Niagara Pump Generating Station
Proven Functionality Unique in Canada

Maricic Tihomir, Haber Don, Pejovic Stanislav[1]

Abstract–Hydropower plant design, construction and operation are complex tasks. A large number of details must be carefully considered, coordinated and executed, in order that the projects achieve safe and economical operation. The Sir Adam Beck Pump Generating Station (PGS) is a six unit station commissioned in 1957. It has a production capacity of 174 MW and also provides regulation of the Sir Adam Beck 1 and 2 forebay level and crossover water level control. Originally constructed by the English Electric Company, this plant with its Deriaz units is unique within Canada and one of very few in the world. Ontario Power Generation (OPG) maintains and operates generating station (PGS) located in Niagara Falls. OPG's generating portfolio also includes a considerable nuclear component not amenable to rapid load changes. There are occasions when the load on the system falls below the available supply from these nuclear assets. OPG also has significant intertie capability with neighbouring utilities and sale of this energy is one of the methods by which this imbalance can be managed. Operating the PGS in the pump mode to supply additional load on the system is another means of managing the load/base generation mismatch. There are times when market conditions exist where these options are limited or not sufficient to balance the system load. At these times other more costly control measures must be implemented.

Keywords: Canada, Electricity, Energy Maintenance, Ontario, Rehabilitation, Smart Generation," "Smart Grid," Society, Storage.

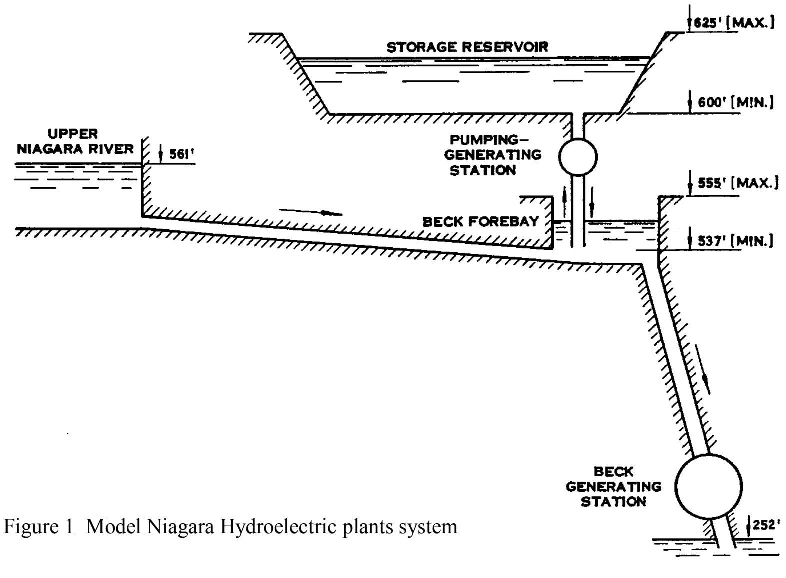

Figure 1 Model Niagara Hydroelectric plants system

1 *NIAGARA HYDROELECTRIC SYSTEM*

Ontario Power Generation (OPG) maintains and operates a unique pump generating station (PGS) in Canada located in Niagara Falls (Figure 1, Figure 2, Figure 3). The water for the OPG facilities is supplied by an open cut canal that goes through the City of Niagara Falls and two tunnels that are beneath the city. These conveyances come together at a "crossover" at which the water for PGS is withdrawn or discharged. The water elevation of the crossover is a critical component in ensuring the appropriate amount of water is diverted from the river flow, and the ability of the PGS to rapidly pump water from this crossover point is fundamental to holding this elevation at the correct level of 165 m (541 ft). Average daily flow to achieve this goal in 2008 is shown in diagram, Figure 4; corresponding turbine head and electricity production presented in Figure 5. In 2008 the PGS delivered 90 GWh but pumped and generated 2 E+12 m^3 of water. This water in addition increased the production generating additional energy at 89 m (293 ft) head flowing through Sir Adam Beck 1 & 2, resulting in an increase of energy production for 1.2 TWh.

Another function of Niagara PGS is to help control the amount of water diverted from Niagara Falls. A treaty between Canada and the USA specifies that the first components of total flow down the river must be used for domestic purposes, followed by water sent over the falls for scenic purposes and the remainder is split equally between the two countries for power generation.

Other benefits of note are that the water used to "fuel" the PGS is typically pumped into the head pond during periods of lower power cost, generally during the night. It is then used for generation during peak hours, a higher value time period. This water is discharged into the crossover, which is also the head pond for the two conventional generating stations, operating at 89 m (293 ft) head. The generation from all six PGS units can supply as much as 174 MW directly to the electrical grid, while their discharge increases the head pond elevation at Sir Adam Beck 1 & 2, resulting in an increase of ~90 MW generator output to finally provides approximately 300 MW of additional generation at those stations.

2 *ONTARIO PUMPED STORAGES TO PROTECT ENVIRONMENT*

The OPG's generating portfolio also includes a considerable nuclear component not amenable to load changes therefore mostly operating at constant power output. There are occasions when the load on the system

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falls below the available supply from these nuclear assets. OPG also has significant intertie capability with neighbouring utilities, and sale of this energy is one of the methods by which this imbalance can be managed. Operating the PGS in the pump mode to supply additional load to the system is another means of managing the load/base generation mismatch. There are times when market conditions exist where these options are limited or not sufficient to balance the system load. At these times other more costly control measures must be implemented.

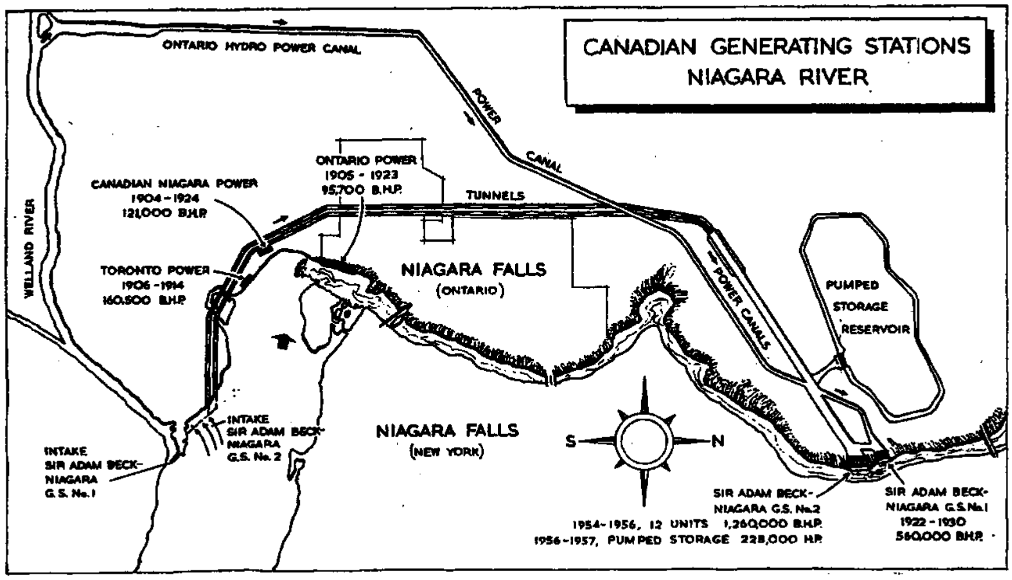

Figure 2 Canadian Niagara Falls hydroelectric plants and hydraulic waterways layout circa 1950

The Ontario generation mix includes a small but growing amount (~900MW) of non-dispatchable renewable generation sources. There are aggressive plans to expand this component of the Ontario generating mix and the PGS provides an easily controlled load source for this condition. [1], [2], [3]

Figure 3 View of Niagara waterways

3 SUPPLY MIX

Since winds tend to blow at times when electricity is needed the least, wind can provide only a small fraction of its installed capacity to meet the required electricity demand.. Solar power is also a popular concept, but it is expensive and best suited for arid locations nearer to the earth's equator. Since it is available less than a third of the time, it is also only capable of supplying a small part of future requirements. Consequently when wind or solar generating equipment is installed, it must be complemented by other sources Conservation is also a valid means to improve the supply/load equation. However the effects of conservation together with solar and wind generation will not solve the near term electricity generation shortfall; they cannot replace aging coal-fired and nuclear base-load generation over the coming years. Given justified concern over air pollution and CO_2 emissions there are three realistic alternatives, namely more gas-fuelled generation, biomass fuelled generation and increased nuclear power production. However to minimize the size of these new facilities units and associated costs, the best solution is to combine them with pumped storage plants in order to proportionally curtail the risk and amount of nuclear waste.

Natural gas has fewer negative environmental impacts when compared to coal, but it still cannot be considered a clean energy source. Current policies and proposals lean more heavily on gas, a diminishing resource whose cost and reliability is questionable. Biomass fuelled generation is a new concept being considered to fuel existing coal fired plants using renewable resources. Although the amount of biomass available to generate electricity is considerable, it is a limited amount which will not increase in availability over time. Pump-generating storage plants are again part of the solution.

Nuclear power production combined with pumped-storage plants is relatively non-polluting, has controllable well defined operating costs, and almost "unlimited fuel sources." Environmentalists should consider supporting nuclear and storage power plants as a possible realistic alternative to greenhouse gas problems caused by burning fossil fuels.

Ontario requires a variety of approaches, including wind solar and biomass power together with economically viable conservation initiatives. Moreover, there is a need for some new gas-fuelled generation for peak load purposes. But unless nuclear and pump storage form the central part of the generating capacity for base and peak loads, the deficit in energy generation linked to cleaner

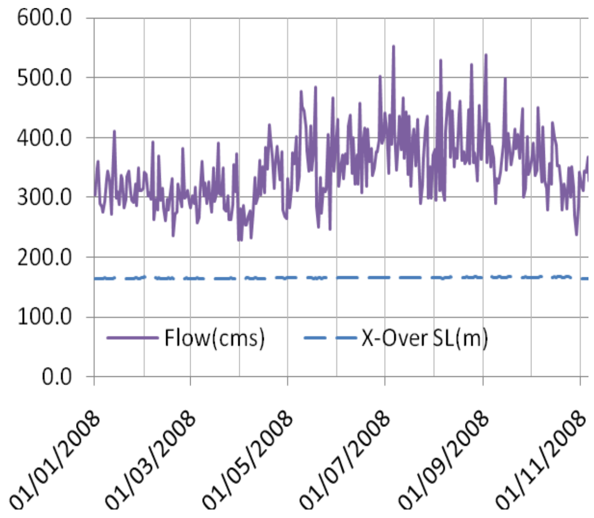

Figure 4 Average daily water elevation above sea level in of the crossover and average. flow during generating operations only for the day (generating hours only)

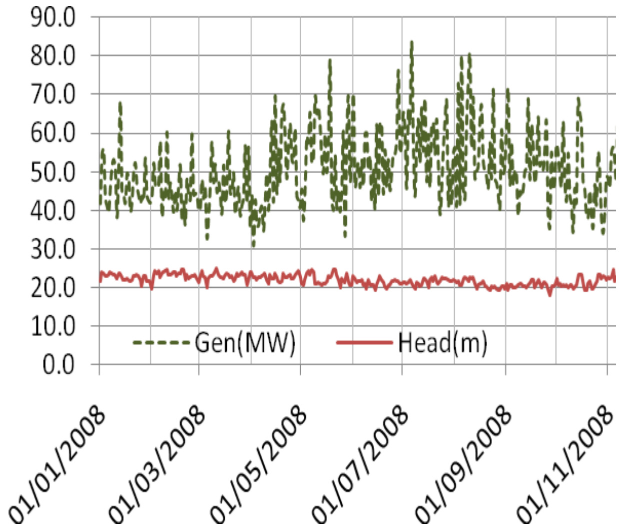

Figure 5 Average daily head and average electricity production during generating operations only.

energy is unlikely to be solved. This has already been stated publicly; however the contributions available from pumped-storage power plants should be highlighted as the most economically viable scheme for generating peak and storage energy. [7]

4 OPTIMISATION OF THE ELECTRICAL SYSTEM

The technology of hydroelectric turbine design results in a hydroelectric units' maximum efficiency corresponding to a lower output than the rated capacity, or maximum output. If the system is optimized to produce electricity at this maximum efficiency point the difference between the highest efficiency and maximum (rated) power (approximately 10% difference) of all units in operation is a spinning reserve that stabilizes the system (market), not only reducing the level and variability of production costs, but also protecting the system as a whole from possible disturbances. Two of the most important goals achieved are: (i) free spinning reserve and (ii) best price of electricity (lowest $/kWh). Such an environment would help the entire economy to flourish. All parties involved in the marketplace, including researchers and designers, are encouraged to investigate the feasibility of using this spinning reserve as an augmentation to the strategies currently employed. The negative effect of an undefined market and investment uncertainty must be averted by clarifying the financial landscape surrounding power generation in the province or erratic prices will continue and effective control of the whole system may be in jeopardy. [4], [6]

5 DERIAZ PUMP TURBINE OPTIMIZATION

•Deriaz pump turbine with its mechanical complexity, as shown in Figure 6 , should be compared with variable speed machines and the better solution selected for further innovation and improvement of existing units.

New variable speed hydraulic machines operate continuously at best efficiency and with highly reduced vibration, decreasing operating and maintenance costs by even 50% or more if appropriately managed. The overall efficiency of a plant can be as high as 85%; that is as much as 85% of the electrical energy that is pumped into the storage at off peak hours is available again as generated energy from the plant, during peak value hours.

6 APPENDIX

6.1 The Sir Adam Beck-Niagara Reversible Pump-Turbines,[1], [2], [3]

A cross section of Deriaz double regulated pump turbines, installed at the Sir Adam Beck-Niagara Pumping/Generating Station of Ontario Power Generation is illustrated in Figure 6 . The machine can be shut down without using a conventional gate apparatus or inlet valve. The omission of this equipment allows considerable simplification and reduction in the size of the machine with a consequent reduction in cost of the power-house structure. The torque required to rotate the runner at full operating speed with the blades shut, as shown in Figure 8, is reduced considerably. Thus, when starting as a pump, the synchronous motor can be started directly on the line with the runner submerged well below the tailwater level. Should operation as a synchronous condenser be required, no tailwater depression by compressed air is necessary.

The change from pump to turbine operation involves reversal of the direction of rotation. It is only necessary to feather the blades, stop, and then restart. This operation requires only a few minutes. The head gate remains fully open. The turbine output is adjusted to meet requirements simply by controlling the blade angle.

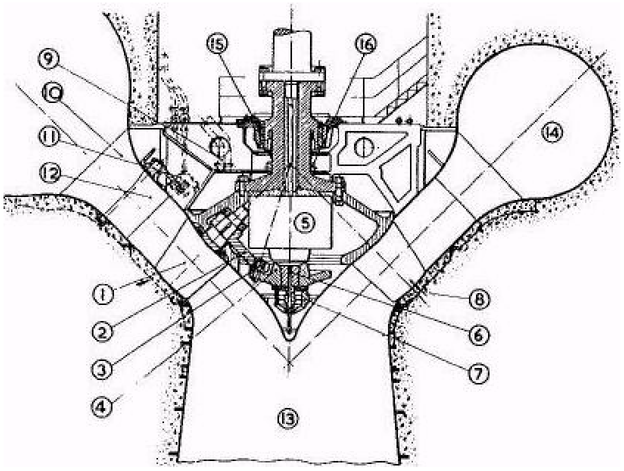

Figure 6 Sectional elevation through reversible pump-turbine at Sir Adam Beck-Niagara Pumping/Generating Station (Ontario). (1) Runner blades, (2) Blade lever, (3) Spider pivots, (4) Spider,(5) Rotating servomotor (6) Restoring tube, (7) Return motion cam, (8) Blade-tip clearance, (9) Balancing pipe, (10) Stay vanes, (11) Flap servomotor, (12) Flaps, (13) Draft tube (suction pipe}, (14) Scroll casing, (16) Guide bearing, (16) Shaft gland

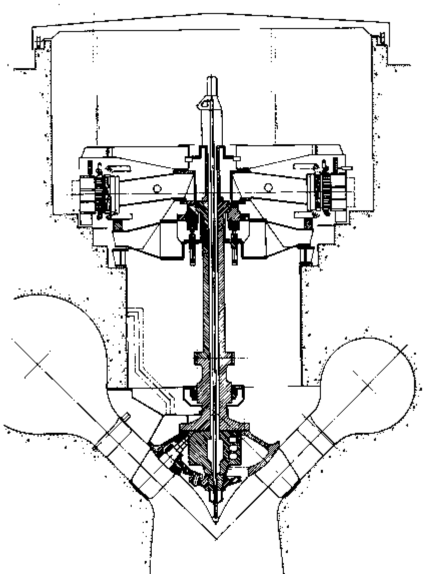

Figure 7 Machine cross-section.

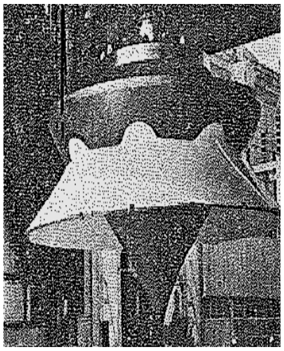

Figure 8 Runner blades shut

Starting for turbine operation is carried out most conveniently by running up as a motor. No synchronizing by governor control is required as the machine is started direct on line. This results in considerably simplified operation, particularly for an automatic plant.

No emptying of the penstock is required on shutdown. The angle of the vanes is utilized to advantage achieve a reduction in tip clearance (Point 8 of Figure 6) during shutdown. This is done by lowering the runner and thus seating the blade tips on the stationary runner envelope. This is achieved by increasing the hydraulic thrust on the turbine by closing the balancing pipe (9) and building up pressure over the hub. The thrust-bearing load is conveniently increased thereby and a precisely preloaded element within the bearing support allows additional axial displacement.

7 *MACHINE OPERATING CHARACTERISTICS*

Figure 9 and Figure 10 show typical discharge and efficiency characteristics, in relation to head, plotted from model tests of the Deriaz runner for Niagara when operating as a pump. In Figure 9 the discharge and efficiency characteristics are plotted for three different blade settings corresponding to 75, 100, and 120 per cent blade opening. As would be expected, each of these characteristics corresponds, in general form, to the performance of a fixed-pitch, modified Francis-type pump. Note the reduction in discharge as the head increases for each individual blade opening.

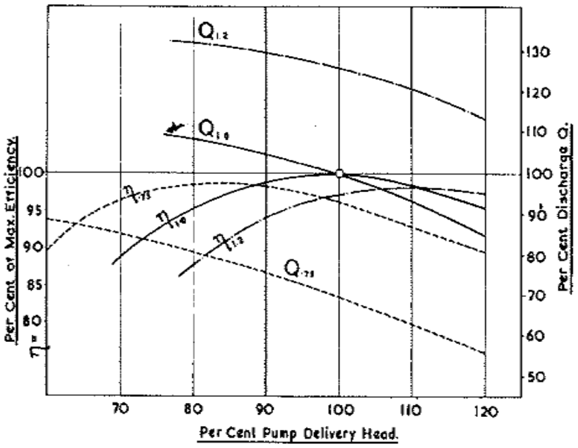

Figure 9 Efficiencies and discharges of the variable-pitch pump versus head. Curves for blade angles of 75,100, and 120 per cent are shown.

However, in Figure 10 the full-line curves show the result of choosing the blade angle for optimum efficiency at each head. This demonstrates how a flat efficiency curve is obtained over a wide head range (Figure 11). The characteristics for the fixed blade setting corresponding to 100 per cent opening are drawn as dotted lines in Figure 10 to show the difference. The shaded area of the Figure 10 thus represents the efficiency gain over the head range resulting from the variable-pitch system.

Moreover, it should be noted how this choice of optimum blade angle results in a rising discharge characteristic with increasing head. This is the opposite of that obtained with the fixed-blade (Francis) runner. This characteristic of increasing discharge with increasing head can be controlled at the design stage by suitable location of the exit edge of the runner blade. The rising discharge characteristic is of major importance in pumped-storage projects where considerable variation in the storage-reservoir area with head can occur. If the setting of the pump-turbine is correctly selected, high overloads at high efficiency are achieved over that range of head where the maximum water volume will be pumped.

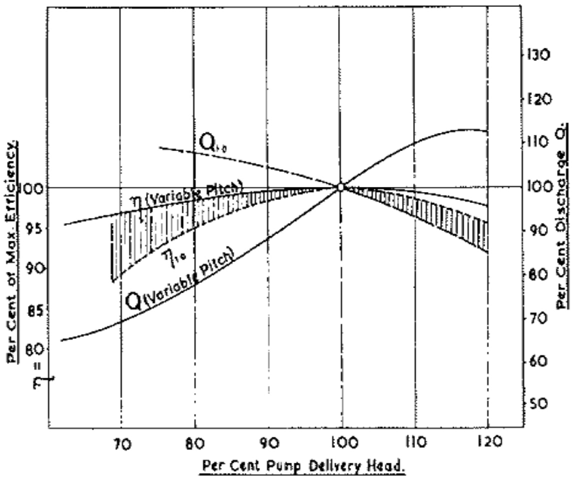

Figure 10 Pump performance: In full lines, operation by adjusting blade angle to best efficiency. In broken lines performance at constant angle

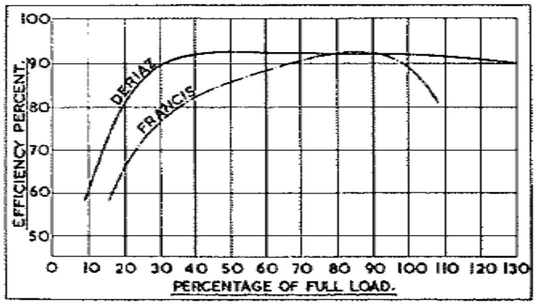

Figure 11 Efficiency versus load of Deriaz turbine and Francis turbine of equivalent specific speed and size

7.1 Runner-Speed Considerations

The high efficiency found over a wide head range permits a variable pitch reversible pump turbine to operate with the advantages of peak efficiency at the same speed for both pumping and generating cycles. Fixed-blade, reversible pump-turbines require a higher speed for pumping operation than for generating to perform at optimum efficiency for both cycles at a given head. In some cases this has led to the choice of different running speeds for pump and turbine operation. This has been achieved using complex synchronous machine pole changing techniques with the attendant complexity. These differing speeds are unnecessary with mixed flow, variable pitch, reversible pump turbines, since the effective runner diameter is altered by feathering the blades and the zones of peak efficiency operation are achieved for both duties. Thus a compromise between the best speeds for pumping and generating is unnecessary.

7.2 Guide Vane and Runner Blade Operating Angles

For optimum conditions when operating as a turbine, the angle at which water is admitted to the runner must be controlled. For reduced losses at the turbine runner exit, the inlet vortex is clearly defined. As the machine operates at constant angular velocity these conditions are fulfilled by guiding the incoming water according to head and discharge. The usual gate apparatus of a Francis or Kaplan turbine is suitable for the mixed flow variable pitch runner. However to reduce equipment size and cost it is desirable to reduce the number of guide vanes. Since the runner blades themselves permit complete closure, the guide apparatus can be greatly simplified.

The guide vane and blade control arrangements to meet these requirements and conditions at Niagara are illustrated in Figure 6 . The guide vane requirements are met by the provision of one adjustable flap on each of the fixed stay vanes (Figure 12). The axis on which the flaps pivot is at 45 degrees to the vertical with each flap being controlled by an individual oil-pressure servomotor. The flaps control the flow angle at inlet to the turbine runner and are deflected to a maximum at the lower heads on turbine duty.

Stabilization of the flow at the runner exit during pumping is achieved by setting the flaps in line with the stay vanes the design being so arranged that they are then held in a preloaded condition against stops on the stay ring. These stops eliminate any backlash effect in the servomotor linkage and flap vibration is thus avoided.

On the original design for Niagara, the flaps are operated in one of two positions only, Figure 12:

- Position in line for pump operation and for turbine above 60 ft head.
- Position deflected for turbine operation at heads below 60 ft.

Also, in the event of runaway, the flaps could be deflected to reduce cavitation in the draft tube.

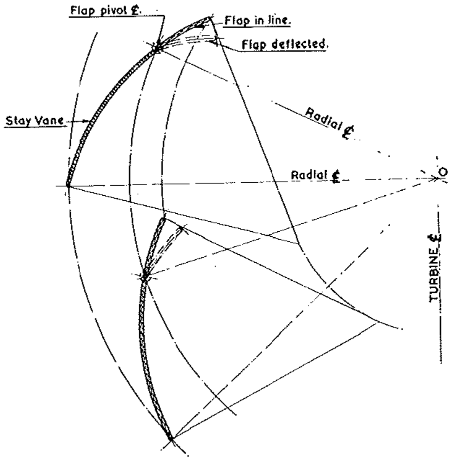

Figure 12 Flaps on ends of stay vanes

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8 BIOGRAPHIES

Tihomir Maricic graduated in Mechanical Engineering from University of Nis, Yugoslavia, in 1981. After the graduation he joined the crew of the builders of Iron Gates 2 Hydroelectric Development Project. For more than 10 years, through the variety of positions he has gained substantial and wide experience in hydro equipment design, manufacturing and installation. After moving to Canada, he has used this experience in international and domestic hydro projects as a design engineer, consultant and project engineer for service and rehabilitation. 2006 Tim has joined Ontario Power Generation as a Senior Plant Engineer with Asset Management Departmen Plant Group. Tihomir (Tim) Maricic is a licensed Professional Engineer in the Province of Ontario.

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