Very Low Head Turbine Deployment in Canada

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Abstract. The Very Low Head (VLH) turbine is a recent turbine technology developed in Europe for low head sites in the 1.4 - 4.2 m range. The VLH turbine is primarily targeted for installation at existing hydraulic structures to provide a low impact, low cost, yet highly efficient solution. Over 35 VLH turbines have been successfully installed in Europe and the first VLH deployment for North America is underway at Wasdell Falls in Ontario, Canada. Deployment opportunities abound in Canada with an estimated 80,000 existing structures within North America for possible low-head hydro development. There are several new considerations and challenges for the deployment of the VLH turbine technology in Canada in adapting to the hydraulic, environmental, electrical and social requirements. Several studies were completed to determine suitable approaches and design modifications to mitigate risk and confirm turbine performance. Diverse types of existing weirs and spillways pose certain hydraulic design challenges. Physical and numerical modelling of the VLH deployment alternatives provided for performance optimization. For this application, studies characterizing the influence of upstream obstacles using water tunnel model testing as well as full-scale prototype flow dynamics testing were completed. A Cold Climate Adaptation Package (CCA) was developed to allow year-round turbine operation in ice covered rivers. The CCA package facilitates turbine extraction and accommodates ice forces, frazil ice, ad-freezing and cold temperatures that are not present at the European sites. The Permanent Magnet Generator (PMG) presents some unique challenges in meeting Canadian utility interconnection requirements. Specific attention to the frequency driver control and protection requirements resulted in a driver design with greater over-voltage capability for the PMG as well as other key attributes. Environmental studies in Europe included fish friendliness testing comprised of multiple in-river live passage tests for a wide variety of fish species. Latest test results indicate fish passage survivability close to 100%. Further fish studies are planned in Canada later this year. Successful deployment must meet societal requirements to gain community acceptance and public approval. Aesthetics considerations include low noise, disguised control buildings and vigilant turbine integration into the low profile existing structures. The resulting design was selected for deployment at existing historic National Park waterway structures. The integration of all of these design elements permits the successful deployment of the VLH turbine in Canada.

Key Words: Very Low Head Turbine, Cold Climate Adaptation, Fish Friendly Turbine, Vertical Extraction, Variable Speed Turbine, Permanent Magnet Generator, Variable Frequency Drive, Historic Waterways, National Park.
1. Introduction
The Very Low Head (VLH) turbine was developed in France in 2004 with the intent to capture the energy at existing river hydraulic structures with very low water level differential from upstream to downstream (i.e. very low head). Although there are several technologies that allow the exploitation of low heads, most are uneconomic due to the high civil structure costs, large environmental impacts and low efficiencies. The VLH turbine design is applicable at sites where the head is the range of 1.4 to 4.2 m. Within this head range the VLH turbine was developed to be integrated into, or adjacent to, the civil works of existing hydraulic structures such as diversion weirs, navigation locks, drop structures, small dams and spillways. These hydraulic structures are usually found on rivers, lakes and canals for water level control, flood management or water diversion but commonly do not have hydropower facilities or provisions for hydropower installation. Deployment opportunities abound in Canada with an estimated 80,000 existing structures within North America for possible low-head hydro development. Integrating the turbines into existing structures such as these greatly minimizes the cost of the civil works, significantly diminishes environmental impacts and reduces the effort to obtain regulatory approval, design and build the facility in comparison to conventional applications.

The VLH is an integrated turbine-generator set, incorporating a Kaplan runner with eight adjustable blades, a distributor composed of 18 fixed guide-vanes separated by radial trash rack bars, a permanent magnet generator directly coupled to the runner, and an automatic trash rack cleaner mounted on the nose of the distributor. The unit is intended to be mounted in an inclined position, with the turbine between 30° and 50° from horizontal. This holistic design is compact and aimed at decreasing intake and outlet structure size by maximizing the diameter of the turbine runner. Figure 1 shows the VLH schematic.

![Figure 1: Very Low Head Turbine (VLH) Schematic (MJ2 2011, CPL 2013).](image-url)
Over thirty-five (35) VLH units have been successfully deployed across Europe since March 2007, but units have yet to be deployed in North America, mainly due to different hydraulic, environmental, electrical and societal requirements. It is well recognized that even if an otherwise worthy technical solution cannot meet all of the necessary technical and regulatory requirements it will not be successfully deployed. Hence, deployment of the VLH turbine in Canada had multiple challenges and required considerable technical research to adapt the turbine to meet North American requirements. Consequently, the first North American VLH deployment is now underway at the historic site of Wasdell Falls in Ontario, Canada.

The purpose of this article is to provide an overview of the associated technical studies and to summarize the knowledge gained from the development of VLH turbine technology for Canada. The main focus of this article is on the hydraulic modelling of VLH deployment alternatives for diverse types of existing structures present in Canada; considerations for deployment in cold climates where ice and extreme temperatures are expected; meeting Canadian utility interconnection requirements and safe fish passage testing. In addition, the societal benefits of low-head waterpower projects, including distributed generation attributes, low noise and the visual appeal of the VLH technology, are noted. These aspects have all been applied to the first VLH North American project at Wasdell Falls as noted in the article.

2. Hydraulic Modelling of the VLH Turbine

Given the diversity of existing weirs, spillways and other structures on which the VLH can be deployed, it is important to understand the effect of structure geometry on performance and hence the operation and economics of a VLH facility. These understandings are important in determining applicable sites across Canada and the USA for the deployment of low-head technology and in particular, the VLH turbine performance. A hydraulic modelling study [1] was performed at the University of Calgary with the Institute of Sustainable Energy, Environment and Economy (ISEEE) to quantify the effects of an upstream obstruction, such as a low weir or drop, on turbine performance. The two year study was funded by Natural Science and Engineering Research Council of Canada (NSERC) and Canadian Projects Limited (CPL) of Calgary and included both numeric modelling and physical modelling using a Water Tunnel as shown in Figure 2, at ISEEE’s experimental hydraulics laboratory.

![Figure 2: Water tunnel used for VLH hydraulic model testing at the University of Calgary, ISEEE experimental hydraulics laboratory [1].](image-url)
The study utilized a backward-facing step (BFS) geometry, as shown in Figure 3, upstream of the turbine as the effective shape of an upstream obstacle or drop that are commonly present at existing low-head hydraulic structures in Canada. Figure 4 shows the 1/15th scale model that was used in an open-channel water tunnel to observe the effects of the step at varying distances upstream of the turbine. Power was determined through torque and power measurements and time resolved particle image velocimetry (PIV) was obtained downstream of the backward-facing step.

Based on the measurements, a drop in efficiency of up to 7% was observed with the introduction of a BFS upstream of the turbine at a distance of half the turbine diameter. Comparable efficiencies were observed with the BFS positioned one diameter upstream. Results suggested that the significant loss in efficiency was a result of the highly non-uniform velocity profile entering the turbine. The study provided valuable input in the selection of turbine positioning within existing structures, since such a reduction in efficiency would have serious impacts on the economics of VLH deployment.

The study results were then correlated to measured efficiency curves to develop comprehensive performance characteristics. Prior to the initiation of the Wasdell Falls project, no full-scale testing of flow versus power over the expected operating range of the VLH turbine had been conducted independently of the turbine manufacturer. Although the VLH technology had been installed across Europe and satisfactory performance has been reported, Canadian stakeholders required verified detailed measurement of the turbines performance index. In collaboration with CPL, the turbine manufacturer conducted an efficiency test of a model 4000 VLH turbine installation at Terrasson, France [2]. An array of acoustic flow meters was installed at the upstream end of the concrete forebay along with water level measurements and power output was recorded by the plant’s EDF revenue meter. The EDF utility meter takes into account all electric losses of the facility to provide the true overall water-to-wire power generation.

The results of the model tests showed that the efficiency matched closely with the manufacturers’ literature values. Whereby, the measured field efficiency was higher than expected for flows below turbine median flows. For higher flows, efficiency dropped slightly below expected values but on average was only slightly lower than expected. For flows in excess of the turbine design flow the turbine efficiency decreased further as expected.

3. Cold Climate Adaptation
Deployment within the cold regions of North America, including Canada and the northern United States, required an evaluation and mitigation of a number of cold-climate issues that do not exist at the European installations, including the effects of very cold air temperatures, humidity, condensation, ice cover and frazil ice. Consequently, with support from Natural Resources Canada, CPL initiated a Cold
Climate Adaptation (CCA) study [3] to examine cold-climate issues and recommend appropriate mitigation measures to adapt the VLH turbine to North American conditions. The overall objective of the CCA study was to adapt the VLH turbine to cold climate conditions.

Under normal operation in winter months the VLH is subject to partially submerged operation where the turbine unit is completely submerged on the upstream side and only partially submerged on the downstream side. Very cold air temperatures create a significant temperature differential across the unit. The portions of the turbine in contact with the water are close to the temperature of the flowing water (~ 0°C) while the portions exposed to the atmosphere are close to the cold ambient temperature of the air (0°C to -40°C). The concerns with this temperature variation include excessive stresses, reduced tolerances and reduction in performance due to alignment of moving parts.

In some operating situations, a turbine may need to be extracted from the water for an extended period of time in an unsubmerged storage position. Such a condition would arise where flows are significantly less in winter and operators choose to remove one or more turbines from service during winter months. Turbines have to maintain operational readiness such that the seals, grease and electrical parts are protected from severe cold temperatures that are expected in some locations.

Frazil Ice occurs in turbulent, slightly supercooled (to -0.05°C) water exposed to cold atmosphere. While the water is supercooled, the frazil particles are considered active; the particles aggregate rapidly and adhere readily to any cold object in the water, including each other and any structures or objects in their vicinity. Active frazil can be a serious problem for a hydropower turbine since it quickly adheres to trash racks and turbine blades, reducing the available flow area and consequently creating significant head loss, imbalanced operation, or plugging the turbine completely.

In rivers which experience extended cold periods where ice cover forms on the water surface, increased loads from ice forces typically occur on the turbine and turbine structure. Ice forces would normally propagate in three ways; as a horizontal dynamic force due to flow, as a horizontal static force due to ice expansion and as a vertical force due to change in water levels from displacement and constriction. Ice cover creates an issue with turbine extraction, in particular for the original European system which pivots from its top mount and swings upstream from the slanted position to a horizontal position above the water surface. The ice cover upstream of the unit would obstruct this swing path and risk damaging the unit.

As part of the CCA study an Ice Study [4] was conducted by Northwest Hydraulic Consultants (nhc) which analysed Canadian river ice behaviour to characterize the ice processes, formation and dynamics as related to the VLH installation attributes. Several river sites across Canada were selected and characterized to provide a broad ice behaviour representation to assimilate. From this understanding the ice management design criteria was derived and possible solutions to address these requirements were formulated. Three types of solutions were considered; turbine and ancillary equipment design modifications, changed installation and configuration arrangement and modified operational procedures.

Based on experience with other cold-climate hydro and dam facilities a range and combination of solutions were developed and evaluated. The expected effectiveness and relative cost of each solution was assessed and specific solutions were selected for inclusion in the “Cold-Climate Adaptation (CCA) Package”. The selected CCA solutions were as follows:

3.1. Insulated Turbine Frame
Relatively simple solution which minimizes the heat transfer from the water to the air to avoid thermal ice growth on the turbine and structure underwater by providing a layer of insulation on the upper part of the downstream face of the turbine frame that would be exposed to ambient air during operation.

3.2. Linear Extraction System
By raising the unit along guides, similar to a vertical lift gate, ice cover obstruction was minimized during extraction. Installation of electric heat tracing along the guides and adjacent surfaces deter
adfreezing and obstruction by ice. The provision of steam jet ports along these areas adds more robust ice management capability to the extraction system.

3.3. Yielding Crest Gate
The European VLH design includes a small hydraulically-operated flap gate mounted on top of the turbine which is lowered to allow flushing of floating debris. For North American application a higher crest gate was selected that exceeded the expected ice cover thickness. The resulting crest gate was three times higher than the European version and used a similar hydraulically-actuated flap gate system. However, for this larger gate the hydraulic actuation system was designed to allow yielding in response to applied ice forces, thus eliminating any extraordinary ice-load transfer to the turbine, its frame or the support structure. This larger flap-gate size allows additional debris flushing capability including broken ice pans, as well as larger logs that are expected for North American deployment with greater water level control and capacity during floods.

3.4. Insulated Hood
The European VLH design included a downstream steel hood shaped like a mitred cylinder of the same diameter as the turbine runner exit. Under certain flow conditions the hood acts as a draft tube to maintain tailwater suction head on the turbine exit. Various hood shapes and orientations were studied to optimize performance and configuration requirements. To reduce effects due to ice adherence and heat transfer, the new steel hood included a resilient ice-phobic rubber cover creating an insulating air gap and a robust shield for the impinging ice and debris from the flap-gate discharge above.

3.5. Generator Bulb Heating
Electrical strip heaters were added to the inside of the generator housing. The strip heaters reduce the risk of cold interior temperatures and frost damage to the generator and turbine hub components particularly when the generator is not in operation or is extracted and not submerged.

3.6. Ice Phobic Coating
An ice-phobic coating was applied to the upstream face of turbine and flap-gate to reduce the ice adhesion to the steel of the turbine and frame. Though operations are modified during winter months to avoid frazil formation and attraction this is not always completely effective. The coating is not expected to prevent frazil accumulation on some components but eases its removal by mechanical means such as the trashrack cleaner.

3.7. Bubbler System
A pneumatic bubbler system to reduce ice formation and accumulation on the upstream face of the turbine was included in the cold-climate adaptation package as an option for more extreme conditions. Air tubing was installed integrally along the turbine frames perimeter such that this bubbler system could easily be added if required.

Several installation and configuration specifics were developed through the results of the Ice Study in addition to the above design modifications for the European VLH design. These include positioning the turbines such that upstream submergence was adequately below the bottom of the thickest expected ice cover and maintaining a reasonably steep installation angle to reduce the vertical flow velocity components that could draw frazil, ice and debris into the turbine inlet. As well, tailwater velocity and exiting flow streams were examined to create a smooth transition of flow thereby reducing the potential for water surface upwelling that would create undesirable frazil ice formation or anchor ice conditions downstream.

A number of operational considerations also resulted from the ice study for VLH turbine deployment in cold-climates. Operational considerations included shutdown of units during critical periods where significant frazil ice formation is expected, managing headpond levels to reduce
headwater changes that result in vertical ice forces and to encourage strong forebay ice cover, as well as monitoring and mechanical cleaning of rime and frazil ice. These considerations have now been included in the detailed plant operating plans and the operation manuals for cold-climate installations.

4. Control and Protection

The VLH turbine generator is a Permanent Magnet Generator (PMG) directly coupled to the turbine. However, the generator is relatively small thus restricting the number of poles it can accommodate. The low rotational speed required for efficient turbine operation under low head and high flow (high specific speed) conditions results in the generator producing power at a low frequency of about 12 Hz, which is well below the North American 60 Hz system or the typical European 50 Hz system. Since this does not allow the generator to be directly connected to the electrical grid the frequency is increased by using a Variable Frequency Converter or Drive (VFD) as they are commonly referred to.

To maximize the turbines hydraulic efficiency a double regulated system is employed. Whereas a typical Kaplan unit has both adjustable runner blades and guide vanes; the VLH employs adjustable runner blades and varies the turbine speed instead, which is afforded by the use of the VFD. This creates a simpler mechanical design and achieves high efficiencies similar to larger more complex Kaplan units. The VFD drive also allows for a wide array of power factors and precise frequency control. These are highly sought after features for electrical grid stability, all attributable to the fundamental hydraulic design of the turbine and its deployment configuration.

When typical VFD drives that control motors are used in regenerative mode (reverse output), they need to be equipped with two insulated-gate bipolar transistors (IGBT), one for the generator side to control the generator speed and one for the grid side to alternate the current from the DC bus to the AC grid frequency. Generally additional filtering is required in regenerative mode to ensure the allowable level of harmonics injected on the grid is not exceeded.

PMG generators have the advantage of not requiring external field excitation, however this presents some challenges. First, it is not possible to control the power factor by adjusting the field current; the drive, via the IGBT performs this function. Second, the voltage at the generator is a function of the speed of the turbine; therefore the voltage increases significantly during a runaway condition (i.e. when the electrical grid goes down) to levels that could damage the VFD drive. The drives must therefore be equipped with an extra contactor on the generator to isolate the generator from the drive during these voltage surge conditions. All the cabling between the generator and the drive must be rated for the maximum overvoltage corresponding to the maximum over-speed that can be reached by the turbine which is a function of the turbine hydraulics for the site. Finally, in lieu of installing large mechanical brakes on the turbine, the VDF drives are equipped with resistor load banks on the DC side to dissipate the energy and bring the turbine to a complete stop via electrical traction. It would however, not be practical to have load banks large enough to accept the full capacity of the units so the units blades are automatically closed intrinsically via an eccentric blade shaft to adequately reduce the turbines hydraulic torque forces during shutdown.

Contrary to the European sites where typically single and sometimes dual VLH turbines are installed at each site adjacent to weirs or dams with fixed crests, many Canadian sites, including the Wasdell site, are equipped with three or more units at existing dams where flows are controlled by water gates or stoplog bays. Therefore, Canadian deployment requires a more elaborate control system to establish the appropriate operational sequence for the turbines to adapt to the available flow as it varies and maintain proper and precise control of the upstream water level. This includes the ability to control the headpond water level once all units are at full capacity. Second, upon load rejection when the electrical grid is interrupted (plant trip) and the turbine overtopping flap gate capacity is not adequate then, the residual flow that once passed through the turbines must be transferred to other dam structures by automatically opening one or multiple adjacent gates whilst maintaining the headpond level within the dictated narrow allowable level fluctuation. This precise hydraulic control design is achieved by level control sequences and priority flow control systems logic with redundancies.
5. Environmental Impact

Deployment of VLH turbines in Canadian rivers, especially those well suited to low-head hydro plants are very often fish-bearing. Additional regulatory approval and permitting requirements associated with the presence of fish creates an additional strain on project economics and development timelines. Without the capacity to demonstrate the safety of fish and the preservation of their habitat VLH projects could not be successfully deployed in Canadian waters.

Consideration for minimizing the impact on the environment has been a driving factor in the design of the VLH turbine and its deployment. There are specific hydraulic design features of the VLH technology that make it particularly safe for fish populations in comparison with traditional hydro turbines. The large rotor diameter reduces turbine inlet velocity and the slow rotational speed of about 35 RPM creates conditions which are quite favorable to downstream fish passage survival.

The VLH turbine meets or exceeds the US Department of Energy five hydraulic design criteria that qualify the degree of fish friendliness of a hydro turbine including; peripheral speed, maximum pressure, rate of change of pressure, shear stress indicators and blade to discharge ring gap. However, given the importance of this critical attribute further field verification was needed.

Several downstream fish passage studies have been conducted in Europe to validate the fish-friendly turbine determination. The Fish Study [5,6,7]consists of six fish test programs to date using live fish in European rivers that have been carried out by the turbine manufacture along with VLH facility owners since April 2007. The tests were performed by injection of live fish at several turbine positions (inner, median and outer) in a full-size operating VLH turbine. Fish were then recovered downstream, remained under observation for 48 hours and condition results recorded. Smolts were first tested in April of 2007 and again in 2008, eels in December 2007 to January 2008 and again in 2010, and trout and carp tested in May and June of 2013. Fish sizes included small to large, including eels 0.7 to 1.2 m in length.

Early fish test results showed an average survival rate of over 94%. This confirmed the low impact of the VLH turbine on fish as these results are much better than conventional low-head hydro turbines. Although these exceptional test results were attained, some areas of improvement of the VLH design were identified and an objective to improve survival rates to above 97% was set.

The VLH was subsequently modified with a discharge ring having a spherical shape at the transition between the inlet cone and the discharge ring. This modification reduced “pinch-points” along the water passages through the turbine generator unit. The outcome of the next fish tests achieved excellent results with no direct mortality verifying that that deployment of VLH units in fish bearing European rivers has minimal direct impact on fish mortality for the sample fish species tested.

To advance this Fish Study even further, recent fish tests were conducted to simulate downstream Salmonids migration. These tests used Salmonids (Salmon, Sea Trout, and Rainbow Trout) to determine survival rates at varying blade positions. The results showed that although survival rates are lower for larger fish they are still excellent in comparison with conventional low-head turbines. The fish survival test results for all blade opening positions for the Salmonids ranged from 95% to 100%.

On the basis of the turbines hydraulic performance and the outstanding Fish Study survival results, the VLH is now qualified by French environmental authorities as a fish-friendly turbine.

6. Societal Impact

Social acceptability and social licence is earned through demonstrated sustainable performance and attention to stakeholders concerns and issues. To have successful deployment a hydro deployment must meet societal requirements to gain community acceptance and public approval.

The VLH’s compact hydraulic turbine and Canadian deployment design brings certain advantages in being able to integrate the turbines at existing sites with minimal impact. The aesthetic aspects addressed include low noise, disguised control buildings and attentive turbine integration with the existing low-profile hydraulic structures. The resulting design has been selected for deployment at existing historic waterway structures and other sites in a Canadian National Park. These key VLH attributes allow its proliferation throughout the country to provide abundant distributed generation in...
concert along with improved electricity supply, reliability and stability for the connected distribution grid including rural and remote communities who are most in need.

7. Conclusion
Small hydro represents a significant potential for the development of renewable energy in Canada. The VLH turbine technology allows economic, low environmental impact construction of low-head facilities by minimizing the civil works typically associated with hydropower projects. VLH technology has demonstrated its promise with the successful installation of over 35 units in Europe. With an estimated 80,000 existing structures within North America, there exists great potential for very low head hydro deployment within North America. For successful deployment of this emerging technology a knowledge base must be built around the specific application to Canadian sites. Several detailed technical studies were done engaging many government agencies, universities, consultants, stakeholders and industrial proponent’s from across Canada and Europe.

Hydraulic studies have quantified the effect of upstream obstacles on VLH performance, allowing deployment criteria to be defined for real-world application. This knowledge, combined with onsite full-scale efficiency testing performed in Europe, provided valuable insight for site selection and predicable performance to facilitate investment. The Cold Climate Adaptation Study identified the critical issues and modification solutions for deploying the VLH European design in Canada’s harsh northern climate to achieve year-round operation and confident performance. Modification to the VFD’s, controls and protection systems were done to meet North American requirements. Comprehensive VLH Fish Study work has demonstrated unprecedented fish friendliness for a variety of fish species at actual installations and garnered agency recognition as safe to operate in fish bearing rivers. The VLH’s low impact environmental and aesthetic design has achieved societal acceptance and public approval at over forty sites now, including historic waterways.

The VLH turbine technology and deployment design has realized the critical aspects from hydraulic considerations of project sites, to robust design for the harsh conditions of Canadian waters, to the protection and control of associated systems and finally to social and regulatory acceptance. Each element has a strong foundation in research and development with specific site knowledge resulting in a turbine deployment technology that presents a new renewable energy supply with commendable environmental and economic benefits.

The knowledge gained in these VLH studies has resulted in the first North American deployment of VLH technology in Canada at Wasdell Falls. The ability to integrate all aspects of VLH deployment as outlined here has created a holistic design that will rival the achievements that the VLH technology has found in Europe.

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