Turbine hydraulic assessment and optimization in rehabilitation projects

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Abstract. As turbines age after years of operation, a major rehabilitation is needed to give new life. The owner has two choices: resetting the turbine to the original state or an upgrade with new hydraulic components designed and optimized using state of the art technology. The second solution is by far a more interesting option which can maximize the efficiency gain, increase the turbine capacity and revenues, eliminate cavitation erosion and the needs for repair, reduce the turbine instabilities and smooth unit regulation, and adapt the design to new operation conditions. This paper shows some aspects of the turbine hydraulic assessment and possible solutions to improve existing water passages.

1. Introduction

Hydro-power has long been a great solution to provide the energy required to develop and sustain human activities, from the grinding of crops using water mills in Ancient Egypt to the modern hydro electric power plants of the 21st century that help to answer the massive energy need of the industrial development. Hydro electricity is a flexible and renewable source of energy which is a key solution to meet the environmental challenge of CO2 gas emissions reduction while delivering the extra energy required to reduce the use of the limited stocks of fossil fuel energy.

Within the installed hydro electric power plants, more than 263 GW of capacity is older than 40 years and are in need of a major rehabilitation to give them a second life. Their rehabilitation is an opportunity to reduce their environmental footprint and to improve the turbine efficiencies and output. In addition to typical mechanical components, such as wearing components and seals, which are affected by hours of operation and need to be replaced, the turbine water passages and the hydraulic profiles are also components that have to be considered in the refurbishment. Most of the turbine water passages are made from standard steels or cast irons. After years of operation, their coating protection are removed or deteriorated due to the abrasive and chemical characteristics of the water flow, the hydraulic surface roughness is increased, significantly affecting the hydraulic performances. The high flow velocity speed associated with low pressure regions make existing runners subject to cavitation phenomena, which is highly erosive for carbon steel. As a consequence, it is a common situation to have to periodically weld repair the eroded surface of the existing runners. However, with reparation at site, it is then very difficult to accurately maintain the original runner hydraulic profiles, and the turbine characteristics and performances are progressively degraded. Other highly stressed components such as stay vanes, wicket gates or runners, may need site reparation if cracks have been noticed. This could be also a concern for the maintenance of hydraulic profiles. For these reasons,
after years of operation, it is common for a turbine to see its efficiency reduced by 1 or 2% when compared to original performances, or even more.

Then, when the time has come to determine the rehabilitation scope of work, the hydraulic concerns must be carefully studied. One possibility is to reset the turbine to the original state by using the same hydraulic profile for the replaced components. The unit will recover its original performance, corresponding to an efficiency gain of 1 or 2%. But a better solution is to upgrade the turbine with new hydraulic components designed and optimized using state of the art technologies [6]. The gain in performance is significantly higher and could reach as much as 40% in output and up to 7% in efficiency, maximizing the return on investment of the rehabilitation project. In this paper, we will discuss the process of analyzing the existing water passages, identifying the hydraulic concerns and proposing adapted corrections to improve the performances.

2. Assessment and analysis of the existing water passages and the hydraulic profiles

Today’s computational fluid dynamics (CFD) tools permit the simulation of the complete existing turbine water passages to analyze whether each existing hydraulic component is optimally adapted to the flow streamlines. A poorly adapted profile leads to local flow accelerations, boundary layer flow separations, and deteriorates the flow (distribution and uniformity) with corresponding hydraulic losses. This flow deterioration could also impact the hydraulic behavior of the components that follow, leading to additional losses. Each component is unique, tolerates non-uniform flow differently and will have a specific impact on the turbine’s global characteristics and performances.

The quality of the hydraulic investigation is of primary importance to correctly identify the potential of performances improvement. These hydraulic studies should be done in preparation for the bid specification, or at the bid stage, to accurately define the scope of work to be addressed during the hydraulic development. We will review typical hydraulic concerns met in older existing installations and present the solutions that have remedied the situations.

3. Casing and stay vanes

Typical turbine runners such as Francis, Kaplan or Propeller runners convert the kinetic momentum of the flow rotation at the runner inlet into mechanical energy then into electrical energy by the generator. The casing, which could be of spiral or semi-spiral shape type depending of the unit operating heads, converts the axial flow delivered by the intake or by the penstock into a rotational flow around the turbine distributor and runner.

To obtain the optimal performances, the flow velocity and kinetic momentum should be as uniform as possible at the stay vanes inlet. This is a challenge in a spiral case, due to secondary flow generated by the casing elbow shape and even more difficult in a semi-spiral case. Modern tools such as CFD are of great help to optimize the casing design, simulate the flow and adapt the stay vanes profile to the hydraulic flow angle delivered by the casing. But older turbines were designed based on experience without numerical tools, and the stay vanes are often mis-adapted to the flow resulting in flow separation that could affect the efficiency by more than 2%.

3.1. Example of Chief Joseph project

The 10 Newport News’ Francis turbines of Chief Joseph’s power plant (89.7 MW at 50.3 m head) have been rehabilitated by Alstom with the first unit commissioned in 2013 [1]. The intensive hydraulic studies done during the development have identified flow separation at the inlet of each stay vane (see Figure 1). Fine computational fluid dynamics (CFD) simulations have confirmed that the 23 stay vane profiles were not adapted to the flow velocity field delivered by the spiral case, resulting in flow velocity acceleration at the stay vane inlet suction side and finally the flow separation of the boundary layer with an impact around 1% on the turbine efficiencies.
The stay ring is a structural component required for the mechanical integrity of machine and powerhouse above the turbine, making stay vanes replacement very difficult. It was instead proposed to modify the hydraulic profiles of the stay vanes by adding extensions to their leading edges in order to obtain inlet angles aligned with the flow delivered by the spiral case. The modification has been tested in laboratory and confirmed the 0.7% efficiency gain, making the modification very profitable (see Figure 2).

Most of the stay vanes extensions are machined from a steel plate welded on the existing stay vanes. However, for two of the first unit stay vanes, with the collaboration of the U.S. Army Corps of Engineers, another solution has been selected and installed on-site. This innovative solution uses a composite material (see Figure 3). The epoxy casting provides a strong link between the shell...
assembly and the surfaces of the existing stay vane and the stay ring. There is no heat input, therefore no risk of stay ring deformation, and the intervention on the stay vane is minimized. It also provides excellent impact resistance properties which have been measured during workshop tests conducted on a full size stay vane extension [2].

![Figure 3. Chief Joseph stay vane extension (composite materials) installation at site.](image)

3.2. Example of Chats Falls project

The 8 propeller turbines of Chats Falls (25MW at 15m head) have been rehabilitated by Alstom [5]. The hydraulic investigation showed that its semi-spiral case presented a quite unusual issue; the two first stay vanes in the frontal area were not well adapted to the flow hydraulic angle (see Figure 4).

![Figure 4. Chats Falls flow separation with existing stay vanes.](image)

It resulted in flow separation at the stay vanes suction side and a non-uniform flow distribution inside the distributor. The velocity field at the runner inlet was also affected and model tests showed vortices inside the runner inter-blades channel, downstream of the affected stay vanes. It corroborated the damaged concrete observed at site, in the same area, just below the draft tube cone steel liner. An extension has been designed for the two first stay vanes, improving the turbine efficiency by 0.8%. The two extensions have been installed on prototype by Ontario Power Generation. They were manufactured using steel plates filled with concrete (see Figure 5).
4. Wicket Gates

The flow velocity progressively increases from the casing up to the wicket gates, and this is why a significant part of the losses is directly linked to the wicket gate hydraulic profile. Old wicket gates were often made from carbon steel while common solutions today use stainless steel, with stronger mechanical properties allowing a reduction of the wicket gate thickness which decreases the flow velocity inside the distributor. Compared to the oldest wicket gates, the hydraulic profiles have also been improved in order to even more reduce the flow velocity in operation.

Replacing old wicket gates doesn’t represent any specific difficulty and is easy to do in parallel with other activities when the rehabilitation project requires the turbine dismantlement, for example, when replacing the runner. The typical efficiency gain for a wicket gates replacement is from 0.5% to 1%, making such an investment very attractive, especially for Francis turbines. In the case of Propeller and Kaplan turbines, the return on investment is usually lower, due to a taller wicket gates implying higher replacement cost and a lower efficiency gain. Another gain should be obtained at site, coming from the better surface finish of the replaced wicket gates. This last point is important in order to have prototype performances in line with the model transposed performances using the IEC model to prototype efficiency step-up formula.

4.1. Example of Chute des Passes project

The 5 Francis turbines of Chute des Passes (173MW at 174m head) have been rehabilitated by Alstom [7]. The scope of the rehabilitation included the runner and wicket gate replacement. The efficiency gain measured on model test with the new wicket gate profile was 0.6%, and the owner, Rio Tinto Alcan retained the new wicket gates option for the prototype (see Figure 6).

Figure 5. Chats Falls stay vanes extension, profile, manufacture and installation.

Figure 6. Chute des Passes new wicket gates efficiency gain, profile and manufacture.
5. Runner

The velocity flow increases inside the runner, from the blade inlet down to the blade outlet, while the hydraulic energy is converted into mechanical energy. For this reason the pressure significantly decreases inside the runner and the pressure at the blades outlet at high loads can be below the vapor pressure inducing cavitation. This is a very aggressive process which can locally remove the runner steel material. Similarly, a mis-adaptation of the blade leading edge to the flow angle at the runner inlet could induce a local flow velocity acceleration which could decrease the pressure down to the vapor pressure. This is why it is very common for old runners to be severely affected by cavitation erosion after years of operation. On the other hand, the runner hydraulic profile controls the flow velocity field below the runner. Then, the runner losses, as well as the draft tube losses, are closely related to the runner design.

Today, the systematic use of numerical tools and flow simulation has allowed impressive improvement in the runner design. It is now possible to avoid any cavitation at the runner blade leading edge over the usual turbine operating range and to significantly improve outlet cavitation. The flow inside the runner is optimized, reducing the runner head losses and the runner outlet velocity field is better controlled to optimize draft tube flow. In addition, it is possible to design the runner to change the turbine characteristics in order to optimize the turbine performance over operating conditions that may have changed from the original conditions. It could be new range of operating heads, higher turbine capacity or a new scheme of operation such as peaking operation. If runner replacement is considered, a new runner design is always a highly profitable investment.

5.1. Example of Chute des Passes project

The Chute des Passes turbines have been rehabilitated after 40 years of operation. Before the rehabilitation, Rio Tinto Alcan has done an extensive performances assessment of the existing runner, including a site efficiency test and an homologous test at model scale. The same performance level has been measured both at model and prototype scale, and no efficiency step-up for the prototype was observed. The runners have been repaired many times due to significant cavitation erosion problems (see Figure 7).
In addition to the new runner and wicket gates, the scope of rehabilitation also included sand blasting the water passages and painting to recover a new surface finish. The new runner design improved the existing performances by 3.1% on model while the accuracy of the runner fabrication and the surface finish improvement brought another gain on prototype as the IEC efficiency step-up was met at site (see Figure 8).

![Figure 8](image)

**Figure 8.** Chute des Passes model and prototype performances, before and after rehabilitation.

### 5.2. Example of Chief Joseph project

In addition to the stay vanes modification considered for the Chief Joseph Francis turbine rehabilitation, as explained in the above section ‘casing and stay vanes’, the runner and the wickets gates have also been replaced. During the hydraulic development, the new runner performances have been measured for several model configurations, including the existing wicket gates and stay vanes as well as the new wicket gates and the modified stay vanes, in order to identify the individual efficiency gain brought by each component. In addition, efficiency site tests have measured the prototype turbine performances before and after the rehabilitation. The new runner has increased the efficiency by around 5.7% while the overall turbine efficiency improvement was close to 7% when including the new wicket gates and the modified stay vanes (see Figure 9).

![Figure 9](image)

**Figure 9.** Chief Joseph prototype performances, before and after rehabilitation.
5.3. Example of Kelsey project
The 5 Propeller turbines of Kelsey (45MW at 15.5m head) have been recently rehabilitated by Alstom [3]. One objective defined by Manitoba Hydro was the power plant capacity increase. The hydraulic studies have shown that the main concern that would limit the Kelsey capacity increase was the cavitation. The existing hydraulic transition between the bottom ring and the discharge ring was not adapted to such discharge. With the higher wicket gates opening and the higher flow velocity, the pressure along the bottom ring decreases too much to avoid cavitation, which generates the turbine power saturation. Therefore, to significantly increase the turbine capacity it was necessary to replace the bottom ring to improve the hydraulic profile (see Figure 10).

![Figure 10. Kelsey with existing and new bottom ring hydraulic profile.](image)

In addition to the bottom ring and runner replacement, stay vane extensions have been provided to better adapt the stay vanes geometry to the flow, as well as a draft tube modification to avoid flow separation (see next section). Model tests showed that it was possible to increase the existing turbine capacity by more than 40% (see Figure 11).

![Figure 11. Kelsey prototype performances, before and after rehabilitation.](image)
6. Draft Tube
The flow kinetic energy at the runner outlet is very high and the draft tube is an important hydraulic component that has to convert that energy into net head. This is especially important for low head turbines. This is done by reducing the flow velocity speed while keeping the flow as uniform as possible inside the draft tube water passages. This is especially challenging as, at the same time, the draft tube has to integrate an elbow to change the main flow direction from vertical to horizontal, and it has to diverge as quickly as possible to reduce the power plant civil costs. Any secondary flows, flow separations and non-uniform flows increase the head losses inside the draft tube itself, but more than that, increase the kinetic energy lost at the power plant outlet. Then, it reduces the head seen by the runner and it decreases the unit output delivered to the network. To minimize the draft tube losses and to recover the highest possible part of the runner outlet kinetic energy, it is important for the runner to deliver the flow velocity field which will be the most favorable for the draft tube. At the same time, the draft tube hydraulic shape should be as tolerant as possible to the inlet conditions, as the runner outlet flow velocity field will change with the turbine discharge.

When considering turbine rehabilitation, runner replacement by a new design optimized using numerical tools and the manufacturer’s experience will improve the flow velocity field quality at the draft tube inlet. But there may be limitations to what can be improved by the runner itself. If the flow velocity speed inside the elbow is too high, if the pier nose leading edge is not well adapted or if the diffuser divergence is too high, even with a new runner design it may be not possible to avoid flow separation inside the draft tube and high losses. In such a case, the draft tube hydraulic profile could be analyzed and optimized to improve the flow [4].

6.1. Example of Kelsey project
During the rehabilitation of the Kelsey turbines, the hydraulic development showed a concern in the draft tube behavior. In this case, a flow separation occurred, for discharges close to the best efficiency point, at the draft tube diffuser inlet, leading to a sudden efficiency drop off of more than 3% (see Figure 12).

![Figure 12. Kelsey flow separation at draft tube diffuser inlet (with pier’s nose).](image)

Several draft tube modifications were studied during the hydraulic development, and tested on model, to improve the flow. The best modification has been retained by Manitoba Hydro and installed
on-site. The prototype turbine performances of the rehabilitated turbine have been measured with and without the draft tube modification. They confirm the efficiency gain (more than 6% at high load) brought by the modification and the smoother turbine operation, with no incidence on the efficiency curve (see Figure 13).

![Figure 13. Kelsey prototype performances, before and after draft tube modification.](image)

### 7. Other examples of Alstom rehabilitation projects

Listed in Table 1, below, are details on some of the rehabilitation projects performed by Alstom. It shows the replaced or modified hydraulic components, the associated efficiency gain as well as the capacity increase.

| Power Plant      | Country | Turbine | Head (m) | Output (MW) | Capacity Increase | Stay Vane Modification | Wicket Gates Replacement | Runner Replacement | Draft Tube Modification | Total Efficiency Gain |
|------------------|---------|---------|----------|-------------|-------------------|------------------------|-------------------------|-----------------------|------------------------|-----------------------|
| KELSEY           | Canada  | Propeler| 15.5     | 45          | 41%               | x                      | x                       | x                     | x                      | >2%                   |
| OUTARDES 3       | Canada  | Francis | 143.5    | 260         | 35%               | x                      | x                       | x                     | x                      | >6%                   |
| GREAT FALLS      | Canada  | Propeler| 15.9     | 26          | 34%               | x                      | x                       | x                     | x                      | >3%                   |
| NOVA MAURICIO    | Brasil  | Francis | 30%      |             |                   |                        |                         | x                     | x                      |                      |
| ISLAND FALLS     | USA     | Francis | 129.5    | 144         | 30%               | x                      | x                       | x                     | x                      | >1%                   |
| SHASTA           | Latvia  | Francis | 34.0     | 83          | 21%               | x                      | x                       | x                     | x                      | >6%                   |
| PLAVINAS          | Latvia  | Kaplan  | 15.0     | 17          | 21%               | x                      | x                       | x                     | x                      | >3%                   |
| KEGUMS 1         | USA     | Francis | 50.3     | 90          | 20%               | x                      | x                       | x                     | x                      | >5%                   |
| CHEIF JOSEPH     | China   | Francis | 116.7    | 255         | 20%               | x                      | x                       | x                     | x                      | >6%                   |
| WU JIANG DU      | Canada  | Propeler| 143.5    | 260         | 16%               | x                      | x                       | x                     | x                      | >1%                   |
| KIPLING           | Sveden  | Kaplan  | 34.0     | 46          | 16%               | x                      | x                       | x                     | x                      | >2%                   |
| GRUNDFORS        | Canada  | Francis | 33.8     | 52          | 15%               | x                      | x                       | x                     | x                      | >6%                   |
| CHUTE SAVANE     | China   | Francis | 63.5     | 173         | 13%               | x                      | x                       | x                     | x                      | >3%                   |
| DAN JIANG KOU    | China   | Francis | 100.0    | 126         | 6%                | x                      | x                       | x                     | x                      | >3%                   |
| LIA JIA XIA      | China   | Francis | 36.0     | 51          | 6%                | x                      | x                       | x                     | x                      | >2%                   |
| YAN GUO XIA      | Canada  | Propeler| 15.2     | 25          |                   | x                      | x                       | x                     | x                      | >5%                   |
| CHATS FALLS      | USA     | Propeler| 24.7     | 75          |                   | x                      | x                       | x                     | x                      | >4%                   |
| ST.LAWRENCE      | Canada  | Francis | 78.3     | 135         |                   | x                      | x                       | x                     | x                      | >4%                   |
| KOOTENAY         | Canada  | Francis | 174.0    | 173         |                   | x                      | x                       | x                     | x                      | >3%                   |
| CHUTE DES PASSES | Brasil  | Francis | 136.2    | 330         |                   | x                      | x                       | x                     | x                      | >3%                   |
| SURI 1           | Canada  | Francis | 105.5    | 28          |                   | x                      | x                       | x                     | x                      | >3%                   |

**Table 1.** Examples of Alstom rehabilitation projects.
8. Conclusion

This paper shows that, when unit rehabilitation is required for mechanical and reliability reasons, the improved project return on investment is a result of an exhaustive hydraulic investigation of the existing water passages and of a systematic hydraulic component optimization. This can result in a turbine capacity increase of up to 40% and in an efficiency improvement of up to 7%. In addition, the cavitation erosion at site is eliminated, reducing the maintenance and repair needs and improving the turbine life time. It also reduces the turbine instability and smoothes the unit regulation.

References

[1] Papillon B, Freeman T, Rehabilitating the Francis at Chief Joseph, HYDRO REVIEW, October 2013
[2] Beaulieu S, Labrecque Y, Sabourin M, Breakthrough in the rehabilitation of stay vanes, HYDROVISION, Denver, 2013
[3] Loiseau F, Derry A, Tonner T, Sabourin M, Couston M, Rehabilitation projects : from model development to prototype feedback, HYDROVISION, Charlotte, 2010
[4] Loiseau F, Sabourin M, Bornard L, Couston M, Draft tube in rehabilitation projects, HYDRO 2010, Portugal
[5] Loiseau F, Munro I, St-Hilaire A, Couston M, Sabourin M, Rehabilitation of propeller turbines, a case study : Chats Falls power plant, WATERPOWER XIV, 2005
[6] Michel B, Couston M, Sabourin M, Francois M, Hydro Turbines Rehabilitation, HYDRO, 2004
[7] Papillon B, Gagne J-L, Giroux S, Sabourin M, Rehabilitation of the Hydraulic Passageways at Chute des Passes, 21st IAHR Symposium, Lausanne, 2002