EXPERIMENTAL STUDY ON LOW-SPEED VERTICAL AXIS CURRENT TURBINE (LS-VACT) WITH DIVERTER

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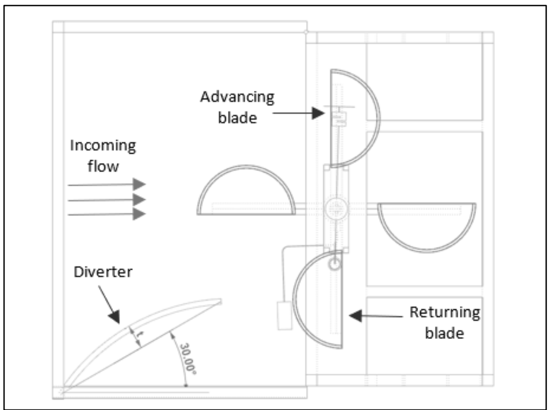
GRAPHICAL ABSTRACT



ABSTRACT

The increasing demand for sustainable energy solutions has intensified the exploration of marine current energy systems in low-speed current regions such as those found in Malaysia. This study investigates the performance enhancement of a low-speed vertical axis current turbine (LS-VACT) through the integration of a curved shape diverter. The primary objective is to evaluate the diverter's effect on power coefficient (C_P), torque coefficient (C_T) and efficiency under controlled towing tank conditions at current speed of 0.4 m/s. Two configurations were tested; the LS-VACT arm attached turbine with and without curved diverter angled at 30 degrees. The turbine with diverter achieved an enhancement for the maximum C_P, reaching up to 50% increase over the baseline at Tip Speed Ratio (TSR) 0.55 while maintaining favourable torque generation and improved TSR across different revolutions per minute (RPM). The diverter improved flow interaction with the advancing blade. The findings validate the application of curved shape diverters as a practical and passive method to improve LS-VACT performance in low-speed marine environments.

KEYWORDS

Vertical axis turbine, marine renewable energy, flow diverter, towing tank experiment, curved shape diverter

INTRODUCTION

Renewable power harnessed from water currents represents a viable and sustainable option for power generation, particularly in coastal and riverine environments where flow conditions are relatively consistent, albeit typically at low velocities. In terms of practicability in Malaysia, vertical-axis current turbines (VACTs), such as the Savonius and Darrieus types, offer an advantage in low-velocity and shallow-water conditions. VACTs are particularly well-suited to Malaysia due to their ability to operate effectively in variable-flow environments and at low speeds [1]. Additionally, VACTs are known for their simple design, low manufacturing cost, and suitability for shallow waters [2].

However, challenges persist in developing hydrokinetic turbines in Malaysia, mainly due to low average water velocities (0.5-1.0 m/s) and shallow water depths (15-50 m) in rivers and coastal areas [3]. Efficient current turbine operation typically requires water velocities above 2.0 m/s, which creates a mismatch between natural conditions and turbine performance requirements [3]. The VACTs should be designed to efficiently capture kinetic energy from slow-moving water currents, making them appropriate for places where conventional high-speed turbines would not work. Low-speed VACTs are particularly applicable in the region of Malaysia, where ocean currents are typically in the range of 0.5 to 2.5 m/s [4]. These VACTs provide an efficient way to recover hydrokinetic energy in river streams, irrigation canals, and coastal zones where minimal head difference exists.

VACTs can generally be classified into two main types based on their operating principles: lift-type or drag-type. The lift-type turbine, such as the Darrieus turbine, utilises the lift force generated by the blade profile to produce rotation. In contrast, the drag-type turbine, such as the Savonius turbine, relies on the differential drag force between the advancing and returning blades. Despite the drag-type current turbine offering advantages such as self-starting capability and simple construction, one of its drawbacks is the relatively low efficiency compared with other types of turbines, which limits its potential for large-scale energy generation. This limitation led to many proposed solutions to improve the drag-type current turbine's performance, especially for the traditional Savonius concept. One of the design evolutions from the Savonius turbine concept is the integration of four semicircular blades mounted at the end of four horizontal arms known as LS-VACT [4]. The arms address the common challenge of torque loss in vertical-axis turbines, particularly at low speeds, making the LS-VACT efficient even at reduced tip-speed ratios [3][5]. Then, the LS-VACT configuration modification is proposed in [6] to align the turbine design with the hydraulic power transmission.

To further improve the performance of the modified LS-VACT, a diverter was employed to redirect water flow toward the turbine's advancing blades, thereby enhancing net torque and overall efficiency. Diverter, also called flow deflectors, which take various forms such as flat plates or curved vanes, can help channel the water flow toward the turbine's blades. This can increase torque and overall efficiency, enabling the turbine to produce more power even at lower speeds. Experimental and numerical investigations have shown that strategically placed deflectors can significantly improve the turbine's power output by directing flow towards the advancing blade while protecting the returning blade from direct impact [7][8]. Deflectors redirect the incoming flow towards the advancing blade to generate larger positive torque while reducing negative pressure on the returning blade, resulting in increased net torque and power output [9].

Curved plate deflectors, as studied by [10], and flow deflectors, explored by [8], have shown significant potential for effectively redirecting currents. Similarly, angled deflectors examined by [7] and wedge-shaped triangular designs combined with circular deflectors investigated by [11] have delivered notable improvements in turbine performance, with the latter achieving a remarkable 73.7% increase in the maximum power coefficient. In terms of configuration, the deflector angle influences turbine performance by altering the flow cross-section [7] [12]. Reference [13] also demonstrated that a ‘C’ shaped deflector could enhance power output by 23%, highlighting its effectiveness in directing flow to optimize turbine efficiency.

Despite the potential of diverters to redirect and concentrate water flow toward the turbine, there has been minimal experimental study on how various diverter configurations affect LS-VACT performance, especially under real low-speed current conditions in Malaysian river and coastal regions. The goal of this study is to determine the effects of various diverter configurations on the lift, drag, torque, and power generation of an LS-VACT in low-speed water conditions. This study aims to investigate whether diverter equipment can improve turbine performance, thereby increasing the potential of LS-VACTs to generate renewable energy in low-speed currents. By addressing this gap, the study aims to provide experimental data that supports future design optimisation and the deployment of LS-VACT systems for low-speed current applications.

THEORETICAL BACKGROUND

Regarding the performance of a current turbine, the tip speed ratio, power coefficient and torque coefficient are essential parameters that should be determined. The tip speed ratio (TSR), often represented by the symbol λ, describes how fast the tip of the turbine blade is moving compared to the speed of the water flowing past it. In other words, it’s the ratio between the blade’s rotational speed and the actual water current speed. TSR is calculated using Eq. 1.

$$TSR\ (\lambda) = \frac{\omega \cdot (\frac{D_T}{2})}{\mathrm{V}} \qquad \text{(Eq. 1)}$$

Where ω is the turbine angular velocity (*rad/sec*), D_T is the turbine diameter (*m*), and V is the water current velocity (*m/s*).

The torque coefficient, C_T and power coefficient (C_P) can be calculated using Eq. 2 and Eq. 3, respectively.

$$C_T = \frac{T}{0.5 \cdot \rho \cdot (H_B \cdot D_B) \cdot (\frac{D_T}{2}) \cdot V^2} \quad \text{(Eq. 2)}$$

$$C_P = \frac{T \cdot \omega}{0.5 \cdot \rho \cdot (H_B \cdot D_B) \cdot (\frac{D_T}{2}) \cdot V^3} \quad \text{(Eq. 3)}$$

Where T is the measured torque (Nm), D_B is the blade diameter and H_B is the blade height in meters, ρ is the water density, D_T is the turbine diameter (meters) and V is the current velocity (m/s).

METHODOLOGY

A series of controlled experiments was conducted in the towing tank at the Marine Technology Centre, Universiti Teknologi Malaysia. The towing tank has a length of 120 m, a width of 4 m, and a depth of 2.5 m. The towing tank facility provides steady flow conditions. The experiments were designed to apply the uniform current flow conditions and to measure critical performance parameters of LS-VACT using a calibrated data acquisition (DAQ) system. The methodology involves preparing and calibrating equipment, systematically applying loads, and collecting real-time data to assess turbine performance.

The geometrical dimensions of the vertical-axis turbine are tabulated in Table 1 and shown in Figure 1. The LS-VACT tested in this experiment is a full-scale drag-based prototype designed explicitly for a low-speed current environment. This full-scale LS-VACT prototype, initially developed by Souf-Aljen and Maimun, comprises four blades attached to turbine arms [14]. The turbine blade was fabricated using fiberglass chopped strand mat (CSM). Each blade is mounted symmetrically about the central shaft. During the experiments, both LS-VACT configurations shared identical turbine diameters, heights, supporting structures, and shafts to ensure consistent comparison under similar operating conditions.

Table 1: The particulars of LS-VACT

Specifications	Dimension
Height of blade, H_B *(m)*	1.000
Diameter of blade, D_B *(m)*	0.355
Swept area, *As* (m^2)	0.525
Diameter of turbine, D_T *(m)*	1.000
Turbine arm length, *r (m)*	0.150

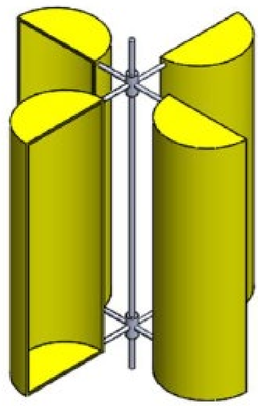


Figure 1: The LS-VACT without a diverter

The curved shape diverter was also fabricated using CSM. The diverter's geometrical dimensions are listed in Table 2 and are shown in Figure 2. It is designed to enhance flow guidance to the turbine. The diverter's position is the crucial aspect. Previous studies on Savonius turbines have examined deflector or diverter angles typically in the range of 20 to 45 degrees, with several works identifying around 30 degrees as a practical compromise between flow redirection and minimized flow separation. As reported in studies by [15][16], performance improvements were observed when the deflector angle was set close to 30 degrees. Therefore, in this study, a fixed diverter angle of 30 degrees, as shown in Figures 3 and 4, was installed on the extended test rig, and the arrangement was designed to achieve an optimal incoming flow to the turbine blade.

Table 2: The dimensions of the curved diverter

Specifications	Dimension
Height *(m)*	1.064
Chord length of circular curve (*m*)	0.669
Mid ordinate of circular curve, t (*m*)	0.008
Thickness *(m)*	0.02

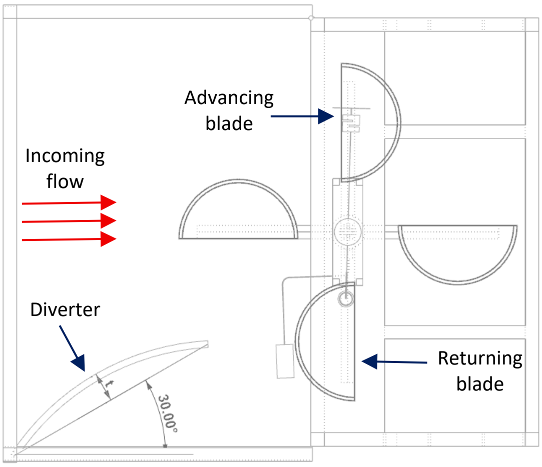


Figure 2: Top-view diagram of turbine and diverter

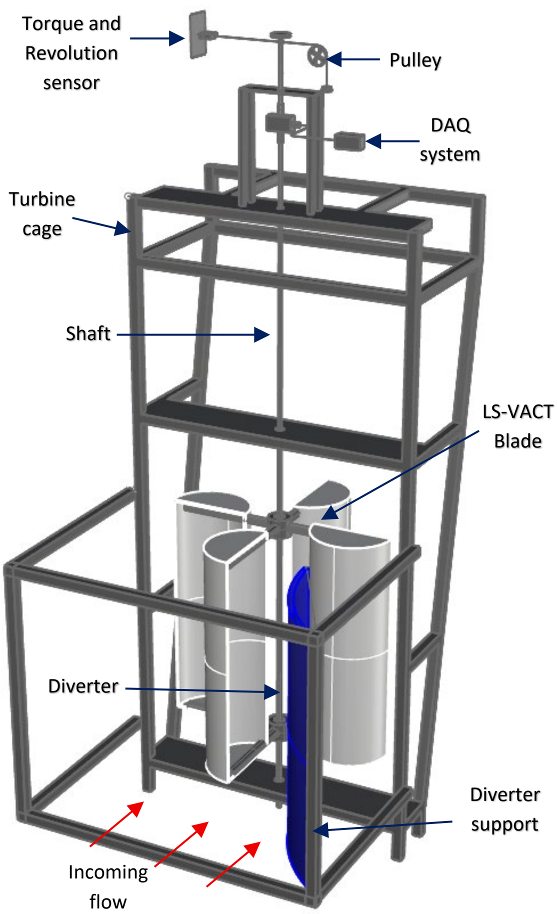


Figure 3: Schematic Diagram of Turbine Cage Setup with Diverter

Each configuration underwent a series of tests under varying load conditions. Resistance was applied using a calibrated deadweight suspended from a stainless-steel wire cable looped over a pulley mounted at the upper shaft end. As the turbine rotated, the deadweight exerted a braking force on the turbine shaft, thereby generating a measurable torque. A calibrated torque meter (Futek705) recorded the torque produced and the corresponding revolutions per minute (RPM). This method has been used in [6] and has been proven effective for determining the torque of a vertical-axis hydrokinetic turbine.

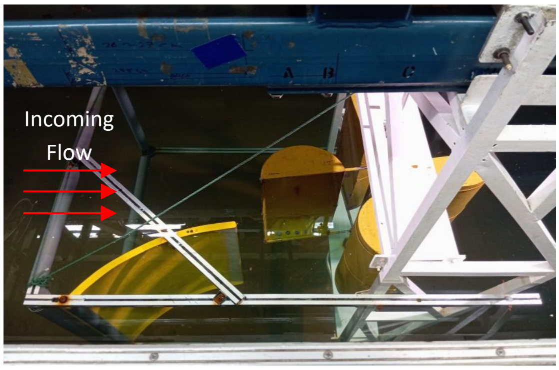


Figure 4: LS-VACT with diverter installed 30 degrees relative to the flow direction.

Before starting the experiment, the supporting structure was carefully lowered to submerge the entire turbine, as shown in Figure 4. The turbine was submerged 0.35 m below the water-free surface, and a clearance of 0.85 m was maintained between the turbine and the bottom of the tank. The submerged depth was determined based on the 2.4 m total height of the supporting structure, of which only 1.7 m could be due to the maximum allowable depth of the towing carriage. A suitable range of current speeds was chosen based on the locations of the field tests reported in [4] and [6]. The field measurements reported that the current velocities in Kukup, Johor, Malaysia, range from 0.2 m/s to 0.6 m/s. The hydrodynamic criteria for Kukup Strait include average current speeds of 0.3 to 0.4 m/s and maximum speeds of 0.7 to 1.1 m/s during tidal phases [17]. Therefore, the speed chosen for the experiment is 0.4 m/s to adapt to the average operational conditions.

RESULTS AND DISCUSSION

The performance of LS-VACT was evaluated by comparing the torque and power coefficients over a range of tip speed ratios for a conventional blade with and without a diverter. The results show a significant impact of the diverter on the conventional blade's energy efficiency under low-speed water velocity conditions.

The torque and power coefficients were evaluated against TSR for a conventional blade without a diverter and a 30-degree diverter configuration under the same experimental conditions, with a constant water velocity of 0.40 m/s. At 0.40 m/s, the 30-degree diverter provided the greatest torque of 11.598 Nm at the 5 kg load condition, as shown in Tables 3 and 4. This indicates that, with a diverter installed on the turbine blades, a more substantial torque is generated at non-zero RPM. This would assist in any mechanical applications that require additional turning force. However, the torque trend is different at maximum load and at zero RPM. The turbine with a diverter can still rotate at the given 5 kg load, whereas the maximum load for the turbine without a diverter is 4 kg. The diverter also affects the turbine torque when the turbine is not rotating.

Table 3: Experiment data without diverter at 0.40 m/s

Mass (kg)	Torque (Nm)	RPM (rad/s)	TSR	Power (W)	C_P	C_T
Freeload	0.039	0.675	0.844	0.026	0.002	0.003
2	5.498	0.483	0.604	2.656	0.234	0.387
4	7.436	0.275	0.343	2.043	0.180	0.524
5	11.576	0.000	0.000	0.000	0.000	0.815

Table 4: Experiment data with 30-degree diverter at 0.40 m/s

Mass (kg)	Torque (Nm)	RPM (rad/s)	TSR	Power (W)	C_P	C_T
Freeload	0.041	0.729	0.911	0.030	0.003	0.003
2	9.879	0.409	0.512	4.042	0.356	0.696
4	10.710	0.378	0.473	4.052	0.357	0.754
5	11.598	0.299	0.373	3.904	0.305	0.817
6	13.874	0.000	0.000	0.000	0.000	1.444

Figure 5 illustrates the relationship between the C_T vs TSR for both configurations, with and without a diverter, at rotating turbine cases. In both configurations, the C_T shows a decreasing trend with increasing TSR, consistent with the expected performance of drag-based turbines, while higher rotational speeds reduce torque generation.

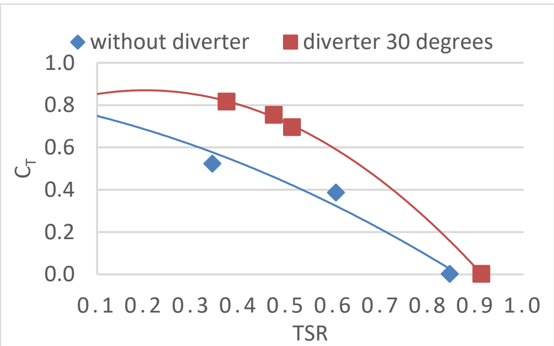


Figure 5: C_T VS TSR graph for conventional blade without diverter and 30 degrees diverter configuration at 0.4 m/s

Both curves in Figure 5 show the reduction in the torque coefficient as TSR increases, until it reaches zero C_T. Both turbines, with and without a diverter, show a direct decline in C_T. This suggests that while the diverter enhances torque, it also shifts the optimal operating point to a slightly lower TSR.

Figure 6 illustrates the relationship between the C_p vs TSR for both configurations, with and without a diverter, at rotating turbine cases. At low TSR, both configurations have zero C_P, which is expected as there is no power generation when the blades are not rotating. The blade with a diverter achieved the maximum peak of C_P approximately 0.363 at TSR = 0.55, while without the diverter C_P reach its peak performance at 0.242 at TSR = 0.54.

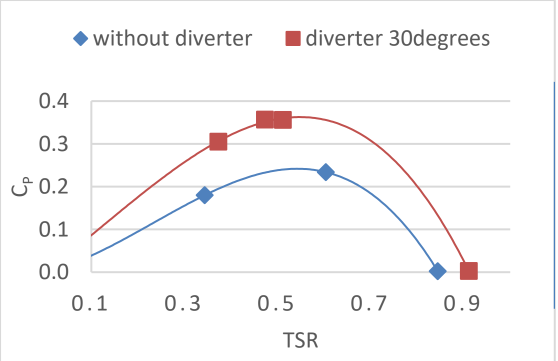


Figure 6: C_P VS TSR graph for conventional blade without diverter and 30 degrees diverter configuration at 0.4 m/s

After both configurations reach the highest C_P, the power efficiency begins to decrease as seen in the graph. For the turbine without a diverter, the lowest is 0.01 at TSR 0.84, while for the turbine with a diverter, the lowest is 0.005 at TSR 0.91. These very low values occur under freeload conditions, where the turbine spins with minimal torque and produces negligible power output. At very high TSR, the value C_P drops significantly for both configurations. This is likely due to stall conditions or an increase in drag, which reduces the ability to extract power from the water flow.

The experimental results demonstrate that the 30-degree diverter configuration is highly effective in enhancing conventional power conversion. This is because the diverter modifies the flow of the working fluid, guiding and diverting it more effectively onto the blades, thereby increasing the energy transfer. The result obtained from this work is compatible with the findings in [7], which show that performance improvement reaches 61% compared to the case without a diverter at TSR 0.86 in the 30-degree diverter configuration.

The percentage of improvement varies and occurs at different TSR values. This indicates that the presence of a diverter with a 30-degree installation angle can enhance the pressure differential between the advancing and returning blades, which improves torque and overall turbine performance at TSRs greater than 0.5.

The observed 50% improvement in the maximum power coefficient at TSR 0.55, from approximately 0.242 to 0.363, with the implementation of a 30-degree diverter, can be attributed to alterations in the local flow dynamics around the turbine. The diverter redirects a greater portion of the incoming free-stream flow toward the advancing blade, thereby increasing the local velocity impinging on the concave surface. This focused redirection not only enhances the effective drag on the advancing blade but also reduces the returning blade's exposure to the free stream.

Consequently, a significant pressure differential is established between the advancing and returning sides of the turbine blades. The advancing blade experiences an increase in dynamic pressure as the flow accelerates. In contrast, the returning blade operates in a region of reduced pressure and flow velocity, resulting in lower opposing drag. This combination amplifies the net torque on the rotor, thereby increasing mechanical power output.

CONCLUSION

This study has shown that the application of a diverter can boost the performance of a Low-Speed Vertical Axis Current Turbine (LS-VACT). This is evidenced by the significant improvements observed in the experiment on LS-VACT with and without the diverter in the power coefficient (C_P) and the torque coefficient (C_T). The study included a fixed diverter angle of 30 degrees, which produced the highest torque at low flow speeds and could be used when mechanical force is required. The presence of the diverter led to 50% improvement in the maximum coefficient of power (C_P). This is a crucial finding, as it indicates a substantial increase in the configurations, as they convert available fluid energy into mechanical power at the turbine shaft, which represents the useful output for subsequent energy conversion processes.

The torque coefficient (C_T) exhibited a comparable enhancement, with its maximum value raising from 0.838 to 1.28 at TSR of 0.1 due to diverter effect. This increase indicates that the diverter can also enhance the drag generated by the flow, which is directly relat d ed to the ability to harness energy from the fluid. In conclusion, the diverter not only increases torque output but also improves efficiency and torque characteristics. The performance of conventional blades is optimised with the presence of a diverter, making it a critical component in applications where power output and efficiency are dominant.

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