INDEX TEST AND BEST CAM CURVES DESIGN PROCEDURE FOR KAPLAN TURBINES

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ABSTRACT

This paper presents in detail the methodology adopted by the Alstom's Special Measurements Team to perform an Index Test and define the best family of cam curves for its Kaplan turbines prototypes.
The new methodology takes into account on-site head loss measurements and the shape of the turbine model's cam curves in order to calculate a new family of cam curves for the prototype.
Finally, this new family of curves is implemented on Alstom's speed governor so that the generating unit will be at its best efficiency at any head.

INTRODUCTION

Low head Kaplan and Bulb turbines have a very large market potential in Brazil. Differently from Francis turbines, Kaplan and Bulb turbines are double regulated, providing them high efficiency over a broad range of head and discharge.
Nevertheless, their double regulation also means a more complex system which requires a very precise combination of guide vanes and blades positions in order to make sure these turbines are operating with their best efficiency. These blade-to-vane combinations, known as cam curves, are controlled by the speed governor as a function of the power setpoint and the measured head.
The best cam curves are usually defined on reduced scaled model tests. Those are then loaded on the speed governor's software of the prototype with the aim of reproducing the model results and maximize efficiency. Although, there are many factors that may decrease the prototype efficiency, such as:

- The theoretical head loss estimative can be imprecise or different from the real loss due to modifications in the water intake or outlet. As the speed governor uses information of gross head, conversion from model test results using net head values to gross head must be as accurate as possible;
- The head information sent to the prototype's speed governor can be incorrect;
- Non homologies between model and the prototype;
- Commissioning errors on the speed governor, creating differences between the position set point indicated by the speed governor's software and the real position of the guide vanes;
- Damage or deterioration sustained from continuous use of the equipment can also cause inaccuracies.

Most of the items above can be verified with an appropriate procedure to perform an index test. This paper presents these general procedures. In addition, as the index test is usually done in a small range of the operational head range of the generating unit, a detailed procedure to extrapolate cam curves to the remaining range of heads is presented.
Some results obtained in units tested by the Alstom's measurements team are presented as examples.

1 GENERAL PROCEDURES: INITIAL MEASUREMENTS AND INDEX TEST

The index tests are usually required to follow the IEC 60041 standard (IEC:60041, 1991) procedures. On this chapter, some of these procedures are detailed and some other procedures are added.

1.1 – Initial Verifications

Before performing the index test itself, it is recommended to make some initial verifications. One very important test is to verify if the head information sent to the speed governor is correct.
There are usually two water level sensors, one upstream the turbine at the water intake and another downstream the turbine at the water outlet, that send these level measurements to the supervisory system (SCADA). The SCADA calculates the difference between those levels and sends this head information to the speed governor. Hence, it is very important to verify that these level measurements are correct. For that, one can measure the pressure at the turbine inlet p_1 and calculate the upstream level H_3 as given in eq.(1):

$$H_3 = \frac{p_1}{\rho g} + z_1 \tag{1}$$

Where z_1 is the pressure sensor level measured in meters above the sea level (masl). This level value must be as precise as possible, normally using topographical indications. The gravity g and the density ρ must be calculated as described in the IEC 60041 (IEC:60041, 1991).
Or, at the turbine outlet:

$$H_4 = \frac{p_2}{\rho g} + z_2 \tag{2}$$

From Alstom's experience, the calculated upstream $\mathrm{H_3}$ or downstream $\mathrm{H_4}$ levels and the value indicated by the SCADA must not have more than 10cm difference. This variation is considered acceptable as there are measurements uncertainties in every term of the equations above, and the head information error will have a very small effect on the speed governor's cam curves.
Another very important verification that must be done before performing the index test is to make sure that the angle information of the blades and guide vanes indicated on the speed governor is indeed the real angle on the machine. As these information come from sensors and a mechanical system that can be damaged or modified with time and use, this check must be done from time to time.
Another very important check regarding the speed governor itself is to certify that the error between the position setpoint of the blades or vanes and the real position are in agreement. The closed-loop feedback system may have a steady-state offset error. The integrator part of the PID controller is meant to minimize this error, but during the real operation of the unit the operational error will depend on how the PID controller coefficients are set.
In other words, before starting the index test and the best cam curve verifications, one must be sure that what is measured and informed to the speed governor of a double regulated turbine is indeed the real state of the machine. Otherwise, cam curves implemented on the speed governor that are based on scaled model results will not be effective.

1.2 – Index Test and Cam Curve Verification

The index test and cam curve verification will generate results such as the graph on Figure 1. The procedure is: the blades are fixed and the guide vanes position is varied, while measuring efficiency for each combination. As the graph shows, there will be a combination of blades and vanes position that will maximize the unit's efficiency. The general calculation and measurements procedures are well described at the IEC standard.

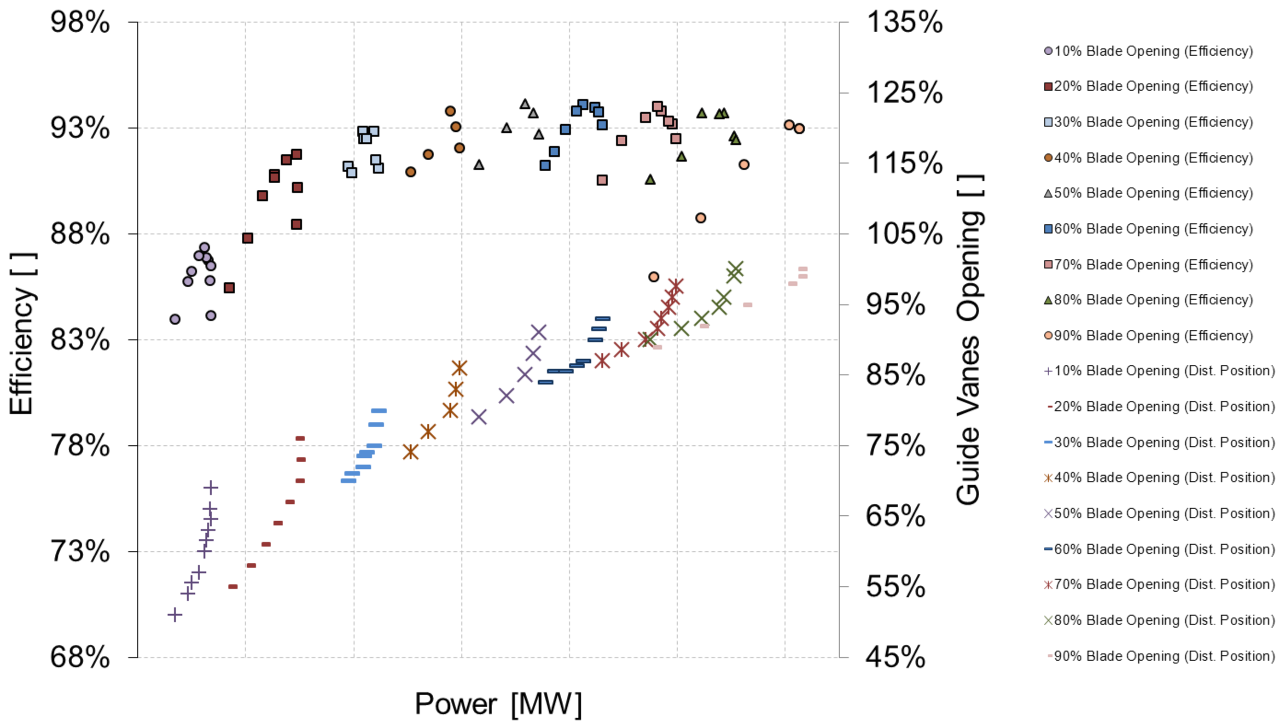

Figure 1 – Efficiency measurements in order to find the best combination of blades and vanes position. The test is divided in steps where the blades positions are fixed while the vanes opening are varied.

1.3 – Head Loss

In addition to the efficiency, the index test can also provide a good estimative of the head loss coefficient.

The net head H_n is calculated as given in the eq. (3):

$$H_n = \frac{p_1 - p_2}{\rho g} + z_1 - z_2 + \frac{\upsilon_1{}^2 - \upsilon_2{}^2}{2g} \tag{3}$$

The gross head H_G is calculated as given in the eq. (4):

$$H_G = H_3 - H_4 \tag{4}$$

The head loss H_L is then calculated:

$$H_L = H_G - H_n \tag{5}$$

As discussed in 1.1, the upstream and downstream level measurements H_3 and H_4 displayed at the SCADA usually have an offset error if compared to the measurements done at the turbine inlet and outlet, as described in equations (1) and (2). As a consequence, the head loss calculated as in eq. (5) will not tend to zero when the discharge approaches zero.
The figure Figure 1 presents an example of head loss measurement. It presents the head loss measurements as a function of the square of the discharge. The red line is the tendency line of these points and shows how the measurements usually do not move towards zero due to the measurement errors explained before. Consequently, the real head loss is expected to be closer to the green line shown in the graph.

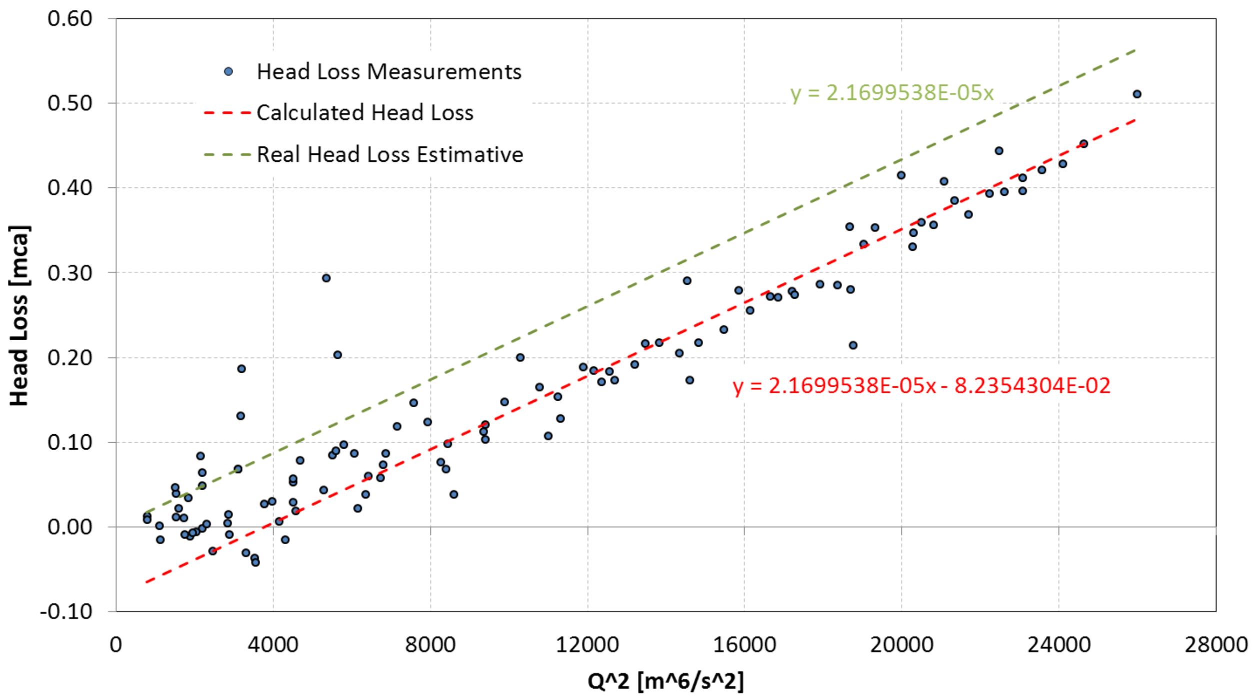

Figure 2 – Example of head loss measurement as a function of the squared of the discharge. The blue points are the measured values and the red line is a tendency line of these points. The green line is the real head loss estimative.

2 GENERATING CAM CURVES FOR THE ENTIRE OPERATIONAL RANGE

With the results obtained from one single index test, the Alstom's special measurements team adapted the procedure proposed by Lee Sheldon (Sheldon, 2012) in order to extrapolate the best cam curve obtained from an index test to a set of 5 cam curves covering the whole operational range of the unit under test.
From the graph on Figure 1, one can define a combination of blades and guide vanes position that will maximize the unit's efficiency. For this unit, the result would be those represented with the square dots on Figure 3. On the Figure 4, the variation of gross head for these measured points is shown. Instead of the value shown at the SCADA, the values presented were calculated using the measured discharge and the real head loss estimative, as described on item 1.3.

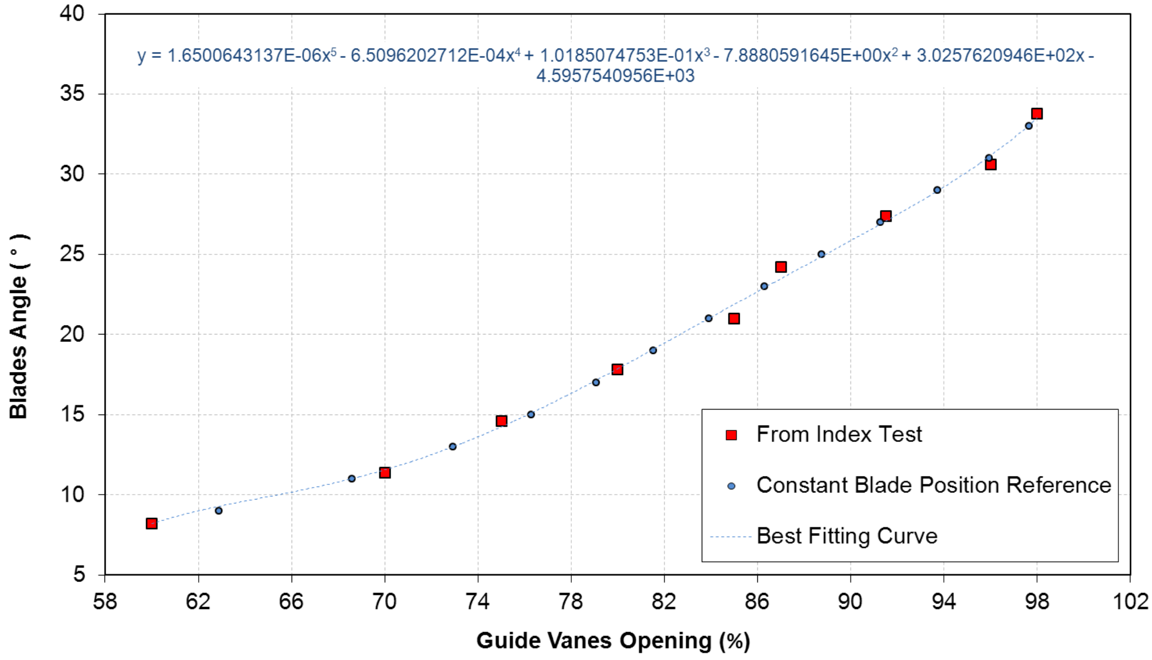

Figure 3 – Best combination of guide vanes angles and blade angles obtained from the index test.

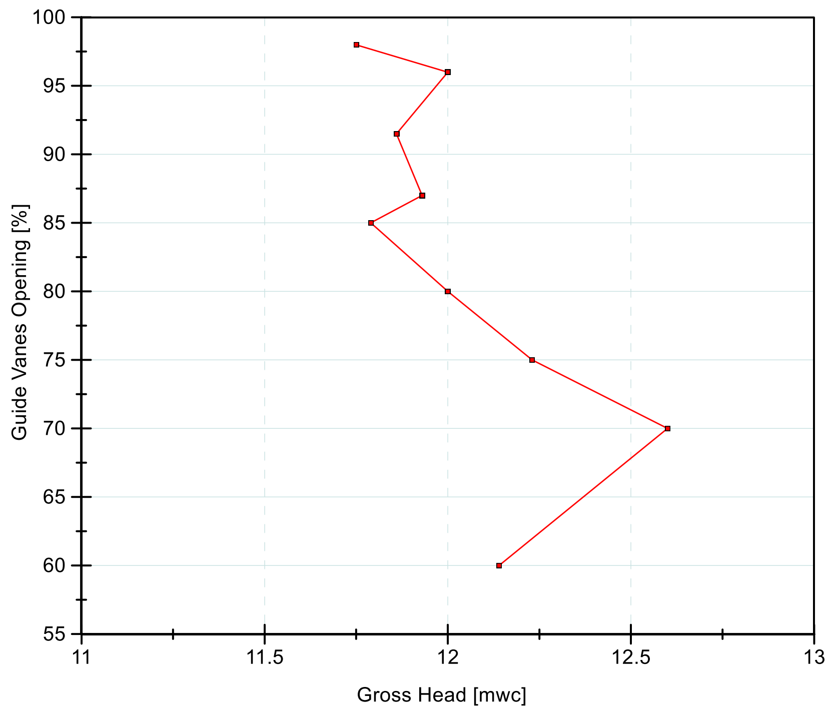

Figure 4 – Best measured guide vanes opening as a function of the measured head.

The next step requires information from the model test. Using the model test hill chart, it is possible to draw lines of constant blade opening as a function of the gross head (Figure 5). Scale model test results are usually given in net head values. The conversion to gross head must also be done with the head loss coefficient measured on-site.

The method presented on this paper is based on graphical analysis and the idea of using scale model results is to visualize how the guide vanes should open or close as the gross head varies. Taking that

in consideration, it is not important if there is a small variation between the best blade position measured on the scaled model test and the position measured on the prototype. The idea is to keep the same shape of the curves found on the model test in order to allow the extrapolation of the index test results to the whole head range.
The blue dots on Figure 5 are the points where the constant blade opening curves cross the lines connecting the points measured on the index test. With the guide vanes opening values of these points, it is possible to find the equivalent blades opening on the graph of Figure 3.

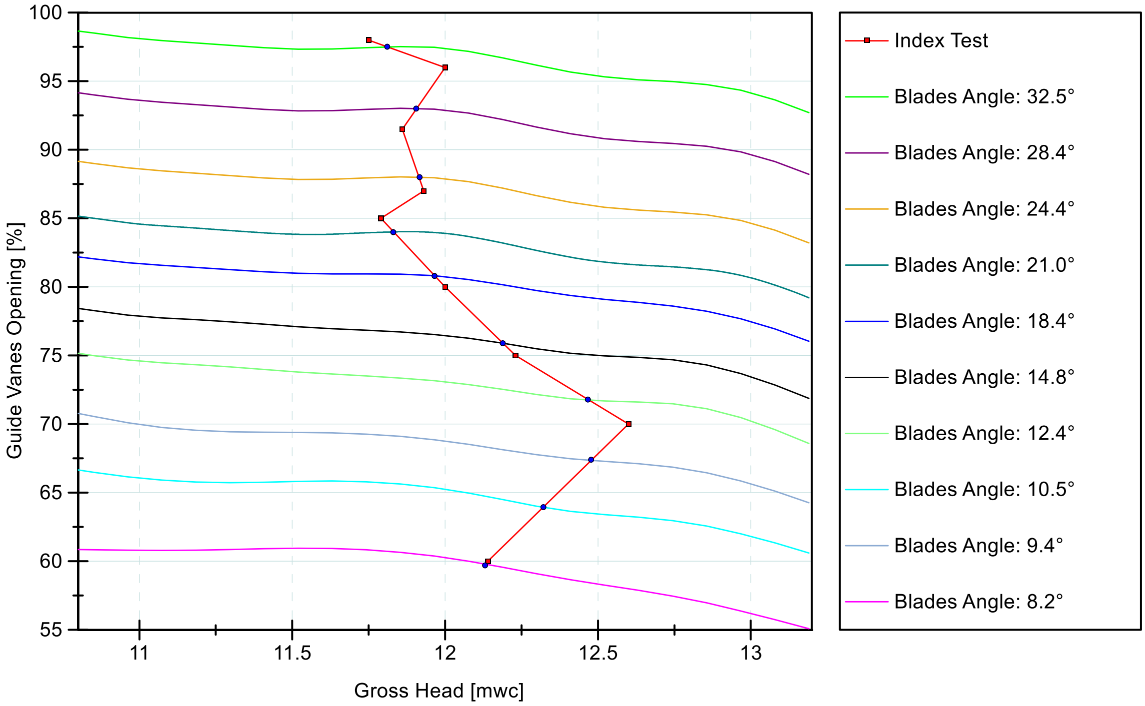

Figure 5 – Plotting constant blade opening curves as a function of the gross head. Even though the shape of the curves is based on model test results, the blades angles are defined on the prototype's index test.

The Alstom's speed governors have 5 cam curves for 5 different heads. Those curves are interpolated in between these heads to cover the operational range of the unit. The graph on Figure 6 defines 5 constant heads for this example: 11, 11.5, 12, 12.5 and 13 meters of water column. The triangles on the graph show the points where the constant blade angle curves cross these heads.
As a result, 5 cam curves that will maximize the unit's efficiency on any head are defined. They are presented on Figure 7.

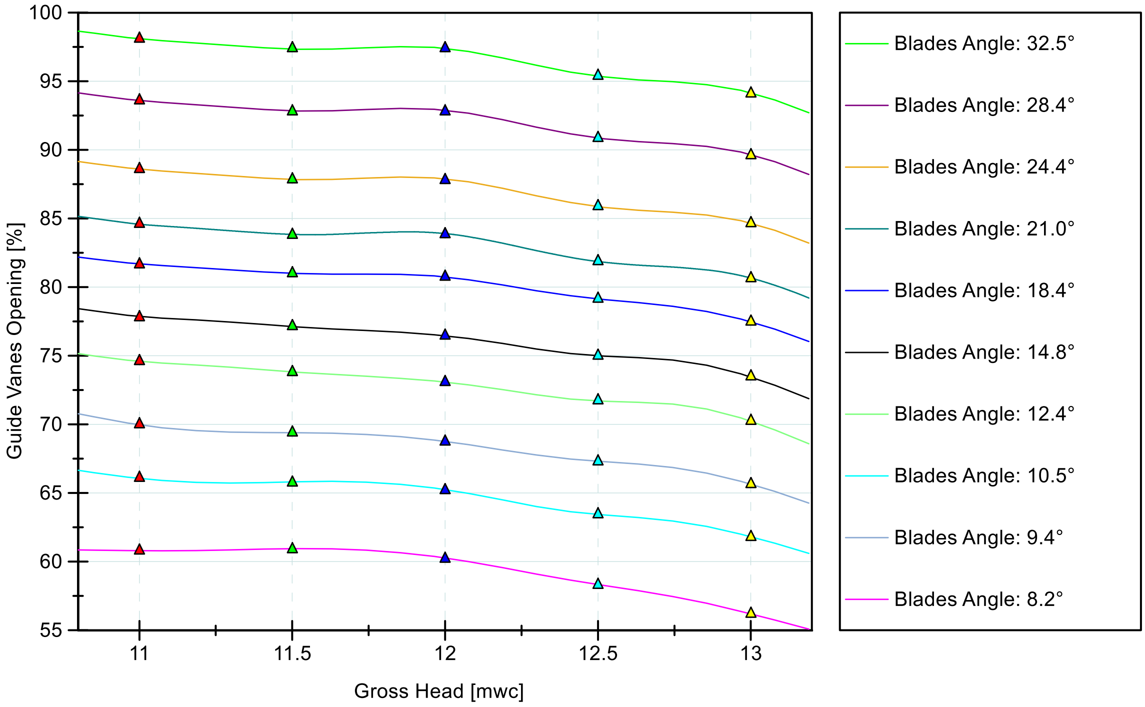

Figure 6 – Defining the blades angle and the vanes opening for 5 different heads.

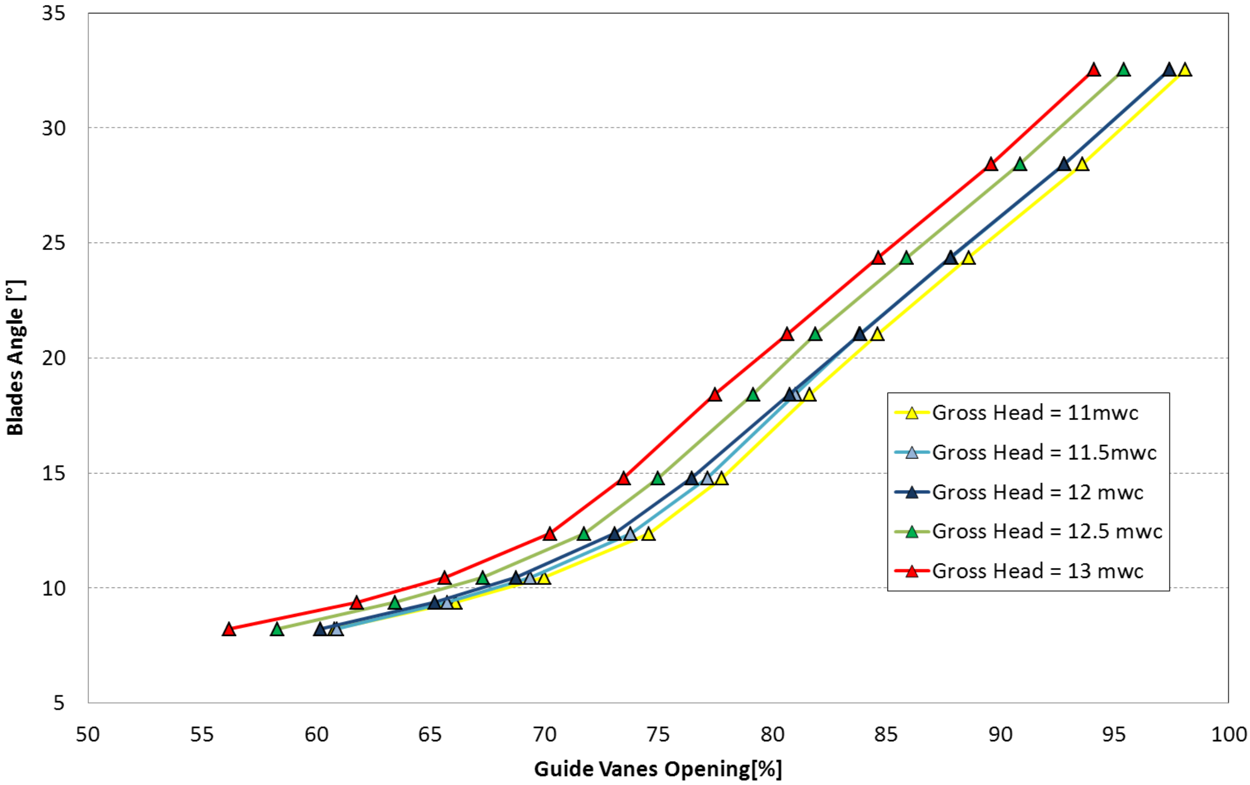

Figure 7 – 5 cam curves covering the whole operational range.

3 CONCLUSION

This paper presents some important steps that must be taken in order to perform an accurate index test followed to a procedure to extrapolate one single cam curve found on an index test to a set of 5 cam curves, covering the entire operational range of the unit.
The measurements results obtained in one power plant in Brazil are presented. The resulting set of cam curves were implemented on the unit's speed governor and are performing very well.

NOMENCLATURE

g	Acceleration due to gravity
H_G	Gross head
H_L	Head Loss
H_n	Net head
p	Gauge pressure
Q	Discharge
υ	Mean flow velocity
z	Level
ρ	Density

Subscritps

1	High pressure reference
2	Low pressure reference
3	Water intake reference
4	Water outlet reference

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Sheldon, L. (2012, March-April). Method to Delevop a Family of Cam Curves from a Single Index Test. *HRW - Hydro Review Worldwide*, pp. 40-45.