Abstract. The Stanley-Adamson project was developed by Trent University and is located on the Trent River in Peterborough, Ontario. It consists of three 1.35MW bulb turbines (ECOBulb type) rated at 33.3 cms and 4 meters of net head. One of three units is interconnected to the grid through a medium voltage power converter to allow variable speed operation. This paper will discuss first of project context and the objectives behind integration a power converter in the plant. The second half of the paper will discuss the challenges of operating a hydro turbine with a power converter.

1. Introduction

The Stanley-Adamson project was developed by Trent University in 2013 and is located on the Trent River in Peterborough, Ontario. It consists of three 1.35MW bulb turbines (ECOBulb type) rated at 33.3 cms each and 4 meters of net head, equipped with direct driven permanent magnet generators. One of three units is interconnected to the grid through a medium voltage frequency converter. The generator is therefore fully decoupled from the grid, allowing the turbine to operate at variable speed, more precisely from 140 RPM to 185 RPM (but range can be extended). The main objective behind this initiative conducted by Andritz Hydro Canada was to prove that a power converter can be successfully integrated into a conventional Compact Hydro power plant with minimal impact. Such a reference would greatly help to promote converter solutions in future hydro project to achieve the following benefits:

• Turbine efficiency maximization for variable head, as variable speed is virtually allowing to shift the turbine hill chart left or right, to always have access to the maximum efficiency point (whatever the net head is). However, the overcome efficiency gain has to overcome the losses due to converter efficiency, which is in the range of 98% with actual technology.

• Turbine operating range maximization, especially for Francis turbine. Improving efficiency is one thing, but improving operation time is even better. Some turbines can’t operate for some period of the year, as the net head is too far from the rated value, either above or below. Operation under these conditions would void the manufacturer warranty, and result in runner cavitation and reduced equipment life. A converter can maximize turbine generation, and is cheaper than the installation of another turbine or generator.
Meeting grid interconnection requirements for reactive power control and grid stability. Andritz’s ECOBulb generators are a very good solution for low head application in Compact Hydro. The direct drive permanent magnet generator offers a high torque density that helps to keep a very compact bulb design, which minimizes hydraulic passage dimensions. A converter allows addressing the electrical setbacks of the fixed excitation for reactive power control and power stability.

The Stanley-Adamson project did not offer substantial benefit for operation at variable speed, but was still selected as it offered several advantages:

- Relatively lower rated power for a Compact Hydro project, to help reduce the cost for the power converter
- Power output high enough so that the same converter technology can be used for the whole range of Compact Hydro projects in the future.
- Use of a permanent magnet generator, which benefits to be coupled to a converter for reactive power control and power stability
- Client is a University, therefore opened to support R&D initiatives and offer time windows for testing despite the impact on generation (although it does not have a technical department with direct interest in the project).
- Urban location (1.5 hour drive from Toronto) to help minimize site intervention costs if necessary

When the potential converter solutions were studied the project was already underway, and main electrical design fixed (bus voltage, single line diagram and single step-up transformer). A few potential solutions were studied, and the most suitable product was found to be General Electric MV7402 converter thanks to its flexibility. The converter ratings are as follow:

- 2,400 kVA
- 1,800 MW
- 4,160 V
- Air-cooling using fans for easy integration (most medium voltage converters require water cooling)

The main market for medium voltage converter (including the MV7402) is for motor drive. The use of such equipment in a generation application, especially in hydroelectricity, offered various challenges during design and commissioning, which are explained in detail in this article.
Figure 1: Plant Simplified Single Line Diagram

Figure 2: Converter Front View
2. **Operation Philosophy**

The turbine operating sequence is described in Figure 2 below. As it consists of a single (runner) regulated Kaplan, the downstream gate is first used to bring the unit to 142 rpm. From that point, the converter automatically detects that it should enter in function by sensing the turbine speed using the generator voltage frequency and starts issuing pulses to its transistors. Once the converter has established control, it issues a signal to the plan control system, which will then fully open the downstream gate. The speed set point, coming from the plant control system, is calculated based on flow and net head in order to maximize efficiency, but also respect turbine torque limitation, and generator current limitations. The converter controls the generator speed acting more or less like a brake: it draws more power (current) to lower the speed and draws less power (current) to increase its speed. In steady state, the power equation is balanced, and the speed remains steady. The blades are controlled to adjust the flow, and directly impact the unit output. For example, if the blades are open more, the torque on the turbine/generator will increase. The converter will see it through a very small speed increase, and will respond by increasing the current draw from the generator, to compensate for the higher torque. As converter suppliers have a wide experience with speed control thanks to the variable speed drive market, in addition to the vast experience of Andritz Hydro in turbine governors, the speed control is very efficient.

![Figure 2: Operation Philosophy Sequence](image)

3. **Generator Design**

During the generator design phase, special care was taken for the rotor to minimize any eddy current losses that could arise from a not perfectly sinusoidal stator current. For example, the retaining metal ring to hold the magnets was replaced by resin bands, a non-conductive material. There was also a concern that the voltage harmonics seen by the generator due to the converter would lead to eddy
currents inside the magnet which would significantly increase their temperature, possibly beyond their de-magnetization point (Curie temperature near 120 degrees C for NdFeB magnets under the most adverse conditions of a short circuit). The rotor was instrumented with thermocouples at critical points and data loggers. One of the data logger was transmitting data by wireless means, allowing temperature monitoring during operation. At multiple point during commissioning, complete data logger recording were extracted and reviewed. Also, a complete heat run of 4 hours was completed at rated load, to comply with typical hydro standards. The data analysis revealed no noticeable temperature increase. Furthermore, the generator current was monitored with a power quality meter. The generator showed very good immunity to the voltage harmonics generated by the converter, as the total harmonic distortion on current remained in the range of 3%.

4. Overspeed and Overvoltage Mitigation

One of the main challenges related to the coupling of a permanent generator with a power converter is the voltage rise during over speed (i.e. load rejection). Due to the fixed excitation, following a load rejection, the generator output voltage will remain proportional to the turbine speed, which can reach 300% of the nominal value. Due to the low inertia (ECOBulb inertia constant in the range of 0.25, significantly less than a conventional synchronous generator), the speed increase will be extremely fast. On the other end, due to economic constraints, the converter parts (transistors, capacitors) are only rated for the nominal voltage, with a 10% margin. An input circuit breaker was therefore included with the converter, to serve as the overvoltage protection. However, there was a concern that the control system and circuit breaker opening time (65ms) time may be too long, resulting in an overvoltage at the converter terminals. To confirm the speed rise rate, a special transient analysis for the worst case condition was performed. In addition, during the commissioning of the parallel units (which are physically identical), the speed was recorded at a high sampling rate during a load rejection. Finally, during the commissioning of the converter, we proceeded gradually with load rejections, starting at 20% load, and then increasing gradually up to 100%. A load rejection was triggered, and the converter DC bus voltage was recorded, to confirm that the peak value remained within acceptable range.
Another problem was the generator no-load voltage. Although the generator is rated for 4.16kV, the no load voltage is set 15% higher per the magnetic design, to give a reactive power supply tendency to the generator when directly coupled to the grid. Furthermore, the magnet strength is higher at cold temperature, which can bring the no load voltage to 125% during start-up. In consequence, if the turbine speed was increased without care up to rated speed, the converter overvoltage protection would trip before it even enters in function. As such, a technique called de-fluxing was used to control the generator terminal voltage. It consists to draw a reactive current from the generator, which will create a voltage drop across its synchronous reactance and brings its terminal voltage down, within converter limits. Consequently, during start-up, the converter rectifier (generator side) is activated at 75% of rated speed (speed then controlled with the blade angle), an operating point where hydraulic behavior was steady and for which the generator output voltage was lower than the
rated voltage, even for cold magnet conditions. From this point on, the generator output voltage was controlled by the converter. At low speed, de-fluxing wasn’t required, and the generator as operator at unity power factor or close to, to improve efficiency. As the speed was increased, the de-fluxing function was active to limit the voltage. It is represented in figure 5 below.

![Graph showing generator voltage and flux control vs speed](image)

**Figure 7: Generator Voltage and Flux control vs Speed**

5. **Step-Up Transformer Arrangement**

Based on industry standard, the station was equipped with a single step-up transformer, to which are connected the 2 parallel units and the converter, as shown Figure 1. Typically, converter requires a dedicated secondary transformer winding, ungrounded. The reason is that due to the transistor commutation in the converter active front end and inverter, the grid side neutral is not at the same potential than the motor/generator side neutral. Consequently, if all equipment neutrals are grounded using a high resistance grounding (which is the standard in Hydro industry), a high frequency current would circulate between the various neutrals. These currents could cause problem with the ground fault detection scheme, increase the equipment phase-to-ground voltage, stressing the insulation or even cause an overheating of the grounding transformer/resistor, which are not designed to sustain continuous current. The problem was solved by increasing significantly the size of the common mode inductor connected on the converter DC BUS. A full additional cubicle was required to install this inductor.
6. Grid Side Harmonic Compliance

The grid side harmonics injection compliance point at the point of common coupling, on the primary of the step up transformer, which is a good thing as the transformer helps to filter the harmonics. Standards for maximum acceptable level are generally based on the IEEE 519 standard. For Stanley-Adamson, the converter had to comply with Hydro-One requirements, which is voltage THD <3% and current THD < 6%. As the project was located in an urban area, the short circuit power was relatively high compared to the converter rating (300MVA vs 1.4MVA), harmonics were not a concern and no special filters were required. The converter supplier has performed a harmonic study during the design phase to demonstrate this.

7. General Impact on Balance of Plant

In order to obtain an unbiased and accurate measure of the converter efficiency, power quality meters SEL-735 and metering grade current and potential transformers were added in the control panel and switchgear. They also allowed monitoring closely the harmonics of voltage or current on either side of the generator during commissioning. The unit was also equipped with a conventional circuit breaker cell and synchronization equipment, so that it can be directly connected to the grid, if need be (i.e. converter maintenance, bypassing converter for better efficiency at rated head, etc.). Finally, the dimensions of such converter are far to be negligible, especially in length, and need to be considered early on in the project. The converter dimensions for Stanley-Adamson are 6m x 3m x 1m. Thanks to the fact that bulb turbine were used at Stanley-Adamson (and thus requiring very little space in the power house), space could easily be found for one converter.
8. Performance

Due to the site limited benefit for variable speed, and the difficulty to measure accurately the flow on very load head turbines, full blown efficiency test could not be performed to demonstrate efficiency gains. The output of the unit with the converter was compared with the parallel unit, and found to be about the same. The efficiency measured for the converter was between 96% and 97%. Considering that the unit was operated at low output then (power ranging from 780kW to 1,080kW due to the low head), this is considered good as the converter peak efficiency will actually occur at 1,800 kW. The results are therefore in line with manufacturer promises of 98% efficiency for larger converters.

9. Conclusion

The Stanley-Adamson project proved that there are commercially available converters to develop variable speed project with Compact Hydro turbines, and that the technical setbacks for a hydro generation application can be resolved at minimal cost if the product is flexible. Andritz Hydro is looking forward for opportunities to demonstrate further the hydraulic benefit of variable speed operation.