Kaplan Turbine cam relationship based on use of electric power ouput value (*P*-cam relation)

Abstract (summary)

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 during usual operation period is a problem nowadays. There is no place for placing sensors for valid laminar water flow to measure discharge. Winter-Kennedy method is unstable and suitable only for special tests, held by professionals. During operation, sensors and Winter-Kennedy measure pipes are spoiling.

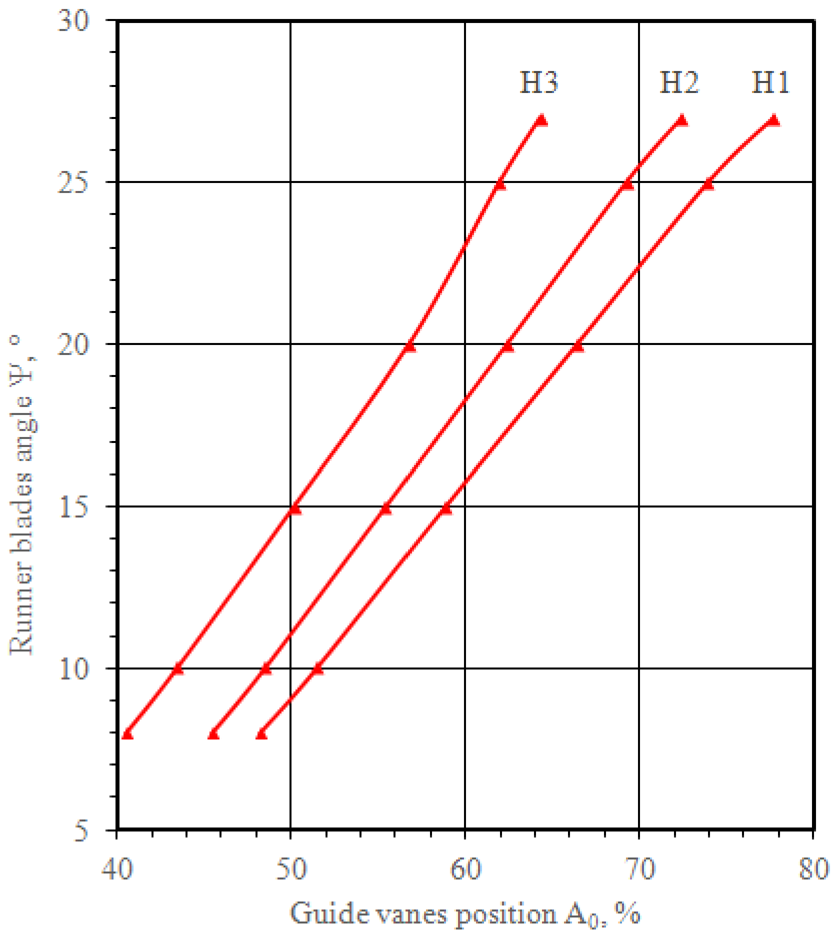
At this moment in Russia, due to experience with serious doubts, all IEC 60041-1991 methods for described hydroturbine are declined as suitable. As for turbine net head, that is calculated through many hard measured parameters, including discharge, error could reach a value up to 20% of actual head:

- There are effects, such as wind water relocation in river, ejection, etc., that noticeably change net head without ability to measure.
- Head loosing before runner is unmeasurable and uncalculated.

All that is strictly critical for Kaplan turbine performance, because it's governor use turbine net head value for cam relationship. It is well known that wrong cam relationship lead to problems with efficiency loss and equipment run-out, what is directly correlated with economic point.

Problems

Due to definition of head, it is a difference between energies of water at input of hydrotubine and draft tube output. Though can't be measured directly, different calculating techniques are used: from water levels to pressure difference. Anyway, it will cause hard maintenance and inaccuracy, especially for large hydroturbines



Classic cam relationship curves

Some held 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%.

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 parameters under single head value. So, in classic case of cam relation, wrong cams are used, even if maximums of CoE were found correctly to build cam curves, parametrized with head values. Hence, there definitely would be an error between head measure during field test and default exploitation.

If, with classic cam relationship, one can not measure head accurately, there would be efficiency loss. Loss depends on various parameters and conditions: trash rack spoil level, side wind, ejection effect due to neighbor hydroturbines and so on. For some turbines, especially at lowest heads and for old ones, loss could rise up to 4% (according to researches of turbine characteristics). You can try to measure head more accurately, set up dozens of individual sensors, but that is not cheap and requires serious maintenance.

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.

Use of power output value

Commonly used classic cam relationship do not use power output value at all, though turbine power, easily calculated from generator active power in most cases of operation, 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:

- turbine head;
- turbine discharge, that in it's case depends on head, guide vanes opening and runner blade angle.

You can't just use turbine power instead of head - you need to change cam mechanism and modern digital systems are able to find a solution.

Power cam relation mechanism

Well known, that cam relation curves basically are sets of points (A_0,Ψ,H) for different head, 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. It is graphically shown by equal power curves on the drawing (black lines). Classic head curves are showed too for comparing (red stroked lines).

Important, that power cam function is strictly monotone, therefore it can be used in control loops.

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

- $x = \frac{n - n_{nom}}{n_{nom}}$ — per-unit turbine speed (relative speed deviation)
- $h = \frac{H - H_{nom}}{H_{nom}}$ — per-unit head (relative head deviation)
- $m = \frac{M}{M_{nom}} = n$ — 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, unit discharge and unit power. 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[1]. Due to well-known turbine design formulas:

$$\begin{cases} n'_I = n \cdot D/\sqrt{H} \\ Q'_I = Q/D^2\sqrt{H} \\ M'_I = N/n'_I = Q/D^2\sqrt{H} \end{cases}$$

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

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

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) $\frac{m}{1+h} = m'_I(\frac{1+x}{\sqrt{1+h}} \mid a_0, \psi)$. Example of curves for modernized Novosibirsk HPP unit is shown on the drawing.

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

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

due to shape of curves (this us fundamental, not just single turbine characteristics):

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

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, 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.

Turbine power can be easily calculated by dividing on generator CoE electric active power, that nowadays is measured very precisely thanks to high-quality digital converters and instrument transformers with accuracy class up to 0.1.

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 was integrated with governor (power output loop) allowed 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 it is very accurate), so method require just a mathematical software slight changes for modern digital governor.

Cam curves

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, where power output value at cam points is also measured (to calculate CoE). 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 organizations, 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 manufactory 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.

Equal power curves

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 drawing). It's obvious that only one point at equal curve for referenced power 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 CoE **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 Δη ≤ 0.1%
- Utanen HPP — Power Machines manufacturer (5 angles) — max Δη ≤ 0.2%
- Sobradinho HPP — Power Machines manufacturer (3 angles) — max Δη ≤ 0.2%
- Svetogorsk HPP — Power Machines manufacturer (7 angles) — max Δη ≤ 0.2%

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 drawing, power cam curves comparison is shown for a head, aligned to 18.09 meters.

Comparison between cam curves correction methods

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.

Advantages list

of power cam relation mechanism with :

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

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 tests, methods and mechanism were finalized and adjusted to enable it permanently (unit 3 and 7 and Novosibirsk HPP). For new equal power method a redesigned search algorithm was invented and integrated.

Power output step response with power cam mechanism

Continuing the work

At this moment our science group is improving software with new possibilities like fully automation for equal power method, increasing reference at different HPP. Unfortunately, we still hadn't opportunity to test in parallel with precise field test measuring (though the method was invented for places without possibility of measuring, to prove it, a test unit would be great and confirmative).

Significant awards

- Best study work in hydroenergy 2016 ПАО "РусГидро" ("RusHydro" is a largest Russian hydroelectricity company)

- Most potential scientific work AES Kazakhstan 2017