THE COMPARATIVE ANALYSIS OF THE METHODS FOR DETERMINATION THE HYDRAULIC AND ENERGY PARAMETERS AT THE AXIAL HYDRAULIC TURBINES WITH DOUBLE REGULATION OF GREAT CAPACITY

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ABSTRACT

The paper considers the two indirect methods of the turbinated discharge determination which may be applied at the Iron Gates I hydroelectric Power Plant respectively the SIMPA method and the SULZER HYDRO (VA TECH HYDRO) method. After the analysis of the methods concerning the advantages, the errors and considering all the elements which influence the discharge calculation, it is considered that the best method of the turbinated discharge calculation at the Iron Gates I hydroelectric Power Plant is the SIMPA method.

NOMENCLATURE

A_0 - Turbine wicket gate opening [mm]
H_{S_i} - Static head, subscript i = m means measured [m water-column]
H_S_{oo} - The static head in the optimum operation point [m water-column]
H_N - Industrial turbine net head [m water-column]
ϕ - Runner blades incidence angle [degree]
S_0 - Wicket gates servomotor stroke [mm]
S_2 - Rotor servomotor stroke [mm]
α - Coriolis coefficient [-]
P_A - the active power [KW]
P_{Ao o} - the active point in the optimum operation point [KW]
P_h - Turbine hydraulic power [KW]
Q_T - Discharge turbinated by the industrial turbine [m^3]
η_A - Hydrounit efficiency [%]
η_{mec} - Mechanic efficiency [%]
η_G - Generator efficiency [%]
η_h - Hydraulic efficiency [%]

1. INTRODUCTION

Beginning year 1841 when was started the first hydraulic test laboratory by Francis and Weisbach at Lowell, concomitantly with the hydraulic turbine production, where were developed different measuring methods of the turbinated discharges in power plants.

We can enumerate some methods which are used for the turbinated discharges in the river hydroelectric power plants: hydraulic chatterbox, Pitot tubes and pressure time (Gibson), trasers, gates, standard devices of differential pressure, volumic method, Winter-Kennedy method, the four parameters method, exploitation method, exploitation static characteristic method, ultrasonic method.

The paper /1/ analyses the methods for the turbinated discharge determination in order to be applied at the Iron Gates I hydroelectric Power Plant:

• seven are excluded with the criterion of area and application conditions respectively the methods: hydraulic chatterbox, Pitot tubes, trasers, gates, standard devices of differential pressure, volumic method.
• two methods was excluded from the “error” criterion respectively: Winter-Kennedy, variant which was applied at the Iron Gates I hydroelectric Power Plant and the Serbia beneficiary.

It is considered applicable at the Iron Gates I electric Power Plant the next methods:

A. Direct
   1. - Ultrasonic method

B. Indirect
   1. – SIMPA method
   2. - SULZER HYDRO method
   3. - Winter - Kennedy method
2. ULTRASONIC METHOD

Making abstraction of the paper conclusion, constructively the hydrounits at the Iron Gates hydroelectric Power Plant can’t efficiently use the ultrasonic method for the turbinated discharge measurement. This is because the inlet length is very short (25 m) accordingly with the international approved condition respectively the guarantee of the straight distance and minimum length of the four intake diameters, upstream and downstream water level from measurement section (between trash rake and shut off valve), as a result the plant purveyor (ACCUSONIC TECHNOLOGIES, INC.) supposed that the error reduction below 2-3% is unlikely.

There are also the great uniformity of the speed spectrum in the measurement section which is near the perturbator source (intake trash rake), which evidently conducts to the greater errors, nearly the Winter-Kennedy error.

3. THE SIMPA METHOD

This method was especially conceived in order to determine the discharge and efficiency at the Kaplan turbines /2/, /3/ and was developed and applied by the authors at the units from the Iron Gates I hydroelectric Power Plant. It is an indirect method which improve the exploitation static characteristic method.

Measuring with precision: the active, reactive power, the levels (at the spiral case intake, the shutt off valve bay and at the draft tube outlet) the head is calculated by relation:

\[ P_A [MW] = 9,81 \cdot \eta_A \times Q_T \times H \]

where:
- \( Q_T = \) the discharge turbinated by the industrial turbine
- \( P_A = \) the active power
- \( H = \) the head

It can be calculated with precision the product \( Q_T \times \eta_A \).

By Simpa method can be separated and determined those two factors, the resulted values have errors below 1%.

3.1. The head calculation can be made:

- “the gross head in accordance with the upstream and downstream level difference from the turbine and considering the cinetic factor \( \alpha v^2/2g \) for every of those sections.
- “the net head” which is the difference between head to turbine intake losses. These losses are determined by applying the Bernoulli equation between the intake admission section (upstream level from the trash rake) and the turbine admission (shutt off valve bay).

- “turbine head” which is the difference between the piezometric level in the piezometric level in the shutt off valve bay and the piezometric level at the draft tube outlet where the kinetic component and partially the intake load losses (\( S_{IMP} = CQ^2 \)).

There aren’t considered the total intake losses because the model which have the energetic tests (\( \phi 460 \) mm), with partial modelling intake, includes in the hydraulic efficiency on the characteristic \( n_1 - Q_1 \) a part from the intake losses.

The SIMPA method uses in the active power calculation “the turbine power” and not uses “the net head” because the kinetic loss at the draft tube outlet is contained in the draft tube efficiency and if this loss is again diminished it will be unjustified increased the product \( \eta_A \times Q_T \).

3.2. The measured parameters

The main measured parameters are:
- the necessary levels for the head determination;
- upstream level from the trash rake in the shutt off valve bays;
- at the draft tube outlet;
- upstream and downstream trash rake level difference;
- active and reactive power;
- rotor and wicket gate servomotor stroke;
- hydrounit rotative speed.

3.3. The determination of the model parameters accordingly the monitoring moment (measured parameters)

With the rotor and wicket gates servomotor stroke the wicket gates \( A_0 \) and rotor \( \varphi \) opening are determined for the industrial turbine and then by the geometric similitude for the model \( (a_0 \| \varphi_m) \).

Knowing \( a_0 \) and \( \varphi_m \) the industrial turbine operating point (defined by the measured parameters) has a correspondent on the model universal characteristic. From this characteristic, the model parameters are studied (the rotative speed, the discharge, the efficiency).

3.4. The determination of the industrial turbine parameters calculated

These parameters are obtained from those determined on the model characteristic with the hydraulic similitude formulae and applying the scale effect correction.

For the active power calculation \( P_A = P_h \times \eta_{mec} \times \eta_g \) it is considered the formula recommended by the purveyor for the mechanic losses and the efficiency curves of the generator (for \( \cos \beta = 1 \) and \( \cos \beta = 0.9 \), using the linear interpolation).
Thus there are obtained the values series for the turbinated discharge, efficiency and hydraulic industrial turbine \((Q_T, \eta_h, P_h)\).

In order to obtain the accurate values of these values the correction coefficient is applied:

\[
\eta_{hc} = k \cdot \eta_{hi}
\]

\[
P_{hc} = \sqrt[k^2]{P_{hi}}
\]

\[
Q_{TC} = k \cdot Q_{Ti}
\]

This is a coefficient of the scale effect supplementary correction and was initially determined and tested by the authors, owing the statistical processing of a great number of measurements achieved in nature, later it was calculated by the measured parameters.

At the SIMPA method the correction supplementary coefficient is self-acting calculated into dynamic conditions to every exploitation effective point of the turbine, its calculation formula is obtained from a measured parameter correlation and it is independent from the turbine where is established..

The correction coefficient \(k\) may be expressed in accordance with the active power measured for the constant (measured) values of the turbine head static component (fig.1).

![Fig. 1](image-url)

The curves \(k = f(P_{AM}/P_{A00}, H_{stn}/H_{st00})\)

1. \(H_{stn}/H_{st00} = 0,862\) = cst.
2. \(H_{stn}/H_{st00} = 0,879\) = cst.
3. \(H_{stn}/H_{st00} = 0,911\) = cst.

From the industrial turbine transducer errors and from the errors at the stand tests of the turbine model, there are evaluated /6/ the (maximum) limit relative errors in order to determine the industrial turbine parameters.

a) Industrial turbine turbine transducer errors:
- Transducer error of the wicket gates 0,15 %
- Servomotor stroke 0,10 %
- Transducer error of the rotor servomotor stroke 0,50 %
- Pressure transducer error of the level measuring 0,20 %
- Transducer error of the active power 0,20 %
- Transducer error of the reactive power 0,05 %
- Rotative speed transducer error 0,03 %

b) Errors at the model turbine stand tests
- Moment measure error "M" (couple) 0,10 %
- Head measure model error "Hm" 0,10 %
- Discharge measure model error "Qm" 0,20 %
- Rotative speed measure model error \(T_m\) 0,01 %
- Model diameter measure error "Dm" 0,06 %
- Measure error of the wicket gates opening model 0,06 %
- Error of the model efficiency determination "\(\eta_m\)" 0,03 %

c) Error determination of the industrial turbine parameters
- The measure error of the water level pneumohydraulic method
  \(\delta_{\text{Vapa}} = +/- 0,5 \times 10 \text{ m} \)
  c.a. pipe immersion depth \(\leq 0,05 \text{ m c.a}\)
- Measure error of the upstream and downstream levels
  \(\delta_{\text{VIR}_{1:2}} = 0,0007194 \text{ m.c.a} \leq 0,072 %\)
  at stop log set nb. 1 \(\leq 2\)
  \(\delta_{\text{H}_{AV}} = 0,00125 \text{ m.c.a} \leq 0,125 %\)
- Head measure error
  \(\delta_{\text{H}_{ST}} = \frac{H_{AM} \delta_{\text{H}_{AM}} + H_{AV} \delta_{H_{AV}}}{H_{AM} - H_{AV}} \leq 0,431\%\)
  \(H_{AM}\) – piezometric level in the section considered the turbine inlet
  \(H_{AV}\) – piezometric level at the draft tube outlet
- Measure error of the industrial turbine rotor diameter "\(D_i\)"
  \(D_i = \frac{\tau}{\phi D_i} = \frac{16}{9500} = 0,00168 \leq 0,17\%\)
  where "\(\tau_{D_i}\)" is absolute value of the execution maximum tolerance
- Measure error of the active power "\(P_A\)" 0,2 %
- Measure error of the reactive power "\(Q\)" 0,2 %
• Error of the apparent power determination "S"
\[\delta_S = \frac{1}{2} \left( \delta_P^2 + Q^2 \right) \leq 0.2\% \]

• Error of the power factor determination
\[\delta_{\cos \beta} = \delta_P + \delta_S \leq 0.4\% \]

• Error of the generator efficiency determination "\(\eta_G\)"
\[\delta_{\eta_G} = \frac{P_A \delta_P + S \delta_S + \cos \beta_1 \delta_{\cos \beta}}{P_A + S + \cos \beta_1} \leq 0.2\% \]

• Error of the mechanic efficiency determination "\(\eta_{mec}\)"
\[\delta_{\eta_{mec}} = \frac{1}{2} \left( \delta_P + \delta_{\eta_G} \right) \leq 0.2\% \]

• Error of the turbinated discharge "\(Q_T\)" at the industrial turbine
\[\delta_{Q_T} = \delta_{D_1} + \delta_{D_2} + \frac{1}{3} (\delta_{\alpha_1} + \delta_{\alpha_2} + 2 \delta_{\theta_0} + \delta_{\theta_1} + \delta_{\theta_2}) \leq 0.78\% \]

• Error of the hydraulic efficiency determination at the industrial turbine "\(\eta_{hi}\)"
\[\delta_{\eta_{hi}} = \delta_{T_i} + \delta_{D_1} + \delta_{D_2} + \delta_{D_m} + \delta_{\eta_m} + \frac{1}{2} (\delta_{H_T} + \delta_{H_m}) \leq 0.87\% \]

4. THE SULZER HYDRO (VA TECH HYDRO)
METHOD

The method consists in the turbinated discharge determination form the conditions which are constant /4/, /5/, for instance the transverse sections at the draft tube opening. These results are corrected varying with rotor opening and the pressure in the respective section.

The complete definition of the operating point of the Kaplan turbine requires the knowledge of the four characteristic parameters: the efficiency, the rotor opening, the wicket gates opening and the cavitation coefficient.

These characteristic parameters can be plotted:
X – the head 
Y – the discharge 
Z – the characteristic value (\(\eta, a_0, \varphi_r, H_s\))

Mathematical these surfaces are defined and described by the B – Spline functions.

The model characteristics are measured on stand and transposed in B – Spline surfaces by special programmes.

At the stand tests on the model, \(\eta\) is measured at different \(a_0\) for \(\varphi_r = \text{ct.}\) and \(H = \text{ct.}\), resulting a Propeller curve (helical regime).

The Propeller curves determined for the different heads at \(\varphi_r = \text{ct.}\) define a Propeller characteristic set with an efficiency surface and wicket gates surface.

The Kaplan efficiency surface considers all efficiency Propeller surfaces resulted from the measurements, realised at 4 ÷ 7 rotor blade angles.

The tangent points of the Kaplan efficiency blades and the Propeller characteristic determine the correspondent positions of the rotor and wicket gates, in accordance with the relation "3D cam".

Without the results of the model tests, or if the differences from the model to the industrial turbine are great, the nature measurements are necessary.

The special programme achieved for the B – Spline (QREG), allows the transformation of the wicket gates and rotor characteristics to Q characteristic functions having as parameters the wicket gates and rotor servomotor strokes (\(s_0\) and \(s_2\)).

This functions contain the B – Spline surfaces of the wicket gates (\(a_0 = f(Q)\) for \(H = \text{ct.}\)) measured at the model stand tests.

The wicket gates, rotor and head characteristics are approximated and compressed for a chosen area with a function of \(n^3\) order. This one conducts to formula:
\[Q = f(s_0, s_2, H_{st}) = \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{l=1}^{n} c_{i,j,k} (s_0^l \cdot s_2^l \cdot H_{st}^l)\]

Varying with the chosen order the \(n^3\) coefficients are obtained.

This precisely describes every combination of \(a_0, \varphi_r, \) and \(H\) and gives the concordant discharge \(Q\).

The coefficients may be determined for the specific values \(Q = f(\varphi', \beta_2, H_{st})\) and for the prototype turbine \(Q = f(s_0, s_2, H_{st})\).

If the characteristic of the prototype turbine are used, the cinematics of the wicket gates \(s_0 = f(\varphi')\), the rotor \(s_2 = f(\beta)\) and the variation curve of the load losses \(h_v = f(Q)\) must be known.

There is a supplementary programme which makes the conversion from the model test values to the prototype values.

In the next stage, the programme QCAL makes the characteristic processing \(Q = \text{c}\) varying with the characteristic of servomotor curves and the positions measured by the reset device.
The discharge value achievement is obtained relatively easy, programming in the Turbine Control System (DTP) the formula for the common coefficients.

The characteristics Q = constant and the curves plotted on the model are intersected in the respective optimum calculation points (fig. 2).

The characteristics Q = constant are then lined in the proximity of these optimum points and the gradient is calculated varying with the rotor opening. Then the gradient is linear for the rotor main openings and this equation is used for the introduction of the parameters in the ACC model (Cam Position Control System).

The discharge value is acquired relatively easy, programming in the Turbine System Control (DTP) the formula for the common coefficients.

For the plants where exists the model tests results achieved by the Sulzer Hydro, the total error is:
- The inaccurate tests on the model (f_m) 1,0 %
- Scale effect (f_s) 0,8 %
- Mathematical description (f_m) 1,0 %
- The imperfection of the regulation mechanism (f_r) 0,7 %
- The vagueness of the transducers (f_t) 0,62 %

The total error at the discharge determination:

$$ f_Q = \pm f_s + \sqrt{f_m^2 - f_s^2 - f_r^2 + f_t^2} \approx 2,39\% $$

5. THE WINTER – KENNEDY METHOD

It is an indirect method of measuring the discharge applied only at the turbines.

The discharge value determination is achieved by measuring the pressure differences between the intake twin mounted in the turbine spiral case.

The discharge value is obtained:

$$ Q = K\Delta h^n $$

where: Δh is the studied value at a pressure differential manometer; n is an exponent with the value from 0,48 to 0,52 in the most unfavorable conditions at the smallest in the spiral case.

For the concrete spiral case the intakes will be mounted thus they aren’t in the corner zone proximity (the joint zone between ceiling or the downward case and the vertical exterior contour).

The interior intakes will be mounted in the exterior from the stator, on the flow line which is on the middle distance of the stator column. A third intake may be mounted in the stator column zone (on the spiral case ceiling between two stator column or at the horizontal axis level of the wicket gates).

The error of determination of the turbinated discharge for the Winter-Kennedy method is about 6 %.

6. CONCLUSIONS

The SULZER HYDRO (VA TECH HYDRO) method essentially is the method of the turbinated discharge characteristic $Q_T = \text{cst.}$ with coordinates $s_0$ and $s_2$ over are overlapped the net head controller correlations at $H_N = \text{cst.}$

This characteristic was obtained by the similitude from helical characteristic of the model obtained by stand tests, the conversion from the model value to the prototype value was made with usual similitude equations while for the real effect correction at the hydraulic efficiency determination it was used the Ackeret formula.

This conclusion results by testing on the same data basis recorded from the process of a procedures for the dinamic determination of the parameters using the similitude usual equations and the hydraulic efficiency conversion from the model to the prototype with one of the next methods: LMZ, Moody, Hutton, Osterwalder and SULZER HYDRO (VA TECH HYDRO-Ackeret).

Thus it is known the turbine net head is the difference between the total energy (potential and kinetic) from the turbine intake section and the total energy at the draft tube outlet.

In the case of the turbine head in the draft tube outlet only the potential energy is substracted.

The methods conducts to thre relatively great differences between the values of those two reference parameters the active power and the static component of the net/turbine head, measured in process and those calculated.

These differences exist because of the errors cumulation respectively by using the net head notion instead of the turbine head, the incomplete hydraulic similitude from the similitude equations, the using for the conversion of the hydraulic efficiency prototype, relied
on the model efficiency, of a speculation formula obtained with the using of some simplification hypotheses which don’t model with sufficiently accuracy the material phenomenon.

These formulae generally direct, for the hydraulic efficiency at overestimated values and insufficiently colligated with the another parameters, with values which are established by the similitude equations.

Thus it results from the diagrams presented in fig. 3,4,5 there are relatively great differences between the values of those two reference parameters, the active power and the static component of the net/turbine head measured in process and those calculated by the procedures specific for the other analysed methods.

At the SIMPA method fig. 3, 5 the deviations of the calculated values from the measured ones, of those two reference parameters – the head static component and the active power – are below the transducer measuring error and much smaller than the minimum limit errors of the parameters. This one using the turbine head notion, a variable coefficient of supplementary correction for the scale effect, obtaining the industrial turbine hydraulic efficiency by solving an equation sistem (of similitude) and correlation between certain parameters acquired from process, ensures the determination or the calibration of parameters and hydraulic coefficients of the exploitation with errors below 1%.

The SIMPA method doesn’t solicit the very qualified personnel because the coefficient of supplementary correction is automatic calculated in the dinamic regime for every exploitation efective point of the turbine, its calculation formula is obtained from a measured parameter correlation and is independent from the turbine where is established.

In the diagrams from fig. 3 and 5 we present the deviations (%), of the measured values and those calculated of the two reference parameters, the active power and respectively the static component of the net/turbine head, resulted from tests on the data basis from the process, by simulating an algorithm compatible with SULZER HYDRO (VA TECH HIDRO-Ackeret).

The curves HT in these diagrams correspond the situation of "turbine head", and the curves HN for the specific situation of these methods respectively "the net head utilization". There are another elements which the analysed methods didn’t take in consideration at the error evaluation respectively: the velocity aleatory distribution from the turbine intake and the draft tube outlet, manufacturing tolerance, installation peculiar conditions, the inherent modifications as a result of the repairs, effective exploitation conditions (of moment) of the turbine, the turbine position in the power plant interaction with the adjoining turbines at the different exploitation characteristic, determined by the similitude and no the actual characteristic of the hydrounit.

The inclusion in the SULZER HYDRO (VA TECH HIDRO-Ackeret) method algorithm of these influens, by numeric simulation practically is impossible and a correction after the nature measurements is very sophisticated and expensive, it requires long temp.

The imperfection is specific to all cases there the parameters are determined bu usual similitude equations and using the conversion formula of the prototype hydraulic efficiency.

When the calculated values of the turbinated discharge and the head are different from the correct ones and the hydraulic efficiency value, calculated by the division of generator power (active measured power) to generator efficiency, mechanical efficiency, turbinated discharge and head product, can’t be correct.

Because the net head, by diminution once more of the kinetic loss at the draft tube outlet, is smaller than the real one, the turbine discharge, because of the incomplete hydraulic similitude formulae is underestimated, it evidently results that the hydraulic efficiency calculated by this proceeding is overestimated.

\[ \text{PRP}_A \% \]

-12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8

0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4

\[ \frac{P_A}{P_{A00}} \]

Fig. 3

\[ H_{Stm}/H_{Stoo} = 0.879 = \text{cst.} \]

1 - SIMPA HT 2 - Moody HT
3 - Moody HN 4 - LMZ HT
5 - Hutton HT 6 - Hutton HN
7 - Osterwalder HT 8 - Osterwalder HN
9 - Sulzer HT 10 - Sulzer HN
**Fig. 4**

\[ \frac{H_{STm}}{H_{S00}} = 0.879 = \text{cst.} \]

1 - Osterwalder \( H_T \)  
2 - Moody \( H_T \)  
3 - Osterwalder \( H_T \), LMZ \( H_T \)  
4 - Moody \( H_N \)  
5 - LMZ \( H_N \)

**Fig. 5**

\[ \frac{H_{STm}}{H_{S00}} = 0.879 = \text{cst.} \]

1 - Sulzer \( H_N \)  
2 - Hutton \( H_N \)  
3 - Sulzer \( H_T \), Hutton \( H_T \)  
4 - SIMPA \( H_T \)
where:

\[ PRP_A = \text{the relative deviation of the active power calculated value from the measured one.} \]

\[ PRH_S = \text{the relative deviation of the turbine static head component calculated value from the measured one.} \]

In the ISPH București paper /1/ for the Winter-Kennedy, there are sufficiently analysed the causes which conducts to this error level, thus generally the method would be used only advisory.

The error degree reduction of this method is very difficult and expensive.

The calibrating only by model measurements, isn’t sufficient because of the scale effect and the nature calibrating, comparatively with another method for the turbinated discharge determination, thus there is included and the method error, it outlasts because for determining the discharge coefficient matrix, there is necessary the browsing of the whole hydraulic exploitation area.

Thus the validity of this matrix is limited because the hydrounit characteristics are debasing in time and it is necessary the calibrating operation.

This determines that the Winter-Kennedy method can be adopted only as alternative method, in parallel with the base method which must have a high precision. By processing the exploitation data stored on a great period of time, it is possible to perform the periodical calibration of the discharge coefficient matrix.

REFERENCES

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