± 20° and it was shown that this passive-pitch mechanism could improve the self-starting behavior of the VAHT–SBC so that the turbine could rotate in slow free stream velocity.

The pitch-angle of the passive-pitch blade changes as the turbine rotates, as illustrated in Figure 6. At an azimuth angle of 0° < θ < 200° the trailing edge touches the inner stopper and at an azimuth of 200° < θ < 0° the trailing edge touches the outer stopper. Meanwhile, at azimuths of 0° and 200° the trailing edge is in the middle between the inner and outer stopper. The movement of the passive-pitch blade tends to follow the flow, which reduces the angle of attack and postpone stall so the turbine can rotate easily.

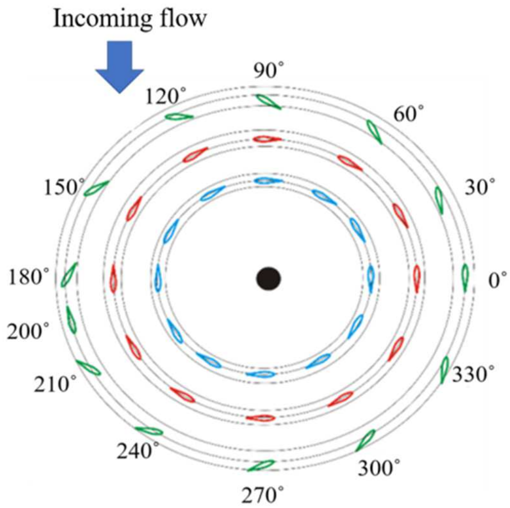


Figure 6 Dynamic behavior of the blades.

6 Results and Discussion

This experimental and numerical study proposed a new design of the vertical axis hydrokinetic turbine aiming to improve its performance and efficiency. The turbine's performance is represented by coefficient of performance (Cp), which is the ratio between the turbine's mechanical power and the water power. A turbine's mechanical power is the ability to extract energy from the energy resource. It can be calculated by multiplying the angular velocity (rad/s) by static torque (N.m).

Our experimental study confirmed that the addition of more blades improves turbine Cp, as shown in Figure 7. The VAHT–SBC with 9 blades (Model 3) had the best Cp result. All VAHT–SBC configurations operated properly at low TSR, which is very appropriate for low current speed application. By increasing the number of blades, the turbines' moment of inertia becomes larger, following Eq. (3). Thus, the turbine becomes inert and has difficulty to rotate. However, the torque is increased, following Eq. (4). Because of this phenomenon, the rotational velocity decreases but the torque significantly increases. The significant enhancement in torque compensates the rotational velocity decrement and the output power increases with a higher number of blades, following Eq.(5). As a result, Cp is increased and TSR is decreased, as depicted in Figure 7.

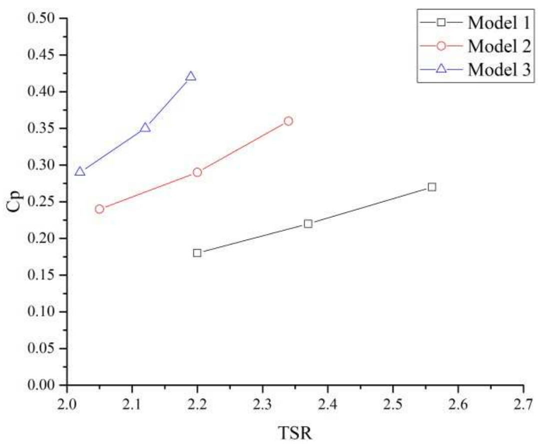


Figure 7 Turbine performance.

$$I \approx m.R^2 \tag{3}$$

$$\tau = I.\alpha \tag{4}$$

$$P = \tau.\omega \tag{5}$$

Model 3 had the best Cp value, which was very close to the theoretical value. The theoretical Cp for a vertical axis turbine is 0.45 while for Model 3 it was 0.42 at a TSR of 2.19. This value was obtained when the turbine was subjected to a flow velocity of 1.1 m/s. Meanwhile, Model 1 had a Cp of 0.27 at a TSR of 2.56 and Model 2 had a Cp of 0.36 at a TSR of 2.34. In this condition, Model 1, Model 2 and Model 3 could generate a torque of 16.56 Nm, 23.58 N.m, and

29.76 N.m respectively. The cascaded blade arrangement enhances the torque, as a higher number of blades are utilized to extract energy. The blockage caused by the outer blades leads to a performance decrement of the inner blades. Due to energy extraction by the outer blades, the flow around the blades is disturbed, so the generation of aerodynamic force is not optimal.

The increment of turbine inertia and replenishment of the cascade blade lead to a decline of turbine self-starting. Nonetheless, this problem is resolved by the passive-pitch mechanism, which is able to adjust the pitch angle according to the blade azimuthal position as the turbine rotates. This mechanism postpones dynamic stall, thus it is able to accommodate the mass added in Model 2 and Model 3.

To supplement the information obtained by the experimental test, a numerical simulation was necessary to provide extra data for the performance analysis. Numerical simulation is an economical and quick method to evaluate the performance of a turbine. Based on numerical simulation, improvement of the turbine design can be done effortlessly and rapidly, without additional cost. Turbine simulation provides a general overview of torque fluctuation, flow characteristics nearby the turbine, and turbine performance. In this study, the simulation was done to perceive the performance of the VHT-SBC model. This model was subjected to three different freestream velocity variations, i.e. 0.5 m/s, 1 m/s, and 1.5 m/s.

The simulation results, as depicted in Figure 8(a), show that as the freestream velocity increases, the torque increases as well. The freestream velocity corresponds to the potential energy of the water that hits the turbines. The higher the freestream velocity, the greater the available energy and the more energy can be extracted by turbine. The energy production increment can be represented as torque enhancement.

A CFD simulation provides the generated torque per azimuth angle. Due to the change of angle of attack as the turbine rotates, torque fluctuation occurs. Figure 8(b) gives an overview of torque fluctuation for all three turbine models, simulated with a freestream velocity of 0.5 m/s. This fluctuation was identical for all freestream velocity variations, i.e. 1 m/s and 1.5 m/s.

For all turbines models, the torque fluctuation establishes a particular periodical pattern. Because each turbine consists of three arms, there are three periodical patterns in one rotational period (360°). Because of the employment of cascaded blades, the pattern is different for each turbine, as illustrated in Figure 4. The employment of cascaded blades enhances the turbulence and Re number around the turbine. The effect of the Re number increment is primarily experienced by the inner blades. It postpones their dynamic stall and influences their position in stall condition. The combination of the effects of the passive-pitch mechanism and the Re number increase leads to a different torque fluctuation behavior.

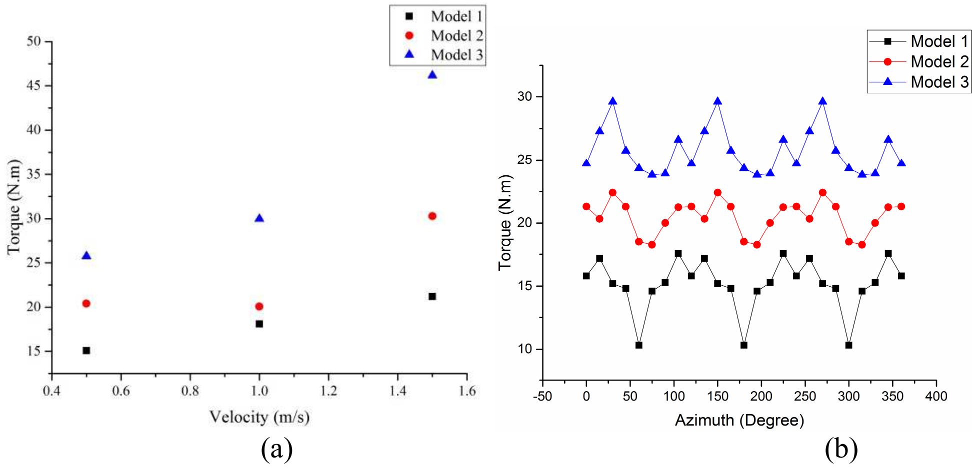


Figure 8 Torque generated by VAHT–SBC, (a) as a function of freestream velocity, (b) torque fluctuation.

The maximum torque for Model 1 occurred at azimuth angles of 105°, 225° and 345°, while the minimum torque was at 60°, 180° and 300°. At a freestream velocity of 0.5 m/s, the difference between maximum and minimum torque was 2.432 N.m. This phenomenon is a consequence of the different fluid pressure, which is larger for these azimuth angles and smaller for others. The aerodynamic force is influenced by the fluid pressure and the shear stress along the spans. The kinetic energy is converted to pressure against the turbine, which makes the turbine rotate. The cascading blades and the passive-pitch mechanism shift the torque fluctuation pattern. For Model 2 and Model 3, the largest torque appeared at azimuth angles of 30°, 150° and 270°. While the minimum is at 75°, 195° and 315° for Model 2 and at 0°, 120° and 240° for Model 3. At a freestream velocity of 0.5 m/s, the difference between maximum and minimum torque of Model 2 was 4.375 N.m, while for Model 3 it was 1.981 N.m. The outer blades contribute more to the torque production than the other blades, as they generate the greatest torque. Although they yield the same aerodynamic force as the inner blades, the greater distance between the outer blades and the shaft leads to a larger torque.

At certain azimuth angles, the fluctuating torque is at its minimum level. This arises due to the difference in pressure on each blade during the turbine's rotation. The aerodynamic force is proportional to the pressure: the smaller the pressure, the smaller the force obtained. At minimum torque production, the inner blades are shaded by the other blades, so they get lower flow velocity and pressure. The occurrence of dynamic stall deteriorates this condition.

Fluctuating torque, which causes vibration, is an essential parameter for designing turbines. It establishes an unsteady load on the blades, shaft and turbine support structure, which considerably influences the power quality and reliability of both the mechanical and electrical components of the conversion system [29]. Inadequate power quality leads to electricity intermittence when integrated into the grid. Meanwhile, poor reliability leads to system failure. Hence, this issue requires further investigation.

7 Conclusion

Due to the low efficiency and lack of self-starting of vertical axis hydrokinetic turbines, improvement of their design should be considered. This study offers a novel VAHT design in 3 configurations, as described previously. The design employs cascaded blades and a passive-pitch mechanism. Experimental testing and a computational fluid dynamic simulation were carried out to investigate the performance of each model. Due to the change of angle of attack as the turbine rotates, the torque displays a periodical pattern that recurs three times per rotation, in accordance with the number of arms. Each turbine model possesses a different periodical torque fluctuation pattern. In accordance with the field test results, the CFD simulation confirmed that Model 3 exhibited better performance compared to the other models. Replenishment of the blade on each arm enhances torque, so finally the Cp of Model 3 could reach up to 0.42, which is very close to the theoretical Cp of vertical axis turbines. The VAHT–SBC operated properly at lower TSR.

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