Recommend Ultra Low-head Mini-hydro Turbine-generator System for Coastal River Application

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***Abstract*— Over the past five years, Canadian small and medium hydro turbines manufacturer Norcan Hydraulic Turbines Inc. lead the team members, as in co-authors above, in the development of an "Innovative Ultra-Low Head (ULH) Mini-Hydro Turbine-Generator System". International Science and Technology Partnerships Canada (ISTPCanada) and Brazilian partners, together with the Natural Sciences and Engineering Research Council (NSERC), supported this R&D project. This industry-led collaborative R&D project has been carried out from 2013 to 2015.**

The proposed ULH Hydro-Turbine technology will bridge the gap between low-head hydro and marine hydrokinetic technologies by developing a cost-effective innovative "pit" type ULH hydro-turbine system to allow head application range extended to less than 2 meter and capture kinetic energy at free-stream zero-head.

Detailed test results explained. Pre-commercialization demonstration has been planned in Canada. Recommend this ULH Turbine system can be applied effectively at coastal river mouth, sea-lock gates, and tidal estuary where there is about 2 meter or more water-head available and further allow operation during river-current or tidal-current periods.

***Keywords*— Ultra Low-head (ULH) Turbine, Mini-hydro, coastal tidal channel, hydrokinetic, double draft-tube**

I. Background

For ultra low-head range for head less than 3.0 m, particularly less than 2.0 m or 1.5 m, traditional hydroelectric technologies are not economically and technically effective. A few companies dedicated the development of new turbine systems for low-head application up to 1.5 m and above, such as "vlh MJ2" and Voith "StreamDiver". There are in-stream free-flow (zero head) water-current turbines. These turbines (or so called "Hydrokinetic Turbine") are only for capturing kinetic energy from water velocity, and they only can be installed at free-stream (zero head) without dam structures. Thus their unit capacity will be small and unit cost of these hydrokinetic turbines is much higher than the conventional low-head turbine systems.

The joint Canada and Brazil R&D team has proposed a practical and innovative solution to overcome the limitations of the present low-head hydro turbine systems. This joint project has developed an innovative pre-commercial small "Bulb" type modular turbine to achieve economic viability operating below 2.0 m and 1.0 m of head.

II. Principal Operation and Design

A. Principle of Operation

The proposed innovative turbine and generator systems, with installed capacity less than 500 kW per unit, will have:

1) Non-regulated axial-flow design: With curved Stay-Vanes that direct the flow toward the three-blade runner and provide structural support without wicket gates, thus providing a simple fish-friendly design

2) Variable-speed permanent magnetic excitation generator (PMG): Direct-drive, without gear-box, to provide low cost, lighter design

3) Double draft-tubes as diffuser: Minimize draft-tube length and cavitation, thus lower civil cost

4) Compact prefabricated submersible modular design: With typical runner diameter of 0.75 m, 1.0 m and 1.5 m, allowing easy installation and removal for maintenance

5) Allow Free-stream Operation: For head range less than 0.5 m or near zero-head drop, operate as hydrokinetic turbine.

B. Hydraulic Design and Turbine Model

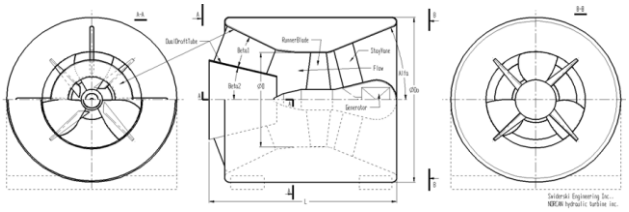


Fig. 1 Sketch of modular ultra-low-head hydro turbine and generating system. (International Patent Application filed July 21, 2015)

As shown in Fig.1, the upstream side of intake structure center will have a shape of “Bulb”. It can be open from the front cover, and variable speed permanent magnet generator (PMG) can be installed with direct-drive within “Bulb”.
The Stay-Vanes served as Guide-Vanes and structure support. The proper designed curved guide vanes will direct the flow to the three-blade runner for optimal performance. The design will take into account of fish-friendly factors.
The exit draft-tubes for energy recovery will be double-cones types that have been used in the 60’s. The proper designed inner and outer cones will provide final uniform flow without separation at end of draft tube exists. This old design will provide shorter draft tube length compare to the normal single cone draft tube. It will save civil cost of the total structure.
The modular design and prefabricated package will allow easy on-site installation. Multiple units can be installed at very low head river weir structures, and at irrigation canal. They will be able to operate in a non-dam free-stream condition.

1) Hydraulic Design: Swiderski Engineering Inc. conducted completed hydraulic design optimization as well as the structural design of the initial model turbine. The hydraulic design process was executed by application of multi-objective design algorithms, where objectives such as: energy efficiency maximizations, minimization of fish mortality were set. The design process was supported by commercial flow analysis software (CFX). Status reviews were conducted with Norcan Hydraulic Turbine Inc. in intermediate stages of the process. The size of the bulb was determined based on consultations and information obtained from the University Of New Brunswick regarding the permanent magnet generator. All technical information with regards to the preliminary design of the model turbine was consulted with the University Federal de Itajuba (Brazil).

2) Turbine Model Equipped with:

a) six (initially four) stay vanes
b) three-bladed runner
c) dual-passage draft tube which incorporates the internal cone
d) four profiled supporting vanes

Fig 2 General arrangement of the turbine (International Patent Application filed July 21, 2015)

3) Optimization Criteria: The major objectives of the optimization process are a combination of the following:

a) Maximisation of energy efficiency (turbine hydraulic efficiency – the greatest amount of energy produced)
b) Maximisation of turbine speed (the smallest possible generator size)
c) Maximisation of turbine unit flow (the smallest possible turbine size)
d) Minimisation of the volume of the fish-mortal local strain (unless 100% of the domain volume is below the mortal value)
e) Minimisation of the volume of the fish-mortal local shear stress (unless100% of the domain volume is below the mortal value)

4) Turbine Configuration Development: The turbine design arrangement targeted for an ultra-low-head dam/structure (static pressure of water at the turbine inlet is 2.5 m of water column) application.

a) Simplification to the overall turbine configuration:

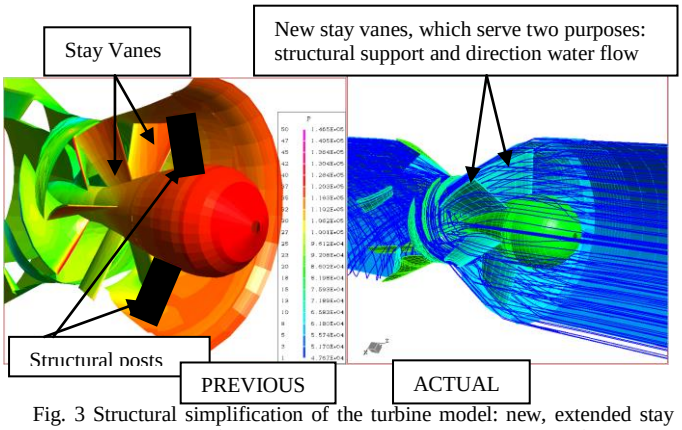
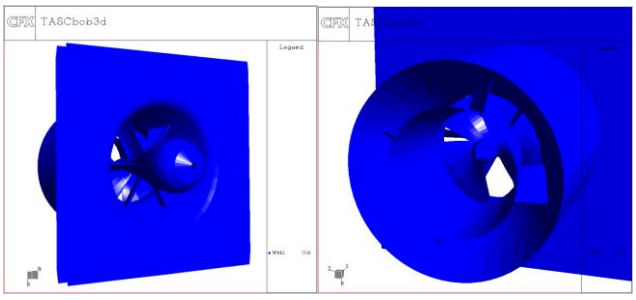


Fig. 3 Structural simplification of the turbine model: new, extended stay vanes to serve purpose of the total structural support (elimination of extra stay posts) and creation of the hydraulic pre-vortex at runner entrance.

Turbine structure simplification was conducted to reduce complexity of the machine in order to lower manufacturing cost. Elimination of the structural posts was achieves by redesigning stay vanes by extending their length and increasing thickness. In order to assure appropriate inflow conditions to the runner chamber, stay vanes were optimized.

b) Low-head dam configuration:

The low-head dam configuration performances were verified again and it was confirmed that the target operating range should be achieved.



SWIDERSKI ENGINEERING INC. ©

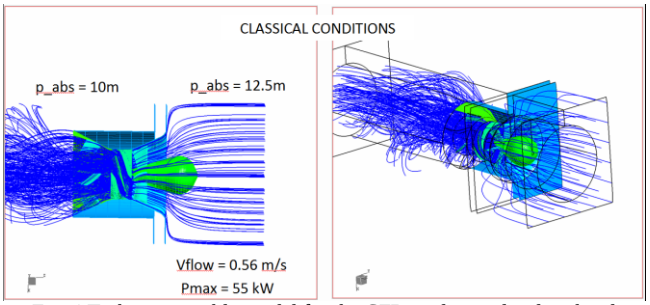


Fig. 4 Turbine assembly model for the CFD analysis: ultra low-head configuration (Hnet<=2.5m).

c) Free-Stream Configuration:

The free-stream configuration flow analysis was performed to find out degree of suitability of this machine to run as a hydrokinetic turbine.

The findings are as follows:

- The free-stream flow has a tendency to by-pass the turbine, leaving minimal flow entering the machine
- Turbine performances strongly depend on the velocity of the stream (Fig. 5a)
- There would be necessity to study possibility of designing an inflow confusor, as preliminary CFD runs indicate that it should have a significant influence on turbine output.

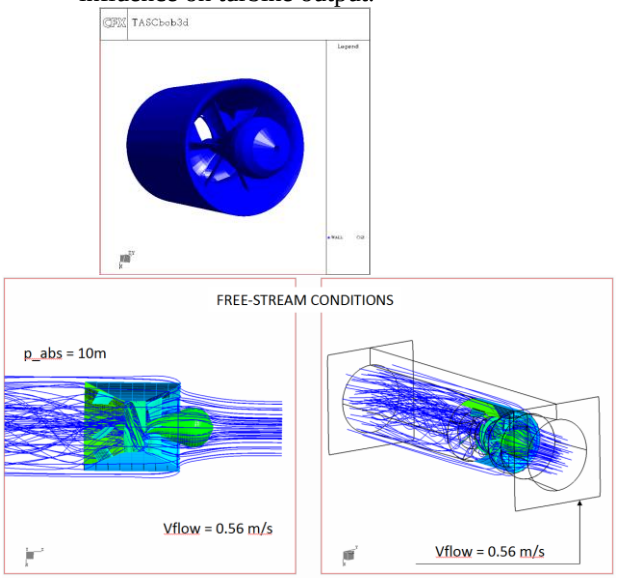


Fig. 5 Turbine assembly model for the CFD analysis: free-stream arrangement.

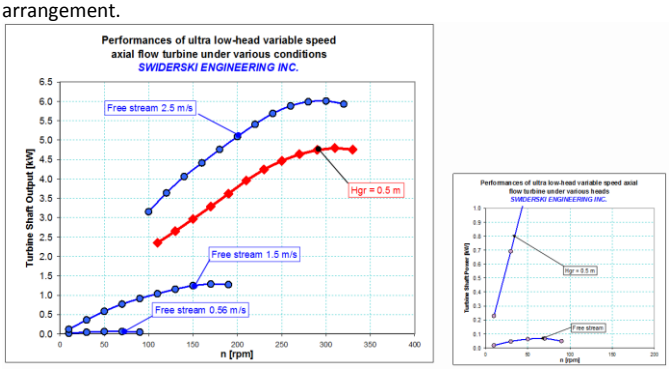


Fig. 5a Free-stream arrangement – turbine performances expected

d) In-penstock arrangement (laboratory testing configuration)

Due to technical restrictions experienced in the laboratory, it was decided to test turbine model not in a low-head dam arrangement, but in the:"in-penstock" configuration. Flow simulations in a laboratory arrangement were computed to establish a comparison baseline and methods how to extrapolate "in-penstock" test results into the originally intended (and target design) arrangement.

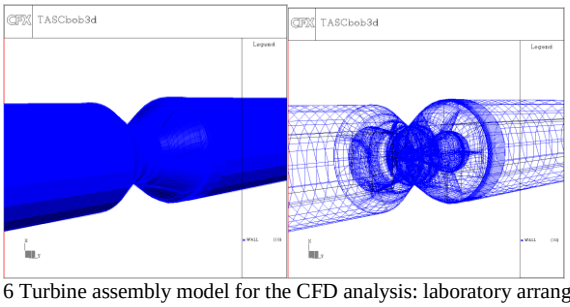


Fig. 6 Turbine assembly model for the CFD analysis: laboratory arrangement

Based on the flow simulation results, turbine performances in an "in-penstock" arrangement are different due to the inflow conditions. The power output anticipated would be some 25% to 30% lower that achievable by this turbine in a low-head dam arrangement.

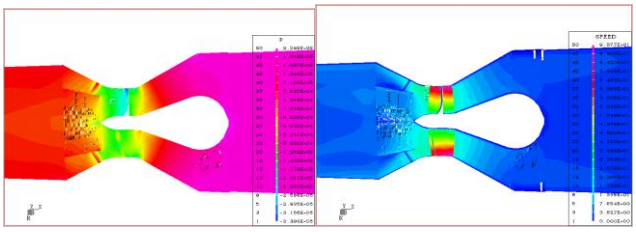


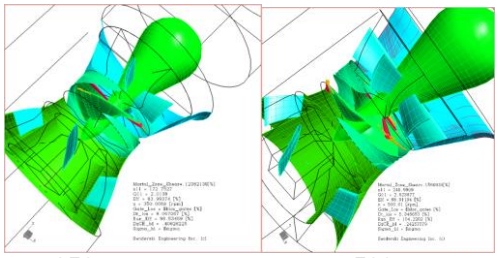
Fig.7 In-penstock configuration (laboratory arrangement)–flow visualization

e) Fish mortality Analysis:

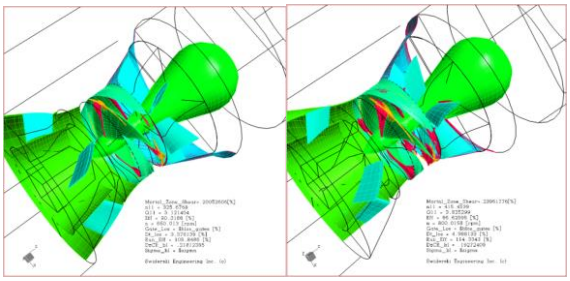
The following principles were applied to determine the locations of potentially mortal zones:

- Pressure rate change
- Shear stress

The probability of mechanical collision, striking or grinding against walls, will be determined as follows: the general fish mortality factor (FMF) is defined as a ratio between mortal volume (MV) and the total volume of flow passages (TV), where the MV is the volume where shear stress or strain rate are equal to or higher than values considered to be mortal to fish.



350 rpm 500 rpm



600 rpm 800 rpm

Fig. 8 Zones within the computational domain, which have critical and close-to-critical values of pressure rate change and hydrodynamic shear

f) Structure Design:

Stress analysis of the new runner was conducted for various operating speeds within a practical operating range from 200 rpm to 800 rpm. Results presented below show combined stresses of the runner blade under 25% of overload conditions (instantaneous pressure increased by 20% over calculated for steady-state operation).

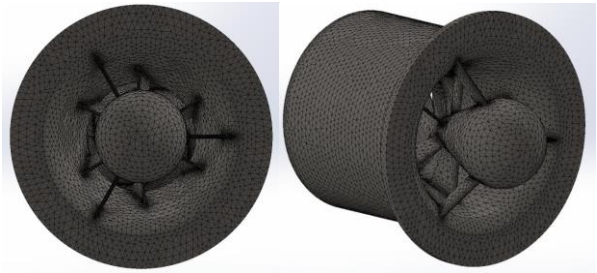


Fig. 9 Mesh used to obtain FEA results presented on the following

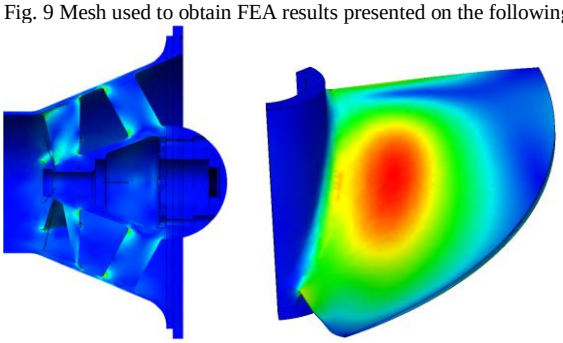


Fig. 10 Model runner FEA analysis. Maximum stresses calculated for the ABS material no not exceed 2000 psi (YP=5200 psi)

C Expected Turbine Performances

Turbine performances presented below are based on CFD results obtained for a fine-grid model. Due to the fact that the detailed mechanical analysis is to be conducted in the next development stage, energy losses in the bearing system and the generator are neglected.

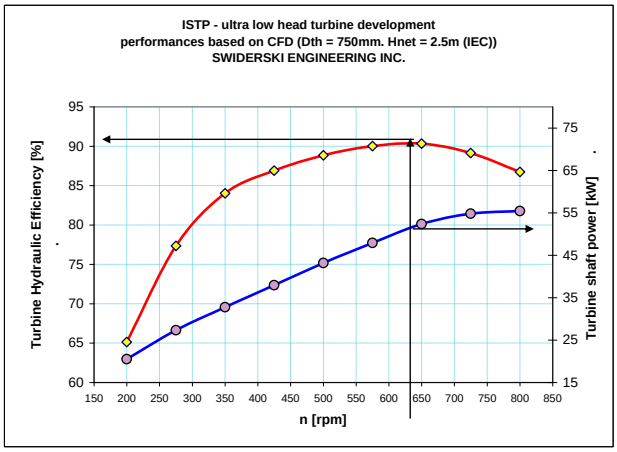


Fig. 11 Turbine performances predicted based on CFD analysis

Q11 = Q/D^2/Sqrt(Hnet) n11 = n*D/Sqrt(Hnet) Sigma = (Hb-Hv-Hs)/Hnet	Q [cms] – turbine flow D [m] – runner throat diameter Hnet [m] – Net head (per IEC code definition) n [rpm] – turbine shaft speed Hb [m H2O] - atmospheric pressure Hv [m H2O] - vapour pressure Hs [m H2O] – turbine setting

Cavitation exposure

Cavitation exposure, represented here by the Thoma number (Sigma – (Hb-Hv-Hs)/Hnet) indicates quite large safety margin for the intended installation of the turbine. As turbine setting will be below the tailrace, under extreme operating conditions, which relate to 800 rpm, there will be approx. 2.2m protection head against cavitation. Lower operating speeds will assure even higher safety margin.

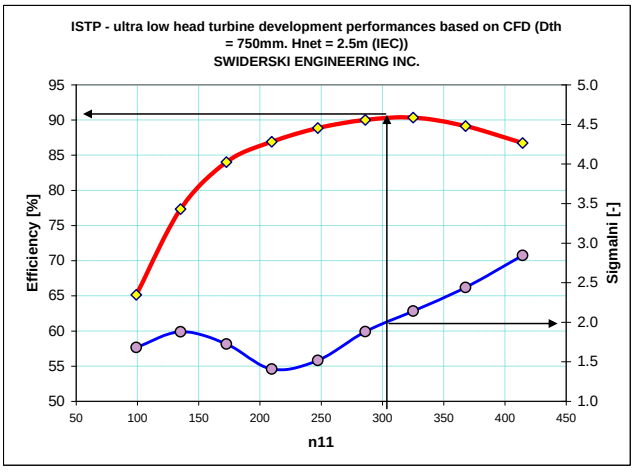


Fig. 12a Turbine performances predicted based on CFD analysis

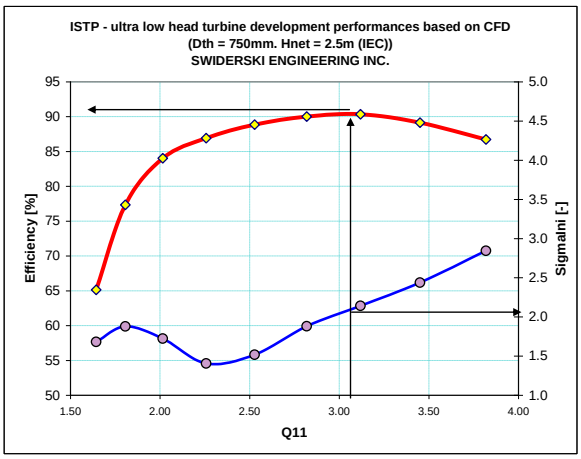


Fig. 12 b Turbine performances predicted based on CFD analysis

D. Electrical System Design by University of New Brunswick (UNB)

The design of electrical system in the project includes the following 3 sub-tasks: (1) selection of a variable speed permanent magnet synchronous generator (PMSG), (2) development of a power converter, and (3) development of a control system.

The major activities in these 3 sub-tasks are listed as follows.

1) Variable Speed PMSG

The UNB team identified the specifications for the prototype PMSG, as shown in Table 1, through intense discusses and consultations with all the collaborating partners of the project. The team also worked with an experienced manufacturer to design the PMSG as shown in the drawing in Figure 20. The prototype PMSG, as shown in Figure 21, was delivered to UNB for testing in September 2014, and then was shipped to Brazil for integration installation in January 2015. This prototype generator has been working well on the integrated mini-hydro system at the test facility in Brazil.

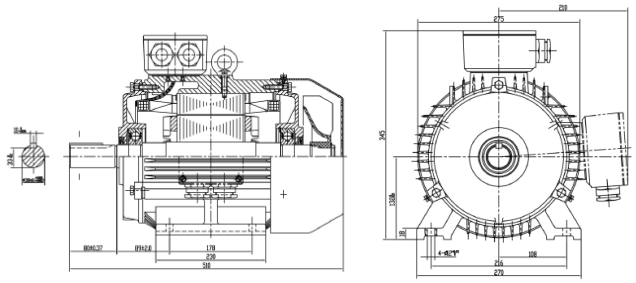


Fig. 13 Drawing of the mechanical design for the Permanent Magnet Synchronous Generator

Fig 14 Picture of the prototype PMSG

MODEL:	TYF 132
TYPE:	Permanent Magnet Synchronous Generator
PHASE:	3 phases
MAXIMUM POWER:	11 kW
RATED POWER:	10 kW
MAXIMUM VOLTAGE:	300 V
RATED VOLTAGE:	280 V
MAXIMUM SPEED:	1630 rpm

Table 1 PMSG data

2) Power Convertor

This hydro-generation system requires an 11kW grid-connected power converter to convert the power from the hydro turbine generator and inject it into the utility grid (10kW at rated conditions, with 11kW peak power). The UNB team worked on the development of the power converter in this sub-task. The power circuit topology for the power converter was developed by the team, and is shown in Figure 15, with the following 3 major modules: AC/DC diode rectifier, DC/DC boost chopper, and DC/AC grid inverter. The diode rectifier is used as a reliable and cost-effective way to convert the variable-voltage and variable-frequency source of hydro turbine generator into a DC; then the DC/DC boost chopper increases the DC voltage to an appropriate level; finally the DC/AC grid inverter converts the DC to AC and injects power into the grid. Based on the design, the UNB team built a prototype power converter as shown in Figure 16 in June 2014, and started testing its functionalities at UNB lab and also verifying developed control algorithms on it. After finishing the lab tests, the UNB team shipped the power converter in January 2015 to Brazil for real life installation on the mini-hydro system. The power converter has been working flawlessly on the real system.

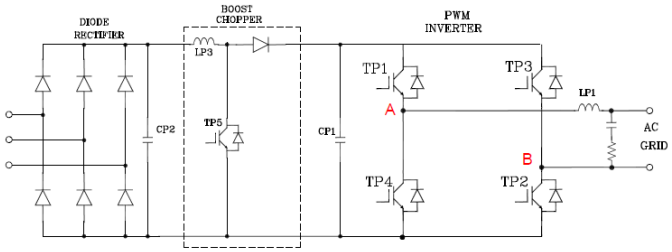


Fig. 15 Topology of the power converter

Figure 16 Picture of the prototype power converter

3) Control System:

The research work for the control system in this sub-task mainly consisted of the development and integration of: 1) innovative Golden Section Search based maximum power point tracking (MPPT) method under un-regulated water flow conditions; (2) variable switching frequency pulse-width-modulation (PWM) strategy to improve the efficiency of the power converter while meeting the grid power quality requirements; (3) grid interconnection system compliant with international standards for distributed generation with advanced control for grid current, system protection strategy, anti-islanding algorithm, etc.; and (4) novel fault diagnosis technology for power semiconductor devices and dc link capacitors based on signal processing of converter voltages and currents. The UNB team first developed a simulation platform under MATLAB/Simulink simulation environment for the electrical system of the hydro generation system. Then the team used the platform to design and verify various control algorithms. Finally, the team implemented the algorithms and tested them on the prototype power converter. Figure 17 shows the diagram of the system simulation model including several subsystem modules: the PMSG, the diode rectifier, the boost chopper, and the grid inverter. More specifically, the detailed simulation diagrams for the boost chopper module and the grid inverter module are given in Figure 18 and Figure 19 respectively.

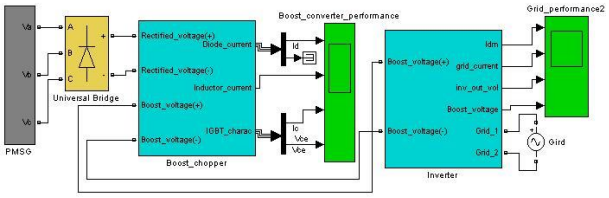


Fig. 17 Simulation model for the electrical system

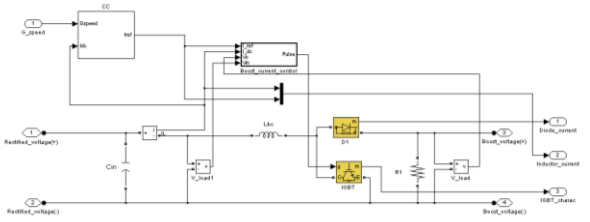


Fig. 18 Simulation diagram for the boost chopper

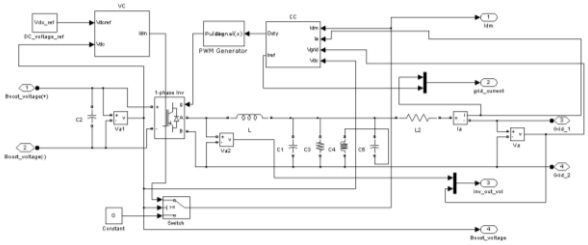


Fig. 19 Simulation diagram for the grid inverter

The UNB team finished the development of all the control algorithms in September 2014, and then completed the implementation and verification on the prototype power converter in December 2014. Although there were challenges of developing the advanced control system, and there was lots of work of testing and debugging during the development process, the UNB team managed to finish the tasks on time and was able to deliver a complete solution of electrical generation system for the real-life installation of a mini-hydro turbine-generator system in Brazil. According to the operation results from the field tests, the system met all the design requirements proposed in this project and demonstrated good performance.

III. Laboratory and System Integration Test

A. Turbine Test Rig at CERPCH

The Brazilian National Reference Center of Small Hydro Power Plants – CERPCH, is located in the Federal University of Engineering of Itajubá – Unifei

For the tests, the existing piping system should be modified for the installation of the turbine. Thus, it was built with a new piping system on the existing one, which is powered by two pumps from Imbil brand model ITAP 250,290, with flow of 900 m³/h each. The pipe has as size the diameter of 26.75 inches. The turbine model is assembled between a conic pipe set, as a Venturi, with runner having 360 mm diameter. Pipe and flanges are made of carbon steel, with anti-corrosive base painting and synthetic enamel painting. Flanges are fixed by bolts and nuts, having rubber seal between flanges.

The set was assembled beside an existing canal for weir tests. As this canal has direct connection to the feeding tank system, the test rig was connected to this canal. Within this canal was adapted with an adjustable barrier for level control and a weir to measure the flow, as an option to measure and check the ultra-sound type flow transducer. Upstream and downstream pressures are measured by pressure transducers and also manometers, for checking, all connected to a data acquisition board. Torque is measured by a 200 N.m torquemeter coupled between turbine and PMS Generator shafts. Angular speed is measured by using a digital tachometer.

Resistance break system is activated by a liquid rheostat. As the steel blades have more area in contact with the water, it creates a resistance to the generator breaking the system, generating opposite forces to the turbine shaft. This way makes possible to control the speed of the runner and to obtain the measure of the torque. Still forms the electrical system a frequency inverter connected directly to the grid.

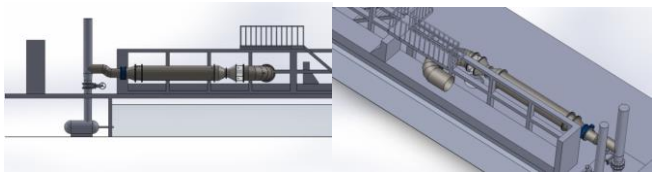


Fig. 20 Turbine test rig layout

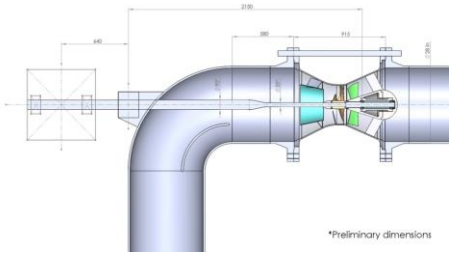


Fig. 21 Model turbine cross section

Fig. 22 Turbine model and pressure acquisition set

Fig. 23 Ultrasound type flow Transducer at upstream pipe

Fig.24 PMSG and torque-meter coupled to the turbine shaft

B. *System Integration and Tests*

The electrical system (generator and power converter) developed in this project by the UNB team was delivered to the Brazil partner along with industry partner Norcan's mini hydro turbine. The electrical system and the turbine were installed at the test facility in Brazil for demonstration of the technologies. The final task of the integration tests in the project was completed in December 2015 at Brazilian test site. Figure 25 shows the test platform for the mini-hydro system in Brazil, including the turbine, the generator, the power converter, and the water circulation tube system which mimics the water flowing as in real rivers. The entire system worked well and performed as expected during the final integration tests. Figure 26 shows the meter readings of the power generated by the mini-hydro system. The turbine-generator power converter system was able to harvest maximum power of the platform with the innovative MPPT algorithm and high efficiency PWM strategy. The power converter complied with international standards for distributed generation by converting hydro power into high quality (low total harmonic distortion on current) AC power to be fed into the grid.

Fig. 25 Integration test platform for the mini-hydro system in Brazil

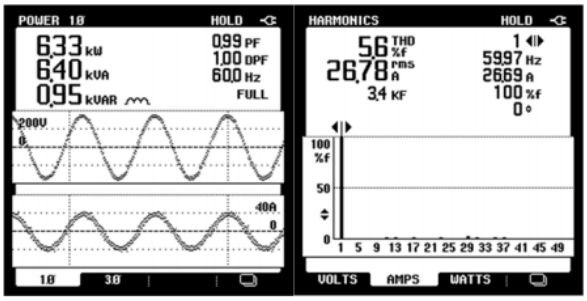


Fig. 26 Generation power of the power converter at the field test

C. *Turbine Model and Electrical System Integration Test Results:*

Followings are test results showing in non-dimensional charts. It shows best efficiency point is at test head 1.5 m., speed n is 440 and test flow Q at 0.24 cms

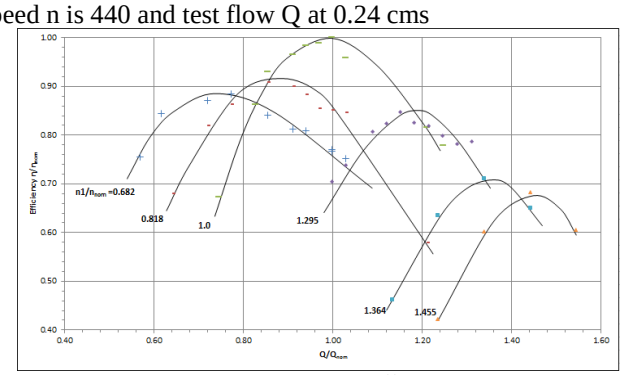


Fig. 27 Non-dimensional efficiency curves

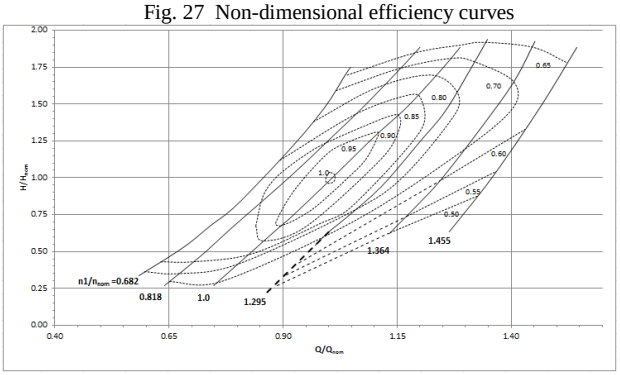


Fig. 28 Application field of the tested model of turbine

	Test Rig Model
D (diameter of the runner) [m]	0.360
H_{net} [m]	1.485
Q_{11}	3.05
n_{11}	130
η	0.816

Where:

$$Q_{11} = \frac{Q}{D^2\sqrt{H_{net}}}$$

$$n_{11} = \frac{nD}{\sqrt{H_{net}}}$$

D. Test Results Conclusion

1) Turbine efficiency scale effects: With the tests results, the efficiency curves for different ranges of operation of the turbine can be projected. The results showed that the model reached maximum efficiency of 81.6%, when worked with Head of 1.485 meters, speed of 440 rpm and flow rate of 0.243 m³/s (nominal condition). This nominal condition can be transposed to similar model using the Turbo Machinery Affinity Laws.

Due to the fact that the tested model is small and it was tested under extremely low heads, we should have at least 5% boost on the efficiency if the real machine is some 1.5m diameter and the head some 2m (based on Hutton formula commonly suggested for Kaplan and axial flow machines)

If compared with the machine modeled in CFD by Canadian group, which reached 0.91 efficiency for 2.5 meters Head, the physical model tested in the test rig, which reached 0.816 efficiency, is a satisfactory result, considering that on the testing rig have friction losses.

2) Integration System as Distributed Generation: This project has delivered a complete solution of a small hydro turbine generator system for ultra low-head application. The project partners have filed the developed turbine and generating system IP with International patent application on July 21, 2015 and national patents for USA, Canada and Brazil filed in 2017-18. The integrated turbine–generating system includes design of hardware and control software with various advanced control algorithms and compliance with international standards for distributed generation, and is thus ready for commercialization.

3) Pre-commercial Demonstration at field-site has been planned: Canadian team has been working with existing ultra low-head dams (non-generation) owners to seek potential application this technology under pre-commercial demonstration arrangements.

One case is to link with local site owner to evaluate the application of this technology by providing green power to their own building of condominium development. Electrical utility Hydro One in Ontario has policy of "Net Metering". Net metering allows you to send electricity generated from Renewable Energy Technologies (RETs) to Hydro One's distribution system for a credit towards your electricity costs. Excess generation credits can be carried forward for a consecutive 12 months period to offset future electricity costs.

IV. Proposed Pre-commercial Demonstration

A. Proposed Site Description:

Fig. 29 water-power mill

Fig. 30 water-control bridge at main-channel

The project proposes the development and demonstration of three typical pre-commercial prototype size turbine generators (ie.~ 70kW,130kW and 300 kW) by retrofitting an existing private non-power generating dam. Proposed pre-commercial demonstration site is at the McArthur Island Inc. Condominium Development located on an island in the Mississippi River in Carleton Place, Ontario. The proposed project is at one side of the island old dam and canal civil works used to power the historic woollen mill activities. (Fig. 29 and Fig. 30)

B) Submersible Modular Systems:

Using three different sizes modular turbine system eliminating traditional powerhouse and will reduce civil costs. (as shown in Fig. 29 and Fig. 31) By-pass stream (main river branch) has sluices with overhead bridge will be modified into automatic crest-gates as flow control and fish passages. (Fig. 30)

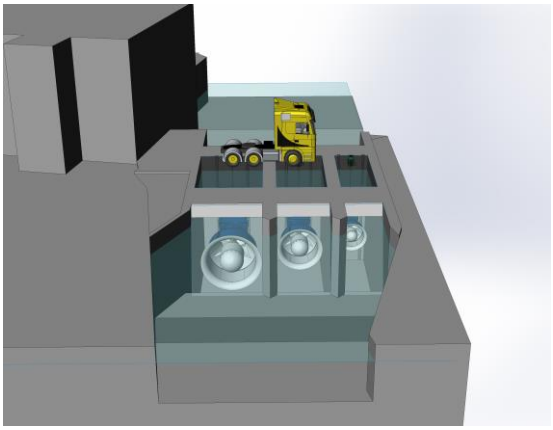


Fig. 31 Proposed McArthur Island existing dam new arrangement

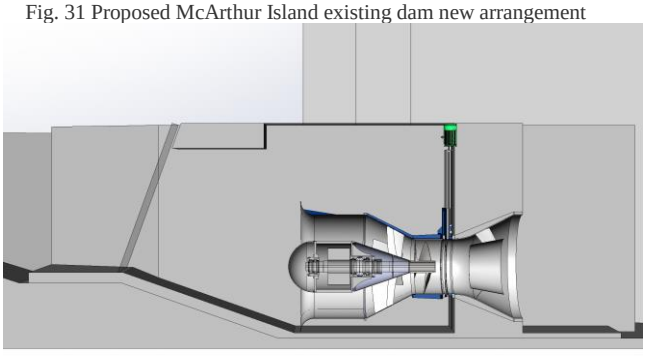


Fig. 32 Modular Ultra Low-head Turbine-generator System cross-section

The main part of submersible modular unit, which includes – turbine runner and hub, guide-vanes and intake distributor assembly, and generator bulb, can be lifted up for easy maintenance after valve-gate closed down. This valve-gate in front of the discharge cone and draft-tube will allow flexible operation to control flow during maintenance.

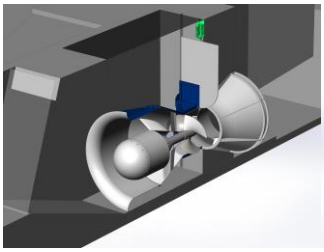


Fig. 33 Section View

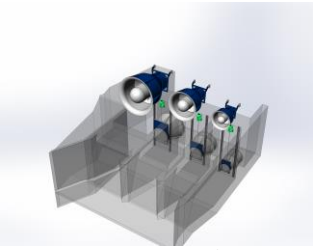


Fig. 34 Turbines Lifted

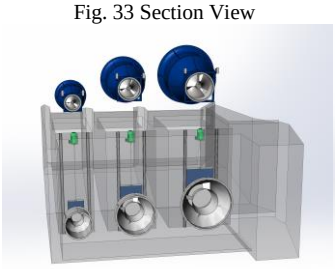


Fig. 35 Turbines Lifted –Valve gates closed

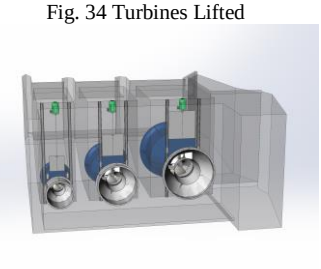


Fig. 36 Valve gates open

C) Turbines expected performance:

Based on tested data and CFD analysis, full sets of turbine-generators expected performance curves and charts are produced. Table 2 is an example for turbine runner at 1.5 m dia. and net-head 3.0 m. Power output of 300 kW.

Hnet =	9.8	ft	=	3.00	m
Dth (nom) =	59.06	in	=	1.500	m
n (nominal) =	150	rpm			

Turbine Efficiency	Flow	Turbine Shaft Power
[%]	[cms]	[kW]
80.00	7.884	186
82.38	9.174	222
83.75	10.246	252
84.14	11.017	273
83.96	11.610	287
83.15	12.264	300

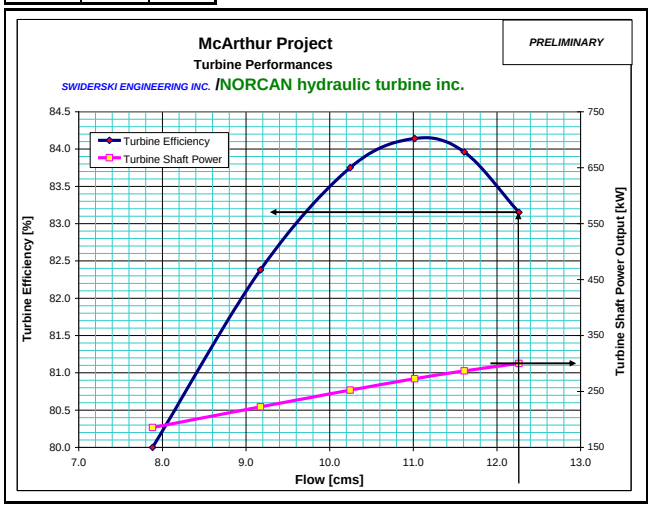


Table 2 Sample efficiency curve for net-head at 3 m and turbine runner dia. at 1.5 m

V. Recommended Application at Coastal Tidal River Mouth (Estuary)

A. Small coastal rivers with incoming tidal range less than 3.0 meters:

For existing causeway, bridges and navigation locks at mouth of the rivers with small tidal range, it is possible to add units of modular ultra low-head (ULH) turbine-generating systems. Since the variable speed generating system allowed capturing electrical power effectively at any tidal-river water level drop particularly less than 3.0 m, we suggest turbine units operation in this tidal range by the Single-effect and Ebb Generation Mode. That is using turbine valve-gates kept closed until sea level falls to sufficient inland water-head 2 to 3 meters created. Then, valve-gates are open and turbine system generating in one-way operation toward seaside until head low and turbine still generating small amount power under hydrokinetic mode.

B. Small Tidal Lagoon and Tidal Reef Application:

For concepts of small "Tidal Lagoon" or "Tidal Reef" designs, recommend adaption of ULH system for environmental-ecosystem compatible and energy production could be one of better choice.

VI. Conclusion

The innovative ultra low-head (ULH) hydro turbine-generating systems can be adapted for small tidal-range (in less than 3.0 m) operation. Further study and simulation can be made to promote the commercial application.

Acknowledgment

The joint authors' team from Canada and Brazil, as well as the proposed pre-commercial demonstration site owner McArthur Island Inc. in Ontario Canada, wishes to acknowledge AWTEC 2018 for presentation of this paper.

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