Iso-Power cam curve testing for optimal blades/wicket gates law for Kaplan Turbines

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Abstract

The article presents the development of a testing technique of cam curves, inspired by an article presented at the IGHEM in 2018. EDF Hydro is working to improve and industrialize the method for quick-finding the optimal blades/wicket gates law for double regulated turbines. This technique has one powerful advantage: it does not need any discharge measurement to find the optimal efficiency of the turbine in specific operating parameters.
As long as the parameters involved in the determination of the optimal relationship are accurate, the need in complementary instrumentation is low and the impact on operating turbines almost non-existent.
In the future, a dynamic adjustment of the blades/wicket gates law can be considered, so as the turbines operate all the time on their best efficiency points

1. Introduction

The optimal blades / wicket gates laws, also called optimal cam curves, can be theoretically determined with calculations and testing on a model, but the validation of those laws with on-site testing is essential. EDF Hydro has historically used the iso-blades position method with discharge measurement in order to determine the optimal cam curve (at a specific head) for Kaplan turbines but nowadays, one of the biggest challenges in the hydroelectric industry is to develop low-cost and yet high-quality testing methods to find the best balance between efficiency and cost of operation of turbines.
To face this challenge and inspired by the article [1] presented at the IGHEM 2018, EDF Hydro is working to improve and industrialize the iso-power cam curve method for quick-finding the optimal law. This technique has major advantages: it does not need any discharge measurement, it is a time-saving method and has almost no impact on operating machines.
EDF Hydro has started post-processing the historical data in order to have a comparison between the original method and the iso-power cam curve method and as these results were promising, on-site tests were scheduled in order to confirm the method.

2. Theoretical optimal blades/wicket gates law for Kaplan turbines

2.1 Definition

Kaplan turbines are double regulated machines and therefore they are quite interesting to operate as they can be precisely controlled with a speed governor over a wide range of head and discharge.

The optimal blades / wicket gates law is a unique and precise combination of regulating equipments' openings and allows the units to theoretically operate with its best efficiency at all time for a given head. Those laws are usually issued from testings on a reduced-scale model but the implementation in the speed governor often reveals discrepancies between the model and the actual prototype.
Many factors may play a part in those deviations such as:

- Head information (net or gross) considered for the model and by the speed governor
- Actual head loss in the unit's water intake which was considered for the model testing
- Errors between the information used by the speed governor and the real position of the blades and/or wicket gates which was either wrongly adjusted during commissioning or shifted due to sensors drifts
- Influence of the unit's disposition in the front of the water flow within the power plant
- Influence of the unit's mechanical general condition (turbines bearing, wicket gates…)
- Existence of hydraulic instabilities at certain operating points due to mechanical disorder, due to non-homologies between the model and the actual unit or due to unreliable equipment

Those theoretical laws must be verified by performing an on-site index test and eventually be modified to minimize the influence of the above factors in order to provide a smooth operation of the unit running within its best possible efficiency.

2.2 Physics behind the optimal blades / wicket gates law

A unit's efficiency is directly linked to certain parameters such as power, head, flow rate, wicket gates opening and blades position which are nothing but reaction turbines operating parameters. Since we can choose to set specific values to certain parameters such as to the couple {Power; Head} or {Blades position; Head}, the unit's efficiency varies with the others parameters.
It is essentially due to the water flow created by the wicket gates opening and the forces generated onto the runner blades.

The analysis of the forces acting upon the runner blades, for each variation of the non-set parameters, helps to understand the shapes of the curves. Each of those curves seems to have systematically a unique inflection point which theoretically corresponds to the best efficiency point. Therefore, the best associated values of the unit's operating parameters can be found.

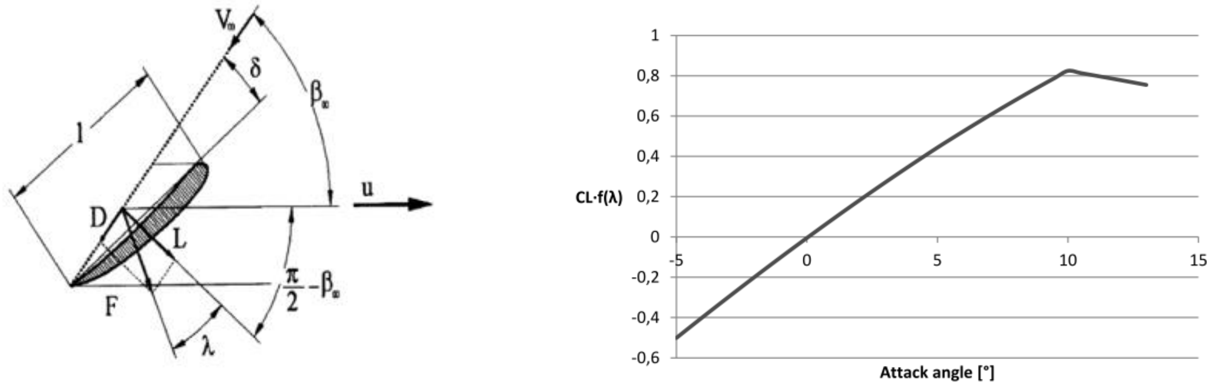

Figure 1: Vector representation of the forces on a runner blade (left) and Influence of the attack angle on the efficiency curve (right) [2]

From the vector representation of the forces on a runner blade in Figure 1 and as detailed in the document [2], the efficiency can be expressed as follows:

$$\eta = C_L.\frac{l}{t}.\frac{u}{H}.\frac{V_\infty^2}{2.V_{ax}}.\frac{\sin(\beta_\infty - \lambda)}{\cos(\lambda)} \tag{1}$$

$$\lambda = \tan^{-1}(\frac{C_D}{C_L}) \tag{2}$$

$$t = \frac{2.\pi.r}{Z} \tag{3}$$

With

λ	angle of the force F, sum of the drag and lift forces, with the normal of the blade
C_D	drag coefficient
C_L	lift coefficient
l	length of the blade
v_∞	relative and average water velocity at the leading and trailing edge of the blade
u	peripheral water velocity
β_∞	angle between v_∞ and u
H	Head
Vax	axial water velocity
t	blade pitch
r	radius of the unit
Z	number of runner blades

The curve displays a clear inflection point which matches the best efficiency point.
This is what one is looking for in order to adjust the cam curves, using whichever method.

3. Comparison of blades/wickets gates law determination methods

3.1 Theoretical reminder of the methods and their implementation

3.1.1 Iso-blades position and discharge measurement

The determination of the optimal cam curves with iso-blades position and discharge measurement is well-described in the IEC 60041 and the American norm PTC-18. This is the historical method used by EDF Hydro
The method will generate results such as shown in the graph on Figure 2.

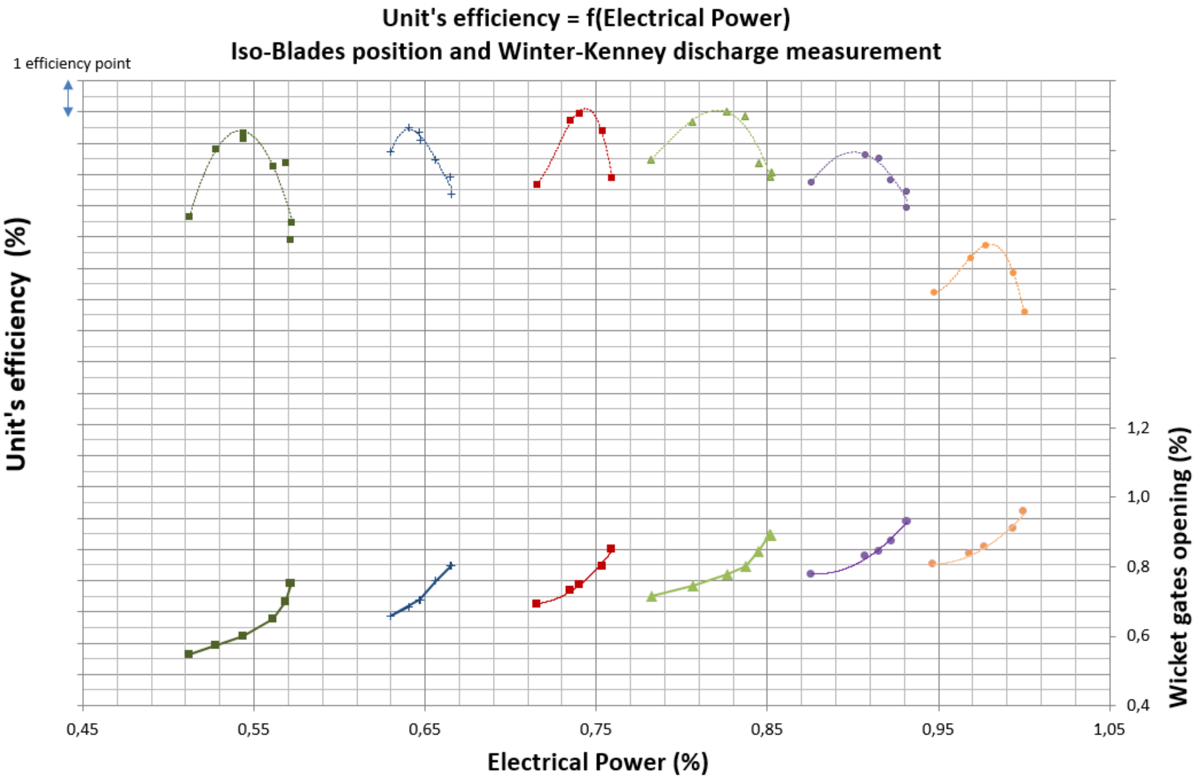

Figure 2: Graph from 2019 on-site test of one of EDF's turbines with iso-blades position and discharge measurement by Winter-Kennedy method for a given head

The instrumentation requires:

- Blades position (complementary and governor)
- Wicket gates opening (complementary and governor)
- Discharge measurement (Winter-Kennedy method or propellers)
- Electrical power (complementary and governor)
- (Gross or net) Head (in a ±2% window around a given head) (complementary and governor)

The procedure is quite time-consuming and consists in fixing the blades position ad varying the wicket gate position while setting the head in a ±2% variation. The efficiency is calculated for each combination. As the above graph shows, a blades/wicket gates law will maximize the unit's efficiency at this specific head.

3.1.2 Iso-Power cam curve

The experiments described in the article [1] are digital speed governor-oriented for integrated power output control loop. It is working only if the hill charts are known and loaded in the governor in order to have automatic adjustments.
The intersection between the iso-power curves and the power cam is the optimal operating point. Only the power output, blades and wicket gates positions need to be measured.

Most of the time, the hill charts are not known or difficult to find out.
The optimal cam curves are therefore determined with on-sites measurements with complementary sensors.
Without the hill charts and any discharge measurement, the iso-power method only need to have the power output and the head set, then the unit's efficiency varies with the other parameters, essentially due to the attack angle of the water flow on the blades, as described in §2.2.

The iso-power curves tend to show inflection points that can be reasonably identified as optimal operating point.
As a consequence, the interpolation between all inflection points of several iso-power curves is the optimal blades / wicket gates law as displayed in the figure below.

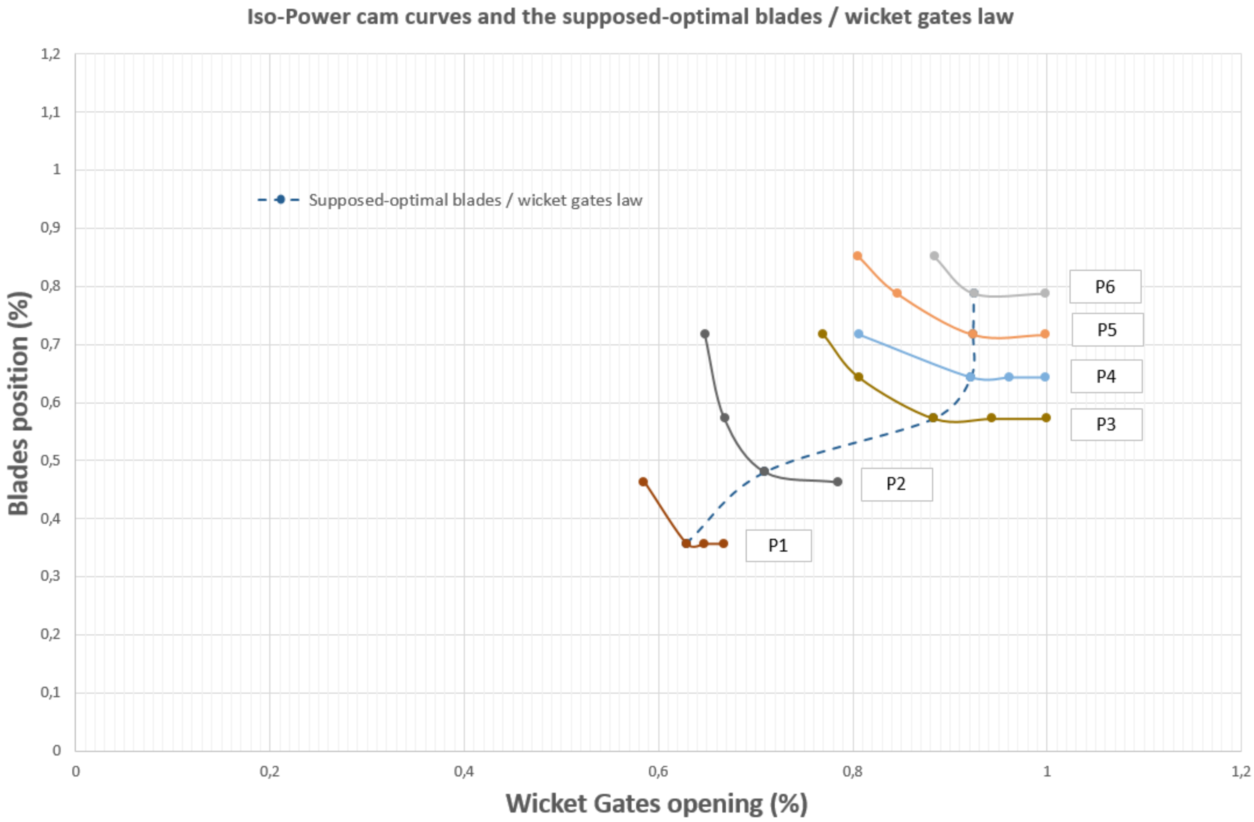

Figure 3: Graph from ancient but complete on-site test on one EDF's unit for a given head

The post-processing of ancient data confirmed the theoretical predictions but as there is a lack of information on the measurements uncertainties or on sensors' details, location, no clear conclusion could be drawn in terms of conformity of the method.
This is the reason why further on-site testing has been performed. The necessary instrumentation for the iso-power cam curve method is time-saving (compared to the historical method) and requires:

- Blades position (complementary and governor)
- Wicket gates opening (complementary and governor)
- Electrical power (complementary and governor)
- (Gross or net) Head (in a ±2% window around a given head) (complementary and governor)

The complementary instrumentation can be avoided with anticipated checking of the sensors consistency and accuracy.

3.2 Comparison and consistency

The comparison has been led on an EDF's unit of a run of river power plant. The methods mentioned above were deployed in order to collect and compare data.

The instrumentation consisted in:

- Speed governor's input information (Electrical Power, gross head, blades position and wicket gates opening)
- Electrical power (EDF Hydro wattmeter)
- Gross head (EDF power plant radars)
- Blades position (EDF Hydro cable sensor)
- Wicket gates opening EDF Hydro cable sensor)
- 3 Winter-Kennedy couples (EDF Hydro differential pressure sensors)

The commissioning errors or sensors drifts between speed governor's input information and the on-site measurements must be known in order to load the right values of the optimal cam curve in the speed governor for a given head.
The consistency between all those parameters is a requirement for implementing any of the mentioned methods.

The cross-checking was done on a specific on-site test as shown in the Figure 4.

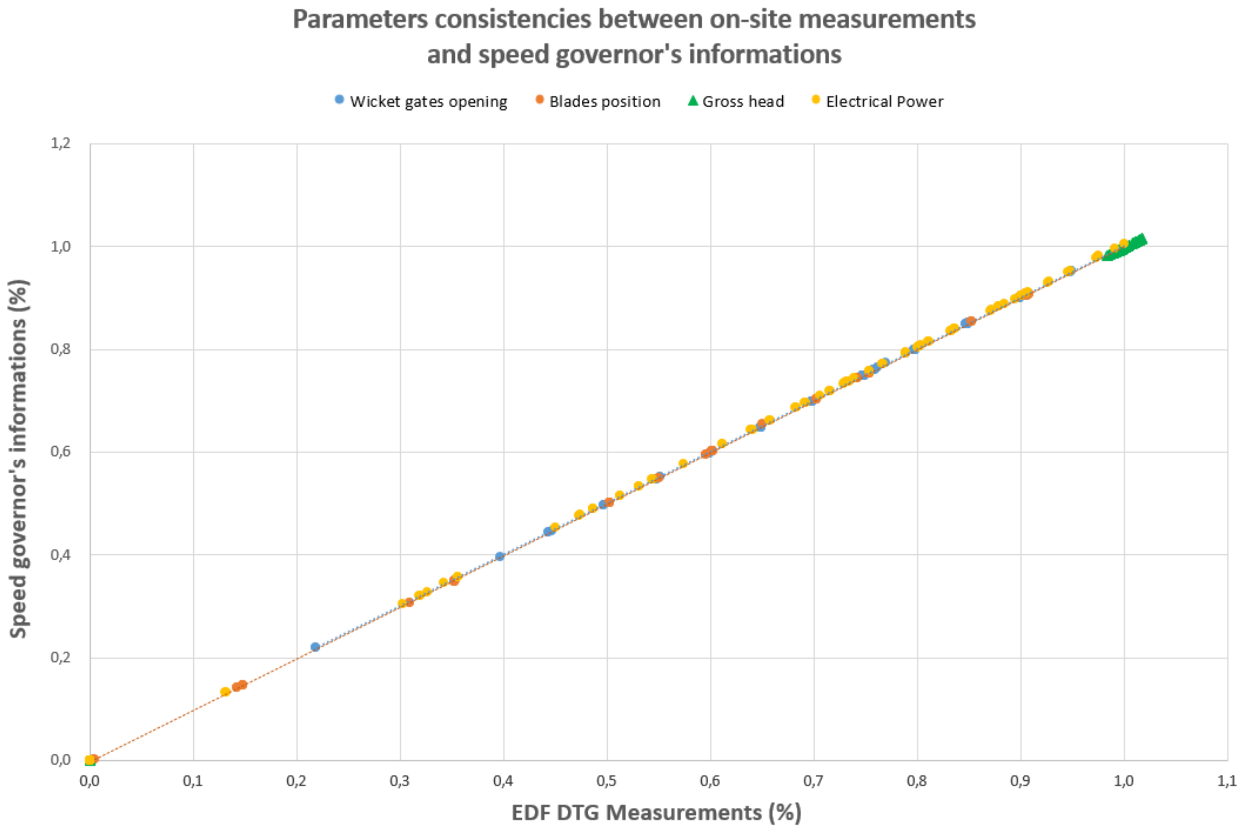

Figure 4: Consistency checking between speed governor's input information and on-site measurements

The iso-blades position method with Winter-Kennedy discharge measurement was done in 3 days (with complementary instrumentation included) and the results are displayed in the Figure 5 below.
The black dotted curve represents the maximized unit's efficiency.

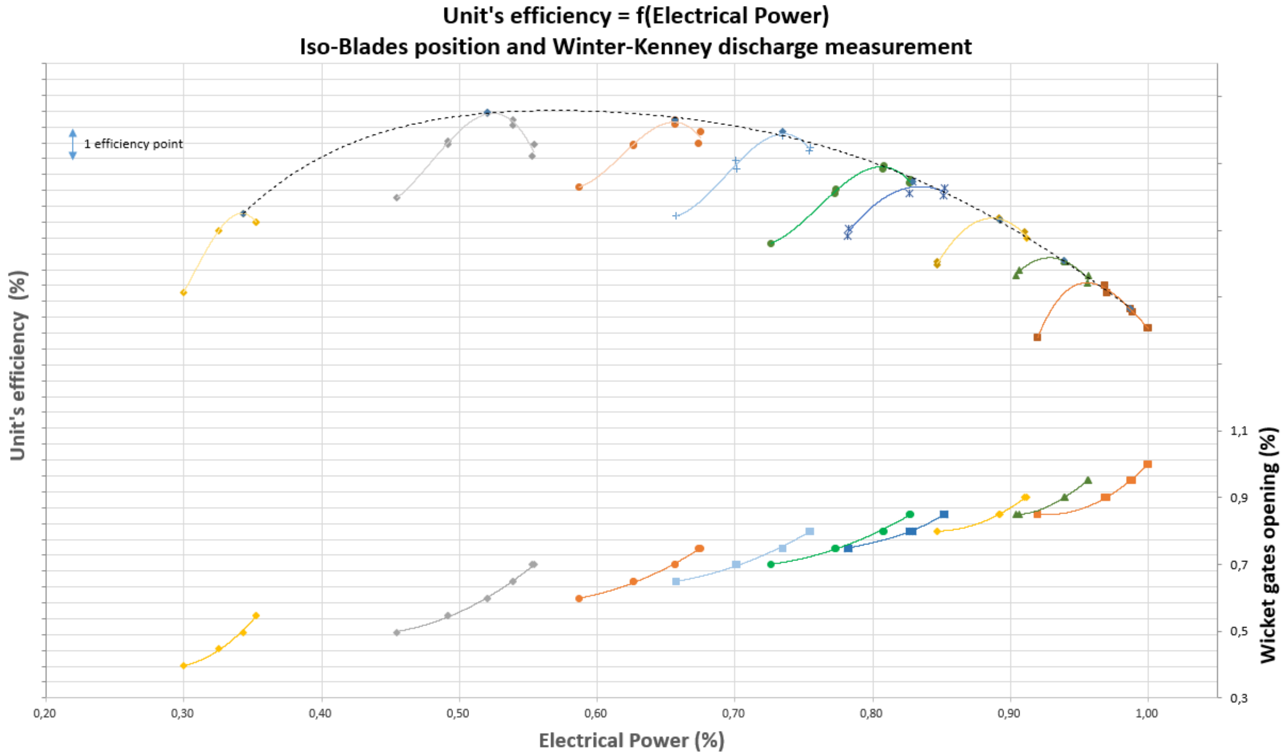

Figure 5: Efficiency curve obtained with the iso-blades position method with Winter-Kennedy discharge measurement for the tested gross head

The corresponding blades / wicket gates law is shown in the following graph in green, with a blue envelope representing a 0,5% efficiency loss due to wicket gates over and under- openings for each set blades position.
In the same graph is integrated the different iso-power cam curves.

However, the inflection points are not quite sharp in this example, probably due to the choices made on site on the gap between different openings.

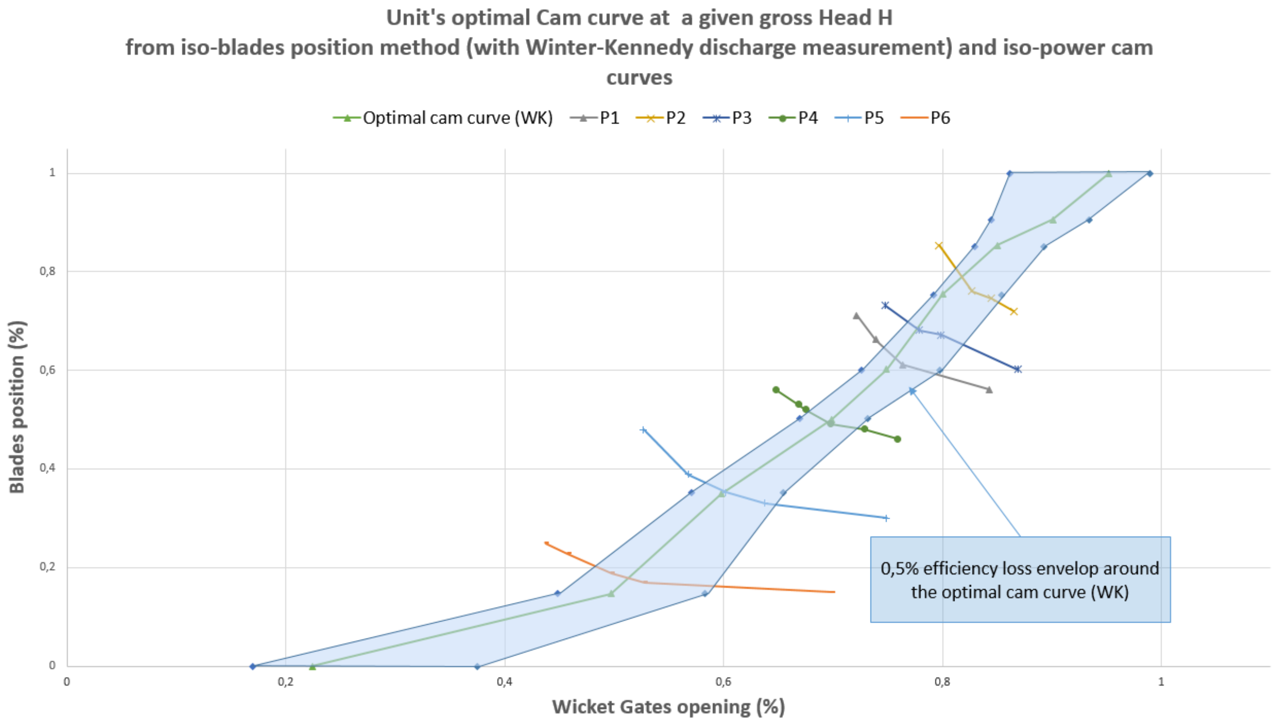

Figure 6: Superposition of the optimal cam curve from the two tested methods

4. Conclusion

As the comparison shows, the iso-power cam curve method seems to be promising. As long as the parameters involved in the determination of the optimal relationship are accurate, the need in complementary instrumentation is low and the impact on operating turbines almost non-existent.
Even though the iso-power method has the drawback of not allowing the knowledge of the unit's performance, EDF Hydro plans to industrialize this low-cost and quick-finding method in a close future and to perform on a large-scale the tests for units on run of river power plants and small facilities.
This method can also be considered to be of help in case of discharge measurement failure by index-testing (due to clogged pressure taps) so as not to waste the cost of the on-site testing.

References

[1] V.O. Voitenok, O.I. Bashnin, D.N. Klevin, « Power cam relationship », IGHEM 2018, Beijing.
[2] Cervantes, « Propellerkurvor », 2015