# CAM CORRELATION ANALYSIS USING ACOUSTIC DISCHARGE MEASUREMENT

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## ABSTRACT

The low head hydro power plant in Wettingen, Switzerland, is in operation since 1933 and no effective cam optimization has been carried out up to now. The goal of the measuring campaign was to provide data enabling an economic study for a retrofit and upgrade project of the plant and the measurement of the efficiency improvement of turbines after refurbishment.
The contribution discusses cam tests using the acoustic transit time method in the intake for discharge measurements. A cam correlation analysis and an efficiency test of the installed Kaplan turbines were performed as a first measurement campaign showing the actual status. While one turbine operated at optimum cam, the other two turbines operated off-cam. After rehabilitation works, based on the recommendations of the first measurements, a second measurement campaign was performed. The results showed the expected efficiency increase due to overhaul of the regulating mechanics (connection between the piston stroke in the machine hall and the regulating ring / guide vane stem at the turbine) of the governor.
With the set of data from the second measurement campaign an optimization study for the operation of the three Kaplan units were conducted. Especially the transition zone from one to two and from two to three machine operation could be optimized due to the knowledge of the individual efficiency curves.

## 1 INTRODUCTION

The hydro power plant (HPP) Wettingen is a run of river plant located at the river Limmat downstream of Zurich. There are three Kaplan units installed with a rated capacity of 8.5 MW each. The head varies in a relatively small range between 21.6 and 22.8 m. In a typical year the plant produces about 145 Mio kWh.
In the context of a planned retrofit and upgrade of the HPP Wettingen, 8-path acoustic transit time (ATT) discharge measurements from HydroVision GmbH were installed in each of the three intakes. The original Winter-Kennedy measurement devices were not anymore reliable and a Winter-Kennedy measurement thus not practicable, Obermoser et al. [1]. The new discharge measurements were also foreseen to be implemented in the governor system of the HPP. Discharge measurements based on the ATT principle are known to be long term stable and a good reproducibility can be achieved therefore. A decision criterion for the HPP operator was - among others - to verify the economic analysis for the planned retrofit
The ATT discharge measurement is described in the appendix of the IEC Standard 60041 [2]. But in the case of the limited installation possibilities in the HPP Wettingen an unconventional solution for the positioning of the transducers had to be found. The only possible location for installation was identified to be in a convergent section, downstream of a central pier in the intake. In order to get an overview on the flow field that had to be expected in the measuring section numerical flow simulations (CFD) were carried out by the Hochschule Luzern, Switzerland. Further goal of these flow simulations was to determine the positions of the transducers and the weighting of the individual acoustic paths. The simulation domain with the measuring section is

depicted in Figure 1. The sensitivity analysis for the weighting of the paths and a discussion of the expected integration uncertainty of discharge based on these simulations are described in Aakti et al. [3].

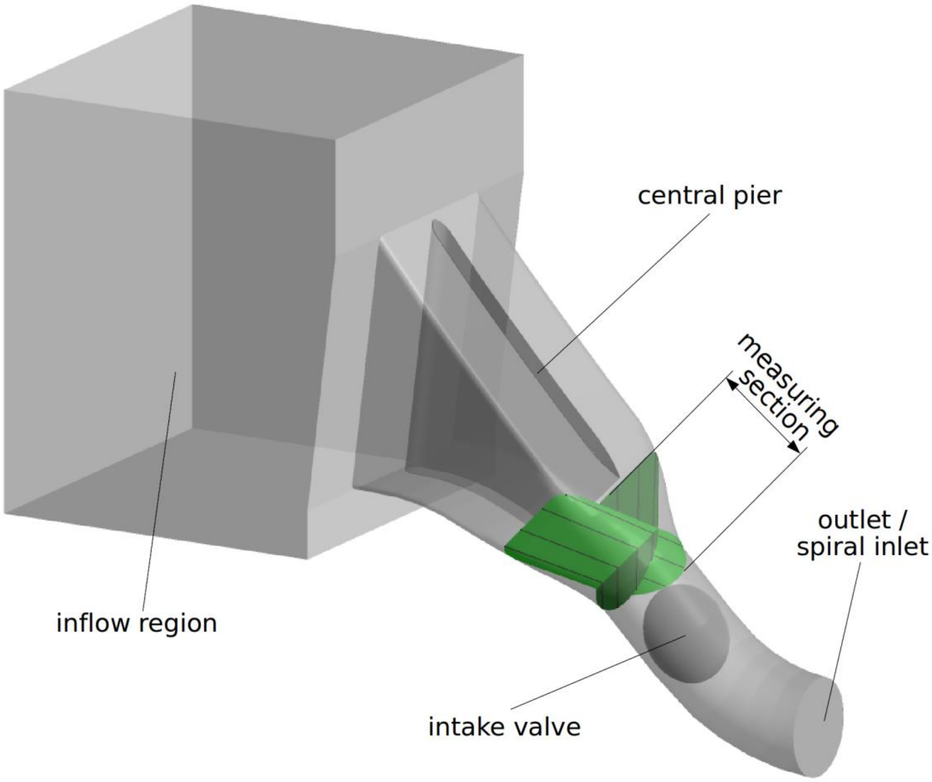


Figure 1 – Simulation domain of the turbine inlets and location of the measuring section

## 2 CAM CORRELATION TEST

Modernizations during overhauls often affect the operating parameters of the different units. Several revisions and repairs have been carried out since the initial commissioning of the HPP Wettingen in 1933, but a cam correlation (CC) test has not been carried out up to now. An effective hydro turbine testing program is important in ensuring that unit characteristics are as accurate as possible (Wolff et al. [4]). The operator decided providentially to perform CC tests on each of the three units to determine possible secondary effects in the case of two or three machine operation. In the past it was observed that the turbines produced different generator outputs according to the scheduling of the turbines.

Especially after each overhaul and modernization of the turbine governor and every component associated with the regulating system, a CC test is recommended to make sure that the maximum power production is reached (Adamkowski et al. [5]). The on-cam correlation between guide vane and runner blade on the prototype is set by the turbine manufacturer on the basis of model tests. In practice some deviations in the prototype can occur mainly due to scaling effects and different inflow conditions between prototype and model.

To perform a CC test on minimum an index test with a relative discharge measurement is required. In practice and due to cost restrictions this will be often being carried out with a Winter-Kennedy differential pressure measurements. Each unit of the HPP Wettingen is equipped with Winter-Kennedy pressure taps for discharge determination, but these measurements were not considered reliable enough for the planned tests. The stability and reproducibility of such Winter-Kennedy pressure differences are based on experience and sometimes reported as critical (Kercan et al. [6]). A further possibility is to use current meter measurements as described by Rolandez et al. [7]. ATT discharge measurements with just 1-path or acoustic scintillation measurements can also be considered in case the flow field does not alter with the load of the machines and the operation of the different units.

Because the HPP operator in the case of Wettingen was interested in knowing the absolute efficiencies as well, an absolute discharge measurement method was required. Beside the acoustic scintillation method, the 8-path ATT discharge measurement was considered to be the only suitable device. Additionally to the discharge measurements during a CC test, water temperature, head (free water level measurements) and an active power measurement was executed.

Through a CC test, several propeller curves over the entire operating range were determined. A single propeller curve results from measurement points with a constant runner blade position and varying guide vane positions in the proximity of the maximum efficiency. In a next step an envelope efficiency curve is fitted on the different propeller curves. The envelope touches the propeller curves tangentially. The envelope characterizes the optimum points of operation at a given head and for different loads. The procedure of CC tests is described in detail in the Annex I in the IEC Standard 62006 [8].

## 3 MEASUREMENT RESULTS

The first measurement campaign was conducted to analyze the actual CC for each of the three turbines. A typical example of a resulting diagram of such a measurement is shown in Figure 2 for the machine group (MG) 1. The first measurement point for a propeller curve was always the on-cam (existing cam) point. Especially for the partial load operation it is obvious that this MG was not operating in the optimum cam (red envelope in Figure 2). The optimum CC propagate a smaller runner blade position for a given guide vane opening.

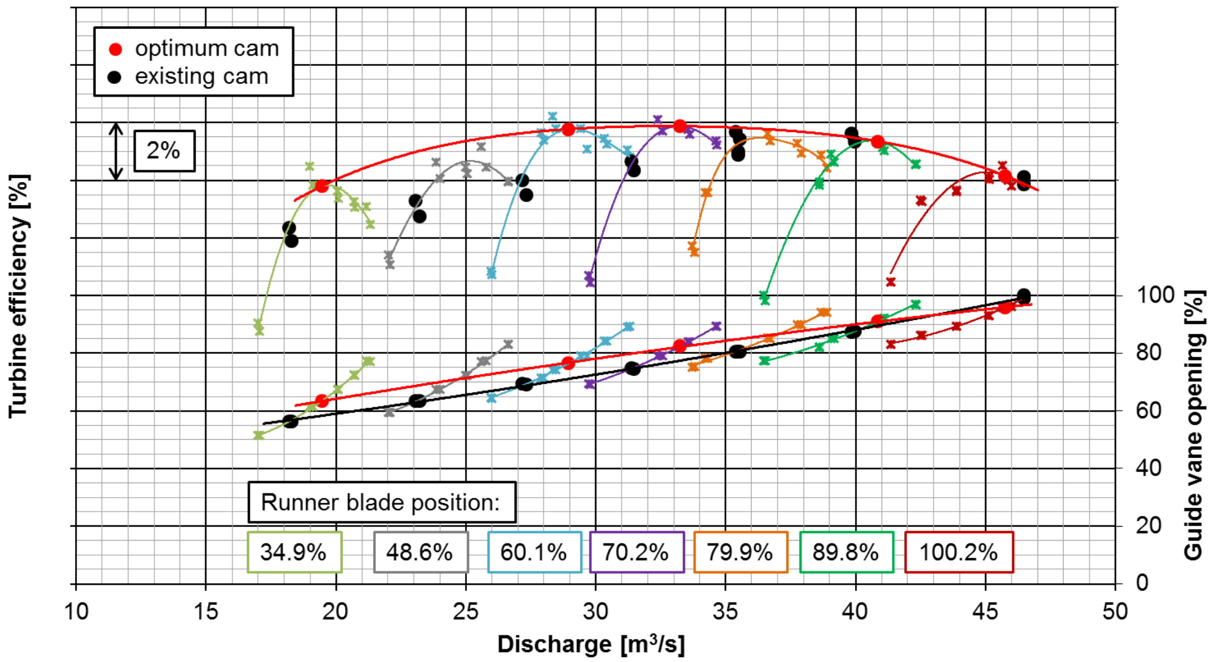


Figure 2 – Turbine efficiency for machine group 1 at the HPP Wettingen

The results for all three turbines are summarized in Figure 3. The differences between the best-fit curve through the existing on-cam points (black lines) and the optimum envelope (red lines) are quantified at the right (green lines). These results suggest a correction of the CC for the MG 1 and 2 (red lines in Figure 4).

In contrast to this finding the identical CC was implemented in the control system for the three MGs and also measured as shown in Figure 4 (black lines). It can be concluded that this CC is optimum for MG 3 and Figure 3. In order to find the reason for these discrepancies, detailed mechanical position measurements were performed (two examples are shown in Figure 5). The position measurements showed considerable deviation of the actual guide vane positions of the individual machines for the same CC from the specified value in the control system. Thus the value in the control system was not the real value of the mechanical position of the guide vane stem. The reason for that is, that the guide vane position is calculated from the piston stroke in the machine hall and is not a measured value on the guide vane stem. Thus the governor assumes that it should regulate the runner blade position to the actual guide vane position, but due to mechanical elasticity and clearances of the connecting components between the piston stroke and the guide vane stem the guide vane opening is actually too small. Therefore the effective guide vane opening and the runner blade position do not correspond.

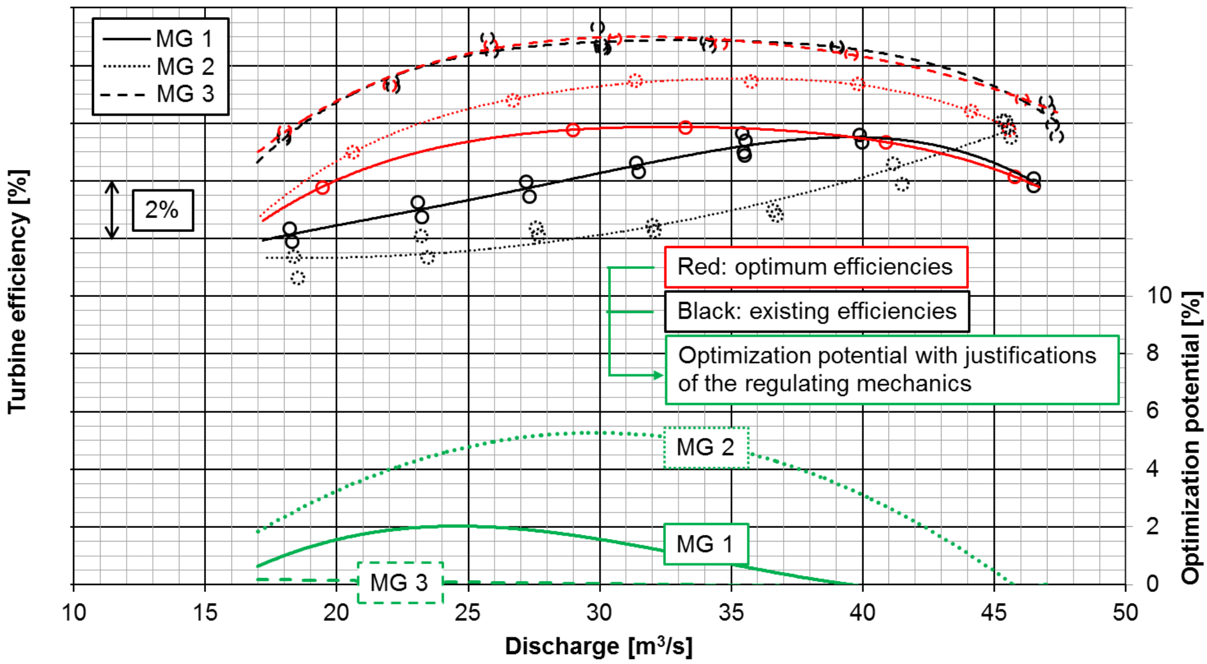


Figure 3 – Optimization potential for optimum cam operation

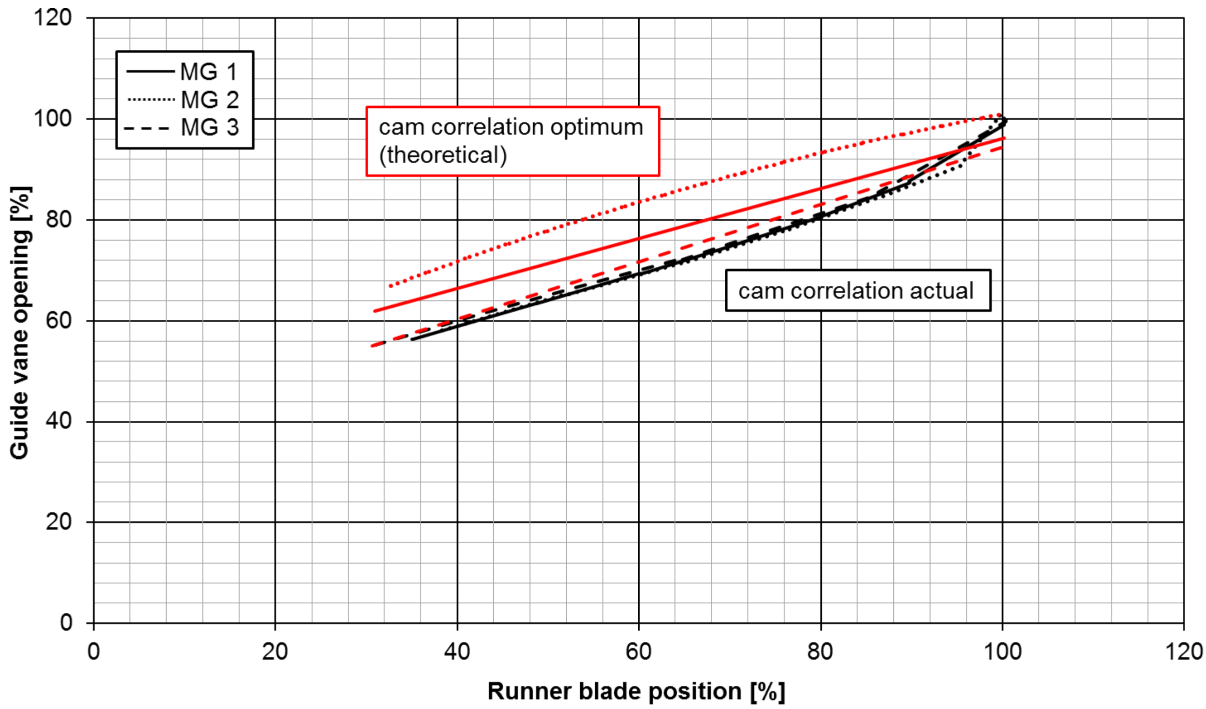


Figure 4 – Cam correlation analysis after the first measurement campaign

Modifications in the mechanical connections between the piston stroke and the individual guide vanes have been realized. Special attention was taken for the rehabilitation works for the MG 1 and 2. As can be concluded from Figure 3, the MG 3 did not show problems regarding the mechanical connections and this result showed that the actual CC was at optimum. The improvements of the efficiency of the HPP were by 7.2 percent, with the existing turbines and with a minimum of rehabilitation work. The improvements were confirmed with the second measurement campaign.

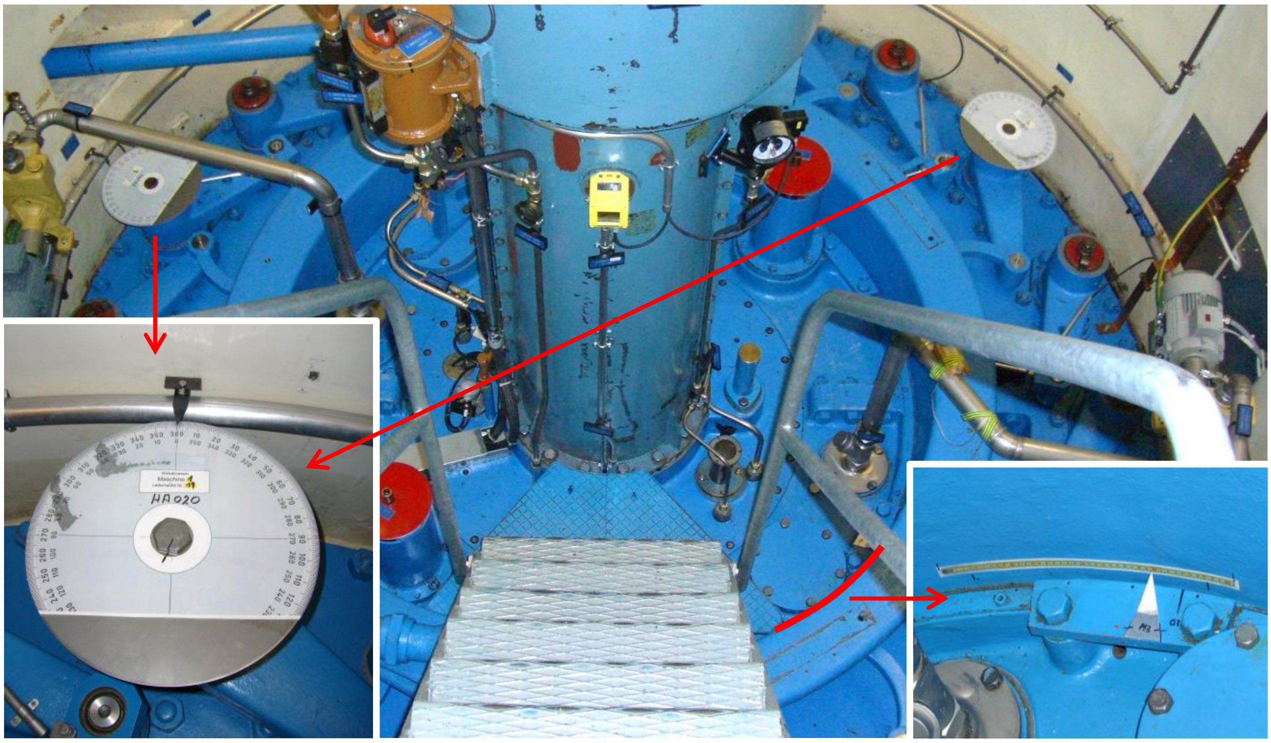

Figure 5 – Position measurements by the regulating ring and the guide vane stem

## 4 OPTIMIZATION STUDY

Based on the efficiency measurements of the second measurement campaign the HPP operator desired to know how the MGs should be scheduled to reach the maximum power output from the provided discharge of the weir control.

The first task was to evaluate the best machines especially for the two machine operation. Based on the results of the individual efficiencies in Figure 3 it becomes obvious to schedule the MG 2 and 3. The difference of the power output by respecting the MG 1 and 2 is increased by 250 kW. This amount to 2 percent of an average production of 12.5 MW in two machine operation. For the single machine operation the MG 3 should be preferenced.

The second task was to evaluate the proportion of the production for the individual MG. This can be solved by the simple equation of

$$P_{tot}(\alpha_1, \alpha_2, \alpha_3) = \sum_{i=1}^{3} P_i(Q_i) = \sum_{i=1}^{3} P_i(\alpha_i \cdot Q_{soll}) = MAX$$

with the resulting proportions $\alpha$. The more the individual efficiency curves of the different MG differ in their curvature from each other the larger the optimization potential from the normal rule of operation (e.g. 33.3 percent for three machines) gets. Therefore, for the HPP Wettingen (as it can be concluded form the red lines in Figure 3) the potential in optimization of the proportions is small in contrast to the situation if we would have a further MG with a different power range.

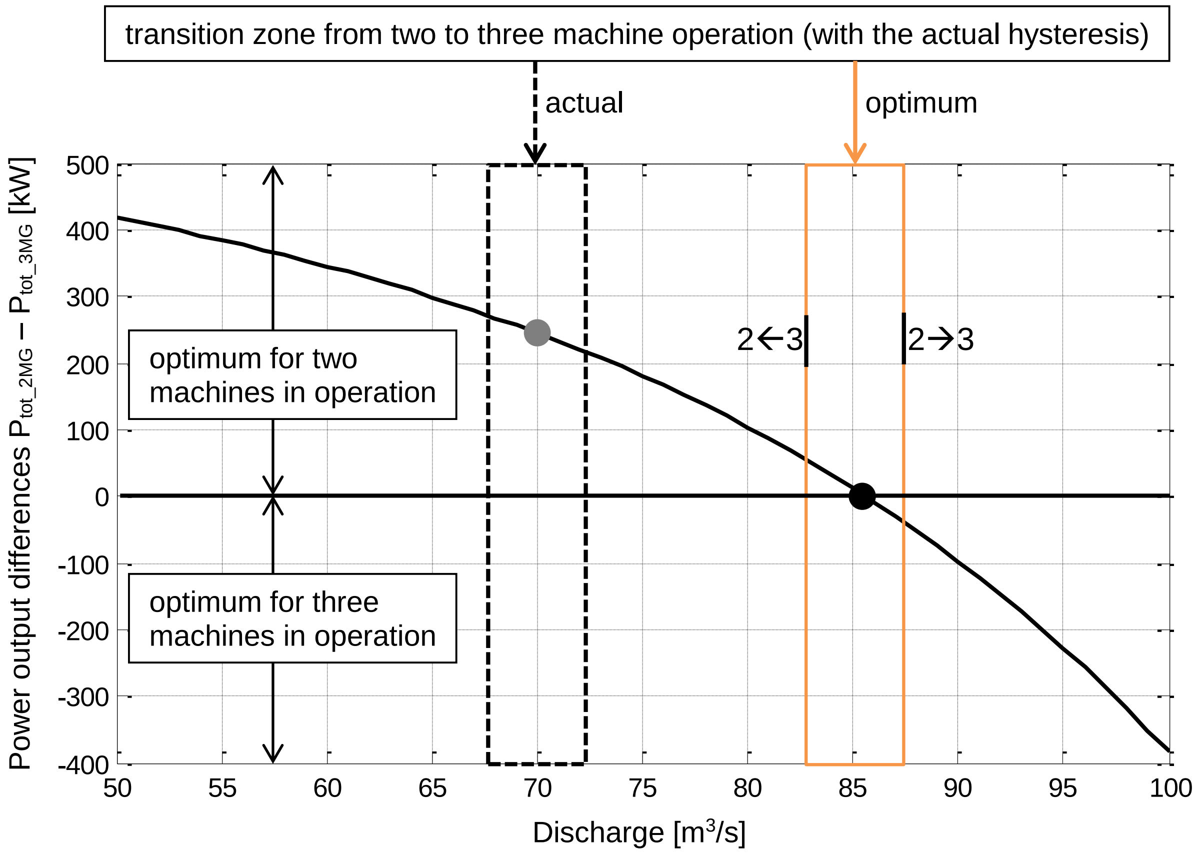


Figure 6 – Optimization of the discharge for the switching of the three machine operation

A third question was to optimize the switching flow rates between one to two and between two to three machine operation. With respect to a hysteresis, the switching flow rates become a transition zone. The analysis for the switching from two to three machine operation is given in Figure 6. The diagram shows that the actual transition zone starts the third machine too early. In fact there is a further optimization potential of up to 250 kW. These correspond to 1.5 percent of the full operation power output of 17 MW in two machine operation. The value of the optimization potential is directly linked to the choice of the hysteresis band (Figure 6).

## 5 CONCLUSION

With the ATT discharge measurements propeller curves were determined for the three machine groups over the interesting operating range. The results showed that only one MG was initially operating on-cam. The resulting efficiencies of the two other MGs were far off the envelope. The two MGs showed deviations of up to 5.2 percent from the optimum envelope.

Due to measurements of the positions of different mechanical parts from the piston stroke to the guide vane, the reason for the deviations could be found. After an overhaul of the entire mechanical connections between the piston stroke and the guide vane the second measurement campaign showed the expected efficiency improvement by up to 7.2 percent for the two MGs which were off the optimum envelope. For normal operating conditions such an efficiency increase will lead to a payback of the installation costs of the ATT and of the complete measuring campaign within less than a year.

From the results of the absolute efficiency measurements it could be demonstrated that maximum efficiencies of the units differ by 2.9, respectively by 1.5 percent. The reason for these differences can eventually be found in the differing mechanical condition of the three turbine runners, in the inflow conditions or in different water flow conditions downstream of the three draft tubes.

With an optimization study for the operation of the three units further profit for the HPP operator could be realized. For any oncoming discharge, provided by the weir control, the unit to be operated is now defined and the ratio of discharge for each unit for the two and three machine operation is quantified. Furthermore, a sensitivity analysis showed that the actual hysteresis for the transition zones from one to two and from two to three machine operation (in both directions) should be halved in order to reduce further power losses.

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