Powering up!

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Khan, Iqbal and Quaicoe describe the performance characteristics of a scale-model vertical axis hydrokinetic turbine in a controlled environment.

Who should read this paper?

Researchers, technology developers and renewable ocean energy enthusiasts will all find this paper to be of interest. Harnessing the power found in ocean waves, currents and tides is seen by many to be a key element of securing an affordable, reliable, environmentally friendly energy future. For this reason, research into the challenges of ocean energy conversion, particularly hydrokinetic technologies for tidal power applications, is enjoying significant attention. Subject to global market 'pull' and technology development 'push,' the authors anticipate that hydrokinetic technologies will see small-scale pre-commercial deployments in 1-5 years, with larger scale, commercial installations likely in 5-10 years.

Why is it important?

This work describes a series of tow-tank tests of vertical-axis hydrokinetic turbines that employ permanent-magnet generators. Being a nascent technology, small-scale tests conducted in controlled environments are an essential first step toward full-scale design and deployment. This work was directly targeted at hydrokinetic system design and performance analysis, especially where effects of the power take-off system (generators, power converters, etc.) are of interest.

The results of this work point to some of the design needs of permanent magnet generators for use in hydrokinetic turbines (i.e. low-speed, low-cogging, high-efficiency), and highlight the need to focus greater attention on the overall robustness of technology to be deployed in the marine environment. The tests and subsequent observations reported here did not identify any fundamental design issues that could not ultimately be addressed in the course of normal commercial development. In this regard, the results may be viewed as steps toward realizing an optimum system.

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TOW TANK TESTING AND PERFORMANCE EVALUATION OF A PERMANENT MAGNET GENERATOR BASED SMALL VERTICAL AXIS HYDROKINETIC TURBINE

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ABSTRACT

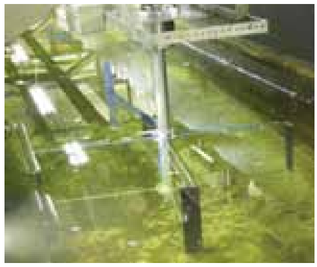
Vertical axis turbines using permanent magnet generators are being considered as options for use in hydrokinetic energy conversion. As a precursor to development of full-scale systems, scale-model turbines need to be tested in controlled environments. In this article, the results of tow tank testing of a small vertical axis turbine employing a permanent magnet generator are presented. Effects of rotor submersion, ripple propagation, and start-up behaviour are presented along with relevant qualitative discussions. Results indicate an overall peak conversion efficiency of 22% for the tested system. General observations and directions for future work are summarized at the end of this paper.

INTRODUCTION

Marine currents, river streams, and other artificial waterways bear good potential for generating electric power. Among a plethora of concepts, hydrokinetic turbines, employing both horizontal and vertical schemes, have been explored to date. While the industry is yet to establish a clear trend on which turbine topology will see greater deployment, vertical turbines have nonetheless gained significant attention [U.S. DEMHT].

Several favourable attributes of such turbines include omni-directional operation, ease of duct augmentation, simplicity of blade design, and reduced requirement of water-sealed components (gearing, bearing, and generators). On the other hand, weak start-up, torque ripple, effects of unsteady hydrodynamics, and claims of lower efficiency are of concern for vertical axis hydrokinetic systems [Shiono et al., 2000; Nicolosi et al., 2005, 2006]. While the field of horizontal axis turbine design and evaluation benefited from the knowledge of wind turbines and ship propellers, studies on vertical axis hydrokinetic systems have seen comparatively limited exploration. It should also be pointed out that contrary to popular belief, experience of vertical wind turbines cannot be directly extrapolated to vertical hydrokinetic turbines because of a multitude of reasons. This includes issues such as higher solidity designs, dominant shear profile in a water channel, cavitation, free surface effects, fouling, and complex unsteady hydrodynamic behaviour [Shiono et al., 2000; Nicolosi et al., 2005, 2006; Calcagno et al., 2006; Kirke, 2008].

(a) University of British Columbia, Canada [Klaptocz et al., 2006]



(b) University College London, United Kingdom [Schöborn and Chantzidakis, 2007]

(c) University of Buenos Aires, Argentina [Ponta and Jacovkis, 2008]

(d) New Energy Corporation Inc., Canada [NECI]

(e) Blue Energy Inc., Canada [BECI]

(f) Ponte di Archimede, Italy [Nicolosi et al., 2005, 2006]

Figure 1: Vertical turbine system (rotor, flotation, augmentation) research and development activities.

From an early development initiative supported by the Intermediate Technology Development Group, UK (involving a year-long performance testing of a 3-m hydro-Darrieus rotor deployed at Juba, on the Nile River) [Ainsworth and Thake, 2006], hydrokinetic technologies have advanced significantly. A number of research and development activities are currently being pursued both in academia and in industry (Figure 1).

A test prototype lent by New Energy Corp Inc. [NECI, 2009] has been tested at Memorial University's Ocean Engineering Research Centre (OERC) facility. The objective of this paper is to share the knowledge gained through a series of tests carried out on this vertical axis turbine system, as well as to highlight various subtle observations on other preceding design activities. While the design aspects will be discussed very briefly, the main focus of this paper will be on a set of subtle observations pertaining to a permanent magnet generator (PMG) based small vertical turbine unit tested in a controlled environment. Such scale-model tests are essential first steps toward full-scale design and deployment. Therefore, these results will have important repercussions on large-scale systems when interpreted with sufficient reasoning.

To specify further, the primary objective of the test arrangement is to observe the system performance in terms of efficiency, start-up, output oscillations, factors leading to performance degradation, and free-surface/submersion effects. A good level of research activities can be observed mostly on rotors' hydrodynamic characteristics with emphasis

Figure 2: Turbine rotors tested at MUN OERC.

on design [Shiono et al., 2000], tank/field trials [Nicolosi et al. 2005, 2006; Calcagno et al., 2006; Klaptocz et al., 2006], and theoretical investigation [Camporeale and Magi, 2000; Zhang et al., 2004] . However, it would be worthwhile to observe the system performance from an electrical power output perspective, as pursued in this work. Another motivation behind the test activities is to identify issues that are of interest to control analysis and synthesis. Issues such as whether one normalized performance curve (efficiency vs. tip speed ratio) is sufficient to backtrack the speed-power relationships; whether a turbine can start on its own; whether the system damping is sufficient to provide stability or too high to cause for excessive losses, etc. are important questions that have bearing on the control aspects of the system. This article primarily investigates these questions through a series of tests conducted in a controlled environment.

Although a high level of research and development activities can be perceived in the field of vertical axis turbines, most of the information has apparently remained protected for commercial reasons. Two examples of extensive vertical axis turbine design, development, tank testing, and field trials can be found in references [Shiono et al., 2000; Nicolosi et al., 2005, 2006]. While these initiatives have given valuable insight into turbine behaviour, the published information mostly deals with issues such as complexity of hydrodynamics, start-up problems, and efficiency characteristics. This work provides time-series performance data and complements the previous studies by considering the effects of power take-off systems. Other relevant publications (horizontal axis marine current turbine [Klaptocz et al., 2006; Bahaj et al., 2007], small wind turbines with similar test setup [Larwood et al., 2001]) were also studied to develop an understanding of the tests carried out as part of this investigation.

TEST APPARATUS

In addition to the test results presented in this work, a series of turbine design, development and tank trials were performed at Memorial University of Newfoundland (MUN). Each of these steps had certain objectives and valuable experience was gained through this exercise. In total, three turbine units were tested at the towing tank in the Faculty of Engineering and Applied Science's OERC. Two of these were designed and built in-house, whereas New Energy Corp Inc. [NECI] contributed the third turbine rotor (Figure 2), which has been machined to fit the mounting frame and towing carriage. A summary of various design and

Rotor	Turbine description	Test objective	Observations	Test summary
MUN 3-bladed	• NACA 63-018 blades, chord 6.25 cm, height 0.75 m, diameter 0.75 m, solidity[1] 25%. • Two radial arms at the top and bottom hold the blades with no centre shaft. The structure is of cantilever type.	• To identify towing tank/carriage suitability. • To observe basic structural, starting, and rotary/oscillatory behaviour.	Clearly the turbine was structurally weak and had high cut-in speed. However, the exercise indicated that the tank facility is suitable for short runs of tests and the rotor had self-starting issues. It would not start unless positioned in certain azimuth angles, and rotary motion was not smooth.	Rotors with higher solidity and support frame needed for structural purposes. Also, number of blades needed an increase to improve start-up performance. All these steps, however, risk reduction in operating efficency.
MUN 6-bladed	• NACA 0012 blades, chord 6.75 cm, height 0.4 m and diameter 0.8m, solidity 50%. • A centre shaft holds the rotor to a frame, which was mounted to the towing carriage. Two self-aligned water sealed bearings were used. Also, two solid disks provide radial support.	• To realize a better structure. • To observe power output, start-up and oscillatory characteristics.	High inertia, slow start-up and low run-time revealed the design to be unsuitable for testing in this tank facility. Also, apparently the skin fricton resulting from the top and bottom disks reduced the performance drastically (i.e. the generated power equalled the system losses, ~200 watts).	A 4 to 5 bladed system with similar or less solidity would be more suitable as long as the radial arms/disks are well machined and optimally sized for reduced mass/inertia.
NECI[2] 4-bladed	• NACA 0015 blades, chord 10.1 cm, height 0.4 m, diameter 1 m, solidity 40%. • A set of four radial arms (piecewise tear-drop shaped) connects the blades to the shaft. The shaft, bearings, and mounting frame have been retroffitted from the previous setup.	• To observe electrical power output characteristics at the generator terminals. • To identify subtle aspects of testing in a controlled environment.	In general, the tests yielded important observations in relation to the intended objectives. Further discussion is given in this paper.	The tests were successful in establishing the basic behaviour of a vertical rotor. However, a number of limitations unique to this test arrangement were observed. These aspects, along with some generic observations, will be presented in the next sections.

[1] Solidity is a measure of a rotor's effective area as well as material usage. This is a dimensionless parameter and is defined as the ratio of blade chord length times number of blades, to rotor diameter.

[2] The prototypes and commercial turbine systems developed by New Energy Corp. Inc. (NECI) have different design and operational features. Therefore, the results presented in the work do not directly reflect NECI's viewpoints.

Figure 3: Rotor descriptions and tests.

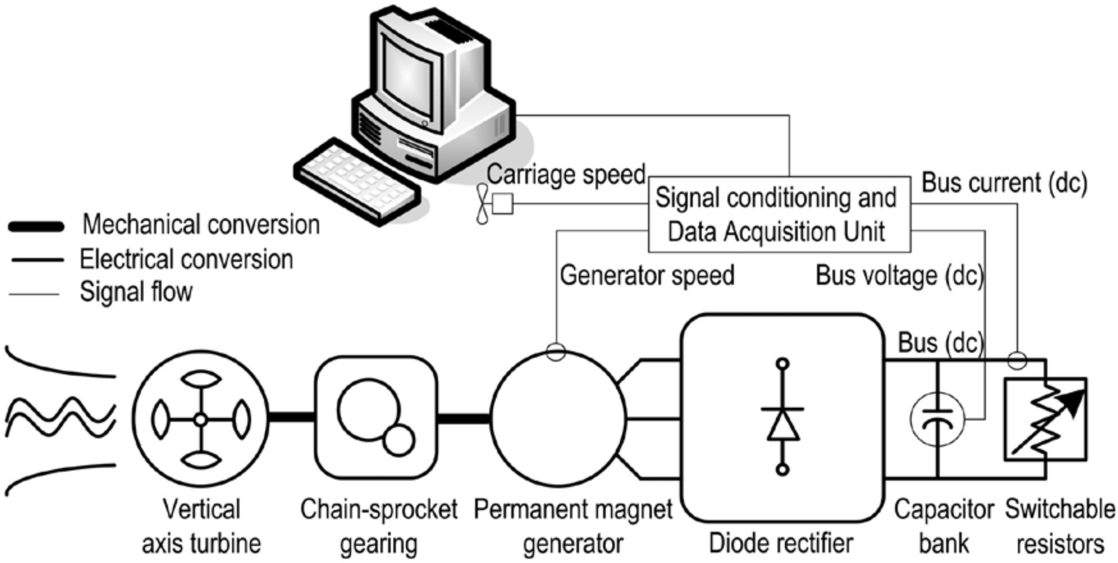


Figure 4: System schematic and data acquisition arrangement.

subsequent test results are given in Figure 3. The NECI 4-bladed rotor is coupled to a PMG using chain-sprocket arrangement with a gear ratio of 1: 3.43. The generator is an outer-rotor multi-pole brushless DC machine, meant for use in electric bikes. The rated speed and power for this generator is around 350 RPM and 600 watts, respectively [Khan and Iqbal, 2006]. This arrangement appeared as a low-cost alternative solution given that there is no standard off-the-shelf generator to match the requirements of this rather unique turbine. An ideal solution would have been a gearless, low-speed, high efficiency, low-cogging generator. To date, only a limited number of manufacturers are realizing this market niche.

The 3-phase output of the generator is connected to a switchable resistive load through a rectifier and filter capacitor (3×1500μF). The DC voltage and current at this point (DC bus) is sensed and fed to a data acquisition card (USB 1208LS). The speed of the turbine is sensed at the generator using a custom-built optical (infrared signal based) sensor. While the intention was to avoid underwater instrumentation, the generator, was subjected to frequent splashes of water. Therefore, the sensor was housed in a water-sealing arrangement. The flow speed/carriage speed is sensed using a setup attached to the carriage. However, the signals appeared noisy and a filtering/scaling circuit was built to interface that to the data acquisition (DAQ) card (Figure 4).

The OERC towing tank has a physical dimension of 70 m x 4 m x 2.5 m (length, width, depth). However, only about 55 m of its length can be used for effective towing purposes. Also the water quality and visibility was restricted during the time of the tests. The carriage has a maximum speed capacity of 5 m/s. The water depth during the test was around 2 m and the turbine system was placed such that the generator stays above the surface.

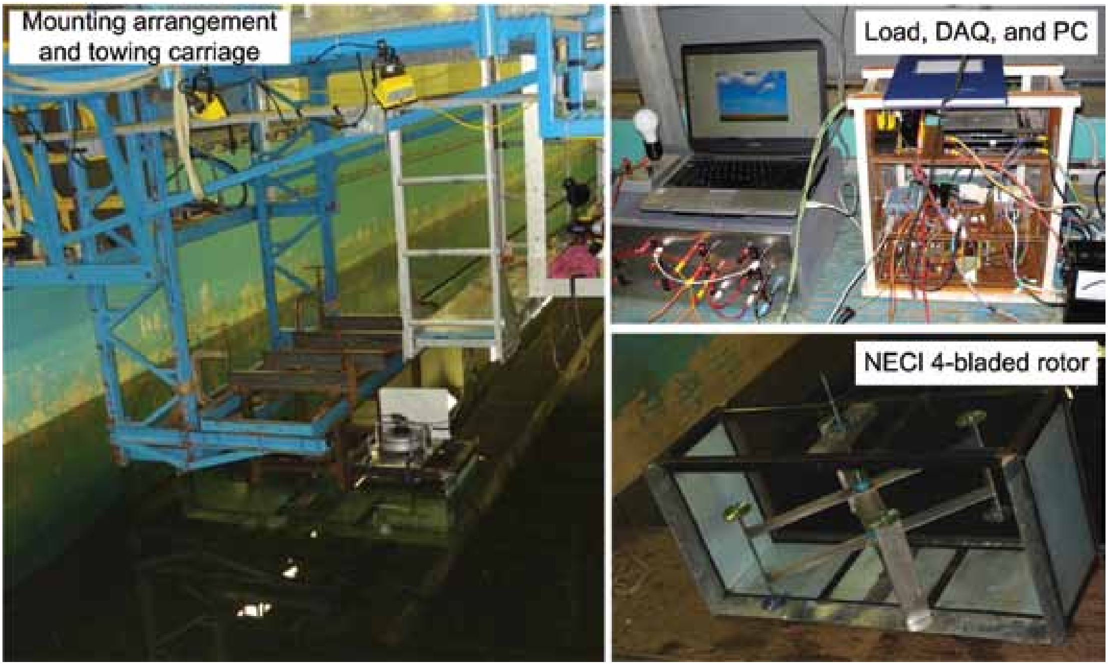


Figure 5: Rotor mounting and test arrangement.

The electrical apparatus was placed on a deck and a splashguard was placed near the optical speed sensor.

The mounting frame holding the turbine rotor has a dimension of 1.5 m x 0.5 m x 0.73 m (length, width, depth). The walls of the frame were filled with high-density styrofoam and the edges of the structure (except the top part) were given an oblique shape to reduce the drag (Figure 5). The exposed part of the structure caused significant turbulence and skew within the rotor's operational area. Also, a set of large bow waves was perceivable at the wake of the rotor structure. The combined effect of flow turbulence, skew, frame-rotor interaction, and near-surface proximity is expected to reduce the overall efficiency of the system.

TEST PROCEDURE AND RESULTS

The basic principle of testing the turbine-generator unit is to ramp-up the flow/carriage speed, allow rotor revolution to reach steady state/high value after the carriage has reached its steady speed, impose electrical loads (from low to high in discrete steps), and gather all the four sensed parameters (rotor speed, flow velocity, bus voltage, and bus current) in a data file. Prior to each run, a carriage velocity was set manually. Since the total towing time is very small (15-25 seconds) and the rotor may not achieve its steady state during the run, a manual push was given to assist the rotor to start up, thereby reducing the initialization period. The effect of such a manual start is limited within the start-up period. All subsequent step changes (electrical load variations) have been introduced only after a steady state has been reached. Therefore, this action contributes minimally to the overall outcome of the tests. In addition to calibrating the sensors for measuring rotor speed, generator voltage, and load current, the carriage velocity was also adjusted for true values. The latter calibration involved measurement of time using a stopwatch and distance using a measuring tape. Linear calibration has been applied for all the sensors and overall error has been found to be <0.5%.

Level of Submersion

With a general assumption that the depth of rotor submersion will linearly change the effective rotor area, the power output should ideally vary linearly with effective water level. However, it is understood that the free-surface proximity and subsequent boundary layer effects, and air suction due to funneling, will play critical roles. The first set of tests, as outlined in the following section, was carried out to gain further insight into this issue.

Figure 6 shows a typical set of time-series plots as collected, analyzed, and evaluated throughout this work. This particular plot, however, focuses on the issue of free surface proximity and depth of submersion. The term 'Full Submersion' implies the rotor is submerged in water and the top of the blade-plane is around 10 cm below the calm water level. On the other hand, 'Partial Submersion' indicates the rotor has around 10 cm of exposed blade-length in free air under calm water conditions.

As the carriage containing the rotor is towed in water, the turbine is manually started. After reaching a carriage speed of 2.35 m/s, the rotor speed and voltages are observed to see if these parameters are 'high' enough. This is done because under unloaded conditions the rotor speed and generator output voltage will increase monotonically until the run time is nearing the end.

As seen in Figure 6, the 'Partial Submersion' case has a better start-up performance probably owing to a higher push during the manual start. Three discrete loads (10W, 5W, and 3.33W) were imposed in each case. The focus of attention in this plot should, however, be the efficiency values. The 'Full Submersion' case indicates an overall efficiency (DC output power to theoretical fluid power) of 12% to 19%. However, the 'Partial Submersion' case indicates significant reduction in efficiency (~5% or less). It can be argued that in the 'Partial Submersion' case the rotor was not allowed to reach a steady state/higher speed (Figure 6, rotor speed plots during t = 5sec to t = 10sec). But in this test, repeated attempts showed the maximum unloaded rotor speed to be around 250 RPM. Therefore, this test has, to some extent, captured the peak performance under the given conditions. A further reduction in water level did not allow the rotor to sustain its rotation and such attempts were discarded.

This set of tests indicates that the relationship between rotor submersion level and effective rotor height is barely linear. The test results are summarized in Table 1.

Comparing the results with regard to the variations in water depth, it can be seen that water level plays a very significant role in rotor performance. The visible free-surface interaction (i.e. formation of bow-waves and air-suction during the rotation) can induce an exponential reduction in overall performance. In contrast, the fully submerged rotor, in spite of being subjected to high levels of drag and turbulence from the frame edges (top part), indicates better efficiency. While the extent of these variations cannot be quantified through

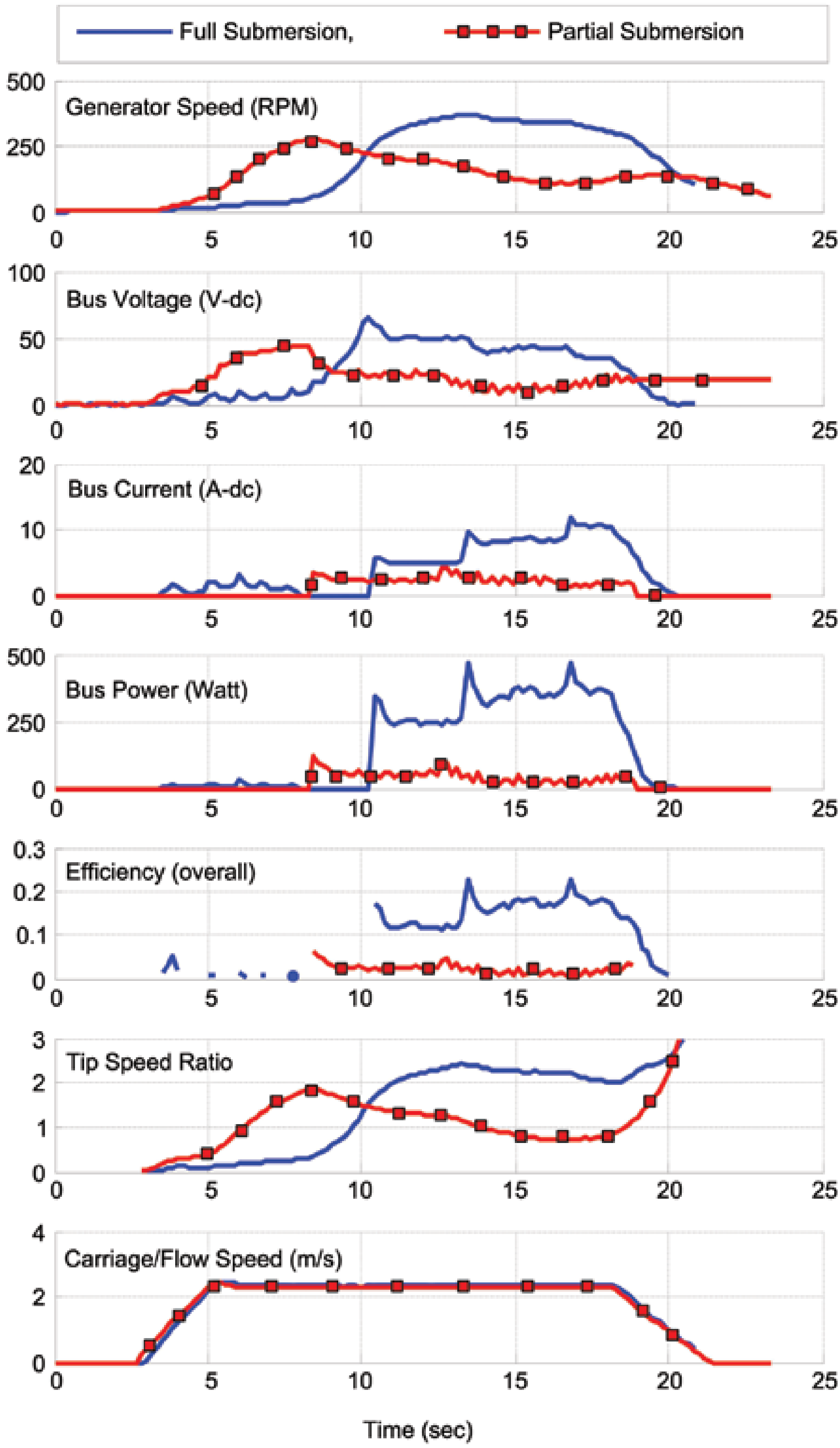


Figure 6: Effect of rotor submersion and free surface interactions.

Submersion	Implications	Overall efficiency	Effective height
Full	rotor is submerged in the water and the top of the blade-plane is around 10 cm below the calm water level	~18%	100% of rotor height
Partial	rotor has around 10 cm of exposed blade-length in free air under calm water conditions	< 5%	27.8% of rotor height

Table 1: Effect of submersion on effective rotor height.

these tests, it can be said that the relationship between power output and water depth is expected to be nonlinear.

Oscillating Behaviour

It is widely known that vertical axis turbines, due to their unique principle of operation, are subject to torque ripples. This phenomenon has been studied extensively in wind energy domain for assessing blade fatigue and structural strength [Homicz, 1991].

In this work, however, we try to see the reflected oscillatory characteristics at the load terminal (DC bus in Figure 4). In Figure 7, a set of time series observations are presented to shed further light on this issue. The tests were conducted with a steady carriage speed of 2.5 m/s. The applied resistive loads are 5W and 2.5W. The voltage output of a PMG depends dominantly on its rotational speed. The oscillations in this quantity as shown in Figure 7 are due to the contributions from variations in generator current caused by the torque ripples.

The output current, as expected, carries the oscillating behaviour at the load terminals. The application of the higher load at around t = 7sec caused the rotor to migrate to a low tip speed ratio condition. While the system runs almost in a limping mode, the oscillatory behaviour is quite dominant and visible in this condition. The ramp during the interval of t = 7sec to t = 10sec shows the gradual increase in the ripple characteristics. It should be noted that the aggregate inertia of the rotor-generator unit and placement of a filter capacitor at the DC bus play important roles in curtailing output ripples, especially at the higher tip speed ratio (TSR) conditions. It can also be observed that the ripple frequency is directly related to the rotor's rotational speed.

Even though it is expected that a hydrokinetic turbine system will operate mostly at the near-optimal tip speed ratio (by means of power tracking control), and hence ripple effects will be minimal, there are other implications of this phenomena. Firstly, when a turbine enters the low tip speed zone (sub-optimal conditions), significant structural stress is imposed on the drivetrain. Secondly, large-scale hydrokinetic systems injecting electric power to a weak grid may introduce flicker conditions as soon as optimum tip speed conditions are not met. The tests performed here bring insight into the characteristics, occurrence, and frequency of the torque ripple phenomena.

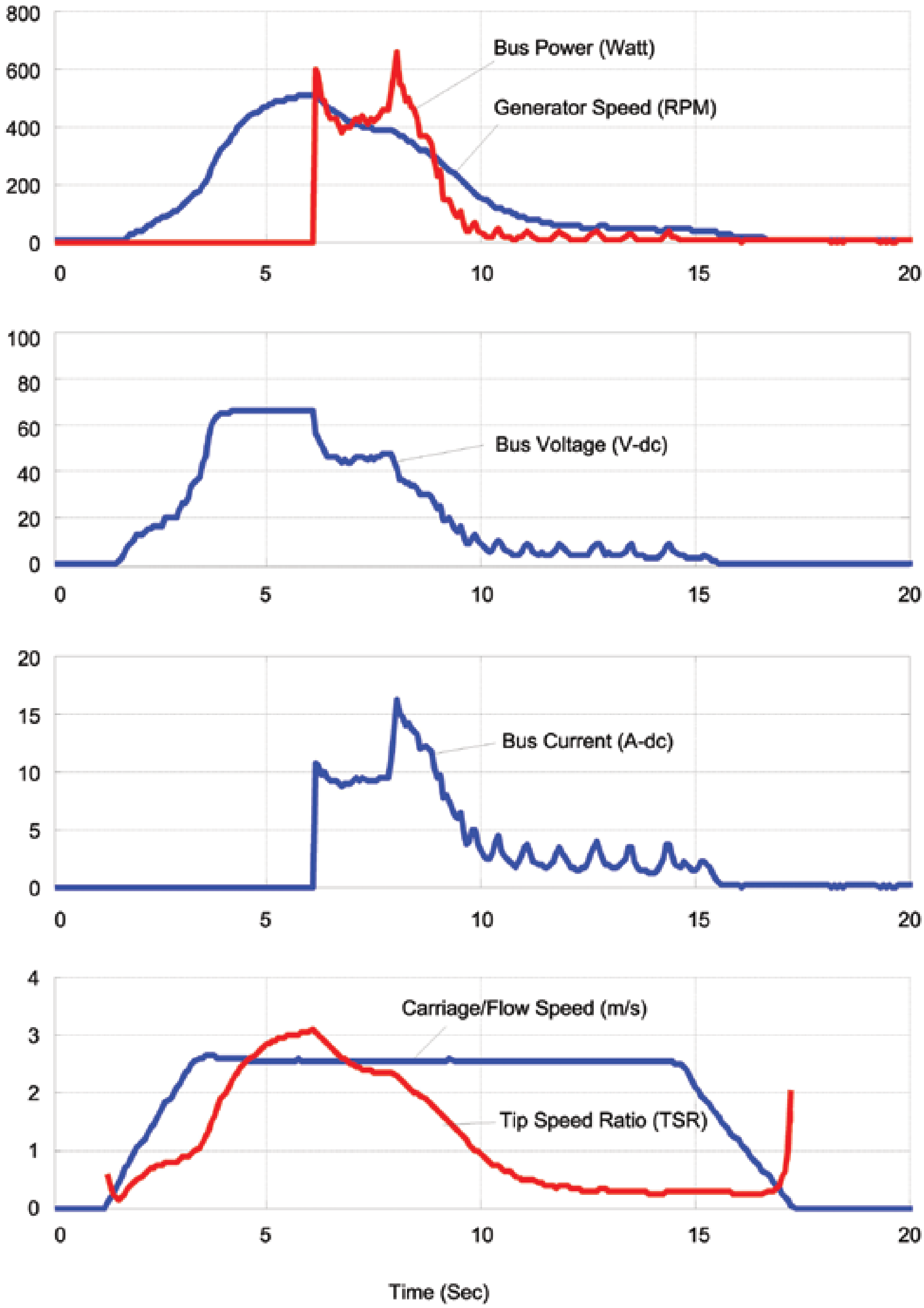


Figure 7: Torque ripple characteristics.

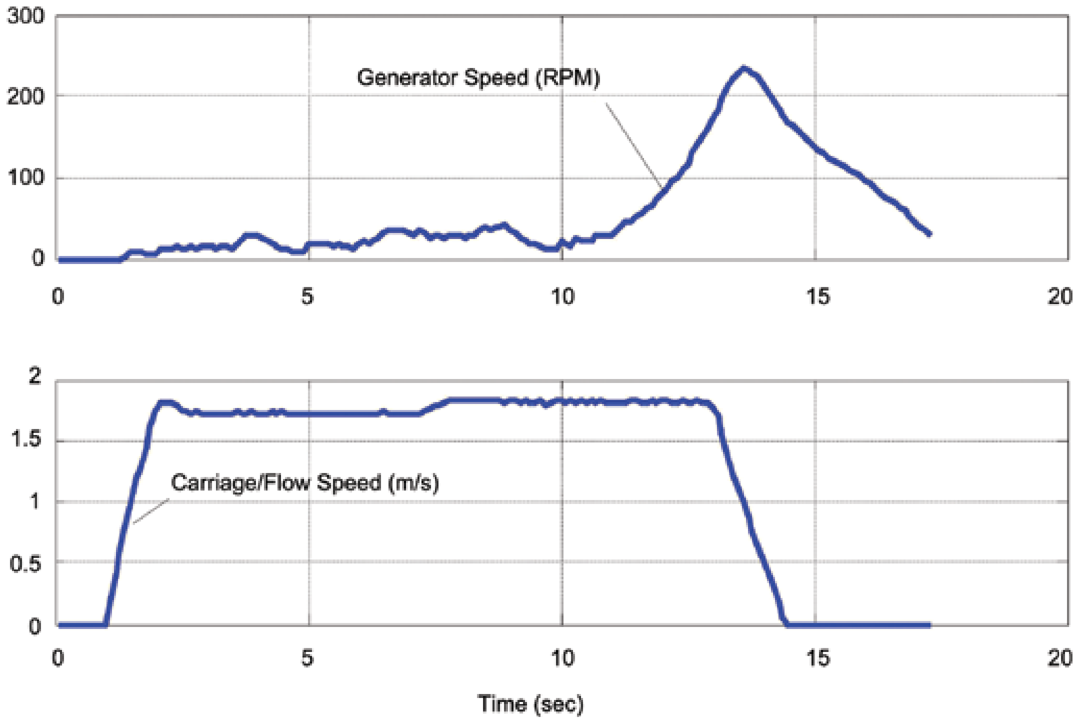


Figure 8: Start-up behaviour.

Start-up Behaviour

The term 'start-up' refers to the condition where a turbine initiates its rotation and sustains its motion following a stalled state. Horizontal axis turbines are inherently self-starting. However, vertical turbines, depending on the number of blades and their shapes, may not bear that feature. Also, starting requirements may become more stringent due to reflected torques from the generator and load side.

Unlike the previous case, as part of this test, the rotor is initially allowed to rotate without any assistance. Also, the generator terminal is unloaded throughout the run and the rotor is fully submerged. Initial tests were carried out with the generator decoupled from the rotor. It was observed that the rotor, by itself, started to rotate at around 0.65 m/s to 0.75 m/s of water velocity. Also, the rotor azimuth angle apparently did not play a great role in this regard.

As the generator is attached to the rotor, the start-up condition degrades greatly when compared to the previous case (rotor without the generator coupled to it). After conducting a number of runs at increasing water/carriage speeds, it became apparent that the turbine (with the PMG) self started at speeds between 1.75 m/s and 1.85 m/s (Figure 8). The rotor blades (NACA 0015) have highest lift coefficients at a 10-15 degree angle-of-attack. Therefore, a favourable azimuth angle to the blades (around 10-15 degrees) was allowed in certain instances. However, it was observed that even with such arrangements, any rotor movement is locked until the start-up velocity (between 1.75 m/s and 1.85 m/s) is attained. Clearly, the generator cogging torque and friction contributed to this problem.

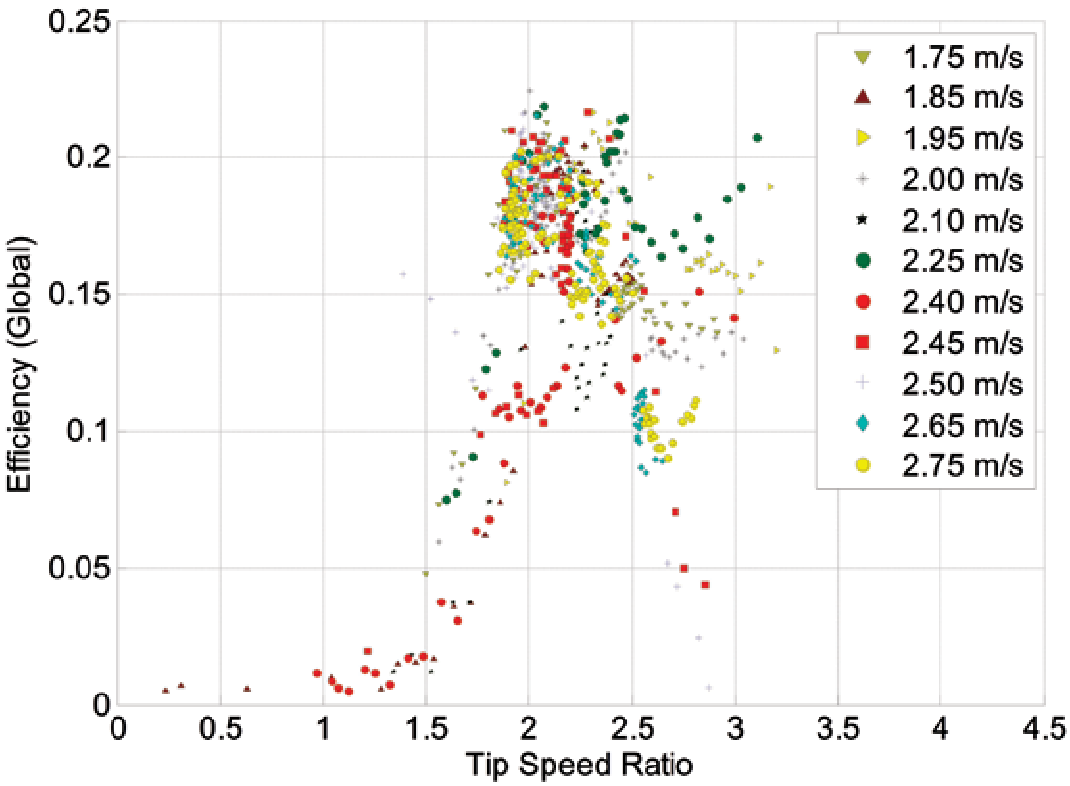


Figure 9: System efficiency at various carriage/water speeds.

System Efficiency

While the system efficiency is an important figure of merit, it is almost impossible to realize an optimistic performance curve through small-scale tests done in controlled environments. In this particular setup, the overall losses (radial arms, frame walls, frame edges, tank walls, gearing, bearing, generator, and rectifier) would undoubtedly be significant compared to the overall output. In this investigation, the turbine system is tested for a number of water/carriage velocities and loading conditions. The data accumulated in each of the runs was reviewed using plots similar to Figure 6. Since efficiency is a steady-state parameter, the transient data points are manually truncated to reflect a more steady-state behaviour. Finally, efficiency (electrical output to fluid power ratio) data is plotted against TSR. These data sets are presented in Figure 9. It should be mentioned that some of the remotely scattered points are due to transient conditions that could not be eliminated from the time series data. The peak efficiency for this setup is above 20% and the optimum TSR is around 2.15.

Even with various losses associated with the conversion process, the efficiency characteristics are encouraging. In fact, for this type of converter peak efficiencies around 20% are very common [Nicolosi et al., 2006; Calcagno et al., 2006; Larwood et al., 2001]. There also exists ample room to improve the power output with design modifications such as hydrodynamic shaping of radial arms, higher efficiency generator fabrication, and elimination of gears.

One interesting phenomenon observed in this test was that at each operating velocity (i.e. operating conditions, in general) there exists a separate performance curve (Figure 9). This arises from the fact that the fluid dynamic interactions at each operating condition are highly non-linear and complex. Also, stability of the structure and initial conditions (startup, level of loading, etc.) contribute to this. As an established norm, these variations are averaged and fitted through a single curve [Larwood et al., 2001]. This raises a question as to whether a single curve can be used in backtracking the various operating conditions, which clearly take dispersed routes. However, performance curves are particularly important in describing the overall system, the issue of possible non-existence of a unique curve is particularly important in system modeling and control synthesis. This behaviour, although mostly overlooked, is also seen in other works [Shiono et al., 2000; Verdant and GCK, 2005].

GENERAL OBSERVATIONS AND SCOPE FOR FURTHER WORK

In order to provide caveats for test results presented in this work, as well as to encourage further research, a set of observations and limitations are presented here. For testing hydrokinetic systems under controlled environments, longer tow-tanks (with an effective length of ~200m) or high-speed flume tanks (>2 m/s velocity capability) are desirable. As experienced in this test exercise, the effective length of the OERC tank was insufficient to carry out longer runs. It should also be pointed out that operations at higher speeds pose risks of damaging the rotor due to strong reflected waves hitting the structure. The flow regime within the rotor frame and in its wake appeared highly turbulent and non-stationary. Any further research should emphasize on quantifying the effects of rotor frame and flow characteristics on the rotor's operation by means of more sophisticated visualization and data acquisition tools.

The permanent magnet generator used in this experiment exhibited weak start-up performance, caused reduced efficiency, and required gear coupling arrangements. However, it should be stated that these issues are not typical for such generators and can be effectively eliminated through proper design as long as the requirements are known. The tests presented here indicate some of the design needs of PMGs for use in hydrokinetic turbines (i.e. low-speed, low-cogging, high-efficiency generators).

While the sensory and data acquisition system proved to be very useful in amassing the test results, the underwater speed sensor faced frequent failures due to water splashing and leaking. In light of this experience, it can be stated that a robust hydrokinetic turbine should avoid usage of underwater electronic equipment in order to reduce the system cost and increase overall reliability.

Typical to any other small sized system tested in controlled environments, several underlying limitations can be identified for this work. For instance, overhead power losses are quite significant compared to the overall system size. Use of rotor frame (which, in an ideal deployment, will be replaced by augmentation ducts) and absence of any flow profiling and visualization tools (needed for more realistic tests) introduced important measurement limitations. Being tested in underwater conditions for about two weeks, the NECI rotor structure went through visible degradation, fouling, and rusting. To date, most hydrokinetic turbines that have gone through field trials have faced significant degradation problems. Any further research should also quantify the extent of such degradation and possibly suggest solutions for system protection and longevity.

CONCLUSIONS

In this article various qualitative observations pertaining to small scale testing of a permanent magnet generator based vertical axis hydrokinetic turbines are presented. The limitations of the tests are also presented. To summarize the test results, the following can be stated:

- Variations in water elevation will induce linear change in power output only in an idealized situation. In reality this imposes a high degree of nonlinearity.
- While permanent magnet generators are effective devices for power conversion, a better design should include features such as direct coupling, lower cogging, and higher efficiency.
- The ripple behaviour is dominant at lower TSR conditions with given system inertia and electrical filtering at the output.
- Rotor start up is not an issue as long as sufficient design considerations are given (i.e. four or more blades and low cogging generator).
- Reducing effects of radial arms, transmission components, and electrical losses can improve system efficiency.
- The system performance curve (efficiency vs. TSR) is enveloped with a high degree of nonlinearity and uncertainty.
- A single efficiency curve is probably not sufficient to accurately describe the wide diversity of operating conditions (e.g. water velocities, loading and unsteady hydrodynamics).
- Over time, structural degradation may introduce divergence from expected performance.
- A hydrokinetic turbine devoid of underwater instrumentation is highly desirable.

While the tests and subsequent observations presented in this paper give a good description of what can be achieved through testing in controlled environments, actual commercial development will undoubtedly identify and address these issues. Therefore, the results generated through this work should not be regarded as inherent bottlenecks. Rather they should be treated as steps toward realizing an optimum system.

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