Water Level Based Control of a Hydro-Electric Generator

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Declaration of Sole Authorship

I, Dan Micallef, confirm that this work submitted for assessment is my own and is expressed in my own words. Any uses made within it of the works of any other author, in any form (ideas, equations, figures, texts, tables, programs), are properly acknowledged at the point of use. A list of the references used is included.

Signed: [*insert signature*]

Date: March 3, 2009

Abstract

In today's society we need to set goals toward greater energy efficiency, reduced pollution, reduced environmental impact and wiser use of natural resources. Water power is a clean renewable source of energy which we need to use in such a way as to reduce dependency on other less clean sources such as coal and natural gas. I will examine the efficient use of a hydroelectric turbine and use this information along with electricity usage patterns in Ontario to maximize the flow through the turbine during the peak demand hours of a typical day using the maximum available water storage. Any excess water available outside the demand period will be used to generate electricity and to prepare the storage area for the next demand period. I will demonstrate how the generator control system can be set up to run automatically with very little input required from an operator.

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List of Illustrations, Diagrams and Tables

1.0 INTRODUCTION

As part of the generator automation process, we needed to make a decision on how we would automatically control the generator. Full time operators would not be available to constantly monitor and adjust the generator. An alternative control system would need to be implemented.

One of the possible solutions would be a personal computer based control system. These systems can work well but the software may be proprietary and difficult for user modifications. The required hardware would need to be industrially hardened and because of this it is not as readily available as standard computer components when replacements are required. Proprietary, industrially hardened systems can also become obsolete more quickly. Implementing a programmable logic controller (PLC) was the second and preferred solution for this project. PLC's are relatively easy to program and components are readily available and easy to change. PLC's are inherently industrially hardened and are well suited to applications of this kind.

Research was completed to determine which PLC system would work well for the project. It was decided an Allen Bradley CompactLogix system would be suitable for the task. Allen Bradley PLC's are the most widely used PLC system in North America and are therefore well supported and the CompactLogix system was reasonably priced for the generator size and budget constraints of the project.

2.0 METHODOLOGY AND RESULTS

2.1 Calculations for Available Water Storage

One of the steps necessary for the generator automation process was a determination of the volume of water storage available. The system is essentially a run of the river watershed, but because of the available fluctuation in the water level some storage is possible. From the available water storage and the discharge rate of the turbine, I calculated the length of time the generator could generate at a certain power output.

To determine the available storage, a map of the area available for water storage was imported into AutoCAD at full scale. The high water boundary was traced electronically allowing AutoCAD to calculate the area. The total area is 781,190m^2. The maximum range of fluctuation allowable for the level of the water is 0.254 metres between the lowest normal level and the highest level before spilling, which provides a usable volume of water of 198,422m^3.

$$\text{Volume} = \text{area x (highest level – lowest level)}$$

$$= 781{,}190m^2 \text{ x } .254m$$

$$= 198{,}422m^3$$

If the shoreline had a vertical slope along its entire length this would be the volume of water available. In actual fact the slope is not vertical. The exact slope of the shoreline for the length of the river was not surveyed for this project as it would have been very costly, time consuming and have very little impact on the final results. Therefore, I assumed an approximate slope of 14.3° giving the following:

Slope = 14.3°

Length of shoreline = 25,835m

Area = ½ base x height = $0.127 m^2$

Volume = 3,281 m^3

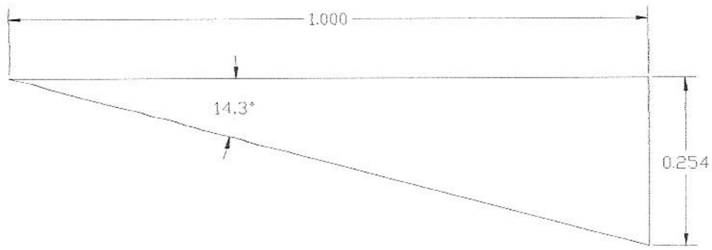

Figure 1: Shoreline Calculation

This volume was subtracted from the initial volume calculation to give a total available water storage of 195,141 m^3.

2.2 Generator Flow and Efficiency

The formula for calculating the flow through the turbine is:

$Q = P/(H \times W \times 7.233 \times E)$[1]

Where:

Q = Discharge (m^3)

P = Power (watts)

H = Net Head (m)

E = Efficiency (approx. 85% for a Francis Reaction Turbine)

W = Weight of 1 m^3 of water (1000 kg)

7.233 represents a system of constants for unit conversions. (units = $\frac{W \cdot S}{m \cdot kg}$)

[1] Adapted from Robert W. Angus, (1930). Hydraulics for Engineers. Pitman, p 159 (converted to metric)

Since we already knew the power output of the generator and the head, we used the above equation to give the flow through the turbine.

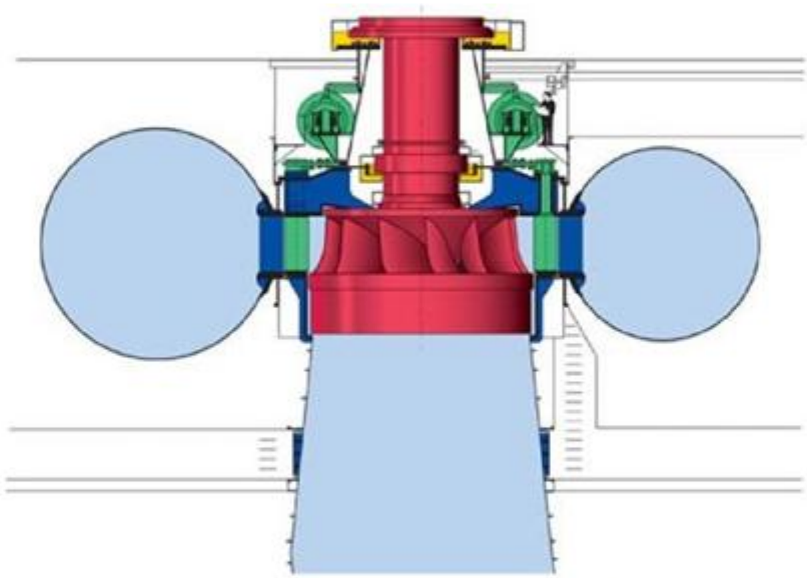

Figure 2: Cross Section of a Francis Turbine[2]

$$Q = 700{,}000\ \text{W}/(7\text{m} \times 1000\ \text{kg/m}^3 \times 7.233\ \frac{\text{W}\cdot\text{s}}{\text{m}\cdot\text{kg}} \times 85\%)$$

$$Q = 16.26\ \text{m}^3/\text{s}$$

$$16.26\ \text{m}^3/\text{s} \times 3600\ \text{s/h} = 58{,}536\ \text{m}^3/\text{h}$$

Dividing the storage volume available (195,141 m^3) by the volume needed for 700kW we get an actual runtime of:

$$195{,}141\text{m}^3/58{,}536\ \text{m}^3/\text{h} = 3.4\ \text{hours}$$

The chart in Figure 3 is the result of a test on the generator at various gate openings (as

[2] Voith Siemens Hydro Power Generation [modified 15 Dec 2008 10:40:44 GMT; cited 18 Feb 2009]. Available from: http://www.voithsiemens.de/vs_e_prfmc_pwrful_prdcts_turbines_francis.htm

shown on the graduations on the governor).

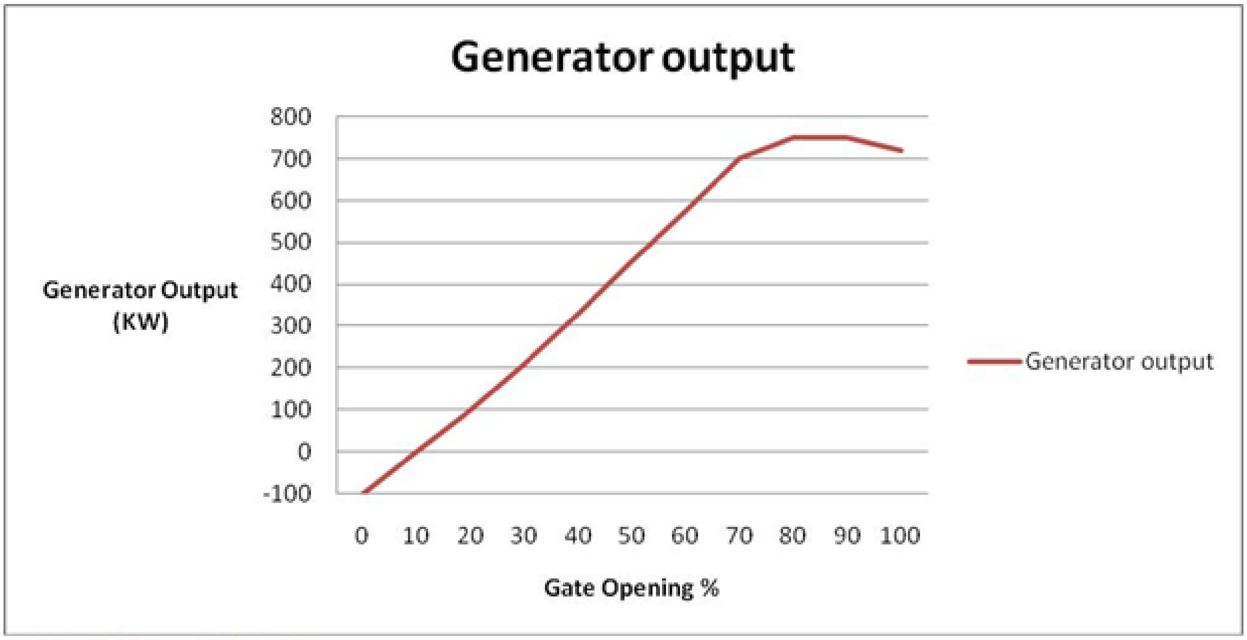

Figure 3: Generator Output

2.3 PLC Implementation

The first step was to determine if and how the PLC would interface with the existing manual control system and if additional components would be necessary to allow the various control devices to be electrically operated. The governor is designed to maintain the generator speed at a constant 100 rpm which is electrically equivalent to 60Hz (see speed calculations in Appendix B) as well as matching the generated output to the connected load when the distribution system is ‘off the grid’ (not connected to the Hydro One distribution/ transmission system) and the total load is less than the generators maximum output. This requires a different operating mode and will not be discussed in this report.

Once the generator is synchronized to the province wide grid, the governor is only capable of controlling the output power and not the speed of the turbine and can therefore be adjusted from minimum to maximum water flow.

Figure 4: Governor

There are two electrically controllable devices on the governor for the existing manual control system, one is referred to as a ‘speeder motor’ and the other is a ‘shut down solenoid’. The speeder motor is a bi-directional DC motor on the governor used to adjust the gates. The shut down solenoid is a device used to close the gates relatively quickly, primarily during an emergency stop. The shut down solenoid needs to be energized to allow the gates to be opened.

Another device required to be controlled electrically is the main generator breaker. The automation system needs to be able to both close and open the breaker. The breaker also needs to have electrical contacts to indicate its ‘opened’ and ‘closed’ positions. Although synchronizing the generator to the grid could be programmed in the PLC, we decided to use a dedicated synchronizing device. The synchronizer matches the frequency, voltage and phase angle of the generator to that of the grid and closes the generator breaker when these quantities are within preset tolerances.

Two additional electrical devices are required on the governor to enhance the control system. One is a speeder motor limit switch, which will interrupt electrical supply to the speeder motor when it is at the end of its travel. The limit system will prevent the motor from being burned out by the control system. The other device is a four position switch, which is used to determine the various critical locations of the wicket gates. These positions are ‘gates fully closed’, ‘gates at speed no load’, ‘gates at 70%’ (to indicate when the gates are at the turbine’s maximum efficiency), and ‘gates fully open’.

The most critical information the system requires to be successful is an accurate and constant indication of the water level. A stainless steel pressure transducer was mounted in the main head pond upstream of the turbine. A low range transducer (two pounds per square inch) was used to allow good water level resolution with a range of 1.4 meters.

The river system supplying the water for the turbine is relatively shallow and therefore has a lot of weeds. These weeds along with other debris are prevented from entering the turbine by a set of grates called trash racks. The main drawback to the trash racks is they eventually become plugged and restrict the water from passing through to the turbine. If too much water is restricted, a special set of wood bearings (lignum vitae) will be exposed to air which will cause serious damage to the bearings, and since the replacement cost is well over $10,000, they must be prevented from being exposed. This means the PLC needs to monitor the water level between the turbine and the trash racks as well. We needed to build into the automation system the ability to reduce the flow or completely shut the generator down if these adverse conditions occur.

The other main component that required control is the excitation system, which converts AC current to DC current to magnetize the poles of the rotor. The exciter output power controls the strength of the magnetic field which in turn controls the output voltage of the generator. The existing exciter did not come equipped with a voltage regulator therefore we decided to do the regulation with the PLC.

One of the capabilities we wanted to design into the system was the ability to run the generator without the PLC. This would allow control of the generator in a completely manual mode and would allow production to continue if the PLC or any of its auxiliary equipment failed.

2.4 PLC Programming

The control system was set up to run the generator in several different modes of operation. A four position control switch was installed on the main panel board. The positions are ‘OFF’, ‘MANUAL’, ‘LOCAL AUTOMATIC’ and ‘REMOTE’. Both ‘LOCAL AUTOMATIC’ and ‘REMOTE’ allow the PLC to have control of the generator. The ‘LOCAL AUTOMATIC’ position allows generator control parameters to be entered on a Human Machine Interface (HMI) mounted on the main generator panel board and disables remote control. The ‘REMOTE’ position allows the generator to be controlled from a remotely located control station.

2.5 Main PLC Sections

For organization the PLC programming was divided into five major sections. All five sections were programmed with the most common PLC programming language; ladder logic. Although some components could be better handled using alternate programming languages such as structured text or function block diagram, ladder logic was chosen because all tasks could be completed with it and the additional languages were not included in the basic programming software package. This also would have added unnecessary costs.

2.6 Starting/Stopping

When the control switch is in ‘LOCAL AUTOMATIC’ or ‘REMOTE’, the PLC will have control of the generator either based on the head water level or on a kilowatt set point. Both control modes can trigger a start or stop request. Once a start request is received, one of the PLC’s outputs is set to ‘ON’. This output is connected to an interposing relay. All outputs are connected to interposing relays as the PLC outputs do not have the capacity to deliver the larger currents the field devices require. This relay in turn triggers a

relay to energize the shut down solenoid which will allow the governor to open the gates. The PLC also initiates a timed output to partially raise the speeder motor which will cause the gates to open and allow the water to turn the turbine. The PLC monitors the speed of the machine (there is enough residual magnetism in the rotor for the multi function meter to indicate the frequency) and when it is at a certain point (approximately ¾ of full speed) the PLC turns the excitation system on. (See appendix B for speed calculations.)
Once the exciter is supplying power for the rotating magnetic field, the PLC hands control over to the automatic synchronizer. There is an input on the PLC to indicate when the breaker is closed. When the PLC sees this input turned on it will issue a momentary raise command to the speeder motor and will then hand control back over to the 'Water Level' control or 'Kilowatt Set Point' control.

2.7 Water Level Control Mode

The PLC will constantly monitor the water level and compare it to a maximum and a minimum water level set point entered by the operator. The water level is also recorded every five minutes and the new water level is compared to the last recorded level. This will allow the PLC to know if the water is rising, falling or not changing. If the generator is "Off Line" or not generating and the demand for electricity is low the system will not allow the generator to start until the water reaches a maximum level. If the water does reach this level the generator is put 'On Line' so that water in excess of the storage capacity is used to generate electricity rather than allowed to go over the waste weir. The system will maintain a level just slightly below this maximum level. The PLC will assign a kilowatt value and will control the gates (by raising or lowering the speeder motor) to maintain the kilowatt assignment to within a certain dead band (approximately plus or minus 25 kW). The PLC continues to monitor the water level and if the level continues to rise, a higher kilowatt value is assigned to the generator. This process continues until the water level stabilizes at or near its highest level before spilling. This allows maximum use of the water storage for when the demand for electricity is higher. If the level starts to fall, the kilowatt assignment is reduced until it reaches a minimum kilowatt set point. If this minimum is reached and the water continues to fall the PLC will take the generator 'off line'. If the generator output is allowed to go lower than the minimum, water is being consumed only to overcome friction in the machine and is ultimately being wasted.

Within the water level control section of the programming is a sub program to monitor the level of the water on the turbine side of the trash racks. The level on this side of the trash racks can fall about 2.5 meters before the risk of exposing the lignum vitae bearings. A second water level transducer was placed in the main penstock near the turbine. The PLC takes readings from the two transducers and calculates the difference. The transducer near the turbine looses a little pressure because of the higher flows at the turbine and therefore requires compensation for this error. As the water behind the trash racks begins to fall to about one meter below the head level, the kilowatt set point is reduced a little. If the level continues to fall to two meters difference and the generator is at its minimum set point, a stop command is issued by the PLC and an alarm is triggered. If the generator fails to shut down because of this sub program, then a back up low pressure switch shuts the generator down. The trash rack level monitoring takes place for all modes of operation.

2.8 Kilowatt Control Mode

Through historical records and the Independent Electricity System Operator (IESO) web site, I determined that the majority of daily peak demand periods occur between about 17:30hrs and 19:30hrs with a secondary peak occurring between about 08:00hrs and 10:00hrs. When the demand for electricity is high the price for power also goes up. To maximize both kilowatt production and revenues the PLC calculates and allocates maximum available water during the primary peak period. If water is still available, the generator will be run during the morning (secondary) peak. Water not used during these two peak periods will be allocated first to the mid day ‘on peak’ period (10:00hrs to 17:30hrs) and secondly to the remainder of the ‘on peak’ period (07:00hrs – 08:00hrs and 19:30hrs – 23:00hrs) and thirdly to the ‘off peak’ period. This gives a total of five periods to prioritize the water.

At the beginning of each week the hydro plant operator would arrange for a certain amount of water flow into the storage area by removing stop logs from the upstream dam. The amount of water varies according to time of year, precipitation, and a set of annual water level curves. The actual water flow into the system dictates which control mode the generator is set to run in. If flows are high (equal to or greater than the maximum capacity) the generator is set to run at its maximum in kilowatt control mode.

If the flow is less than the turbine capacity, then the actual flow value is entered into the PLC by the operator and the PLC will determine when the generator should run.

The table (Figure 5) will be used by the PLC (through ladder logic programming) to prioritize and run the generator according to the available water flow. The table was developed using the formulas for flow and power in the Generator Flow and Efficiency section.

Priority	Time	Demand *(kW)*	Hours	*Energy (kWh)*	Water Flow (m^3/s)	Accumulated Water Flow ($^{m3}/^{s}$)	Water Volume (m3)	Accumulated Water Volume (m3)
1	17:30 - 19:30	700	2	1,400	1.36	1.36	117,072	117,072
2	08:00 - 10:00	700	2	1,400	1.36	2.71	117,072	234,144
3	10:00 - 17:30	700	7.5	5,250	5.08	7.79	439,020	673,164
4	07:00 - 08:00, 19:30 - 23:00	700	4.5	3 , 150	3.05	10.84	263 , 412	936 , 576
5	23:00 - 07:00	700	8	5,600	5.42	13.21	468,288	1,141,452
	Totals		24	16,800	16.26		1,404,864	

Figure 5: Generator Runtime Priority

The PLC will determine which of the various time periods can be run according to the accumulated water flow. The water flow represents the amount of water needed in a full 24 hour period for the generator to run at maximum for the allotted time slot. These values assume the available storage is completely consumed and the amount of water flowing in will replenish the storage area when the generator is not running within the same 24 hour period. The PLC also calculates the equivalent kWh and if for any reason the generator does not produce the projected kWh for the time slot, the PLC increases the assigned kW in the next sequential time slot. The PLC also recalculates the chart if the operator changes the maximum output of the machine (there are times when reducing the output will prevent weed build up at the trash racks).

2.9 Voltage/VAr Control

The PLC will also be required to control the generator voltage when ‘off line’ or when running separated from the grid. When the generator is put ‘on line’, the control is automatically changed to volt-amps reactive (VAr) control. VAr is a measurement of the reactive power in an alternating current (ac) electrical system. The PLC will continuously monitor the generator VArs and will make adjustments to the exciter to maintain the VAr output of the generator to within pre-determined limits.

2.10 Analog Input Scaling

The other main section within the PLC is the conversion of the analog inputs into actual scaled units. Since this application uses a multi-function meter, the only scaling necessary will be for the water level transducers. The PLC will calculate the real time units using a straight line equation with slope and intercept.

Output = slope x input + intercept

The input transducers are standard 4 – 20 mA pressure units. The transducer for the head pond will have a range of 0 – 2 pounds. Since 0.71 metres of water is equal to one pound per square inch (psi) therefore the two pound transducer will allow a 1.42m range for water level monitoring. Records from the last 15 years have shown that the highest level the water has reached is approximately 82.50m above sea level. We can use this level as our maximum reading. For the PLC to be able to read the maximum historical level we should place the transducer at 81.08m (82.50m – 1.42m). For the calculation of the slope the difference between the maximum level and the minimum level (1.42m) is divided by the difference between the maximum and minimum current (20mA – 4 mA = 16mA) :

$$\text{Slope} = \frac{\Delta Y}{\Delta X} = \frac{(82.50 - 81.08)}{(20 - 4)} = .08875 \text{ m/mA A}$$

Substituting one set of coordinates into the equation gives:

82.50 = .08875 x 20 + intercept

82.50 – 1.775 = intercept

Intercept = 80.725

Giving:

Output = 0.8875m/mA x input(mA) + 80.725m

The trash rack level transducer is similar except that it is a 0 to 5 pound pressure transducer; this transducer is required to be mounted closer to the turbine at a level well below the 1.42m range of the 0 - 2 psi transducer. This transducer gives a range of 3.556m and will be mounted 3.5m below the maximum level (82.50 – 3.50m = 79.00m) The equation for the straight line for this transducer using the same method as for above is (see Appendix C):

Output = 0.22225 m/mA x input(mA) + 78.055m

Since all other analog values are obtained through the multifunction power meter, no other scaling is required. The power meter scales its values internally and communicates these scaled results to the PLC.

3.0 CONCLUSIONS

The automation system was commissioned at the beginning of August. Both the KW control mode of operation and the water level control mode were tested extensively from the middle of August to the end of November. The generator was set to run in KW control mode during the weekdays and was switched to water level control on weekends. The main way to test the benefits of the new system was to monitor the revenues for the period. During the testing period the kW production was recorded hourly. This information was merged with the hourly pricing information available from the IESO website. We saw an approximate 20% increase in revenues as compared to how the generator would have been run without automation.

To test the water level control mode, we recorded the actual water level every five minutes while the controller was in water level mode. We graphed and analyzed the data to verify water was recovering from its lower levels reasonable quickly and was maintaining a consistent level once its set point had been reached. We were also watching for periods when water was being wasted (flowing over the waste weir) by setting a level control point at 1cm below the waste weir. If the level went 2cm over the set point water was being wasted. We also compared the water level to the kw production so we would know when the control system was running the generator. From the data, we observed that the control system was able to maintain the water level within 5% of the set point 90% of the time and within 10% of the set point 99% of the time. The water never dropped below the minimum set point and only once went over the waste weir (by 2cm) and this was due to the abnormal amount of rain that occurred through the night.

4.0 RECOMMENDATIONS

There are two recommendations I would make regarding this PLC based control system. The first is that I would suggest the control mode be automatically changed to water level mode through the off peak period. The reason for this suggestion is to allow better recovery of the water storage in preparation for the next on peak period. The second recommendation I would make is that this design be extended to all five of the other run of the river hydro plants. With minor modifications the same type of components and programming could be implemented at each of the plants and the financial benefits could fairly quickly cover the capital costs. The simple payback period (disregarding interest and full time operator costs) could be as little as two years.

References

Angus, Robert W. (1930). Hydraulics for Engineers. Pitman, p 159.

Voith Siemens Hydro Power Generation [modified 15 Dec 2008 10:40:44 GMT; cited 18 Feb 2009]. Available from: www.voithsiemens.de/vs_e_prfmc_pwrful_prdcts_turbines_francis.htm

Glossary of Terms

AC - Alternating current - current flows in one direction for half a cycle than reverses for the other half cycle

DC - Direct current - current flowing in one direction only

Dead band - a point above or below the set point where the control system is not required to make adjustments

Demand - a measurement of the maximum power used or produced within a pre-determined time interval

Exciter - a device which converts AC current into variable output DC current to supply power to the electromagnetic poles of the rotor

Frequency - a measurement of the number of cycles in a second in an alternating current (AC) electrical system

kVA - a measurement of the apparent power in an alternating current (AC) electrical system. It is the vector sum of the real power and the reactive power.

kVAr - a measurement of the reactive power in an alternating current (AC) electrical system

kW - a measurement of the real power in an alternating current (AC) electrical system

kWh - the total real power produced or consumed per hour

Off Line - the generator is not connected to the distribution system, the main breaker is open

Off Peek - the time in a day when demand for electricity is typically low. In Ontario it is Monday to Friday from 23:00hrs to 07:00hrs and weekends

On Line - the generator is connected to the distribution system, the main breaker is closed

On Peek - a set time within a day when demand for electricity is typically at its highest. In Ontario it is Monday to Friday 07:00hrs to 23:00hrs

Phase angle - the difference, measured in degrees, between the sine wave of the generator and the sine wave of the grid as a fraction of a complete cycle of the grid (1/60th of a second)

PLC - Programmable logic controller - a digital industrial type modular computer designed for multiple input and output arrangements.

Run of the river generator - generator uses natural flows in a river to generate electricity, typically there is no water storage available.

Shut down solenoid - a device on the governor designed to close the wicket gates quickly, usually during an emergency trip

Speed Governor - "governor" controls the speed of the generator by regulating the amount of water passing through the turbine

Speeder Motor - an electric DC reference setting motor on a speed governor

Trash racks - a barrier to prevent large debris from entering the turbine while still allowing water through.

Trip - action to cause the main generator breaker to open.

Voltage - a measurement of the pressure available to push current between two points in an electrical system

Waste weir - a water control dam designed to allow water to pass if the level of the water is greater than the top surface

Wicket gates - gates within the turbine to control the amount of water passing through

Appendix A: PLC Inputs/Outputs

The following inputs and outputs will be required:

<u>Inputs - Digital</u>

Mode Switch	-Manual -Local Automatic -Remote
Governor Position	-Closed (0 % Gate Opening) -Speed-No-Load (Approximately 12%) -70% Gate Opening -Fully Open (100 % Gate Opening)
Breaker Status	
Lockout Relay status	
Trash rack level low	

<u>Inputs - Analog</u>

Water Level	
Trash Rack Level	
Generator Quantities	-Kilowatt Production* -Voltage* -Current* -Vars* -Frequency*

<u>Outputs</u>

Start Generator
Stop Generator
Raise Governor
Lower Governor
Raise Voltage (or Vars)
Lower Voltage (or Vars)

*As an alternative to multiple transducers a single multi-meter with communications will be used.

Appendix B: Generator Speed Calculations

To determine the actual speed of the turbine, the following formula is used:

Speed (RPM) = Frequency (cycles per second or Hz) 60(S/M)
(No. of poles)/2

Speed (RPM) = 60s x 60Hz x 2 No. of Poles

RPM = revolutions/ minute

s/m = sec/ min For our generator:

Number of poles = 72

Speed (RPM) = 60s x 60Hz x 2 72

= 100RPM

Therefore our generator speed is 100RPM.

Appendix C: Scaling Calculations for Trash Rack Level Transducer

3.556m and will be mounted 3.5m below the maximum level (82.50 – 3.50m = 79.00m)

The equation for the straight line for this transducer using the same method as for above is:

Output = 0.22225 m/mA x input(mA) + 78.055m

(20mA – 4 mA = 16mA) :

$$\text{Slope} = \frac{\Delta Y}{\Delta X} = \frac{(82.50 - 79.00)}{(20 - 4)} = 0.22225 \text{ m/mA}$$

Substituting one set of coordinates into the equation gives:

82.50 = 0.22225 x 20 + intercept
82.50 – 4.445 = intercept
Intercept = 78.055

Giving:

Output = 0.22225 m/mA x input(mA) + 78.055m