DETERMINATION OF HYDRAULIC TURBINE EFFICIENCY BY MEANS OF THE CURRENT METER METHOD

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Abstract - The paper presents methodology used for determining the efficiency of a low head Kaplan hydraulic turbine with short converging intake.
The measurement method used was the current meters method, the only measurement method recommended by the IEC 41standard for flow measurement in this case.
The paper also presents the methodology used for measuring the flow by means of the current meters method and the various procedures for calculating the flow.
In the last part the paper presents the flow measurements carried out on the Fughiu HPP hydraulic turbines for determining the actual operating efficiency.

Keywords: hydraulic turbine, current meter method, efficiency, low-head hydro power plant

1. INTRODUCTION

Modernization and development of energy production in general and of hydro power energy in particular is undeniably linked to the continuous improvement in the design, construction and operation of the hydro power development and their hydro power installations.

The hydro power developments represent constructions that modify the natural regime of water courses so that to ensure the utilization of the respective water resource in optimal technical and economic conditions.

Optimal utilization of this resource is ensured both through the design and the rational (optimal) operation of the development installations.

Obtaining maximum electrical energy to the same consumed water volume is one of the ways to increase the efficiency of electricity production.

The operation of the hydro power development and of its installations at any time is characterized by certain values of their characteristic parameters such as: volumetric flow rate Q, head H, power P, efficiency ηetc. The correlation between the values of these parameters within the limits of their variation range, is determined by the type, construction and dimensions of the hydro power developments is graphically defined by the so-called characteristic curves of the development or of the hydropower units the hydro power plant is equipped with (turbines, pumps etc.).

The vector of the numeric values of the respective parameters characterizing the hydro power plant operation (hydro power unit etc.) at a certain point is represented by a point on the respective curves that is called the operation point.

In general, this vector includes only one value for each of the parameters that are linked through bi-univocal relationships. This is a condition of the hydro power development/unit stable functioning. Nevertheless, there are situations when, in the respective correlation, one of the parameters may have two values for only one value of the other parameters. This is a situation that defines the unstable functioning of the respective hydro power unit.

The optimal characteristic curves, zones or operation lines are determined as early as the design stage. Due to the fact that it is mandatory to include spinning reserves through the design and due to the influence of the specific character of execution, the actual characteristic curves differ not only from the designed ones, but also from one hydro power unit to another even if they have been manufactured by the same manufacturer according to the same design.

Modern measurement theory and technique enables determination of each unit individuality thus creating the prerequisites necessary for getting to know and use both the internal resources resulting from the hydro power unit designed spinning reserve, and those represented by the differences between the hydropower units of the same hydroelectric power plant, orienting operation towards an optimal differentiated operation of the hydropower units.

The optimal operation of a hydropower unit / hydro power plant or of a hydro power plant cascade is equivalent with an increase in energy or with the existence of a certain development (theoretical) that would yield a supplementary production of electricity of at least 2%.

2. DETERMINATION OF HYDRAULIC TURBINE EFFICIENCY

The hydraulic turbine is a machine that converts hydro energy into mechanic energy through a rotor equipped with blades. The hydraulic turbine is one of the main components of a hydropower unit.

The efficiency of a hydraulic turbine η_T is the ratio between the useful power transferred from the turbine shaft, or the mechanical power at the turbine coupling P and the power absorbed by the turbine shaft or the hydraulic power P_h.

$$\eta_T = \frac{P}{P_h} \tag{1}$$

Where:

- the mechanical power transferred to the turbine shaft is given by the following relationship:

$$P = QH_n \tag{2}$$

Q is the discharge and H_n is the turbine useful or net head

- The hydraulic power has the following relationship:

$$P_h = \gamma QH \tag{3}$$

γ is the specific weight of water (9810 N/m^3) and H the turbine gross head.

By utilizing the relationships (2) and (3) in (1) we obtain the efficiency of a hydraulic turbine in relationship to the discharge Q, head H, and the turbine mechanical power P:

$$\eta_T = \frac{102P}{QH} \tag{4}$$

The efficiency of a hydraulic turbine can be determined by means of in situ measurements, or can be obtained from the turbine hill chart that is a diagramdeveloped on the basis of the turbine guaranteed curve.

3. DESCRIPTION OF DISCHARGE MEASUREMENT METHOD

From among the parameters measured for determining the efficiency of a hydraulic turbine the parameter whose measurement is the most difficult one is the discharge. The measurement of this parameter requires a complex measurement methodology.

The methods for the flow rate measurement and the way they are applied is described in detail in the international measurement standards ASME PTC 18 [1], IEC 41 [2], IEC 62006 [3], ISO 3354 [4]. The periodicity of the hydraulic turbine performance tests is set in the energy norm PE 301[5].

The measurement standard IEC 41 establishes the method of the velocity field exploration by means of the current meters, also known as the current meter method as the only measurement method for the low-head hydro power plants.

3.1. The measurement method principle and the calculation relationships

The current meter method represents the adaptation of the fundamental formula of the fluid mechanics to the actual flow in the channels with a free flow or in the conduits under pressure. According to it the value of the discharge is the result of the product between the values of the water that flows through a normal section S in the flow direction and the area A of a section S. The real flow is characterized by lack of velocity uniformity v of water in the flow section S.

The principle of the method consists in mounting a certain number of measurement transducers (current meters or acoustic sensors) in a cross-section (the section can be circular, rectangular or trapezoidal as in the case of the upstream cofferdam recesses of the hydro power plants, or the channels with free flow surface) by means of which the water velocity in the respective points is determined. The flow rate is determined by integrating the local velocities simultaneously measured over the entire measuring section.

Usually, the flow rate for a rectangular (fig.1)or trapezoidal measurement area is calculated in the following way [6]:

$$Q = \iint_S v(x,y)dxdy \cong \sum_i v_i \Delta x_i \Delta y_i \, . \tag{5}$$

Equation (5) can be expressed in the form of a simple integral in two ways:

$$Q = \int_0^L \left(\int_0^H v dy \right) dx \quad \text{(a)} \quad \text{or} \; Q = \int_0^H \left(\int_0^L v dx \right) dy \quad \text{(b)} \tag{6}$$

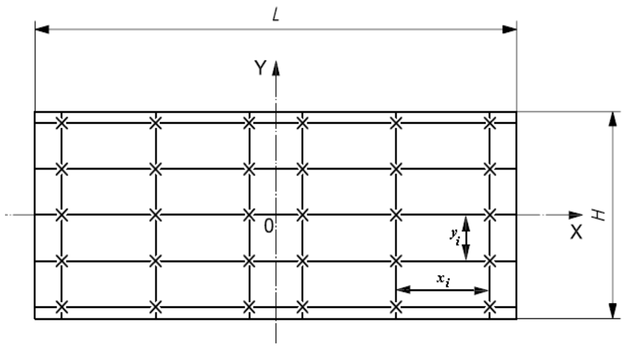

Fig. 1 Rectangular measuring section for the discharge calculation

Where:

- v_i are the velocities in the measurement points,
- x_i are the horizontal distances between the measurement points,
- y_i the vertical distances between the measure points,
- L the measuring section length and
- H the height of the measuring section.

The information on the profile of the flow through the measuring section is obtained only through the velocity field method by means of the current meters and, to a certain extent, by means of the acoustic method utilizing several measurement possibilities.

3.2. Procedures for calculating the measured discharge

In order to calculate the integral from the formula (5) we can use the graphic calculation procedure, the first integration being made along the vertical lines and the second by marking the product $v{\times}L$ along the horizontal lines, the analytical procedure where the integral determination is made by means of the cubic spline, B spline [7] interpolation, Lagrange interpolation polynomials, by means of the equal areas method, or the integration method from the ISO 3354 [8] standard.

At the same time, the calculation of the integral $\int_0^H v dy$ from the formula (6a) that we will further marked *I* can be made by means of a graphic-analytical [9]. The velocity distribution on each vertical is graphically mapped on the basis of the measurement points so that the curve obtained is as smooth as possible and the connection in the border zone observes continuity. For the integration of the function that approximates this curve you can usethe cubic spline functions [10].

The*cubic splines functions*consists in dividing the interval into an even number of divizions integration Δ_n(fig. 2), establishing the velocity in the division points and calculating the integral by means of the equation:

$$I = \int_0^L A(y - y_{p-1}) + B \ln \frac{y}{y_{p-1}} + v_{p-1} \qquad (7)$$

After determining the integral *I* average velocity on the vertical v_{mv} is calculated by means of the relationship:

$$v_{mv} = I / H \ , \qquad (8)$$

where *H* is the height of the measuring section.

After calculating all the average velocities on the measurement verticals we draw distribution graphs of the horizontal velocities on their basis. The average velocity in the measuring section is:

$$Q = \int_0^L H \cdot v_{mv} dx \qquad (9)$$

For mapping the distributions in the border zone it is necessary to take into consideration the fact that the velocity from the wall to the first current meter is given by Kármán law (10), [11].

$$v_x = v_a \cdot \left(\frac{x}{a} \right)^{1/n} , \qquad (10)$$

where

v_x - is the velocity in the extrapolation zone at a distance *x* from the section wall,

v_a – is the velocity in the measurement point *a* the closest to the section wall,

n – is a coefficient that takes into consideration the roughness of the wall and the flow conditions and is applied close to the walls and the foundation plate, but not in the nearby of the free surface of water where the velocity profile should be extrapolated through continuity. When there are no special counter indications we can consider *n* = 7.

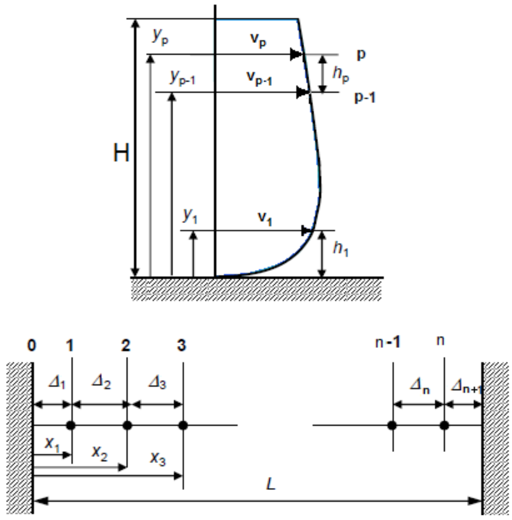

Fig. 2 Determination of mean velocity through graphic-analytical integration, cubic splines

The extrapolation from the current meter to the free water surface is made with the observance of the continuity of the mapped curve. In case superficial velocity is also measured by means of current meters the value of the former has also to be considered.

4. APPLICATION TO A 5.9 -14.7 TYPE KAPLAN TURBINE

As early as the commissioning of the hydroelectric power plant it is necessary to carry out performance tests on the hydropower units of the plant for determining its actual operational parameters:

- Absolute discharge measurements for the calibration of the pressure intakes on the spiral chamber of the turbine and the determination of the maximum efficiency and optimum operational range of the turbine.
- Relative measurements on the actual cam combination and with the cam combination dismounted for determining the optimum operational cam.

In order to exemplify the way the hydraulic turbine efficiency is determined by means of the current meter method we will further present the performance tests carried out on the hydro power unit HA1 of Fughiu low-head hydropower plant. The hydroelectric power plant is equipped with two 5.9-14.7 type Kaplan turbines with a maximum gross head of about 15 m, a power plant installed power of 10 MW, a power plant discharge of 90 $m^3s^{-0,5}$and an electricity production of 20.6 GWh/average year.

4.1. The utilized measurement methodology

The discharge was measured by means of the current meter method in the upstream cofferdam recesses of the hydropower unit HA1 of Fughiu HPP. During the performance tests the gross head and power were maintained quasi-constant on the power plant.

The main difficulty of this type of hydrometric measurements is caused by the fact that the measuring section is situated in a short penstock that also determines an oblique flow to the flow meters, as well as an irregular and/or unstable velocity field.

The measurements were carried out by means of a hydrometric frame on which 7 Ott current meters were mounted as in fig. 3.

The average angle at which the hydrometric current meters were mounted for carrying out the performance tests was of 21^0.

Fig.3 Current meter frame ready to be installed in the cofferdam recesses

The number of measurement points for measuring the velocities necessary for determining the discharge in the 18 m^2 measuring section was set in accordance with CEI 41 requirements and varied between 63 and 95 measurement points. The measurementswere carried out by sweeping the entire measuring section and placing the current meter frame in the stop logs at 10 measuring horizontal levels. On each measuring position 7 velocities were measured obtaining 70 measured points [11].

The discharge, the mean velocities in the measuring sections from the upstream cofferdam recesses of Funghiu HPP respectively were determined through mathematical integration of the measured velocities by means of a calculation program called *Debit.m*that is based on the equal area method. Subsequently, in order to verify the discharge the mean velocities were also calculated utilizing a grapho-analytical procedure based on Simpson' rule.

4.2. Measurement results

As a result of the flow rate measurements in the two upstream cofferdam recesses of the hydro power unit HA1 the following mean velocities and flow rates were obtained:

- For the left side recess the mean velocity was of v_{m11} = 0.723 $[ms^{-0,5}]$ and the average flow rate Q_{m11} = =13.29 $[m^3s^{-0,5}]$;
- For the right side recess the mean velocity was of v_{m12} = 0.601 $[ms^{-0,5}]$and the average flow rate Q_{m12} = 11,21 $[m^3s^{-0,5}]$.

The total average flow rate of the HA1 hydro power unit, Q_{m1} = 24.50 $[m^3s^{-0,5}]$, was obtained by summing up all the flow rates measured in the left side recess and the right side niche.

By means of the Winter-Kennedy formula (11), [12] the discharge measured in situ and the differential pressure Δhmeasured on an intake pair from the turbine spiral chamber of the hydro power unit HA1,the calibration coefficient of the intakes in the turbine spiral chamber of HA1 $\Rightarrow K_e$ = 3.2 $[m^3s^{-1}mm^{-0,5}]$ was obtained.

$$Q = K_e\sqrt{\Delta h} \tag{11}$$

The measurements were carried out for a power of 3 MW at the terminals of the HA1 generator and a gross head of 14.5 m.

During the tests, in order not to influence the results of the measurements carried out on the turbine of the hydro power unit HA1, the hydro power unit HA2 was stopped.

As a result of the discharge measurements an actual image of the velocity field distribution in the two recesses of the upstream cofferdams of the HA1 turbine was obtained.

The 3D distribution of the velocities measured by means of the current meter frame in the two recesses of the HA1 according to the head (*H*) and the length (*L*) of the measuring section is given in fig. 4 [13].

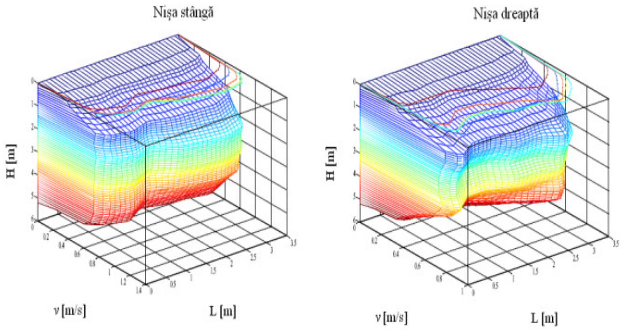

Fig. 4 3D representation of the velocity distribution in the hydro power unit HA1 recesses

At the same time, fig. 5 [13] graphically presents the equal velocity lines for the two turbine recesses of HA1.

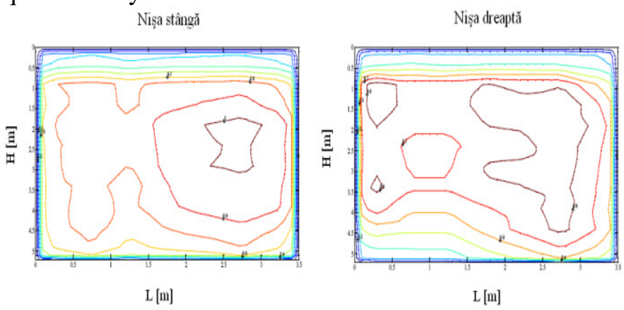

Fig. 5 Equal velocity lines in the HA1 hydro power unit recesses

By means of the data obtained as a result of the measurements the actual consumption characteristic Q = f(P) (fig. 6) and the actual operational η_T = f(P) of HA1 turbine were mapped (fig. 7).

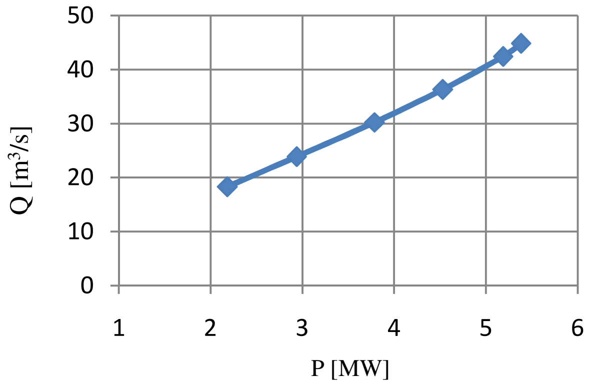

Fig. 6Actual consumption characteristic of the hydro power unit (HA1) turbine

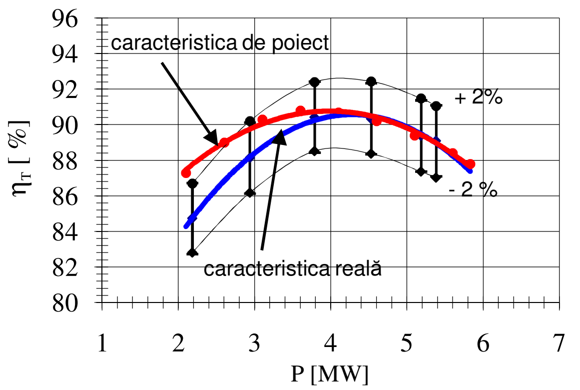

Fig.7. Actual operating characteristic of the of the hydro power unit (HA1) turbine

The optimal operational range of the hydro power unit hydro power unit HA1 turbine according to fig.7 ranges between 2.9 MW and 5.8 MW (zones where operation efficiency is ≥ 88 %).

The calculation error of the actualoperating efficiency of the hydraulic turbine obtained by means of the current meter method was of± 1.7 %, lower than the ± 2 % limit set in the CEI 41 standard.

5. CONCLUSIONS

- The tests prove that the turbine of the hydro power unit HA1 observes the efficiency warranties for the net head to which the tests were carried out.
- The maximum operating efficiency by turbine efficiency characteristic according to the turbine power (fig.7), determined by means of the data obtained by means of in situ measurementswas of**90.3%**for a net head of 14.2 [m].
- The discharge measured in the left side recess is greater than the discharge measured in the right side of the HA1 turbine, a fact that confirms the hypothesis formulated in paper [14] by the Romanian researchers Muntean S. and Susan-Resiga R. according to which the discharge in the left recess represents only 55% of the total discharge of the turbine and the discharge in the right side recess is 45 % of the total turbine.
- Fig. 5 points out that the repartition of velocities is approximately uniform in both recesses indicating that the grates were clean during the discharge measurements.
- By means of the data in fig. 6, fig. 7 respectively, realistic optimization programs for managing the Funghiu HPP water stock as efficiently as possible can be developed.
- The $K_e$coefficient obtained as a result of the pressure intake calibration on the spiral chamber of the HA1 turbine can be utilized for carrying out discharge metering installation.
- Operation of HA1 within the optimal operating range of 2.9 MW ÷ 5.8 MW is proposed.
- The paper proposes the introduction into the practice of the hydro power development operation actual water consumption monitoring and the former's optimization by means of the flow metering installations that are periodically calibrated, their costs following to be covered from the increase in energy of at least 2% obtained as a result of the hydro power unit functioning within the optimum operating ranges.
- The paper aims at increasing awareness relating to the necessity to carry out performance tests on the hydraulic turbines by means of an absolute flow metering method for an as precise as possible determination of their optimal operating ranges.

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