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TITLE:

Hydraulic turbines - Testing of governing systems

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CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

HYDRAULIC TURBINES – TESTING OF GOVERNING SYSTEMS

FOREWORD

IEC 60308 has been prepared by IEC technical committee 4: Hydraulic turbines. It is an International Standard.

This third edition cancels and replaces the second edition published in 2005. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) adoption of parts of IEC 61362:2024 which deal with test matters;

b) introduction of new technical aspects;

The text of this document is based on the following documents:

Draft	Report on voting
4/XX/FDIS	4/XX/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn, or
- revised.

IMPORTANT – The "colour inside" logo on the cover page of this document indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

The first and second editions of this document were developed to have a comprehensive description for the test of hydraulic turbine governing systems according to the corresponding state of the art. They were published independently of the guide to specification of hydraulic turbine governing systems (IEC 61362). This third edition was developed together with IEC 61362 in order to harmonize their contents and their publishing dates. Furthermore, the standards are kept open for state of the art by introducing new topics and harmonizing the structure as well as the terms and definitions for both standards.

HYDRAULIC TURBINES –
TESTING OF GOVERNING SYSTEMS

1 Scope

This document covers acceptance tests and the related specific test procedures for hydraulic turbine governing systems. It can be used to fulfil following tasks:

- verification of system characteristics according to specification;
- verification of technical guarantees;
- verification of general proper functioning in the workshop and/or on site;
- assessment of the actual state of an existing governing system.

This document covers the tests for systems and devices described in IEC 61362.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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, *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines*

IEC 60545, *Guidelines for commissioning and operation of hydraulic turbines, pump-turbines and storage pumps*

IEC 61362, *Guidelines to specification of hydraulic turbine governing systems*

ISO 4406, *Hydraulic fluid power – Fluids – Method for coding the level of contamination by solid particles*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 61362 apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at https://www.electropedia.org/
- ISO Online browsing platform: available at https://www.iso.org/obp

4 Recommendations on tests

4.1 General

In order to keep the commissioning period as short as possible, it is recommended that the largest part possible of the required contractual tests be carried out in the manufacturer's works (workshop tests). On site tests should be limited to the verification of such characteristics, which:

– are indispensable for the safety, and
– cannot be carried out without the generating unit and the pressure supply system.

In 4.2 and 4.3, some basic aspects are summarised.

4.2 Recommendations on workshop tests

The scope of the tests, the best set up and the extent of the test documentation should be stipulated in the contract in accordance with the requirements.

In case of type tests including EMC (clectromagnetic compatibility), type tests already performed by the manufacturer of the equipment or assembly, the corresponding certificates shall be accepted in order to reduce the tests efforts to a reasonable level.

It should be early and clear enough stipulated, who will witness the tests.

For workshop tests, it is not necessary to set up all components of the governing system in a complete loop, the electronic governor and the oil hydraulic governor can rather be tested separately. During these independent tests, signals at interfaces between the electronic governor and the oil hydraulic governor shall be clearly defined and measurable.Only if it is explicitly required in the contract, the complete governing system, including the electronic and the oil hydraulic governor should be assembled in the workshop. In this case the individual testing of the systems is not needed.

In exceptional technically challenging situations, it can be an advantage to employ a plant simulator for the workshop test of the digital governor (see also Clause 7). The use of a plant simulator in the workshop test has to be clearly stipulated in the contract.

4.3 Recommendations on field tests

4.3.1 New governing systems

For governing systems, the following measures and steps apply.

– Safety devices, displays, alarms and trip settings shall be verified prior to conducting the field tests.
– Commissioning of the complete generating unit shall be performed including load rejection tests. The testing of governing systems shall be coordinated with the overall commissioning of the hydro generating equipment; refer to IEC 60545.

For the actual governing system tests:

- The relevant control mode and operational mode to be checked is set, for example speed control in island operation; subsequently defined test signals are superimposed and resulting changes for the specified values through the entire operating range are observed and/or recorded, whereby control settings can be optimized during the process. The results of such tests can be used as baseline values in order to be compared with the results of verification tests which are carried out during the lifetime of the equipment.

- The test of the insensitivity of the governing system is only needed if the power station will be participating in primary regulation of grid frequency, especially in peak load power stations and in power stations with special requirements for high control accuracy (for recommended insensitivities, see IEC 61362; acceptable measuring uncertainties are given in Clause 6).
- In some cases, the parameters of the governing system can be determined based on physical measurements. If the expected behaviour is not achieved and the reason for this has to be identified, then other factors influencing the governing system behaviour shall be examined. These factors can include: inertias, generator-load characteristics and the influence of hydraulic forces on actuating times. The determination of the governing system's parameters and of the turbine transfer function can be used to provide models of the power plant, in order to carry out studies of the power system's dynamic behaviour.
- Special attention shall be given to the test of pump-turbines because of their complex turbine characteristics (e.g. S-shape characteristic).

4.3.2 Existing governing systems

4.3.2.1 Motivation for a field test in an existing governing system

Existing governing systems can have deficiencies causing one or more of the following effects, which can lead to the decision to conduct a field test:

- long settling times of the controlled variable;
- long synchronization times;
- drifting operating points;
- changes in actuator speeds;
- unusual oscillations (e.g. in no-load and/or island grid operation);
- excessive insensitivities and/or hysteresis effects;
- excessive leakages (long pumping periods, high oil temperature, etc.);
- general inconsistent governor performance.

4.3.2.2 Identification of deficiencies

Depending on the observed effects the following checks can be made:

- measurement of the insensitivity and dead time, see Clause A.1 and Clause A.2;
- recording of step responses/transient functions (unit step responses) by applying defined signals at the input (command signal, controlled variable, frequency, etc.), for example see Clause D.6 to Clause D.14;
- indexing the servomotors, see Clause A.3;
- checking the runner/guide vane relationship in Kaplan turbines, i. e. cam relation;
- checking the deflector/nozzle relationship in Pelton turbines;
- identifying possible resonances (with oscillations in the draft tube, surge tank, waterways: penstock and/or channel system, the generator, the grid, etc.);
- measurements of the parameters of the governing system and comparison to the original values recorded during the first commissioning, for example see Clause D.7 and Clause D.8;
- checking of the overall functionality of the oil hydraulic system, for example see Clause A.4.

4.3.2.3 Deciding whether to replace or to repair existing governing systems

The above-mentioned checks give information about the possible causes of the deficiencies, allowing to decide on the measures to be taken, such as for instance:

– overhauling of individual components;
– replacement of components or of complete governing systems;
– changes in the configuration.

Besides the above-mentioned points, the following facts can also influence the decision to replace or repair existing elements or systems:

- the assessment of operating costs;
- the assessment of repair costs;
- the potential for operating and efficiency improvement of replacement versus repair;
- general safety and any other demands required by authorities.

5 Governing system tests

5.1 Test conditions to be fulfilled

5.1.1 General

The following test conditions apply, unless there is an explicit exception made in this document. They can be modified by mutual agreement.

5.1.2 Turbine operation conditions

– Operating head on the turbine shall be within the limits specified in the turbine contract, otherwise the method of correction should be agreed upon.
– Tailwater elevation and power output of the turbine shall be such that the net positive suction head (NPSH), see IEC 60041, is not less than the lower limit of the turbine manufacturer’s guarantee or recommendation.
– Steady-state power output of the turbine for constant position of the regulating devices (e.g. wicket gate, runner, needle, deflector) shall not deviate from the specified value by more than ±1,5 % of rated output.

5.1.3 Hydraulic pressure unit condition

Tests should be performed under approximately constant oil pressure. The fluctuations of the supply oil pressure shall not exceed ±10 % of average oil pressure.

5.1.4 Deviation of values from specified operating conditions

5.1.4.1 General

It is important that specified values stated in the contract, upon which stated guarantees are based, be adhered to as closely as possible. The relative deviations from specified values under which it is permissible to make a governing system acceptance test are specified in 5.1.4.2 and 5.1.4.3.

5.1.4.2 Speed

If acceptance tests cannot be performed at the specified speed, the permissible deviation from the specified speed and its effect on the acceptance test results shall be agreed upon prior to tests.

5.1.4.3 Oil hydraulic system

The acceptance tests of oil hydraulic systems pertain to the following parameters:

a) Pressure

   Acceptance tests, performed on a governing system installed on site with the turbine running or at standstill, shall be performed with the oil pressure as specified in the contract; for tests performed in the workshop of the governing system manufacturer, because of the absence of regulating force required by the turbine, the oil pressure of the last amplification stage of the controller system can be reduced correspondingly after demonstrating satisfactory operation at the specified pressure. This reduction in oil pressure shall be mutually agreed upon prior to performing the tests.

b) Oil quality and temperature

   Acceptance tests shall be performed with the oil quality specified in the contract. Otherwise the oil quality should be agreed upon.

   The prescriptions of the manufacturers of components regarding oil purity and absence of foam in the oil shall be strictly observed.

   Oil temperatures during the tests shall correspond to normal sustained operating conditions and lie within the range indicated by the manufacturers of components.

5.1.5 Provisions for instruments

The final report shall state the manufacturer and manufacturer’s serial number of the instruments and completely describe special devices or modifications to standard instruments used in connection with the acceptance test.

5.1.6 Calibration of instruments

All instruments shall carry calibration certificates, valid on the date of the tests, issued by an institution which is acceptable to both parties. The provision of calibration certificates shall be the responsibility of the party providing the test instruments.

5.2 Electrical checks

5.2.1 General

Electronic systems like the digital governor are sensitive to electrical-magnetic interference. Therefore, the following shall be given special attention:

– quality of the power supply;
– overvoltage protection;
– filter and shielding measures;
– immunity of the components to interference;
– grounding;
– anti-static protection.

If certain basic safety measures are taken and guidelines adhered to, testing can concentrate on checking the governing systems for proper functioning. Electrical checking is usually performed in the form of type tests, because electrical checking is expensive and requires qualified personnel as well as special testing equipment. For specifications of the electromagnetic compatibility (EMC) tests refer to IEC 61362.

5.2.2 Selection of test location

To carry out the functional checks on site, a centrally located, quiet place (control room) should be selected where all important signals of the process are available.

If the governor is not located near the generating unit, provision for local emergency operation of the governor should be made in the vicinity of the generating unit.

5.2.3 Power supply

The check of the power supply with a volt- and ampere meter, oscilloscope or transient recorder should normally be carried out in the workshop and is generally limited to:

– tolerance limits and ripple factor;
– current input;
– if applicable, test of switch-over of redundant supply voltage;
– failure monitoring.

5.2.4 Overvoltage protection and suppression of interference voltage

The following can be checked:

– certification of the electronic equipment with respect to EMC;
– the electric isolation of the power supply unit for withdrawable electronic parts;
– the contact separation of the binary and analogue signals during take-over and/or transfer;
– shielding of the cables to the peripheral devices;
– the physical separation of the signal cables from power lines;
– grounding of inactive metal parts;
– protection of the peripheral devices against overvoltage by protective elements;
– wiring of inductive devices (relay coils, solenoid valves).

Ground connections are to be tested with ohmmeters. In the event of interferences, a measurement is to be carried out at the ends of the signal cables with an oscilloscope.

5.3 Test of the process interface system

The electrical signals for actuator position, speed, power, flow, head (up-stream and tail race), etc., shall be checked for:

– open circuit characteristic and hysteresis (actuator position);
– interference;
– filtering (power, flow, water level);
– limit value acquisition;
– fault monitoring, if available.

Signals communicated by bus systems shall also be checked for:

- proper transmission;
- network status.

5.4 Test of converters, amplifiers and actuators

5.4.1 Electrohydraulic and electromechanical converters

5.4.1.1 General

The converters dealt with here are the connecting element between the electronic and the hydraulic-mechanical part of the governing system, as described in IEC 61362. They are of great importance for the overall behaviour of the governing system. Therefore, insensitivity, precision (including temperature stability) and also the dynamic behaviour shall exceed the corresponding properties of the subsequent amplifier stages.

5.4.1.2 Electrohydraulic converters

The most important characteristic is to establish the oil flow rate as a function of the electrical command signal and of the pressure drop.

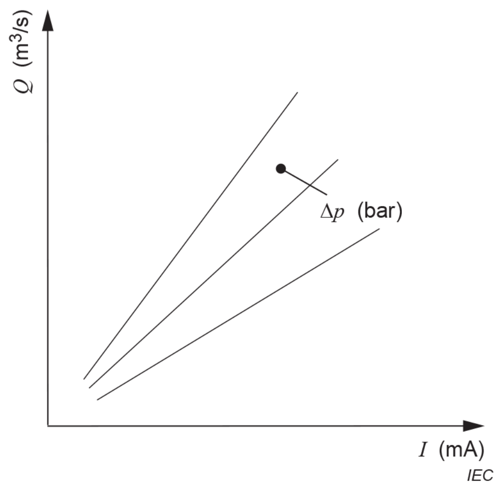


Figure 1 – Oil flow Q function of input current I and pressure drop Δp

The curves of Figure 1 should be provided by the supplier of the electrohydraulic converter with various pressure differences and, in addition, oil temperature and type of oil (viscosity grade) should be indicated.

It is furthermore possible to check

– the dead time;

– the actuating forces as a function of the oil pressure;

– the dynamic characteristics.

If an emergency trip and failsafe (for example shutdown in the event of power failure) are available, their function shall also be tested.

Generally, to achieve the specified performance, a vibration (dither) signal is applied, which shall also be checked.

NOTE Multi-stage servo- and/or proportional valves often have an additional position controller for the second stage and can therefore only be tested as a system including the corresponding electronic device.

5.4.1.3 Electromechanical converters

In principle, these converters are electro-motor driven (rotating or linear). For hydro turbines controlled by such electric actuators, they consist of electric motor, gearbox and operating mechanism. These converters are, for instance, used for the direct actuation of the regulating elements (guide vanes, runner blades, nozzle, deflector) or to drive control valve systems.

This type of actuator does not depend on the oil pressure system. It is generally suitable for small hydro turbines, designed to withstand sustained runaway operation, in the event of the total failure of electric supply. Suitable back-up protection shall be provided, to reduce the turbine discharge to an acceptable level. Some examples of the protection are:

– closing of guide vanes by self-closing characteristics;
– closing of inlet valve, with guide vanes open;
– counter weight or spring.

For testing purposes, measurement of current input and actuating times is usually sufficient.

5.4.1.4 Two-stage electrohydraulic control

Two-stage electrohydraulic control is generally composed of an electrohydraulic converter (see 5.4.1.2) which acts on the main distributing valve.

In some special cases, electromechanical/electrohydraulic converters additionally have a small pilot servomotor and a position feedback, (see Figure 2), the pilot servomotor will then actuate the main distributing valve. For measurement, no additional aspects have to be considered.

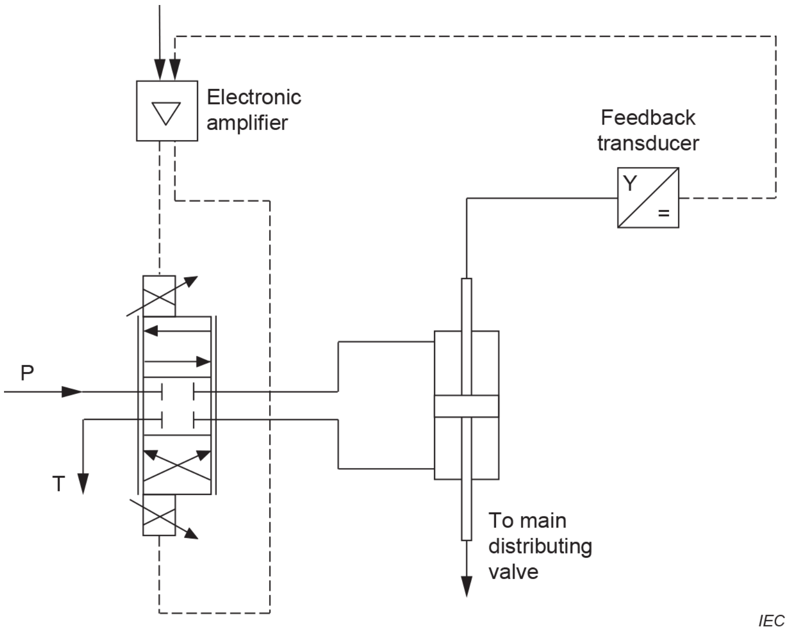


Figure 2 – Two-stage electrohydraulic control with pilot servomotor

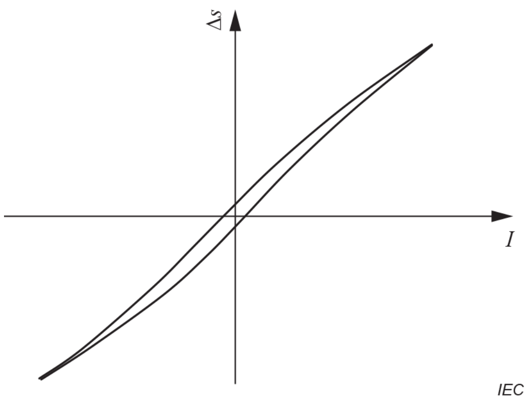


Figure 3 – Output stroke Δs of a converter versus input current I

The correlation between output stroke and input current shall be established or shall be proven by a type test from which the hysteresis can also be seen, see Figure 3,

It is furthermore possible to check

– the dead time;
– the actuating forces as a function of oil pressure;
– the dynamic characteristics.

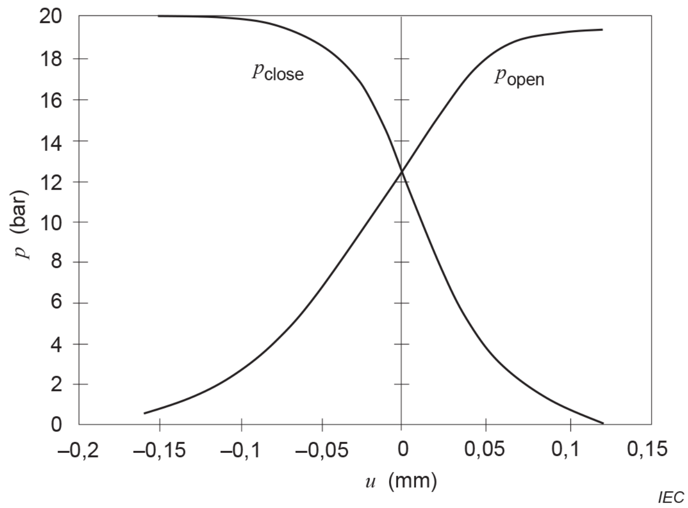
During these checks, the corresponding vibration (dither) signal, oil losses, oil temperature and oil viscosity should be recorded.

5.4.1.5 Main distributing valves

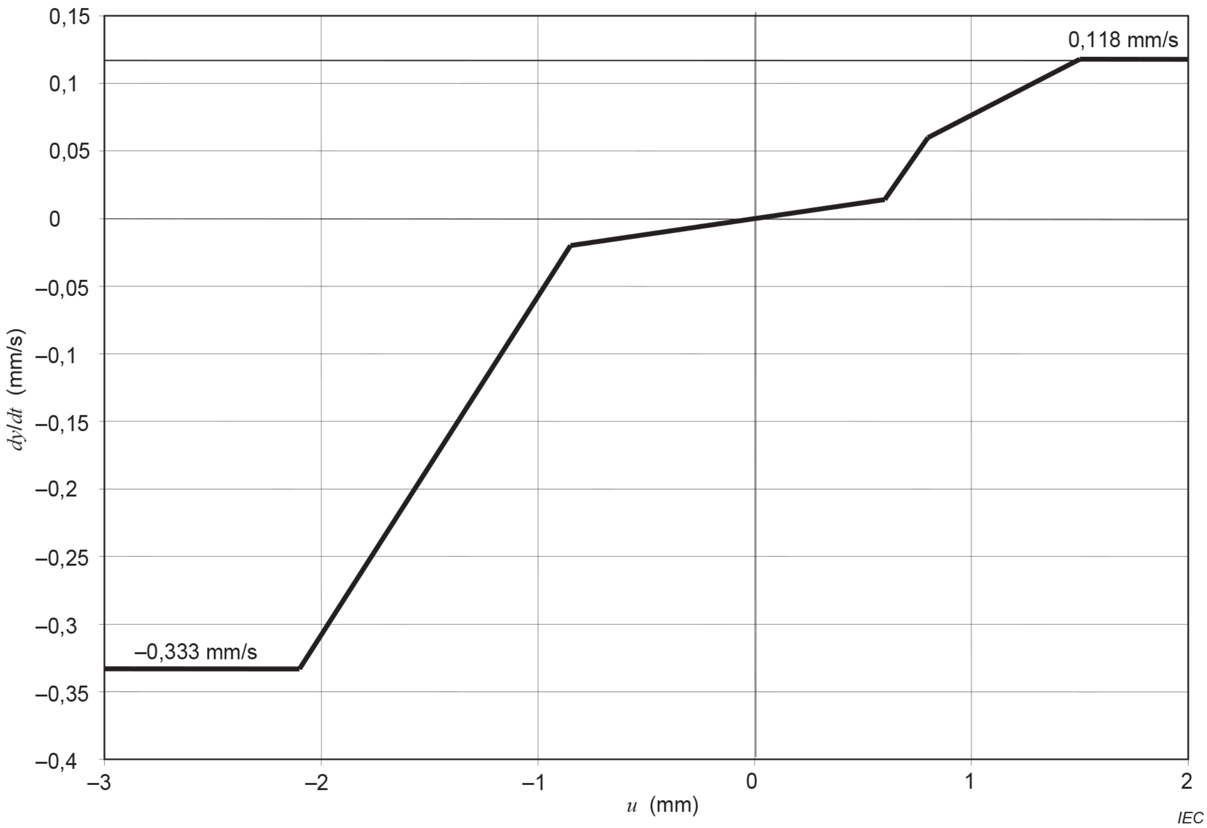
For workshop checks, it is recommended to connect the main distributing valve with the servomotor. If the servomotor is not available, a test servomotor can be used in its place.

The characteristics of the main distributing valve should be established for type testing, troubleshooting or modelling purposes. They are recorded as a function of the valve spool position and consist of the pressure characteristic (pressure in the valve connection ports with the flow to the servomotor blocked or with the servomotor at its end position), see Figure 4 a), and the flow characteristic (actuating speed of the servomotor), see Figure 4 b) (see also Clause A.4).

The slope of the pressure characteristic depends on the internal leakage of the main distributing valve or the main distributing valve and the servomotor.



a) Pressure *p* curves in closed pipes versus displacement *u* of the valve spool (example)



b) Servomotor speed *dy/dt* versus displacement *u* of the valve spool (example)

Figure 4 – Performance curves of control valves

These measurements are especially important for valves provided with pre-opening notches on the control edges. From the pressure curve, which is only affected by the internal overlap, the displacement necessary to produce the required actuating force of the servomotor can be derived. The flow curve shows the size of the overlap in the individual notches. The widths of the notches are determined on the basis of the chosen time constants. For checking, these can be re-calculated from the inclination of the characteristic curves. The time constants are of importance for the stability and the dynamic performance (overshoot and settling time when positioning), whereas the overlaps are responsible for the governing system insensitivity and/or positioning accuracy.

For onsite testing this measurement can only be made with a spiral casing or a distributor isolated from the water conductor system.

In some Kaplan turbines, the lubrication and cooling of the runner oil supply takes place via the runner control valve. When checking the valve, it has to be made sure that there is sufficient lubrication in the steady state centre position of the piston.

The control valve spool can be overlapped, zero-lapped or underlapped.

5.4.2 Servomotors

5.4.2.1 General

Generally, the servomotor is tested together with the distributing valve assembly. However, it can also be tested without the distributing valve assembly with other pressurization.

5.4.2.2 Servomotor indexing

The measurement of the friction forces, for example via a pressure measurement, is important to ensure the actuator force capacity is suitable for the application. The loading on the servomotor can be measured via pressure measurement during servo movement.

The servomotor full-stroke travel time for hydraulic servomotors is affected by several factors. The mechanical loading of the servomotor affects its rate of travel. This mechanical loading consists of both frictional loading (of the turbine control device and its connecting linkages) and dynamic loading of the water passing through the turbine control device.

The mechanical loading of a turbine control servomotor is reflected as a differential pressure across the servomotor piston considering the area of each chamber.

Both the frictional loading and the hydraulic loading on the turbine control devices determine the servomotor differential pressure required to move the servomotor in the opening or closing direction.

The hydraulic loading on a servomotor can be evaluated at a position by calculating the average between the force to move the servomotor in the opening and closing direction at that position.

The friction loading can be evaluated by calculating one half of the difference between the force to move the servomotor in the opening and closing direction at that position under the assumption that the friction force is roughly equal in both directions and always opposes the motion. Friction loading should be measured during operation of the turbine as the loading on the turbine regulating devices affects the friction load.

Care should be taken to perform the test at a slow enough rate of movement that hydraulic transients and losses in the piping system do not affect the test results.

5.4.2.3 Servomotor opening and closing laws

The actuating times and actuating laws shall be recorded.

In many cases, the closing and opening velocities of the servomotors are not constant but result in two or more velocity steps. All timing controls slopes shall be verified separately.

For safety reasons, the actuating times and actuating laws are pre-checked at maximum supply oil pressure of the plant prior to filling waterways during dry testing.

Upon commissioning, the opening and closing laws shall in any case be retested and adjusted, if necessary, in order to be sure that unacceptable pressure variations in the water passages are avoided.

5.4.3 Dead time, insensitivity

For dead time measurement, the main distributing valve and/or the pilot control valve is(are) displaced stepwise into both directions from the centre position. The time between displacement and the beginning of the servomotor movement is recorded. It is recommended that this measurement shall be carried out in connection with a dead time measurement of the complete governing system.

The insensitivity of the amplifier stage is determined by the valve overlap, the servomotor friction and frictional forces of the positioning mechanism; to overcome these, a corresponding pressure difference and the corresponding valve displacement (see Figure 4 a) are required. Oil leakages also can have a considerable influence.

Measurement of the governing systems insensitivity is of particular interest for units which are used for primary control. The various possibilities are described in 5.5.3.3.

5.4.4 Provision of actuating energy

5.4.4.1 Systems without accumulator

The hydraulic pumps shall have enough capacity to achieve the desired turbine maximum opening and closing velocities under the worst operating conditions, amongst others the maximum servomotor load.

In order to check the safety margin it is recommended to make a servomotor indexing, see 5.4.2.2.

The characteristics of the system required for achieving the amount of the actuating energy are described in IEC 61362.

5.4.4.2 Systems with accumulator

The hydraulic system shall have enough capacity to achieve the desired number of opening and closing servomotor strokes.

Under steady state conditions the accumulator gas temperature is the same as the ambient temperature. The gas temperature has an influence on the capacity of the accumulator. The test shall be carried out considering the specified range of the ambient temperature, for example 10 °C to 35 °C.

The test begins at the minimum operating pressure p_{omin} and the pumps are deactivated. After achieving the desired number of opening and closing servomotor strokes the remaining pressure in the accumulator shall be higher than the minimum required oil pressure (p_{R}), as described in IEC 61362.

This test can only be done during dry testing.

In order to check the safety margin it is recommended to make a servomotor indexing, see 5.4.2.2.

5.4.4.3 Filtering (see ISO 4406)

For a reliable and safe operation from oil hydraulic control systems, it is necessary to check that:

– the total oil volume is very well cleaned with off-line or in-line filters, as specified by the equipment supplier;
– the electrohydraulic converters (servo valves, proportional valves) are protected by in-line filters directly in front of their supply port as specified by the equipment supplier.

In order to check the cleanliness of the oil according to ISO 4406, a sample of oil has to be taken and has to be analysed by a specialised laboratory.

5.4.5 Oil leakage

It is difficult to measure the oil leakage of the control valves and of the servomotor separately.

Normally oil leakages are measured for steady state position of the servomotor. In this case the proportional valve is around the centre position.

The oil leakage can be measured using the signal of the oil level in the pressure accumulator.

When using a fixed displacement pump in systems with accumulator, the shutoff or unloading period should be considered during steady state operation, as a measure to detect increased leakages.

When using a pressure-controlled adjustable pump, for example an axial or radial piston pump, the increase in no-load electric power consumption of the motor can be taken as a measure to detect increased leakages.

5.4.6 Test of the positioning loop

The positioning loop is the basic control loop in the system. To adjust it properly is a precondition for a good performance of the main control functions. The adjustment needs to consider one or two-stage configurations, where a main distributing valve is used.

The performance and stability criteria, which apply for these tests are described in IEC 61362.

The control equipment consists of the following elements: position controller, electrohydraulic converter and servomotor.

– Input signals: position set-point value, actual position value.
– Output signal: servomotor, main distributing valve position, if available.
– Limit values:
  - servomotor opening ramp,
  - servomotor closing ramp,
  - mechanical limits.

A special design of the turbine control is the provision of individual guide vane servomotors and electrohydraulic controls requiring synchronization, to maintain all guide vanes at the same position. The synchronization is achieved with the help of mechanical linkages or electronically, depending on the system adopted.

5.5 Tests of governor characteristics

5.5.1 General

Examples of the tests described in the following are included in Annex A and results of real measurements are shown in Annex D.

5.5.2 Test of the governing system

The most important steps are:

- activation of the respective control mode;
- input of defined test signals, i.e.:
  - command variables;
  - set-point changes of the follow-up controls;
  - auxiliary and disturbance variables.

  Each of the above defined operating points shall be within the control range maintaining limits (for example with respect to pressure range, servomotor speed etc.);
- determining the criteria for evaluating the results achieved by optimization of the controller settings;
- according to specified criteria of control quality (for example determining the damping ratio 0,8 < D < 1,1 for a time response, measuring the control area (integral criterion) etc.);
- adhering to the admissible limit values and loads (for example minimum system deviation, limitation of speed changes, pressure surge, and surge and suction waves);
- using recommended uncertainties in measurement according to Clause 6.

NOTE For the damping ratio D (or sometimes denoted as ζ) the formula $D = 0{,}5\ (T_1/T_2)$ applies, whereby T_1 and T_2 are the time constants of an element of second order delay; $D = 0$ is zero damping and $D \geq 1$ is aperiodic damping.

5.5.3 Determination of governing system's parameters

5.5.3.1 Step responses, transient functions

Prior to the test, the following is important:

- determination of operating states;
- selection of step amplitudes. The input signals shall be such that they cannot be invalidated by possible disturbing influences;
- choice of the evaluation criteria of the results for determination of the parameters, particularly if non-linearities occur during the tests (for example actuating speed limitations).

5.5.3.2 Frequency response characteristics

Since the control behaviour can usually be better evaluated on the basis of transient functions and since, on the other hand, measurements and evaluations are costly, frequency response measurements should only be made in special cases. The execution of such measurements is to be stipulated in special agreements. Type test results should be acceptable.

5.5.3.3 Insensitivities

5.5.3.3.1 General

Insensitivity testing is only to be carried out on governing systems in power plants with special importance on the grid stability. Suitable input and output variables should be agreed within selected opening ranges. It can be performed for speed control, power control water level control and flow control.

For power control, the actual power value often includes superimposed noise and therefore should not be used for evaluation of insensitivity. As an input parameter, the frequency, which via the frequency-power droop is always available as an additional input variable, or the power set-point can be chosen instead. However, in this case the power measurement device is not included in the insensitivity test.

For the recommended insensitivity, see IEC 61362. Acceptable measuring inaccuracies are given in Clause 6.

5.5.3.3.2 Localization of insensitivities

The localization of insensitivities can be achieved as described below:

– The tests are started with the servomotor position as an output variable. In some instances, for example with individual wicket gate control, the mean value can be chosen as output variable.
– If insensitivity is too high, it is recommended to measure the output variables of each device in the control loop in opposite direction of the signal flow up to the controller output.

5.5.3.3.3 Insensitivity test with X-Y recording

The controller shall have a short reset time since otherwise the insensitivity appears to be increased. For instance, the quotient of integral action time T_i and proportional-action gain K_P should be as low as possible (ideally, proportional action only). Therefore, it is necessary to change the parameters of the controller during the test.

The most important steps are

– recording of the interdependence between output variable and input variable for selected operating openings;
– determination of insensitivity $i_\mathrm{x}/2$ from the dead band.

5.5.3.3.4 Insensitivity test by means of transient response functions (time characteristics)

The controller shall have a short reset time since otherwise the insensitivity appears to be increased. For instance, the quotient of integral action time T_i and proportional-action gain K_P should be as low as possible (ideally, proportional action only). It is therefore necessary to change during the test the parameters of the controller to carry out the test.

The main steps include:

– recording of input and output variables with small defined changes of the input variable for selected operating openings;
– determination of the insensitivity $i_\mathrm{x}/2$ from the dead band. If the input variable is superposed by high noise, the insensitivity cannot be measured correctly.

5.5.3.4 Synchronism tests of two mechanical or hydraulic variables with X-Y recording

The synchronism tests are carried out with synchronous operation of positioners and serve to record mechanical and/or hydraulic discontinuities. It is assumed that in the steady-state condition the absolute positions are in accordance with each other.

The tests can for instance include:

– the position of two pump-turbine guide vanes during load operation (admissible deviation with slow adjustment usually < 1 %);
– the position of one guide vane against the mean value of all guide vane positions with individual guide vane control (admissible deviation usually < 0,5 %).

The most important steps are:

- selection of a suitable input variable;
- recording of the movement of both output variables when changing the input variable in both directions by the same amount for selected openings;
- determination of mechanical or hydraulic deviations from synchronous operation from the hysteresis.

5.5.4 Test of main control loops

5.5.4.1 Opening control

The opening control works either as an operating mode in grid operation or as a backup control of main control operations (for example speed control).

The control equipment consists of the elements: opening controller and the servo positioner.

– Input signals: opening set-point value, if necessary, speed dependent with permanent droop, actual opening value.
– Output signal: servomotor set-point.
– Limit values:
  - servomotor opening ramp,
  - servomotor closing ramp,
  - opening limiter.

5.5.4.2 Speed control

The control equipment consists of:

– a series arrangement of speed controller and servo positioner
  - Input signals:
    i) speed set-point value;
    ii) actual speed value;
    iii) necessary, auxiliary and/or disturbance parameters (for example spiral pressure, water level, head, power, servomotor position).
  - Output signal: controller output resp. the servomotor set-point.
  - Limit values: admissible speed changes in the event of load rejection; surge, suction wave and pressure changes in the event of loading, unloading and load rejections; maximum frequency changes in island operation with defined load changes.

5.5.4.3 Power control

The control equipment consists of:

– a series arrangement of power controller and servo positioner
  - Input signals:
    i) power set-point; if necessary, speed dependent with permanent droop;
    ii) actual power value;
    iii) if necessary, auxiliary and/or disturbance parameters (for example spiral pressure, water level, head).
  - Output signal: controller output respectively the servomotor set-point.
  - Limit values: upper and lower power limitation and prohibited zones dependent on head, cavitation, partial load and dynamic condition of the system (for example surge-tank condition).

5.5.4.4 Water level control

The control equipment either consists of:

– a series arrangement of water level controller and servo positioner, or
– a series arrangement of water level controller, flow controller and servo positioner
  - Input signals:
    i) water level set-point; if necessary, speed dependent with permanent droop;
    ii) actual water level value;
    iii) if necessary, auxiliary and/or disturbance variables (for example gate position, discharge of station, locking).
  - Output signal: controller output respectively the servomotor set-point.
  - Limit values:
    i) maximum value of head race water level;
    ii) minimum value of tail race water level.

5.5.4.5 Flow control

The control equipment consists of:

– a series arrangement of flow and servo positioner
  - Input signals:
    i) flow set-point; if necessary speed dependent on speed with permanent droop;
    ii) actual flow value (mostly calculated);
    iii) if necessary, auxiliary and/or disturbance variables (for example gate position, water level).
  - Output signal: controller output respectivelythe servomotor set-point.
  - Limit values:
    i) water level;
    ii) surge and suction waves in the event of flow changes.

5.5.4.6 Primary control

An evaluation of the primary control capability of the governor requires a closed loop test together with the power unit connected to the grid. Generally applicable test criteria cannot be given in this document because they depend on the regulations as defined in the local grid codes.

An example for a common test is to simulate the grid frequency measurement and test the response of the power unit to frequency steps around nominal frequency while the set-point of the underlying control loop (opening, power, water level, flow) is held constant.

This test verifies whether the power output of the unit responds to frequency disturbances in the grid according to the specification in the relevant grid code. Commonly used criteria are to check whether the final steady-state value according to the specified permanent droop is reached and the evaluation of the power variation with time regarding delay and deviation of the linear gradient.

However, it is important to note that the dynamic behaviour of the primary control depends not only on the governor but also on the properties of power unit, water passages and grid. This is valid especially for the limitations.

The control equipment consists of:

– Closed loop control using opening, power, water level or flow controller with frequency influence
  - Input signals:
    i) simulated grid frequency
    ii) opening, power, water level or flow set-point
  - Output signals:
    i) controller output respectively the servomotor opening,
    ii) actual power value
    iii) water level or flow if applicable
  - Limit values:
    i) delay
    ii) deviation of linear gradient
    iii) settling time

5.5.5 Considerations for island grid field tests

5.5.5.1 Preconditions

The decision whether to perform an island grid test and the type of testing to be performed should be stated by the station owner/operator at the time of the tender. The following factors should be considered by the owner/operator when defining the scope of island grid testing:

– the performance constraints of the turbine, for example due to maximum opening and closing rates;
– the intended role of the machines in the grid management philosophy;
– cost implications such as direct costs (for example cost of test and equipment) and indirect costs (for example lost generation revenue);
– the details of the test should be based on the predicted island grid conditions;
– the owner/operator shall co-ordinate with the grid managing body to determine the details of the test. It should be remembered that the response of the control system is affected by the characteristics of the island grid and the generator.

Three methods to investigate the behaviour of the plant operating on an island grid can be considered: numerical simulation of all components (see Clause 7), field tests by simulated island operation and field tests on a real island grid.

5.5.5.2 Tests by simulated island operation

A very practical test method is on-line simulation and is usually sufficient for most cases. The stability of island grid operation depends essentially on the optimum selection of the dynamic parameters of the speed control system which are used for this mode. Before the field tests, the suitable values of these parameters are generally calculated with optimization specific software, based on more or less accurate models of water passages, turbine, generator and load.

However, real power plants are sometimes different from mathematical models, data can be erroneous, and equipment subject to contingencies and modifications during their lifetime: therefore, the quality of numerical calculations can appear relatively inadequate in certain cases.

For this reason, it is often desirable, before or in place of carrying out real island grid field tests, to develop an intermediate method, based on an "on-line island grid simulator".

Figure 5 represents the main scheme of such a simulator (the variables are in relative values): the generating unit is operating in parallel with the interconnected power system at different values of power output (corresponding to the different operating points desired for the island grid operation). Therefore, the speed of the unit is held constant (or nearly constant) by the power system.

The principle of the simulator can be described as follows: a signal, representing the speed/frequency variations which would occur if the unit were supplying an island grid load, is developed by calculation from the measured electrical power output of the generator. This simulated speed/frequency signal is then delivered to the controller in place of (or in addition to) the actual speed/frequency signal.

The simulated frequency is obtained by integration of the difference between the power output measurement and an adjustable power reference (sum of the initial value of the power and of a test signal); it takes into account:

– the inertia of the unit (unit acceleration constant T_a);
– the inertia of the load (load acceleration constant T_b; this constant is often taken to be equal to zero);
– the controlled system self-regulation factor (e_n), which is the difference between the load self-regulation (e_g) factor and the turbine self-regulation factor (e_t).

One typical simulated island operation test is the step-response test: a step signal is applied to the adjustable power reference, and the simulated speed/frequency signal following this step change is recorded in the time domain. Attention should be paid to the magnitude of the step signal, which shall be significant, but with a typical maximum value corresponding to 10 % of the rated power output.

In this on-line simulation, the dynamic effects of the real components of the hydraulic system are included, i.e. the waterway hydraulic dynamics, the turbine (for simplicity, its dependence on the speed can also be taken into account by the turbine self-regulation factor), the controller, including all non-linearities.

The effect of the simulated unit speed change to turbine flow in these tests is neglected as the actual unit speed is held constant, therefore the inaccuracy will be increased by this simplification.

One particular point is the behaviour of the generator, which is different in interconnected grid operation and island grid operation. In interconnected grid operation, the generator can be represented as a second-order system (natural frequency typically between 0,8 Hz and 1,5 Hz); the power output is affected by electromechanical oscillations at this natural frequency. In most cases (except in cases with fast acting deflector control of Pelton turbines) the response time of the speed control is longer, so that the influence of this phenomenon can usually be neglected and the power output of the generator can be assumed equal with the mechanical power of the turbine (losses of the generator neglected).

Moreover, the island grid can be modelled very simply, neglecting the complex dynamical behaviour of the loads.

As a precautionary measure, for safety reasons, it is necessary that the simulator allows the controller to quickly revert back to normal operating conditions of the control system, i.e. to the measured frequency of the interconnected grid in place of the simulated frequency; these precautions are essential in case of divergent oscillations during the test, for example due to un-adapted values of parameters of the speed control system.

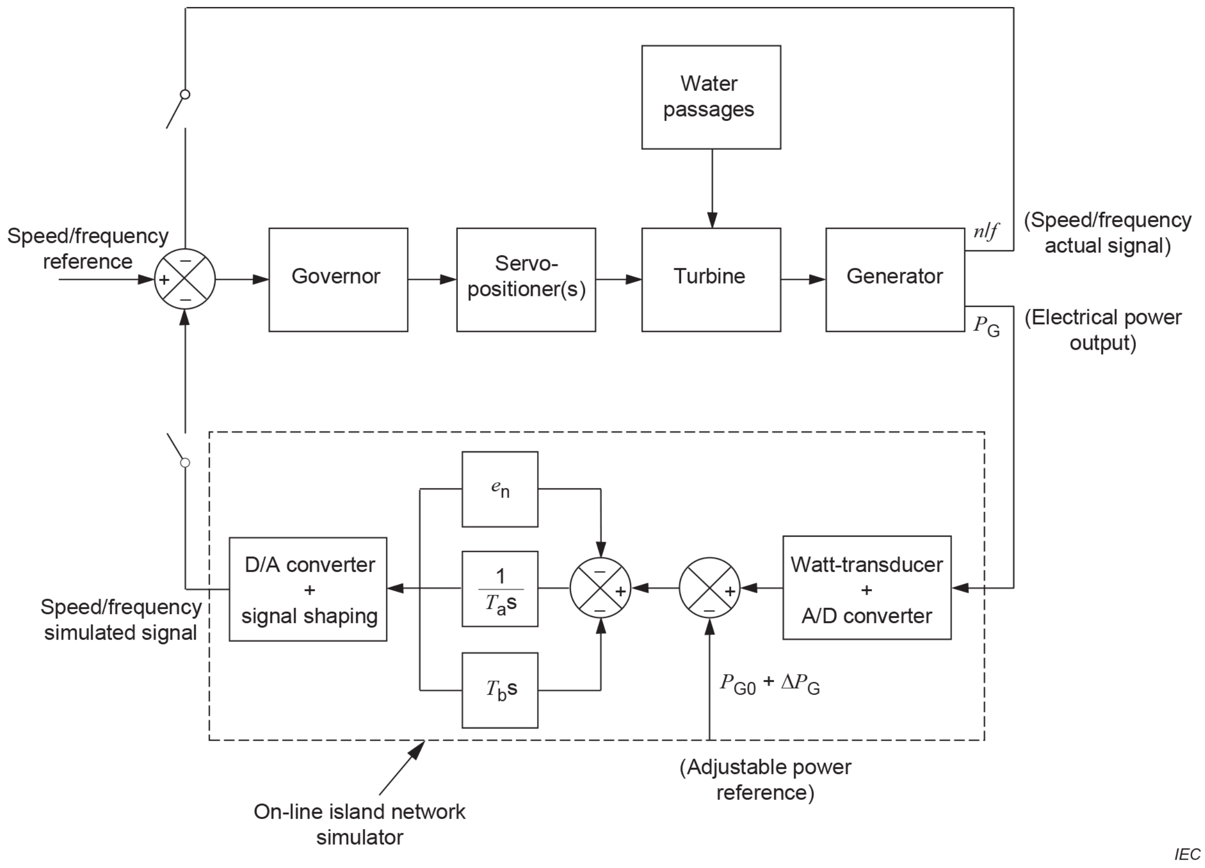


Figure 5 – Example of on-line simulated island grid test

5.5.5.3 Tests on real island grid

Real island grid tests are usually carried out only if the grid operator requires them specifically. They can be costly, with the involvement of numerous parties (the operators of the power plant, of the transmission grid and of the distribution or of the industrial consumer to be supplied in island operation mode). They require careful planning and execution in order to prevent unacceptable disruption to the island grid.

The amplitude of the load change when transferring from the interconnected grid to the island grid should be initially relatively small. This amplitude and the dynamic parameters of the speed control system can be pre-determined by calculation and/or on-line simulation.

The amplitude of the load changes can be gradually increased to determine the point at which the frequency variations become unacceptable.

Figure D.8 presents a field recording of such a step-response with a Pelton turbine.

5.6 Servomotor pressure indication test

The pressures in the opening and closing sides are measured to determine the size and direction of the hydraulic and frictional torque (both in the opening and in the closing direction).

These torques depend on:

– machine size;
– head and/or flow rate;
– opening of the servomotor;
– friction;
– geometric form of wicket gate, runner blades, needles or deflectors.

Servomotors shall be moved slowly and uniformly to achieve sliding friction.

The test can be carried out in dry and wet conditions.

Pressure measuring instruments shall be connected as near as possible to the servomotor chambers and not to a supply piping, but in between servomotor chamber and orifice.

On control devices with water pressurized chambers, the water pressure shall also be measured or recorded over the whole stroke, since the pressure is not constant because of the varying penstock pressure.

5.7 Safety tests

5.7.1 General

The function and the scope of the safety devices, such as:

– quick shutdown;
– emergency shutdown;
– overspeed protection device;
– interlocks;

are described in IEC 61362. While safety functions can include parts which are not in the scope of the supply of the governing system, the critical reliance on those safety functions requires that safety systems shall be tested as a complete system. The safety tests shall prove that the protection devices fulfil their tasks. Safety tests often subject equipment to additional stress and equipment risk than under normal operating conditions (overspeed, load rejection, pressure surges). Therefore, the manufacturer, owner respectively the operator and, if required, public authorities should agree on the test plan.

5.7.2 Test strategy

5.7.2.1 General

All signal routes shall be checked. In order to limit the number of stressing tests like trips, the monitoring and protection equipment can be checked in sections. This can be necessary when testing complex protection systems. The number of sections should be optimized by ensuring that there is no interruption of the signal route.

The function of the individual safety actuators (inlet valve, wicket gate) shall be verified by specific tests.

5.7.2.2 Sensor test

The function of the sensors shall be checked under the most realistic conditions (for example real pressure reduction in the accumulator tank respectively pressure vessel down to the tripping value).

5.7.2.3 Functional check

Interlocking conditions and the various tripping possibilities shall be checked during standstill (dry test) as far as possible.

5.7.3 Test plan

The scope, sequence and procedure of the tests as well as the responsibility shall be defined in a test plan. In addition, the initial and boundary conditions (for example head, power) have to be specified for the individual tests.

If necessary, additional measuring and recording facilities shall be installed. This can include equipment to measure:

– valve switching times;
– delay times of emergency and safety shutdown valves;
– actuating pressures in servomotor;
– pressures in the water ways;
– actuator openings;
– control oil pressures;
– turbine speed, power.

The test signals can be generated either internally or externally.

6 Inaccuracies in tests of governing systems

Generally, all tests have errors up to a certain extent.

Systematic errors cannot be eliminated by repetition of measurements, as they are defined by the characteristics of the measuring instruments and by the measuring arrangement.

However, random errors can be reduced by repeated measurements. In case of measurements of governing systems, random errors can only seldomly be determined since these measurements are hardly ever repeated several times.

Therefore, systematic uncertainties are dealt with in the following paragraphs. If no random errors are determined, the real uncertainty of measurements is larger by an unknown but generally small random portion.

In the following, recommendations are given for the admissible, systematic inaccuracies with respect to the most important measured variables dependent on the task to be carried out.

The inaccuracies always cover the complete measuring chain from the transmitter to the display and/or recording including telecontrol transmission.

Disturbing oscillations or noise on the measured variables can be filtered out. The filter should be selected taking into account the essential frequency to avoid perceptible damping and a major phase shift of the signal. For digital acquisition appropriate sampling frequency and proper anti-aliasing have to be considered.

For all measured variables the difference is to be made between plants grouped in the categories defined in Table 1.

Table 1 – Unit and plant categories

Level	Description
I	Units for peak load operation
II	Units for base load operation Units for island operation
III	Other units without special requirements

Tables listing the specific test plans are presented in Annex B.

The admissible values of the instrument inaccuracies for the different categories are shown in Table 2.

Table 2 – Admissible measuring instrument inaccuracies

Item No.	Description	Level I and II	Level III
6.1	**Frequency, speed**		
6.1.1	Insensitivity measurements Inaccuracy relative to rated value f_r absolute inaccuracy (with f_r = 50 Hz)	±0,002 % ±0,001 Hz	±0,1 % ±0,05 Hz
6.1.2	Frequency/speed when measuring static curves Inaccuracy relative to rated value f_r Absolute inaccuracy (with f_r = 50 Hz)	±0,1 % ±0,05 Hz	±0,4 % ±0,2 Hz
6.1.3	Speed during start-up and switching-off processes Inaccuracy relative to rated value f_r absolute inaccuracy (with f_r = 50 Hz)	±0,5 % ±0,25 Hz	±2 % ±1 Hz
6.1.4	Speed during synchronization Inaccuracy relative to rated value f_r Absolute inaccuracy (with f_r = 50 Hz)	±0,05 % ±0,025 Hz	±2 % ±1 Hz
6.2	**Strokes**		
6.2.1	Insensitivity measurement inaccuracy relative to maximum value	±0,05 %	±0,5 %
6.2.2	Synchronism test (synchronous operation) measurements (guide vane – guide vane) Inaccuracy relative to maximum value	±0,05 %	±0,5 %
6.2.3	Strokes during start-up and shut down processes, interconnected grid and island grid operation Inaccuracy relative to maximum value	±1 %	±2 %
6.3	**Power inaccuracy relative to rated power**	**±0,5 %**	**±2 %**
6.4	**Pressure/heads**		
6.4.1	Water passages Pressure/heads during steady state and transient conditions, for example start-up and shut-down processes, interconnected grid and island grid operation Inaccuracy relative to rated head	±2 %	±2 %
6.4.2	Oil pressures Inaccuracy relative to the design pressure p_D	±1 %	±1 %
6.5	**Water levels**		
6.5.1	Water level control Absolute inaccuracy	±0,5 cm	±2 cm
6.5.2	Water level fluctuation in surge tanks. Inaccuracy relative to the difference between the highest and lowest water level in the surge tank	±1 %	±1 %
6.6	**Time**		
6.6.1	Dead times absolute inaccuracy	±0,02 s	±0,05 s
6.6.2	Actuating, synchronising and transient times absolute inaccuracy	±0,2 s	±0,2 s
6.7	**Oil flow** Inaccuracy relative to rated flow	**±5 %**	**±5 %**

7 Simulation of governing and control operations

The simulation of physical processes can reduce the number of tests on the real unit, which saves time and effort.

Workshop acceptance tests of governing and control system can be performed by simulation of physical processes. In those tests, parts of the controlled system which cannot be physically present at the test are simulated. For this, a real time simulator is provided, see also IEC 61362.

The simulation can run as part of the digital governing system or in a separate device, which is connected as hardware-in-the-loop simulator to the governing system.

Different extensions of the simulation can include:

– oil hydraulic system (servomotor, electrohydraulic amplifier);
– unit (water passages, turbine, generator, etc.);
– power plant (multi-unit operation, etc.);
– grid (inertia, island operation, etc.).

The advantage of the separate device is that the interfaces between the control system and the plant simulator can be used just like in the plant itself.

When simulating electronic control functions in workshop tests, important interlocking functions which shall operate reliably have to be implemented.

Regarding inaccuracies introduced by the simulator in the control loop refer to IEC 61362.

8 Organizational aspects of test management

In the process of verifying guarantees set up according to IEC 61362, the following is recommended in case of new governing systems for new plants as well as for existing power plants:

– identify the characteristics of the controlled system (e.g. turbine characteristics, properties of the water passages, servomotor operating times, etc.);
– define scope of governing system tests to verify guarantees and scope of documentation;
– define measures to be taken in the event of failure to comply with guarantees.

For rehabilitation projects, the actual state of the existing governing system shall be verified based on existing documents or site assessment including tests which are agreed upon.

For each test, the following shall be documented:

– instrument parameters;
– list of measured variables;
– limit values;
– test conditions;
– test procedure;
– test results.

The documentation shall be usable as reference for repetitions of the test in order to validate the performance and safety requirements.

The measured values can be recorded and processed either:

– by using suitable data acquisition system with or without separate sensors; or
– directly by internal data acquisition of the digital governing system.

The final report should demonstrate that

– the unit is operating according to specification;
– the safety requirements are fulfilled;
– the specific contractual guarantees are fulfilled.

Annex A
(informative)

Test procedures

A.1 Insensitivity test procedure

(Speed control)

a) Test method 1 (Figure D.2 and Figure D.3)

Measuring values to be recorded:

- ordinate: injected value of speed/frequency or value of set-point corresponding to control mode, actual value of servo motor stroke;
- abscissa: time.

Test procedure:

The desired value of speed/frequency has to be changed in steps (with a disturbance signal) with defined plus/minus steps after reaching steady state. From step to step, the amplitude of speed/frequency change becomes reduced until the servo motor shows no more movement caused by the speed/frequency changes.

The corresponding value of the amplitude of speed/frequency change shows the insensitivity of the governing system. This test should prove that the insensitivity is below a specified value.

b) Test method 2 (Figure D.1)

Measuring values to be recorded:

- ordinate: actual value of speed/frequency (measured from the grid or from an injected signal);
- abscissa: actual value of servo motor stroke.

Test procedure:

If the frequency fluctuations in the grid are too high, an injected signal should be preferred. In the range of insensitivity, where only the speed/frequency signal is changing, the record shows the insensitivity as a band with accumulated, partly vertical lines.

The test should be performed for an appropriate duration until the dead band is identified properly.

The inclination from the band of insensitivity corresponds to the adjusted permanent speed droop.

A.2 Dead time test procedure

Test method:

Measuring values to be recorded:

- ordinate: injected value of speed/frequency, actual value of servomotor stroke;
- abscissa: time.

Test procedure:

The speed/frequency has to be changed in one step which, regarding the droop, corresponds to a change of the servomotor position of more than 10 %. The time between the step of the injected value of speed/frequency and the beginning of the movement of servomotor is the dead time. The test should be performed both in the opening and in the closing direction.

On site the dead time can also be derived from a load rejection. It is the time between the beginning of speed increase and the beginning of the movement of the servomotor.

A.3 Test procedure for the servomotor pressure indication

Test method:

Measuring values to be recorded:

- ordinate: the pressures measured on the opening and closing sides of the servomotor;
- abscissa: the servomotor stroke and/or the corresponding angle;
- with the unit in operation the following additional values can be recorded:
  - oil system pressure;
  - the static head;
  - the tail race level;
  - the generator power.

Test procedure:

In general, the servomotor shall be moved slowly and uniformly to ensure dynamic sliding friction.

The test shall be carried out with the generator connected to the grid from full open position to no-load position and vice versa.

A.4 Procedure for the measurement of the pressure and flow characteristics of control valves

a) Pressure characteristic (see Figure 4 a))

   Measuring values to be recorded:

   - ordinate: pressure in the valve connection ports for opening and closing;
   - abscissa: valve spool position.

   Test procedure:

   The valve connection ports shall be closed or the servomotor shall be in the corresponding end position, where the servomotor piston cannot move, when the control valve opens. The slope of the pressure curve depends on the internal leakage of the control valve or the control valve and the servomotor.

b) Flow characteristic (see Figure 4 b))

   Measuring values to be recorded:

   - ordinate: servomotor speed (flow);
   - abscissa: valve spool position.

   Test procedure:

   The valve spool is displaced to a defined stroke. The inclination from the curve of the servomotor stroke is proportional to the flow under a specified pressure drop. The flow can be calculated with the formula:

   $Q = A \times v$ with the servomotor area A and the velocity v of the servomotor piston.

   $v = \frac{Y}{t}$ with the servomotor stroke Y and the measuring time t.

   The test shall be repeated for several values of the valve spool position.

The flow also depends on the pressure difference Δp between the control valve connection ports to pressure source and tank. The relation is shown by the formula:

$$Q \approx \sqrt{\Delta p}$$

Annex B
(informative)

Recommendation for testing of turbine governing systems

Some of the field tests, as per the Table B.1 to Table B.3, shall be conducted during the pre-start stage prior to filling waterways, commonly referred to as dry tests. All the other field tests are commonly referred to as wet test. Refer to Annex C.

Some of the tests are required to be performed on the hydro-generating unit prior to rehabilitation in order to get reference test results, etc.

The equipment under test shall be operating in the same conditions as in the intended normal operation.

Table B.1 to Table B.3 provide recommended test plans for use in the workshop or on site for the different categories of units.

Table B.1 – Test plan for units for peak load operation, level I

			Workshop tests			Field tests		
Functional group	**Part**	**Test**	**N[a]**	**C[b]**	**Test conditions**	**N[a]**	**C[b]**	**Test conditions**
Overall system	Assembled system	Sensitivity/dead band	-	X	Actual or dummy servomotor Simulated unit, hydro and grid system	-	-	
		Dead time	-	X		-	-	
		Closed loop control (frequency step, load step)	-	X		-	-	
		Full load rejection	-	X		-	-	
Overall system	Complete system	No-load stability	-	-		X	X	Wet test Isolated operation test: Island operation or interconnected operation with simulated speed deviation
		Load stability	-	-		X	X	
		Load rejections	-	-		X	X	
		Shutdowns (ESD, QSD)	-	-		X	X	
		Isolated operation stability test	-	-		-	X	
Subsystems	Servo systems	Static characteristic and accuracy	-	X	Actual or dummy servomotor	-	X	Dry test Wet test
		Dynamic test (step or harmonic response,normally only for type test)	-	X		-	X	
Main modules	Oil hydraulic governor	Servo/proportional valve functional test	X	-	Actual or dummy servomotor	X	X	Wet test
		Distribution valve assembly characteristic	-	X		-	-	
		Shut down functions	X	X		X	X	
		Opening/closing speed	X	X		X	X	
		Manual functions	X	X		X	X	
		Check the overall oil leakage in steady state position of the servomotor	-	-		-	X	
	Electronic governor	Opening control	X	X	Actual or simulated servosystems Simulated unit, hydro and grid system	X	X	Wet test
		Permanent droop and other control functions	-	X		-	X	
		Sequences (if part of the governor)	-	X		X	X	
		Multiple actuator control	X	X		X	X	
		Optimization of parameters	-	X		X	X	
		Supervision/alarms	X	X		X	X	
		Other functions if applicable	X	X		X	X	
Sub-modules	Oil pressure system	Pressure control (if part of the governor)	X	X	Oil quality and temperature within "normal" range	X	X	Wet test
		Pump capacity	X	X		-	-	
		Energy storage capacity	-	X		-	-	
		Power supply	X	X		X	X	
		Alarm/trip signals	X	X		X	X	
	Speed monitoring system	Speed levels	X	X		X	X	
		Supervision/alarms	X	X		X	X	

[a] Normal test plan.

[b] Comprehensive test plan.

Table B.2 – Test plan for units for base load operation, level II

			Workshop tests			Field tests		
Functional group	**Part**	**Test**	**N[a]**	**C[b]**	**Test conditions**	**N[a]**	**C[b]**	**Test conditions**
Overall system	Assembled system	Sensitivity/dead band	-	X	Actual or dummy servomotor Simulated unit, hydro and grid system	-	-	
		Dead time	-	X		-	-	
		Closed loop control (frequency step, load step)	-	X		-	-	
		Full load rejection	-	-		-	-	
Overall system	Complete system	No-load stability	-	-		-	-	Wet test Isolated operation test: Island operation or interconnected operation with simulated speed deviation
		Load stability	-	-		-	-	
		Load rejections	-	-		X	X	
		Shutdowns (ESD, QSD)	-	-		X	X	
		Isolated operation stability test	-	-		-	X	
Subsystems	Servo systems	Static characteristic and accuracy	-	X	Actual or dummy servomotor	-	X	Dry test Wet test
		Dynamic test (step or harmonic response,normally only for type test)	-	X		-	X	
Main modules	Oil hydraulic governor	Servo/proportional valve functional test	X	-	Actual or dummy servomotor	X	X	Wet test
		Distribution valve assembly characteristic	-	X		-	-	
		Shut down functions	X	X		X	X	
		Opening/closing speed	X	X		X	X	
		Manual functions	X	X		X	X	
		Check the overall oil leakage in steady state position of the servomotor	-	-		-	X	
	Electronic governor	Opening control	X	X	Actual or simulated servosystems Simulated unit, hydro and grid system	X	X	Wet test
		Permanent droop and other control functions	-	X		-	X	
		Sequences (if part of the governor)	-	X		X	X	
		Multiple actuator control	X	X		X	X	
		Optimization of parameters	-	X		X	X	
		Supervision/alarms	X	X		X	X	
		Other functions if applicable	X	X		X	X	
Sub-modules	Oil pressure system	Pressure control (if part of the governor)	X	X	Oil quality and temperature within "normal" range	X	X	Wet test
		Pump capacity	X	X		-	-	
		Energy storage capacity	-	X		-	-	
		Power supply	X	X		X	X	
		Alarm/trip signals	X	X		X	X	
	Speed monitoring system	Speed levels	X	X		X	X	
		Supervision/alarms	X	X		X	X	

[a] Normal test plan.

[b] Comprehensive test plan.

Table B.3 – Test plan for other units without special requirements, level III

Functional group	Part	Test	Workshop tests N[a]	Workshop tests C[b]	Workshop tests Test conditions	Field tests N[a]	Field tests C[b]	Field tests Test conditions
Overall system	Assembled system	Sensitivity/dead band	-	-		-	-	
		Dead time	-	-		-	-	
		Closed loop control (frequency step, load step)	-	-		-	-	
		Full load rejection	-	-		-	-	
Overall system	Complete system	No-load stability	-	-		-	-	Wet test
		Load stability	-	-		-	-	
		Load rejections	-	-		-	-	
		Shutdowns (ESD, QSD)	-	-		X	X	
		Isolated operation stability test	-	-		-	-	
Subsystems	Servo systems	Static characteristic and accuracy	-	-		-	X	Dry test
		Dynamic test (step or harmonic response,normally only for type test)	-	-		-	-	
Main modules	Oil hydraulic governor	Servo/proportional valve functional test	X	X		X	X	Wet test
		Distribution valve assembly characteristic	-	-		-	-	
		Shut down functions	X	X		X	X	
		Opening/closing speed	X	X		X	X	
		Manual functions	X	X		X	X	
		Check the overall oil leakage in steady state position of the servomotor	-	-		-	-	
	Electronic governor	Opening control	X	X		X	X	Wet test
		Permanent droop and other control functions	-	-		-	-	
		Sequences (if part of the governor)	-	-		X	X	
		Multiple actuator control	-	-		-	-	
		Optimization of parameters	-	-		-	-	
		Supervision/alarms	X	X		X	X	
		Other functions if applicable	-	-		-	-	
Sub-modules	Oil pressure system	Pressure control (if part of the governor)	X	X	Oil quality and temperature within "normal" range	X	X	Wet test
		Pump capacity	-	X		-	-	
		Energy storage capacity	-	X		-	-	
		Power supply	-	X		-	X	
		Alarm/trip signals	X	X		X	X	
	Speed monitoring system	Speed levels	X	X		X	X	
		Supervision/alarms	X	X		X	X	

[a] Normal test plan.

[b] Comprehensive test plan.

Annex C
(informative)

Field test of governing systems

C.1 General

The commissioning procedure of hydro turbines is described in detail in IEC 60545.

C.2 Data on operating conditions

The following data shall be available prior to the commissioning of the governing system:

– guide vane opening (or needle opening of impulse turbines) for no-load, starting and cavitation limits as function of headwater and tail water levels respectively the head and where applicable, runner blade or deflector opening;
– servomotor opening and closing laws;
– turbine governing system (controllers, etc.) and servomotor characteristics;
– adjustment of overspeed protection device;
– maximum steady-state runaway speed and allowed maximum speed
– water pressure variations according to hydraulic transients limits;
– information about type and cleanliness of the fluid for the oil pressure system;
– information on oil pressures and levels at which the pumps and accumulator should be normally operated;
– maximum and minimum pressures of the oil pressure system.

C.3 Pre-start tests prior to filling waterways

Step No. 1 is as follows:

– calibration of scales and feedback devices for guide vane opening (or needle opening of impulse turbines) and where applicable, for runner blade or deflector opening;
– operation of the oil pressure system consisting of pumps, accumulator, automatic and manually operated starting and stopping devices (control valves, isolating valves etc.) and signalling devices;
– check oil levels and pressures of the oil pressure system; oil pressure system capacity check;
– check protective devices, such as oil level, pressure and temperature alarms and trips, with final adjustments;
– check gatelock operation and interlock function where required, calibration of power transducer;
– check operating time of the servomotors, only limited by orifices, not applicable for some impulse turbines with operating needles by water pressure;
– check operating time of the servomotors with emergency shutdown device.

Step No. 2 is as follows:

– operation of converters (servo valve, proportional valve, etc.);
– check operating times of the servomotors with use of the governing systems, not applicable for some impulse turbines with operating needles by water pressure;
– check the correct operation of the positioning loops;
– verification of safety functions relevant to the governing system.

C.4 Test after filling waterways

Automatic protection devices which actuate the wicket gate (or needles/deflectors for impulse turbines) shall be checked. If required, the operating time of the servomotor can be determined after filling the turbine from the tailrace side. For impulse turbines the operating time of the needles can be checked with the penstock filled and the deflector closed.

C.5 Initial run

During the initial run the operation of the speed measurement systems shall be checked by manually opening the guide vanes or needles until the unit starts turning.

C.6 No-load tests

The generating unit shall be kept under manual control at or above the starting speed (depending on the design of thrust bearing and other bearings). The machine speed shall be increased to the rated value, in order to check that the generator is balanced.

The speed shall be kept at the rated value, until the bearings reach their steady state temperature, which is known as bearing run.

Afterwards a shutdown shall be initiated by a stop command, first by manual operation and then by automatic operation by simulating a fault.

After the bearing run, the generating unit shall be started under automatic control. It shall be checked that the governing system controls the guide vane opening (or needle opening of impulse turbines) and where applicable, for runner blade or deflector opening and that the steady state speed is attained without excessive speed overshoot taking care of the water pressure in the penstock.

The controller parameters shall be optimized for unsynchronised speed no-load operation. The performance shall be checked by varying the speed set point by approximately 1 % to 5 % followed by the governing system to stabilise the speed at the set value.

Machine trips shall be performed by simulating faults, ensuring that the generating unit is not harmed.

Before the load rejection test, the generator unit shall be subject to overspeed test to check the functionality of the mechanical overspeed device or overspeed monitoring system.

C.7 Load and load rejection tests

The synchronizing of the generator to the grid shall be tested. The frequency adjustment is realized by the turbine speed governor as commanded from the synchronizer.

The function of the governing system for load variations shall be checked and the controller parameters for stable operation on the grid shall be optimized.

The operating time of the servomotors shall be re-checked.

The maximum speed rise and pressure rise during load rejection tests, to be performed at 25 %, 50 %, 75 % and 100 % of the rated load shall be determined. For the case that the 100 % of the rated power cannot be reached, the last test shall be performed with the maximum available power.

C.8 Measurement and recordings

The following variables shall be recorded during the above mentioned tests:

– headwater and tailwater levels;
– power output;
– servomotor opening;
– pressure at turbine inlet;
– pressure in draft tube;
– unit speed;
– pressure of the oil pressure system;
– pressure in the servomotor opening and closing chambers;
– any additional governing system variables useful for interpretation.

Annex D
(informative)

Governing system test examples

D.1 General

The following examples refer to specific plants with special governing systems and requirements. Therefore, they cannot be transferred directly to other plants. The test scope, the admissible values as well as the type and extent of the representation can differ considerably from case to case. The examples show briefly the corresponding test procedure, the evaluation methods and the results.

D.2 Insensitivity test under speed control with X-Y recording (example referring to 5.5.3.3.3 and Clause A.1 b))

6-jet Pelton turbine, H_r = 1 260 m, P_Gr = 260 MW; electronic PI speed controller; unit in interconnected grid operation; minimum integral action time T_i, maximum proportional-action gain K_P for stable operation; insensitivity of a needle position to frequency variations.

a) Measuring recording, see Figure D.1
   - Ordinate: power system frequency, taken from wall socket, filtered (low-pass filter, frequency 55 Hz).
     - Measuring instrument: cycle measuring instrument with 0,25 mHz resolution within 2 s integration time.
     - Measuring uncertainty:

       $| f_\mathrm{n} | = 10^{-5}$ = 0,001 %, $| \Delta f |$ = 0, 5 mHz.
   - Abscissa: needle stroke Y_nz in percent.
     - Measuring instrument: capacitive angular transmitter, resolution approximately 0,01 mm needle stroke.
     - Measuring uncertainty:

       $| f_\mathrm{y} |$ = 0,01 % needle stroke.

b) Evaluation and results
   - Dead band (vertical distance of the envelope line):
     i_x = 0,011 1 Hz, related to 50 Hz in p.u.: $2{,}2 \times 10^{-4}$.
   - Insensitivity (dead band / 2):
     $i_\mathrm{x}/2 = 1{,}1 \times 10^{-4}$ corresponding to 0,005 5 Hz..
     (recommended limit according to IEC 61362: 2×10^{-4}).
   - Permanent speed droop:
   - $b_\mathrm{p} = \dfrac{\Delta f\,[\mathrm{Hz}]/50}{\Delta Y_\mathrm{nz}/Y_\mathrm{nz\,max}} \times 100\ \% \sim 4\ \%$.
   - The requirement for a peak-load power plant is fulfilled.

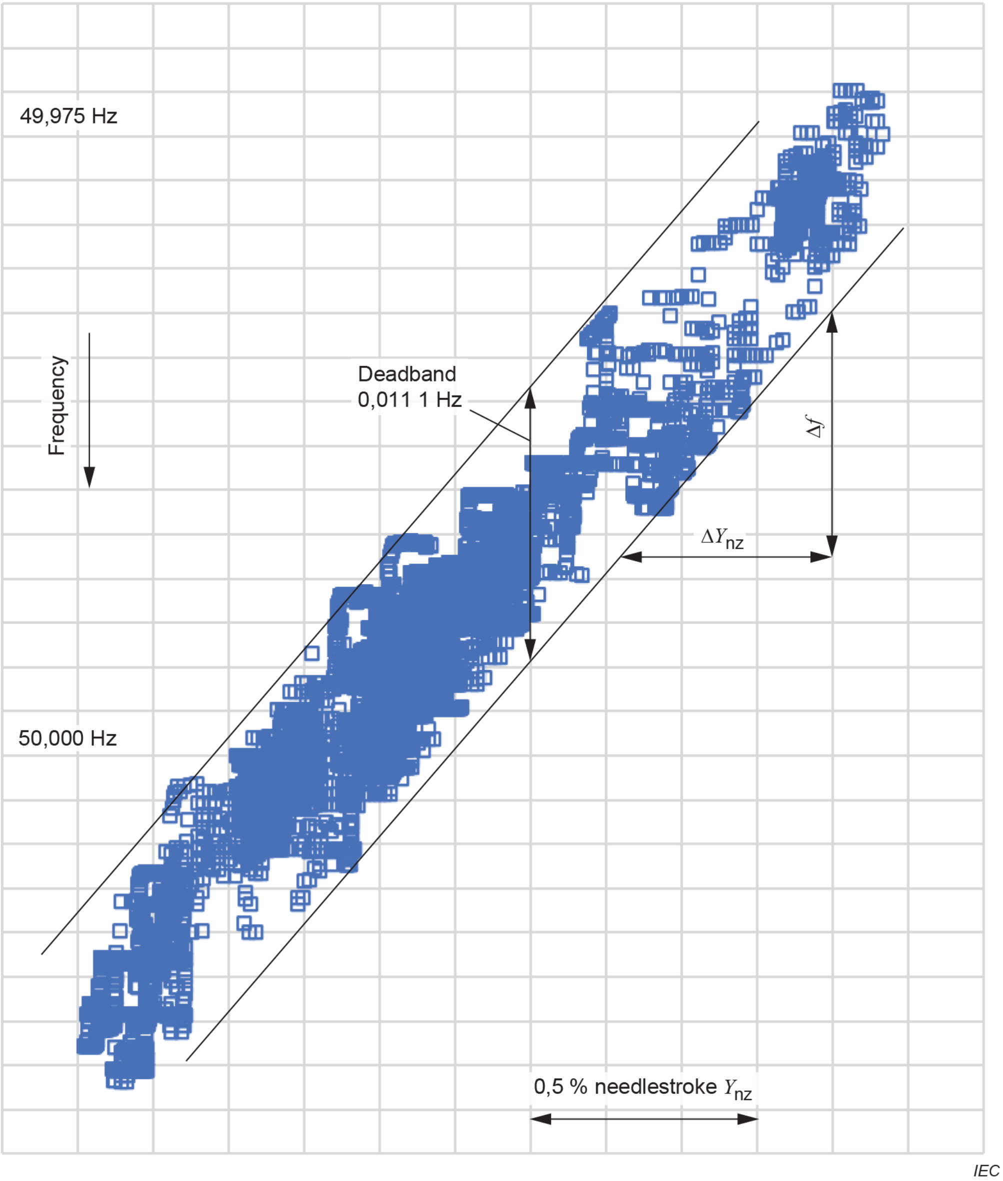


Figure D.1 – Insensitivity test under speed control with X-Y recording

D.3 Insensitivity test under opening control with frequency-opening-droop and time characteristics (example referring to 5.5.3.3.4 and Clause A.1 a))

4-jet Pelton turbine, H_r = 748 m, P_{Gr} = 72 MW; electronic opening controller; machine in interconnected grid operation; frequency-opening-droop switched on; insensitivity of a jet needle with frequency step change; minimum step amplitude ± 0,003 Hz.

a) Measuring recording, see Figure D.2
   - Ordinate: needle stroke Y_{nz} as unit step response.
   - Measuring instrument: linear sensor, resolution approximately 0,1 mm.
   - Measuring uncertainty: $|f_y|$ = approximately 0,05 % needle stroke.
   - Abscissa: time.

b) Result and evaluation

- Clear response to a set-point step change of ±0,06 % of full load.
- Insensitivity: $i_x/2 < 0{,}6 \times 10^{-4}$ (recommended limit according to IEC 61362: $i_x/2 < 2 \times 10^{-2}$).
- The requirement for a peak-load power plant is fulfilled.

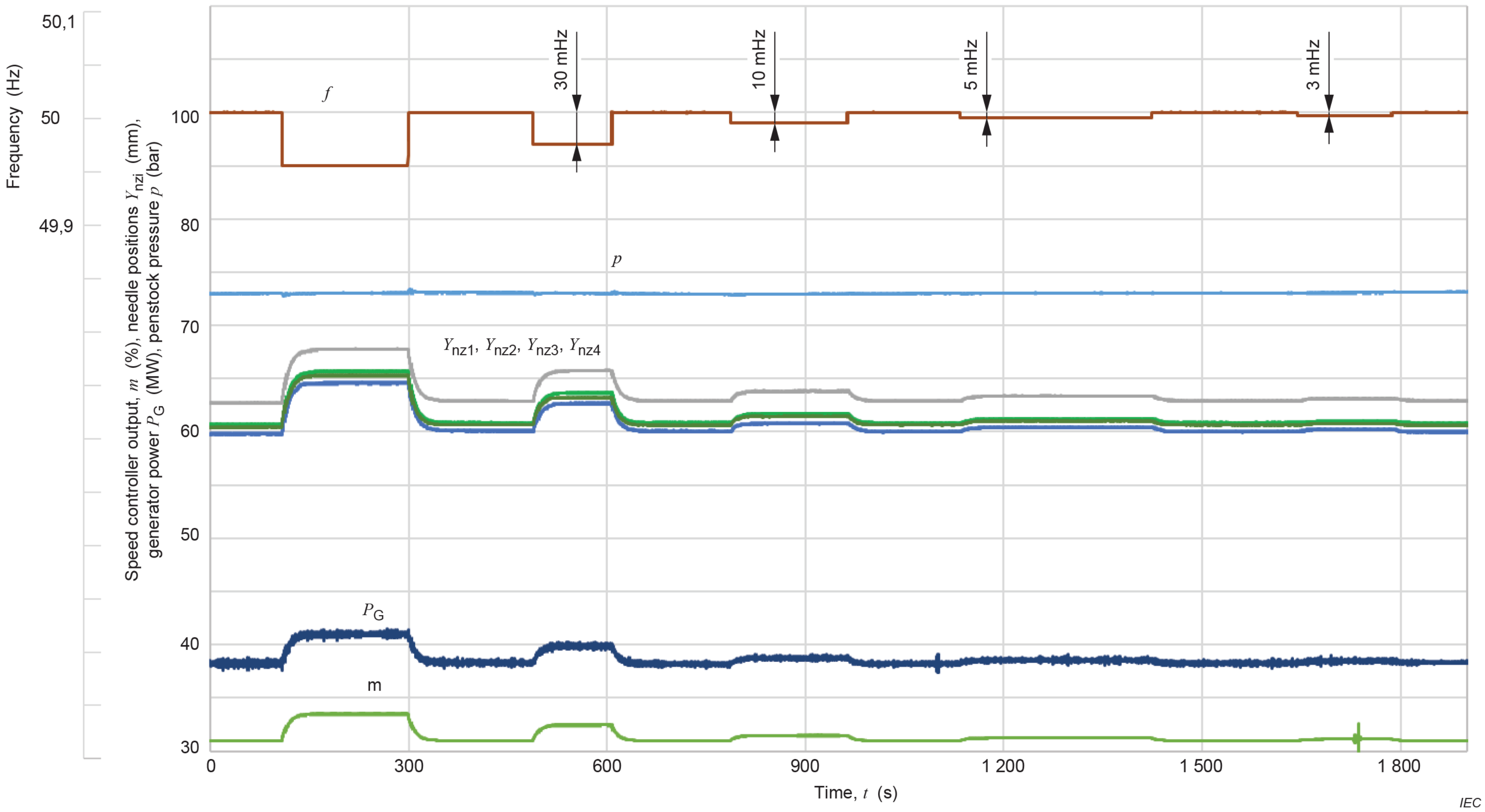


Figure D.2 – Insensitivity test under opening control with time characteristics

D.4 Insensitivity test under power control with time characteristics (example referring to 5.5.3.3.4 and Clause A.1 a)

6-jet Pelton turbine, H_r = 1260 m, P_{Gr} = 260 MW; electronic PI power controller; machine in interconnected grid operation; frequency-power-droop switched off; insensitivity of a jet needle with power set-point step changes; minimum step value in negative direction: -3 mV corresponding to -320 kW or -0,12 % of total load.

a) Measuring recording, see Figure D.3
   - Ordinate: needle stroke Y_{nz} as unit step response.
   - Measuring instrument: capacitive angular transmitter, resolution approximately 0,01 mm.
   - Measuring uncertainty: $|f_y|$ = approximately 0,01 % needle stroke.
   - Abscissa: time.

b) Result and evaluation
   - Clear response to set-point step change of -0,12 % of full load in negative direction.
   - dead band: $i_x < 0{,}12\ \% = 12 \times 10^{-4}$
   - Insensitivity: $i_x/2 < 6 \times 10^{-4}$ (recommended limit according to IEC 61362: $i_x/2 < 1 \times 10^{-2}$).
   - The requirement for a peak-load power plant is fulfilled.

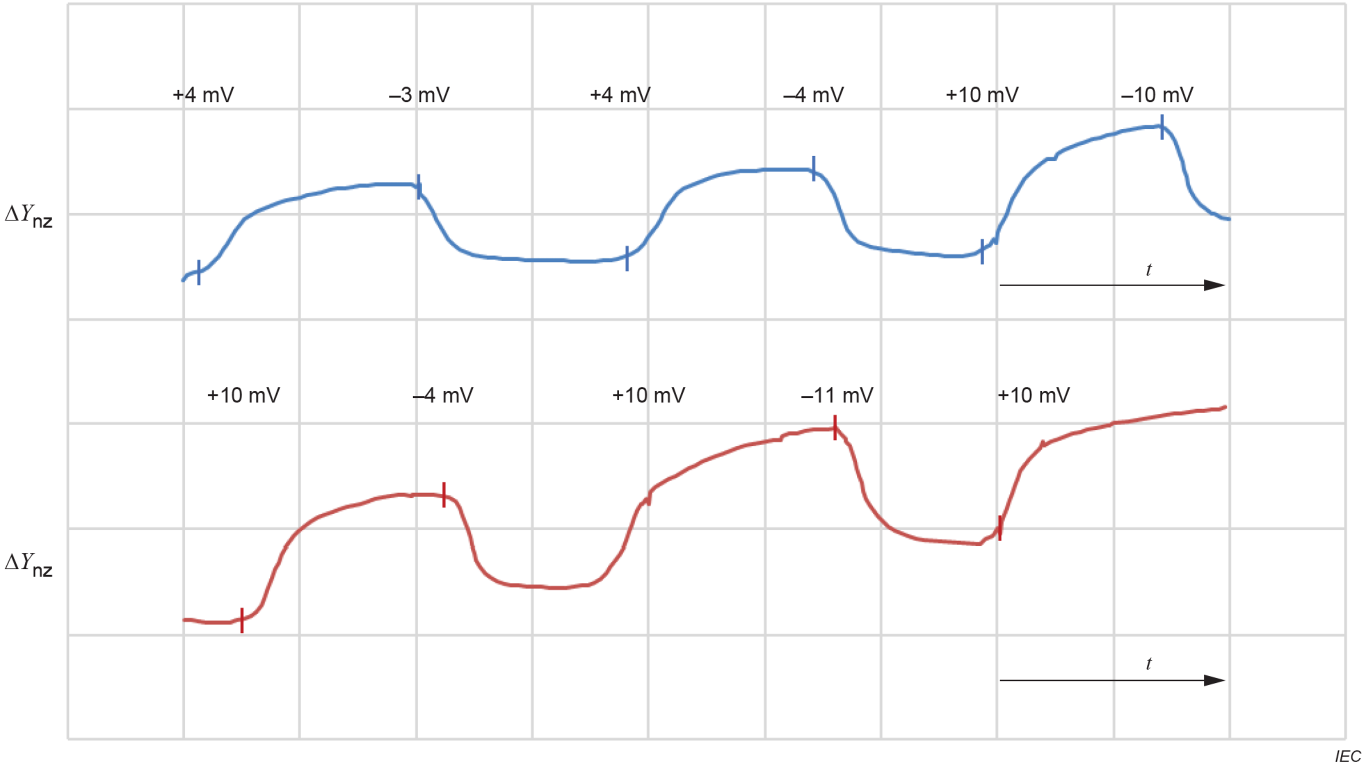


Figure D.3 – Insensitivity test under power control with time characteristics

D.5 Synchronism test of two controlled quantities with X-Y recording (example referring to 5.5.3.4)

Pump-turbine, H_r = 350 m, P_{Gr} = 275 MW; electronic speed and power controller with power feed-forward-control; individual guide vane control; slow adjustment of gate limiter in the range between 50 % and 80 % of the guide vane opening.

a) Measuring recording, see Figure D.4
   - Ordinate: stroke of guide vane No. 12, Y_{12ga} in percent.
   - Abscissa: stroke of guide vanes No. 2 and No. 20, Y_{2ga}, Y_{20ga} in percent.
   - Measuring instruments for ordinate and abscissa.
   - Angular transmitter (feedback transducer), resolution approximately 0,005 % of full guide vane angle.
   - Measuring uncertainty: | f_y | = 0,01 % of full guide vane angle.

b) Result and evaluation
   - Synchronism performance: largest deviation (hysteresis) approximately 0,27 % between guide vanes 20 and 12, and approximately 0,16 % between guide vanes 2 and 12.
   - The synchronous operation of the guide vanes is good.

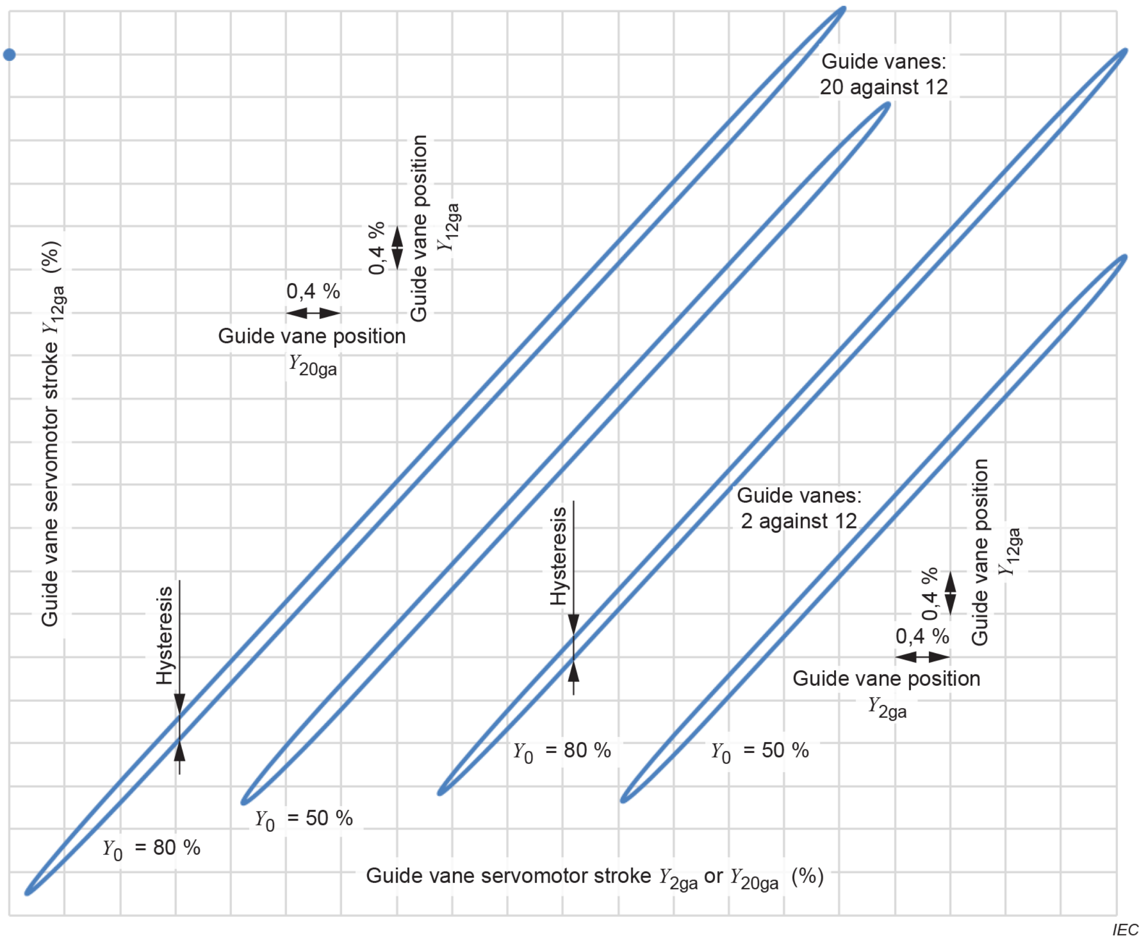


Figure D.4 – Synchronism test of two controlled quantities with X-Y recording

D.6 Measurement of a unit step response with PID speed controller (example referring 5.5.4.2 and 5.5.3.1)

Pump-turbine, H_r = 430 m, P_{Gr} = 154 MW; electronic PID speed controller with permanent speed droop, individual guide vane control; unit in grid operation, controller speed input open, controller mode “island operation“, Triggering: input of a simulated speed step of +1 %.

a) Measuring recording, see Figure D.5
   - Ordinate for triggering signal: without scale.
   - Ordinate 1, percent values: speed controller output m_1, input to the servo-positioner m_2 (according to actuator laws), mean value of servomotor stroke Y_{ga}, generator actual power value P_G.
   - Ordinate 2: head on pressure side ΔH in m.
   - Measuring instruments: industrial measuring instruments.
   - Measuring uncertainty (estimation):
   - For all percentage values related to the nominal range, approximately ±1 % absolute; for the head ±2 m.
   - Abscissa: time.

b) Result and evaluation
   - The speed controller output shows a clear PID behaviour.
   - Due to the limitation of the actuating speed, the derivative action at the input to the servo-positioner can hardly be recognised. The same applies to the servomotor stroke. The derivative action mainly serves for compensating delays and insensitivities.
   - The average servomotor movement starts delayed by approximately $T_q \approx 0{,}25$ s.
   - The power characteristic clearly shows the influence of the pressure surge; power only starts changing in the correct direction after approximately 3,6 s (non-minimum phase behaviour).

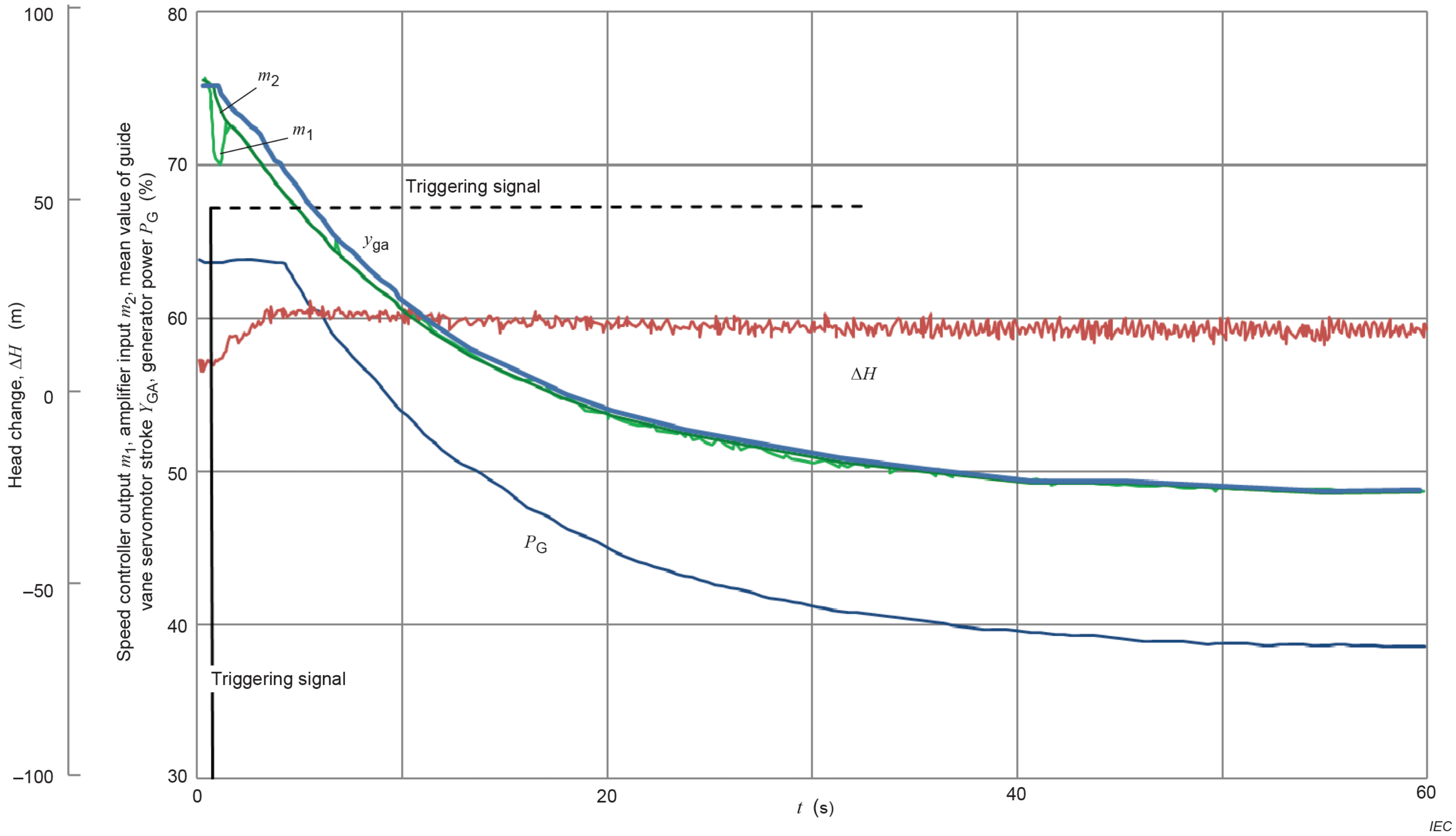


Figure D.5 – Measurement of a unit step response with PID speed controller

D.7 Measurement of a unit step response with speed control for determination of PID controller parameters (example referring to 5.5.4.2; 5.5.3.1)

2-jet Pelton turbine, H_r = 1 250 m, P_{Gr} = 85 MW; digital speed controller with PID algorithm and permanent speed droop; unit in grid operation; frequency controller input open; mode of speed controller – "Opening Control"; input of a simulated frequency step of ± 200 mHz.

a) Measuring recording, see Figure D.6
   - Ordinate 1: penstock pressure in bar (measured with a dedicated sensor)
   - Ordinate 2: injector position in mm (measured with a dedicated sensor).
   - Ordinate 3: PID controller output in % (measured on an analogue output of the controller)
   - Ordinate 4: deflector position in mm (measured with a dedicated sensor)
   - Ordinate 5: power in MW (measured with a dedicated sensor)
   - Ordinate 6: aimulated frequency (injected by a frequency generator and measured with a dedicated sensor)
   - Abscissa: time.

b) Result and evaluation
   - The speed controller output shows PID behaviour.
   - Considering the sudden frequency change of –0,2 Hz the following controller parameters result with reference to the controller output:

Proportional gain:	K_p = (1/0,004) × 0,008 = 2	(PID controller output deviation = 0,8 %)
Integral action time:	T_i = 0,8 s	
Permanent speed droop:	b_p = 100 × (0,004/0,10) = 4 %	(PID controller output deviation = 10 %)

These calculations can also be done by measuring the relative injector position deviation instead of the PID controller output deviation but results are less relevant.

If the PID controller structure is well known, it is possible to compare the time response for a 63 % deviation and to compare it to the theoretical time response.

For example: Theoretical 63 % time response for this controller is equal to
$(K_p \times b_p) \times T_i/(1 + K_p \times b_p)$ = 8,1 s

The "63 % time response measured" = 8,3 s (positive sense) 8,2 s (negative sense)

Additional comments:

The D-part at the speed controller output can be clearly recognised; it is practically eliminated by the limitation of the positioning speed of the servomotor.

For this example, deflector's positions are also controlled by the PID controller (with a special structure developed to improve the behaviour of the turbine for island grid operation or load rejection mode).

Controller parameters: b_p = 4 %, K_p = 2, T_i= 0,6 s, T_d = 0,3 s, K_d = 5

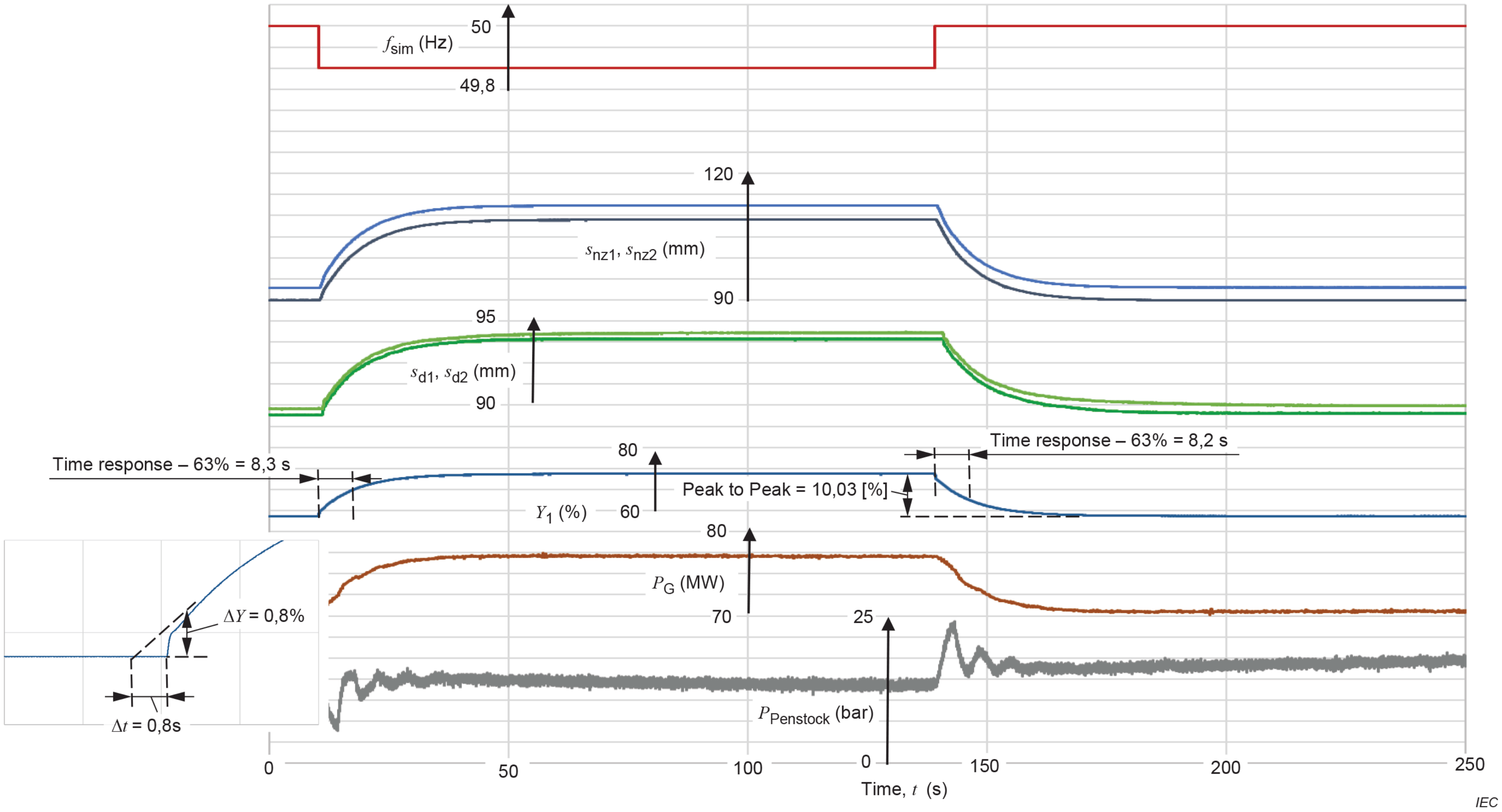


Figure D.6 – Measurement of a unit step response with speed control for determination of PID controller parameters

D.8 Measurement of a unit step response with speed control for determination of PID controller parameters (example referring to 5.5.4.2; 5.5.5)

Two-jet Pelton turbine, H_r = 714 m, P_{Gr} = 30 MW; digital speed controller with PID algorithm and permanent speed droop; unit in grid operation; speed controller input open; mode of speed controller – "island operation"; input of a simulated speed step of –0,42 %.

a) Measuring recording, see Figure D.7 a)
   - Ordinate 1: speed n in percent.
   - Ordinate 2: penstock pressure H in m.
   - Ordinate 3: percentage scale for speed controller output s, needle stroke Y_{nz} and generator power output P_G.
   - Measuring instruments for ordinates: industrial measuring instruments.
   - Measuring uncertainty (estimation):
   - For all percentage values related to the nominal range, approximately ±1 % absolute; for the head ±2 m.
   - Abscissa: time.

b) Measuring recording, see Figure D.7 b)

   The controller output s and the needle stroke Y_{nz} are plotted scaled up.

c) Result and evaluation
   - The speed controller output shows PID behaviour.
   - Considering the sudden frequency change of –0,21 Hz respectively –0,42 % the following controller parameters result with reference to the controller output:
     - proportional gain: $K_p = \frac{1}{0{,}004\,2} \times 0{,}012\,5 = 3$ (servomotor stroke: 1,25 %);
     - integral action time: $T_i \sim 6{,}5$ s (sub-tangent);
     - permanent speed-opening droop: $b_p = \frac{0{,}004\,2}{0{,}106} \times 100\,\% = 4\,\%$ (servomotor stroke: 10,6 %).
   - The derivative action at the speed controller output can be clearly recognised; it is practically eliminated by the limitation of the positioning speed of the servomotor.

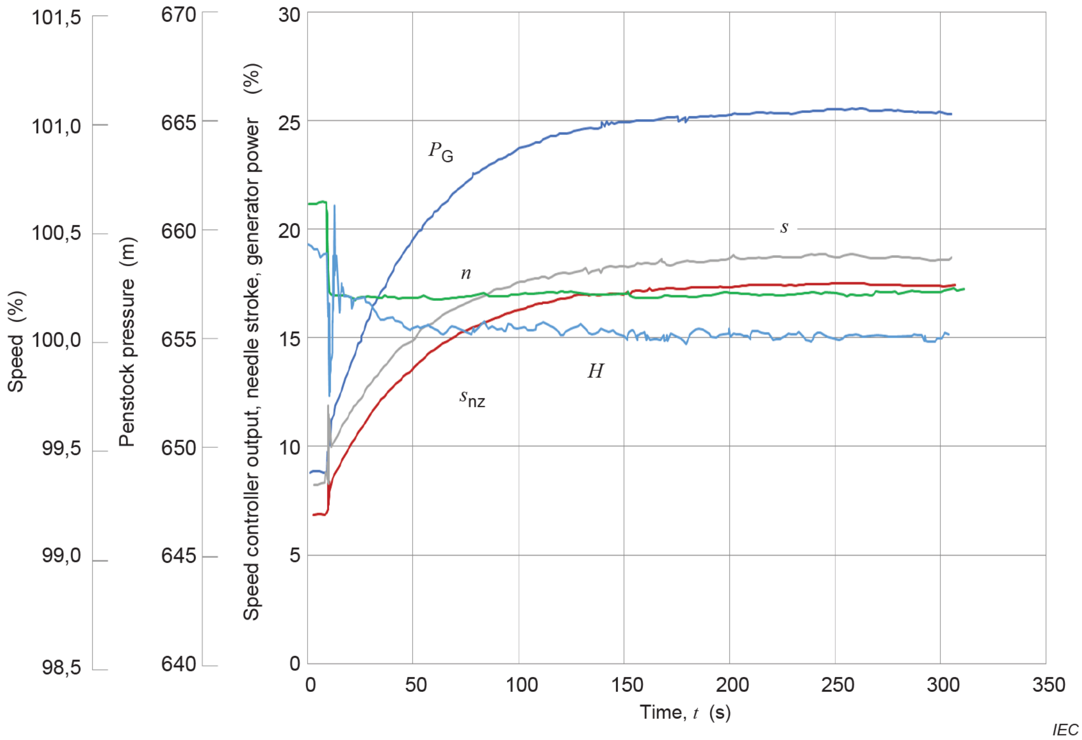


Figure D.7a)

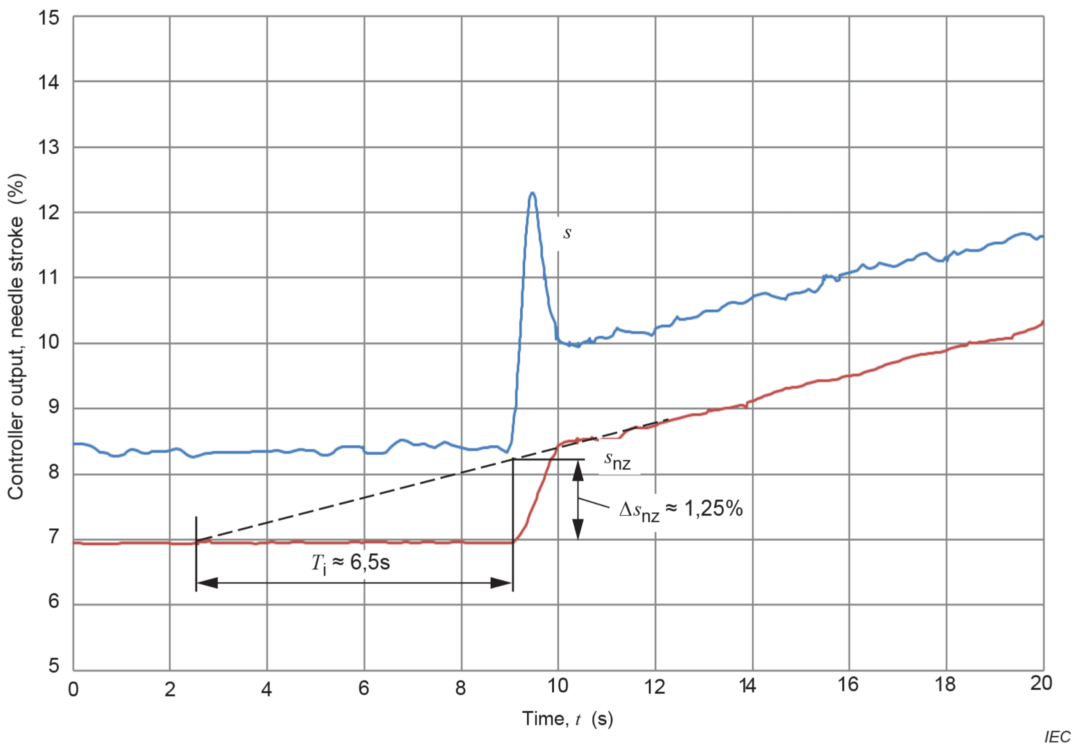


Figure D.7b)

Figure D.7 – Measurement of a unit step response with speed control for determination of PID controller parameters

D.9 Measurement of a unit step response in island operation (example referring to 5.5.5.3)

Two-jet Pelton turbine, H_r = 714 m, P_{Gr} = 30 MW; digital speed controller with PI – algorithm and permanent speed droop; island operation with load from pumps; load step –4,6 MW = –15,3 % P_{Gr}.

a) Measuring recording, see Figure D.8
  - Ordinate 1: speed n in percent.
  - Ordinate 2: percentage scale for penstock pressure H and deflector stroke Y_{de}.
  - Ordinate 3: percentage scale for speed controller output s, needle stroke Y_{nz} and generator power P_G.
  - Measuring instruments for ordinates: industrial measuring instruments.
  - Measuring uncertainty (estimation):
  - For all percentage values related to the nominal range approximately ±1 % absolute; for the head ±2 m.
  - Abscissa: time.

b) Result and evaluation
  - The frequency rises temporarily by approximately 3 % causing the deflectors to engage. After a short undershoot, the frequency reaches the new final value after approximately 45 s.
  - The speed controller output overrides in the closing direction.
  - The needles close for about 7 s with maximum velocity until speed decreases again and reaches the new final value after about 30 s.
  - The pressure variations are damped relatively quickly, a small power oscillation remains with an amplitude of approximately 0,75 %. Frequency variations can hardly be noticed.
  - The control circuit is stable.

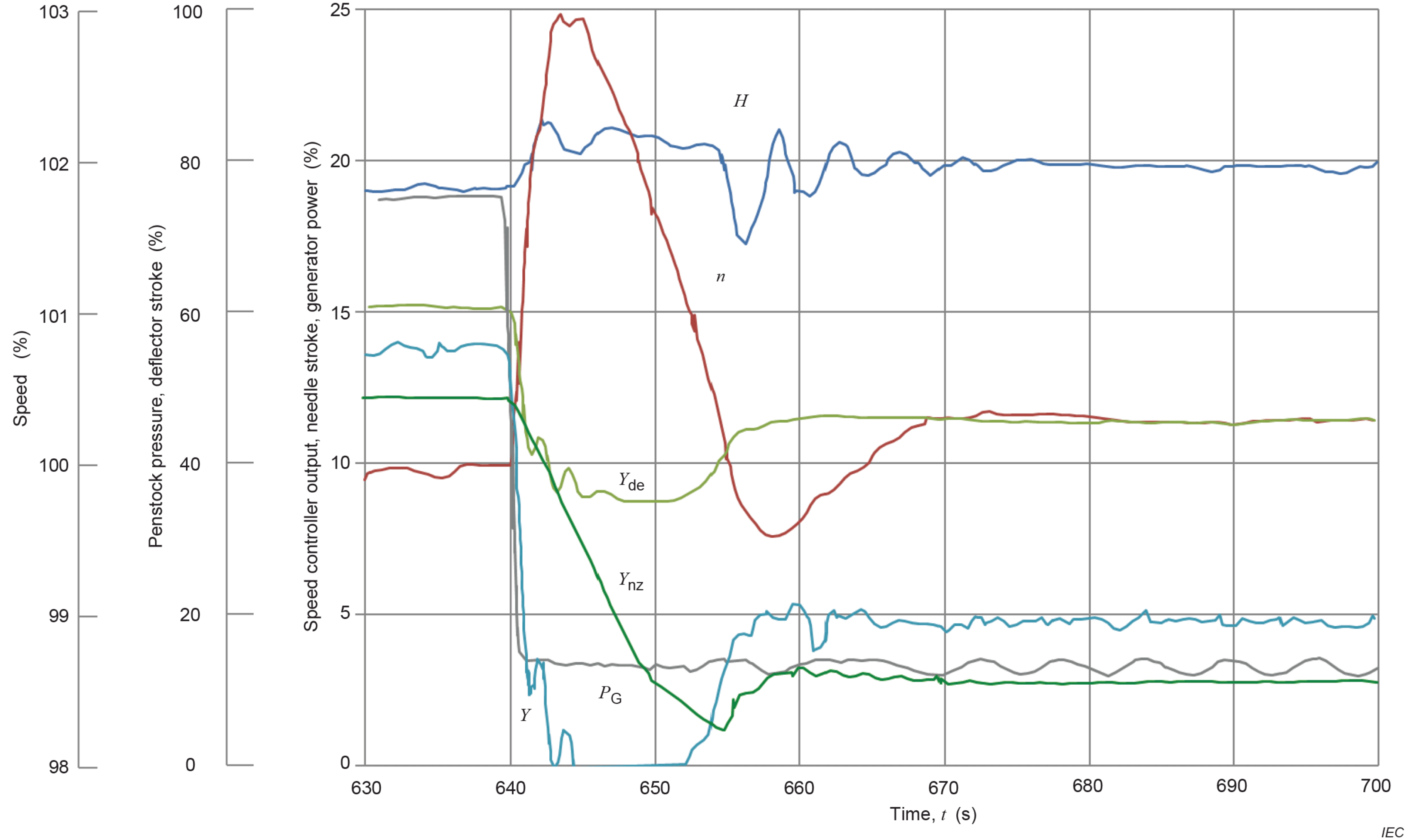


Figure D.8 – Measurement of unit step response in island operation

D.10 Measurement of unit step responses with power control (example referring to 5.5.4.3 and 5.5.4.6)

Two-jet Pelton turbine, H_r = 714 m, P_{Gr} = 30 MW; digital power controller with PI algorithm and permanent speed droop without power feedforward control; unit connected to the grid with power controller; input of simulated frequency steps of ±0,42 % at the power controller frequency input.

a) Measuring recording, see Figure D.9
   - Ordinate 1: speed n in percent.
   - Ordinate 2: penstock pressure H in m.
   - Ordinate 3: percentage scale for controller output s, needle stroke Y_{nz} and generator power P_G.
   - Measuring instruments for ordinates: industrial measuring instruments.
   - Measuring uncertainty (estimation):
   - For all percentage values related to the nominal range approximately ±1 % absolute; for the head ±2 m.
   - Abscissa: time.

b) Result and evaluation
   - The power controller output shows PI behaviour.
   - The limitation of the closing velocity can clearly be noted.
   - In each case, the steady-state load is reached after approximately 40 s.
   - Permanent speed-power droop. $b_p = \frac{0,0042}{0,14} \times 100\% = 3\%$ (power change 14 %).

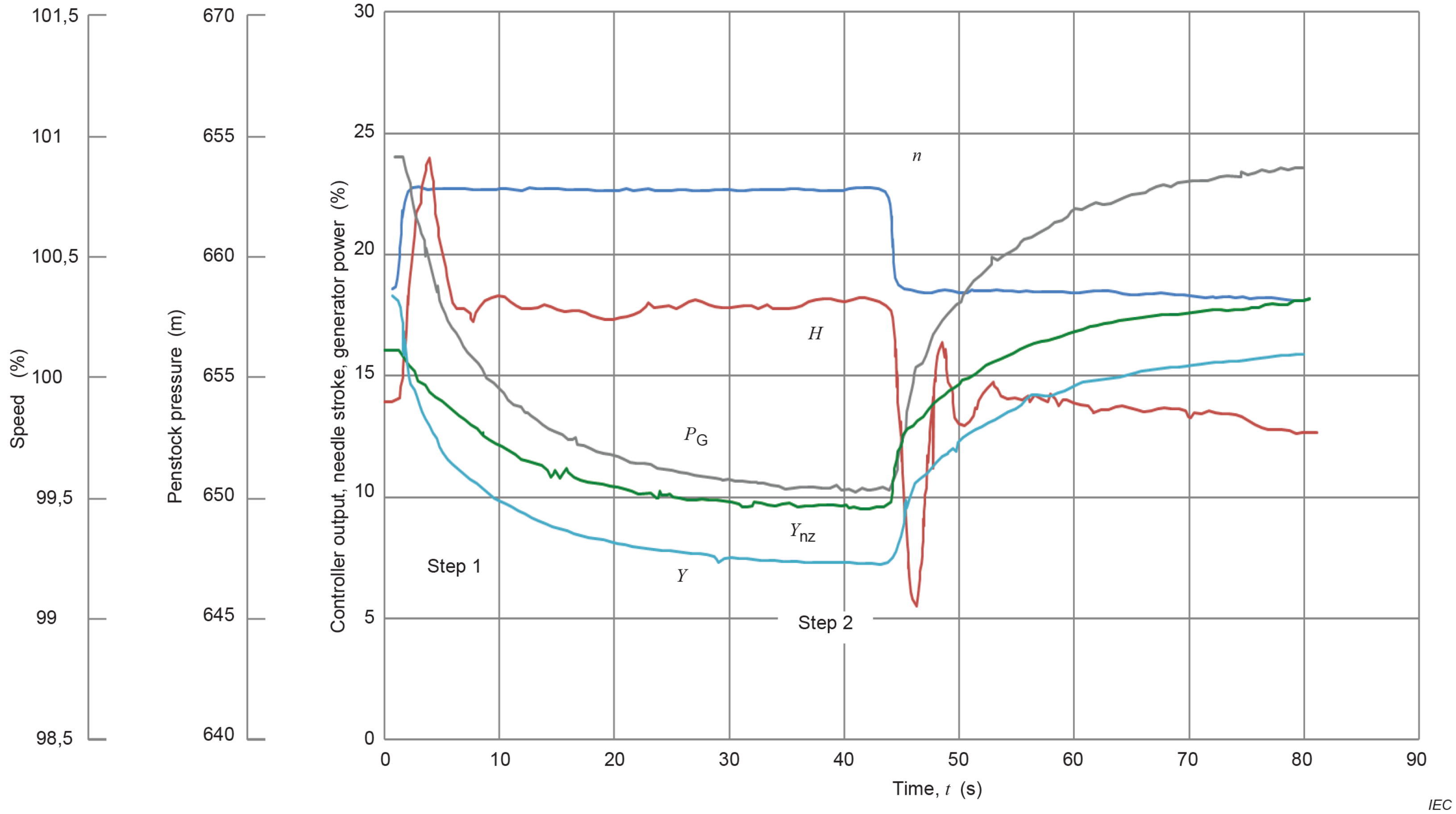


Figure D.9 – Measurement of a unit step responses with power control (Pelton turbine)

D.11 Measurement of unit step responses with power control (example referring to 5.5.4.3 and 5.5.4.6)

Pump-turbine, H_r = 350 m, P_{Gr} = 275 MW; electronic power controller with power feed-forward control; individual guide vane control; unit connected to the grid with power control; step change of the power set-point.

a) Measuring recording, see Figure D.10
   - Ordinate 1: percentage scale for guide vane position Y_{ga} and generator power P_G.
   - Ordinate 2: penstock pressure H in bar.
   - Measuring instruments for ordinates: industrial measuring instruments.
   - Measuring uncertainty (estimation):
   - For all percentage values related to the nominal range approximately ±1 % absolute; for the head, ±0,2 bar.
   - Abscissa: time.

b) Result and evaluation
   - Due to the effect of the feed-forward control, the guide vane movement is almost linear up to the final position. Because the change of power is delayed, the guide vane overrides a little.
   - Due to the pressure surge, the power changes first in the opposite direction (approximately 1 %) and shows a time delay referred to the change of the guide vane position (approximately 1,5 s when closing and 3 s when opening).

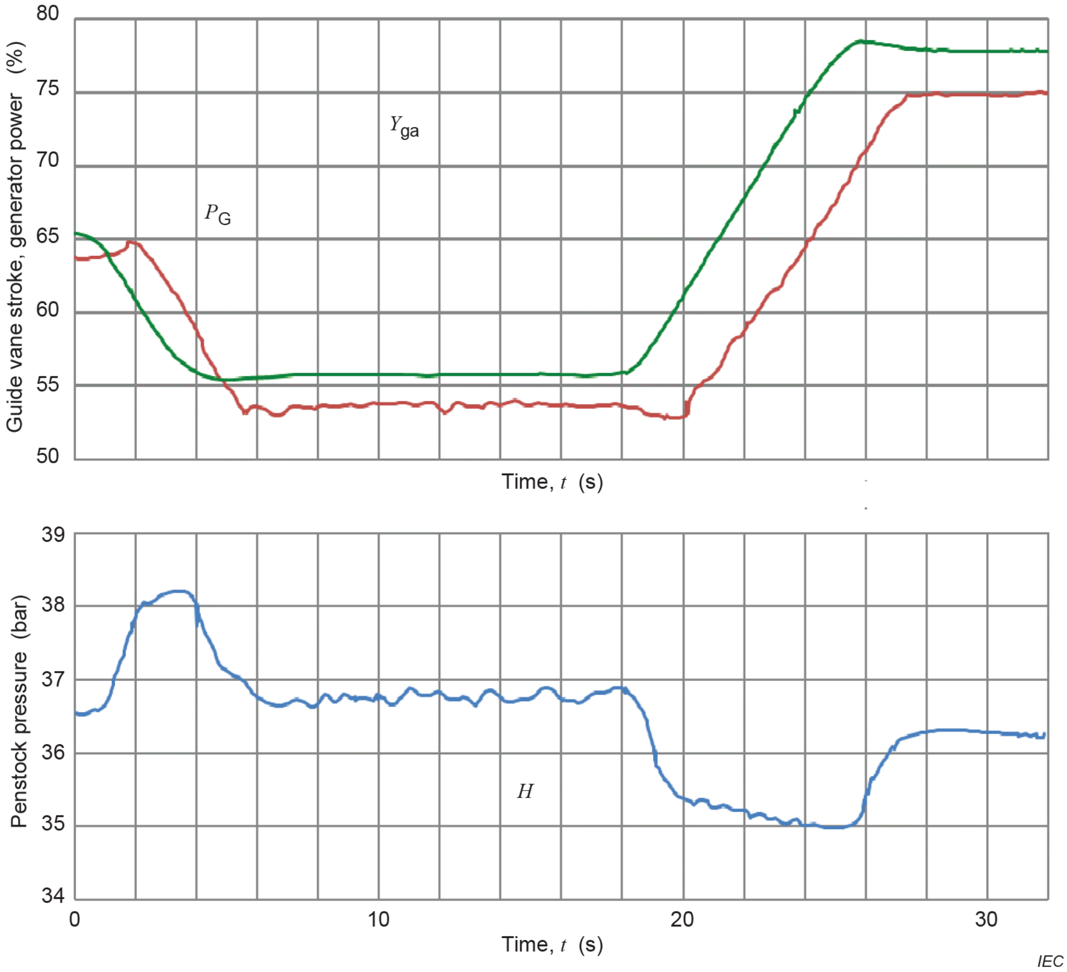


Figure D.10 – Measurement of unit step responses with power control (pump-turbine)

D.12 Measurement of a unit step response with power control for determination of PI-controller parameters (example referring to 5.5.4.3)

Pump-turbine, H_r = 430 m, P_{Gr} = 154 MW; electronic PI power controller with power feed-forward control; individual guide vane control; unit connected to the grid, controller inputs for the actual speed and power values are open; input of a simulated permanent power variation of 5 % (power feed-forward not active), simulated speed remains constant.

a) Measuring recording, see Figure D.11
   - Ordinate 1: percentage scale for power controller output Y, mean value of the servomotor strokes Y_{ga}, generator power P_G, (trigger signal without scale).
   - Ordinate 2: change of penstock pressure ΔH in m on pressure side.
   - Measuring instruments for ordinates: industrial measuring instruments.
   - Measuring uncertainty (estimation):
   - For all percentage values related to the nominal range approximately ±1 % absolute; for the head ±2 m.
   - Abscissa: time.

b) Result and evaluation

– The power controller output has an almost ideal PI behaviour.

– The average servomotor movement starts with a delay of T_q = 0,27 s; the limitation of the closing velocity can clearly be seen.

– Considering a simulated 5 % power variation on the actual power value, the following controller parameters result related to the controller output:

– Proportional gain: $K_\mathrm{p} = \frac{1}{0{,}05} \times 0{,}024\,7 = 0{,}49$ (servomotor stroke = 2,47 %).

– Integral action time T_i = 4,2 s (sub-tangent).

– The measuring uncertainty is estimated to be: $|\Delta K_\mathrm{p}| \approx 0{,}1$; $|\Delta T_\mathrm{i}| \approx 0{,}5$ s.

– The power curve clearly shows the influence of the pressure surge.

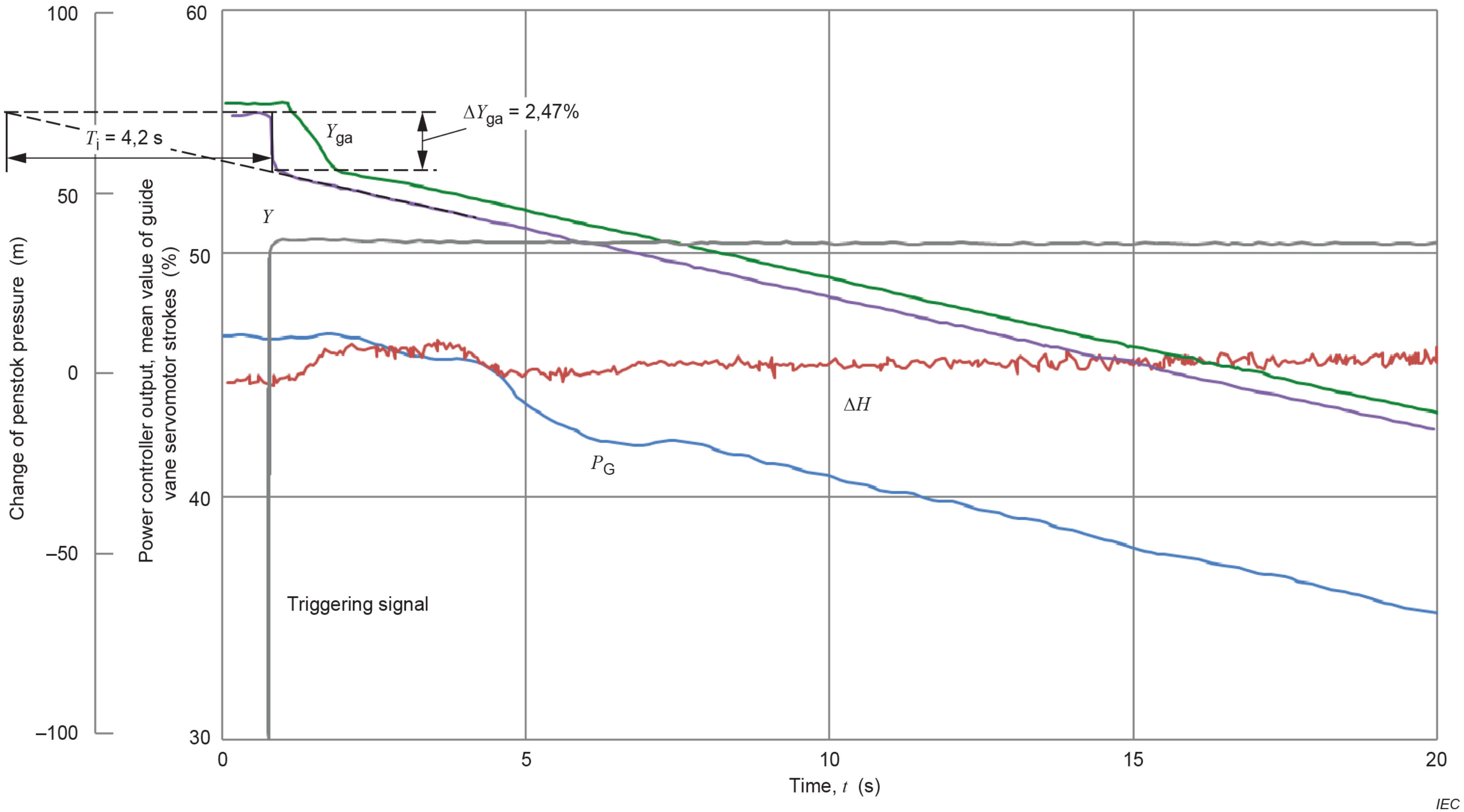


Figure D.11 – Measurement of a unit step response with power control for determination of PI-controller parameters

D.13 Measurement of a unit step response with headwater level control (example referring to 5.5.4.4)

Plant with two Francis and two Pelton turbines, H_r = 190 m; for each turbine P_{Gr} = 6 MW, Q_r = 3,5 m^3/s; equalising basin of approximately 2 000 m^2 surface.; mechanical turbine speed controller with superimposed digital level controller acting on the opening limiters of the four mechanical turbine controllers via a three-position controller; input of a 0,5 m set-point step change when operating a Pelton turbine with P_G ~ 4,9 MW.

Limits: minimum load 1 MW, maximum load 5,9 MW.

a) Measuring recording, see Figure D.12 a) and Figure D.12 b)

   Figure D.12 a)

   – Ordinate: headwater level set-point and actual value in m.

   – Abscissa: time.

   Figure D.12 b)

   – Ordinate 1: variation of penstock pressure ΔH in m.

   – Ordinate 2: generator power P_G in MW.

   – Abscissa: time.

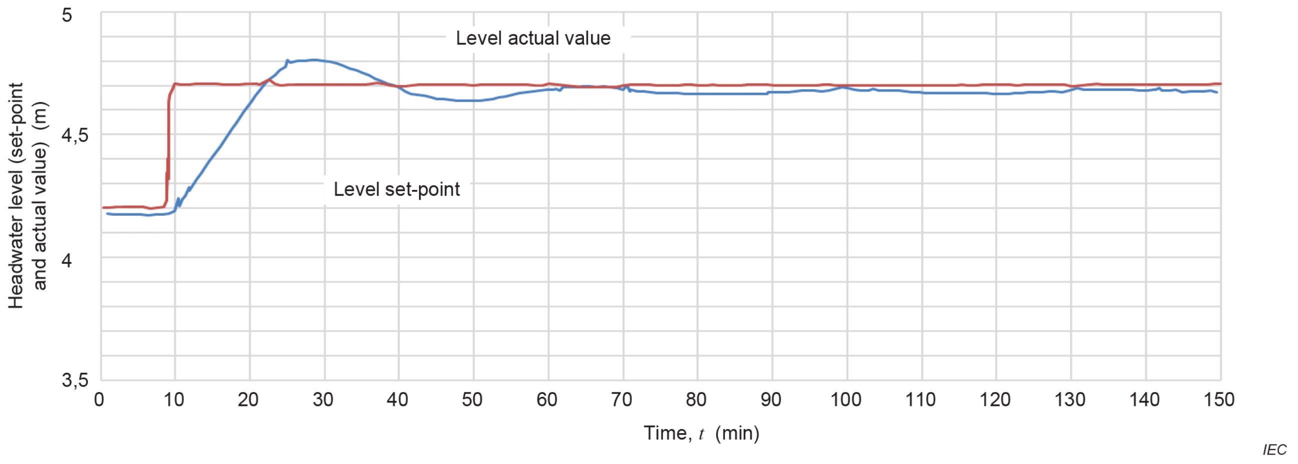
   Measuring instruments: industrial measuring instruments, digital recorder.

   Measuring uncertainty (estimation): level ±0,02 m; load ±0,1 % of nominal load.

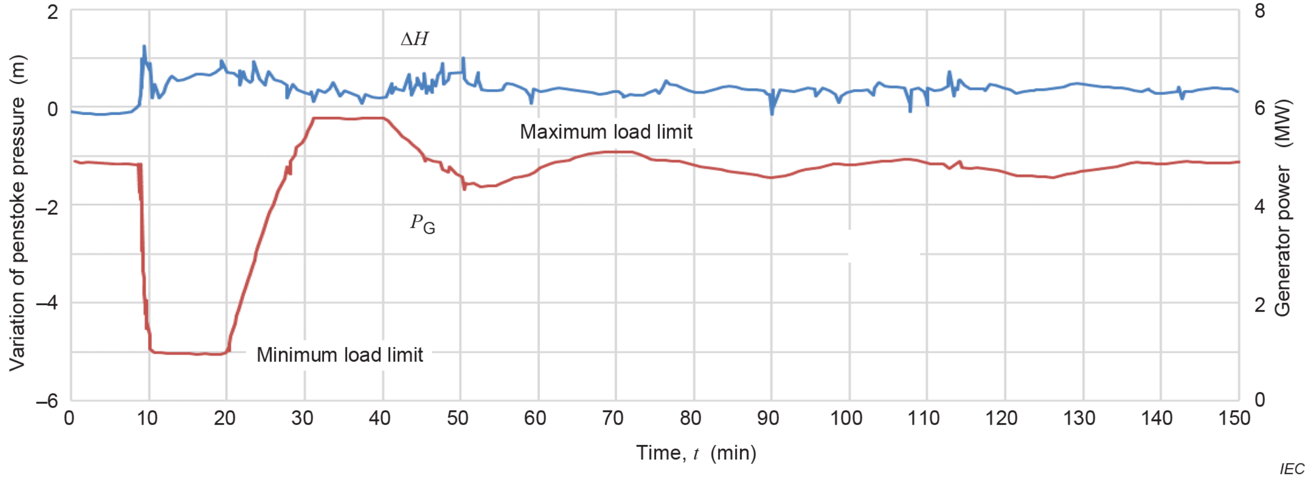
b) Result and evaluation

   The actual level value reaches the new set-point value after an overshoot; the largest overshoot is approximately 0,1 m, thus remaining below the admissible deviation of 0,2 m.

   Temporarily, the turbine is reaching both load limits.



a)



b)

Figure D.12 – Measurement of a unit step response with headwater level control

D.14 Measurement of the unit step responses with headwater level control, in multi-unit operations (example referring to 5.5.4.4)

Plant with two Francis and two Pelton turbines, H_r = 190 m; for each turbine P_{Gr} = 6 MW, Q_r = 3,5 m^3/s; equalising basin of approximately 2 000 m^2 surface; mechanical turbine controller with superimposed digital level controller acting on the opening limiters of the four mechanical turbine controllers via a three-position controller; plant operating two Francis and one Pelton turbine; after 5 min, input of a –0,5 m set-point step change; after 38 min, input of a +0,5 m set-point step change; after 96 min – unit 3 switched off from level control and machine load reduced to 1 MW.

Limits: minimum load – Francis turbine – 2 MW; minimum load – Pelton turbine – 1 MW; maximum load – 5,5 MW.

a) Measuring recording, see Figure D.13 b)

   Figure D.13 a)

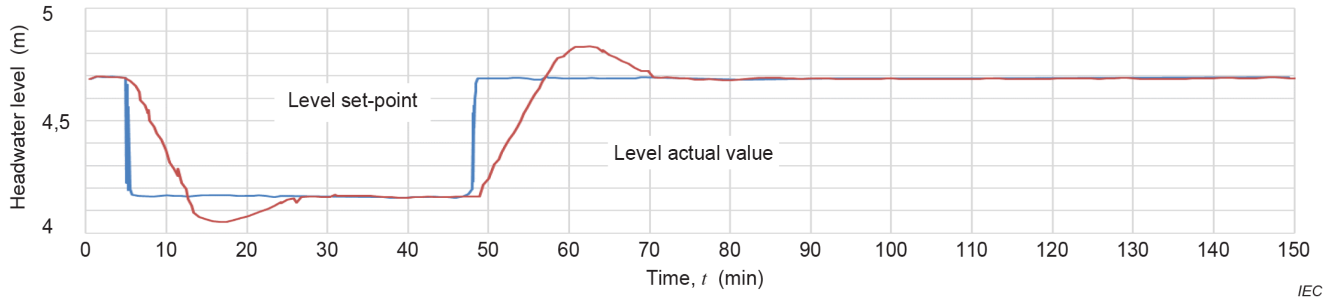
   – Ordinate: headwater level set-point and actual value in m.
   – Abscissa: time.

   Figure D.13 b)

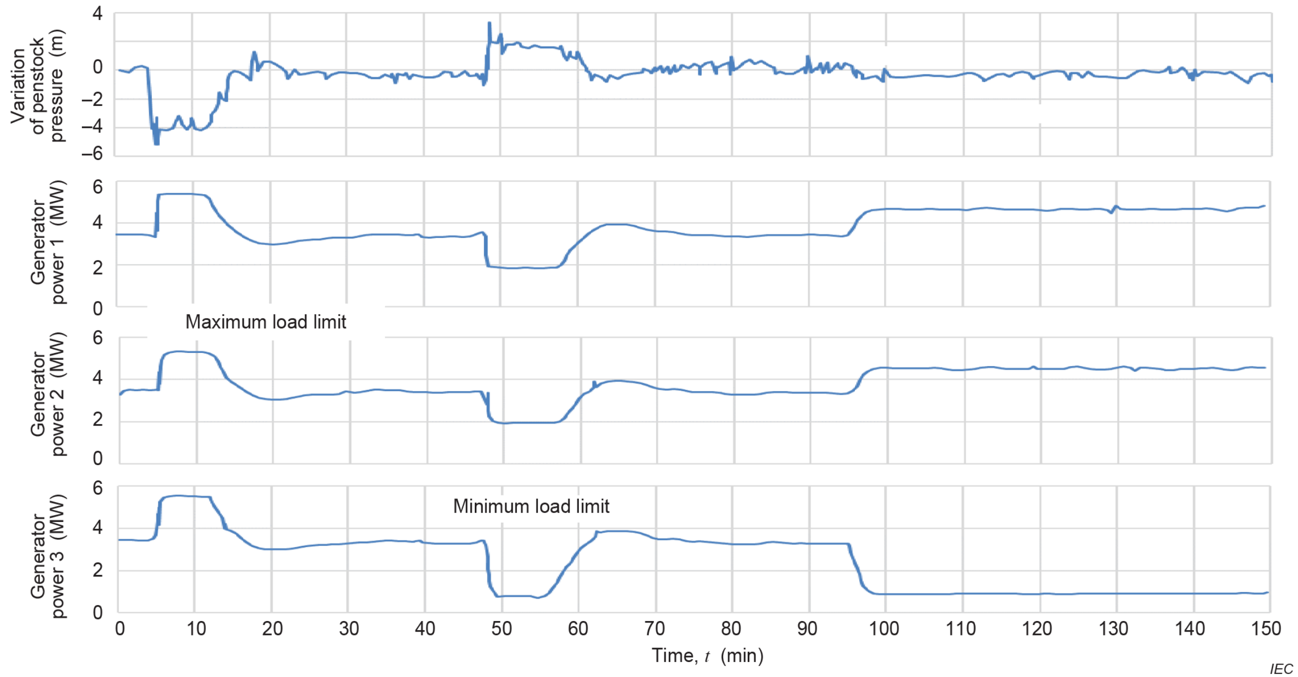
   – Ordinate 1: variation of penstock pressure ΔH in m.
   – Ordinate 2: turbine loads in MW.
   – Abscissa: time.
   – Measuring instruments: industrial measuring instruments, digital recorder.
   – Measuring uncertainty (estimation): level ±0,02 m; load ±0,1 % of nominal load.

b) Result and evaluation

   – The actual level value reaches the new set-point value after an overshoot. The overshoot is approximately 0,1 m, thus remaining below the admissible deviation of 0,2 m.
   – Temporarily, the turbines are reaching both load limits



a)



b)

Figure D.13 – Measurement of the unit step responses with headwater level control in multi-unit operations

D.15 Measurement of a load rejection with transition into no-load operation (example referring to 5.5.4.2)

Kaplan turbine, H_r = 2,75 m, P_{Gr} = 1 395 kW; electronic PID speed controller; generator separated from the grid at P_G = 1 360 kW.

a) Measuring recording, see Figure D.14
   - Ordinate 1: runner servomotor position Y_{ru} in percent.
   - Ordinate 2: wicket gate servomotor position Y_{ga} in percent.
   - Ordinate 3: speed n in percent.
   - Measuring instruments for ordinates: industrial measuring instruments.
   - Measuring uncertainty (estimation): for all percentage parameters approximately ±1,5 % in relation to the nominal range.
   - Abscissa: time.

b) Result and evaluation
   - In order to avoid a speed undershoot after the overshoot, the wicket gate closes at maximum velocity until the edge point (maximum speed) and after that with a reduced gradient.
   - At approximately 103 % speed, the wicket gate reopens without having reached the closed position.
   - The runner blades close with the value corresponding to the cam relation. In the no-load range, they are held constant to achieve better stability.
   - The speed reaches the nominal value almost aperiodically.

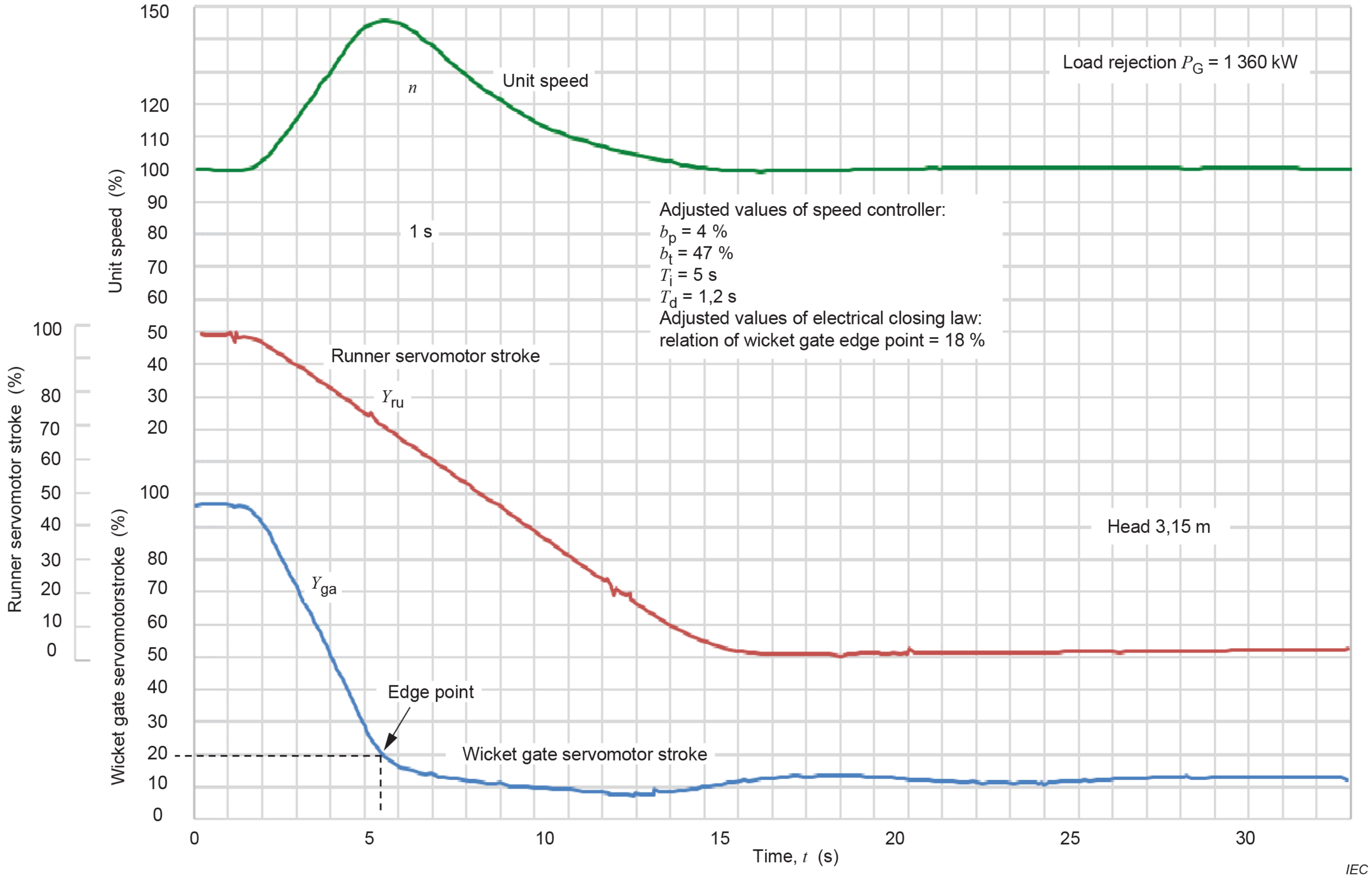


Figure D.14 – Measurement of a load rejection with transition into no-load operation

D.16 Measurement of a load rejection with limit control of surge and suction waves and with transition into no-load operation (example referring to 5.5.4.2)

Kaplan turbine, H_r = 2,75 m, P_{Gr} = 1 395 kW; electronic PID speed controller; generator is disconnected from the system at P_G = 1 300 kW.

a) Measuring recording, see Figure D.15
   - Ordinate 1: runner servomotor position Y_{ru} in percent.
   - Ordinate 2: wicket gate servomotor position Y_{ga} in percent.
   - Ordinate 3: speed n in percent.
   - Measuring instruments for ordinates: industrial measuring instruments assigned voltage signals from the controller.
   - Measuring uncertainty (estimation): for all percentage parameters approximately ±1,5 % in relation to the nominal range.
   - Abscissa: time.

b) Result and evaluation
   - In comparison to the example in Clause D.15, the runner is fixed at the so-called “surge-opening“ for limitation of flow change and thus surge and suction waves. When this state is reset, the runner slowly closes to the normal cam position.
   - Initially, the wicket gate closes at the maximum closing speed, but is regulating at a relatively large opening, because the runner is fixed at a larger opening.
   - Due to the turbulent surge operation (draft tube vortex), the wicket gate performs large control movements in order to be able to maintain a steady speed. The speed shows slight variations.
   - The maximum speed increase is, due to the larger runner opening, smaller than in the example in Clause D.15.

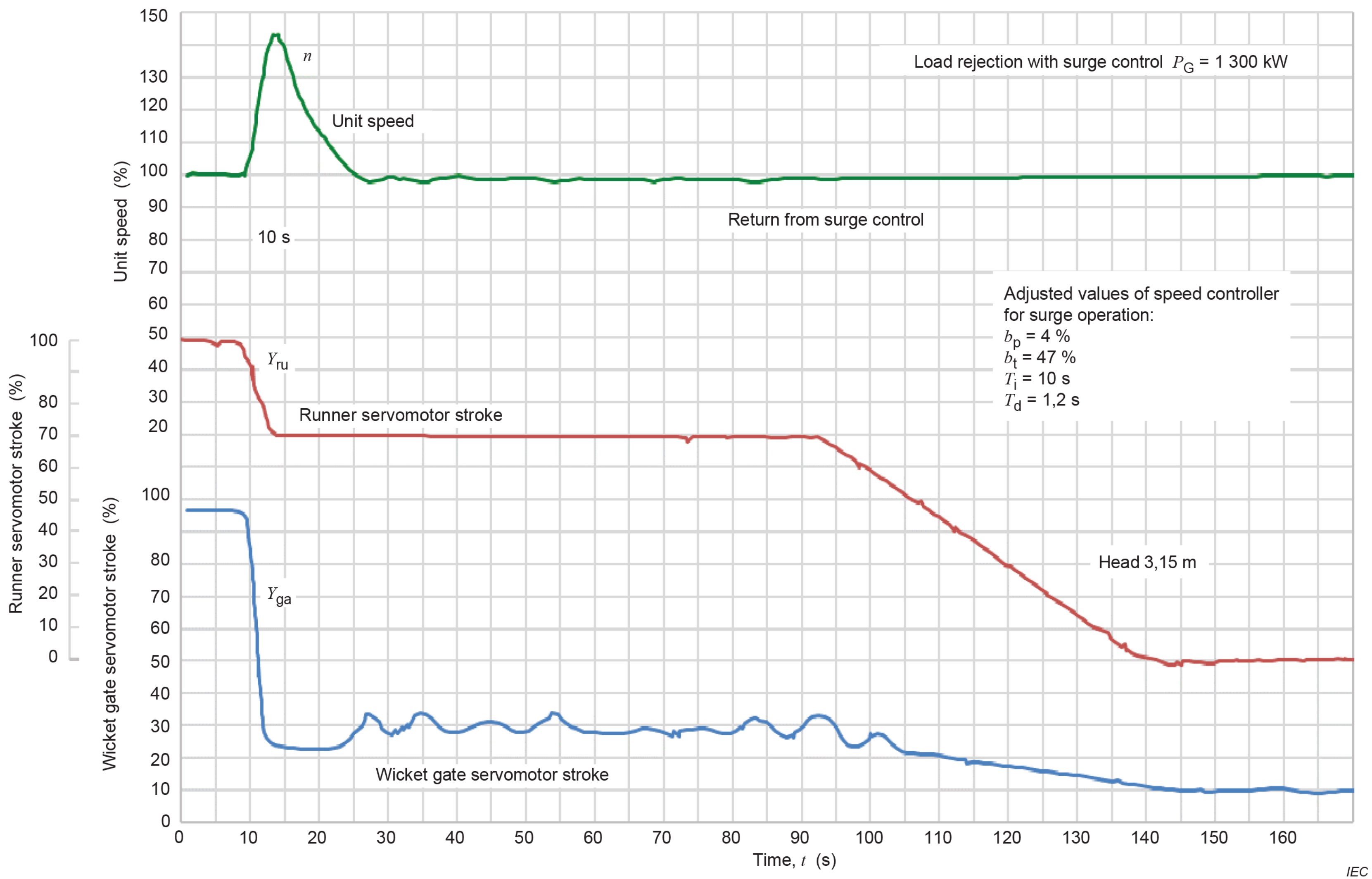


Figure D.15 – Measurement of a load rejection with limit control of surge and suction waves and with transition into no-load operation

D.17 Measurement of a start-up process and loading (example referring to 5.5.4)

Six-jet Pelton turbine, H_r = 1 260 m, P_{Gr} = 260 MW. Needle No. 6 is controlled to open for start-up, when reaching 20 % of nominal speed the needles 1 to 5 open temporarily in addition for faster acceleration of the unit.

a) Measuring recording, see Figure D.16
   - Ordinate 1: head change ΔH in m.
   - Ordinate 2: percentage scale for needle positions 1 to 6 Y_{nz}, generator load setpoint $P_{G\ set}$, actual generator load $P_{G\ act}$, speed n.
   - Measuring instruments for ordinates: industrial measuring instruments.
   - Measuring uncertainty (estimation): for all percentage parameters approximately ±1 % absolute in relation to the nominal range; for head change ±4 m.
   - Abscissa: time.

b) Result and evaluation
   - 80 % of the nominal speed is reached after $t_{0,8}$ = 38 s.
   - Readiness for synchronising reached after $t_{SR} \approx 70$ s = 1,84 × $t_{0,8}$ (value according to recommendation of IEC 61362 $t_{SR}/t_{0,8}$ = 1,5 to 5,0).
   - Synchronization after $t_s \approx 71$ s = 1,87 × $t_{0,8}$.

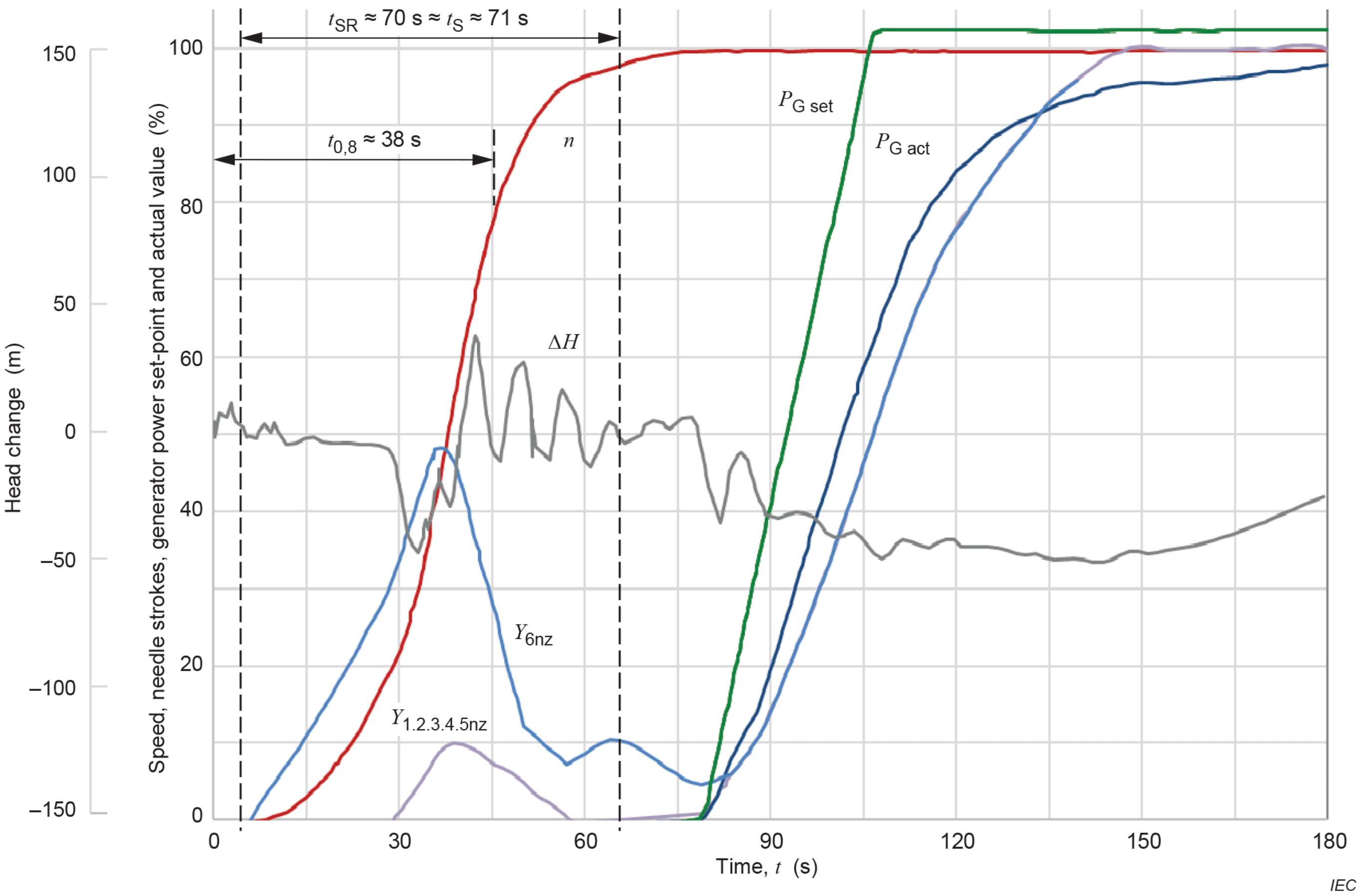


Figure D.16 – Measurement of a start-up process under load

D.18 Measurement of changeover from full turbine load to synchronous condenser operation (example referring to 5.5.4)

Six-jet Pelton turbine, H_r = 1 260 m, P_{Gr} = 260 MW; the six needles close with maximum closing speed.

a) Measuring recording, see Figure D.17
   - Ordinate 1: head change ΔH in m.
   - Ordinate 2: percentage scale for needle stroke Y_{nz}, actual generator load P_G, speed n.
   - Measuring instruments for ordinates: industrial measuring instruments.
   - Measuring uncertainty (estimation): for all percentage parameters approximately ±1 % absolute in relation to the nominal range; for head change ±4 m.
   - Abscissa: time.

b) Result and evaluation
   - Linear change of needle and load set-point values (not shown in Figure D.17).
   - The needle movement in the upper opening range is non-linear as a result of the effect of the hydraulic forces.
   - Slower closing for small needle openings is necessary due to the pressure surge. Needle No. 6 closes somewhat faster.
   - The maximum head increase is 112 m, far below the admissible value.

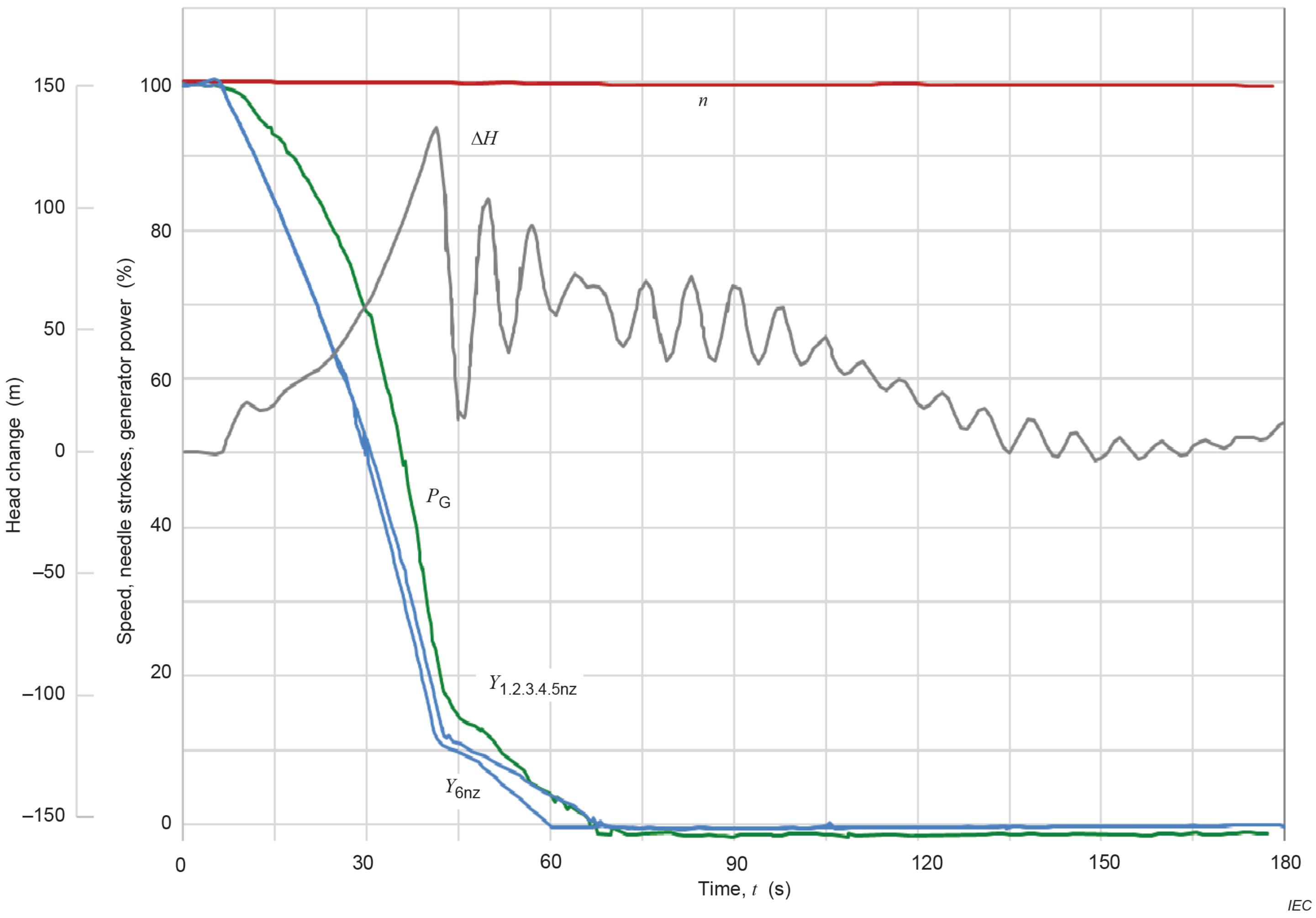


Figure D.17 – Measurement of changeover from full turbine load to synchronous condenser operation

D.19 Measurement of a power step-response in on-line simulated island operation test (example referring to 5.5.4, 5.5.5)

Francis turbine, H_r = 90 m, P_{Gr} = 13 MW; servomotor stroke Y_{max} = 273 mm; electronic PID speed controller; generator connected with the interconnected grid, controller connected to the on-line island grid simulator.

Simulation of a power step-response with the following characteristics of the simulated island grid:

– initial power output P_{G0} = 10,5 MW,

– unit acceleration time constant T_a = 7,2 s,

– load acceleration time constant T_b = 0,

– controlled system net self-regulation factor e_n = 1,

– simulated power load step ΔP_G = 2 % P_{Gr}.

a) Measuring recording, see Figure D.18
   - Ordinate 1: simulated frequency.
   - Ordinate 2: electrical power output.
   - Ordinate 3: servomotor position.
   - Ordinate 4: mechanical power (normally not required).
   - Abscissa: time.
   - Measuring instruments for ordinates: industrial measuring instruments (except the torque meter combined with a remote transmission for the measurement of the mechanical power), digital recorder.
   - Measuring uncertainty (estimation): less than ±1 % for all variables related to the nominal range.

b) Result and evaluation
   - The simulated frequency has a stable behaviour, similar to the result of numerical simulation; the undershoot reaches about 0,8 % of the nominal frequency for a power step of 2 % of the rated output.
   - The servomotor opening, the mechanical power and the electrical power come close to their final values in less than 3 s.
   - The electrical power output is affected by electromechanical oscillations at a natural frequency between 1 Hz and 2 Hz; the amplitude of these oscillations is relatively small, and with an adapted filter on this measurement of power, the calculation of the simulated frequency is not disturbed.

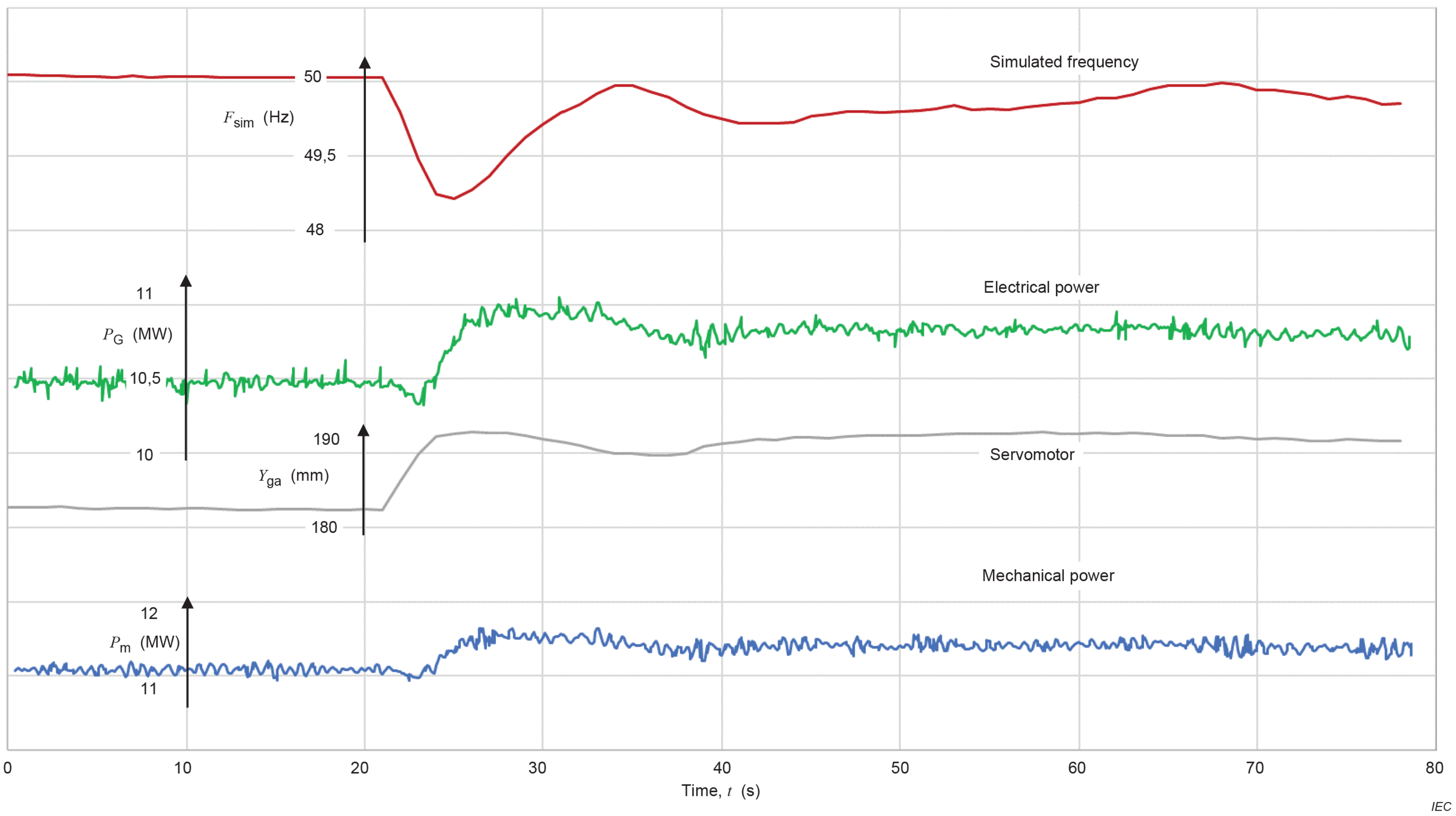


Figure D.18 – Measurement of a power step response in on-line simulated island operation test