Power cam relationship

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Abstract

During usual operation, turbine net head and discharge measurement for **powerful** (higher than 50 MWt) **low-head** (at absolute values up to 20 meters) Kaplan turbines without penstock period is a problem nowadays, as well as a fact that they are used for cam relation.
This article is not about new turbine head and discharge measurement, it is about a new technology to solve the problem from the other side.
Current governor cam relationship mechanism was invented more than century ago and have not changed through these times, despite a digital progress and significant disadvantages. Described scientific work results suggest a new proper full-efficient cam relation mechanism for all digital turbine governors, which request only default governor precise measures without need of head and discharge values.
The methodology is now putted in operation at Novosibirsk (7xPnom=72 MWt, Hnom=17 m) and Shulbinsk HPP (6x120 MWt and 28 m) and already has shown significant results during preliminary tests. Solution is **integrated inside power output control loop** without harm to stability and performance.

1. Introduction

For mentioned turbine type, discharge measure during operation is a headache. There is no place for placing ultrasonic sensors for valid laminar water flow to measure discharge. Absolute current method is not suitable for continuous operation. Winter-Kennedy method is unstable and suitable only for special tests, held by professionals. During operation, sensors and Winter-Kennedy measure pipes are spoiling. At table 1 comparison between different methods for low head (<50 m) turbines is shown, for lower heads (<20 m) situation is even worse.

Table 1: Available discharge measurement method and its development status for low head plants[1].

Method	Type	Development status for low head	Estimated cost (MSEK)	Practical Uncertainty at 95% confidence level
Winter-Kennedy	Relative	Low	0.2	<±10%
Pressure-time	Absolute	Very low	0.2	<±1.4%
Transit time	Absolute	Average	1	<±0.1%
Scintillation	Absolute	Low	1	<±0.5%
Current meter	Absolute	Very good	1	<±1.2%
Dilution	Absolute	Very low	0.2	<±3%
Volumetric	Absolute	Very low	0.2	<±1.2%
Model testing	Absolute	Very good	5	<±0.2%

Due to definition of turbine (net) head, it is a difference between energies of water at input of hydrotubine and draft tube output. As it can't be measured directly, different calculating techniques are used: from water levels to pressure difference. For example, according to this source[2], calculation take some complicated way with hard measure values:

$$\mathrm{H} = H_{head} - H_{tail} - h_{loss} + \frac{\alpha_0 v_0^2}{2g} - \Delta h_{tail} - \frac{v_{tail}^2}{2g} \qquad (1)$$

That will cause hard maintenance and inaccuracy, especially for large hydroturbines. Because it's calculated through many hard measured parameters, including discharge, error could reach a value up to 20% of actual head[3]: there are effects, such as head loosing before runner, trash rack spoil, wind water relocation in river, ejection effect due to neighbour hydroturbines, etc., that noticeably change net head without ability to measure.
All that is critical for Kaplan turbine performance, because it's governor use net head value for cam relationship (Fig. 1). It is well known that wrong cam relation lead to problems with efficiency loss and equipment run-out, what is directly correlated with economic point.

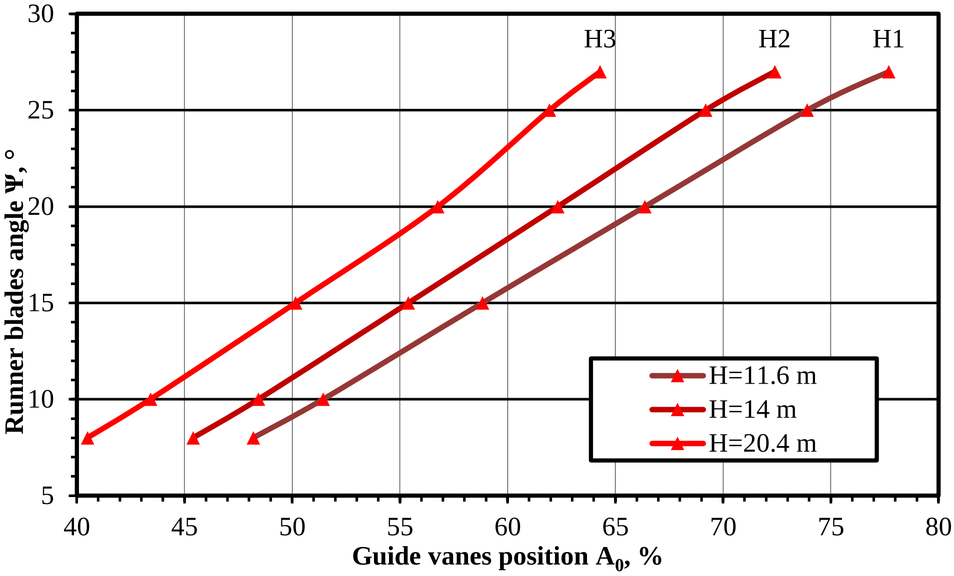

Figure 1: Classic cam relation curves

Some researches through most of largest low-head HPP at CIS showed, that using difference between water levels as head could bring to measurement error from +3.8% to -11.6% [3].

More than that, head measurement in turbine IEC 60041-1991 field acceptation tests could not be suitable too, though it held by professionals with special measure instruments, because this value is used to rate other parameters under single head value. Hence, there definitely would be an error between head measure during field test and usual operatiion. So, in classic case, governor do wrong cam relations, even if maximums of CoP were found correctly to build cam curves, **but parameterised with head values**.

If, with classic cam relationship, one cannot measure head accurately, there would be efficiency loss. Loss depends on mentioned various parameters and conditions. For some turbines, especially at lowest heads and for old ones, loss could rise up to 4% [8] (according to researches of turbine characteristics). For modern system estimate loss is up to 1%.

You can try to measure head more accurately, set up dozens of individual sensors, but that is not cheap and requires serious maintenance. What if there is a way to evade using hard-measured variables? **After all, classic cam relationship has been invented in early 20th century, but still being used in same form even for digital governor systems in spite of mentioned problem.**

2. Power cam relation mechanism

2.1 Use of power output value

Commonly used cam relation mechanism do not use power output value at all, though mechanical turbine power, easily calculated from generator active power in most cases (usual operation in grid), includes integral information about it. Turbine power is a complex operation mark and should be used at the top of the agenda. It depends on desirable unknown parameters: head and discharge. Turbine power can be easily calculated dividing an electric active power by generator CoP, that nowadays is measured very precisely thanks to high-quality digital converters and instrument transformers with accuracy class up to 0.1[2]

The solution is to switch from net head value to turbine power for Kaplan turbine cam relationship.

Of course, one cannot easily change the used value: one need to change cam mechanism and modern digital systems are capable to bring a solution.

2.2 Theory

Well known, that cam relation curves basically are sets of points (A_0,Ψ,H) for different heads, where mode would be most efficient — "cam related". If we add to every point information about turbine power at that moment, so it would be sets of (A_0, Ψ, H, N), we achieve a new interpolation function N=f(A_0, Ψ), that can be called power cam function[4]. It is graphically shown by equal power curves on the Fig. 2 (black lines). Classic head curves are showed too for comparing (red stroked lines).

Important, that power cam function is **strictly monotone and almost linear** for all turbines in normal operation state; therefore, it can be used in control loops.

To continue an explanation, some basic turbine governor terms are to be told:

- $$x = \frac{n - n_{nom}}{n_{nom}} \quad (2)$$

— per-unit turbine speed (relative speed deviation);

- $$h = \frac{H - H_{nom}}{H_{nom}} \qquad (3)$$

— per-unit head (relative head deviation);

- $$m = \frac{M}{M_{nom}} \qquad (4)$$

— per-unit turbine torque (moment of force), equals per-unit power.

It is a common practice in turbine design to use so-called unit quantities: unit speed n'_I, unit discharge Q'_I, unit power N'_I and unit torque M'_I. The unit values are defined respectively as the speed, discharge, and power of a turbine having a runner diameter of 1 m, for a head of 1 m[5]. Due to well-known turbine design formulas:

$$n'_I = n \cdot \frac{D}{\sqrt{H}} \quad N'_I = \frac{N}{D^3 H \sqrt{H}} \quad M'_I = \frac{N'_I}{n'_I} = k\frac{QH}{n} \cdot \eta \cdot \frac{1}{D^3 H} \qquad (5)$$

And now one can define per-unit unit quantities values formulas:

$$\begin{cases} \dfrac{n'_I}{n'_{Inom}} = \dfrac{n}{n_{nom}} \cdot \dfrac{\sqrt{H_{nom}}}{\sqrt{H}} = \dfrac{n_{nom} + (n - n_{nom})}{n_{nom}} \cdot \dfrac{\sqrt{H_{nom}}}{\sqrt{H_{nom} + (H\text{-}H_{nom})}} = \dfrac{1+x}{\sqrt{1+h}} \\ m'_I = \dfrac{M'_I}{M'_{Inom}} = \dfrac{k}{k} \cdot \dfrac{M}{M_{nom}} \cdot \dfrac{H_{nom}}{H} = \dfrac{m}{1+h} \end{cases} \qquad (6)$$

Using hydro turbine universal characteristics, per-unit quantity torque curves for different guide vanes opening and different runner blades angle can be built (as a function of relative per-unit quantity speed, **that is equivalent to head change**) $\frac{m}{1+h} = m'_I\left(\frac{1+x}{\sqrt{1+h}} \mid a_0, \psi\right)$. Example of curves for modernised Novosibirsk HPP unit is shown on the drawing. Curves were made with model test by manufacturer, and, as well known, models don't have rotary runner blades and that's why different models with set of angles are used (in this case it's 5, 10, 15, 20, 25, 30, 35 degrees).

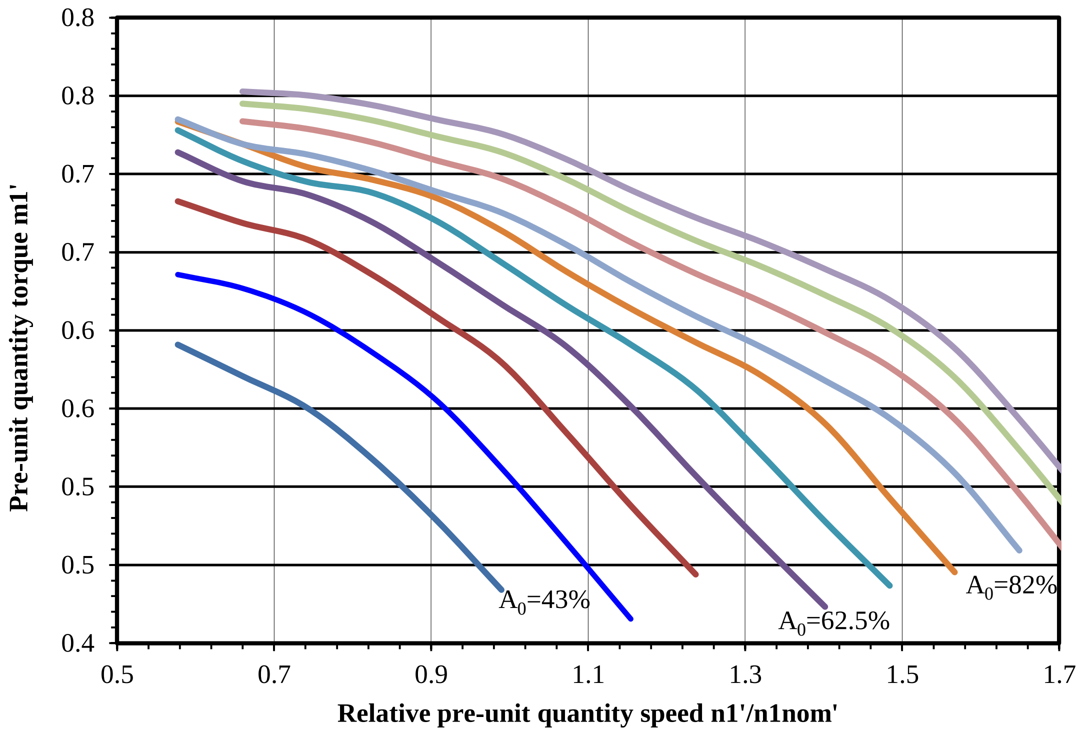

Figure 2: Per-unit quantity torque quantity curves for 20 degrees runner blades angle

Now, if we define derivative of per-unit torque as a function of head, it can be assured to be always positive:

$$\frac{\partial m}{\partial h} = \left(m_I'(\frac{1+x}{\sqrt{1+h}} | a_0, \psi) - \frac{1}{2\sqrt{1+h}} \cdot \frac{\partial m_I'(\frac{1+x}{\sqrt{1+h}} | a_0, \psi)}{\partial(\frac{1+x}{\sqrt{1+h}})} \right) > 0, \quad (7)$$

due to shape of curves (fundamental, not just single turbine characteristics): $\frac{\partial m_I'(\frac{1+x}{\sqrt{1+h}} | a_0, \psi)}{\partial(\frac{1+x}{\sqrt{1+h}})}$ is strictly negative.

All this confirm that cam relation points (A_0, Ψ, H) are unique same as A_0, Ψ, N). Developments, based on these conclusions allow to build workable and stable control system

2.3 Mechanism

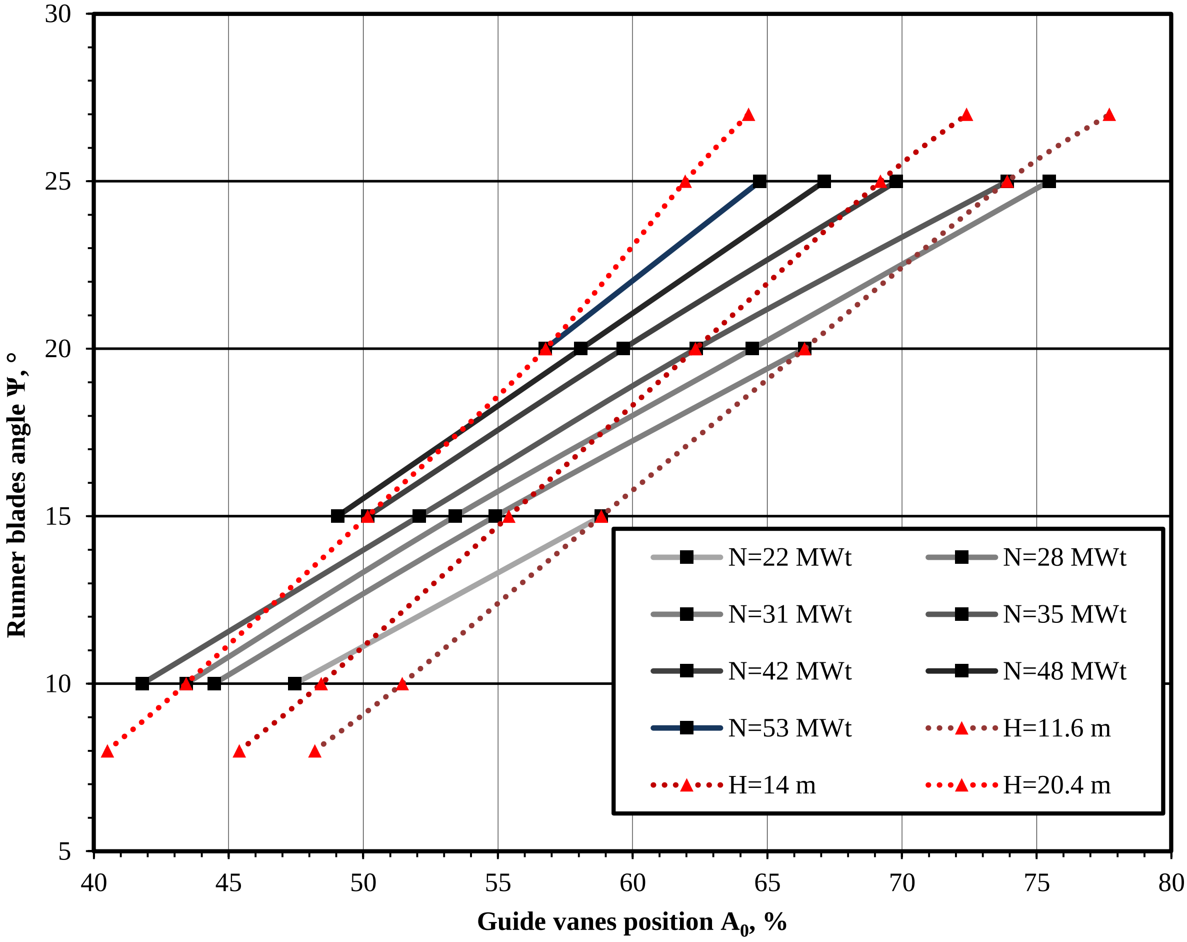

Figure 3: Used cam relations

It can be proved, that anytime during field tests or default operation in synchronous generator mode just one pair of guide vanes and runner blade can be found, where current turbine power would be equal to calculated power cam function (for current servomotors position), and more than that — **this point would be cam related** and most efficient for current conditions and power reference. Such cam relation mechanism should be called power cam: it doesn't need a head value at all, only turbine power required.

In simple terms: if in cam related point (a_0,Ψ) (during field or manufacturers model tests) there was certain power, but another day (after adequate period of operation after tests) with normal hydropower unit operation in same point (a0,psi) power is lower (higher), it could happen only if head decreased (increased). **That is the way to calculate a head** and use it in Ψ=f(a_0, H) relation.

Mechanism, based on these principles was developed during described science work. It is important for cam mechanism not to spoil dynamic performance of a governor, because it is a part of it and could seriously affect. The way it is

integrated with governor (power output loop) allows to operate with the same performance. Solution also integrated with "feed-forward" control type, that bring high-quality control in all control range.
Proposed mechanism doesn't requires measuring anything but servomotors positions and electric parameters to operate. It's obviously necessary measuring for every governor (and they are very accurate), so method require just a slight software changes for modern digital governor.

3. Method for power cam curves identification

3.1 Current status
As much as classic cam relation, power cam mechanism requires curves data to set it up. One can also use IEC 60041-1991 field test methods[6], where power output value at cam points is also measured (to calculate CoP). Cam curves could be found with records of power output in characterized points and be easily transformed without that head value needed. But in some cases (especially mentioned above) existing field test methods are not suitable due to inaccurate discharge measure or it requires too strong financing: hire external organisations, install special equipment, stop electric grid control and so on. And it should be repeated a least at 3 different heads during the year. More than that, tests have to take place again after some continuous operation.
By default, turbine manufacturer can provides cam relation curve based on model tests (with precise discharge and head measure), that could be enough accurate at least for new runner.
But to replace IEC 60041-1991 methods with another way without mentioned weaknesses, research was held.

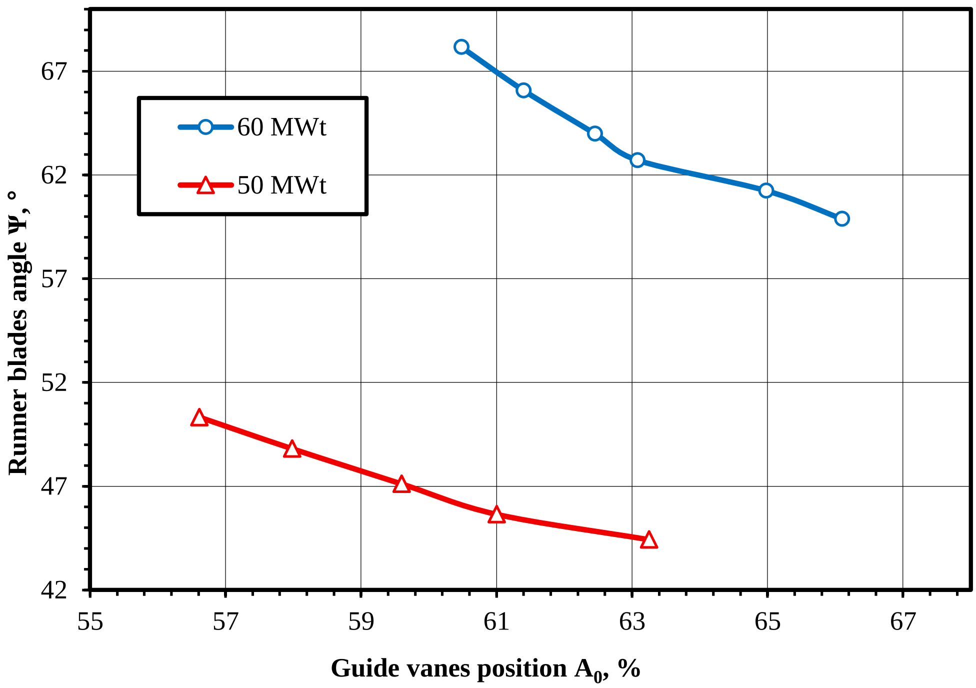

Figure 4: Equal power curves

3.2 Experimental method
New method was developed specially for use by power cam mechanism. It is based on existed experimental equal power methods, that use fundamental feature Kaplan turbine (and others with changeable wheel angle) of keeping same power with different guide vanes and runner blade relations (shown at Fig. 4). It's obvious that only one point at equal curve for referenced power at current moment of time is cam related. In simplified terms, developed method extract information from curve shape (in A_0, Ψ coordinates) and based on physical laws and common turbine properties. Requires only default governor measurements, same as power cam mechanism, servomotors position and electric power.
It was tested on significant number of digital hydroturbine models (that uses hill chart curves for different runner blade angles) and was confirmed with accuracy of CoP **lesser than 0.1%**, though part of it is definitely an interpolation error.
Following turbine models were tested:

- Novosibirsk HPP — TurboAtom manufacturer (hill charts for 7 runner blades angles) — max $\Delta\eta \leq 0.1\%$
- Utanen HPP — Power Machines manufacturer (5 angles) — max $\Delta\eta \leq 0.2\%$
- Sobradinho HPP — Power Machines manufacturer (3 angles) — max $\Delta\eta \leq 0.2\%$
- Svetogorsk HPP — Power Machines manufacturer (7 angles) — max $\Delta\eta \leq 0.2\%$

4. Field tests

Power cam mechanism and experimental equal power method actually were tested at Novosibirsk HPP and Shulbinsk HPP: Siberian low head stations with giant water flow through hydroturbines. While preliminary tests, methods and mechanisms were finalised and adjusted to enable them permanently (for now it unit 3 and 7 at Novosibirsk HPP). For new equal power method a redesigned search algorithm was invented and integrated.

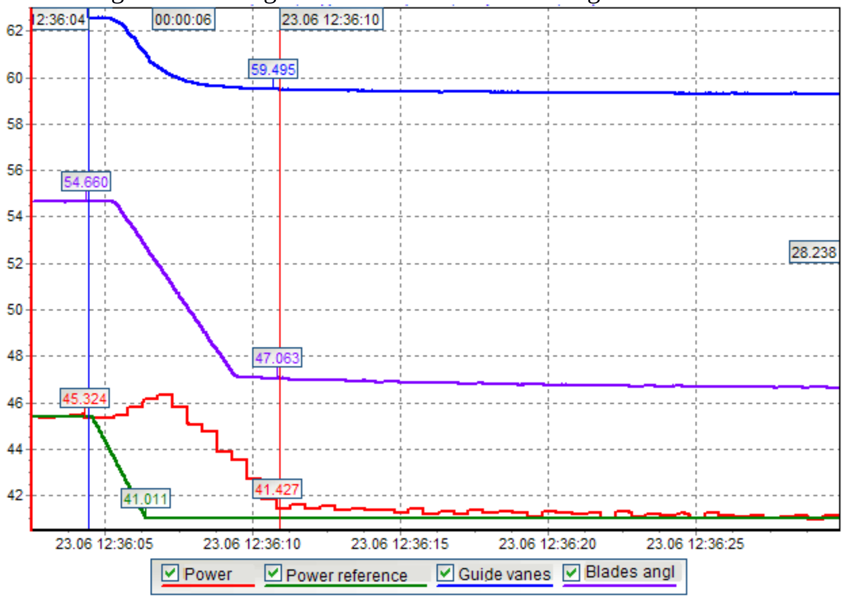

Figure 6: Power output step response with power cam mechanism

With use of provided by manufacturer full model turbine characteristics at Novosibirsk HPP tests were held instantly after total replacement of hydroturbines. Example of power reference change response for power cam relation mechanism is shown on Fig. 6. Also functions of finding head and calculating discharge were tested. Manufacturer model test field is well-build and precise[7], so characteristics can be trusted. For different power reference, described values were found, as shown on Fig. 7. Head failing with increased power looks right, because of obvious increased loss (proportional to squared discharge).

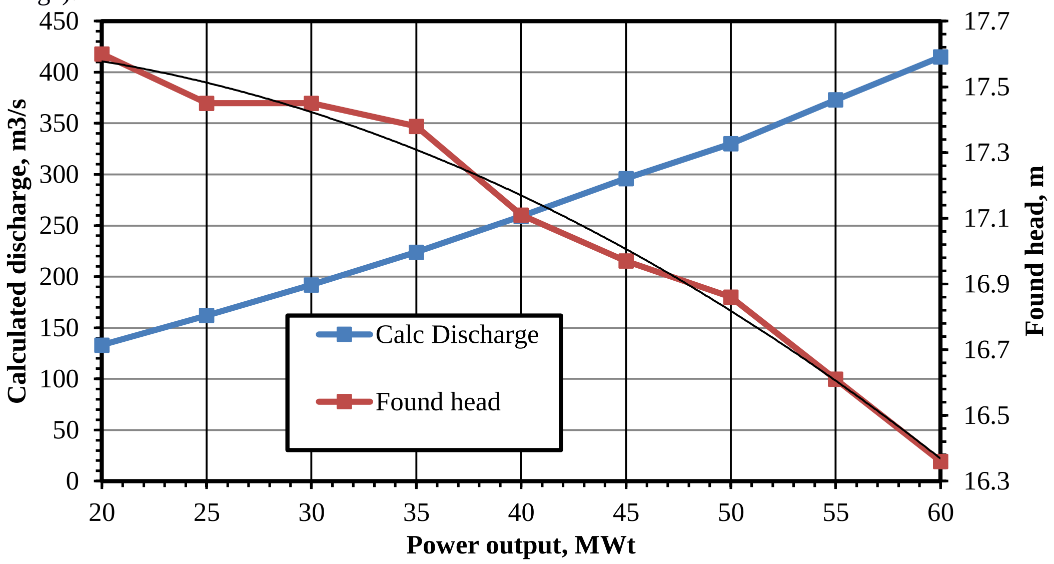

Figure 7: Calculated discharge and found head during field tests

At Novosibirsk HPP, also, joint side-by-side tests of Winter-Kennedy method and experimental equal power method were held at three different heads. Though the measurement can't be completely reliable, results are significant and grant reasons to continue a research. At the Fig. 5, power cam curves comparison is shown for a head, aligned to 18.09 meters.

Significant advantage of equal power methods in comparison with classic field tests is a capability to schedule power reference of turbine in advance before running any tests. Thanks to good measuring, in theory, method can be fully automated. At current state it can be run by local stuff without specially contracted engineers anytime during exploitation for different heads.

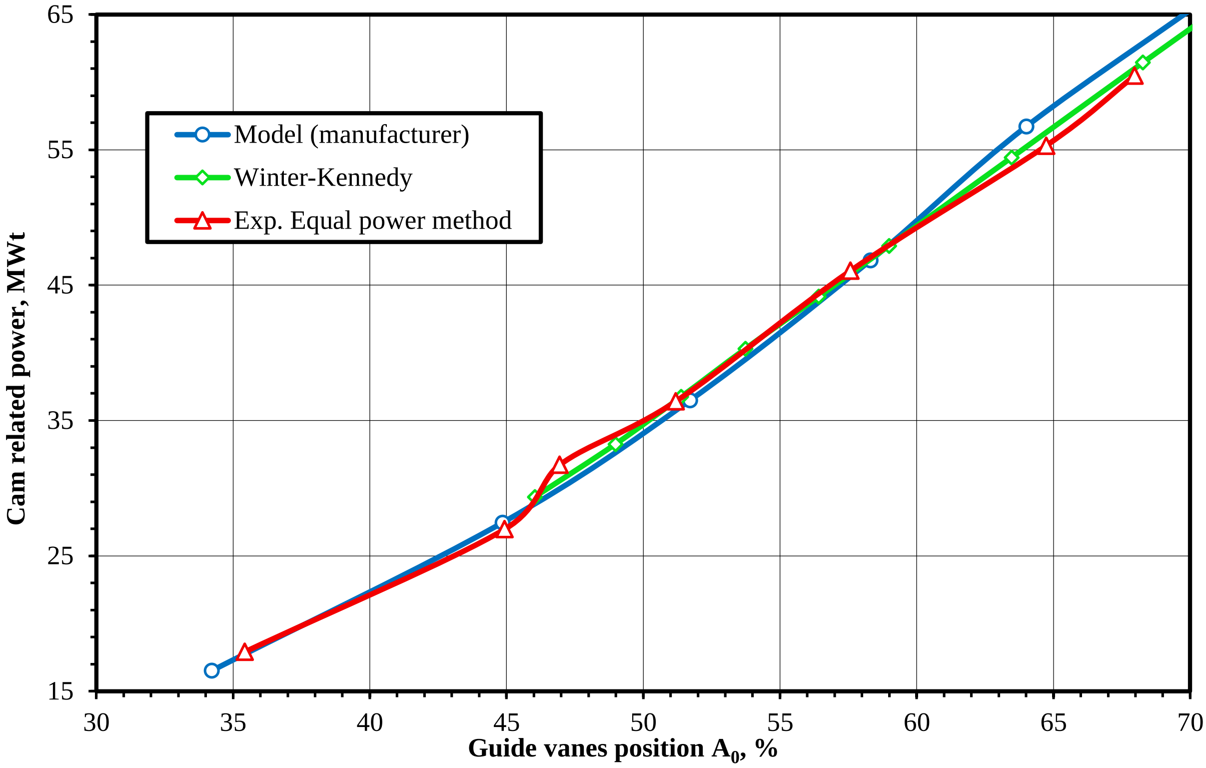

Figure 5: Comparison between cam curves identification methods

Conclusion

Advantages of power cam relation mechanism with:

- high accuracy cam relation due to accurate measuring;
- no need of head and discharge measuring;
- easy to integrate into existing systems;
- keeping dynamic and static performance on top level;
- integrated with 'feed-forward' type power output loop with slight enabling/disabling;
- automated method of adjusting power cam curves without discharge measure (*experimental).

At this moment our science group is improving software with new possibilities like fully automation for equal power method and some other features, increasing experience and reference at HPP with available-to-change governor systems. Unfortunately, we still hadn't opportunity to test in parallel with precise field test measuring with current meters and long straight penstock (though the method was invented for places without possibility of measuring, to prove it, a test unit would be great and confirmative).

Further work would take place at least at Cheboksarsk HPP (where we are going to change governors), as well as mentioned plants. We hope that results of this work would continue to spread international with improving global hydroenergy. We are open for new contacts and joint work.

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