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Hydraulic machines — Acceptance tests of small hydroelectric installations

National foreword

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Foreword

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The following dates were fixed:

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Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 62006:2010 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60994	NOTE	Harmonized as EN 60994.
IEC 61116	NOTE	Harmonized as EN 61116.
IEC 61260	NOTE	Harmonized as EN 61260.
ISO 4373	NOTE	Harmonized as EN ISO 4373.
ISO 5167 series	NOTE	Harmonized in EN ISO 5167 series (not modified)

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60041	1991	Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines	EN 60041	1994
IEC 60193	-	Hydraulic turbines, storage pumps and pump-turbines - Model acceptance tests	EN 60193	-
IEC 60308	-	Hydraulic turbines - Testing of control systems	EN 60308	-
IEC 60609	Series	Hydraulic turbines, storage pumps and pump-turbines - Cavitation pitting evaluation	EN 60609	Series
IEC 60651	-	Sound level meters	EN 60651	-
IEC 61362	-	Guide to specification of hydraulic turbine control systems	EN 61362	-
ISO 1680	-	Acoustics - Test code for the measurement of airborne noise emitted by rotating electrical machines	EN ISO 1680	-
ISO 1940-1	2003	Mechanical vibration - Balance quality requirements for rotors in a constant (rigid) state - Part 1: Specification and verification of balance tolerances	-	-
ISO 3746	-	Acoustics - Determination of sound power levels of noise sources using sound pressure - Survey method using an enveloping measurement surface over a reflecting plane	EN ISO 3746	-
ISO 4412	Series	Hydraulic fluid power - Test code for determination of airborne noise levels	-	-
ISO 5168	-	Measurement of fluid flow - Estimation of uncertainly of a flow-rate measurement	-	-
ISO 7919-5	-	Mechanical vibration - Evaluation of machine vibration by measurements on rotating shafts - Part 5: Machine sets in hydraulic power generating and pumping plants	-	-
ISO 10816-3	-	Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts - Part 3: Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15 000 r/min when measured in situ	-	-

Publication	Year	Title	EN/HD	Year
ANSI/IEEE 810	-	Hydraulic Turbine and Generator Integrally Forged Shaft Couplings and Shaft Runout Tolerances	-	-

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HYDRAULIC MACHINES – ACCEPTANCE TESTS OF SMALL HYDROELECTRIC INSTALLATIONS

1 Scope

This International Standard defines the test, the measuring methods and the contractual guarantee conditions for field acceptance tests of the generating machinery in small hydroelectric power installations. It applies to installations containing impulse or reaction turbines with unit power up to about 15 MW and reference diameter of about 3 m. The driven generator can be of synchronous or asynchronous type.

This International Standard contains information about most of the tests required for acceptance of the hydraulic turbine such as safety approval tests, trial operating and reliability tests, as well for verification of cavitation, noise and vibration conditions, if required.

This standard represents the typical methods used on smaller hydroelectric installations, and is divided into three classes as follows (see Table 1 for more detail):

Class A	Normal test program (panel measurement) To determine the maximum power output of the installation.	**Default**
Class B	Extended test program To determine the performance characteristics of the installation.	**Recommended**
Class C	Comprehensive test program To determine the absolute efficiency of the installation.	**Optional**

NOTE All classes contain safety tests, trial operating tests, and reliability tests.

This standard gives all necessary references for the contract in order to execute the test, evaluate, calculate and compare the result to the guarantee for all the classes A, B and C.

The manufacturer or consulting engineer is responsible for ensuring that standardized connections are installed for performing these tests. This standard does not cover the structural details of a hydroelectric installation or its component parts.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60041:1991, *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump turbines*

IEC 60193, *Hydraulic turbines, storage pumps and pump-turbines – Model acceptance tests*

IEC 60308, *Hydraulic turbines – Testing of control systems*

IEC 60609 (all parts), *Hydraulic turbines, storage pumps and pump-turbines – Cavitation pitting evaluation*

IEC 60651, *Specification for sound level meters*

IEC 61362, *Guide to specification of hydraulic turbine control systems*

ISO 1680 *Acoustics – Test code for the measurement of airborne noise emitted by rotating electrical machinery*

ISO 1940-1:2003, *Mechanical vibration – Balance quality requirements for rotors in a constant (rigid) state – Part 1: Specification and verification of balance tolerances*

ISO 3746, *Acoustics – Determination of sound power levels of noise sources using sound pressure – Survey method using an enveloping measurement surface over a reflecting plane*

ISO 4412 (all parts), *Hydraulic fluid power – Test code for determination of airborne noise levels*

ISO 5168, *Measurement of fluid flow – Procedures for the evaluation of uncertainties*

ISO 7919-5, *Mechanical vibration – Evaluation of machine vibration by measurements on rotating shafts – Part 5: Machine sets in hydraulic power generating and pumping plants*

ISO 10816-3, *Mechanical vibration – Evaluation of machine vibration by measurements on non-rotating parts – Part 3: Industrial machines with nominal power above 15 kW and nominal speeds between 120 r/min and 15 000 r/min when measured in situ*

ANSI/IEEE 810, *Hydraulic Turbine and Generator Integrally Forged Shaft Couplings and Shaft Runout Tolerances*

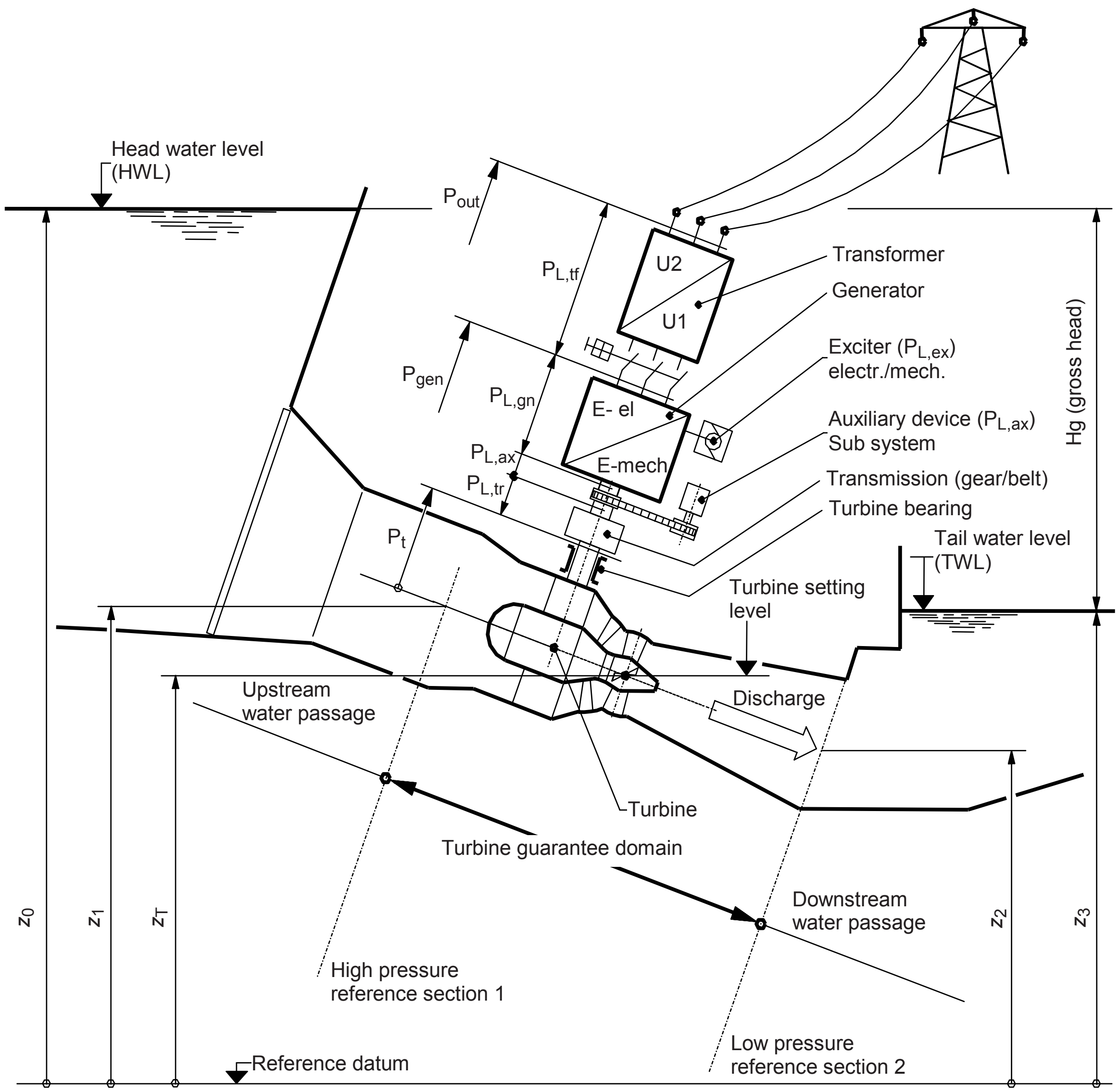
3 Terms, definitions and schematic layout

3.1 Terms and definitions

A complete list of terms and definitions is given in Annex A.

3.2 Schematic layout of a hydroelectric installation

In general, there are three connected hydraulic regimes in a hydroelectric installation as shown in Figure 1 below. These are the upstream water passage, the turbine guarantee domain, and the downstream water passage.



NOTE The losses in the upstream and downstream water passage are not part of the turbine losses. Nevertheless, they may influence the hydraulic conditions in the turbine guarantee domain and lower the efficiency of the turbine. Only the energy losses in the turbine guarantee section are to be considered when measuring the efficiency of a turbine. If it is not possible to measure the energy in the reference section 1 and 2, the measuring section should be changed in agreement with all parties.

The definition of the reference section 1 and 2 and that of net head and specific energy for the most common small turbines is given in Annex B.

Figure 1 – Schematic layout of a hydroelectric installation (water to wire system)

4 Nature and extent of guarantees

4.1 Grouping of classes A, B, C

4.1.1 General

The scope of the measurement classes for hydroelectric installations is shown in Table 1.

Table 1 – Scope of classes A, B, and C

Class A	**Normal (panel measurement) test program**
Class B	**Extended test program**
Class C	**Comprehensive test program**

Measurement of class		**C**	**B**	**A**	**Clause**
Safety tests	(commissioning)				5
Pre-start tests	(dry test)	yes	yes	yes	5.1
Closing devices	(dry and wet tests)	yes	yes	yes	5.2
First run operation and control	(wet tests)	yes	yes	yes	5.3
Bearing run at rated speed		yes	yes	yes	5.4
Emergency shutdown (no load)		yes	yes	yes	5.5
Electrical protection		yes	yes	yes	5.6
Overspeed test		yes	yes	yes	5.7
Runaway test		no/opt	no/opt	no/opt	5.8
Overpressure, emergency trip and load rejection tests		yes	yes	yes	5.9
Trial operating and reliability tests	(commissioning)				6
Temperature stability of rotating parts		yes	yes	yes	6.2
Speed controller system		yes/opt	yes/opt	yes/opt	6.3
Control of cam correlation (double regulated turbines)		yes	yes	yes	6.4
Performance guarantees and tests					7
Maximum generator (transformer) power output		[a]	[a]	yes	7.2
Index test					7.3
- Shape control		[a]	yes	–	7.3.3
- Index plant efficiency		[a]	yes	–	7.3.4
- Optimizing cam correlation		[a]	[a]	[a]	7.3.5
Turbine efficiency					7.4
- Absolute discharge measurement		yes	–	–	7.4.1
- Thermodynamic method		yes	–	–	7.4.2
Computation of results and comparison to the guarantee		yes	yes	yes	8
Error analysis		yes	yes	yes	9
Other guarantees					10
Cavitation		yes/opt	yes/opt	yes/opt	10.1
Noise		no/opt	no/opt	no/opt	10.2
Vibration		no/opt	no/opt	no/opt	10.3

NOTE Definitions used in Table 1 are the following:

yes – may be required.

yes/opt(ional) – normally yes, but depends on the turbine type and site conditions.

no/opt(ional) – normally no, but depends on the turbine type and site conditions.

[a] included in other tests.

– not required.

4.1.2 Contract conditions

The contract specifies the guarantees, and includes the scope of the tests, and the classification of measuring instruments. Safety tests shall always be included. The condition of the plant, water quality, and setting levels shall all be specified (see Annex F).

4.2 Scope of performance guarantee

4.2.1 General

All guarantees concern the hydraulic passage between reference section 1 and 2 (turbine guarantee domain) and the corresponding net head. The guaranteed data required for each class is given below:

4.2.2 Class A: Maximum power output

a) Maximum power output of the generator, including losses a) to d) of 4.2.5 — $P_{gen,\ max} = f\ (H)$

b) Maximum power output of the transformer, including losses a) to e) of 4.2.5 — $P_{out,\ max} = f\ (H)$

- Power output versus net head, see Figure 15
- Discharge versus turbine opening, see Figure B.18
- Electrical connection sheet, see Annex D

4.2.3 Class B: Index test

Shape control of turbine characteristic for newly commissioned turbines, and for refurbishment projects to compare pre- and post- refurbishment measurements.

a) Shape control — $\eta_{ix} = f\ (P_t)$

- Expected shape of plant efficiency, see Figure 16
- Possible deviation to the shape, see Figure 16
- Hill chart if the head differs by more than 3 %, see Figure 19

b) Index plant efficiency — $\eta_{\ plant\ Ix} = f\ (P_{out})$

- Hill chart, see Figure 19
- Generator losses, see Annex D
- Electrical connection sheet, see Annex D

c) Optimizing of cam correlation for double regulated turbines

- Pre-adjusted opening of guide vane versus runner blade opening as a function of static head, see Annex I

4.2.4 Class C: Turbine efficiency

a) Absolute discharge measurement — $\eta_t = f\ (P_t)$

b) Thermodynamic method — $\eta_t = f\ (P_t)$

- Hill chart, see Figure 19
- Generator losses, see Annex D
- Electrical connection sheet, see Annex D

4.2.5 Interpretation of losses

The parties shall agree on interpretation of losses due to the following mechanical and electrical equipment:

a) turbine bearings and additional equipment;

b) mechanical power transmission devices such as gears and belts;
c) generator including bearings, excitation system, mechanically driven or electrically connected auxiliaries;
d) mechanically or electrically driven auxiliaries;
e) transformer.

The following subsystems and devices are excluded from consideration:

f) devices which are needed for dewatering (mud pumps);
g) temporary heating and / or cooling systems;
h) any lights.

4.3 Scope of tests

4.3.1 Safety tests

If testing reveals that operation of the unit is not safe, then no further operation of the plant may be continued, until such deficiency is located, evaluated and repaired.

4.3.2 Trial run and reliability tests

When all the safety tests are completed, and within the allowable limits, the time limited trial run can be started. The duration of the trial run is normally at least 72 h.

4.3.3 Performance test

4.3.3.1 General test condition

a) Method of measurement: the methods to be used for the measurement or computation of discharge, power, head, efficiency, speed, and losses shall be stated in the general procedure (see Clauses 7, 8, and 9).
b) Number of points, runs and readings: a performance curve such as the ones shown in Figure 15 (class A), Figure 16 (class B), and Figure 18 (class C) requires a minimum of six and preferably eight or ten points. Each point will be obtained from one or more runs (see Figure 25 and Table H.4). The number of measurements taken during a run depends upon the methods of measurement used. To eliminate outliers, at least three runs are to be taken over an agreed time or over the duration of any time-based measurement.
c) The interval of time used for instrument recording shall generally be the same for each variable.
d) Small hydro turbines are often built from standard components. Care shall be taken to avoid operating the turbine above its maximum power (see Figure 15).

4.3.3.2 Test condition to be fulfilled

a) Fluctuations and variations during a run (see Figure 22, Figure 23, and Figure 24). Fluctuations are defined as high frequency changes, of more than 1 Hz, in the values of head, power output, discharge and rotational speed about average values. They are often caused by head and pressure variation in the peripheral areas such as the river, canal, reservoir, penstock, and outlet channel. Variations are longer period changes or trends.
b) The extreme variation of power shall not exceed ±1,5 % of the average value of power.
c) The extreme variation of head (pressure) shall not exceed ±0,5 % of the average of value of head (pressure).
d) The extreme variation of rotational speed shall not exceed ±0,5 % of the average of value of rotational speed.

4.3.3.3 General check after the tests

The preliminary computation of the test results shall be made at site. If the plant appears to fail its guarantee, steps shall be taken to identify the cause before disconnecting the instrumentation.

a) Check the data for errors, and recalculate the results if any errors are found.
b) Check all the instrumentation for correct connection, calibration, absence of air in the measuring pipes, and for irregular fluctuations.
c) Check for random errors and outliers.
d) Check for any hydraulic failure within the waterway such as the inflow conditions.
e) Check for suspended particles within the turbine such as grass, algae, or industrial fibre, etc. (stop the turbine, and clean the turbine and the water passages).
f) Check of the reference levels.
g) Check of the unit for any abnormal hydraulic and/or electrical behaviour.
h) Check for possible air release at the draft tube outlet.
i) Investigate unexpected vibrations and/or noise level.
j) Verify the equipment set-up and the flow passage geometry:
   - turbine opening in closed and full opened position, check for any signal offset;
   - cam correlation (double regulated turbines);
   - deflector correlation to needle opening;
   - runner geometry.

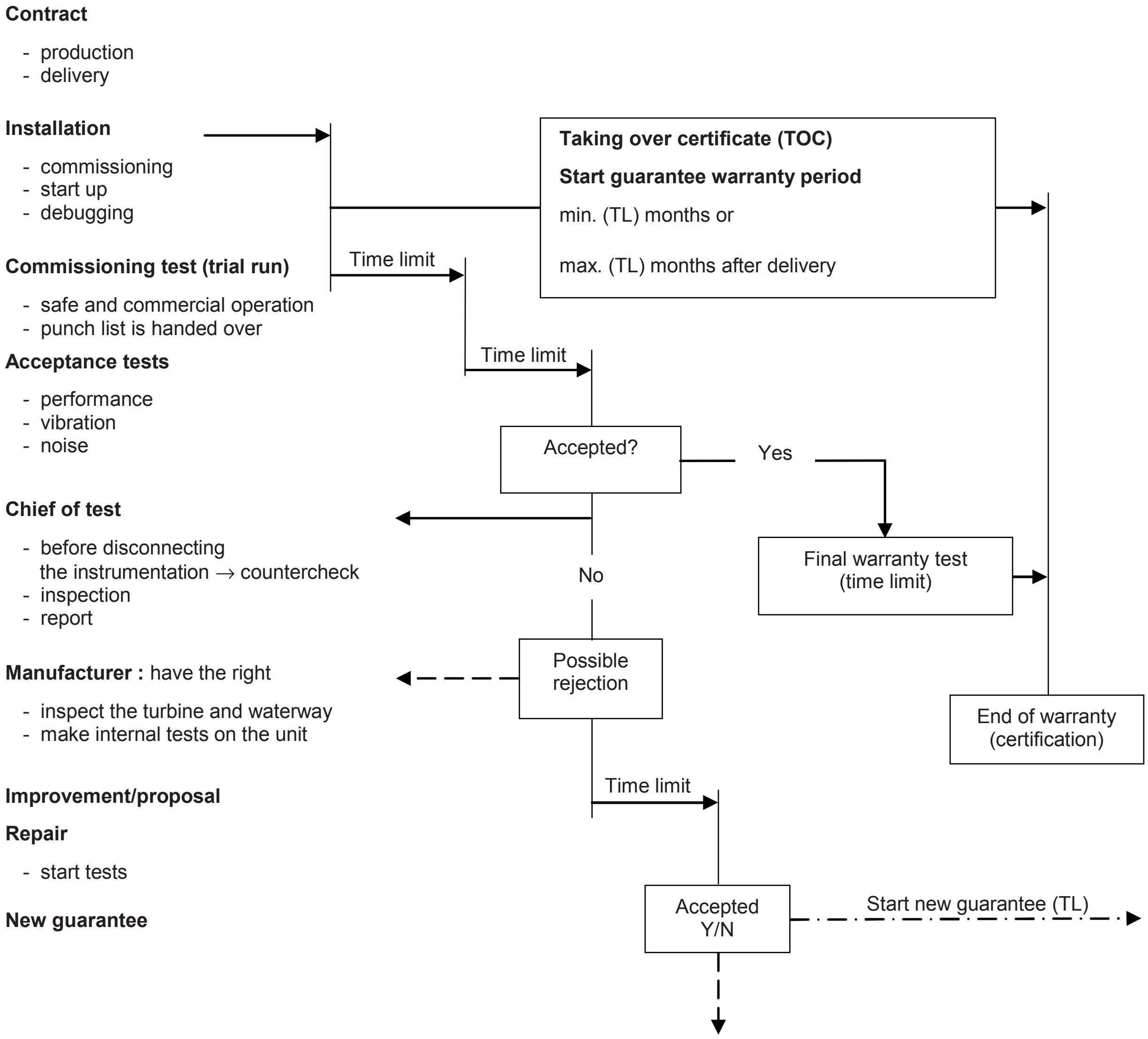
After this investigation, the chief of tests shall make a short report to indicate the possible reason for failure. The manufacturer shall have the right to inspect the dewatered turbine and the upstream and downstream water passages at this time.

4.4 Aptitude

All parties shall have confidence in the test team with respect to responsibility and competence when testing the unit under critical conditions. Commissioning engineers shall normally carry out class A tests. Specialists may be required to carry out class B and C tests.

4.5 Warranty

An example of a procedure for installation, acceptance and warranty of a hydroelectric installation is shown in Figure 2.



NOTE TL is the mutually agreed **T**ime **L**imit (normally 6 months).

Figure 2 – Warranty period

5 Safety tests (commissioning)

5.1 Pre-start tests

Small hydro installations vary considerably as to their complexity. Some general guidance as to the nature of commissioning is given in Annex G.

5.2 Closing devices

5.2.1 General

Ensuring that the water supply can be turned off safely under all circumstances is a matter of safety. The following control devices should be carefully checked.

5.2.2 Intake gate or valve

This device is normally designed to close in any condition including leakage or rupture of the penstock. The closing time shall be set to prevent dangerous surges or water waves in the channel or in the upper bay.

5.2.3 Turbine inlet valve

This valve should be normally designed to close against maximum discharge, and when the turbine is at runaway conditions. Closing characteristics and closing time are generally selected so that surges and water hammer effects are less than the effects caused by the turbine.

5.2.4 Guide vanes (Francis and Kaplan turbines)

This component is the main regulating device and shall be able to close against full discharge both in normal and emergency conditions. Operation of the guide vanes should be tested under all known operating conditions. The friction forces and hydraulic forces should be compared with relevant design values for dry and wet opening and closing pressures, and load ramps from no load to full load and back, see Figure 3 and Figure 4).

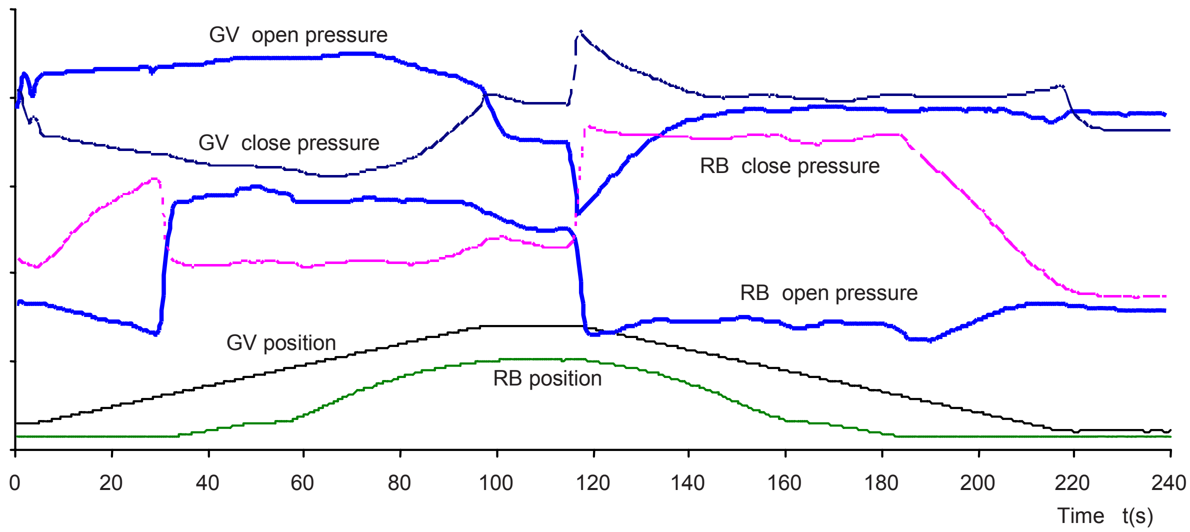
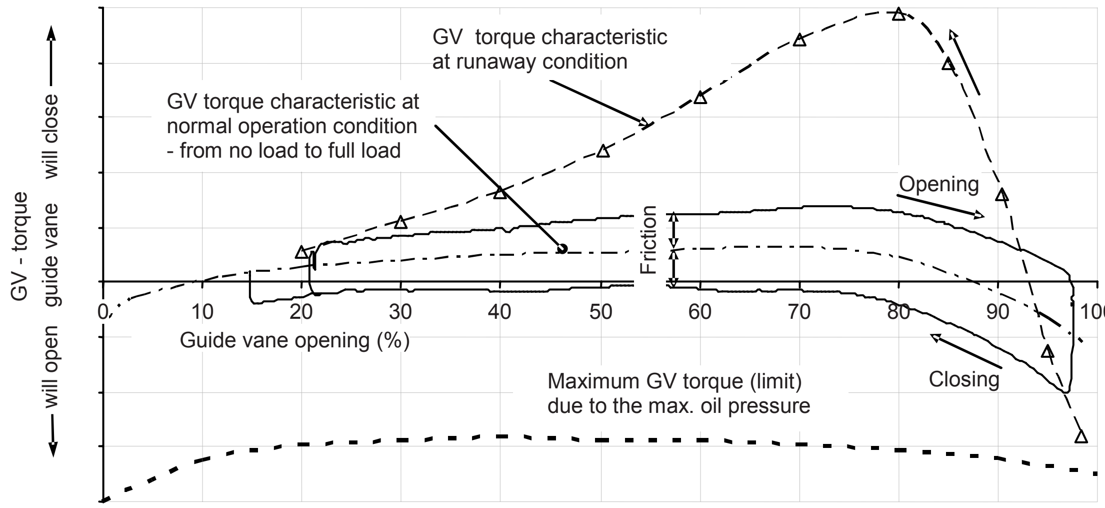


Figure 3 – Vanes and blades servomotors force measurements (Kaplan on line)

The guide vane closing characteristic and closing time are generally defined in order to optimize the opposing effects on overpressure (water hammer) and overspeed. Generally, the most severe conditions occur during emergency shutdown or during load rejection.

In double regulated Kaplan or bulb turbines the overspeed under normal operation may be controlled by the opening of the runner blades (see Figure 3). In these cases, opening and closing pressures of the runner blade servomotors shall also be recorded, in order to calculate friction and hydraulic forces and to compare those with design values.



NOTE The characteristics of the guide vane (GV) torque represents a typical design. However, the individual characteristics of the curve, in terms of opening and closing, depend on the individual GV shape and profile.

Figure 4 – Evaluation of the guide vane (GV) closing characteristic

5.2.5 Needle valve and deflector (Pelton and Turgo turbines)

The needle is the main regulating device and shall be able to close in presence of full flow both in normal and emergency conditions. The deflector (if fitted) shall also be designed to intercept the full flow and is used as the regulating device in some systems. The friction forces and hydraulic forces should be compared with relevant design values for dry and wet opening and closing pressures, and load ramps from no load to full load and back (see Figure 5).

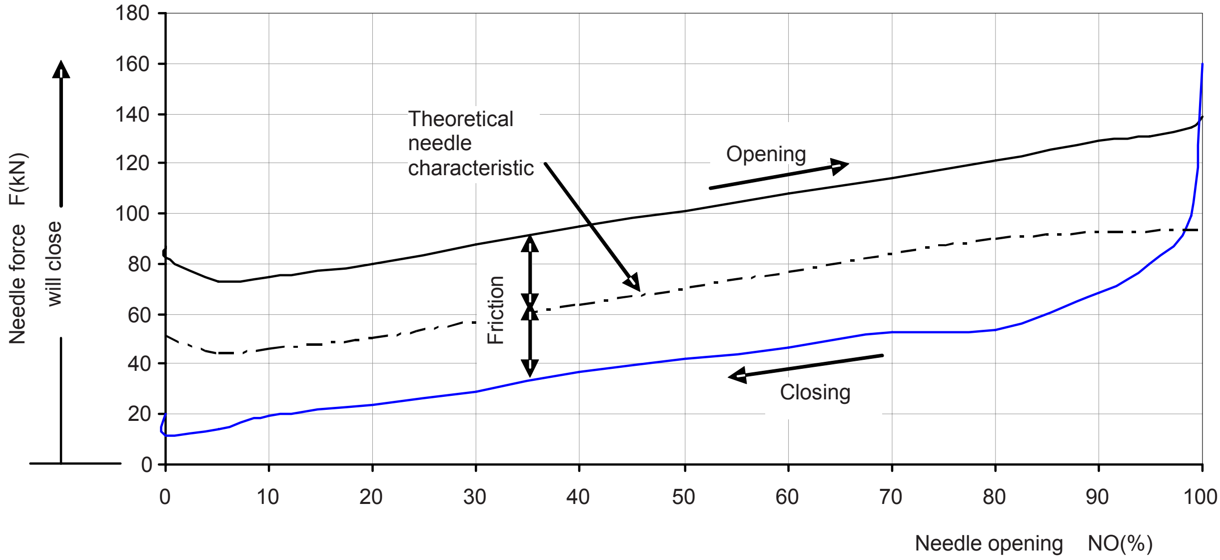


Figure 5 – Needle servomotor force

The needle closing characteristic and the closing time is generally defined in order to control overpressure (water hammer) while the deflector is used in order to control overspeed (see 5.5, and 5.7).

If a cam is fitted to control the relationship between needle and deflector, this relationship shall be verified in order to obtain safe overspeed values without any interference between jet and deflector on all needles.

NOTE It is important to individually check each cam for correct needle stroke/governor stroke/deflector position relationship.

5.3 First run operation and control

The commissioning engineer will decide if the unit can be started. If, during this or any of the following tests, any abnormal behaviour is observed, the unit shall be shut down immediately. Particular care shall be taken to detect any anomalous noise, scraping etc., see Figure 6.

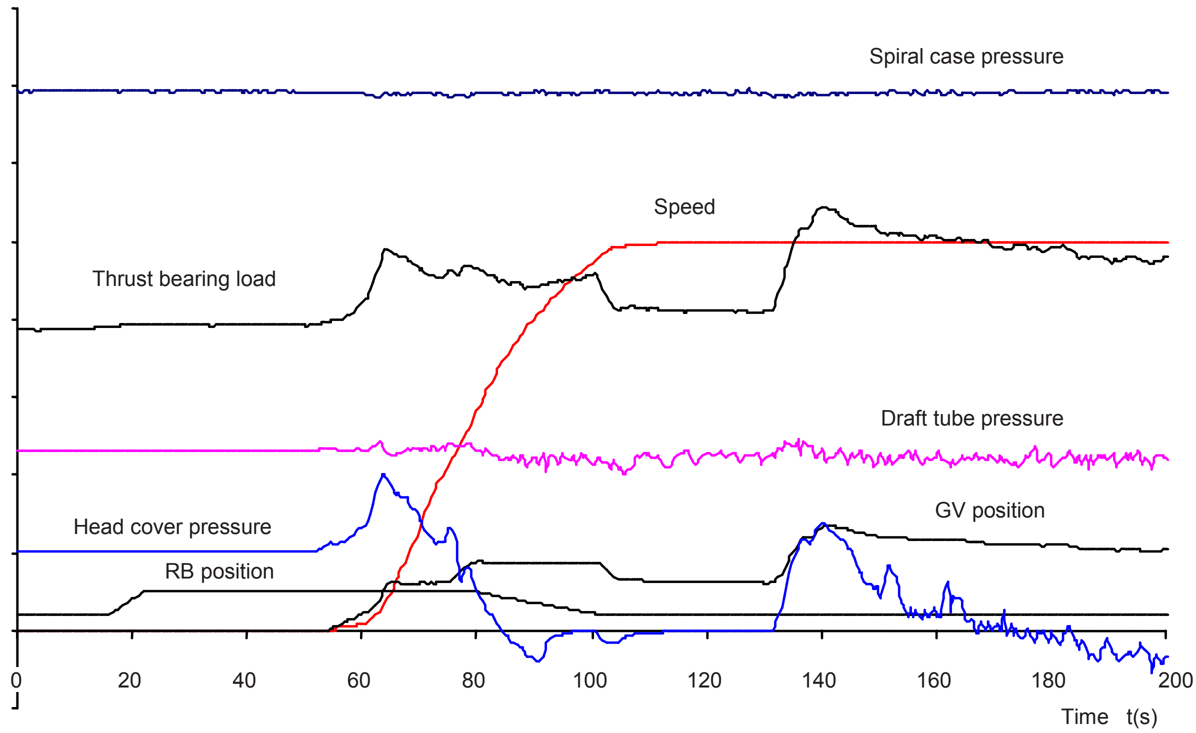


Figure 6 – Automatic start – Synchronization – No load test (Kaplan turbine)

5.4 Bearing run at rated speed

The speed shall be increased in steps to the rated value. The number of required steps and the time spent at each step should be decided in advance between the parties. Note that hydrodynamic bearings can be damaged if run at slow speeds, and the minimum speed should be specified by the manufacturer.

The criteria for accepting the turbine at each speed step will be decided between the manufacturer's representative and the commissioning engineer. This could be either the time for all bearing temperatures to stabilize sufficiently to determine the final temperature value, or just to determine whether there is any internal rubbing.

If a bearing temperature increases rapidly, or is excessive, the unit shall be shut down and the causes of the phenomenon investigated and corrected. The condition of the lubrication system should be monitored, and if water is noticed in oil or oil foaming is observed, the cause shall be located and eliminated. Other control devices may be tested during the bearing run. The correct behaviour of the governing system may be checked at this time and, when the governor is operating correctly, it may be used for running the unit.

Unless specifically required by the manufacturers, the above mentioned checks do not require specific instrumentation, only those normally installed in the plant or available during the erection (i.e. micrometer-comparators to check the shaft run-out). Vibration measurements need only be conducted if contractually required.

5.5 Emergency shutdown (no load)

The turbine will be tripped when running at rated speed and no electrical load. The closing time of the guide vanes (or needle valves), and the hydraulic pressure or electric current to operate them shall be measured. These values should be compared with the design values.

The pressures in the water passages and the run down time of the turbine shall also be measured. Correct operation of the brake (if fitted) should be verified, see Figure 7.

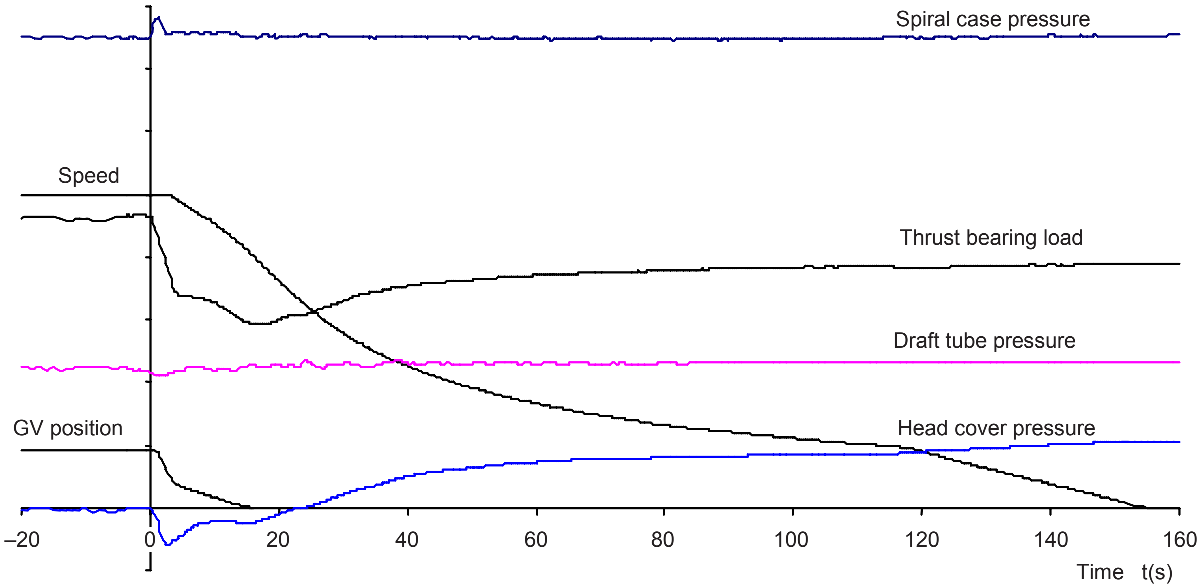


Figure 7 – Emergency shutdown from no load test (Kaplan turbine)

5.6 Electrical protection

When a small hydroelectric generator is connected to a grid, there is a need for electrical protection to ensure that the generator is safely disconnected from the grid in the event of a fault. The electrical fault can occur either on the generator or on the grid. The protection should guarantee that the generator is disconnected when repairs are being made to the grid.

The common elements of the protection system are relays that detect under- and over-voltage, under- and over-frequency, and rate of change of frequency. The operators of the local grid should specify the protection relays required and the nature of the acceptance tests.

After the mechanical tests have given satisfactory results, the testing of the electrical protection shall be undertaken according to the contractual conditions. During the tests, the manufacturer's requirements shall be strictly observed.

NOTE The electrical protection tests have normally to be completed before any electric connection to the grid is made and any power is exported.

The acceptance tests normally include the sequence and time to open circuit breakers, once the fault has been detected (simulated during the test). The results of the electrical protection tests shall be recorded.

5.7 Overspeed test

The turbine speed is carefully increased under manual control, and any speed set points are checked. The operation of the runner blade servomotor of a double regulated Kaplan or bulb turbine shall be checked at this time.

5.8 Runaway test

A total runaway speed test may also be performed especially in the case of turbines with guaranteed steady state runaway. The steady state runaway tests shall only be carried out if expressly laid down in the contract. The real need of performing this test shall be deeply evaluated by all parties taking into account all possible risks.

All runaway tests shall be time limited. The runaway test concerns the worst case for each type of turbine when all closing regulation is locked in the full open position. As an example, the maximum expected runaway speeds are shown in Table 2 below. If the vibration level rises after a runaway test, the cause should be investigated and remedied.

Table 2 – Maximum runaway speeds (n_{run}) expressed as a percentage of rated speed

Turbine type	n_{run}%
Francis turbine	160 to 210
Pelton and Turgo	200
Crossflow	190 to 230
Kaplan propeller type	200
Double regulated Kaplan	300 to 360
Bulb turbine	300 to 360
NOTE For double regulated turbines this speed is expected when the wicket gate is locked in the full open position and the runner is closing out of cam correlation.	

A runaway test shall be executed as shown in Figure 8. The time at stabilized runaway speed shall be limited to an agreed value. Generally, the runaway guarantee refers to the maximum guaranteed head, but the actual runaway test shall be carried out at the head available when the test is performed.

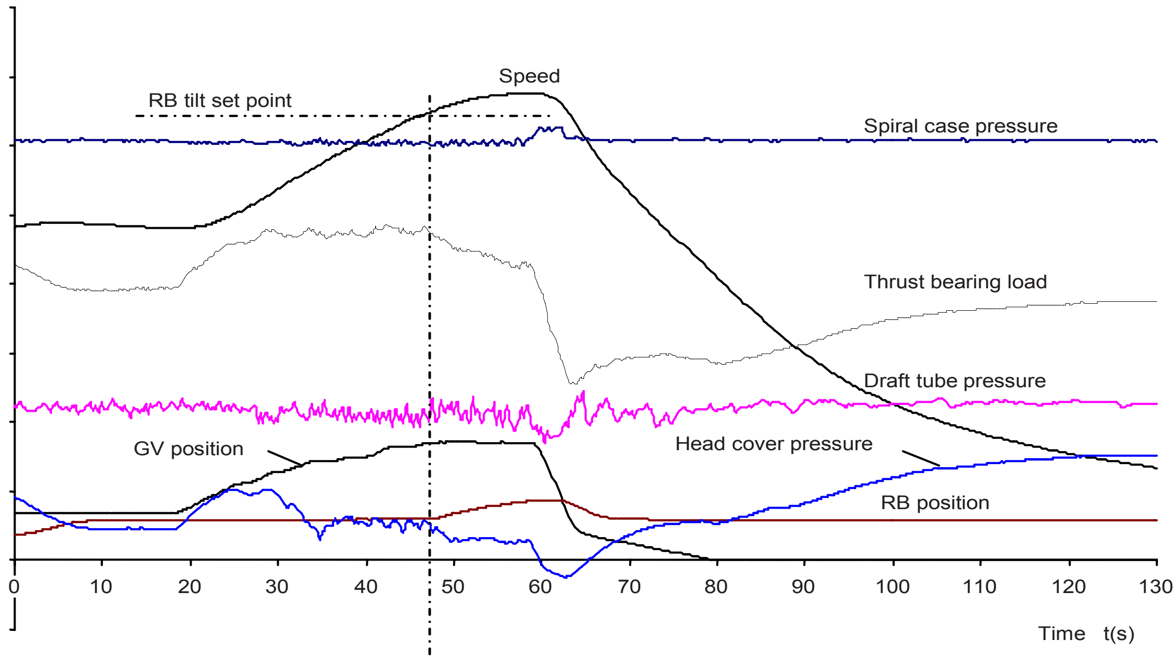


Figure 8 – Runaway test (Kaplan turbine)

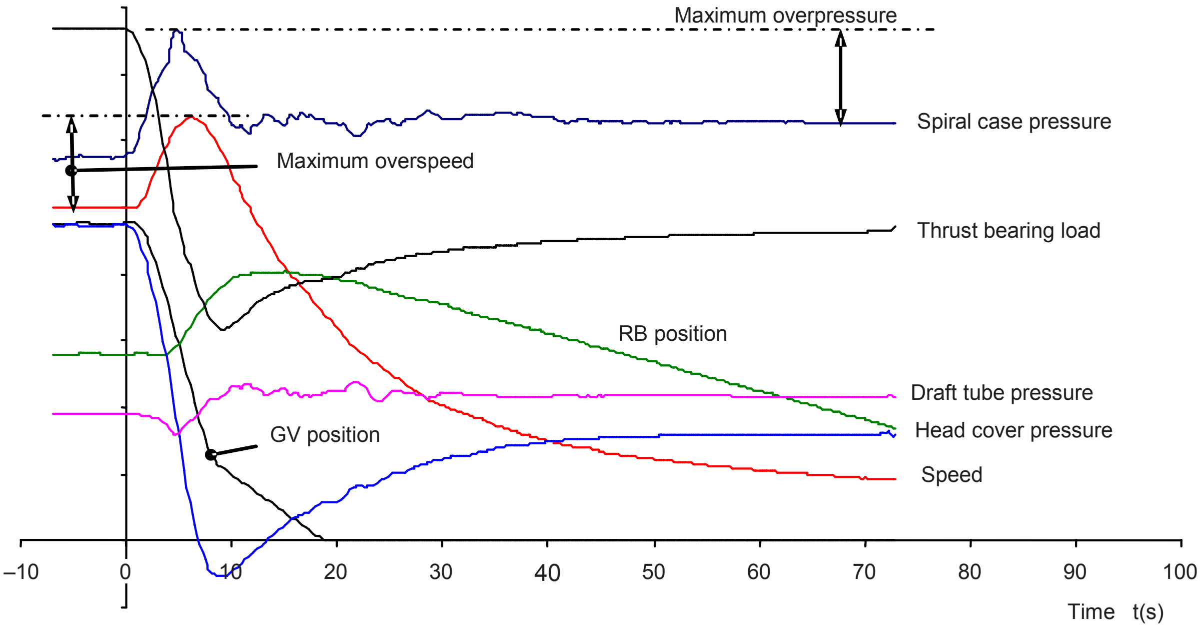
5.9 Overpressure, emergency trip and load rejection tests

5.9.1 General conditions

The load shall be increased in steps to the maximum value. At each step, observations and measurements in steady state condition shall be repeated and the operating stability of the turbine shall be verified. In so far as the load conditions so permit, the hydroelectric unit shall be subjected to load rejection tests at each stage (generally 1/4, 1/2, 3/4 and 4/4 of rated load). If the governor parameters are readjusted, then all the tests affected by these readjustments shall be repeated.

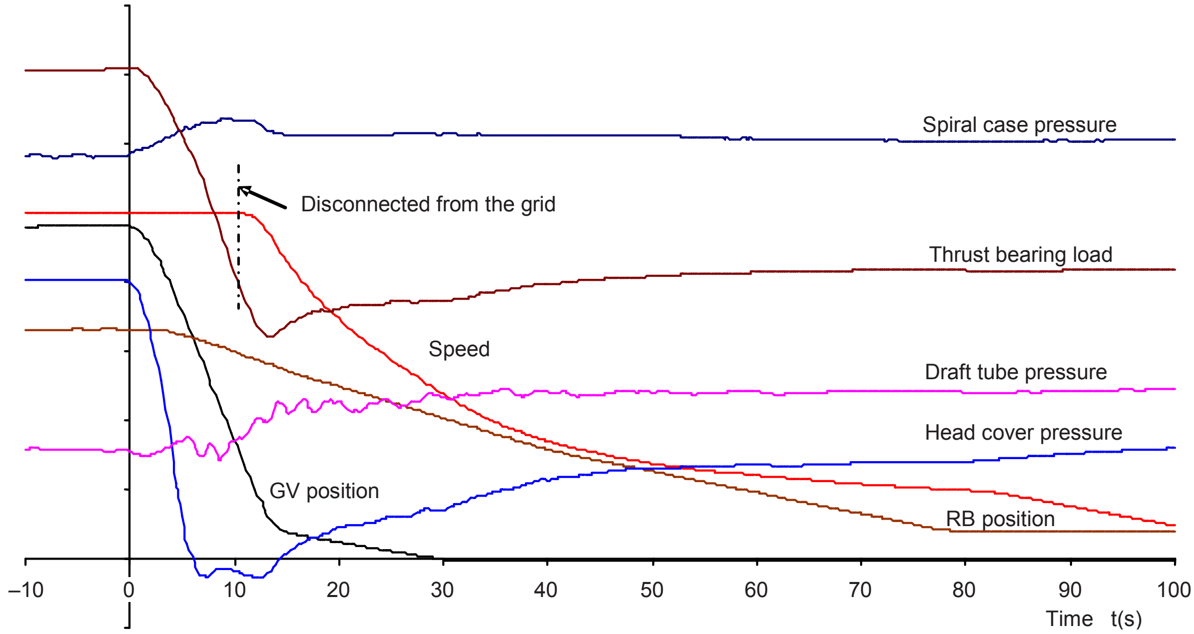
The unit can be subjected to different types of load rejection including emergency shutdown (due to electrical or mechanical failure), normal stopping sequences and normal shutdown with or without return to no-load operation. For safety reasons the emergency shutdown tests shall be performed first.

The test sequence shall include the most unfavourable conditions within the guaranteed operating range. This may correspond to load rejections from full opening, partial opening (with pressure relief valve) or low loading. If the plant includes several units with common intake, the most unfavourable condition may correspond to the simultaneous closure of the shut-off components of all the units, rather than the simultaneous load rejection. Some typical examples of emergency shutdowns are shown in Figures 9, 10, 11, and 12.



NOTE The turbine is closing and disconnecting from the grid immediately. The closing is controlled by the governor (Kaplan turbine).

Figure 9 – Emergency shutdown due to an electrical fault



NOTE The turbine is closing and disconnecting from the grid at no load. The closing is controlled by the governor.

Figure 10 – Emergency shutdown due to a mechanical fault

5.9.2 Testing the guide vanes or needle valves

The closing time of the guide vanes (or needle valves), and the hydraulic pressure or electric current to operate them shall be measured. These values should be compared with the design values.

5.9.3 Testing the turbine inlet valve

If the turbine inlet valve is the only method for isolating the turbine from the waterway, the operation of the valve shall be tested when the turbine is at full discharge.

NOTE This is a potentially dangerous test, and it should be carried out in stages at ¼, ½, ¾ of full discharge first.

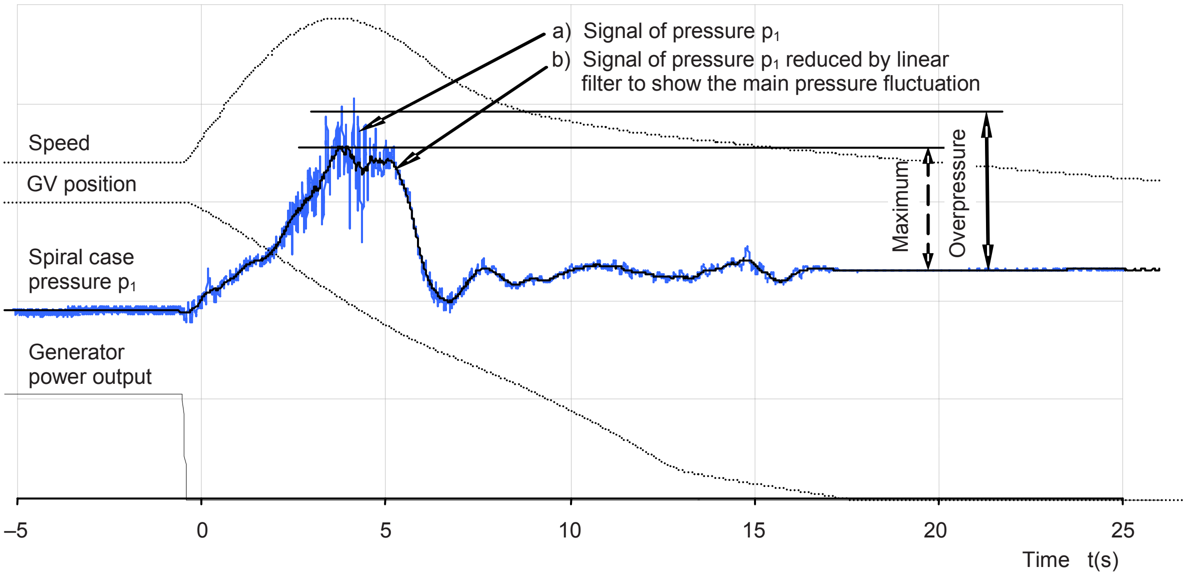
5.9.4 Testing the pressure relief valve

If a pressure relief valve is fitted, operational tests should be made to show that the turbine can be shut down in a safe manner under all circumstances, even when the valve fails to open.

5.9.5 Pressure rise

The curves given in Figure 11 show the pressure rises caused by closing the guide vanes, and are from actual site test results. The superimposed fluctuation is due to runner rotation and other dynamic phenomena such as cavitation or hydraulic resonance. Normally, for small installations, the mean pressure should be used for comparison with the guarantees.

However, when the fluctuation is large, the procedure outlined in Figure 11 and Figure 12 may be applied to find the maximum pressure due to the hydraulic transients. In order to avoid ambiguity, the method of plotting the high frequency signal envelope should be agreed upon with the purchaser, and clearly explained in the test report. This example uses a low pass filter with a high cut-off with half of the noise band deducted before calculating the maximum pressure.



NOTE The turbine is closing and disconnecting from the grid immediately. The closing time and characteristics are controlled by orifices. Example for pressure fluctuation (Francis turbine).

Figure 11 – Emergency shutdown due to the governor failure

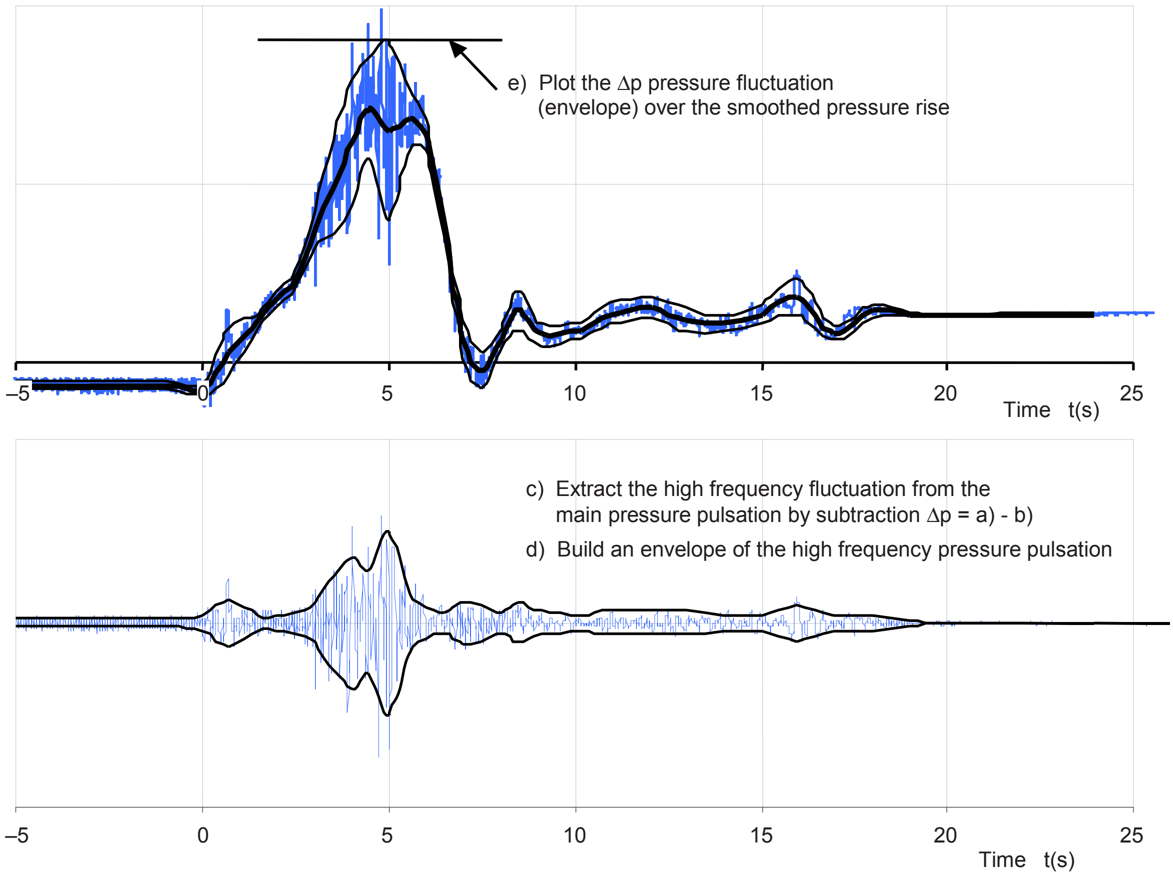


Figure 12 – Evaluation of the maximum overpressure

5.10 Measured quantities

5.10.1 Pressure

Pressures shall be measured using taps located at the inlet and at the outlet of the turbine as close as possible to the upstream and downstream pressure reference section (see Annex B).

If the maximum pressure in the upstream waterways is of importance, four pressure taps should be used placed 90° apart round the same cross section upstream of the inlet valve. The pressure taps should be connected by steel pipes to a ring manifold and with the pressure transducer directly connected to the manifold. Dimension of the pressure taps, ring manifold etc. should be as given in B.4.1.

The use of pressure transducers is recommended so that the transient over pressure and under pressure can be acquired and preferably recorded. The equipment used shall have a response time compatible with the frequency of the pressure fluctuations being studied. For this purpose the transducers shall be placed in the immediate proximity to the pressure taps.

5.10.2 Speed

Rotational speed shall be measured using a tachometer or by using the governor signal.

5.10.3 Control components

The movement of control components (guide vanes, blades, or needle and deflector) shall be recorded by using governor signals or displacement transducers.

6 Trial operating and reliability tests (commissioning)

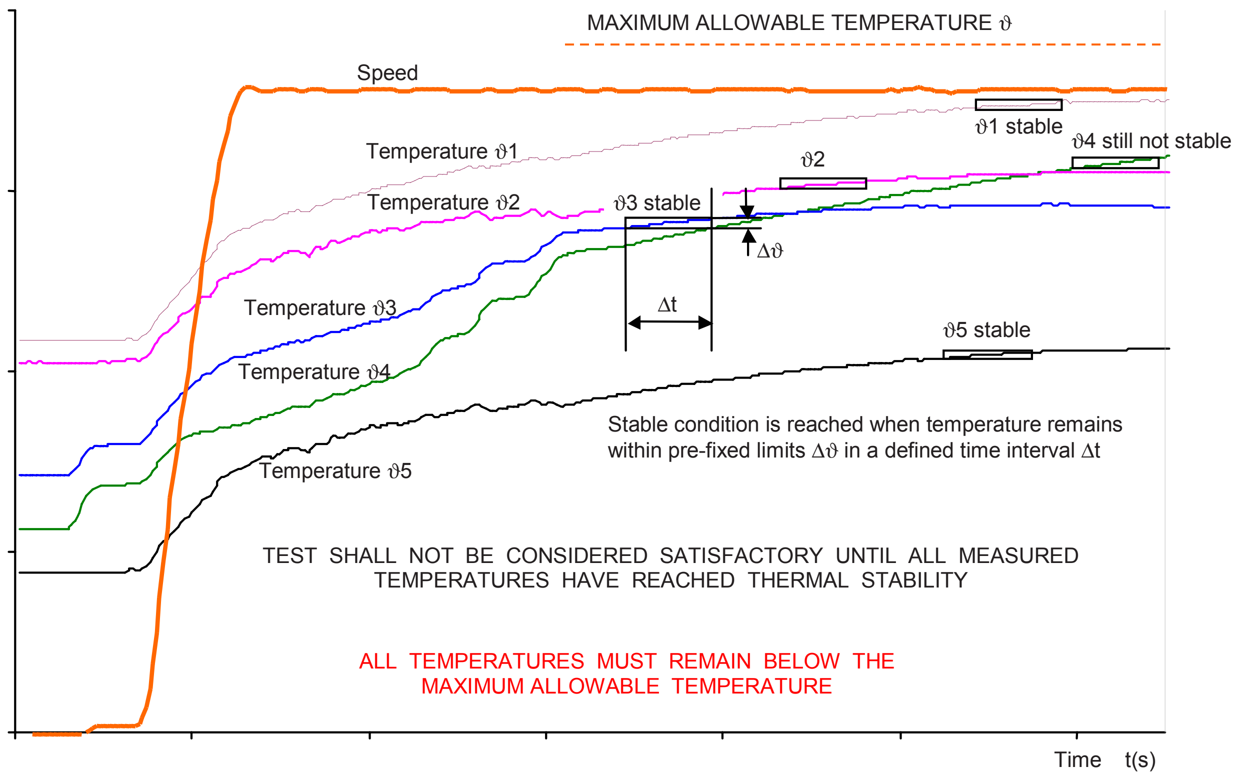
6.1 General

During these tests, the hydroelectric unit shall be on “trial run” to enable any necessary adjustments to be made while operating over the full load range. The duration of “trial run” of the complete equipment shall be for a specified period agreed between purchaser and manufacturer. The “trial run” shall be accepted if each item has operated successfully.

6.2 Temperature stability of rotating parts

6.2.1 General

The unit shall be run under the most arduous conditions to check that the bearing and generator temperatures achieve stability. The behaviour of radial bearings, thrust bearings and core temperature of the generator and all other circuits or mechanical components likely to suffer a temperature increase shall be verified.



NOTE During this test, the ambient air and cooling water temperature should not be higher than the values indicated in the contract. If this occurs, all parties should decide on how to rectify the situation. Higher maximum temperature limits can be proposed provided all parties agree that the safety margins are still reasonable.

Figure 13 – Temperature stability, recording at no load up to stable conditions

6.2.2 Temperature guarantees

The temperature rises and absolute temperature values shall be compared with the maximum admissible values stated in the contract or agreed between parties. A typical recording showing the stabilisation of various temperatures is given in Figure 13.

6.3 Speed controller system

6.3.1 General

There may be various combinations of the following types of control.

- No active regulation because the speed is set by the grid frequency.
- A speed governor.
- A voltage governor adjusting the excitation of the alternator.
- A head level controller maintaining the water level at inlet or outlet.
- A load management controller maintaining a set power output.
- An electric load governor absorbing the excess generator output.

6.3.2 Unit operating without regulation

Asynchronous generators can be connected to a grid when the speed is 1 % to 2 % above synchronous speed. The control system should cope with the inrush of current when connection is made to the grid. Small synchronous generators can be connected to a stiff grid without using a speed governor provided frequency and voltage are maintained within the grid limits whilst synchronizing.

6.3.3 Unit operating with a speed governor

6.3.3.1 General

The nature of the tests varies according to the role of the governor and the precision required. If the governor is expected to provide stable operation, the acceptable frequency variation should be stated in the contract. The speed governor should be set up for stable operation by a speed variation test with no external load. The test should demonstrate that when the control device is opened or closed rapidly, the speed returns to the set point within one cycle of speed variation. An example of a satisfactory response is given in Figure 14.

For a more complete study of the speed governor, reference is made to the publications IEC 61362 for specification and IEC 60308 for testing.

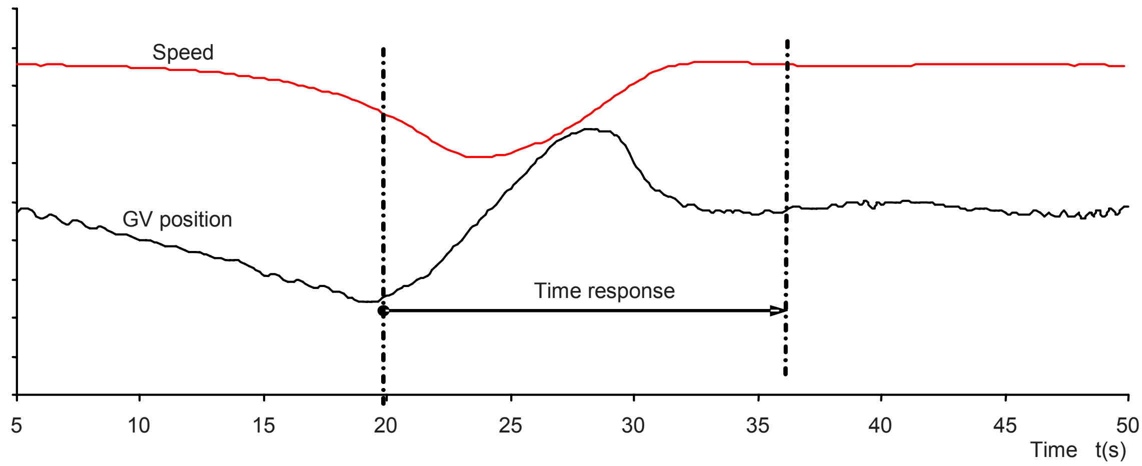


Figure 14 – Speed governor check at no load

A small hydroelectric turbine may be fitted with a speed governor for one or more of the reasons described below.

6.3.3.2 Synchronizing only

This mode is used when a small turbine is required to connect to a large grid. The speed governor may then be used to load the turbine, using speed droop, or may switch to another management system such as level control.

Once synchronized, the governor should automatically switch to the appropriate operational mode. The timing of the changeover is important if delay could cause a conflict between the grid frequency control and the turbine governor.

6.3.3.3 Frequency control on an isolated system

A small turbine may have difficulty in accepting the load changes on an isolated grid without large frequency fluctuations. The contract should state what size and type of load is expected and the frequency tolerance that is to be achieved. A grid supplied by a single hydroelectric unit shall be configured so that the plant can be started. The load should be segmented so that load increments are applied as agreed in the contract.

6.3.3.4 Frequency stability in conjunction with diesel generators

A small local grid may contain a mixture of turbines and other prime movers, such as diesel generators. The contract should state what role the small hydroelectric turbine is expected to provide. The ability of the turbine to provide frequency stability depends on its relative size compared to the other generators, and its speed of response. The governor shall be tested to verify that it can cope with the expected load changes within the frequency tolerance stated in the contract.

6.3.4 Unit operating with a voltage governor

A voltage governor is used when the generator takes part in controlling the reactive energy on the grid. The excitation of a synchronous generator is adjusted to maintain the voltage or power factor within prescribed limits. The voltage or power factor variation should be measured using a data logger during the load tests and load rejection tests. The ability of the voltage governor to maintain the voltage depends on the other generators feeding the grid. The acceptable limits shall be specified in the contract.

An asynchronous generator may have a controller to adjust the power factor of the unit. This is usually in the form of extra capacitors across the load.

6.3.5 Unit operating with a controller

6.3.5.1 Head level controller

The discharge through the turbine is controlled to maintain the head or tail water level. The discharge should be varied throughout its operational range to identify whether the controller can operate in a stable manner. If there are two or more hydroelectric units, or single units with multiple jets, connected to the same supply, there should be an overall water management system to start up or shut down the turbines in order to maintain the head level.

If operational guarantees have been specified in the contract, then measurements of the variation of head level should be made.

6.3.5.2 Unit operating with a load management controller

The load management controller maintains power output from the generator at the present level. The controller should operate in a stable manner throughout the permissible operating range. Variations of voltage and head that affect the control and the allowable limits of variation of power shall be agreed contractually.

If operational guarantees have been specified in the contract, the measurement of the load deviation from the set point should be made.

6.3.5.3 Unit operating with an electric load governor

The electric load governor is used on an isolated system so that the generator produces a constant power output. Excess power is switched to and from a resistor to match the load changes on the system. The resistance has to dissipate the excess power as heat and shall be able to operate within the temperature limits defined by the manufacturer. The operational temperature of the governor should therefore be monitored during load tests and load rejection tests.

The load governor can cause electrical emissions of radio frequency interference when switching loads. The level of emissions should be measured if operation guarantees have been specified in the contract.

6.3.6 Measurements when testing the control system

The stability of the hydroelectric unit shall be tested throughout the operational range. If instability in frequency, voltage or power is observed then the following measurements should be taken:

- position of all control servomotors;
- grid frequency or the speed of the turbine;

- voltage at the generator terminals;
- active and reactive power or current supplied;
- headwater or tailwater levels;
- pressures in the inlet and/or outlet turbine sections.

If there are operational guarantees specified in the contract, they should specify the allowable variation and the allowable grid frequency or voltage variation that may occur at the same time.

6.4 Control of cam correlation

Cams are used to provide a relationship between the controls of a turbine for the following reasons:

- to achieve optimum efficiency on double regulated turbines such as Kaplan and bulb turbines. See also 7.3.5;
- to correlate the movement of needle and deflector on Pelton or Turgo turbines.

The relationship should be tested throughout the entire operational range of the turbine.

7 Performance guarantees and tests

7.1 General

The aim of performance tests is to verify contractual guarantees as listed in the main performance guarantee in 4.2. These guarantees shall be verified under contractually defined site conditions. The turbine and hydroelectric unit performance (efficiency) is evaluated from the parameters shown in Table 3.

Table 3 – Performance test parameters

Class		Measured parameters
A,B,C	H	Net head related to the turbine guarantee domain between the high pressure section 1 and the low pressure section 2, measured and evaluated as an absolute value.
A,B,C	P_{gen} (P_t) P_{out}	Generator power output (transformer input) measured directly as an absolute value. Transformer power output measured directly as an absolute value.
B,C	Q_{ix}	Discharge passing the sections 1 or 2. The discharge is measured as a relative value by an index.
C	Q, η	Discharge or efficiency, which is measured as an absolute quantity by a primary method.
NOTE A preliminary test of class A category is highly recommended. If, after the analysis of test results, there are justifiable doubts about the performances of the turbine, additional tests could be made with more accurate instrumentation.		

Before testing, the hydroelectric unit shall be in a state of commercial operation. The following data are required according to the test being made:

a) Hill chart, with operation and cavitation limit, and with a list of rated data for different heads.
b) Maximum power output P_t, P_{gen}, P_{out} as a function of the net head, see Figure 15.
c) Physical, geometrical and geodetic data, see 8.1.2 and Table 5.
d) Head losses in water passages as a function of discharge or power output.
e) Losses in the generator, transformer, and auxiliaries (mechanical /electrical).

f) A diagram showing discharge Q as function of turbine opening (guide vanes or needle) and static head to calculate the velocity head, see Figure B.18.

7.2 Maximum generator (transformer) power output as a function of net head

7.2.1 Guarantee

The guaranteed maximum generator (transformer) power output shall be equal to or greater than the measured and evaluated output taking into account systematic and random errors. The reference head for this guarantee is the net head between the turbine guarantee domain sections 1 and 2.

7.2.2 Instrumentation

The panel equipment can be used; the accuracy class shall be known and shall be in accordance to the agreed systematic uncertainties. Care shall be taken of the position for head measuring sections, refer to Annex B. Precision instrumentation with calibration certification should be used if the contract provides for a penalty (or a premium).

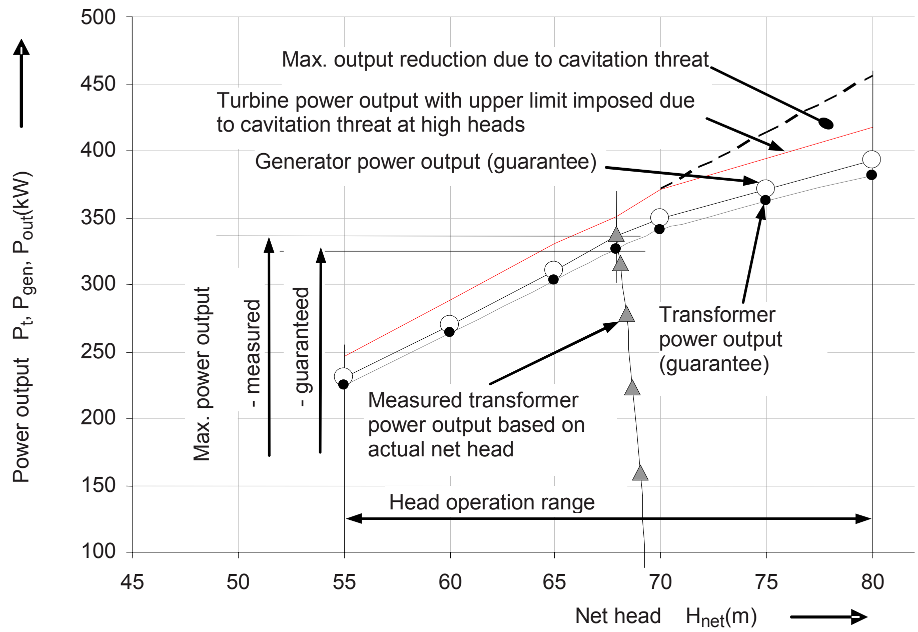


Figure 15 – Maximum power output: procedure to compare measured power output at actual net head to the guarantee

7.3 Index test

7.3.1 General

An index test may be used for any of the following purposes:

a) to determine the shape of the performance characteristics and the relative efficiency of the turbine (shape control) alone, or the plant overall;

b) to assess the change of performance when upgrading turbines. When using an index test for this purpose it shall be noted that modification may affect flow patterns in the measurement sections;

c) to assess the change in performance due to cavitation resulting from a change in the tail water level and/or net head;

d) to optimize the maximum annual energy of single or multiple units;

e) to calibrate the discharge for monitoring over the operation range of discharge and net heads based on the guaranteed hill chart;

f) to determine the optimum cam correlation between the runner blade and guide vane opening for most efficient plant operation of double-regulated turbines;

g) an index test may be used as part of a performance test to complement the primary method of discharge measurement, for any of the following purposes:

   1) to provide additional test data during a field acceptance test, to interpolate and extrapolate the range of data produced by the primary method;

   2) to make a cross check of the index discharge to any primary method;

   3) to obtain calibration data for permanent powerhouse flow measuring instruments by measuring an absolute value of turbine efficiency at some operation points.

7.3.2 Index discharge measurement

An index test is based on a relative measurement of discharge, and one of the following methods given in Table 4 may be used. The discharge may be assumed to be nearly proportional to the square root of the differential pressure.

Table 4 – Index discharge measurement methods

Device		Usual differential pressure (Δp) at maximum load kPa
Differential pressure methods		
Full spiral case	(Winter-Kennedy)	10 to 40
Tubular turbine	(bulb, pit turbine)	10 to 30
Convergent pipe	(conical pipe)	10 to 40
Stagnation probe		15 to 60
Flow indicators		
Simplified flow measuring methods		
Needle stroke on Pelton and Turgo turbines		

7.3.3 Shape control

Figure 16 shows how the shape of turbine performance characteristics can vary within the allowable deviation range (systematic errors). The deviation can be weighted as a function of the turbine power output or discharge.

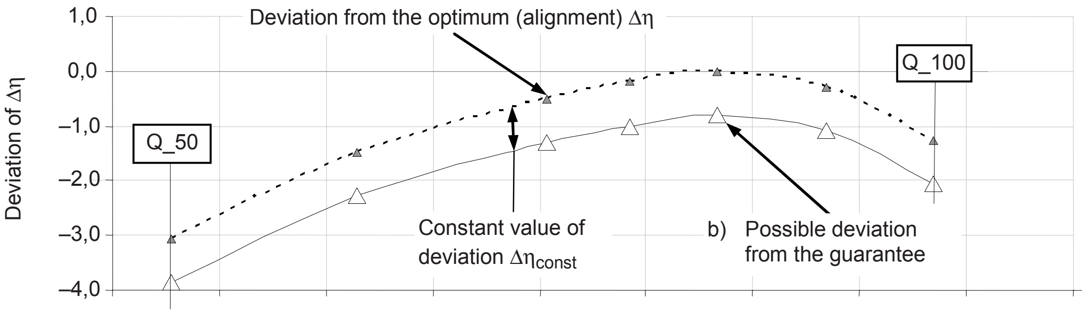


Figure 16a – Deviation of the turbine characteristic from the guarantee

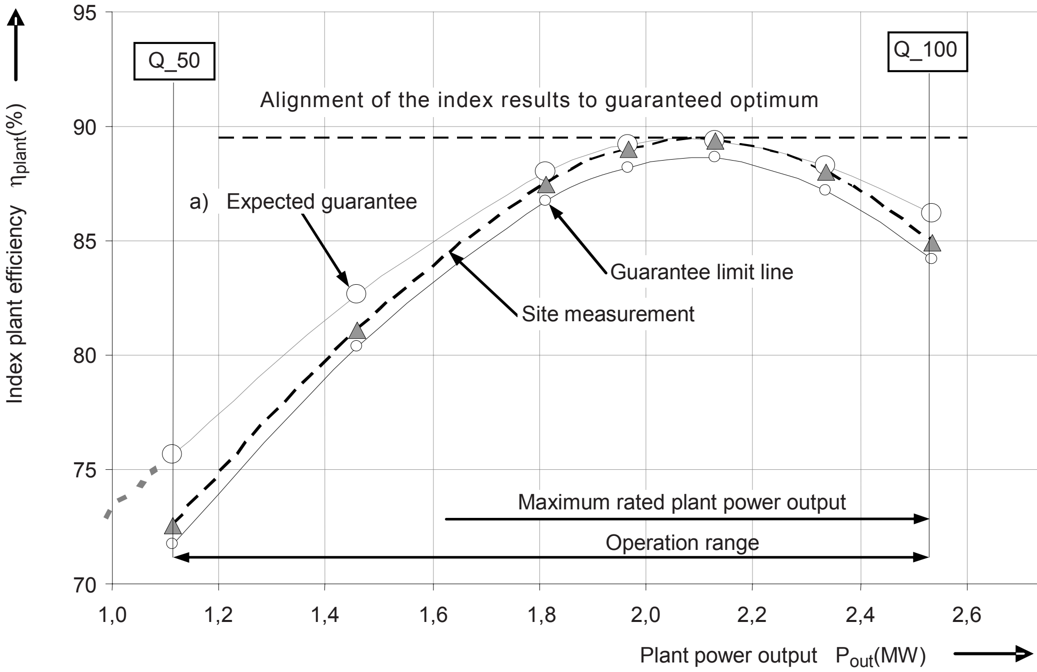


Figure 16b – Alignment of the turbine characteristic to the guarantee

NOTE Q_100 refers to the full discharge at maximum power output, and Q_50 is half the full discharge.

Figure 16 – Comparison of the shape of the turbine characteristic to the guarantee

7.3.4 Index plant efficiency

This test determines the relative efficiency of the turbine or overall plant. These results give information about the plant efficiency curve at actual plant conditions. They can be used to optimize the joint control of all the units in order to attain the maximum annual energy production. Figure 17 shows the switch band for starting or stopping the second unit optimized to attain the maximum annual energy production.

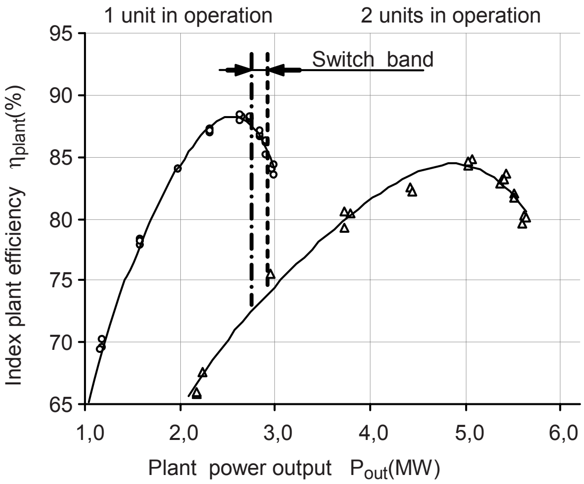


Figure 17a – Switching on power output

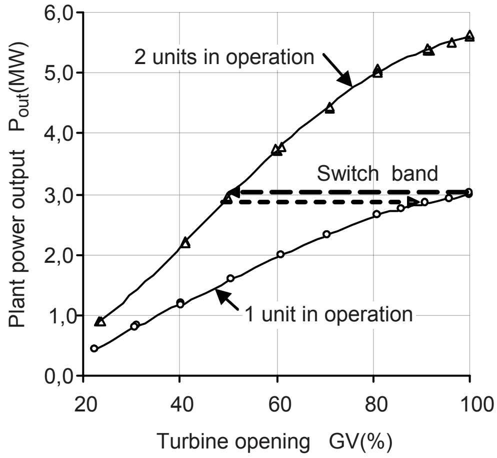


Figure 17b – Switching on turbine opening

Figure 17 – Example of an optimized switch band for 1 and 2 turbine operation

7.3.5 Optimizing cam correlation

The cam correlation from a homologous model can differ by up to 6 % of the guide vane opening from the measured optimum. If the results of model test are adapted by empirical values from site testing, the uncertainty referred to in the optimized turbine conditions are in the range of 0 % to 2 % over the whole operation range. Errors in kinematics (angle of blades to signal display of governor) are additional.

The main sources of this deviation can be due to

- model to prototype scaling effect,
- different inflow conditions between model and prototype,
- optimizing plant efficiency instead of turbine efficiency.

A procedure, similar to an index test, has to be applied to verify the proper cam correlation of a double-regulated unit (Kaplan or bulb turbine). This test has the aim to correlate the openings of both guide vanes and runner blades in order to obtain the best performance from the unit. Generally, the best correlation changes with the head. If the plant is designed to operate in a wide range of head, for example the head variation is more than 5 % of the total head, a 3-dimensional cam (blade, vanes and head) is required. The measurement shall be carried out within the range of the rated head. The adoption for a different head can be taken from the model test. For more detail see Annex I.

7.4 Turbine efficiency

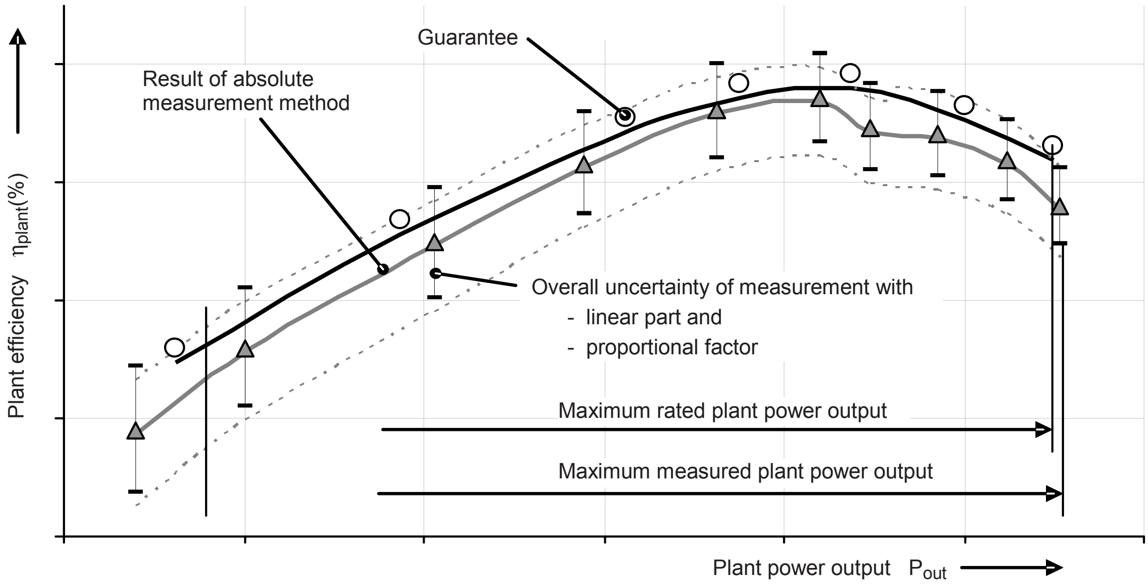
7.4.1 Efficiency test by absolute discharge measurement

The measurement of discharge in a hydraulic plant can only be performed with the desired accuracy when the specific requirements of the chosen method are satisfied. It is therefore in the interest of the parties involved to select the method(s) to be used for an acceptance test at an early stage in the design of the plant because later provision may be expensive or even impracticable. It is suggested that provision be made to make an index test at the same time.

The application and scope of guaranteed efficiency test with absolute flow measurement can be used for the following purposes:

- to measure the absolute value of turbine or unit efficiency over the guarantee range under plant condition and compare it with the guarantee;

- to determine the maximum turbine or unit power output;
- to prove and calibrate the flow rate of energy recovery turbines in irrigation and drinking water supply systems, using the turbine as the discharge indicator.



NOTE In Figure 18, the error band is shown as a straight vertical line rather than an ellipse. This simplification is normally used for small hydroelectric installations. See IEC 60041 for a more precise representation of the error band using an ellipse.

Figure 18 – Efficiency test: procedure to compare guaranteed turbine efficiency to the prototype measurement results, including the overall uncertainties

7.4.2 Efficiency test by thermodynamic method

All hydraulic energy, which is not converted into mechanical energy within a turbine, is transformed into heat. This means that the temperature of the water at the outlet of the turbine is different from that at the inlet. The difference of the temperature between inlet and outlet section of the turbine can be estimated by the formula:

$$\Delta T = H(1-\eta)/426$$

Note that the measurement of the discharge is not required to calculate the efficiency. The accuracy and sensitivity of the temperature measuring instrumentation shall indicate the temperature difference within 0,001 K. The discharge can be calculated indirectly from the parameters H, P and η. For further details of this method see IEC 60041.

7.5 Correcting the efficiency using the model curve

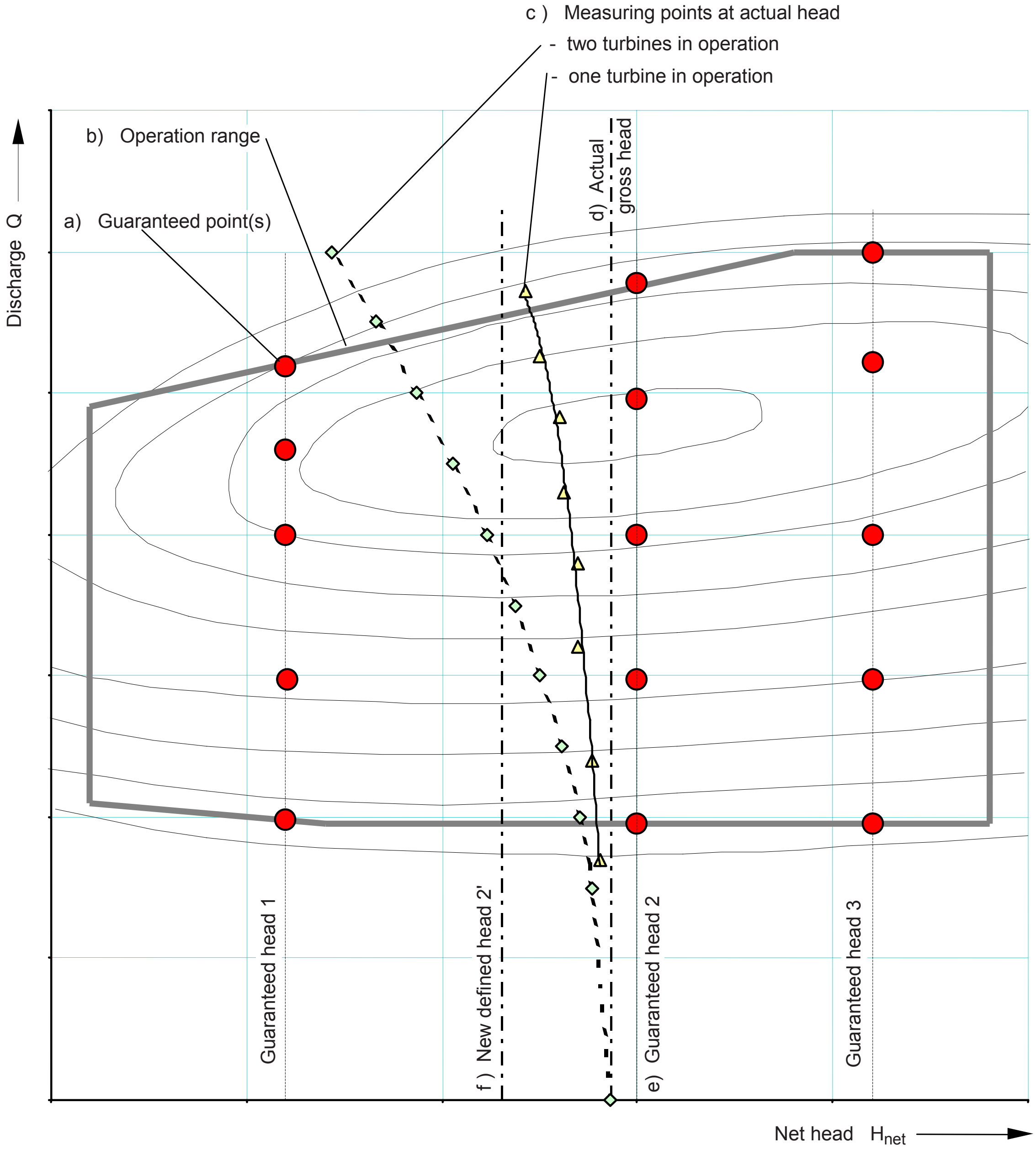
If the measured net head differs slightly from the guaranteed head, the turbine power output and turbine discharge can be corrected using the formulae in 8.2.3 and 8.4.2. The limits for the allowable discrepancy are given in these sections.

When there is a large discrepancy between measured net head and the guaranteed head, an adjustment can be made using the model curve. This adjustment can only be made with the mutual consent of all parties.

Figure 19 shows a typical situation where the guarantee has been given at constant head, and the measured head varies because of head losses. The efficiency can be corrected in the following way.

- Plot the measured point on the model curve.

- Find the change in efficiency between the measured point and the guaranteed point.
- Add or subtract the change in the efficiency to the measured efficiency.



Key

a) Guaranteed points for different heads and discharge.

b) Operation range for the turbine.

c) Measured points, deviation of head as a function of flow and number of units on the same penstock.

d) Actual gross head at start of tests at no flow.

e) Guaranteed head.

Figure 19 – Hill chart – Showing head loss examples with one and two units in operation using the same penstock

8 Computation of results and comparison to the guarantee

8.1 General

8.1.1 Site data

Before the tests, the following data shall be obtained.

Table 5 – Site data

	Physical property	Example			
a	Temperature of water	δ_W	=	3,0	°C
b	Temperature of air surrounding the turbine housing	δ_A	=	18,0	°C
	and concrete wall of tailwater channel (thermodynamic method)	δ_C	=	--,-	°C
c	The acceleration due to gravity				
	Latitude	φ	=	48	degree
	Elevation above the sea level $z = (z_o+z_T)/2$	z	=	102	m
	For calculation, see Annex A.4.1	g	=	9,808 6	m/s^2
d	The density of water, see Annex A.4.2	ρ	=	1 000,4	kg/m^3
	Absolute pressure p_1	p_1	=	10,0	bar
e	Area of the high pressure reference section, see Annex B	A_1	=	0,503	m^2
	Area of the low pressure reference section	A_2	=	1,431	m^2
f	Geodetic levels				
	Setting level of the turbine	z_T	=	45,70	m
	Reference level for measuring head water	z'_1	=	44,37	m
	Reference level for measuring tail water	z'_2	=	46,02	m
	For reaction turbine for cavitation purposes				
	Elevation of draft tube outlet	$z'_{2,3}$	=	42,35	m
	Minimum allowable tailwater elevation				
	At minimum discharge	$z'_{2,2}$	=	42,70	m
	At maximum discharge	$z'_{2,1}$	=	43,20	m
	For impulse turbine for aeration purposes				
	Minimum tailwater level line at maximum	$z'_{2,1}$	=	--,---	m
	Maximum expected channel / river level	$z'_{2,2}$	=	--,---	m
	For information				
	Maximum level in upper reservoir at no discharge	$z_{0,max}$	=	160,80	m
	Minimum level in upper reservoir at no discharge	$z_{0,min}$	=	152,20	m
NOTE For all classes, compare the panel readings at zero discharge with the static head calculated from the elevation of headwater and tailwater.					

8.1.2 Measured values (readings)

The measured values should be plotted against guide vane or needle opening as the test proceeds. Any reading that appears to be in error may indicate that the turbine needs adjustment, or the test equipment is faulty. Any readings taken before a change is made should be kept for reference.

All records shall be completed before disconnecting any instruments, and then critically examined to detect any errors. Any reading suspected of being in error shall be tested by the criteria for outliers, see IEC 60041. The results should also indicate whether the test is within the permitted operational limits.

The average of all readings shall be corrected, using the average of the pre-test and post-test calibration curves for each instrument, plus any zero offset.

Recommendation: make a preliminary reference test at a turbine output from 70 % to 90 % of rated power output to check the instrumentation and stability of the signals.

8.1.3 Scale effect due to water temperature

If the water temperature at site differs from the temperature used for the model test by more than ±5 °C, a correction can be made. The effect should be calculated in accordance with IEC 60193.

8.1.4 Shifting of the plant characteristic

The hydroelectric unit may be capable of exceeding the maximum power originally guaranteed by the manufacturer. If the purchaser gives consent, the manufacturer may set a new maximum power output. To construct the new characteristic, shift the original turbine characteristic to the new measured maximum power using the example given in Figure 20. Every point of the turbine characteristic is shifted by the same percentage. The maximum limit of the shift is 10 % of the rated power. The newly chosen power output shall be a reference for all other guarantees such as maximum transient overspeed, maximum and minimum transient pressures, runaway speed and cavitation pitting.

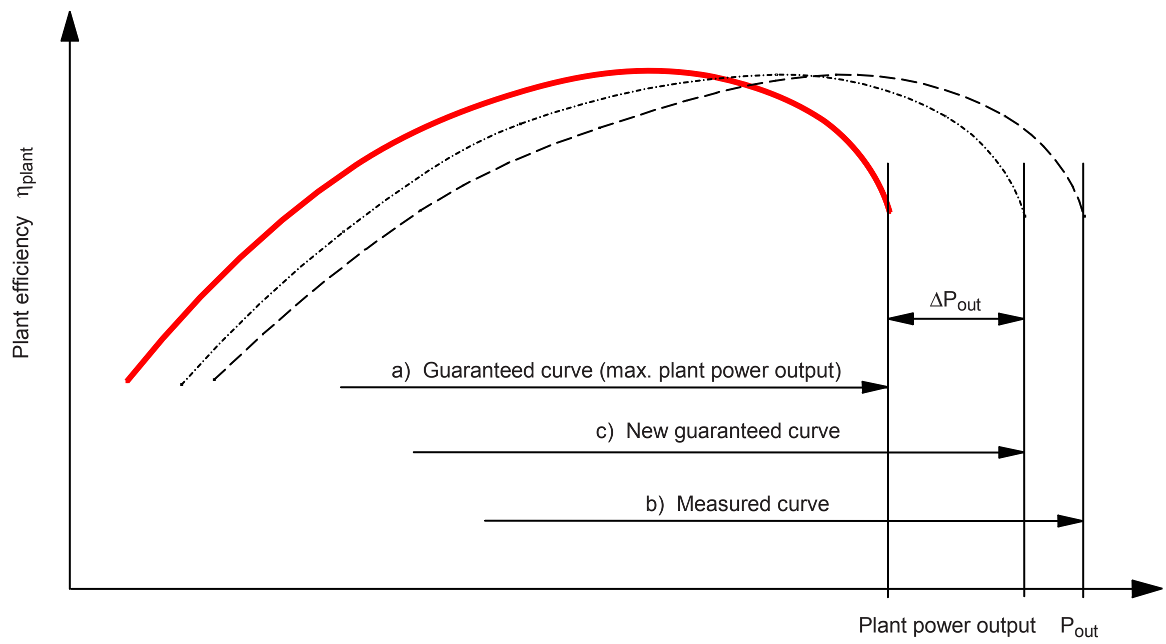


Figure 20 – Shifting of the performance curves

8.2 Power output

8.2.1 Plant power output measurement

a) Directly on transformer PTs and CTs	$P_{out,M} \times (1+ f_{P,out})$	$\geq P_{out,sp}$
b) Indirectly on generator PTs and CTs	$(P_{gen,M} - P_{L,tf} - P_{L,ax}) \times (1+ f_{(P)})$	$\geq P_{out,sp}$

Where total uncertainty in power output, $f_{(P)}$, is a function of the errors $e_{Pgen,M}$, $e_{L,tf}$ and $e_{L,ax}$,- see 9.4.3.1.

8.2.2 Generator power output measurement

a) Directly on generator PTs and CTs $P_{gen,M} \times (1+ f_{P,gen}) \geq P_{gen,sp}$

b) Indirectly on transformer PTs and CTs $(P_{out,M} + P_{L,tf} + P_{L,ax}) \times (1+ f_{(P)}) \geq P_{gen,sp}$

Where total uncertainty in power output, $f_{(P)}$, is a function of the errors $e_{Pout,M}$, $e_{L,tf}$ and $e_{L,ax}$, see 9.4.3.2.

8.2.3 Turbine power output measurement

The turbine power output is generally determined indirectly by measuring the generator power output and adding the generator losses

$$(P_{gen,M} + P_{L,gen}) \times (1+ f_{(P)}) \geq P_{t,sp}$$

where total uncertainty in power output, $f_{(P)}$, is a function of the errors $e_{Pgen,M}$, $e_{L,gen}$, see 9.4.3.3.

If necessary, transpose the measured turbine power outut, P_t, to the rated guaranteed head using the following formula:

$$P_{t,r} = P_t\left(\frac{H_R}{H}\right)^{1,5} \text{ provided } 1,03 \geq \left(\frac{H_R}{H}\right)^{0,5} \geq 0,97$$

8.3 Relative turbine efficiency (index test)

8.3.1 General

The relative turbine efficiency $\eta_{t,ix}$ is calculated by the following formula:

$$\eta_{t,ix} = \frac{P_t}{H \cdot g \cdot \rho \cdot Q_{ix}} \times 100 \quad \%$$

where

P_t	turbine power output	see 8.2.3;
Q_{ix}	relative discharge	see 8.3.2;
H	net head	see Clause B.5.

8.3.2 Relative discharge

A relative discharge measurement can be made using the Winter-Kennedy method or another index method. If the discharge cannot be calibrated by an absolute method, the discharge may be adjusted with help of the guaranteed hill chart. In this case the coefficient k and the exponent x are selected in such a way, that the maximum of the measured shape of the relative efficiency corresponds to the maximum predicted efficiency of the turbine at the best efficiency point.

The calculation of the relative discharge measured by differential pressure is as follows:

$$Q_{ix} = k \cdot \sqrt{\Delta p} \qquad \text{or} \qquad Q_{ix} = k \cdot \Delta p^x$$

The exponent x is used to alter the measured shape if the function of the discharge Q_{ix} is not exactly the square root of the pressure difference Δp. Exponent x shall be in the range of 0,48 to 0,52, which means that the variation of the discharge can differ by about ±2 % at 60 % of the flow related to the optimum.

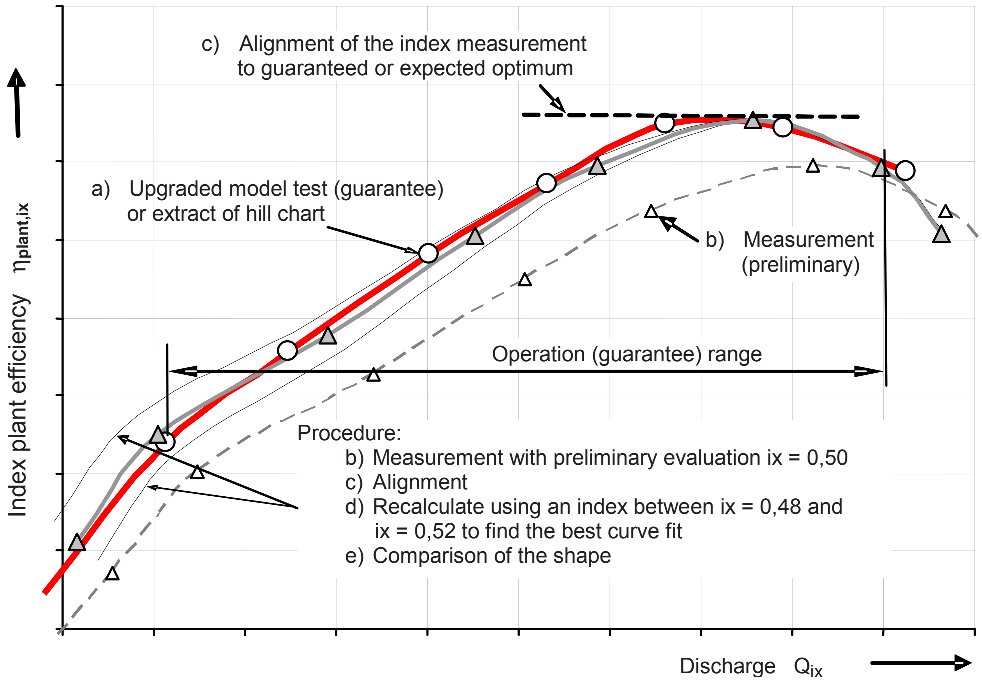


Figure 21 – Variation of factor k and exponent x on turbine index efficiency

8.3.3 Guarantee of the shape of the plant characteristics

Use the following steps to compare guaranteed efficiency curve shape with the results of the index test, see Figure 21.

- Plot the results' curve: relative turbine efficiency versus relative turbine discharge $Q_{ix,sp}$. If necessary, transpose the measured discharge Q_{ix} to the specified guaranteed head by using the formula:

$$Q_{ix,sp} = Q_{ix}\left(\frac{H_{sp}}{H}\right)^{0,5}$$

- Plot the guaranteed efficiency curve (or extract of the hill chart) upon which the contractual guarantees are based.
- Compute the uncertainties as described in 9.4.4.
- Create a total uncertainty bandwidth by adding the total uncertainties on the results curve.
- Analyze the position of the guaranteed efficiency curve: the guarantee is met if the curve is placed inside the uncertainty bandwidth for the whole guaranteed range.

If the guarantees are not met, another method to control the turbine performances shall be agreed between supplier and purchaser. Normally this situation should be foreseen in the contract, for example to perform absolute measurements.

NOTE Generally the index test method is not used to calculate penalties related to lack of efficiency. The Winter-Kennedy method is also influenced by changing inflow conditions, especially when used on semi spirals. An example of this may be caused by different load distribution among multiple units.

8.3.4 Relative index plant efficiency

These results indicate the shape of the plant efficiency, and include all the losses within the plant. They can be used to optimise the power sharing by turbines within the plant, and to analyse the amount of upgraded annual energy production on rehabilitation projects.

$$\eta_{plant} = \frac{P_{out}}{H_g \cdot g \cdot \rho \cdot Q_{ix}} \times 100 \quad \%$$

8.4 Absolute turbine efficiency

8.4.1 General

The absolute turbine efficiency η_t based on flow measurements is evaluated as follows:

$$\eta_t = \frac{P_t}{H \cdot g \cdot \rho \cdot Q} \times 100 \quad \%$$

If the thermodynamic method is used, see 7.4.2.

8.4.2 Absolute discharge

Plot the measured absolute discharge against turbine opening to check for errors. An index measurement can also be used at the same time to interpolate or extrapolate data, and reduce the number of absolute discharge measurement points. Irregularities can also be detected from Q versus Q_{ix} or Q versus log (Δp) plots.

Normally, the head decreases as the turbine power output is increased. To transpose the discharge at the measured head to that at the specified guaranteed head the following formula is used:

$$Q_{sp} = Q\left(\frac{H_{sp}}{H}\right)^{0,5} \text{ provided } 1,03 \geq \left(\frac{H_{sp}}{H}\right)^{0,5} \geq 0,97$$

If the head is outside the given limits, a correction factor based on the hill diagram from the model test can be used after mutual agreement, see 7.5.

8.4.3 Guarantee of the plant efficiency and comparison to the results

The measured efficiency η is plotted with the uncertainty bandwidth against the turbine power P or discharge Q converted as necessary to correspond to the specified head and speed. If the guarantee is given at one or more individual points, or as a curve, it is met if, at the specified head, the guaranteed values lie below the upper limit of the total uncertainty bandwidth over the specified range.

If the guarantee is given as a weighted efficiency the guarantee is met if, at the specified head, the guaranteed average efficiency is exceeded by the average efficiency calculated at the same specified points, using the upper limit of the total uncertainty bandwidth.

9 Error analysis

9.1 General

Every measurement is attended by unavoidable uncertainties in measurement, even when the methods, instruments and calculations employed fully comply with the requirements of the international standard. These uncertainties shall be taken into account in a suitable manner when comparing the test results with the guaranteed figures. Uncertainties relate only to the measurements themselves and do not relate to the performance or to the quality of the tested machine.

For the purpose of this International Standard, an "error" is defined as a value equal to twice the estimated standard deviation. It is assumed that there is a 95 % probability that the estimated value of the true error will not exceed twice the estimated standard deviation. See ISO 5168.

NOTE e_X is the absolute uncertainty (error) of the value X, both being expressed in the same units. $f_X = e_X / X$ is the corresponding relative uncertainty expressed without units or sometimes in percent.

9.2 Estimation of systematic (bias) uncertainties

9.2.1 General

Systematic uncertainties are higher at partial load than at full load, especially for the parameters discharge and power. The uncertainty will be affected by the actual instruments and measurement method.

9.2.2 Typical systematic uncertainties

The typical systematic uncertainties of the measured values at full load, with 95 % confidence limit, are shown in Table 6.

Table 6 – Systematic uncertainties at full load

Method	Typical uncertainty at normal conditions
Velocity-area method	
• current meter method	
○ open channels	f_Q = ±1,5 %
○ closed inlets and conduits greater than or equal to 1 m diameter	f_Q = ±1,3%
• stagnation probe[a]	f_Q = ±2,0 %
Pressure-time method	
• uniform cross-section	f_Q = ±1,2 %
• non-uniform cross-section	f_Q = ±1,7 %
Ultrasonic (acoustic) method (under favourable conditions)	
• strap on meter	f_Q = ±2,5 %
• two crossing planes, four paths each	f_Q = ±1,5 %
• four crossing planes, four paths each	f_Q = ±1,0 %
Volumetric gauging method	f_Q = ±1,5 %
Electromagnetic flow meters	f_Q = ±1,5 %
Pressure measurement (f_p) (see Figure 27)	
• spring pressure gauge (calibration check on site)	f_p = ±0,50 %
• transducers	f_p = ±0,20 %
• deadweight manometer	f_p = ±0,10 %
• free water level (see Figure 26)	See B.4.2.4

Method	Typical uncertainty at normal conditions
Generator power output (f_{gen})[b]	
• Panel measurement (CT and PT are class 1,0 %)	
○ synchronous generator	f_{gen} = ±1,50 %
○ asynchronous generator	f_{gen} = ±1,80 %
• Power analyser	f_{gen} = ±0,5 %
Rotation speed	f_n = ±0,05 %
Mechanical transmission efficiency	$f_{\eta,tr}$ = ±0,20 %
Transformer efficiency	$f_{\eta,tf}$ = ±0,10 %

NOTE The systematic uncertainty for other measurement methods can be found in IEC 60041.

[a] The accuracy depends on number of probes / section, diameter of the pipe and expected flow profile.

[b] f_{gen} may increase depending upon the method employed for the determination of generator losses, and also in cases where a shunt is used for large direct currents. Conversely, f_{gen} may reduce when using accurate modern electronic instrumentation.

9.2.3 Systematic uncertainty for turbines used to indicate discharge

The turbine can be used as a discharge indicator when used for energy recovery in water supply or irrigation systems. The expected systematic uncertainty is given in Table 7.

Table 7 – Systematic uncertainties of discharge versus turbine opening

Conditions	Q_50	Q_100
Without calibration	f_Q = ±7,0 %	f_Q = ±5,0 %
With calibration by an index test based on a guaranteed hill chart	f_Q = ±3,5 %	f_Q = ±2,5 %
With calibration by an absolute method	f_Q = ±2,1 %	f_Q = ±1,5 %

9.3 Estimation of random (precision) uncertainties

9.3.1 Measurement at a single operation point

9.3.1.1 Stochastic behaviour

This case is only applicable if the operating conditions can be maintained constant for the duration of the test. The random uncertainty is due to a combination of the characteristics of the measuring system and variations of the measured quantity, and appears directly as a scatter of results.

Unlike the systematic uncertainty, the random uncertainty can be reduced by increasing the number of measurements of the same quantity under the same operating condition. The minimum number of runs shall not be less than two. If the flow rate is measured using current meters, the run time for one operating point shall be divided so as to provide at least three equally spaced single readings.

9.3.1.2 Periodic behaviour

Typical periodic behaviour is shown in Figure 22. This case is applicable if the measured value shows a continuous fluctuation or oscillation behaviour. A typical value can be the input pressure on the spiral case due to water hammer. This fluctuation energy can have an influence on the turbine efficiency.

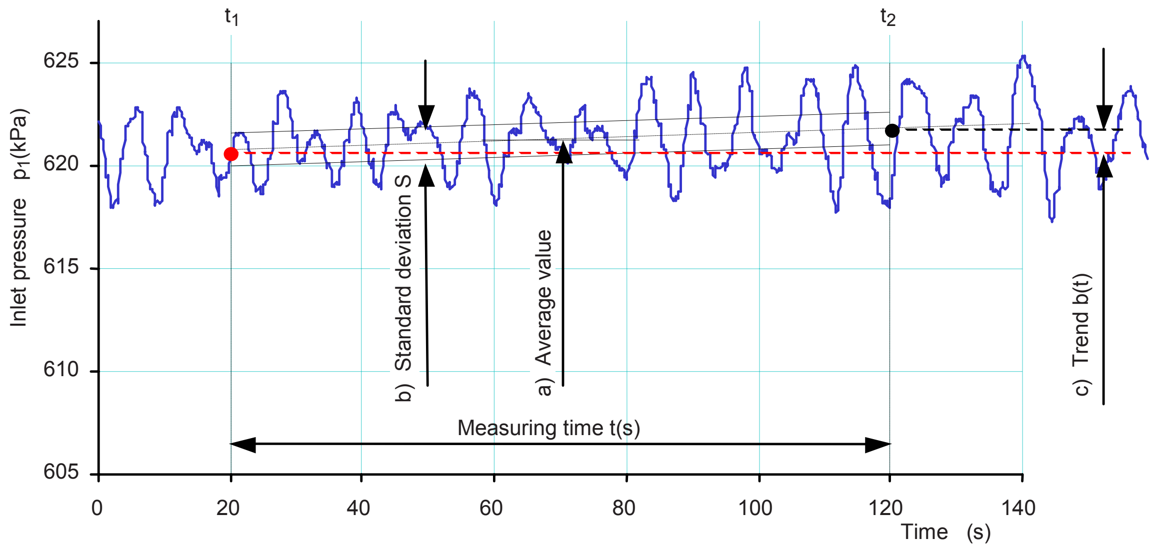
9.3.1.3 Computation of the standard deviation and the trend

The standard deviation s(y) is the root-mean square of deviation of the measurements from the mean. The standard deviation is rarely, if ever, known exactly. Therefore, an estimate s is made from the available measurements. Given n independent measurements of y, an estimate s of the standard deviation of y is given by:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2}$$

The trend b over time t, during which the n measurements are taken, gives a good indication as to whether the conditions are steady. The trend can be calculated from the following formula:

$$b = \frac{n\sum xy - \left(\sum x\right)\cdot\left(\sum x\right)\cdot\left(\sum y\right)}{n\sum x^2 - \left(\sum x\right)^2}$$



Example:

Measuring time	$t_2 - t_1$	=	100 s
Average (mean value)	p_1	=	621,3 kPa
Maximum value	$p_{1\ max}$	=	624,8 kPa
Minimum value	$p_{1\ min}$	=	617,7 kPa
Standard deviation	s(y)	=	1,6 kPa
Trend	b(t)	=	0,64 kPa /min

The random uncertainties for pressure fluctuation $f_{p1,ra}$ = ± 1,6 × 100/621,3 = ± 0,26 %

NOTE Calculating the random uncertainty in this way is sufficiently accurate for most small hydro installations. However, a more rigorous method can be found in IEC 60041.

Figure 22 – Random uncertainties of a single operation point, example for penstock pressure variation and fluctuation

9.3.2 Measurement over a range of operating condition

9.3.2.1 Outliers

A practical way to select and identify outliers is to plot the fluctuating data (flow, pressure p_1, p_2, power, differential pressure) versus stable values (guide vane opening, needle stroke) in linear and/or logarithmic form. See Figure 23.

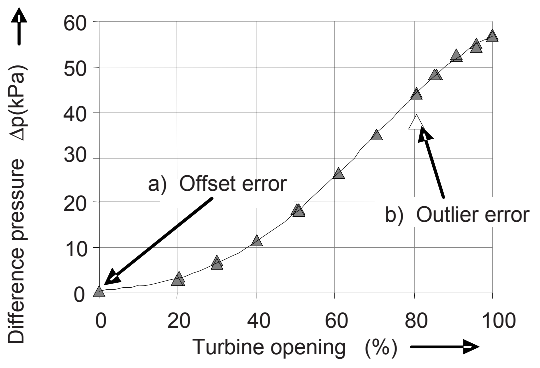


Figure 23a – Linear plot of outliers

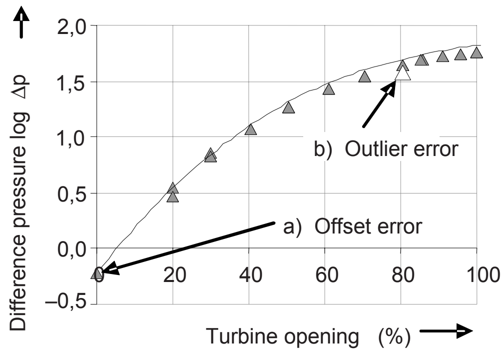


Figure 23b – Logarithmic plot of outliers

Figure 23 – Detection of outlier errors: example to find offset and reading errors by plotting in linear and logarithmic form with the same data

9.3.2.2 Curve fitting

Measurements of variables such as head, flow rate, and output over a range of operating conditions may be expected to change according to the function relating the variables. An estimate of the function relating the variables is provided by a smooth curve fitted to the observed data. To any collection of x and y data many different smooth curves may be postulated and fitted. It is usual to limit the choice to polynomial models of first, second or third order and the choice will depend on the relationship. For example, hydraulic losses normally use second order. The smooth fitted curve will not necessarily pass through all the observed data points. The quality of the fitted smooth curve depends on the number of elements and the variance of the observations, see Figure 24.

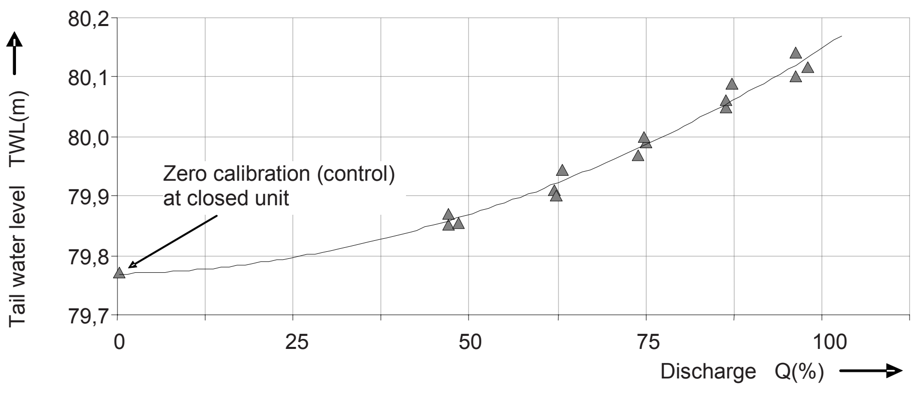


Figure 24 – Example of scattered points with function of second order

9.3.2.3 Discontinuities

Sets of data points are often encountered showing discontinuities, which cannot be easily or correctly interpreted by mathematical techniques. These should not be smoothed by an analytical method. The data points on either side of a discontinuity should be treated separately and the fitted curve segments joined by eye to represent the data as closely as possible, see Figure 25.

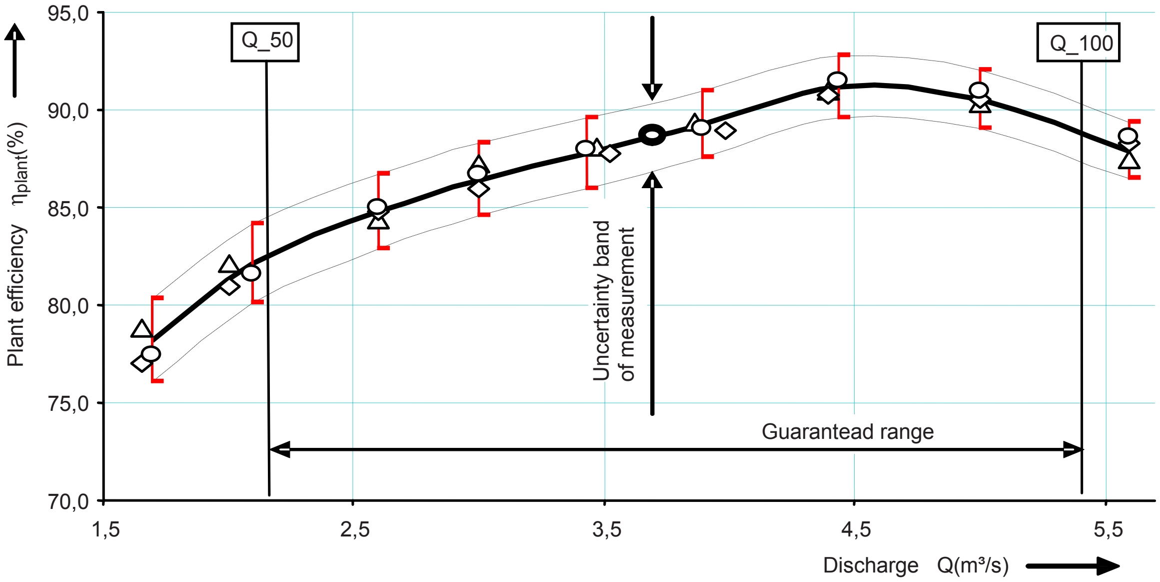


Figure 25 – Scattered points smoothed by individual fitting on adjacent sections

9.4 Evaluation of the uncertainties

9.4.1 General

The overall measurement uncertainty of any of the measured quantities (x) shall be calculated using the square root of the sum of the squares of the associated systematic x,sy and random uncertainties x,ra:

$$f_x = \sqrt{f_{x,sy}^2 + f_{x,ra}^2}$$

9.4.2 Head

9.4.2.1 Measurement with a free water level

The uncertainty in head measurement is a combination of systematic and random uncertainties in the measurement at turbine inlet and outlet. These may be caused by wind and wave disturbance at the inlet, and the turbine discharge at the outlet. In case of unexpected head fluctuations, the individual errors are to be recorded and evaluated.

Figure 26 – Overall uncertainty of head for free water level for low head turbines

Example calculation of total uncertainty of head measurement for a 7 m gross head. A reading of 4,00 m on a pressure transducer located at datum 3,45 m gives a head water level = 7,45 m. A reading of 0,45 m on a tailrace gauge board gives the tail water level = 0,45 m directly.

Systematic uncertainties associated with head water level

Manufacturer's transducer uncertainty	±0,15 %
Error in pressure transducer reading	4,00 × 0,001 5 = ±0,006 m
Error in setting of geodetic datum	±0,010 m

Systematic uncertainty associated with tail water level

Error in setting of geodetic datum	±0,010 m

Combined systematic uncertainty, $f_{Hg,sys}$

$$\frac{\sqrt{0{,}006^2+0{,}010^2+0{,}010^2}}{4{,}00+3{,}45-0{,}45}\times 100=\pm 0{,}22\%$$

Random uncertainty associated with measuring the levels

Error in measuring head water level	±0,010 m
Error in measuring tail water level	±0,020 m

Combined random uncertainty, $f_{Hg,ra}$

$$\frac{\sqrt{0{,}010^2+0{,}020^2}}{4{,}00+3{,}45-0{,}45}\times 100=\pm 0{,}32\ \%$$

Overall uncertainty of gross head, f_{Hg}

$$\sqrt{0{,}22^2+0{,}32^2}=\pm 0{,}39\ \%$$

NOTE See Clause H.6 on formulae for combining uncertainties.

9.4.2.2 Measurement in a closed conduit

Pressure transducers are normally used for this measurement. The systematic uncertainty is taken from the data sheet and shall not be greater than 0,15 %. Additional uncertainties are the diameter of the pipeline, the flow profile, and the velocity of the flow. The velocity is the most important of these uncertainties. The combination of linear and square root errors as a function of velocity can be taken from Figure 27.

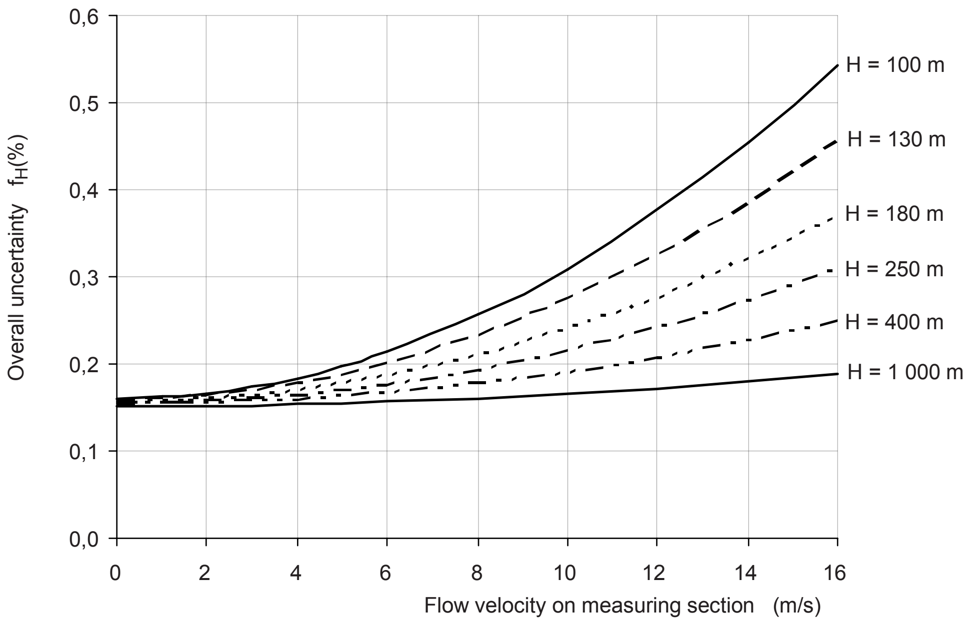


Figure 27 – Overall uncertainty of head in a closed conduit

9.4.3 Power output

9.4.3.1 Uncertainty of plant power output

NOTE See Clause H.6 on formulae for combining uncertainties.

The overall uncertainty in plant power output is estimated from the transformer or generator measurements as follows:

a) Measured directly on the transformer

The total plant power output is the sum of the transformer power output and the power supplied to the auxiliaries.

Systematic uncertainty of transformer power output $f_{P,out,sys} = \sqrt{f_{WH}^2 + f_{PT}^2 + f_{CT}^2}$

Total uncertainty in plant power output $f_{(P)} = \sqrt{f_{P,out,sys}^2 + f_{P,out,ra}^2}$

b) Measured indirectly on the generator terminals

Systematic uncertainty of generator power output $f_{P,gen,sys} = \sqrt{f_{WH}^2 + f_{PT}^2 + f_{CT}^2}$

Total uncertainty of generator power output $f_{P,gen} = \sqrt{f_{P,gen,sys}^2 + f_{P,gen,ra}^2}$

Error in generator power output measurement $e_{P,gen} = P_{gen} \times f_{P,gen}$

Error in transformer loss measurement $e_{L,tf} = P_{L,tf} \times f_{L,tf}$

Error in auxiliary power loss measurement $e_{L,ax} = P_{L,ax} \times f_{L,ax}$

Total uncertainty in plant power output $f_{(P)} = \dfrac{\sqrt{e_{P,gen}^2 + e_{L,tf}^2 + e_{L,ax}^2}}{P_{gen} - P_{L,tf} - P_{L,ax}}$

9.4.3.2 Uncertainty of generator power output

The overall uncertainty in generator power output is estimated from the generator or transformer measurements as follows:

a) Measured directly on the transformer terminals

Systematic uncertainty of transformer power output $f_{P,out,sys} = \sqrt{f_{WH}^2 + f_{PT}^2 + f_{CT}^2}$

Total uncertainty of transformer power output $f_{P,out} = \sqrt{f_{P,out,sys}^2 + f_{P,out,ra}^2}$

Error in transformer power output measurement $e_{P,out} = P_{out} \times f_{P,out}$

Error in transformer loss measurement $e_{L,tf} = P_{L,tf} \times f_{L,tf}$

Error in auxiliary power loss measurement $e_{L,ax} = P_{L,ax} \times f_{L,ax}$

Total uncertainty in generator power output $f(P) = \frac{\sqrt{e_{P,out}^2 + e_{L,tf}^2 + e_{L,ax}^2}}{P_{out} + P_{L,tf} + P_{L,ax}}$

b) Measured directly on the generator terminals

Systematic uncertainty of generator power output $f_{P,gen,sys} = \sqrt{f_{WH}^2 + f_{PT}^2 + f_{CT}^2}$

Total uncertainty of generator power output $f(P) = \sqrt{f_{P,gen,sys}^2 + f_{P,gen,ra}^2}$

9.4.3.3 Uncertainty of turbine power output

The turbine power output is generally determined indirectly by measuring the generator power output and then adding the generator losses. The total uncertainty in turbine power output is estimated as follows:

a) Measured directly on the generator terminals

Systematic uncertainty of generator power output $f_{P,gen,sys} = \sqrt{f_{WH}^2 + f_{PT}^2 + f_{CT}^2}$

Total uncertainty of generator power output $f_{P,gen} = \sqrt{f_{P,gen,sys}^2 + f_{P,gen,ra}^2}$

Error in generator power output measurement $e_{P,gen} = P_{gen} \times f_{P,gen}$

Error in generator loss measurement $e_{L,gen} = P_{L,gen} \times f_{L,gen}$

The total uncertainty in turbine power output $f(P) = \frac{\sqrt{e_{P,gen}^2 + e_{L,gen}^2}}{P_{gen} + P_{L,gen}}$

b) Calculation example of total uncertainty in turbine power output

Assume power output is measured at the generator terminals.

Systematic uncertainty of generator power output:

- Energy counter (2 or 3 watt meter method) $f_{WH} = \pm 0{,}20$ %
- Potential transformer (PT) $f_{PT} = \pm 0{,}30$ %
- Current transformer (CT) $f_{CT} = \pm 0{,}30$ %

Systematic uncertainty $f_{P,gen,sys} = \pm\sqrt{0{,}20^2 + 0{,}30^2 + 0{,}30^2} = \pm 0{,}47\ \%$

Random uncertainty in power measurement $f_{P,gen,ra} = \pm 0{,}40$ %

Total uncertainty of generator power output $f_{P,gen} = \pm\sqrt{0{,}47^2 + 0{,}40^2} = \pm 0{,}62\ \%$

Measured power output of generator $P_{gen,M} = 3\,011$ kW

Error in generator power output measurement $e_{P,gen} = 3\,011 \times 0{,}006\,2 = 18{,}7$ kW

Measured loss in generator output (factory tests) $P_{L,gen} = 120$ kW

Uncertainty in generator loss measurement $f_{L,gen} = \pm 10$ %

Error in generator loss measurement $e_{L,gen} = 120 \times 0{,}01 = 12$ kW

Total uncertainty in turbine power output $f(P) = \pm\frac{\sqrt{18{,}7^2 + 12^2}}{3\,011 + 120} \times 100 = \pm 0{,}71\ \%$

9.4.4 Index test measurement

9.4.4.1 Uncertainties for shape control

Because the turbine discharge is evaluated as a relative value by moving the expected maximum turbine efficiency point, the assessment of the measured prototype to the guarantee can only be made by reference to the following values:

- Head f_H uncertainty of net head.
- Power $f_{P,t}$ uncertainty of shaft power on the turbine.
- Discharge $f_{Q,ix}$ the flow is transposed from the model test hill chart, and adjusted to the alignment of maximum expected optimum of turbine efficiency.
- Efficiency $f_{\eta,ix}$ the deviation between measured and guaranteed include the overall uncertainties $\Delta\eta$.

The uncertainty values shown in Table 8 can be taken at 50 % of maximum discharge.

Table 8 – Overall uncertainties of the shape of turbine characteristics with respect to the guaranteed efficiency

Type / Location	Type of turbine	Method / Equipment	Differential pressure Δp kPa	Q_50 $\Delta\eta$	Const. $\Delta\eta_{const}$
Semi spiral case	Kaplan turbine	Winter Kennedy method	3 to 8	−3,5 %	−0,7 %
Spiral case	Kaplan turbine	Winter Kennedy method	15 to 25	−3,0 %	−0,7 %
Bulb / Pit / Straflo	Kaplan turbine	Index method	15 to 30	−2,5 %	−0,7 %
Spiral case	Francis turbine	Winter Kennedy method	20 to 30	−2,5 %	−0,5 %
Distributor	Pelton turbine	Index method	>25	−2,0 %	−0,5 %
Conical pipe	All turbines	Index method	>20	−2,0 %	−0,5 %
NOTE An additional constant uncertainty band over the guarantee range is required, $\Delta f\eta$ = −0,5 % to −0,7 %.					

9.4.4.2 Uncertainties for pre- and post measurement (REHAB)

If the index measurement is used for pre- and post comparison of the upgrading turbine characteristics and/or performance of maximum power output, systematic and random uncertainties shall be taken into consideration.

- Head f_H the same benchmarks shall be used for pre- and post test.
- Power $f_{P,t}$ the same PTs and CTs shall be used for pre- and post generator power measurement.
- Discharge $f_{Q,Ix}$ the coefficients k and x are fixed during the pre-tests. The same coefficients are used for post tests.
- Efficiency $f_{\eta,ix}$ the difference of $\Delta\eta$ of the upgraded turbine is to be compared.

9.4.4.3 Evaluation of the overall expected uncertainties for index discharge

a) Causes of systematic uncertainties

- Offset of the signal, which can be caused by instrumentation zero error (electrical and mechanical hysteresis), and air in the piping.
- Proportional differential pressure Δp signal errors caused by linear instrumentation errors.
- Proportional discharge errors caused by changing of local flow velocities in the measuring sections.
- Dynamic head versus flow velocity.

When using index tests for rehabilitation, it is most important to carefully maintain the same measurement conditions before and after any changes. The location, surface, orifice radius, and length of pipe connection of the pressure taps should be kept the same. Any difference leads to additional systematic uncertainties.

The systematic uncertainties increase with decreasing differential pressure. The most important properties for discharge measurements by index tests are the full scale differential pressure and the possible offset at zero flow. The systematic uncertainties shall be estimated before making the measurements.

b) Causes of random uncertainties:

- Pulsation of the differential pressure.
- Stability of the turbine opening.

In most cases the random uncertainties increase with decreasing differential pressure. The most important properties for discharge measurements made by index tests are the full scale differential pressure and the possible offset at zero flow.

c) The overall uncertainty

Figure 28 shows the overall uncertainty of index discharge varying with pressure differential. The overall uncertainty for Figure 28 includes both systematic and random uncertainties and is calculated according to the formula:

$$f_{Q,ix} = \sqrt{f_{Q,ix,sy}^2 + f_{Q,ix,ra}^2}$$

Table 9 shows the data used to create Figure 25. The uncertainty line $f_{Q,ix}$ corresponds to a single measurement of index discharge. A higher overall uncertainty is assumed to occur for comparison measurements used pre- and post- rehabilitation.

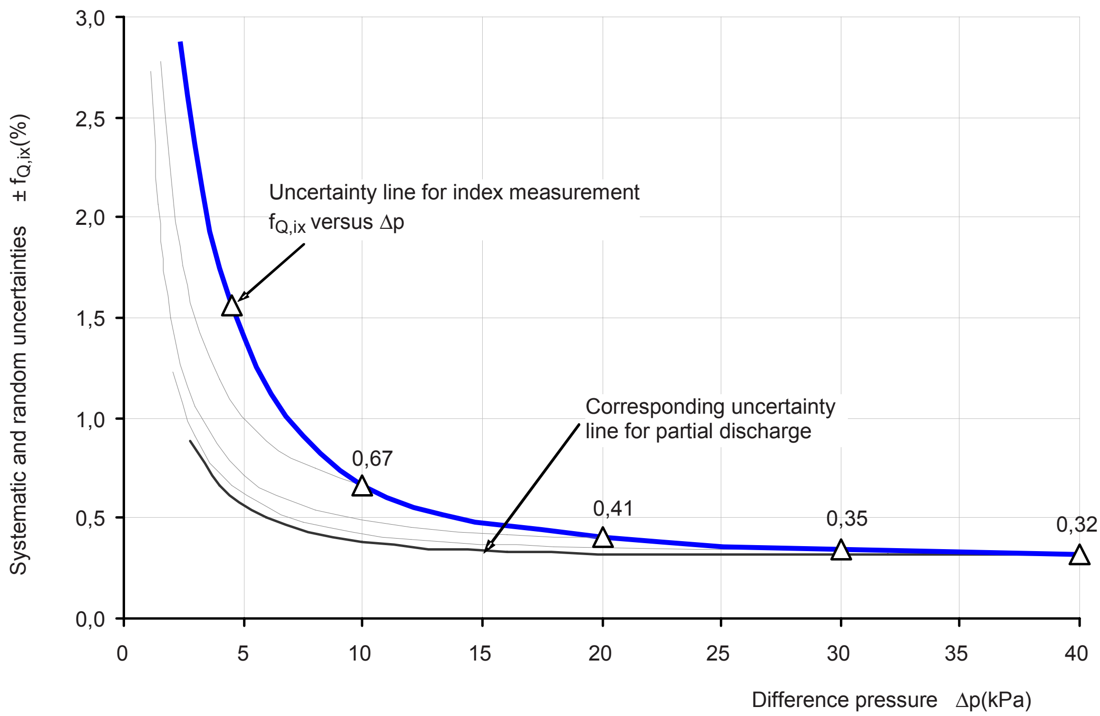


Figure 28 – Estimated overall uncertainties of the discharge by index measurement versus full scale differential pressure

Table 9 – Data used in Figure 28

			Q_100 single	Q_100 pre + post
Δp kPa	$f_{Q,ix,sy}$ %	$f_{Q,ix,ra}$ %	$f_{Q,ix}$ %	$f_{Q,ix}$ %
5,00	0,95	1,24	1,56	2,21
10,00	0,45	0,50	0,67	0,95
20,00	0,27	0,31	0,41	0,58
30,00	0,21	0,28	0,35	0,49
40,00	0,17	0,27	0,32	0,45

9.4.5 Efficiency test by absolute discharge measurement

The uncertainty of the turbine efficiency is calculated from the estimated individual component uncertainties of flow rate (f_Q), head (f_H), and power ($f_{P,t}$) using the formula:

$$f_{\eta,t} = \sqrt{f_{P,t}^2 + f_Q^2 + f_{H,net}^2}$$

9.4.6 Efficiency test by the thermodynamic method

This is a direct method for measuring the turbine efficiency. The estimated uncertainty of the efficiency is reverse head dependent (i.e $f_{\eta,th}$ = ± 1,0 % at low head). For further information about calculating the uncertainty see Clauses A.2 and A.3 of IEC 60041:1991.

10 Other guarantees

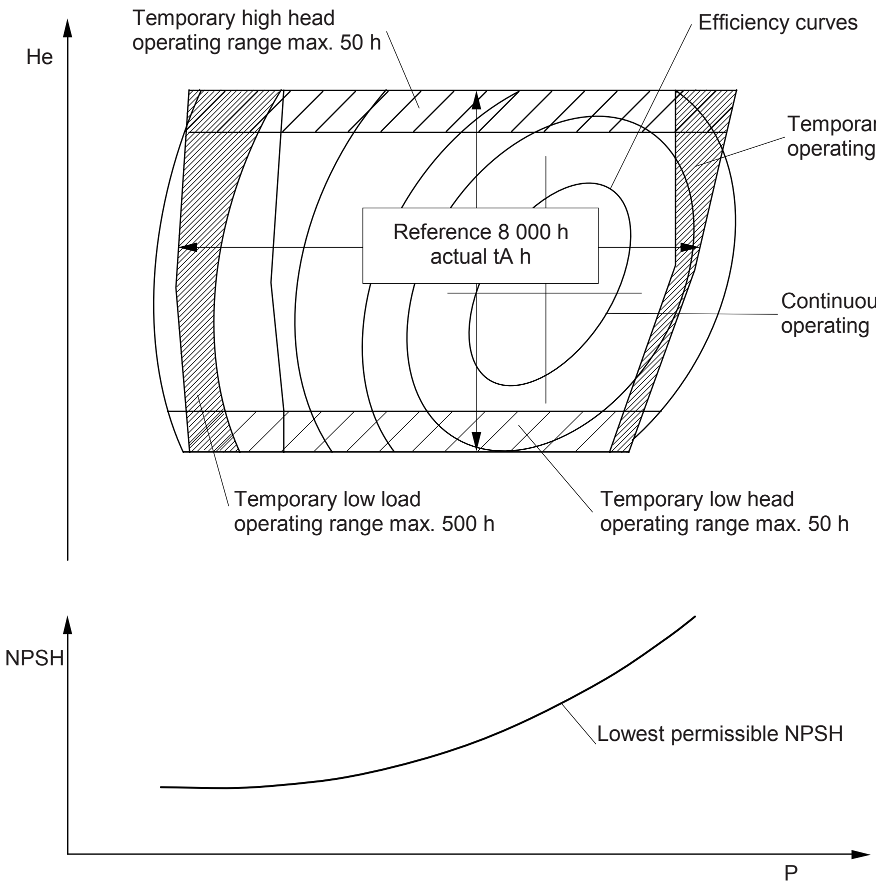
10.1 Cavitation

10.1.1 General

The range of head and NPSH for continuous and temporary operation shall be defined in the contract. An example for a typical reaction turbine is shown in Figure 29. The cavitation damage shall be evaluated at the end of the guarantee period, and the manufacturer has the right to inspect the unit after a reasonable operating period in order to undertake corrective measures if required. A record of the operating parameters (duration, power, head and tail water level) shall be kept during the guarantee period in order to ensure the correct operation of the unit. The cavitation guarantee normally covers damage to the material solely due to cavitation pitting in clean water. The guarantee does not generally cover damage due to the following:

– wear or corrosion caused by suspended materials in the water;
– corrosion caused by the chemical characteristics of the water;
– cavitation pitting caused by wear or corrosion damage.

If the materials have been specially selected, or coated to resist abrasion or chemical attack then the guarantee should cover that type of damage. For reference see IEC 60609.



NOTE When cavitation damages are evaluated, the allowable operating hours for temporary operation is scaled by t_A/8 000 h, where t_A are the actual operating hours. Different NPSH curves can be used for each head range if the head varies more than ±5%.

Figure 29 – Operation range and cavitation limits

10.1.2 Measurement methods

The purchaser and the manufacturer shall, at the end of the guarantee period, jointly outline all areas where the depth of cavitation pitting exceeds 0,5 mm. The following measurements shall be taken with an uncertainty not exceeding ±10 %.

- The area, a (cm²), of each pitted area. The areas may be delineated by a suitable paint and transferred to stable paper before making the calculation.
- The maximum depth, s (mm), of each pitted area. A depth gauge may be used together with a template of the original contour supported on undamaged areas.

Unless otherwise stated in the contract, the overall maximum depth S (mm) is the maximum of the individual maximum depths s.

The total volume V (cm^3) is then calculated as $V = \Sigma \{0,5 \times (0,1 \times s) \times a\}$.

10.1.3 Comparison with specified guarantees

Unless otherwise stated in the contract, cavitation pitting on stainless steel rotating parts shall not exceed the following figures shown in Table 10.

Table 10 – Limits for cavitation damage

Turbine type	Pelton, Turgo-turbines, etc.	Francis, Kaplan turbines, etc.	Crossflow turbines
Depth (mm)	$S \leq 2 \times t_A/8\,000 \times B^{0,5}$	$S \leq 4 \times t_A/8\,000 \times D^{0,4}$	$S \leq 4 \times t_A/8\,000 \times D^{0,4}$
Volume (cm^3)	$V \leq 60 \times t_A/8\,000 \times B^2$	$V \leq 20 \times t_A/8\,000 \times D^2$	$V \leq 20 \times t_A/8\,000 \times D \times L$

D (m) is the runner (outlet) diameter for Francis and Kaplan turbines etc. as well as Crossflow turbines.

B (m) is bucket width for Pelton and Turgo turbines, etc.

L (m) is the length of the rotor for Crossflow turbines.

t_A is the actual operating hours within the guarantee period.

The cavitated volume on one single runner/impeller blade shall not exceed k/Z times the guaranteed volume for the entire runner/impeller, where Z is the number of runner vanes, not counting splitter vanes, or buckets, and k = 2,0.

For all non-rotating parts, the depth of cavitation pitting shall not exceed the values given for rotating parts. The cavitated volume on axial flow reaction turbines shall not exceed the values given for rotating parts. For all other types of reaction turbines and impulse turbines the cavitated volume shall not exceed 0,5 times the values given for rotating parts.

10.2 Noise

10.2.1 General

Noise from hydroelectric generating sets can be produced in several different ways:

- Generator noise comes mainly from the fan blades and the air-cooling system. Intense noise may also occur due to resonance phenomena in the stator core, housing etc.
- Turbine noise comes mainly from the energy conversion in the runner. The noise may be due to some inefficiency within the turbine, but this is not always the case. The exception happens in high head Francis turbines where hydraulic noise from the interaction between stay vanes, guide vanes and runner inlet can dominate. Noise can also occur within the draft tube cone due to a cavitating rope downstream of the runner. At times, this vortex rope can give rise to significant noise levels and pressure pulsations within the turbine.
- Gear transmission, if provided, as well as hydraulic oil pumps and other minor equipment are also frequent noise sources.

This noise is mainly generated inside the power station building. The noise can sometimes occur outside the power station building, for Pelton and Turgo turbines, because of the air flow down an open outlet channel. This noise also increases considerably during load rejection.

The manufacturer shall specify the expected noise emission from the hydroelectric unit. This information can be used to make an appropriate civil engineering design to keep the outside noise at an acceptable level in accordance with the location and local regulations.

10.2.2 Measurement methods

The noise shall be measured by a calibrated sound level meter with type A weighting filter in averaging mode. The calibration shall be done with an accuracy of ±1 dBA, and shall be performed using standardised equipment according to IEC 60651 type 1 and according to relevant standards, such as ISO 1680, ISO 3746, ISO 4412.

The reference surface for measuring the noise from a hydroelectric unit is the smallest hypothetical surface (parallelepiped, cylinder etc.) that encloses the unit, or parts thereof as agreed, and terminates on reflecting planes (floor, walls etc.). The measurements shall be performed at points corresponding to the nodes of a 1 m × 1 m grid located at 1 m distance from the reference surface.

The object is to measure the free field sound emission of the source, and any effect due to the environment, background noise and reflections from the room boundaries shall be subtracted from the measured value.

10.2.3 Comparison with specified guarantees

The sound pressure noise emission from the hydroelectric installation shall not exceed the level stated in the contract or that required by local legislation. For normal operation the noise emission would be expected to be below 93 dBA.

10.3 Vibration

10.3.1 General

Vibrations that occur in hydroelectric generating sets are generally of three different types, as follows:

- pressure fluctuations or vibrations in the water passages, often caused by hydraulic unbalance or resonance phenomena or problems with air admission in draft tubes;
- vibrations of the rotating shaft, often caused by mechanical or hydraulic unbalance;
- vibrations in non-rotating parts, such as bearing housings, are often resonance phenomena caused by vibrations in the rotating parts.

In order to minimise the risk for excessive vibrations and discussions about the responsibility, the following shall apply unless otherwise stated in the contract.

- The manufacturer shall specify the requirements regarding the foundations of the hydroelectric unit.
- The manufacturer is entitled to all relevant drawings and specifications of the waterways upstream and downstream of the hydroelectric unit, in order to ensure that no resonance or interaction phenomena will occur between the unit and other components during stable or transient conditions.
- All rotating parts shall conform to balance quality grade G 6.3 of ISO 1940-1:2003, at maximum service speed, including on-cam runaway speed at maximum design head.
- The assembled rotating shafts, flanges etc. shall have run out tolerances not exceeding the limits in ANSI/IEEE 810.
- Shafts and rotating components shall be positively located by the thrust bearing during all constant load conditions. Except for bearing surfaces, mechanical contact between stationary and rotating parts shall be avoided at any operating condition.

10.3.2 Measurements and measurement methods

Vibrations caused by pressure fluctuations in the water passages shall be measured during the acceptance tests by use of pressure recorders or data loggers used as a part of the normal acceptance tests.

Vibrations of the rotating and non-rotating parts are not normally measured as a part of the acceptance tests, unless stated in the contract or demanded by one of the parties. If measurements are required then they should be made as follows.

- On rotating shafts, vibrations are usually measured by a set of two non-contacting displacement transducers placed close to the bearings 90° apart, measuring relative and/or absolute displacement of the shaft.

- On non-rotating parts, vibrations are usually measured by a set of accelerometers placed on bearing housings, frames or other parts to be investigated. Measurements are conducted in all three main directions.

10.3.3 Comparison with specified guarantees

10.3.3.1 General

The vibration level shall not exceed the values given below for the normal continuous operating range as defined in Figure 29 unless otherwise stated in the contract. In the temporary operating range, including start up and shut down, the allowable values can be increased. Outside this range, including off-cam operation, load rejection and runaway conditions, vibrations shall not endanger the safety or the mechanical stability of the unit including foundations and waterways.

10.3.3.2 Pressure fluctuations

Pressure fluctuations are measured during constant load conditions in the spiral casing or penstock as RMS values. Pressure fluctuations in the spiral case and penstock are inherently higher in case of single regulated versus double regulated turbines. This is a particular problem for low head machines at part load (<50 % load).

In all cases, the values shall not exceed the limits given in the contract. As a guide, the RMS value is typically expected to be within the following limits:

- 0,5 % of the net head for the normal operating range;
- 1,5 % of net head for the temporary operating range;
- 5 % of net head for low head machines at part load (<50 % load).

Pressure fluctuations in the draft tube of reaction turbines may be higher than in the penstock. They are only of importance if the draft tube shall sustain structural damage or if there is evidence of power or vibration swings.

A measurement shall also be made of the peak-to-peak fluctuations so that subsequent fatigue analysis can be made, if necessary.

10.3.3.3 Vibration of rotating shafts

Units shall conform to ISO 7919-5 class B in the normal operating range. Radial shaft movement, measured from zero to peak, shall not exceed 60 % of the radial bearing clearance for any constant load condition.

10.3.3.4 Vibration of non-rotating parts

Units above 1 MW with oil or grease lubricated hydrodynamic bearings shall, in the normal steady state operating range, conform to ISO 10816-5 class B, considering the relevant machine group.

Units below 1 MW, or with water-lubricated bearings, can conform to class B for the normal operating range, considering the relevant machine group.

Units with roller bearings operating in the normal range shall conform to ISO 10816-3 class B.

Vibrations of minor non-rotating parts like hatch covers, etc., due to resonance phenomena shall not cause undue noise.

Annex A
(normative)

Terms, definitions, symbols and units

A.1 Terms and definitions

A.1.1 General

For the purposes of this document, the following terms, definitions, symbols and units apply.

The International System of Units (SI) has been used throughout this standard.

A.1.2 Subscripts

Term number	Term	Definition / Description	Symbol
A.1.2.1	Upstream water passage	The inlet section before the trash rack, which does not normally have a defined sectional area	0
A.1.2.2	High pressure reference section	The high pressure section of the turbine to which the performance guarantee refers, see Figure 1 It can be upstream of the unit valve if contractually specified, see Figure B.1	1
A.1.2.3	High pressure measuring section	Whenever possible the measurement sections should coincide with section 1, otherwise the measured values shall be adjusted to section 1	1', 1''
A.1.2.4	Low pressure reference section	The low pressure section of the turbine to which the guarantee refers, see Figure 1	2
A.1.2.5	Low pressure measuring section	Whenever possible measurement sections should coincide with section 2: otherwise the measured values shall be adjusted to section 2	2', 2''
A.1.2.6	Downstream water passage	The outlet section after the draft tube, which does not often have a defined sectional area	3
A.1.2.7	Specified symbol	Symbol denoting values of quantities such as rotational speed, discharge, etc. for which other quantities are guaranteed	sp
A.1.2.8	Measured symbol	Symbol denoting the values of quantities, measured during testing	M
A.1.2.9	Transposed (Rated) symbol	Symbol designating the values of quantities re-set to the guarantee conditions (rated)	R
A.1.2.10	Weighted symbol	Value calculated from several values with different weights	w
A.1.2.11	Index	Related to index test	ix

A.1.3 Geometric terms and definitions

Term number	Term	Definition / Description	Symbol	Unit
A.1.3.1	Area	Net cross sectional area normal to general flow direction	A	m^2
A.1.3.2	Guide vane opening	Average guide vane angle or opening measured from closed position	α a0 GV	° mm %
A.1.3.3	Needle opening	Average needle stroke measured from closed position	s NO	mm %
A.1.3.4	Runner blade opening	Average runner blade angle measured from a given position	β RB	° %
A.1.3.5	Level	Elevation of a point in the system above the reference datum (usually mean sea level)	z	m
A.1.3.6	Turbine reference level	Elevation of a point in a turbine taken as a reference	z_T	m

A.1.4 Main physical quantities

Term number	Term	Definition / Description	Symbol	Unit
A.1.4.1	Mass	Mass = ρV	m	kg
A.1.4.2	Acceleration (due to gravity)	Local value of g as a function of altitude and latitude of the place of testing	g	m/s^2
A.1.4.3	Temperature	Thermodynamic temperature Celsius temperature $\vartheta = \Theta - 273{,}15$	Θ ϑ	K °C
A.1.4.4	Density	Mass per unit volume	ρ	kg/m^3
A.1.4.5	Kinematic viscosity	Ratio of the dynamic viscosity to the density	ν	m^2/s
A.1.4.6	Mean velocity	Discharge divided by the area A	v	m/s
A.1.4.7	Rotational speed	Number of revolutions per unit time	n	1/min
A.1.4.8	Momentary over speed	The highest speed attained during a sudden specified load rejection from a specified governor setting	n_m	1/min
A.1.4.9	Maximum momentary overspeed	The momentary overspeed attained under the most unfavourable transient conditions (in some cases the maximum momentary overspeed can exceed the maximum steady state runaway speed)	$n_{m,max}$	1/min
A.1.4.10	Maximum steady state runaway speed	The speed at the maximum head, for that position of needles or guide vanes and/or runner/impeller blades which gives the highest value after all transient waves have been dissipated, and with the generator disconnected from load or network and not excited	n_{run}	1/min
A.1.4.11	Final speed	The steady state turbine speed after all transient waves have been dissipated	n_f	1/min
A.1.4.12	Absolute pressure	The static pressure of a fluid measured with reference to a perfect vacuum	p_{abs}	Pa
A.1.4.13	Ambient pressure	The absolute pressure of the ambient air	p_{amb}	Pa
A.1.4.14	Gauge pressure	The difference between the absolute static pressure of a fluid and the ambient pressure at the place and time of measurement: $p = p_{abs} - p_{amb}$	p	Pa

A.1.5 Head terms and definitions

Term number	Term	Definition / Description	Symbol	Unit
A.1.5.1	Specific hydraulic energy of water	Energy of water per unit mass in a measurement / reference section between two sections	E e	J/kg
A.1.5.2	Total head	$h_{tot}= e/g$	h_{tot}	m
A.1.5.3	Kinetic head	$h_{dyn}= v^2/(2g)$	h_{dyn}	m
A.1.5.4	Static head	In a measurement / reference section: $h_{stat} = h_{tot} - h_{dyn}$ between reference sections: $H_{stat} = h_{stat,1} - h_{stat,2}$	h_{stat} H_{stat}	 m
A.1.5.5	Gross head	Head between the head water and tailwater level H_g= HWL – TWL, $H_g = (e_0 – e_3)/g$	H_g	m
A.1.5.6	Net head	$H = (e_1 – e_2)/g$	H	m
A.1.5.7	Rated head	Net head at the design conditions	H_R	m
A.1.5.8	Difference head	Measured head referred to the water surface	h’	m
A.1.5.9	Water passage losses	Water passage losses in head, upstream of the turbine	h_{Li}	m
A.1.5.10	Net positive suction specific energy	Absolute specific energy at section 2, minus the specific energy at vapour pressure, referred to the reference level of the machine; for the formula see IEC 60193	NPSE	J/kg
A.1.5.11	Net positive suction head	NPSH = NPSE/g	NPSH	m

A.1.6 Discharge terms and definitions

Term number	Term	Definition / Description	Symbol	Unit
A.1.6.1	Discharge (volumetric flow rate)	Volume of water per unit time flowing in any section of the system	Q	m^3/s
A.1.6.2	Rated discharge	Discharge at the design conditions	Q_{sp}	m^3/s
A.1.6.3	Index discharge	Discharge during an index test $Q_{ix}= k \cdot \Delta p^x$ k → proportionality factor x → exponent	Q_{ix}	m^3/s

A.1.7 Power terms and definitions

Term number	Term	Definition / Description	Symbol	Unit
A.1.7.1	Hydraulic power	Hydraulic power available in water to produce energy $P_h = gH(\rho Q)$	P_h	W
A.1.7.2	Mechanical power output	Mechanical power on the turbine shaft	P_t	W
A.1.7.3	Rated power	Mechanical power at the design conditions	P_R	W
A.1.7.4	Generator power output	Electrical power output of the generator (measured directly)	P_{gen}	W
A.1.7.5	Plant power output	Electrical power output of the hydroelectric installation (measured indirectly via P_{gen} or directly via P_{out})	P_{out}	W
A.1.7.6	Losses of - transmission	Mechanical losses in the transmission (gear/belt)	$P_{L,tr}$	W
A.1.7.7	- auxiliary devices	Losses of power in sub-system (losses in auxiliaries and part of the losses of the thrust bearing due to axial hydraulic forces)	$P_{L,ax}$	W
A.1.7.8	- generator	Internal losses of the generator including bearing losses	$P_{L,gen}$	W
A.1.7.9	- transformer	Electrical losses of the transformer	$P_{L,tf}$	W
A.1.7.10	- exciter	Losses for the excitation in case of external electrical connection or mechanical drive	$P_{L,ex}$	W

A.1.8 Efficiency terms and definitions

Term number	Term	Definition / Description	Symbol	Unit
A.1.8.1	Turbine efficiency	Index $\eta_{t,ix} = P_t / (H . g . \rho . Q_{ix})$ Absolute $\eta_t = P_t / (H . g . \rho . Q)$	$\eta_{t,ix}$ η_t	-
A.1.8.2	Generator efficiency	$\eta_{gen} = P_{gen} / (P_{gen} + P_{L,gen})$	η_{gen}	-
A.1.8.3	Plant efficiency	Index $\eta_{plant\,,ix} = P_{out} / (H_g . g . \rho . Q_{ix})$ Absolute $\eta_{plant} = P_{out} / (H_g . g . \rho . Q)$	$\eta_{plant,ix}$ η_{plant}	-
A.1.8.4	Transformer efficiency		η_{tf}	-
A.1.8.5	Transmission (gear) efficiency	$\eta_{tr} = (P_{gen} + P_{L,gen}) / P_t$	η_{tr}	-

A.1.9 Uncertainty terms and definitions

Term number	Term	Definition / Description	Symbol
A.1.9.1	Absolute error (uncertainty) in the value x of a measured quantity		e_x
A.1.9.2	Value of measured quantity		x
A.1.9.3	Relative error (uncertainty)		$f_x = e_x / x$
A.1.9.4	Systematic uncertainty		$f_{x,sy}$
A.1.9.5	Random uncertainty		$f_{x,ra}$
A.1.9.6	Overall uncertainties in power output including systematic and random errors of power and head	Turbine power output (shaft power)	$f_{P,t}$
A.1.9.7		Generator power output (to terminal block)	$f_{P,gen}$
A.1.9.8		Hydroelectric unit power output (to service line)	$f_{P,out}$
A.1.9.9		The relative uncertainty in calculated power	$f_{(P)}$
A.1.9.10	Overall uncertainties in the value of efficiency including systematic and random errors	Turbine efficiency, absolute	$f_{\eta,t}$
A.1.9.11		Turbine efficiency, thermodynamic method	$f_{\eta,th}$
A.1.9.12		Turbine efficiency, index test	$f_{\eta,t,ix}$
A.1.9.13		Plant efficiency, index test	$f_{\eta,out}$
A.1.9.14	Uncertainties in the value of head	Pressure measurement	f_p
A.1.9.15		Net head	f_H
A.1.9.16	Uncertainties in the value of discharge	Absolute discharge	f_Q
A.1.9.17		Index discharge	$f_{Q,ix}$
A.1.9.18	Uncertainties due to directly driven or connected components	Generator losses	$f_{L,gen}$
A.1.9.19		Mechanical transmission losses	$f_{L,tr}$
A.1.9.20		Transformer losses	$f_{L,tf}$
A.1.9.21	Systematic uncertainties due to instrumentation for power measurement	Energy counter (watt hour meter)	f_{WH}
A.1.9.22		Potential transformer	f_{PT}
A.1.9.23		Current transformer	f_{CT}
A.1.9.24		Timer	f_T

A.1.10 Other terms and definitions

Term number	Definition / Description	Symbol
A.1.10.1	Guide vane opening (wicket gate opening)	GV
A.1.10.2	Runner blade opening	RB
A.1.10.3	Needle opening	NO
A.1.10.4	Potential (voltage) transformer	PT
A.1.10.5	Current transformer	CT
A.1.10.6	Power factor	$\cos \phi$
A.1.10.7	Head water level	HWL
A.1.10.8	Tail water level	TWL

A.2 Definition of specific hydraulic energy

According to Bernoulli's equation, the conservation of hydraulic energy along a stream tube can be written in three forms as follows:

1	E	= Energy per mass	$= v^2/2 + p/\rho + gz$	Dimension: Nm/kg = m^2/s^2 =J/kg
2	H	= Energy per weight	$= v^2/(2g) + p/(\rho g) + z$	Dimension: Nm/N = m
3	p_{tot}	= Energy per volume	$= \rho v^2/2 + p + \rho gz$	Dimension: Nm/m³ = N/m^2

All three forms are equivalent and can be used without any loss in accuracy for any type of calculation. For all three forms it is correct to use the term "specific hydraulic energy".

The first equation corresponds to the definition in IEC 60041. In this form the term E is used for the total 'Specific Hydraulic Energy'. According to IEC 60041 the single terms are specified as:

- $V^2/2$ specific kinetic energy,
- p/ρ specific pressure energy,
- gz specific potential energy.

The second equation is proposed for small hydroelectric installations in order to simplify the procedure as well as to avoid mistakes. Then the single terms of the "specific hydraulic energy" are:

- $v^2/(2g)$ kinetic energy head (velocity head),
- $p/(\rho g)$ pressure head,
- z geodetic head (height).

The calculation of the total "specific hydraulic energy" E according to IEC 60041 is then E = gH.

A.3 Definition of transient pressure variation

The maximum or minimum pressure is the momentary pressure under the most unfavourable transient condition usually under a condition of maximum head and/or discharge. The maximum pressure p_{+m} is illustrated in Figure A.1. The minimum pressure p_{-m} is illutrated in Figure A.2.

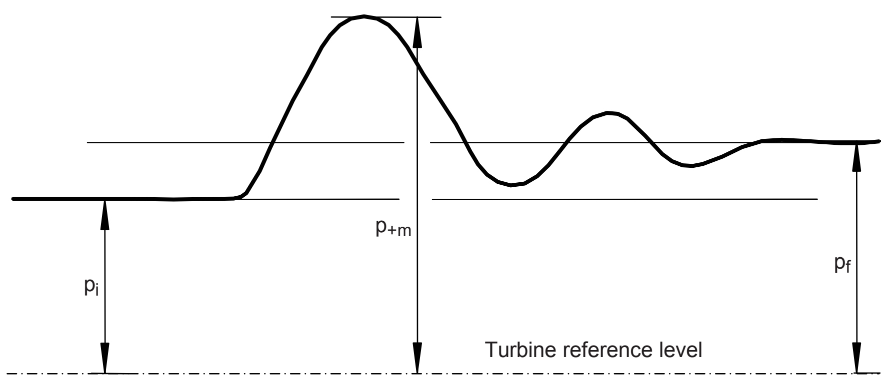


Figure A.1 – Transient pressure fluctuation at the turbine high pressure reference section, when a specified load is suddenly rejected

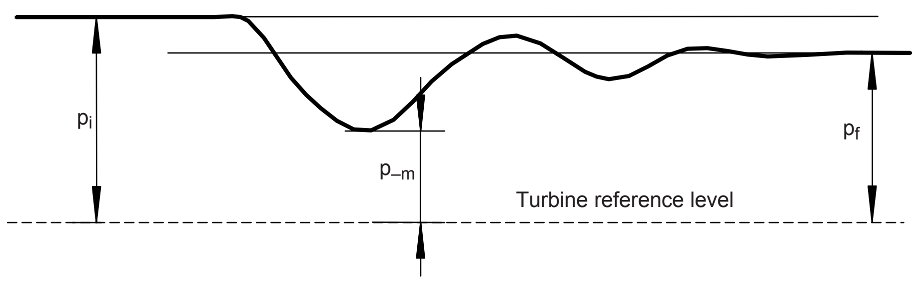


Figure A.2 – Transient pressure fluctuation at the turbine high pressure reference section, when a specified load is suddenly accepted

NOTE The curves do not show pressure fluctuations caused by higher frequencies, mainly induced by runner rotation and other dynamic phenomena. See 5.9 and Figure 11 and Figure 12 for an example of how to treat this pressure fluctuation influenced (modulated) by pulsations of higher frequency.

A.4 Physical data

A.4.1 Acceleration due to gravity as a function of latitude and altitude

The international standard value of g is 9,806 m/s^2.

The acceleration due to gravity may be calculated by the following formula:

$$g = 9{,}780\,3\,(1 + 0{,}005\,3 \sin^2\varphi) - 3\times10^{-6}\,z$$

where

φ is latitude in degrees,

z is altitude in metres.

A.4.2 Density of pure water

For the calculation of these values, the formula according to Herbst and Rögener is used (see IEC 60041). Values are tabulated in Table A.1, and intermediate values may be derived by linear interpolation. For numerical calculations, simple formulae with sufficient accuracy can be used, such as the Weber formulae.

Table A.1 – Density of water

Temperature	**Absolute pressure** 10^5 Pa					
°C	**1**	**10**	**20**	**50**	**100**	**150**
0	999,8	1 000,3	1 000,8	1 002,3	1 004,8	1 007,3
5	999,9	1 000,4	1 000,9	1 002,4	1 004,8	1 007,2
10	999,7	1 000,1	1 000,6	1 002,0	1 004,4	1 006,7
15	999,1	999,5	1 000,0	1 001,4	1 003,7	1 005,9
20	998,2	998,6	999,1	1 000,4	1 002,7	1 004,9
25	997,0	997,4	997,9	999,2	1 001,5	1 003,7
30	995,7	996,1	996,5	997,8	1 000,0	1 002,2
35	994,0	994,4	994,9	996,2	998,4	1 000,5
40	992,2	992,6	993,1	994,4	996,5	998,7

A.4.3 Density of air

The density of air ρ_a (kg/m^3) is calculated using the following formula:

$$\rho_a = \frac{p_{abs}}{\Theta} \times 3{,}483\,7 \times 10^{-3}$$

where

p_{abs} is in Pascal,
Θ is in Kelvin.

Annex B
(normative)

Head definition

B.1 General

In this standard the terms net head H, gross head H_g, total head H_{tot} and static head H_{stat} are mainly used for energy and pressure.

If necessary, the specific energy e can be calculated by e = gH.

The net head H of the turbine is defined as:

$$H_{net} = \frac{(p_{abs1} - p_{abs2})}{\overline{\rho}\,\overline{g}} + \frac{(v_1^2 - v_2^2)}{2\,\overline{g}} + (z_1 - z_2)$$

The influence of the change in ambient pressure p_{amb} between sections 1 and 2 is very small and for small turbines can be neglected. For the same reason the average of g or ρ is also usually neglected. The reference for altitude is taken as the setting elevation of the turbine z_T. The formula for net head can therefore be simplified as follows using $p = p_{abs} - p_{amb}$.

$$H_{net} = \frac{(p_1 - p_2)}{\rho\,g} + \frac{(v_1^2 - v_2^2)}{2\,g} + (z_1 - z_2)$$

B.2 Selection of a pressure measurement section

B.2.1 General

The net head of the machine is a main characteristic and it shall be measured in any test of a hydraulic machine. In order to calculate the net head of turbine, it is necessary to determine either the head in each of the reference sections or their difference.

Measurement sections should be chosen, and agreed by all parties, to have smooth uniform flow patterns. Avoid sections where the velocity pattern is distorted by an elbow, valve or other flow disturbances outside of the hydraulic machine. The plane of the section shall be normal to the mean direction of flow. The area of the section is used to calculate the mean velocity, and shall be easy to measure.

Whenever possible, the measurement sections 1’, 2’ should coincide with the reference sections 1, 2. If this is not possible, the method for correcting the data to the reference section shall be agreed. Evaluation of this head difference may be based on theoretical knowledge and practical experience.

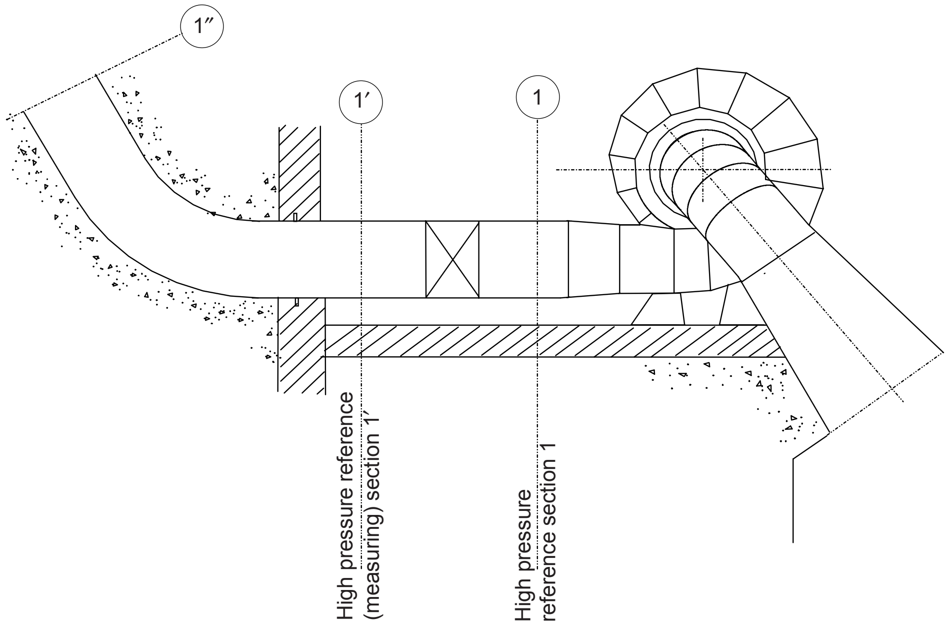


Figure B.1 – High pressure reference and measuring sections

B.2.2 Upstream reference section

Ideally this shall be located in a straight conduit section at a distance of two diameters upstream from the inlet of the turbine (spiral case or nozzles). The conduit may be slightly divergent or convergent. If all parties agree, the reference section for guarantee can be shifted from the turbine inlet section 1 to 1’ by allowing for the losses of the closing device.

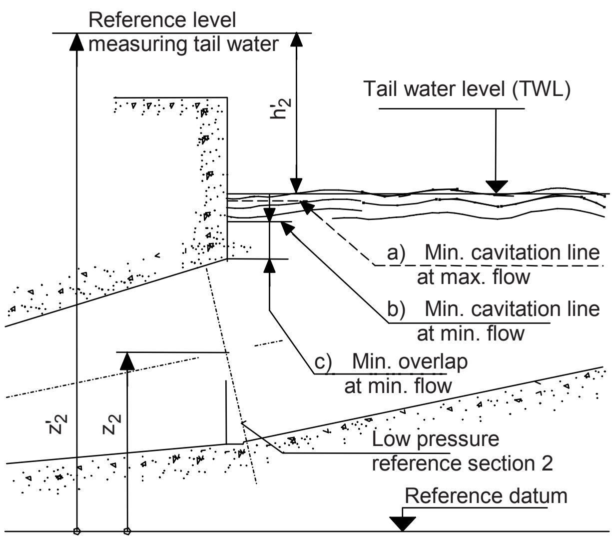
B.2.3 Downstream reference section

B.2.3.1 Impulse turbines

The downstream reference level shall be the average of the elevations of theoretical points of contact between the jets and the runner. The pressure inside the turbine case is assumed to be equal to atmospheric pressure. Corrections shall be applied in the case of a depressurized or pressurized turbine.

B.2.3.2 Reaction turbines

An example of a measurement section in a tailrace is shown in Figure B.2. Another example that considers the velocity head in the tailrace pit is shown in Figure B.5. An alternative is to make the measurement section in the draft tube, as shown in Figure B.3, if it is possible to find suitable measurement conditions. In both cases, the velocity head shall be calculated using the mean velocity in the draft outlet section. If all parties agree, the reference section for guarantee can be shifted from the draft tube outlet section to the tailrace level just outside the draft tube, by including the draft tube outlet losses in the turbine losses.



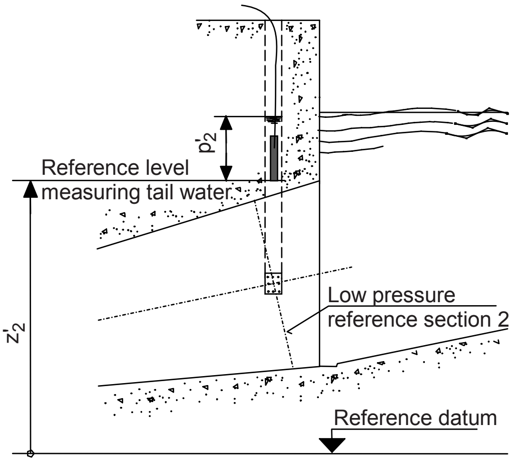


Figure B.2 – Measuring section at tail water

Figure B.3 – Measuring section at draft tube

B.3 Definition of measuring sections

B.3.1 General

The recommended method for calculating H is to plot separate curves for $h_{1,tot}$ and $h_{2,tot}$ versus discharge (or turbine opening) as shown in Figure B.4. The control of outliers and estimates of error should be carried out separately for $h_{1,tot}$ and $h_{2,tot}$. This allows any HWL and TWL restrictions to be checked.

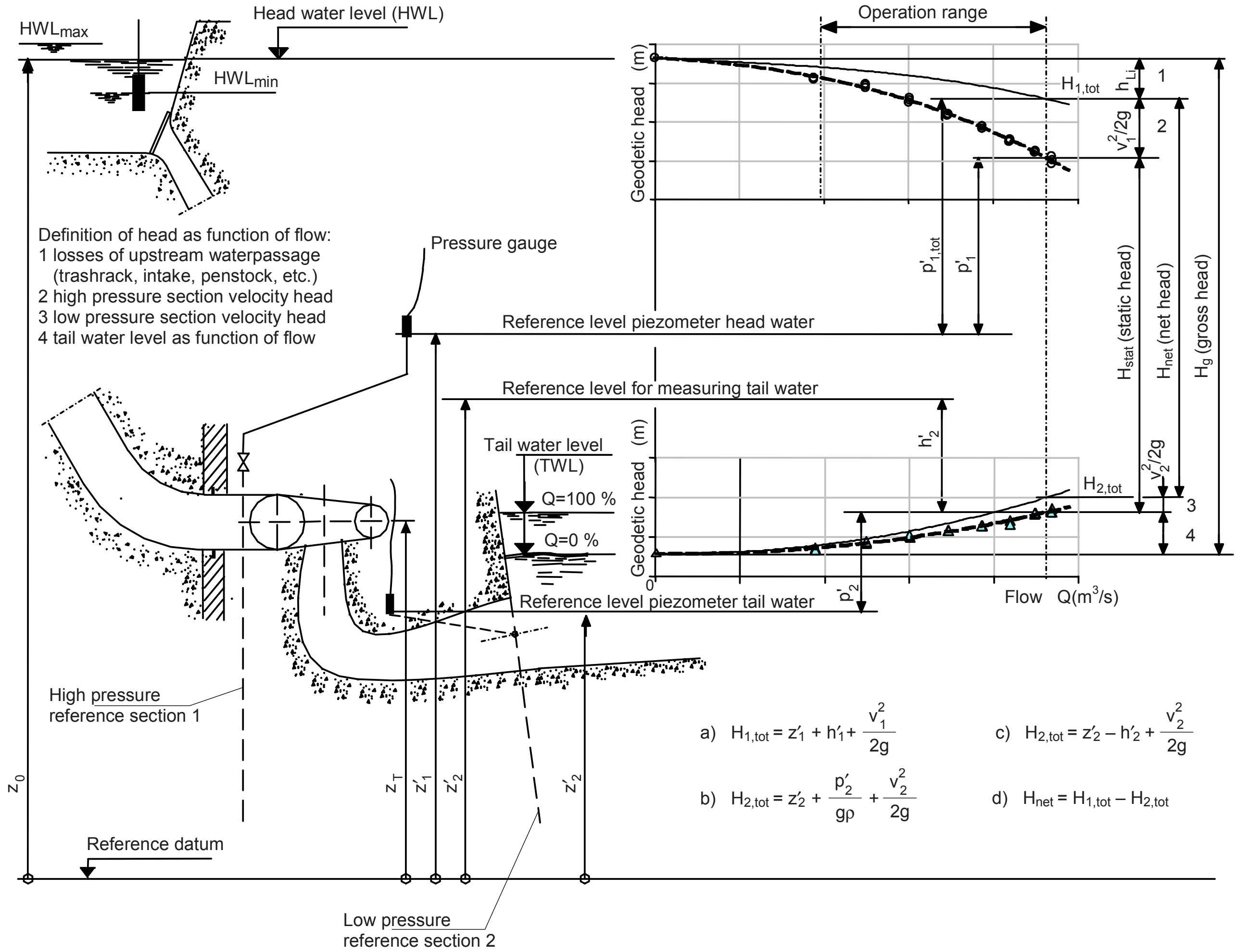


Figure B.4 – Definition of measuring sections

B.3.2 Definition of head for Kaplan turbines

The head for Kaplan turbines is defined in Figures B.5 and B.6.

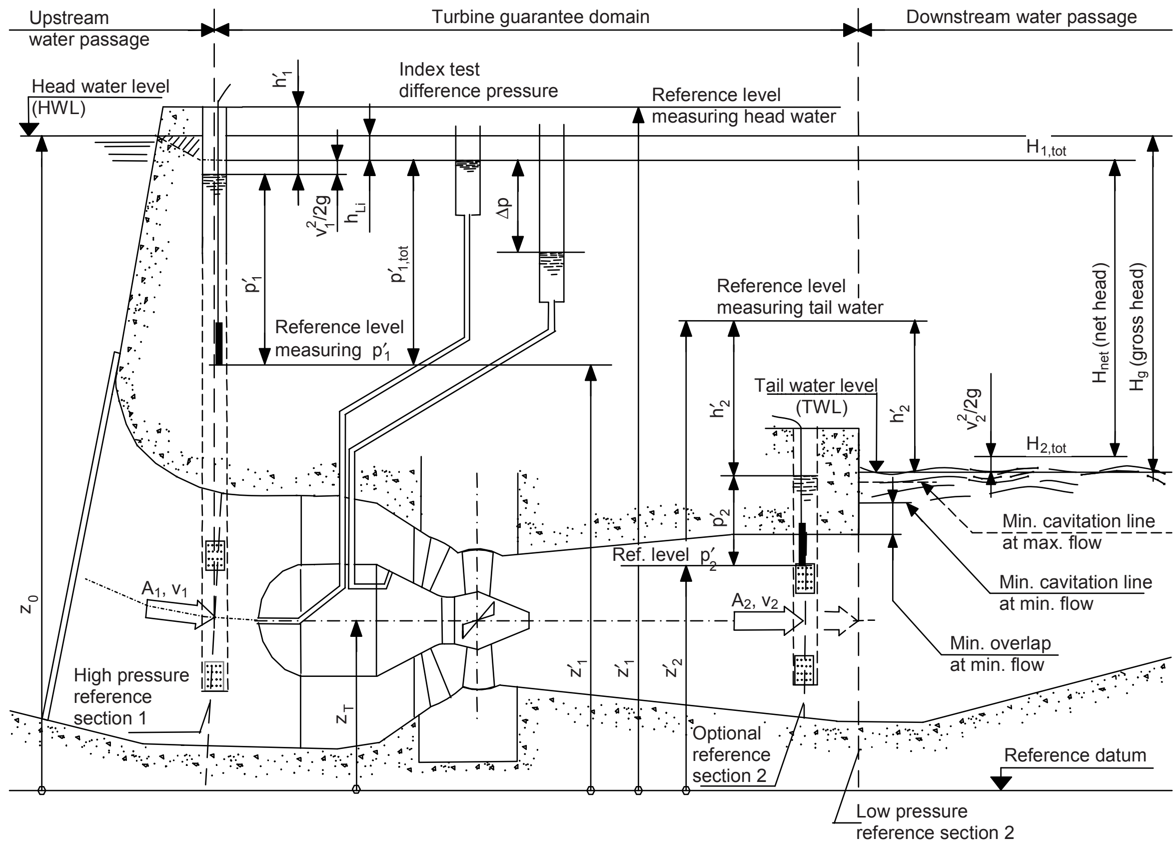


Figure B.5 – Kaplan turbine with horizontal shaft

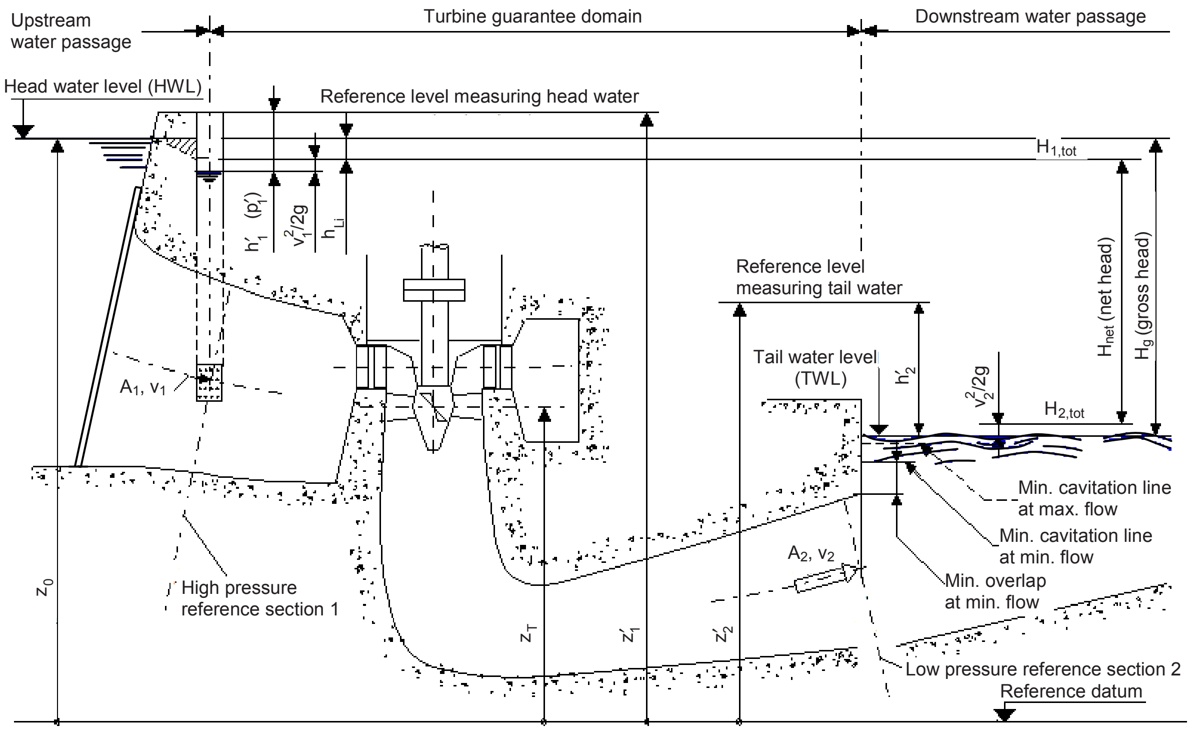


Figure B.6 – Kaplan turbine with vertical shaft

B.3.3 Definition of head for Francis turbines

The head for Francis turbines is defined in Figures B.7, B.8, B.9, and B.10.

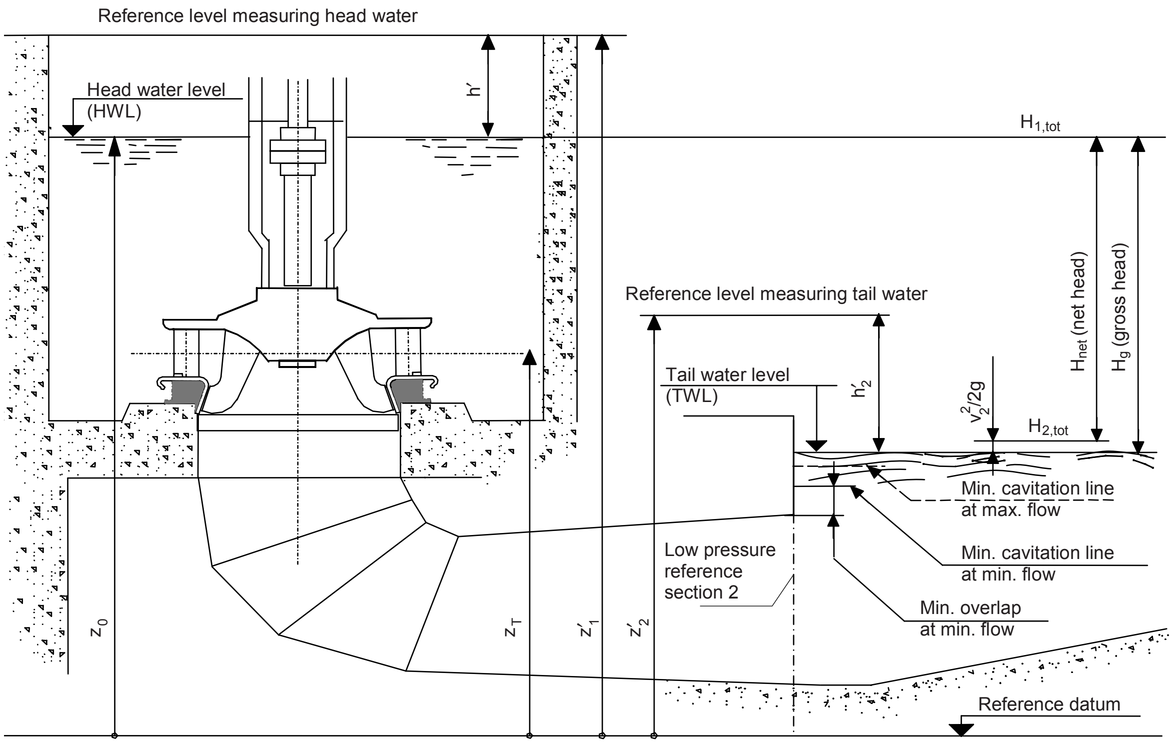


Figure B.7 – Francis open flume turbine with vertical shaft

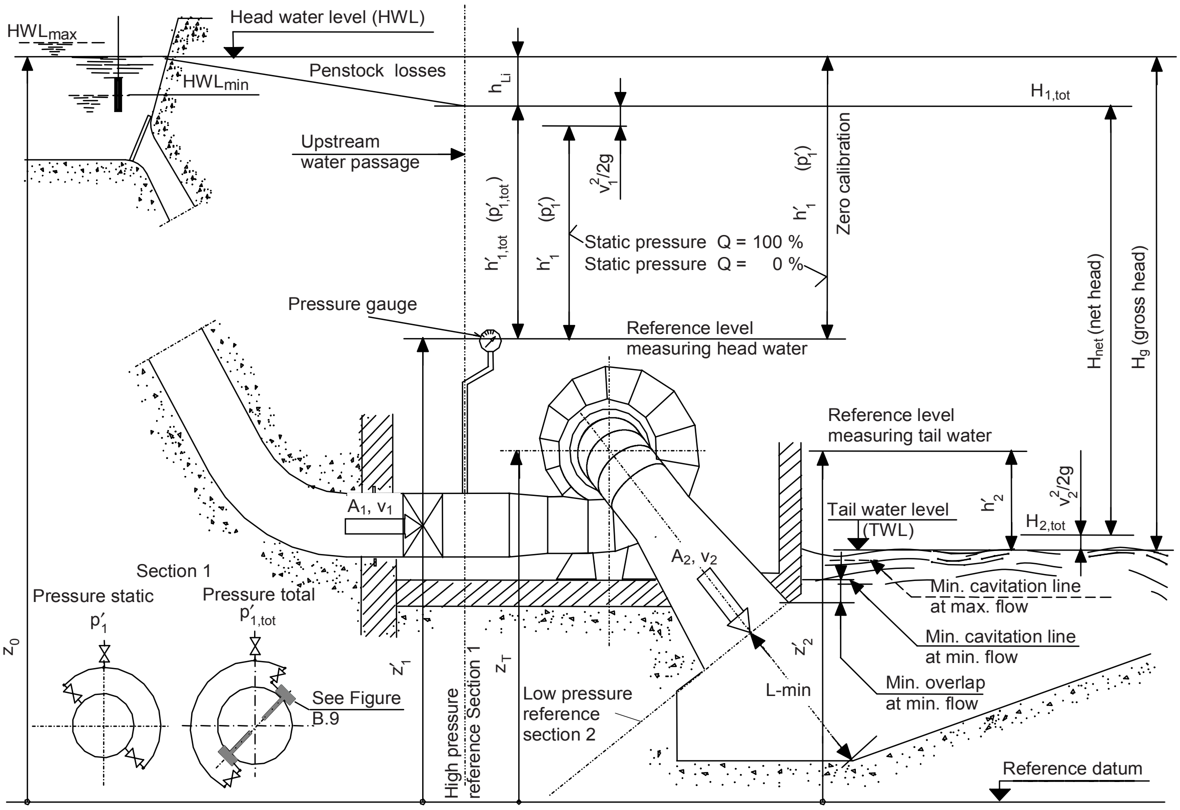


Figure B.8 – Francis turbine with horizontal shaft

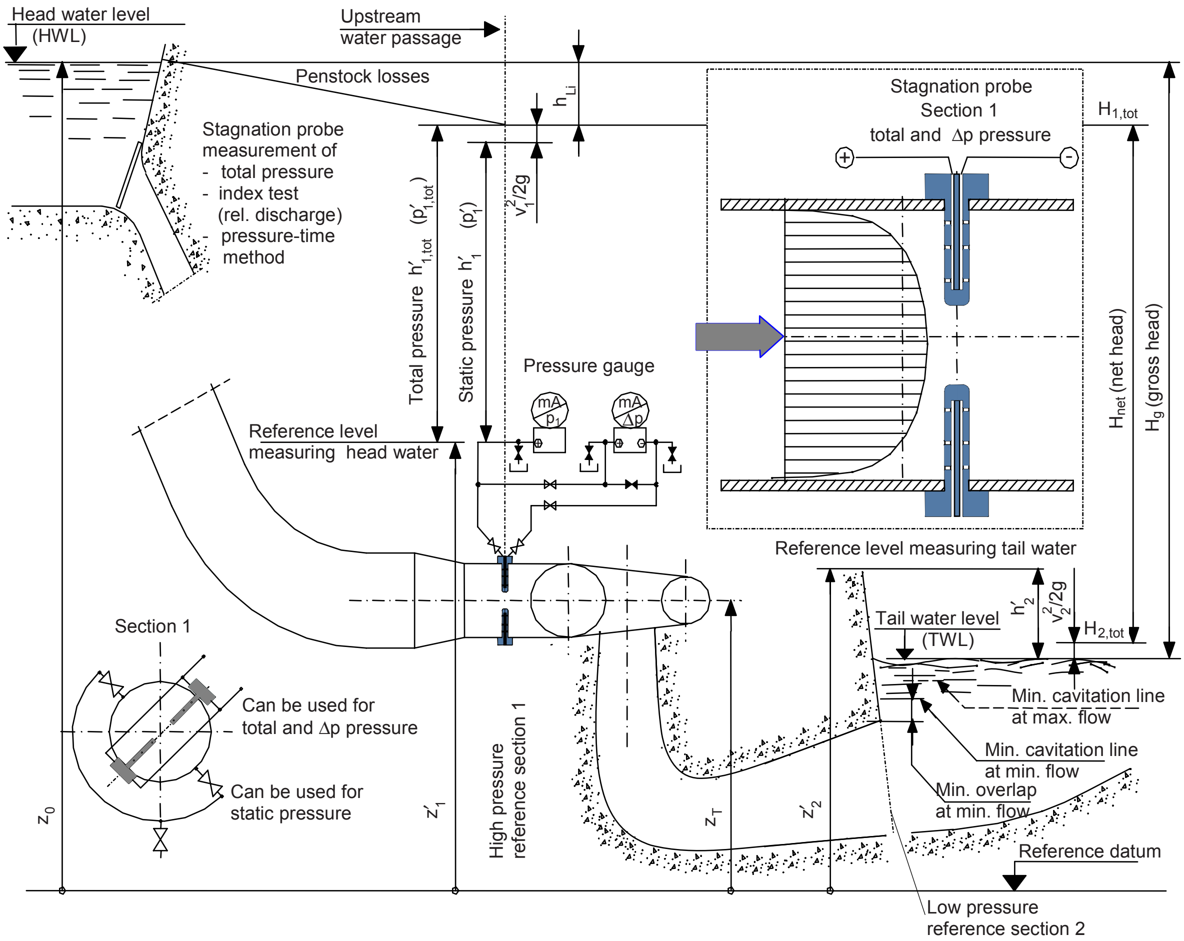


Figure B.9 – Francis turbine with vertical shaft, with stagnation probe

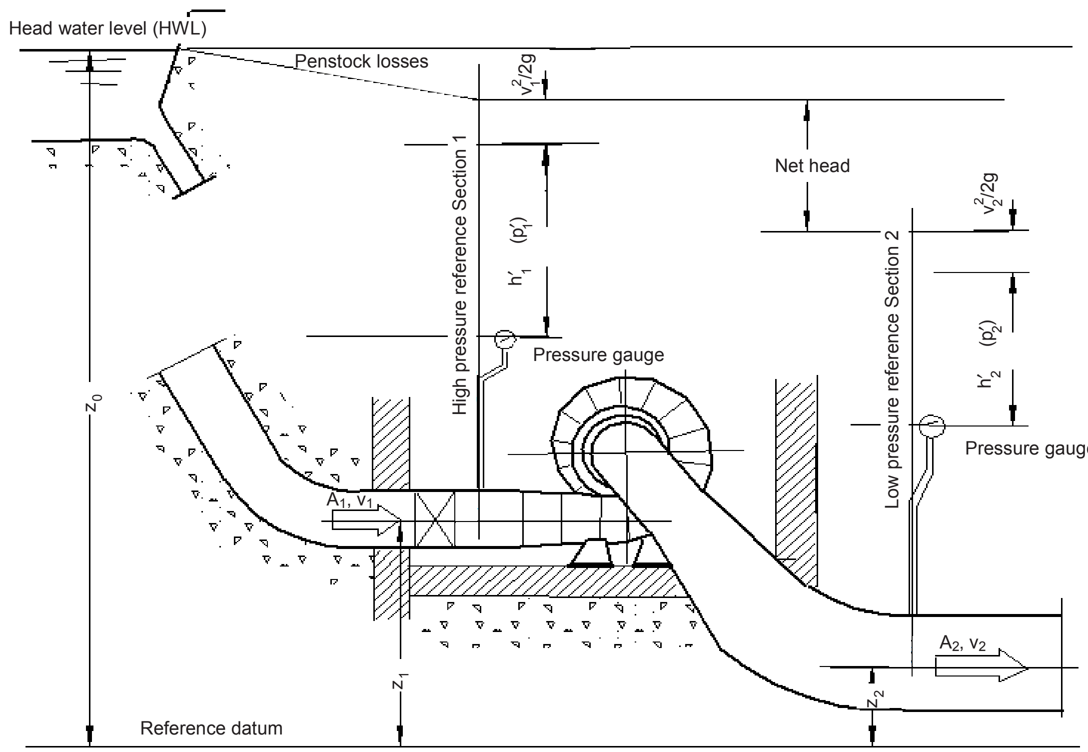


Figure B.10 – Francis turbine with horizontal shaft with pressure on suction side

B.3.4 Definition of head for Pelton turbines

The head for Pelton turbines is defined in Figures B.11 and B.12.

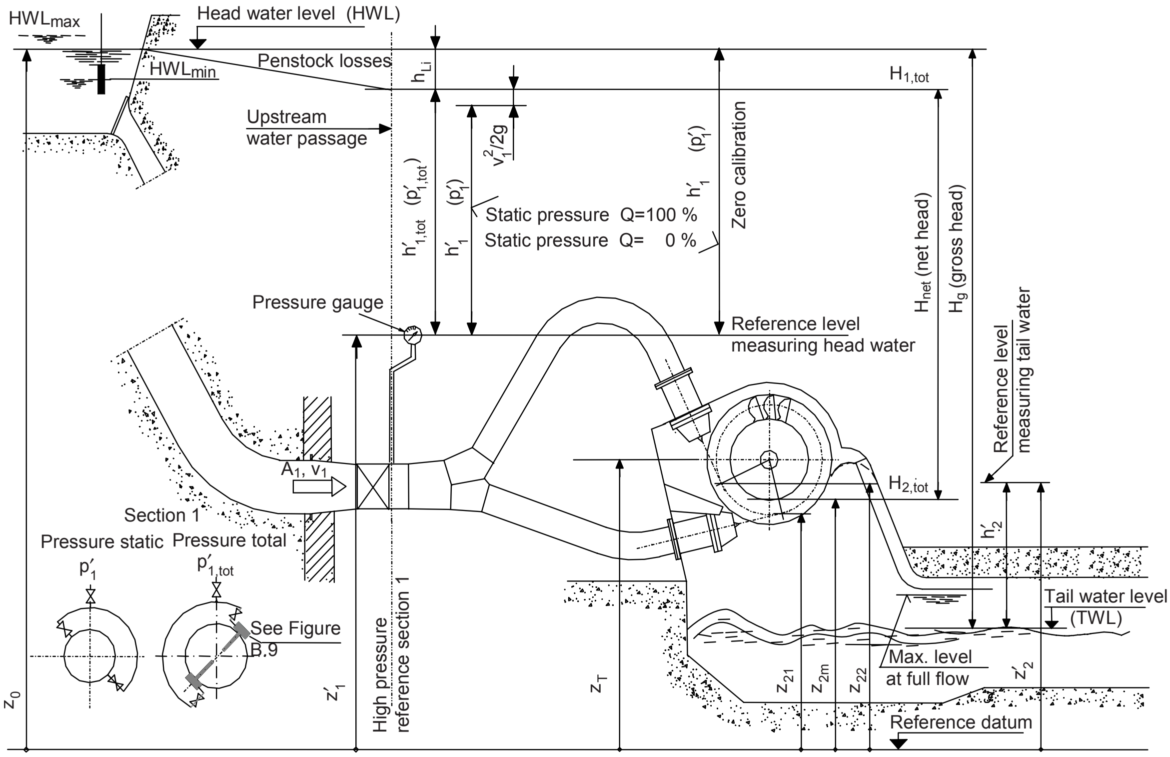


Figure B.11 – Pelton turbine with horizontal shaft

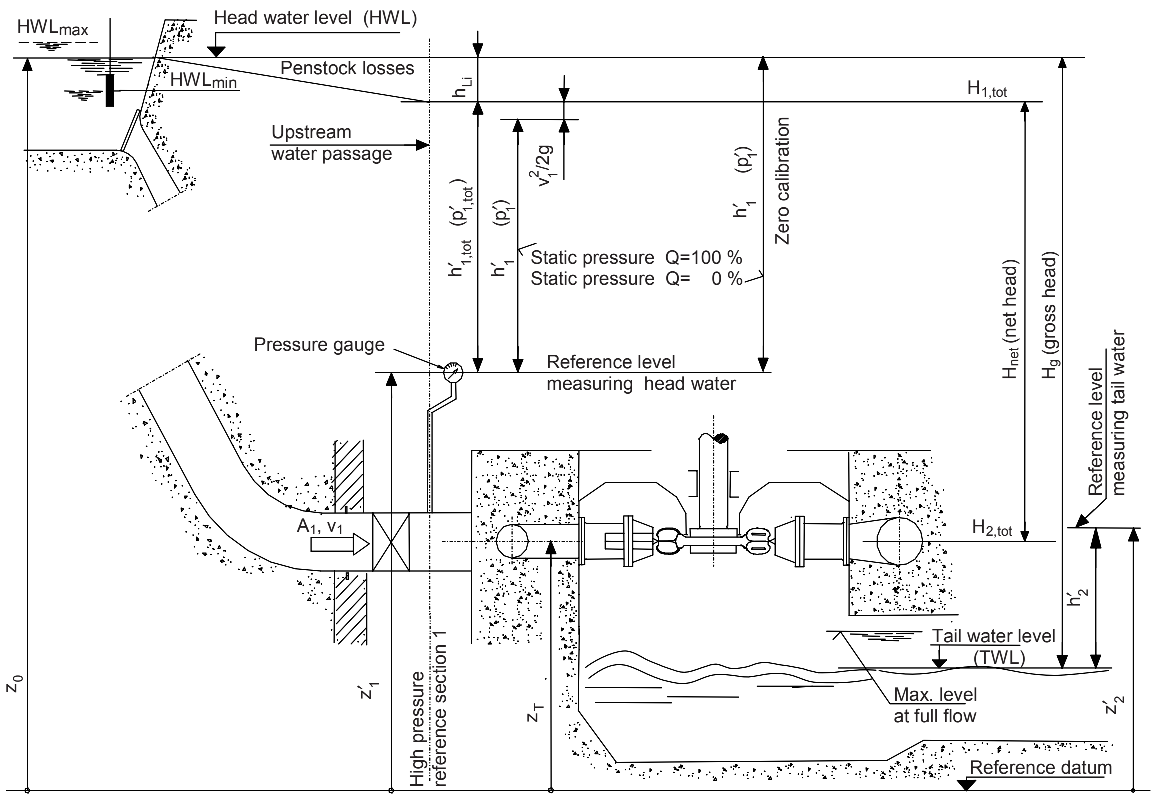


Figure B.12 – Pelton turbine with vertical shaft

B.3.5 Definition of head for Turgo turbines

The head for turgo turbines is defined in Figures B.13 and B.14.

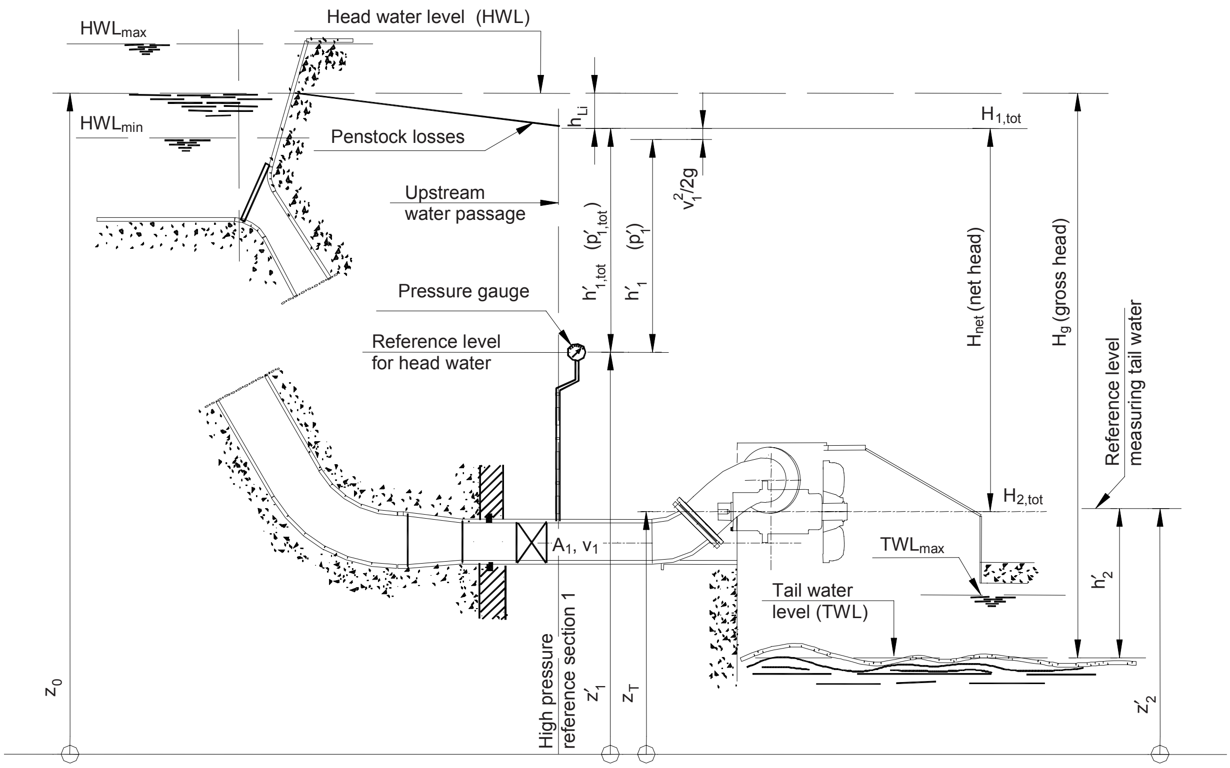


Figure B.13 – Turgo turbine with horizontal shaft

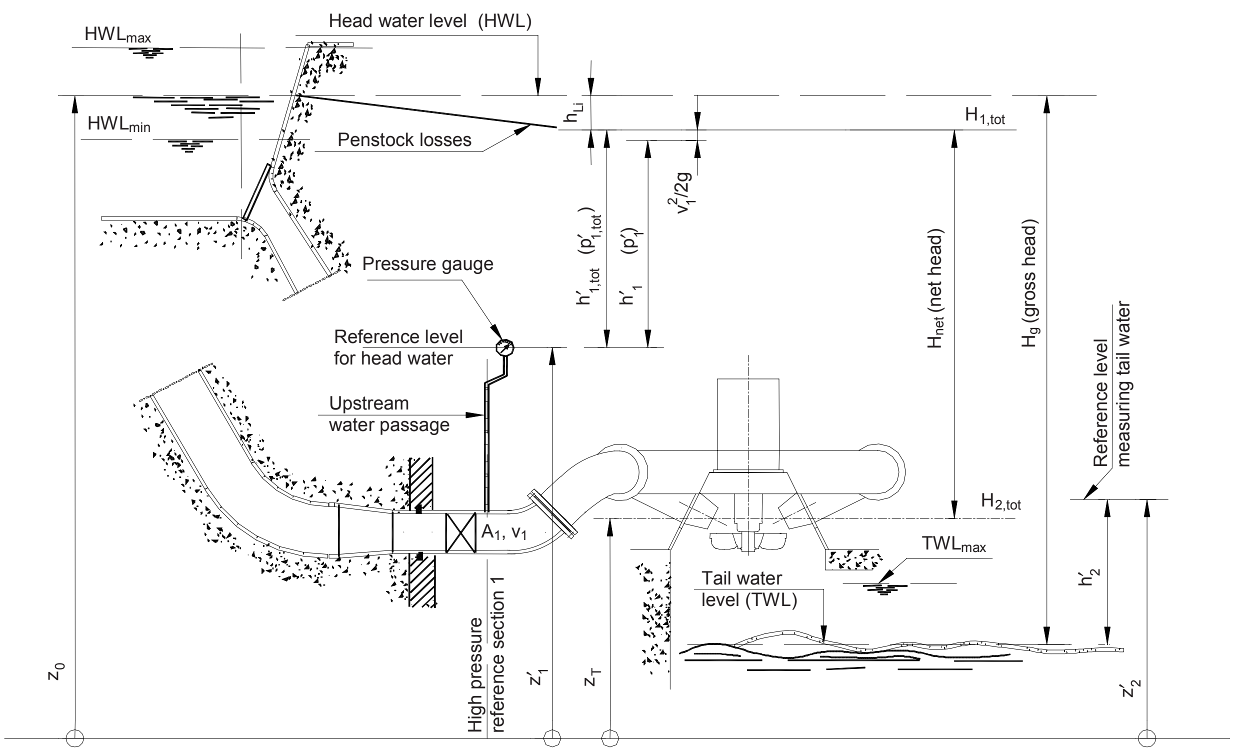


Figure B.14 – Turgo turbine with vertical shaft

B.3.6 Definition of head for crossflow turbines

The head for crossflow turbines is defined in Figures B.15 and B.16

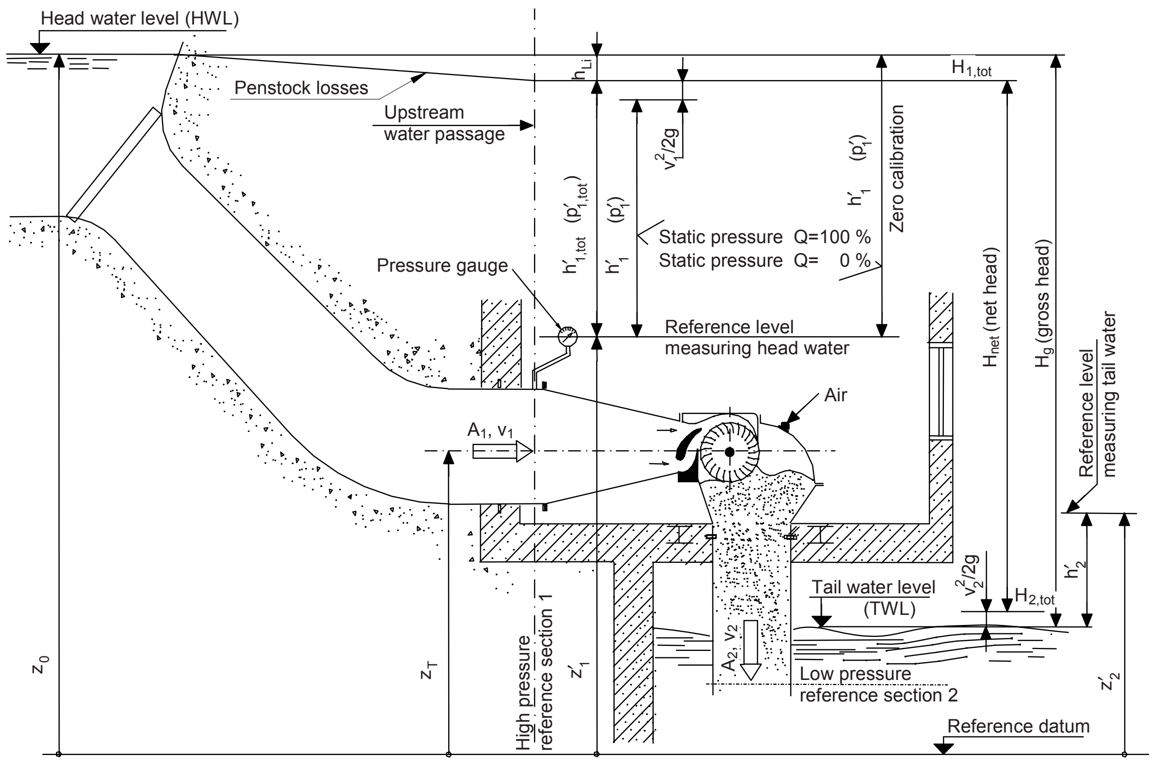


Figure B.15 – Crossflow turbine with horizontal shaft, with draft tube

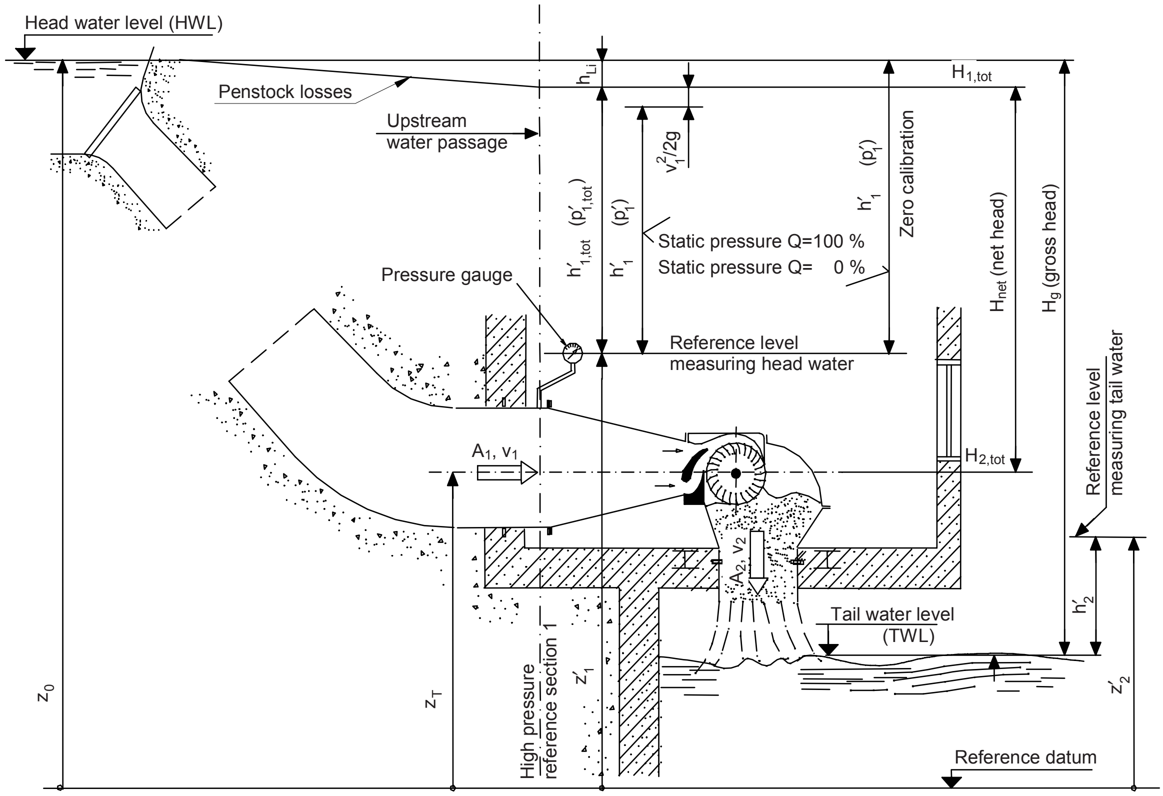


Figure B.16 – Crossflow turbine with horizontal shaft, without draft tube

B.4 Method of head measurements

B.4.1 General

Ideally a measurement section shall be equipped with four static pressure taps made out of stainless steel. The bore axis of the pressure taps shall be normal to the axis of the pipe work and their implementation shall observe the general provisions of Figure B.17. The diameter of the tap holes shall be between 3 mm and 6 mm. Preferably the edges of the openings should be provided with a radius r ≤ d/4 smoothly joining the flow passage. The length (l) of a pressure tap hole shall not be less than twice its diameter. A boss shall be installed for pipes that have a thin wall section.

Pressure taps shall be machined flush to the internal wall of the pipe and they shall be free from burrs and irregularities. Particular care should be taken to avoid any paint accumulation around the tap hole, and to clear built up dirt from any taps located at the bottom of a section.

The pressure taps shall be connected by isolating valves to a manifold or a ring manifold, the cross-section of which shall be at least equal to twice the cross-section of a pressure tap. Before making observations, the pressure shall be measured separately with each pressure tap opened, one after the other, under normal test conditions. The pressure reading is acceptable if the arithmetic mean of the four measurements does not deviate by more than 0,5 % of the net head of the turbine or by more than 20 % of the velocity head in the measurement section. If it is not possible to correct the faulty tap, then a mutual agreement should be reached to eliminate the faulty tap, to select another location, or to accept this deviation.

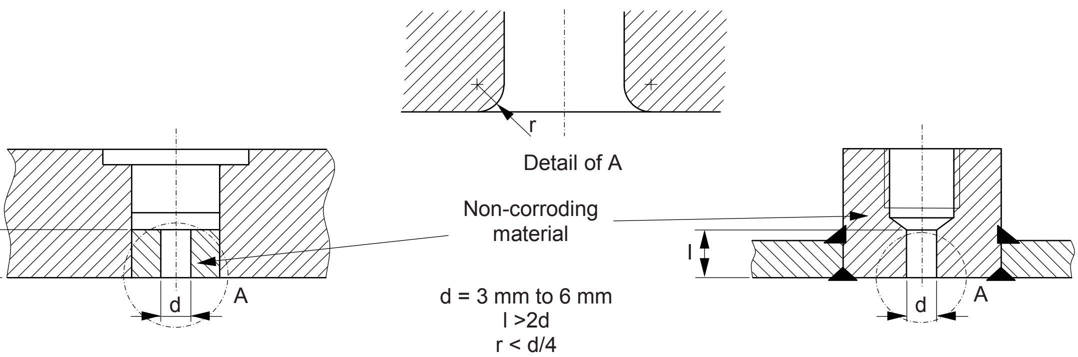


Figure B.17 – Specifications for static pressure taps

B.4.2 Pressure measuring instruments

B.4.2.1 General

Liquid column manometers and dead-weight manometers shall be considered primary measuring instruments. Dead weight manometers, or a modern equivalent, can be used as pressure calibration devices.

B.4.2.2 Pressure transducers

Pressure transducers are electromechanical devices in which the mechanical effects produced by pressure are converted into electrical signals. The range of a pressure transducer shall be selected taking into account the range of the pressure to be measured.

Some of the advantages associated with the use of pressure transducers are as follows:

- ease of integration into an electronic data acquisition system;

- a rapid and accurate response because of the negligible discharges across the pressure taps;
- easy production of the mean value of fluctuating differential pressures;
- recording of transient pressures using ordinary electronic equipment.

Pressure transducers shall have the following characteristics:

- adequate calibration stability;
- high repeatability and negligible hysteresis;
- low zero shift and low temperature sensitivity;
- the calibration of the transducers used shall be valid.

There is a wide range of differential pressure transducers, which can be used to obtain the following value directly from a single measurement: $(p_1 - p_2) /\rho g + (z_1 - z_2)$. However, the following potential problems should be considered:

- panel instrumentation: using differential transducers can lead to errors if the areas of the two measuring sections are different;
- acceptance tests: the source of possible pressure variation cannot be located.

B.4.2.3 Spring pressure gauges

This type of pressure gauge uses the mechanical deflection of a simple spiral loop tube or an orifice plate to indicate pressure. The range of this kind of pressure gauge shall be selected taking into account the range of pressure to be measured. This may be used by agreement between the parties, providing the device is of sufficient accuracy, in its optimum range (normally between 60 % and 100 % of the graduation) and providing the calibration is valid.

B.4.2.4 Free level measuring instruments

The measurement section for determining a water level shall be selected to satisfy the two following conditions.

- The water surface shall be calm and free from disturbances. Sections where the flow velocity profile is disturbed by an elbow or by any other special feature shall be avoided.
- The area used to determine the mean velocity of the water shall be precisely defined and shall be easily measurable.

The free levels are generally measured from a measuring reference level for the instrument z_M, and the possible methods shall include:

- plate gauge;
- point or hook gauge;
- float gauge;
- staff gauge;
- ultrasonic transducer.

These methods are only applicable for accessible free levels. For inaccessible levels, the following may be used:

- liquid column manometer;
- immersed pressure transducer;
- measurements using compressed air (bubble apparatus).

NOTE Requirements concerning the design and use of level measuring devices are given in ISO 4373.

B.5 Estimation of kinetic head for class A tests

The theoretical turbine discharge can be plotted against guide vane or needle opening using the model data as shown in Figure B.18. The discharge can be estimated from the curve, and used to calculate the velocity at the reference section.

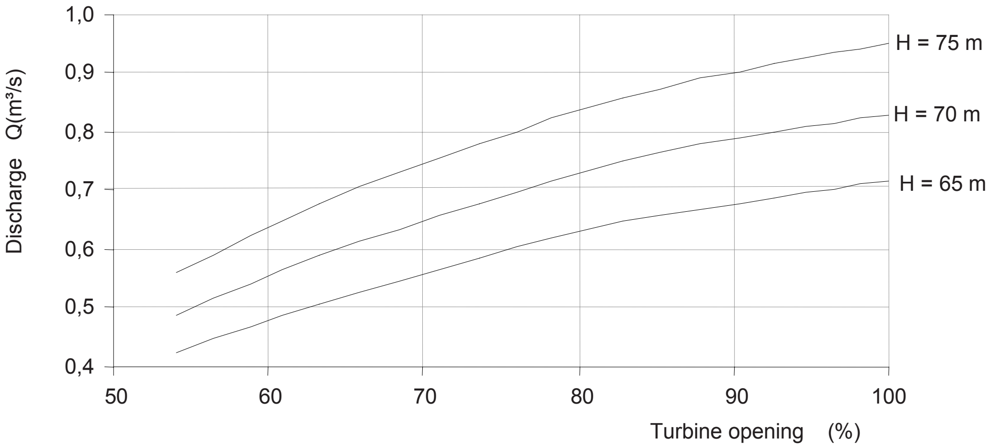


Figure B.18 – Example: discharge versus guide vane opening

Annex C
(normative)

Method of speed measurements

C.1 Rotational speed

C.1.1 Speed measurements in the case of direct measurement of power

The rotational speed shall be measured by means of a calibrated tachometer or electronic counter, and shall be made without any slip relative to the hydraulic machine shaft.

C.1.2 Speed measurements in the case of indirect measurement of power

The rotational speed of a synchronous machine can be measured indirectly using the panel frequency meter under the following conditions:

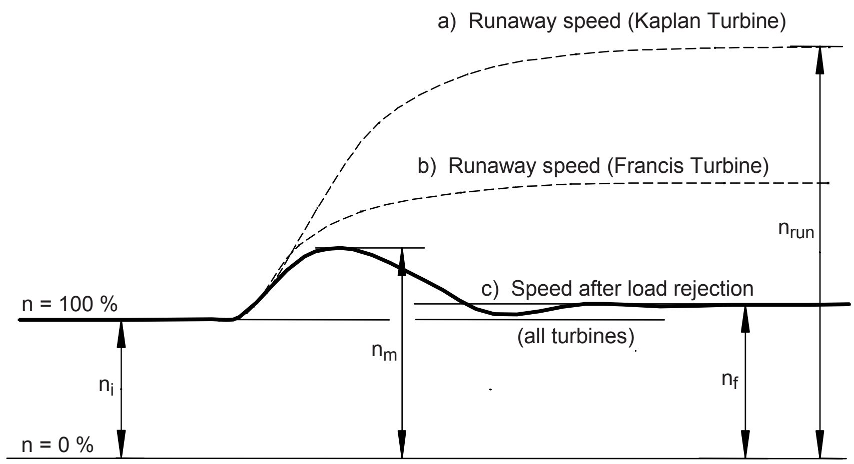
- the system load shall be steady,
- the frequency meter shall be checked against a suitable precision instrument.

The rotational speed of an asynchronous electrical machine can be measured in accordance with IEC 60041:1991, 13.3.

C.2 Definition of overspeed and runaway speed

Overspeed is the maximum momentary speed attained during a sudden specified load rejection from a specified governor setting, and shown as n_m in Figure C.1.

Runaway speed is the final steady speed for a given head and position of needles or guide vanes and/or runner blades with the electrical machine disconnected from load or network and not excited. This is shown as n_{run} in Figure C.1.



Key

a), b) Runaway speed after sudden load rejection with locked closing devices.

c) Variation of turbine speed during sudden load rejection.

Figure C.1 – Overspeed and runaway

Annex D
(normative)

Power output measurement

D.1 General

The electrical power output is normally measured at the generator terminals, or at the transformer. The turbine power is then calculated using the test data for the generator efficiency, and gearbox if fitted. The turbine power output can be measured directly using a torquemeter, but this is rare.

From known generator efficiency values, the generator losses can be determined. Losses are comprised of several components that are either constant or a second order polynomial function of the load, enabling interpolation to be made with high accuracy. An example curve is given in Figure D.1 showing the different losses.

D.2 Measurement of power output

D.2.1 Synchronous generator

The generator shall be operated as near to specified voltage and a power factor equal to one as existing conditions permit. If this is not possible, suitable corrections in the computation of the power output and losses shall be made.

The power shall be measured from the panel instruments or by the means of a power analyser. Figures D.3 and D.4 show the principles of installing a power analyser using the two-wattmeter and three-wattmeter methods respectively. The number of readings shall depend upon the duration of the run and the load fluctuations. Sufficient readings shall be taken to give a true average of the output during the run.

Instrument transformers used for the test shall be calibrated prior to installation or immediately prior to the test by comparison with standards acceptable to the parties to the test. The instrument transformers shall be tested to determine the ratio of transformation and the phase angle deviations for secondary burdens, which are equivalent to actual instrument burdens of the instruments to be used during the performance test. The correction data shall be available before the start of testing.

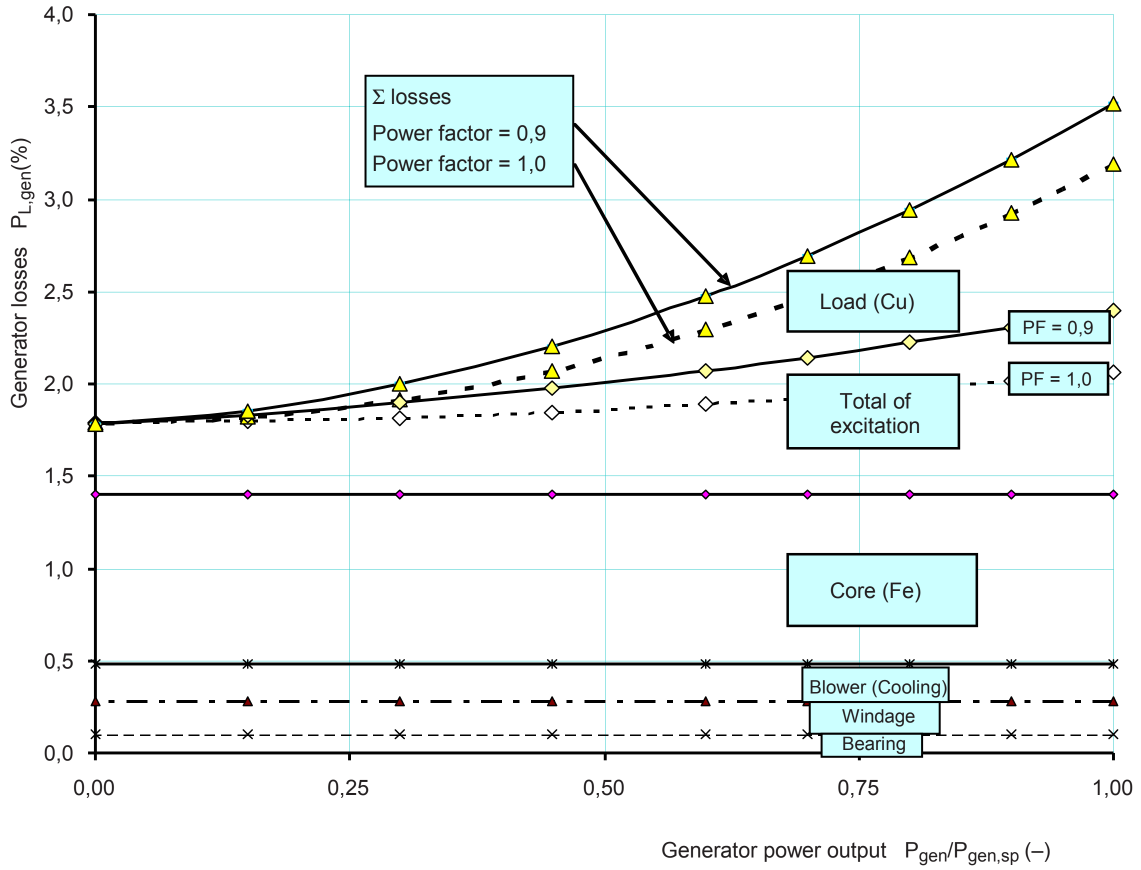


Figure D.1 – Typical losses of a synchronous generator

The following formula shall be used if the losses have to be calculated from the generator efficiency:

$$P_{Los} = P_a \frac{1-\eta_{Gen}}{\eta_{Gen}}$$

D.2.2 Asynchronous generator, indirect method of power output measurement

The measurement, connection and evaluation are normally done in the same way as for a synchronous generator. Special care shall be taken to measure the power-factor over the whole guarantee range (see Figure D.2) and compare it with the guarantee. The rotational speed should also be measured because it varies with power output.

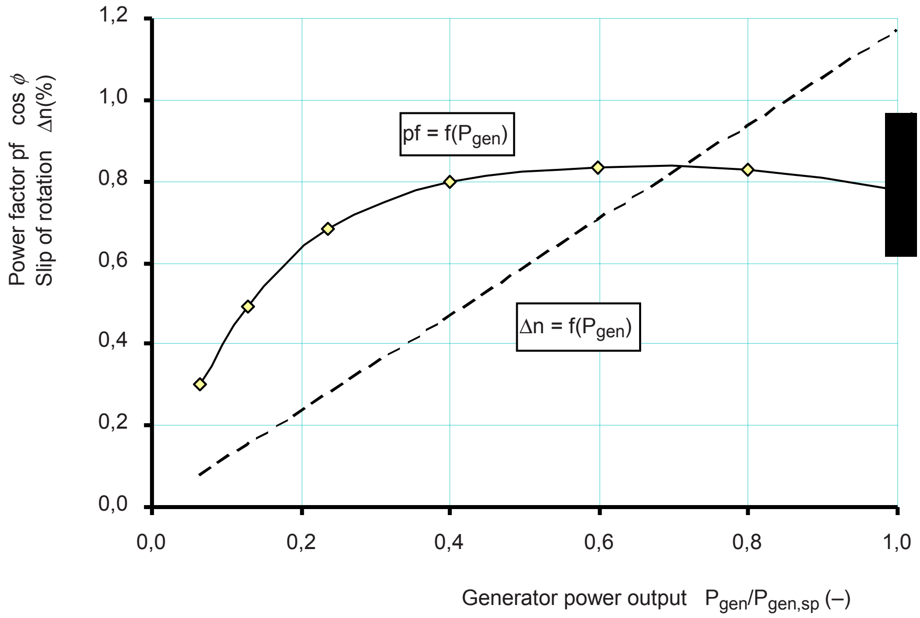


Figure D.2 – Asynchronous generator: typical power factor and slip factor

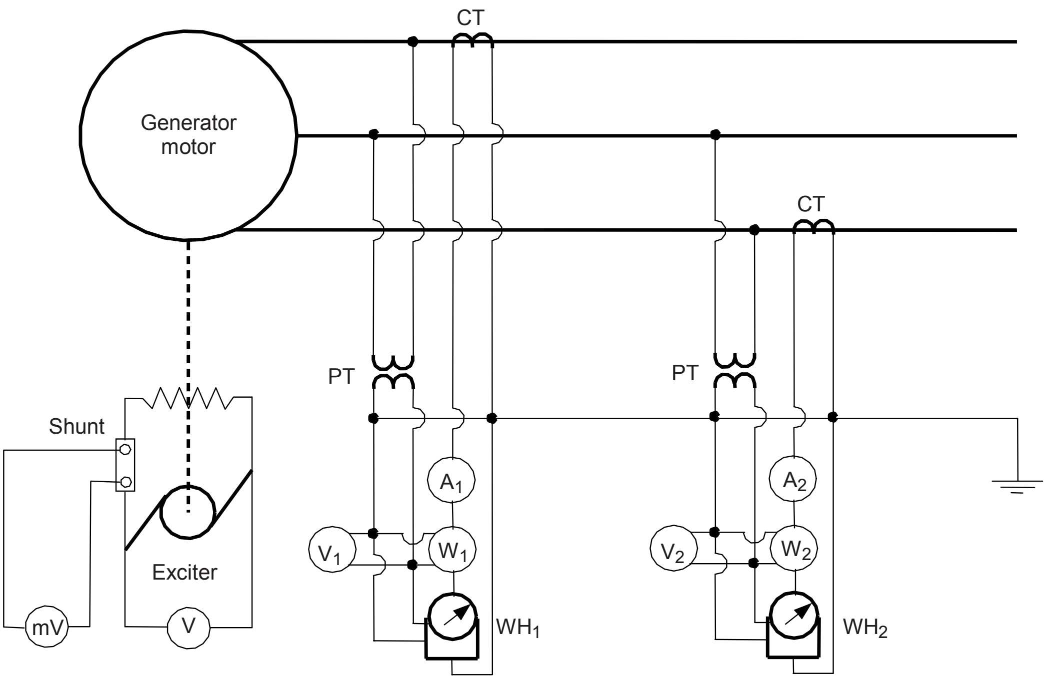


Figure D.3 – Power measurement using the two wattmeter method

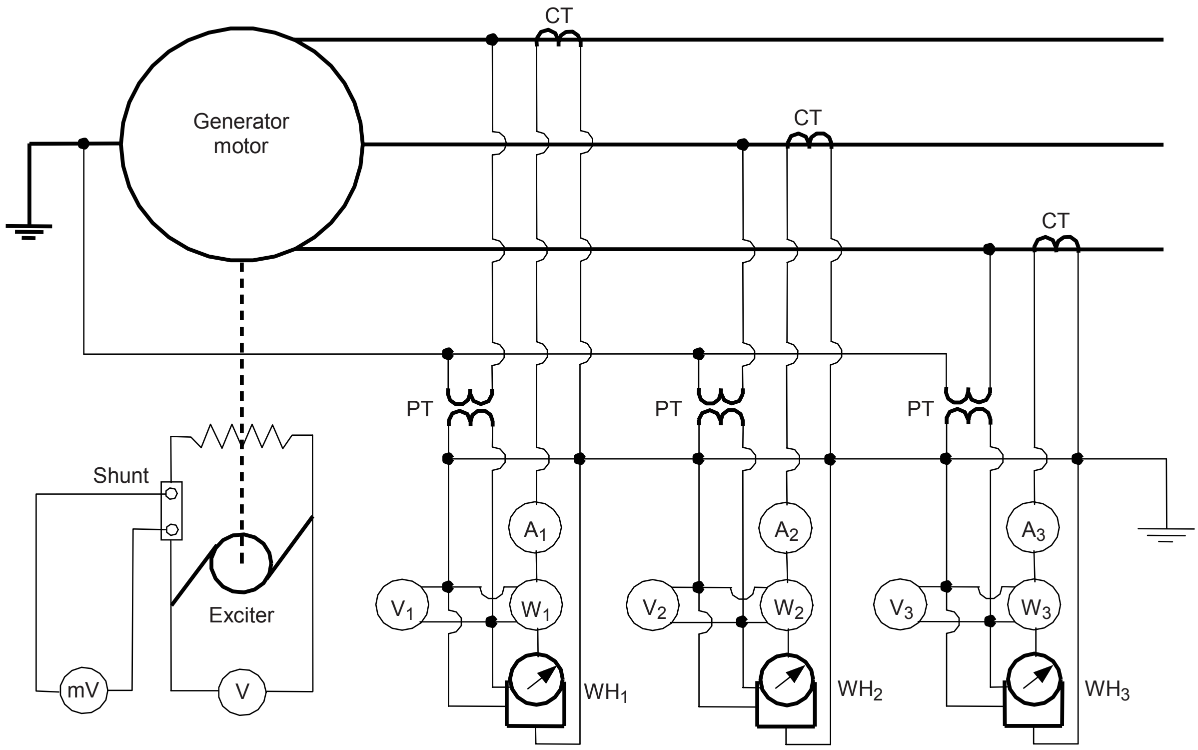


Figure D.4 – Power measurement using the three wattmeter method

Annex E
(normative)

Methods of discharge measurement

E.1 General

E.1.1 General conditions

Discharge measurement in a hydroelectric plant can in general only be carried out with the required accuracy if specific requirements of the measurement method are satisfied. It is therefore in the interest of the parties involved to select this method when the plant is being designed and to facilitate its implementation.

E.1.2 Selection of measurement method

Table E.1 shows usual requirements or limits for the various measurement methods. Deviations might influence the measurement accuracy.

Table E.1 – Selection of flow measurement method

Method	Water passage condition	Test preparation
Velocity area	Closed conduit $v > 0,4$ m/s current meter $v > 1$ m/s pitot tube $D > 1,4$ m and $D/d > 14$ straight pipe $L/D > 25$ Open conduit $v > 0,4$ m/s current meter only $H > 0,8$ m and $H/d > 8$ straight conduit $L > 3,5$ m	Rig for velocity meter
Pressure time	$\rho.Q \cdot \left(\int dL/A\right) > 50$ kPa/s Closed conduit between measuring sections $L/D > 10$ upstream $\Delta L \cdot v > 50$ m²/s $\Delta L > 10$ m	Pressure taps
Acoustic single path	$v > 1,5$ m/s, $D > 0,8$ m straight pipe: $L/D > 10$ upstream $L/D > 3$ downstream	Surface to mount transducer
Acoustic four paths		Transducer holes
Electromagnetic	straight pipe: $L/D > 10$ upstream	Flange connections
Volumetric gauge	No condition	Volumetric tank Deflector
Thermodynamic (indirect flow measurement)	Head > 100 m	Tap for probe Rig for temperature distribution

<table>
<tr><th>Method</th><th>Water passage condition</th><th>Test preparation</th></tr>
<tr><td colspan="3">A: penstock area d: propeller diameter D: penstock diameter
H: depth of open conduit L: length of water passage Q: discharge
v: average velocity ΔL: distance between measuring sections</td></tr>
<tr><td colspan="3">NOTE 1 The determination of efficiency using the thermodynamic method described in 7.4.2 makes it possible to calculate the discharge.

NOTE 2 Electro-magnetic flowmeters should be calibrated in the laboratory before mounting in the waterway.

NOTE 3 A simple single path ultrasonic method can be used, but see E.2.2</td></tr>
</table>

E.1.3 Flow stability

Discharge measurement is only valid if the flow is steady during each run. It may be considered steady if the variations in the generator power, net head and rotational speed of the unit are gradual. The discharge values shall be plotted on a graph as a function of time, to evaluate the nature and size of possible fluctuations.

E.1.4 Leakage, infiltrations and diversions

There shall be no leaks, infiltrations or diversions between the measurement section and the reference section closest to the measurement section. If this is unavoidable, the infiltration or leakage discharge shall be measured separately with appropriate accuracy.

If there is a free surface (a surge shaft, for example) between the measurement section and the reference section closest to the measurement section, the difference in discharge between the measurement section and the reference section due to the variation in the level of the surface shall be taken into account.

E.2 Absolute flow measurement methods

E.2.1 General

The various methods of absolute flow measurements are well described in IEC 60041 as well as ISO standards. Only two methods are described below, because these are particularly well suited for small hydro installations.

E.2.2 Acoustic method for small turbines

Simpler acoustic methods that can be used with small turbines are shown in Figure E.1. However, the single path arrangement shall not be used for class C acceptance tests. The use of simplified ultrasonic techniques for acceptance tests should be subject to mutual agreement between the parties.

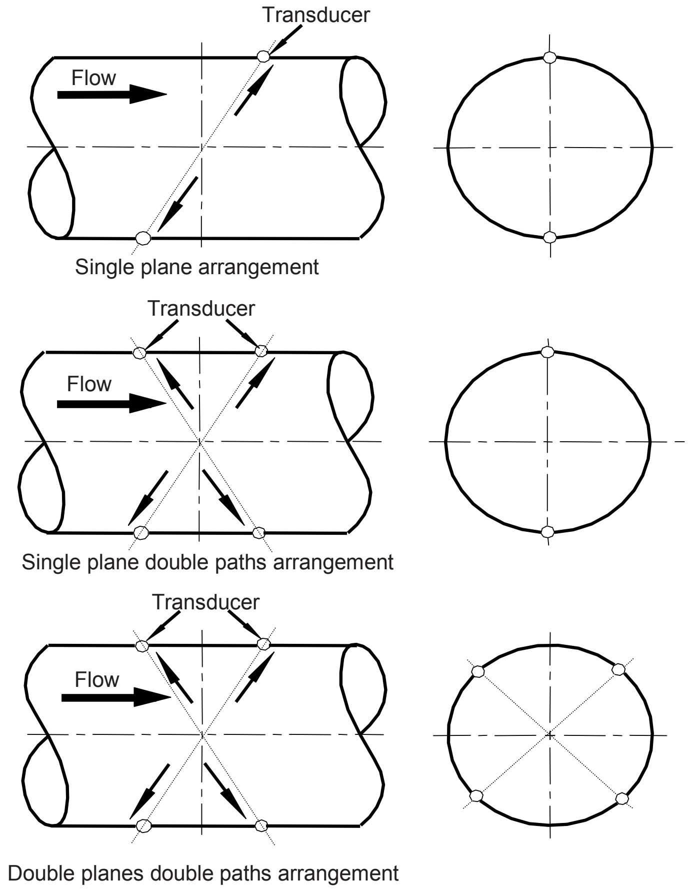


Figure E.1 – Typical arrangements of acoustic transducers

The accuracy of the simpler arrangements will be less than that for four path, two plane flowmeters, but the cost for instrumentation and installation is much less. Strap-on types can be used for class B tests, but the installation instructions shall be followed carefully. More accurate results are obtained using transducers mounted into the pipework.

It is preferable that the acoustic equipment is calibrated using one of the primary methods described in IEC 60193. It is generally desirable that the calibration conditions should reproduce the configuration of the circuit where the equipment shall be used. If it is installed permanently at a site, it shall be possible to verify the calibration periodically.

E.2.3 Pressure-time-method (Gibson method)

E.2.3.1 General

This is an economical way to indirectly measure discharge in situations where the water flows through a closed conduit. The general arrangement is shown in Figure E.2. Two sections are carefully chosen on the pipeline and fitted with pressure tappings. The pressure differential between the sections is measured while the guide vanes (or needle) are closed. The initial discharge can then be calculated from the resulting pressure time diagram, as shown in Figures E.3 to E.5. The conditions of validity can be evaluated before the test as shown below.

The turbine and penstock should be dewatered prior to testing, to flush and pressure test all the instrument pipework, to check that everything is working correctly and that there are no leaks. The geometrical dimensions of the penstock shall be measured. In addition to the requirements of Table E.1, the leakage through the closed turbine shall be less than 5 % of the rated discharge.

Downstream of an elbow or change in cross-section, the pressure at each tapping in a section should be compared during running using a separate pressure transducer. The pipeline can have a uniform or non-uniform cross-section. The method can be used on relatively short straight lengths of uniform pipeline because the systematic and random uncertainties are lower than for a non-uniform section. However, sometimes access to the sections can be difficult. Conversely, a non-uniform section requires a relatively long pipeline to obtain accurate results. The calculation of the penstock factor is also more difficult because of the combination of changes in section and bends in the pipeline.

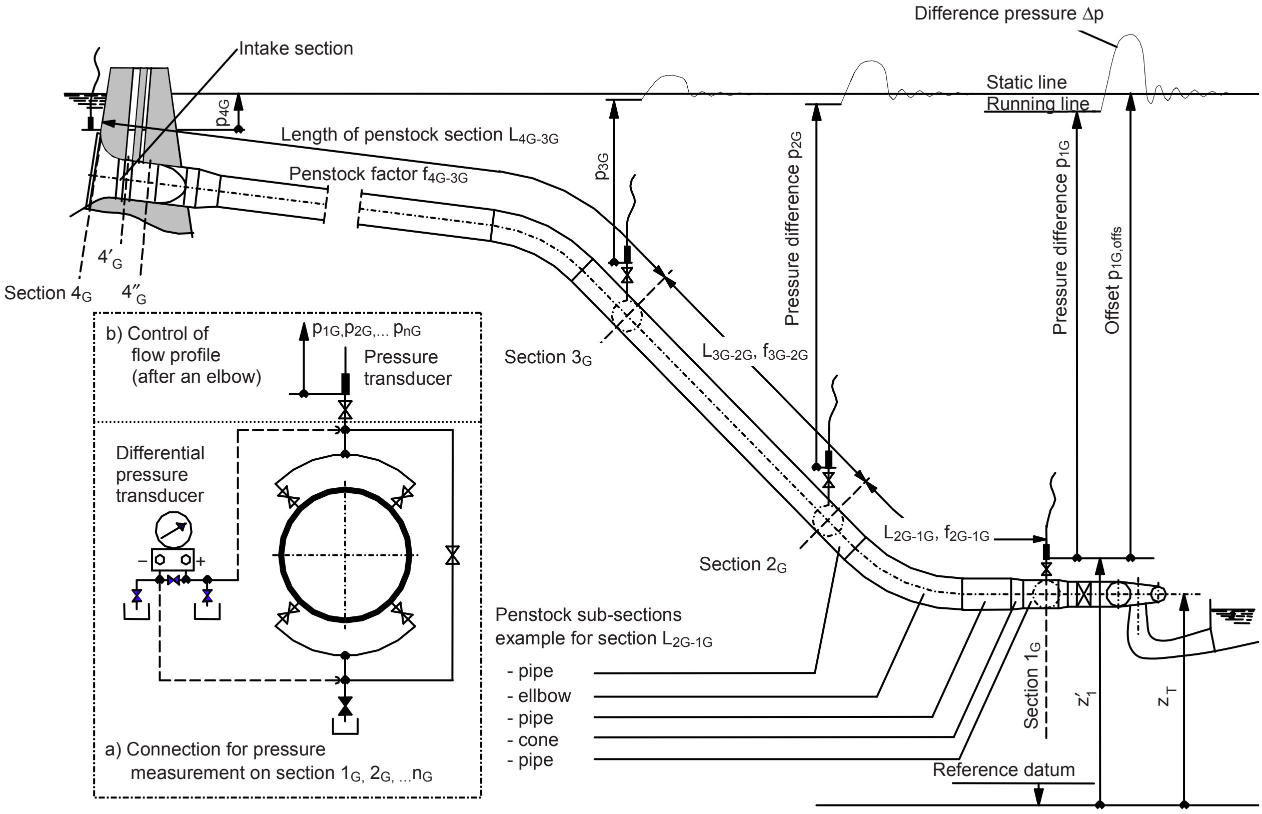


Figure E.2 – Arrangement for pressure time method

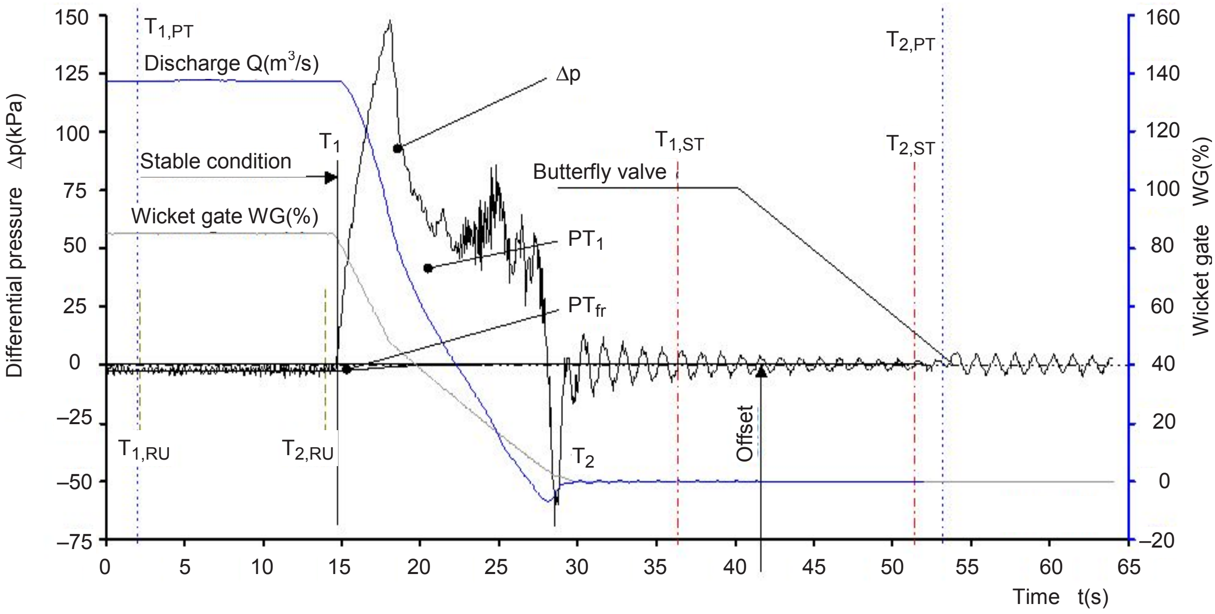


Figure E.3 – Example of pressure-time diagram for a uniform conduit

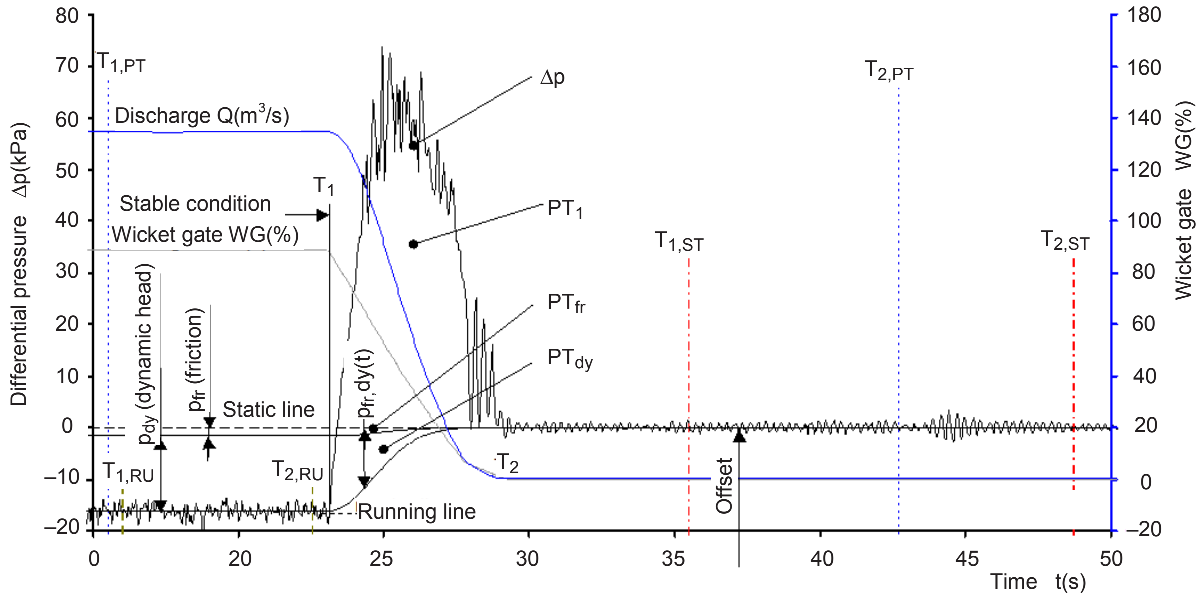


Figure E.4 – Example of pressure-time diagram for a non-uniform conduit

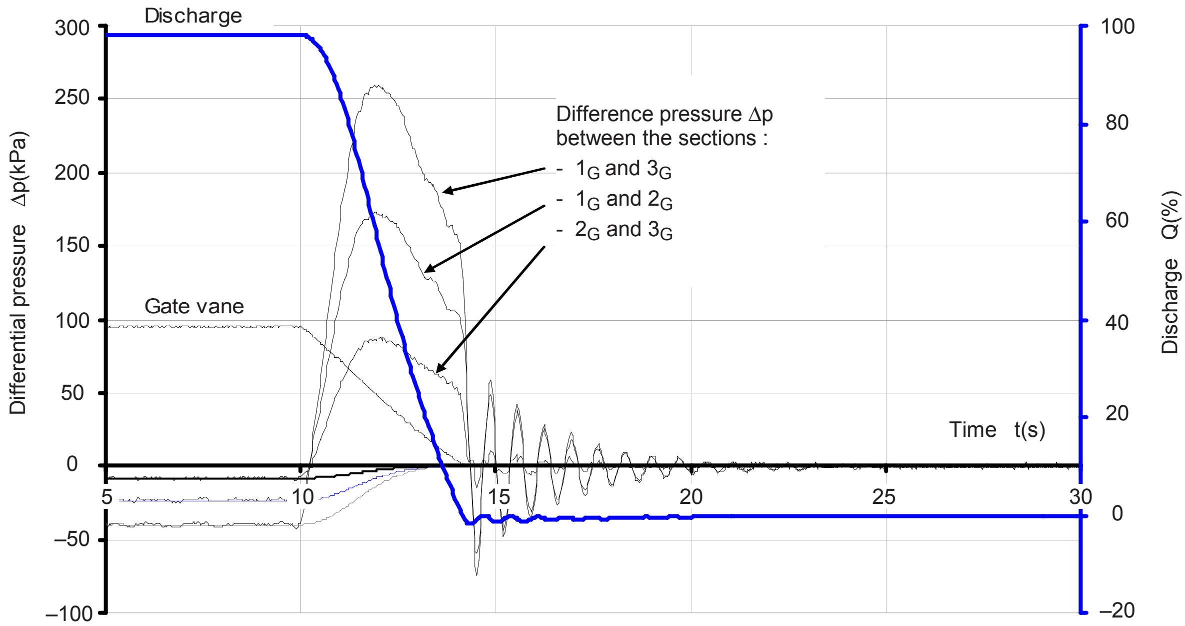


Figure E.5 – Example of pressure-time diagram for a combination of uniform and non-uniform conduits between several sections

E.2.3.2 Theoretical background

This method presented in about the year 1920 by Norman R. Gibson is based on the Bernoulli equation. Assuming frictionless and incompressible fluid we can write the following formulae for two sections in a conduit:

$$\frac{p_1}{\rho} + \frac{v_1^2}{2} = \frac{p_2}{\rho} + \frac{v_2^2}{2} + \int_1^2 \frac{\partial v}{\partial t} \times ds$$

For a uniform conduit this becomes $$\frac{p_2 - p_1}{\rho} = \frac{\Delta p}{\rho} = -\int_1^2 \frac{\partial v}{\partial t} \times ds = -L_{2G-1G} \times \frac{\partial v}{\partial t}$$

Integrating gives $$\int_{t=T1}^{T2} \left(\frac{\Delta p}{\rho}\right) dt = -L_{2G-1G} \times \int_{v=V1}^{V2} dv$$

or $$\int_{t=T1}^{T2} \left(\frac{\Delta p}{\rho}\right) dt = L_{2G-1G} \times (v_{T1} - v_{T2})$$

where

v_{T1}, v_{T2} are the velocities at any measuring section at time T_1 and T_2;

$L_{2G\text{-}1G}$ is the length between sections 1_G and 2_G.

The pressure difference between sections 1_G and 2_G is measured as function of the time. If it is assumed that the turbine is operating under stable conditions prior to closure of the gate, and the velocity of the water v_{T2} is zero after the gate is fully closed, then the initial discharge at time T_1 before closing is given by:

$$Q_{T1} = v_{T1} \times A = \frac{A}{L_{2G-1G} \times \rho} \times \int \Delta p \times dt \qquad (E.1)$$

In practise this theory needs some corrections.

There may be some leakage flow Q_{T2} passing through the closing device after time T_2. This shall be added to the evaluated flow Q_{T1}.

There should be a factor for friction head loss between the sections.

$$\frac{p_f}{\rho} = \zeta \times \frac{v(t)^2}{2} \qquad (E.2)$$

where

v(t) is the velocity at time t;

ζ is a loss coefficient.

Including these corrections into Equation (E.1) gives a flow as a function of pressure time for a uniform conduit:

$$Q_{T1} = \frac{\overline{A}}{L_{2G-1G} \times \rho} \times \int (\Delta p + p_f) \times dt + Q_{T2} \qquad (E.3)$$

where

$\overline{A}$ is the average of the measured area between section 1_G and 2_G.

The penstock factor $f_{2G\text{-}1G}$ is a geometrical relationship for the penstock, and can be calculated as follows for a uniform conduit:

$$f_{2G-1G} = \frac{L_{2G-1G}}{\overline{A}}$$

Inserting the penstock factor into the pressure time Equation (E.3) gives the following relationship for uniform conduits.

$$Q_{T1} = \frac{1}{f_{2G-1G} \times \rho} \times \int (\Delta p + p_f) \times dt + Q_{T2}$$

The integration shall be made from $T_{1,PT}$ to $T_{2,PT}$ to take into account the steady state condition before closing. The expression of the integrated pressure time diagram is:

$$PT = \int_{T_{1,PT}}^{T_{2,PT}} (\Delta p + p_f) dt$$

The flow rate shall be computed by: $Q = \frac{PT}{f_{2G-1G} \times \rho} + Q_{T2}$

For a non-uniform conduit we can use a similar expression for the penstock factor

$$f_{2G-1G} = \int \frac{dL}{A} \quad \text{or} \quad f_{2G-1G} = \sum \left(\frac{L_i}{A_i} \right)$$

where

A_i is the area of a sub-section, and

L_i is the length of the centreline of that sub-section.

An example calculation of the penstock factor for a non-uniform conduit is given in Table E.2.

For a non-uniform section the dynamic head difference between the sections shall be included in the term p_f, so that Equation (E.2) becomes

$$\frac{p_f}{\rho} = \zeta \times \frac{v(t)^2}{2} + \frac{v_2^2(t) - v_1^2(t)}{2}$$

$v_1(t)$, $v_2(t)$ are the velocities at sections 1_G and 2_G at time t, and are given by

$$v_1(t) = \frac{Q(t) + Q_{T2}}{A_{G1}}$$

$$v_2(t) = \frac{Q(t) + Q_{T2}}{A_{G2}}$$

E.2.3.3 Evaluation of leakage flow

Leakage discharge shall be measured if the closing device (guide vane or needle) does not seal tightly. This can be done as follows once the turbine gate is closed:

- by closing the intake gate, and measuring the head change versus time;
- by closing the turbine inlet valve and calculating the discharge by Gibson integration.

If the turbine needs to be kept running at synchronous speed after closure of the gate, an estimate of the leakage discharge can be evaluated from the model test results.

NOTE The guide vane leakage can also be estimated using the measured guide vane clearances to determine the total leakage area through the guide vanes. The leakage velocity is assumed to be Q_{T2} = 0,5 × area × √(2·g·H) where H is the head across the guide vanes.

E.2.3.4 Estimation of the systematic uncertainty

The systematic uncertainty of the measured discharge can be estimated using the list given below. If this is done before the test, all parties can either accept or reject the method. The position of the measuring sections will be determined during the process.

The following parameters are needed for this estimate:

- evaluation of the penstock factor (see Table E.2);
- calculation of the expected $PT = Q \times f_{2G-1G} \times \rho$;
- the friction loss and dynamic head between the measuring sections are taken from the penstock design calculation;
- for the first approximation the maximum pressure rise during the closing can be estimated as Δp_{max} = PT / t_{close} × 2,3.

a) Geometric dimensions

The geometry of the penstock can be taken from a certified drawing. The lengths are taken on the centreline, and the average diameter if the pipe section is not uniform. The estimated systematic uncertainty of L/A is the sum of the length between the measuring sections.

The recommended factors for different sub-sections are given below:

- intake bell-mouth $f_{L/A}$ = ±5 % to 20 %
- conduit rectangle to round (pipe) $f_{L/A}$ = ±1,0 %
- elbow $f_{L/A}$ = ±1,0 %
- cone $f_{L/A}$ = ±0,5 %
- straight pipe $f_{L/A}$ = ±0,3 %

The relative uncertainty for each subsection is given by the formula: $\Delta f_{penst} = \frac{\Delta L/A}{\sum (L/A)} f_{L/A}$

Table E.2 shows how the systematic uncertainty is calculated. f_{penst} = ±0,65 %

This evaluation can be made between all measuring sections.

b) Steady state condition L/A

- Static line (zero calibration)
- A zero calibration shall be made before and after the test series, by control of the offset. After every test run the offset shall be compared
- The systematic uncertainty of zero pressure f_{sta} = ±0,15 %
- Transient line expressed by pressure variation f_{run} = ±0,35 %

c) Transient condition (during closing)

- Changing of the flow profile
- Integration pressure–time diagram from $T_{1,PT}$ to $T_{2,PT}$
- Pressure noise, filtering, setting of integration boundaries f_{PT} = ±0,80 %

d) Dynamic head uncertainty

The ratio of dynamic head p_{dyn} to the pressure differential Δp_{max}. This is mainly caused by changes in the velocity profile during gate closure, and can have a large influence on the result.

Assume p_{dyn} is 20 % of Δp_{max} then f_{dyn} = 1,0 %

Δp_{max} = 72 kPa and p_{dyn}= 14 kPa f_{dyn}= ±0,97 %

e) Friction head uncertainty

The ratio of friction head p_{fr} to pressure differential Δp_{max}

Assume p_{dyn} is 20 % of Δp_{max} then f_{dyn} = 1,0 %

Δp_{max} = 72 kPa p_{dyn} = 4 kPa f_{fr} = ±0,28 %

f) Pressure transducers and data acquisition (resolution ≥16 bit)

Linearity, hysteresis, low thermal shift and dynamic behaviour f_{inst} = ±0,10 %

g) Leakage of the guide vane after closure f_{leak} = ±0,20 %

Expected uncertainty for the discharge measured by pressure time method

$$f_Q = \sqrt{0{,}65^2 + 0{,}15^2 + 0{,}35^2 + 0{,}8^2 + 0{,}97^2 + 0{,}28^2 + 0{,}1^2 + 0{,}2^2} \qquad = \pm 1{,}51\ \%$$

This procedure can be repeated with real data after the measurement.

Table E.2 – Evaluation of the penstock factor with estimation of the systematic uncertainty

Measuring section	Sub-section	ΔL	L_{pst}	A	Penstock factor ΔL/A	Penstock factor Σ L/A	Uncertainty absolute L/A	Uncertainty relative L/A
		m	m	m²	1/m	1/m	%	%
1_G		0,00	0,00			0,00		
	pipe	1,50	1,50	2,54	0,59	0,59	0,3	0,03
	cone	0,80	2,30	2,84	0,28	0,87	0,5	0,03
	pipe	3,19	5,49	3,14	1,01	1,88	0,3	0,06
	elbow	7,85	13,34	3,14	2,50	4,38	1,0	0,48
	pipe	2,55	15,89	3,14	0,81	5,20	0,3	0,05
2_G			**1_G to 2_G**	**f_{pst} =**		**5,195**	**$f_{f,pst}$ =**	**0,65**
	pipe	18,49	18,49	3,14	5,88	5,88	0,3	0,30
3_G			**1_G to 2_G**	**f_{pst} =**		**5,884**	**$f_{f,pst}$ =**	**0,30**
	pipe	4,14	4,14	3,14	1,32	1,32	0,3	0,01
	elbow	6,65	10,80	3,14	2,12	3,44	1,0	0,06
	pipe	90,00	100,80	3,14	28,65	32,08	0,3	0,26
	cone	1,40	102,20	4,03	0,35	32,43	0,5	0,01
	pipe	1,46	103,66	4,91	0,30	32,73	0,3	0,00
	pipe/ rectangle	1,75	105,41	4,91	0,36	33,09	2,0	0,02
	rectangle	2,10	107,51	6,25	0,34	33,42	1,0	0,01
	bell-mouth	1,70	109,21	8,04	0,21	33,63	20,0	0,13
4_G			**1_G to 2_G**	**f_{pst} =**		**33,633**	**$f_{f,pst}$ =**	**0,49**

E.2.3.5 Procedure for the measurement

The pressure transducer at measuring section 1_G shall be located upstream of the closing device. The elevation of the transducer shall be measured with respect to the turbine centre line.

NOTE The closing device is normally the guide vane or needle valve. The closing time should be temporarily increased, if possible, to reduce the pressure pulsation (water hammer).

Procedure after connecting the measuring equipment:

a) Set the rate of data recording to between 50 to 100 readings per second. This should result in 250 to 1 000 values measured during the closing time. The readings are started at least 20 s before shutdown and continue for about 20 s after the turbine gate is closed.

b) On each section, carefully flush each pipe connection separately to check the functionality and to bleed the pipeline of any air.

c) Check the closing position of the gate vane or servomotor when the turbine is stopped.

d) Take readings from all the pressure taps p_{1G}, p_{2G}, $p_{3G...}$ to make sure that there is no more pressure variation within the pipeline.

e) Based on p_{G1} for each measuring section the static line is to be fixed. A theoretical levelling point (offset) of each pressure tap $p_{1G,offset}$, $p_{2G,offset}$ ….. is made.

f) If the Gibson method is used for index calibration at least two discharge values are needed. Each discharge point shall be made with two or three shutdowns. Good results are expected with the turbine running at its optimum output, because the pressure pulsation is normally low at this condition. The calibration point for partial load shall avoid any vortex zones.

g) Open the turbine slowly and continuously up to the required load.

h) The governor should be set to the open limiter (not under load, or speed control).

i) Shut down the turbine after conditions have stabilised in the penstock.

j) Instead of making a load rejection, the turbine can remain connected to the grid and the control vanes closed at the normal rate. If this method is used, the reverse power relay will have to be temporarily disabled to allow the generator to run for a short time as a motor.

k) After the measurements a post calibration is to be made. See d).

E.2.3.6 Calculation of the discharge

The differential pressure measured by the transducers is recorded and processed in a computer. Programs of calculation by digital computer are available which determine the running line (dynamic and friction head), static line, and the integration of the pressure versus time diagram.

The results can be filtered and an average filter is very useful for reducing any noise or high frequencies. Low pass filters shall be applied with care, and are rarely used.

If measurements of different sections are made simultaneously, a crosscheck can be made by computing the results for various combinations, see Figure E.5.

Special programs are available for dealing with the end of integration. A detailed description of the method of computation, with the formulae used, shall be presented with the pressure time diagram. The report should also contain an evaluation of the penstock factor with a drawing of all sections and sub section between the measuring sections, see Table E.2.

E.3 Relative flow measurements

E.3.1 General

It is not always considered necessary to use absolute discharge measurement techniques during testing. Relative discharge measurement is sufficient for Class B tests, where index discharge is calculated from measurements of differential pressure or by using a secondary method of flow measurement.

E.3.2 Differential pressure method

The relative discharge through a conduit where there is a change of velocity can be calculated by measuring the differential pressure between two sections. The simplest case is using a convergent section of pipe such as may be found upstream of a turbine inlet valve, as shown in Figure E.6.

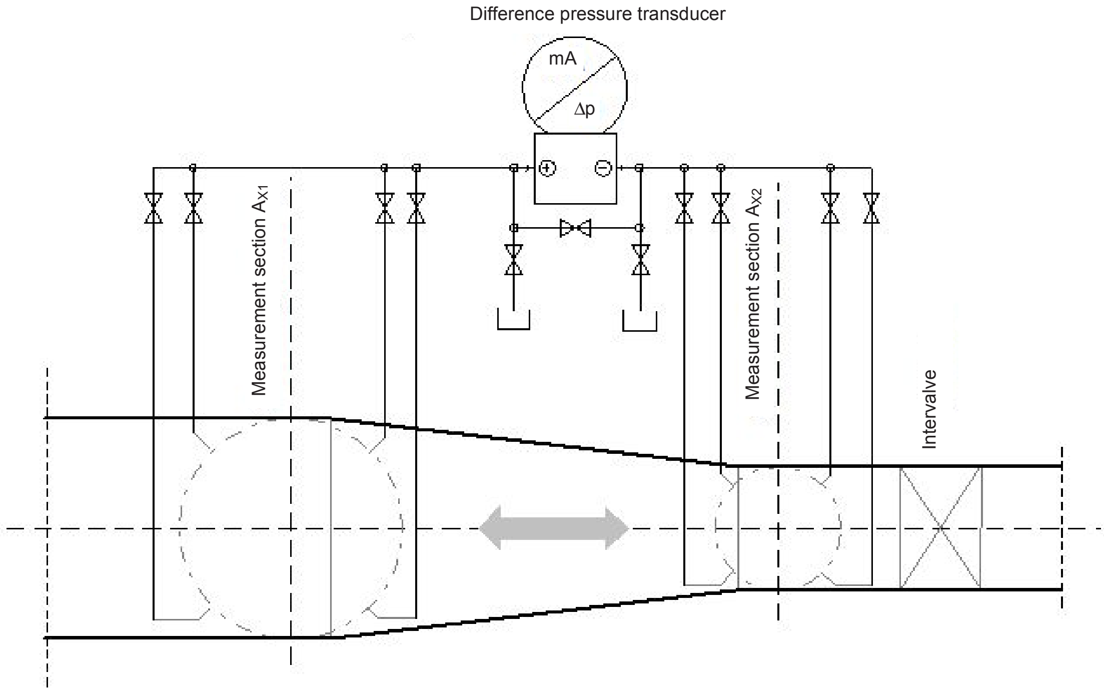


Figure E.6 – Location of taps for differential pressure method of discharge measurement

The index discharge through a bulb unit may be measured using the differential pressure method and the taps may be located as shown in Figure E.7.

- The high pressure tap may be arranged at the stagnation point of the bulb.
- The low pressure tap should be located on the wall directly upstream from the guide vanes with sufficient distance from their leading edge to give clearance at maximum guide opening.

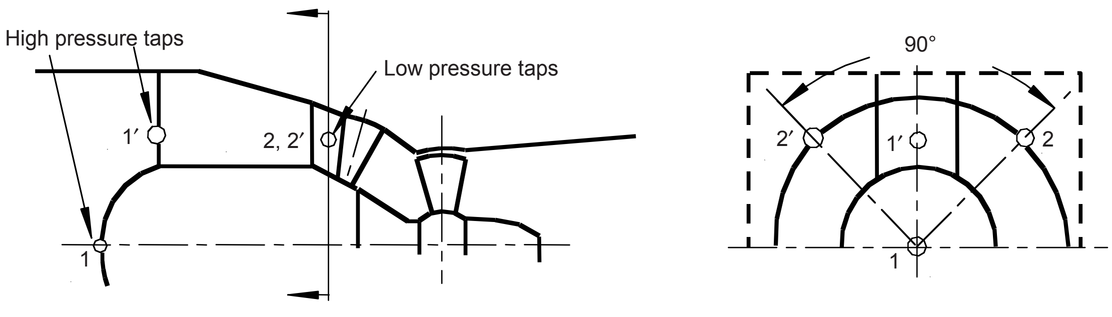


Figure E.7 – Location of taps for differential pressure measurement of discharge in a bulb turbine

The index discharge through a turbine with a spiral case may be measured using the Winter-Kennedy method and the taps may be located as shown in Figure E.8.

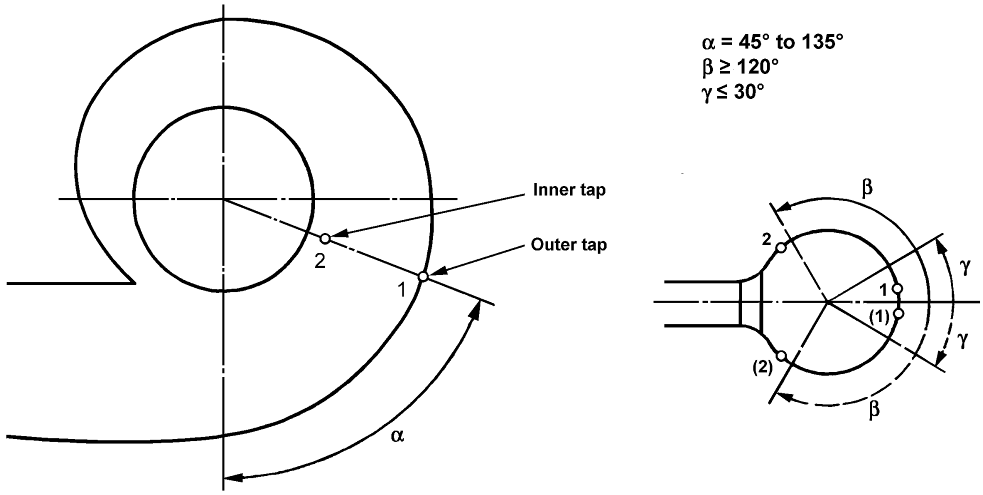


Figure E.8 – Location of taps for Winter-Kennedy method of discharge measurement through a turbine equipped with a steel spiral case

E.3.3 Secondary method of discharge measurement

The relationship between needle stroke and discharge may be used for a Pelton or a Turgo turbine. It may be used to give an index discharge provided that the discharge/stroke characteristics shape has been checked by tests on homologous model of the turbine. Great care shall be taken to ensure that, during the test, the needle, nozzle and support vanes are clean and in good order.

Annex F
(informative)

Plant condition

F.1 Plant condition list

F.1.1 General

For design of the plant, and for purposes of tendering, the purchaser shall supply the various values and parameters on which the guarantees are based. The upstream and downstream water passages are normally under the responsibility of the purchaser, but they shall be agreed upon with the turbine manufacturer. Below are lists that indicate which data should be included.

F.1.2 Purchaser supplied data

a) Upstream water level maximum / minimum / rated.
b) Downstream water level maximum / minimum / rated.
c) Available hydraulic energy either as:
   - rated head and discharge, or
   - head and discharge line (annual average flow duration curve).

F.1.3 Contractually agreed levels

a) Turbine elevation.
b) Minimum tailwater elevation to prevent cavitation.
c) Submergence at draft tube exit.
d) Minimum distances for free flow at draft tube exit.
e) Maximum free tailwater level for ventilation.

F.1.4 Quality of water

a) Volumetric percentage of sand/suspended particles for erosion.
b) Suspended particles such as grass, algae, industrial fibre content, etc.
c) Chemical influence.
d) Temperature range of the water.

F.1.5 Hydraulic losses and technical data for the whole water passage

a) Channel
b) Intake
c) Trash rack
d) Penstock
e) Inlet valve
f) Downstream water passage

F.1.6 Flow conditions

A disturbed velocity profile in the upstream and downstream water passage has a significant influence on the turbine efficiency and hence the plant performance. Therefore, especially for low head turbines, the design of water passages shall be made in accordance with the requirements of the turbine manufacturer for an acceptable velocity profile in sections 1 and 2 of the turbine.

F.2 Setting of geodetic benchmarks

The purchaser is normally responsible for setting of benchmarks. The following benchmarks are to be provided:

a) Turbine setting level z_T
b) Reference level at penstock intake z_0'
c) Reference level measuring high pressure at turbine intake z_1'
d) Reference level measuring low pressure at turbine outlet z_2'
e) Control of minimum TWL to prevent cavitation $z_{2.1}'$
f) Control of maximum TWL to allow aeration (Pelton, Turgo) $z_{2.2}'$

F.3 Specification of test equipment

The requirements of the equipment shall be selected correctly. The instrumentation shall be subjected to appropriate testing.

a) Commissioning: panel instrumentation and / or external commercial instrumentation for pressure, temperature, and speed with an accuracy of < ±1 % can be used.
b) Acceptance tests: in the case of penalties, the maximum permissible measurement uncertainty shall be agreed between the participants. The systematic uncertainties of the measurement are to be determined by means of the uncertainty analysis, see 9.2.

Annex G
(informative)

Commissioning

G.1 Check list

The following list enumerates items that should be included for commissioning.

NOTE The check list given below is not an exhaustive list and there may be additional inspection or verification required.

a) Inspection of all the hydraulic conduits and removal of any foreign bodies, verification of the appropriate operation of all measuring sections and all pressure taps to be used during the future turbine tests.

b) Verification of the electrical power supply (AC and DC) backup and batteries intervention.

c) Execution of pressure tests on all lubricating circuits, check of oil and grease levels and of the conditions of all oil filters and filtering systems, check of correct operation of all grease and oil circuits.

d) Verification of the correct operation of pressure oil units, hydraulic shut-off valves, pressure relief valves and discharge control component.

e) Execution of pressure tests in the governing system, check of oil levels and of the conditions of all oil filters and filtering systems.

f) Verification of all protective devices such as oil level and temperature alarms and relays with adjustment if needed.

g) Measurement of bearing and seal clearances for several shaft positions, check of the oil injection system if any; calibration of opening scales for gate (and/or needles, runner blades, deflectors) including their cam relationship; verification of relevant clearances.

h) Adjustment of dry opening and closing times of governing elements (i.e. guide vanes, runner blades, or needles and deflectors, pressure relief valves) and possibly command signal dead band if water is not needed for their operation.

i) Adjustment of dry opening and closing times of main unit valve or gate, if water is not needed for their operation.

j) Verification of cooling, drainage and pumping water circuits. The main powerhouse draining system shall be checked.

k) Verification of correct locking of all manholes.

l) Verification of start-up and shut down sequences, manual and automatic.

m) Testing of electrical controls and protection circuits.

n) Verification of the proper operation of the braking system of the unit.

G.2 Commissioning report

After the end of the commissioning (see Clauses 5 and 6), the commissioning engineer should prepare a report that includes the following points:

a) All the geometric measurements made.

b) All the values set for alarm tripping, and latching times of the unit.

c) All the values set of orifices for closing (cooling) devices.

d) All the results of measurements made, including

- transient pressure variation,
- overload,

- bearing temperatures,
- closing time of cut off-devices.

e) All figures, diagrams necessary for a further correct operating of the unit(s).

Annex H
(informative)

Performance test efficiency calculation

H.1 General test conditions

The following example calculations demonstrate typical procedures for class A and B tests for a horizontal Francis machine with synchronous generator.

- Class A Maximum power output test
- Class B Index test using Winter-Kennedy taps

H.2 Guarantees to be met

H.2.1 Class A

The maximum plant output at a power factor (cos ϕ) of 1,0 and 100 % guide vane opening under the rated net head of 115,0 m shall be not lower than 2 870 kW.

H.2.2 Class B

The index test shall demonstrate that the shape of the measured plant performance characteristics follows the guaranteed shape under the rated net head of 115,0 m. Allowable deviations to the guaranteed shape tabulated in Table H.1 include systematic and random uncertainties.

Table H.1 – Plant index efficiency guarantee

Power	Plant performance at rated net head		Allowable deviation
%	P_{out} kW	$\eta_{plant.g}$ %	Δ_{η} %
25	718	64,7	−4,0
50	1 435	77,7	−1,5
75	2 153	85,9	−1,0
87,5	2 511	87,5	−0,8
95	2 727	86,0	−1,5
100	2 870	81,3	−2,0

H.2.3 Transformer efficiency

The advised transformer efficiency is tabulated in Table H.2. The overall uncertainty associated with the transformer losses is 10 %.

Table H.2 – Transformer data

Power %	P_{out} kW	η_{tf} %
25	775	97,7
50	1 550	98,6
75	2 325	98,9
87,5	2 713	98,95
95	2 945	99,0
100	3 100	99,0

H.3 Physical constants

Typical physical constants are given in Table 5.

H.4 Measuring conditions

The following measuring conditions apply.

a) The type of turbine and setting of instrumentation is similar to Figure B.8.

b) The mechanical scale of the guide vane opening was calibrated before the test, both when closing and when opening, using the electrical control signal.

c) A zero calibration was made with both units stopped.

d) Test took place on unit 1 with unit 2 isolated.

e) Three measurements were taken at each of eight different guide vane openings.

f) The power output was measured at the generator terminals using a 3-wattmeter method, see Figure D.4.

g) The power factor cos ϕ was set to automatic 1,0.

h) There were no auxiliary losses, $P_{L,ax}$ = 0 kW.

i) Using the calibration sheet of the stagnation probe, the variation of exponent ix in the formula $Q_{ix} = k \times \Delta p^{ix}$ can be between $0{,}49 < \times < 0{,}51$. The exponent was set to 0,51 and the proportional factor k was preliminarily set to 0,13.

H.5 Data measurements and calculations

H.5.1 Data measurements

The following data measurements are necessary. Table H.3 gives an example of data measurements.

NOTE The numbers, refer to the columns in Table H.3.

1 GV guide vane opening electrical signal

2 P_{gen} power output measured at the generator terminals

3 Δp differential pressure taken from the stagnation probe (see Figure B.9)

4 $p'_{1,tot}$ taken from the stagnation probe directly as total pressure

5 h'_2 measured by tailrace gauge board

Table H.3 – Data measurements (not all tests included)

		1	2	3	4	5
Test	**Time**	**GV** %	P_{gen} MW	Δp mbar	$p'_{1,tot}$ kPa	h'_2 m
zero	10:17	0,0	0,000	0,0	1 134,4	3,30
1a	10:44	22,3	0,428	51,0	1 132,4	3,24
1b	10:47	22,3	0,428	54,2	1 132,4	3,23
1c	10:49	22,3	0,427	54,2	1 132,3	3,24
2a	10:53	31,0	0,840	93,5	1 130,7	3,24
		(tests 2b to 7c are not shown)				
8a	11:54	100,0	2,966	615,1	1 112,9	3,06
8b	**11:58**	**100,0**	**2,988**	**616,8**	**1 112,2**	**3,07**
8c	11:59	100,0	2,990	612,3	1 112,6	3,09

H.5.2 Data calculations

Table H.4 gives an example of data calculations based on values from Table H.3.

NOTE The numbers refer to the columns in Table H.4.

The calculated measured discharge shall be calibrated against the discharge from the guarantees so that the index test curve aligns with the guaranteed efficiency curve at the point of optimum efficiency. Therefore the proportional factor is adjusted to k = 0,121 6.

Using test 8b as an example:

6 Q_{ix} $= 0{,}121\,6 \times 616{,}8^{0{,}51}$ $= 3{,}220\ \text{m}^3/\text{s}$

7 $v_1 = Q_{ix} / A_1$ $= 3{,}220 / 0{,}503$ $= 6{,}40\ \text{m/s}$

8 $v_2 = Q_{ix} / A_2$ $= 3{,}220 / 1{,}431$ $= 2{,}25\ \text{m/s}$

9 $h_{1,tot} = z'_1 + p'_{1,tot}/g$ $= 44{,}37 + 1\,112{,}2 / 9{,}808\,6$ $= 157{,}76\ \text{m}$

10 $h_{2,tot} = z'_2 - H'_2 + v_2^2/2g$ $= 46{,}02 - 3{,}07 + 2{,}25^2/(2 \times 9{,}808\,6)$ $= 43{,}21\ \text{m}$

11 $H = h_{1,tot} - h_{2,tot}$ $= 157{,}76 - 43{,}21$ $= 114{,}55\ \text{m}$

From Table H.2 transformer efficiency at test output is 99,0 %.

12 $P_{L,tf} = 2{,}988 \times 0{,}01$ $= 0{,}030\ \text{MW}$

13 $P_{out} = P_{gen} - P_{L,tf} - P_{L,ax} = 2{,}988 - 0{,}030 - 0$ $= 2{,}958\ \text{MW}$

14 $\eta_{plant} = P_{out} \times 10^8 / (H \times g \times \rho \times Q_{ix})$

$= 2{,}958 \times 10^8 / (114{,}55 \times 9{,}808\,6 \times 1\,000{,}4 \times 3{,}220)$ $= 81{,}72\%$

Table H.4 – Calculation of results

		6	7	8	9	10	11	12	13	14
Test	**Time**	Q_{ix} m³/s	v_1 m/s	v_2 m/s	$H_{1,tot}$ m	$H_{2,tot}$ m	H m	$P_{L,tf}$ MW	P_{out} MW	η_{plant} %
zero	10:17	0,000	0,00	0,00	160,02	42,72	117,30	0,000	0,000	
1a	10:44	0,903	1,80	0,63	159,82	42,80	117,02	0,013	0,415	40,03
1b	10:47	0,932	1,85	0,65	159,82	42,81	117,01	0,013	0,415	38,81
1c	10:49	0,932	1,85	0,65	159,81	42,80	117,01	0,013	0,414	38,72
2a	10:53	1,230	2,45	0,86	159,65	42,82	116,83	0,019	0,821	58,21
8a	11:54	3,216	6,39	2,25	157,83	43,22	114,61	0,030	2,936	81,19
8b	**11:58**	**3,220**	**6,40**	**2,25**	**157,76**	**43,21**	**114,55**	**0,030**	**2,958**	**81,72**
8c	11:59	3,208	6,38	2,24	157,80	43,19	114,61	0,030	2,960	82,04

H.6 Uncertainty

H.6.1 Combination of uncertainties

The following rules are used to combine uncertainties:

$$\eta = \frac{P}{\rho g H Q} \quad \text{gives} \quad f_\eta = \sqrt{f_P^{\,2} + f_H^{\,2} + f_Q^{\,2}}$$

$$H = \frac{P}{\rho} - z + \frac{v^2}{2g} \quad \text{gives} \quad f_H = \frac{e_H}{H} = \frac{\sqrt{e_{P/\rho}^{\,2} + e_z^{\,2} + e_{v^2/2g}^{\,2}}}{H} \quad \text{where} \quad e_{v^2/2g} = \frac{v^2}{g} f_v$$

$$P_R = P_t \left(\frac{H_R}{H}\right)^{1,5} \quad \text{gives} \quad f_{P,R} = \sqrt{f_{P,t}^{\,2} + (1{,}5 f_H)^2}$$

H.6.2 Random uncertainty

The data acquired during each test run is used to calculate random uncertainties and plot the trend (see 9.3.1). The test run is repeated if the observed value of random uncertainty was greater than 0,10 %. Hence, for head and power, the random uncertainty was assumed to be 0,10 %.

H.6.3 Systematic and overall uncertainty

H.6.3.1 Head

The overall uncertainty for the calculation of upstream pressure using a transducer is taken from Figure 27 (this includes uncertainty of the velocity component).

Upstream pressure reading $H'_{1,tot} = 1\,112{,}2 / 9{,}808\,6 = 113{,}4 \text{ m}$

For v = 6,40 m/s and H = 113,4 m $f_{H'_{1,tot}} = \pm 0{,}22 \text{ \%}$

Error in upstream pressure reading $e_{H'_{1,tot}} = 113{,}4 \times 0{,}002\,2 = 0{,}249 \text{ m}$

The overall uncertainty for the calculation of downstream pressure using a gauge board is similar to the uncertainties in 9.4.2.1.

Error associated with setting of geodetic datum $e_{z'_2} = \pm 0{,}010$ m

Error associated with measuring gauge board $e_{H'_2} = \pm 0{,}012$ m

The uncertainty related to the downstream velocity head has also to be added.

NOTE The upstream velocity head does not have to be taken into account in this particular case because the pressure was measured using the stagnation probe i.e. the velocity is zero at the pressure tapping.

Overall uncertainty on index flow (see Figure 28) $f_{Q,ix} = \pm 0{,}32$ %

Error associated with velocity head component $e_{v^2/2g} = \frac{v^2}{g} f_Q$

Error associated with downstream velocity head $e_{v_1^2/2g} = \frac{2{,}25^2}{9{,}808\ 6} \times 0{,}003\ 2 = 0{,}001\ 6$ m

Overall uncertainty in head measurement

$$f_H = \pm \frac{\sqrt{0{,}249^2 + 0{,}010^2 + 0{,}020^2 + 0{,}001\ 6^2}}{157{,}76 - 43{,}21} \times 100 \qquad = \pm 0{,}22\ \%$$

H.6.3.2 Power output

The plant power output is calculated indirectly from measuring the power output at the generator terminals. The transformer losses have therefore to be subtracted from the generator output power to calculate the plant power output. There are no auxiliary power losses.

Systematic uncertainties associated with measurement of generator power output:

- Digital power meter (power analyser) $f_{PM} = \pm 0{,}20$ %
- Potential transformer $f_{PT} = \pm 0{,}30$ %
- Current transformer $f_{CT} = \pm 0{,}30$ %

Systematic uncertainty of generator power output $f_{P,gen,sys} = \pm\sqrt{0{,}20^2 + 0{,}30^2 + 0{,}30^2} = 0{,}47$ %

Random uncertainty of generator power output $f_{P,ra} = \pm 0{,}10$ %

Overall uncertainty of generator power output $f_{P,gen} = \pm\sqrt{0{,}47^2 + 0{,}10^2} = 0{,}48$ %

Measured generator power output $P_{gen} = 2\ 988$ kW

Error in generator power output measurement $e_{P,gen} = 2\ 988 \times 0{,}0048 = 14{,}3$ kW

Transformer power loss $P_{L,tf} = 30$ kW

Overall uncertainty in transformer loss calculation $f_{L,tf} = \pm 10\%$

Error in transformer loss calculation $e_{L,tf} = 30 \times 0{,}1 = 3{,}0$ kW

Overall uncertainty in plant power output $$f_{(P)} = \frac{\sqrt{e_{P,gen}^2 + e_{L,tf}^2 + e_{L,ax}^2}}{P_{gen} - P_{L,tf} - P_{L,ax}}$$

$$f_{(P)} = \pm \frac{\sqrt{14{,}3^2 + 3{,}0^2}}{2\,988 - 30} \times 100 = \pm 0{,}49\ \%$$

For guarantee purposes the power output has to be transposed to the rated head, refer to 8.2.3, and therefore the uncertainty in head measurement has to be included as follows:

Overall uncertainty for plant power output $$f_{P,out,R} = \sqrt{f_{(P)} + (1{,}5 \times f_H)^2}$$

$$\sqrt{0{,}49^2 + (1{,}5 \times 0{,}22)^2} = \pm 0{,}59\ \%$$

H.7 Comparison with specified guarantee to result

H.7.1 Class A: maximum generator power output

The mean plant output and mean net head for tests 8a to 8c are as follows:

	H = 114,59 m	$P_{out,M}$	=	2,952 MW
Measured test transposed to rated head (8.2.3)	H = 115,00 m	$P_{out,R}$	=	2,967 MW
Guaranteed plant output at rated head	H = 115,00 m	$P_{out,sp}$	=	2,870 MW

Conclusions

- The measured power output is +3,4 % greater than the specified guarantee.
- The uncertainty in the power output value is ±0,59 %.
- The guarantee of maximum generator power output is met.

H.7.2 Class B: shape control of the turbine-generator characteristic

The results of measurement tests 1a to 8c are plotted against the guaranteed data, (see Figure H.1). The guaranteed data are taken from the hill curve (see Figure 19) with one turbine running at the actual measured head.

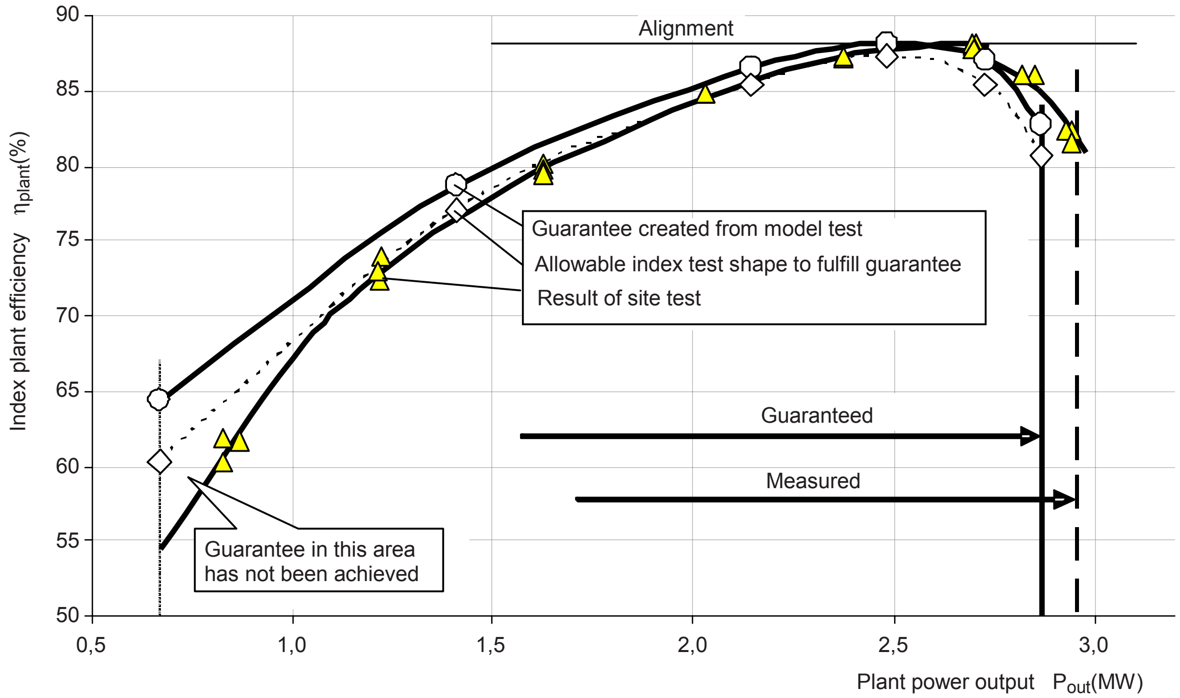


Figure H.1 – Comparison of measured index efficiency with the guaranteed values

The shape at full load shows that the turbine performance is better than expected. However, at partial load, the measured line is less than the guarantee.

By shifting the guarantee points +3 % (see 8.1.4 and Figure 20), most of the line hits the guarantee. The guarantee will be fulfilled if the gain at full load outweighs the loss at partial load, but this shall be mutually agreed by all parties.

Annex I
(informative)

Cam correlation test

I.1 General

A procedure, similar to the one used for index tests, should be applied to verify the proper cam correlation of a double-regulated unit (Kaplan or bulb turbine). This test has the aim to correlate the openings of both the guide vanes and runner blades in order to obtain the best performance from the unit.

Generally, the best correlation changes with the head. If the plant is designed to operate over a wide range of head, a 3-dimensional cam (runner blade, guide vane and head) is required.

The cam is based on homologous model tests and is verified by site measurements, as model tests generally do not reproduce the exact intake configuration.

I.2 Test procedures

The test procedure should be implemented as follows.

a) The unit shall be started and operated until all temperatures indicated on the unit's temperature recorder have stabilized before starting the measurements.
b) The main procedure is to set the runner blade opening and to vary the guide vane opening in steady steps. Single blade relative efficiency curves (propeller curves) can be obtained as shown in Figure I.1.
c) Before starting the test, the differential pressure for determination the index-discharge, has to be adjusted in the following way:
   - set the turbine to 75 % P_{gen} and start a measurement for P_{gen} and H as absolute values;
   - determine the discharge Q_{ix} according to the hill chart for the measured power output and head and define the coefficient and exponent for the Index discharge.
d) The test runs should be made at constant time intervals, as follows:
   - set the runner blade to the first opening, e.g. 20 % and GV = 37 % ,“on-cam”;
   - change the governor to auxiliary control for manual adjustment of guide vane and blade angle positions separately;
   - reduce the guide vane opening by about –6 % to GV = 31 %, “off-cam”;
   - repeat the following procedure 5 to 7 times until the propeller curve has exceeded the optimum;
   - allow the hydraulics to stabilize;
   - take the required measurements and record all necessary signals;
   - increase the guide vane to the next position, say +2 % to GV = 33 %.
g) Repeat the procedure given in d) for about 6 to 8 different runner blade openings as follows:
   - change governor to automatic control “on-cam”;
   - set the runner blade to the next position, e.g. 30 %.

The governor should be returned to automatic control again once the test is complete.

The best correlation between runner blade and guide vane opening is the one that corresponds to the enveloping curve of the peak efficiencies, see Figure. I.1.

For RB = 55 % → GV_{opt} = 62 %.

Using the site test results to adjust the model predictions for other operating heads, a new 3-dimensional cam correlation GV = f(RB,H) can be derived and can be replicated in the governor. See Figure I.2.

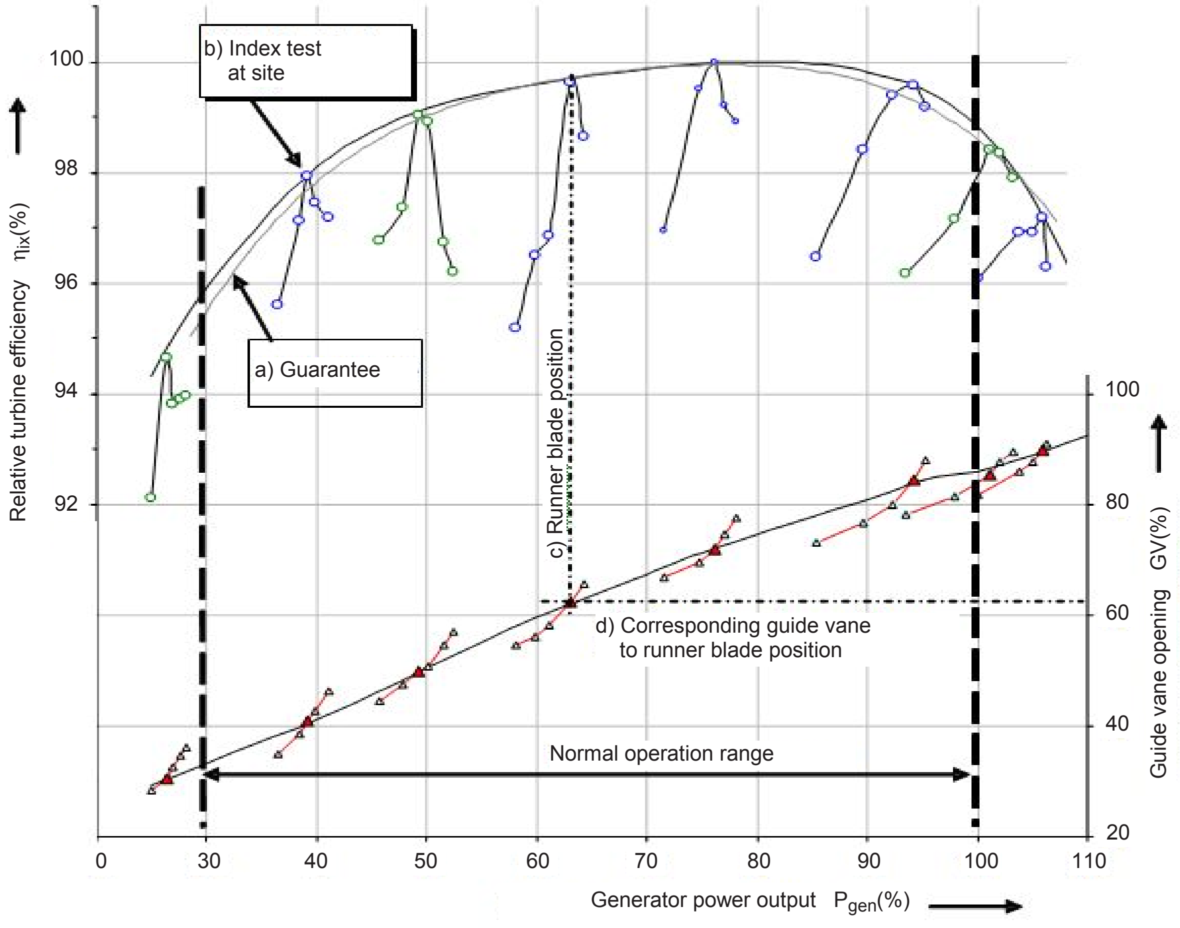


Figure I.1 – Index measurement to optimize the efficiency

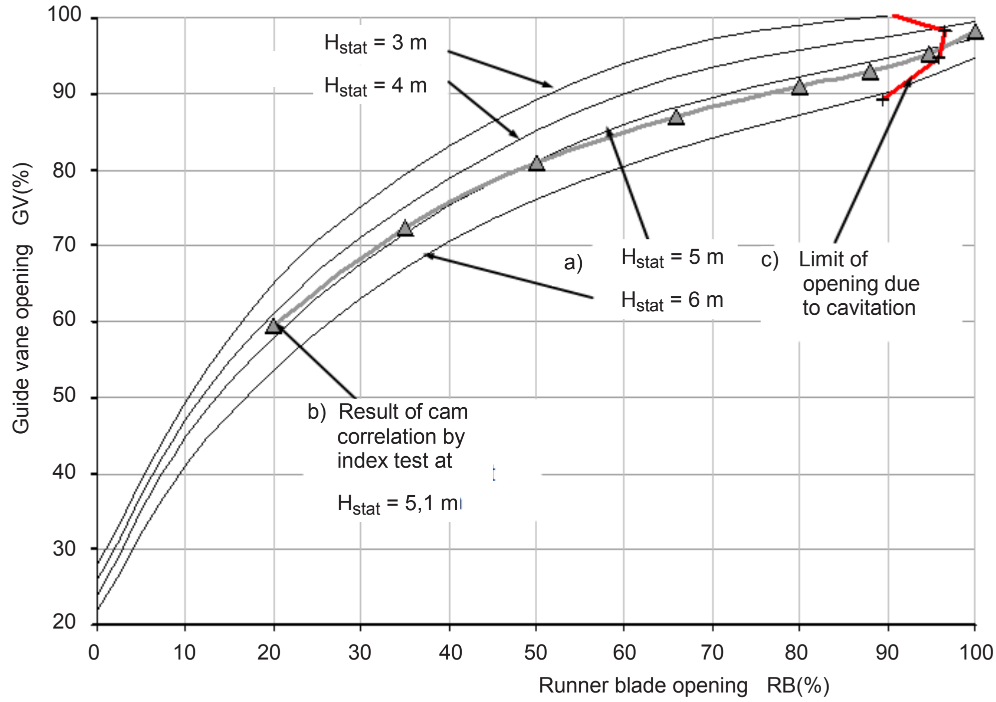


Figure I.2 – Three dimensional cam correlation

Bibliography

The following standards are not referenced in this standard, but are suggested for general guidance on the subjects contained in this standard:

IEC 60545, *Guide for commissioning, operation and maintenance of hydraulic turbines*

IEC 60994, *Guide for field measurements of vibrations and pulsations in hydraulic machines (turbines, storage pumps and pump-turbines)*

IEC 61116, *Electromechanical equipment guide for small hydroelectric installations*

IEC 61260, *Electroacoustics – Octave-band and fractional-octave-band filters*

IEC/TR 61364, *Nomenclature for hydroelectric powerplant machinery*

ISO 555 (all parts), *Liquid flow measurement in open channels – Dilution methods for measurement of steady flow*

ISO 2186, *Fluid flow in closed conduits – Connections for pressure signal transmissions between primary and secondary elements*

ISO 2954, *Mechanical vibration of rotating and reciprocating machinery – Requirements for instruments for measuring vibration severity*

ISO 2975 (all parts), *Measurement of water flow in closed conduits – Tracer methods*

ISO 3354, *Measurement of clean water flow in closed conduits – Velocity-area method using current-meters in full conduits and under regular flow conditions*

ISO 3455, *Hydrometry – Calibration of current-meters in straight open tanks*

ISO 3966, *Measurement of fluid flow in closed conduits – Velocity area method using Pitot static tubes*

ISO 4373, *Hydrometry – Water-level measuring devices*

ISO 5167 (all parts), *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full*

ISO 7919 (all parts), *Mechanical vibration of non-reciprocating machines – Measurements on rotating shafts and evaluation criteria*

ISO 10816 (all parts), *Mechanical vibration – Evaluation of machine vibration by measurements on non-rotating parts*

ASME PTC 18, *Hydraulic Turbine and Pump-Turbines performance test codes*, ASME International, published 2002-01.

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