Fish Farm Electrification Utilising a Hybrid Device of Low-Speed Vertical Axis Turbine and Solar Panels

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Abstract. The demand for seafood is continually increasing. The best way to meet that is through the aquaculture. In Malaysia, the important alternative source of fish supply is the fish-farms. Nowadays, fish-farms use unclean and expensive energy, which cannot meet the environmental and climate goals. This paper presents a hybrid device consisting of two Low-Speed Vertical Axis Current Turbines (LS-VACTs), generators, batteries, controller and solar-panels. This device is used as a hybrid solution because of the lake of electricity, low water/marine current speed surrounding the fish-farms and variable nature of both resources solar and marine-currents. This device has lower cabling and infrastructure requirements and reduced capital costs. This paper investigates the performance of the hybrid system and predicting power take-off and the number of solar panels required to provide sufficient energy for fish-farm using MATLAB-Simulink environment. The experimental results of LS-VACT show that the turbine has a power coefficient (Cₚ) =19.4% and high torque coefficient of 0.76 at a speed of 1 m/s. The simulation results indicate that the power output of the system can provide 20 kWh/day with water/marine current speed higher than 1 m/s. This combination of both resources can sustain and produce enough power for electrification of fish-farm.

1. Introduction
The aquaculture in Malaysia has developed rapidly, owing to the importance of aquaculture as an alternative option or source of fish supply. Today, the fish farms use energy which is not clean and expensive and cannot meet the environmental and climate goals. In 2009, Malaysia formulated the National Green Technology Policy [1] to promote green technology usage for economic growth as in reference [2]. The research and development of renewable energy production techniques are of great importance to overcome the environmental issue due to burning fossil fuels to generate electrical energy. Marine current turbines and solar power can be free green potential power sources. Horizontal-axis turbines are a complex system and they are appropriate only for large size, power plants where high expenses of the installation and maintenance are balanced by producing large power energy. On other hand, vertical-axis turbines are relatively simple and represent a promising technology to exploit marine currents due to their small power plants with reduced costs of the installation, repairs and maintenance [3] and they are suitable for deployment in remote areas [4,5].

Due to the low flow velocities of Malaysian ocean which are ranges between 0.5 to 2 m/s [1], one
solution to the energy problems is to have drag marine vertical current turbines. The Savonius turbine as a drag rotor can extract energy from the low marine current speed \[6,7\]; however, this rotor has lower torque to match it with PMG generator. LS-VACT has arms to increase the torque, which allows it to integrate with wide ranges of generators efficiently. The fish farms demand power is high (about 20 kWh/day or more) \[6\]. So, one solution to the energy problems is to have a balance of the current (tidal) and solar power sources to sustain the energy for a long period of time and to reduce the charging time of the batteries. This device as a hybrid solution may have the potential to provide sustainable electricity. In another hand, this device can significantly reduce the fuel costs of electric power generation and CO\(_2\) emissions. Increased awareness of air pollution, carbon dioxide emissions and the greenhouse effect has also contributed to this research and development. Many researchers and experts have focused on feasibility and system performance of the hybrid renewable energy systems, mainly concentrating only on solar cell or photovoltaic (PV)/wind, PV/wind/diesel, PV/fuel cells and geothermal energy options. However, the study on water/marine current turbine-solar cell hybrid system has been neglected. Therefore, this paper presents the hybrid system mainly the prototype of the low-speed vertical axis current turbine drag type turbine and provides a study and analyse the performance of this turbine model experimentally. Moreover, this paper presents the performance and the power output of the prototype turbine, solar panel and the hybrid system in general, using MATLAB-Simulink environment.

2. **Hybrid device - low-speed vertical axis turbine and solar panel**

The system contains the following units; two LS-VACT turbines, two PMSG generators of 2 KW, ten solar panels (each 300W) in two groups, eight deep cycle batteries (250 AH each battery) divided into two groups or banks (4 batteries in each bank), one hybrid charger-controller and one inverter. The battery storage banks can give one-day autonomy and to ensure quality power supply to the applications in the fish farm with two turbines operating at the average water current speed of 1m/s. The LS-VACT prototype is a drag turbine like the conventional Savonius turbine modified with arms between the shaft and the blades (buckets) to increase the torque. The main particular of the LS-VACT is presented in the following table 1 and functional and dimensional principal sketch and schematic drawing of the LS-VACT are shown in figures 1.
Figure 1. The LS-VACT and its dimensional principal sketch

Table 1. The principal particulars of the drag turbine - LS-VACT

| No | Specification                      | Parameters |
|----|------------------------------------|------------|
| 1  | Height of Rotor, H(m)              | 1.5        |
| 2  | The diameter of the bucket, d (m)  | 0.35       |
| 3  | Blade Area $A_s$ (m$^2$)           | 0.525      |
| 4  | The diameter of the turbine, $D_p$ (m) | 1          |
| 5  | Arm length, $r_m$ (m)              | 0.15       |
| 6  | Current speed, $U_{\infty}$ (m/s)  | 0.5 to 2.5 |

The system of solar power size is based on the irradiance (radiation data or sun hours per day) and load evaluation. The Sun hours per day in Malaysia ranges from 4 to 8 hours [9]. Assuming that the mean daily sunshine hours are 6 h, so to ensure power supply to one fish farm (using only the solar power) 14 solar panels of 300 Watt each are required to be installed. To reduce the number of solar panels, current (tidal) power sources can be utilized using LS-VACTs and by balancing the solar and current (tidal) power sources. The proposed hybrid system for a fish farm is illustrated in figure 2.
3. Methodology
This study focused on performing and conducting a series of experimental tests in order to determine the torque, angular velocity and hence the mechanical power of the turbine. Most of the researchers had used a load mass technique/method to investigate turbine performance [7–11]. The procedure of connecting the turbine with a torque measurement arrangement using a load cell to capture the torque and laser tachometer to measure the RPM was adopted in this work as stated in the literature.

The purpose of this experiment is to obtain the torque and RPM of the LS-VACT and then calculate the delivered power of the turbine and the power converter and torque coefficients using equations (1-4). The power coefficients obtained were incorporated into the computer simulation program developed to assess the power output of the prototype turbine. The interface of the simulation program is shown in figure 4. Straight line tests that had been performed in a towing tank at MTC-UTM by attaching the LS-VACT to the carriage as illustrated in figure 3. This tank has a total length of 120 metres, a width of 4 metres, and a depth of 2.5 metres. After that, the turbine is towed along the towing tank at constant carriage velocities of 0.17, 0.32 and 0.64 m/s to simulate the various current speeds.

Figure 2. Standalone water current-solar hybrid system for fish farm
From the torque values measured and RPM (to calculate the angular velocity), the mechanical power extracted by the turbine was evaluated at every current speed as:

\[ P = T \omega \]  

Where: \( T \) – is the mechanical torque in (Nm), \( \omega \) – represents the angular velocity. The angular velocity is obtained in rad/s by:

\[ \omega = \frac{2\pi n}{60} \]  

Where: \( n \) – is the turbine RPM. The power coefficient ‘\( C_P \)’ and the torque coefficient ‘\( C_t \)’ can be determined from the following equations:

\[ C_P = \frac{P}{0.5\rho A_S U_\infty^3} \]  

\[ C_t = \frac{4T}{\rho A_D U_\infty^2} \]

Where: \( \rho \) – donates to the water density, \( A_S \) – Swept area (m²), \( R \) – is the radius of the turbine (m) and \( U_\infty \) – water current speed (m/s).
Sizing of the hybrid system is starting with the estimation of the electric load. The power (W) of individual loads and their estimated energy consumption (Wh) can be tallied to calculate the fish farm’s average daily load. This step will help identify opportunities for efficiency improvements and pave the way for sizing the system components. The following step is sizing the battery bank. The battery type recommended is a deep cycle battery for this hybrid system. Deep cycle battery is specifically designed for to be discharged to low energy level and rapid recharged or cycle charged and discharged day after day for years. The capacity of the batteries should be large enough to store sufficient energy to operate the appliances at different situations such as at night, cloudy days and if there is no water flow current or the water current speed is very low. To find out the required ampere-hour capacity of the deep-cycle battery, the following expression can be used as follows:

$$\text{Battery Capacity (Ah)} = \frac{\text{Total Watt - hours per day used by appliances} \times \text{Days of autonomy}}{(0.85 \times 0.5 \times \text{Nominal battery voltage})} \quad (5)$$

Where: Days of autonomy - the number of days that are needed to operate the system, when there is no power produced by the turbines and solar panels. ‘0.5’ for the depth of discharge – the important major design criterion for sizing batteries is the depth of discharge (DOD). While deep-cycle lead-acid batteries are designed to discharge 80% of their capacity, the deeper they are discharged on a regular basis, the fewer charge/discharge cycles they can provide over their lifetime. To increase the lifetime, many system designers will specify a 50% DOD to be used as recommended in the datasheet. ‘0.85- 0.9’ for battery loss – which is the extra energy lost by inverting from direct current (DC) to alternating current (AC).The next step is sizing the array of solar panels. The array size in watts and the number of solar panels needed. The array calculations were considered the Wh per day (calculated from the average daily load), daily peak sun-hours (based on the location’s solar resource), battery efficiency losses (about 20%), module temperature losses (about 12%), possible array shading and other things to account such as wire losses. The peak sun-hours are the equivalent number of hours per day when solar irradiance (intensity) averages 1,000 watts per square meter (irradiance (Ir) =1000 is used in the simulation program), as derived from the National Solar Radiation Database.

The simulation model was primarily designed for the opportunity analysis of the LS-VACT and its performance using a MATLAB, Simulink environment. This simulation program was validated using
experimental tests to increase the accuracy results. Also, this computer program was upgraded to simulate the standalone LS-VACT- electric generator system as a renewable energy system. Now the simulation program is improved and developed for the study of real-time system operation and for power quality analysis of the hybrid water current/solar/battery system for the study of problems that may occur due to the electrification of fish farms. The diagram of the simulation models of this hybrid system is shown in figure 5. In this simulation model, the LS-VACTs were simulated utilising the non-dimensional power coefficients ($C_P$) obtained experimentally. These LS-VACTs were connected to the generator models through simple gears. Every gear of base and follower wheels with adjustable gear ratio and friction losses was simulated using Simscape model. The generator model is a Low RPM Permanent Magnet Synchronous Generator (PMSG) that has been simulated using Simscape electric model available in the Simulink library. The battery banks are two in the system and each bank with the dc/dc unit is simulated using battery blocks from the Simscape library. The direct current (DC) electricity produced by the solar panel module is used to supply the user loads with power through the inventor and charge batteries via a charge controller. The solar panels were simulated using Simscape model and connected with the DC-DC converter via current-voltage (I-V) Simscape interface.

The water current velocity is simulated using a look-up table. The data is derived based on the measured records on the site using a current meter. Example of the data measured is shown in figure 6. The LS-VACT can rotate in one direction regardless of current directions. So it is multi-directional turbine and the direction of the current is neglected in this simulation. It is clear from the water current speed measured on the site is very low. So the data in the look-up table, which is based on actual tide changes, was supported with extra random values to simulate the other changes in the marine current velocities.

**Figure 5.** A diagram of the simulation models of the hybrid system for fish farm.
Figure 6. Water current speed data measured for 24 hours

4. Main results and discussions
The summary of the operation results of the LS-VACT is illustrated in table 2.

Table 2. Experimental test results of the model of LS-VACT

| Current Speed ($U_\infty$) (m/s) | RPM | $\lambda$ | Torque (N.m) | Power (W) | $C_p$ | $C_l$ |
|----------------------------------|-----|-----------|--------------|-----------|------|------|
| 0.17                             | 1.116 | 0.329    | 0.625        | 0.07      | 0.056 | 0.17 |
| 0.32                             | 1.87  | 0.29     | 10.11        | 1.75      | 0.194 | 0.76 |
| 0.64                             | 6.15  | 0.47     | 19.40        | 8.6       | 0.12  | 0.36 |

Table 2 indicates that the mechanical power output and the torque of the LS-VACT are increased by increasing the current speed, but the power and torque coefficients are decreasing increasing the current speed. The peak power and maximum torque values are 8.6 W and 19.4 Nm respectively were measured and recorded at a flow velocity of 0.64 m/s while the highest power and torque coefficients of 0.194 and 0.76 respectively were captured at the current speed of 0.32 m/s. the power coefficient is decreasing when the current speed is increasing from 0.32 to 0.64 m/s due to the flow separation is happening behind the convex returning buckets so makes vortices. This leads to low pressure and pulling the bucket to turn back to the direction opposed to the movement of the turbine buckets (extra drag). Also, at downstream, the lift forces are being huge and contribute to the reduction of the torque of the turbine and hence the power of LS-VACT. The summary of the operation results of the LS-VACTs with both generators is illustrated in table 3.
Table 3. Summary of operating results of the LS-VACTs and generator

| Current Speed (m/s) | Turbine RPM | LS-VACT Mech. Power (Watt) | Generator I & II power (Watt) | The generator I & II Voltage (V) & Electric current (A) |
|---------------------|-------------|---------------------------|-------------------------------|-----------------------------------------------|
|                     | I           | II                        | I                             | II                                            |
| 2.5                 | 12.79       | 12.79                     | 1051.56                       | 1051.56                                      |
|                     | 504.88      | 504.88                    | 258.66                        | 258.66                                       |
| 2                   | 11.55       | 11.55                     | 538.398                       | 538.398                                      |
|                     | 15.67       | 15.67                     | 32.22                         | 32.22                                        |
| 1.5                 | 10.89       | 10.89                     | 298.7                         | 298.7                                        |
|                     | 13.74       | 13.74                     | 18.00                         | 18.00                                        |
| 1                   | 10.24       | 10.24                     | 88.5                          | 88.5                                         |
|                     | 13.49       | 13.49                     | 1.5                           | 1.5                                          |
| 0.8                 | 9.86        | 9.86                      | 52.68                         | 52.68                                        |
|                     | 20.24       | 20.24                     | 16.57                         | 16.57                                        |
| 0.5                 | 3.053       | 3.053                     | 3                             | 3                                            |
|                     | -           | -                         | -                             | -                                            |
|                     | 4.07        | 4.07                      | -                             | -                                            |

The results in Table 3 indicate that the LS-VACT can produce sufficient mechanical power to rotate the generator to get the electricity at 1 - 2.5 m/s current speeds. At the very low current speed of 0.5 m/s, the power is low due to lower pressure and lower forces acting on the bucket of the turbine. Moreover, the very low velocities result in larger added mass effect which leads to power loses and contribute in reduction of the mechanical power which causes in lower power output of the generator.

Table 4. Summary of the hybrid performance based on the simulation results

| Current Speed (m/s) | The power of two generators kWh/day | Total power Required kWh/day | Balance kWh/day | Solar power Required kWh/day | Number of solar panels (300 W) |
|---------------------|------------------------------------|-----------------------------|-----------------|-----------------------------|--------------------------------|
| 2.5                 | 46.560                             | 20                          | +26.560         | -                           | -                              |
| 2                   | 24.192                             | 20                          | +4.192          | 9.000                       | 4                              |
| 1.5                 | 12.408                             | 20                          | -7.592          | 18.000                      | 10                             |
| 1                   | 3.312                              | 20                          | -16.688         | 23.400                      | 13                             |
| 0.8                 | 0.960                              | 20                          | -19.040         | -                           | -                              |

Table 4 indicates that the fish farm can be supplied with hybrid power when the current speed ranges between 1 to 1.5 m/s. Moreover, the simulation results show that when the current speed is higher than 1.5 m/s the turbines can provide the power sufficiently without the need for solar power. In another hand, the only solar power can be the sufficient source to supply the fish farm if the current speed is below than 1m/s.

5. Conclusion
This paper presents a hybrid device as a standalone system for electrification a fish farm. This system is consisting of two turbines, two battery banks and solar panels. Theoretical studies on the basis of an experiment and simulation are carried out in order to investigate the performance and the power output of the drag turbine. Then, the prototypes of the LS-VACTs’ performance and power take-off were predicted and assessed using a validated computer simulation program developed. For future work, a hybrid standalone system contains two marine vertical axis current turbines and solar panels can be built and tested using field tests or site experiments to validate the simulation results and to increase their accuracy.
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References
[1] Faez Hassan H, El-Shafie A, Karim OA. 2012 Tidal current turbines glance at the past and look into future prospects in Malaysia. *Renewable and Sustainable Energy Reviews*. 2012.
[2] Oh TH, Hasanuzzaman M, Selvaraj J, Teo SC and Chua SC. 2018 Energy policy and alternative energy in Malaysia: Issues and challenges for sustainable growth – An update. *Renewable and Sustainable Energy Reviews*. 2018.
[3] Khan MJ, Iqbal MT and Quaicoe JE. 2007 A technology review and simulation based performance analysis of river current turbine systems. In: *Canadian Conference on Electrical and Computer Engineering*. 2007.
[4] Das A and Balakrishnan V 2012 Sustainable energy future via grid interactive operation of spv system at isolated remote island. *Renewable and Sustainable Energy Reviews*. 2012.
[5] Rae C and Bradley F 2012. Energy autonomy in sustainable communities - A review of key issues. *Renewable and Sustainable Energy Reviews*. 2012.
[6] Khan MJ, Bhuyan G, Iqbal MT and Quaicoe JE 2009 Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. *Appl Energy [Internet]*. 2009;86(10):1823–35. Available from: http://dx.doi.org/10.1016/j.apenergy.2009.02.017
[7] Yaakob O Bin, Tawi KB and Sunanto DTS 2010 Computer simulation studies on the effect overlap ratio for Savonius type vertical axis marine current turbine. *Int J Eng Trans A Basics*. 2010;
[8] Soufaljen S.A and Maimun A 2015. Low-speed vertical axis current turbine for electrification of remote areas in Malaysia. *Recent Adv Renew Energy Sources*. 2015; (May 2017):75–82.
[9] Mekhilef S, Safari A, Mustaffa WES, Saidur R, Omar R, Younis MAA. Solar energy in Malaysia: Current state and prospects. *Renewable and Sustainable Energy Reviews*. 2012.
[10] Kadam A, Patil S. A Review Study on Savonius Wind Rotors for Accessing the Power Performance. *IOSR J Mech Civ Eng [Internet]*. 2013;(September 2015):18–24. Available from: http://iosrjournals.org/iosr-jmce/papers/RDME-Volume5/RDME-45.pdf
[11] Kamoji MA, Kedare SB, Prabhu S V. Experimental investigations on single stage modified Savonius rotor. *Appl Energy*. 2009;
[12] Sahim K, Ihtisan K, Santoso D, Sipahutar R. Experimental Study of Darrieus-Savonius Water Turbine with Deflector: Effect of Deflector on the Performance. *Int J Rotating Mach*. 2014;2014:1–6.
[13] Yaakob OB, Suprayogi DT, Abdul Ghani MP, Tawi KB. Experimental studies on Savonius-type vertical axis turbine for low marine current velocity. *Int J Eng Trans A Basics*. 2013;
[14] Bai X, Avital EJ, Munjiza A, Williams JJR. Numerical simulation of a marine current turbine in free surface flow. *Renew Energy [Internet]*. 2014;63:715–23. Available from: http://dx.doi.org/10.1016/j.renene.2013.09.042
[15] (http://rredc.nrel.gov/solar/pubs/redbook/).