BS EN 61362:2012

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Guide to specification of hydraulic turbine governing systems

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National foreword

This British Standard is the UK implementation of EN 61362:2012. It is identical to IEC 61362:2012. It supersedes BS EN 61362:1998 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee MCE/15, Hydraulic turbines.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Published by BSI Standards Limited 2012

ISBN 978 0 580 72947 8

ICS 27.140

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 30 September 2012.

Amendments issued since publication

Amd. No.	Date	Text affected

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 61362

August 2012

ICS 27.140

Supersedes EN 61362:1998

English version

Guide to specification of hydraulic turbine governing systems
(IEC 61362:2012)

Guide pour la spécification des systèmes de régulation des turbines hydrauliques
(CEI 61362:2012)

Leitfaden zur Spezifikation der Regeleinrichtung von Wasserturbinen
(IEC 61362:2012)

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European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
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Management Centre: Avenue Marnix 17, B - 1000 Brussels

Ref. No. EN 61362:2012 E

Foreword

The text of document 4/270/FDIS, future edition 2 of IEC 61362, prepared by IEC/TC 4 "Hydraulic turbines" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 61362:2012.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2013-02-28
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2015-05-25

This document supersedes EN 61362:1998.

EN 61362:2012 includes the following significant technical changes with respect to EN 61362:1998:

This technical revision takes into account the experience with the guide during the last decade as well as the progress in the state of the art of the underlying technologies.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 61362:2012 was approved by CENELEC as a European Standard without any modification.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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

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

Publication	Year	Title	EN/HD	Year
IEC 60050-351	2006	International Electrotechnical Vocabulary (IEV) - Part 351: Control technology	-	-
IEC 60068-2-6	2007	Environmental testing - Part 2-6: Tests - Test Fc: Vibration (sinusoidal)	EN 60068-2-6	2008
IEC 60068-2-27	2008	Environmental testing - Part 2-27: Tests - Test Ea and guidance: Shock	EN 60068-2-27	2009
IEC 60308	2005	Hydraulic turbines - Testing of control systems	EN 60308	2005
IEC 61000-4-1	2006	Electromagnetic compatibility (EMC) - Part 4-1: Testing and measurement techniques - Overview of IEC 61000-4 series	EN 61000-4-1	2007
CISPR 11 (mod)	2009	Industrial, scientific and medical equipment - Radio-frequency disturbance characteristics - Limits and methods of measurement	EN 55011	2009
ISO 3448	1992	Industrial liquid lubricants - ISO viscosity classification	-	-

CONTENTS

INTRODUCTION

While a standard for the testing of hydraulic turbine governing systems had been existing for a very long time (IEC 60308 published in 1970)[1], a guide for the specification of hydraulic turbine governing systems was missing until 1998. The need for such a guide became more and more urgent with the fast development and the new possibilities especially of the digital components of the governor.

The current second edition of the guide takes into account the experience with the guide during the last decade as well as the progress in the state of the art of the underlying technologies.

While the first edition was written more or less as a supplement to the already existing guide for testing, the objective of the second edition is to be the leading guide with respect to turbine governing systems.

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[1] IEC 60308:1970, *International code for testing of speed governing systems for hydraulic turbines*. This publication was withdrawn and replaced by IEC 60308:2005.

GUIDE TO SPECIFICATION OF HYDRAULIC TURBINE GOVERNING SYSTEMS

1 Scope

This International Standard includes relevant technical data necessary to describe hydraulic turbine governing systems and to define their performance. It is aimed at unifying and thus facilitating the selection of relevant parameters in bidding specifications and technical bids. It will also serve as a basis for setting up technical guarantees.

The scope of this standard is restricted to the turbine governing level. Additionally some remarks about the control loops of the plant level and about primary and secondary frequency control (see also Annex B) are made for better understanding without making a claim to be complete.

Important topics covered by the guide are:

- speed, power, water level, opening and flow (discharge) control for reaction and impulse-type turbines including double regulated machines;
- means of providing actuating energy;
- safety devices for emergency shutdown, etc.

To facilitate the setting up of specifications, this guide also includes data sheets, which are to be filled out by the customer and the supplier in the various stages of the project and the contract.

Acceptance tests, specific test procedures and guarantees are outside the scope of the guide; those topics are covered by IEC 60308.

2 Normative references

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

IEC 60050-351:2006, *International Electrotechnical Vocabulary – Part 351: Control technology*

IEC 60068-2-6:2007, *Environmental testing – Part 2-6: Tests – Test Fc: Vibration (sinusoidal)*

IEC 60068-2-27:2008, *Environmental testing – Part 2-27: Tests – Test Ea and guidance: Shock*

IEC 60308:2005, *Hydraulic turbines – Testing of control systems*

IEC 61000-4-1:2006, *Electromagnetic compatibility (EMC) – Part 4-1: Testing and measurement techniques – Overview of IEC 61000-4 series*

CISPR 11:2009, *Industrial, scientific and medical equipment – Radio-frequency disturbance characteristics – Limits and methods of measurement*

ISO 3448:1992, *Industrial liquid lubricants – ISO viscosity classification*

3 Terms, definitions, symbols and units

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

NOTE This guide uses as far as possible the terms and definitions of IEC 60050-351. For clarification, the simplified differential equations and transfer functions of the idealized PID-controllers as used in this guide are given in Annex A. Additional reference is made to IEC 60308 for purposes of tests of governing systems.

3.1 General terms and definitions

3.1.1
turbine governing system
technical equipment governing the opening (guide vane, runner blade, needle, deflector position) of hydraulic turbines

Note 1 to entry At the present state of the art, the turbine governing system consists of an oil hydraulic and an electronic part, the "oil hydraulic governor" and the "electronic governor".

3.2 Terms and definitions related to control levels and control modes

3.2.1
turbine governing level
control functions directly related to the governing system of a single turbine

Note 1 to entry The following control modes are related to the turbine governing level:

- speed control;
- power output control;
- water level control;
- opening control;
- flow control (the term flow used in this guide has the same meaning as the term discharge).

Note 2 to entry The scope of this standard is restricted to the turbine governing level. Additionally some remarks about the control loops of the plant level and about primary and secondary frequency control (see Annex B) are made for better understanding without making a claim to be complete.

3.2.2
unit control level
control functions directly related to the overall control of a single unit (turbine, generator, unit auxiliaries) including turbine governing, voltage regulation, start-stop-sequencing etc.

3.2.3
plant control level
control functions related to the overall control of a whole plant including the control of several units

Note 1 to entry In automatic unit and plant control operation, the turbine governing system gets its modes and setpoints from the unit and plant control level.

3.2.4
grid control level
control functions related to the overall control of the grid as a whole

Note 1 to entry If required the turbine governing system participates in grid control over the primary and/or secondary frequency control mode (see Annex B).

3.3 Terms and definitions from control theory

3.3.1
differential equation
equation describing the dynamic system behavior in the time-domain, as shown in Annex A

3.3.2
transient response
system response (output) to a step change of the input

3.3.3
frequency response
dynamic response of the linearized system to a sinusoidal change of the input signal derived from the differential equation by applying the Fourier transformation

3.3.4
transfer function
dynamic response of the linearized system to an arbitrary variation of the input signal derived from the differential equation by applying the Laplace transformation

3.4 Subscripts and prefixes

Sub-clause	Term	Definition	Symbol	Unit
3.4.1	**rated**	subscript indicating the rated operation point of the system	r	–
3.4.2	**maximum** **minimum**	subscript indicating maximum or minimum values of any term	max. min.	–
3.4.3	**deviation**	deviation of any term from a steady-state value	Δ	–
3.4.4	**guide vanes**	subscript associating a quantity to guide vane position	ga	–
3.4.5	**runner**	subscript associating a quantity to runner blade position	ru	–
3.4.6	**nozzle**	subscript associating a quantity to needle position	ne	–
3.4.7	**Deflector**	subscript associating a quantity to deflector position	de	–

3.5 Terms and definitions related to the plant and the machines

Sub-clause	Term	Definition	Symbol	Unit
3.5.1	**specific energy of machine**	specific energy of hydraulic water available between the high- and low-pressure side sections of the machine	E	$\mathrm{J \cdot kg^{-1}}$
3.5.2	**turbine head**	$H = E/g$ definition of E, see 3.5.1 g = acceleration due to gravity = 9,81 $\mathrm{m \cdot s^{-2}}$ (at sea level)	H	m
3.5.3	**flow**	volume of water per unit time flowing through any section in the system	Q	$\mathrm{m^3 \cdot s^{-1}}$
3.5.4	**rotational speed**	number of revolutions per unit time	n	$\mathrm{s^{-1}}$ [a]
3.5.5	**frequency**	cycles per second	f	Hz
3.5.6	**generator power output**	generator power measured at generator terminals	P_G	W
3.5.7	**moment of inertia of mass**	moment of inertia for calculation of fly-wheel effect. $I = M D^2/4 = MR^2$ (M = mass, D = diameter of gyration, R = radius of gyration)	I	$\mathrm{kg \cdot m^2}$

[a] The unit rpm is frequently used.

3.6 Terms and definitions relating to the governing system

Sub-clause	Term	Definition	Symbol	Unit
3.6.1	**controlled variable**	variable which has to be controlled as speed n, output P_G, water level h, servoposition opening y, flow Q:		
		– absolute, dimensional value	X	var.
		– relative deviation from a steady-state value, $x = \Delta X/X_r$	x	– –
		rotational speed	x_n	–
		power output	x_p	–
		water level	x_h	–
		opening	x_y	–
		flow	x_q	–
3.6.2	**command signal**	a signal which can be set by an external adjustment:		
		– absolute, dimensional value	C	var.
		– relative deviation from a steady-state value, $c = \Delta C/C_r$	c	–
		rotational speed	c_n	–
		power output	c_p	–
		water level	c_h	–
		opening	c_y	–
		flow	c_q	–
3.6.3	**servomotor stroke**	stroke of the main servomotor which moves the guide vane/runner blades/needles/deflectors		
		– absolute value	Y	m
		– relative deviation from a steady-state value, $y = \Delta Y/Y_{max}$	y	–
		Note 1 to entry The effective max. servomotor stroke Y_{max} has to be defined between customer and supplier.		
3.6.4	**controlled variable range**	adjusting range for the setting of a controlled variable (rotational speed in speed control, or water level in level control) with an average setting of the permanent droop, if applicable (see 3.6.8 and 5.3.2):	X_{max} X_{min}	– –
		– maximum value of the controlled variable for $Y/Y_{max} = 0$		
		– minimum value of the controlled variable for $Y/Y_{max} = 1,0$		
		SEE: Figure 1		

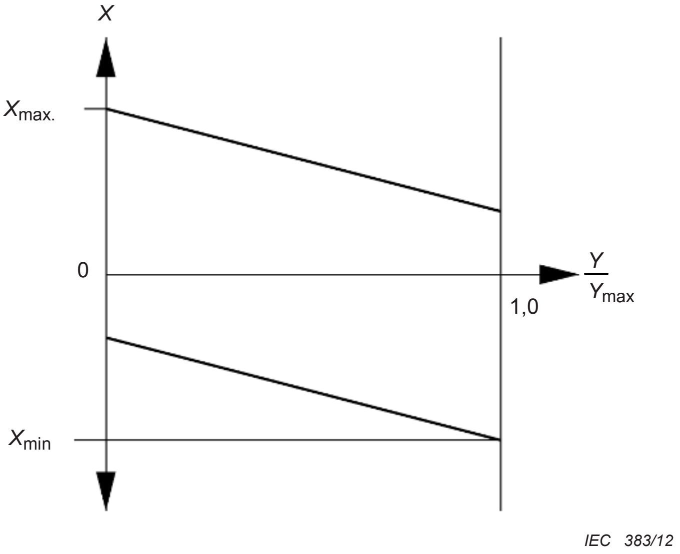


Figure 1 – Controlled variable range

Sub-clause	Term	Definition	Symbol	Unit
3.6.5	**electronic governor output signal**	output signal at the electronic governor = input signal of the following servo-positioner Relative deviation from a steady-state value	s	–
3.6.6	**output signal of a pilot servo-positioner**	output signal of a pilot servo-positioner = input signal of the following main servo-positioner Relative deviation from a steady-state value	s_v	–
3.6.7	**droop graph**	a graph showing the relationship between a relative controlled variable (speed n/n_r, or in some cases water level H/H_r) as a function of the relative servomotor stroke or the relative power output under steady-state conditions SEE: Figure 2		

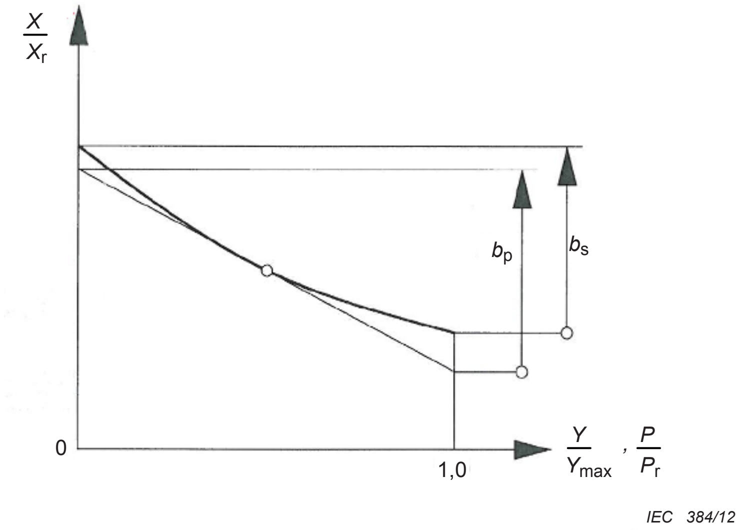


Figure 2 – Permanent droop

Sub-clause	Term	Definition	Symbol	Unit
3.6.8	**permanent droop**	slope of the droop graph (see Figure 2): – at a specific point of operation, – defined by the end values of the droop graph	 b_p b_s	 % %
3.6.9	**proportional action coefficient**[a]	proportional amplification, defined by the step response of an idealized PID-controller with $b_p = 0$, $K_D = 0$ and input signal $x = 1$ SEE: Figure 3	K_p	–
[a] In accordance with IEC 60050-351.				

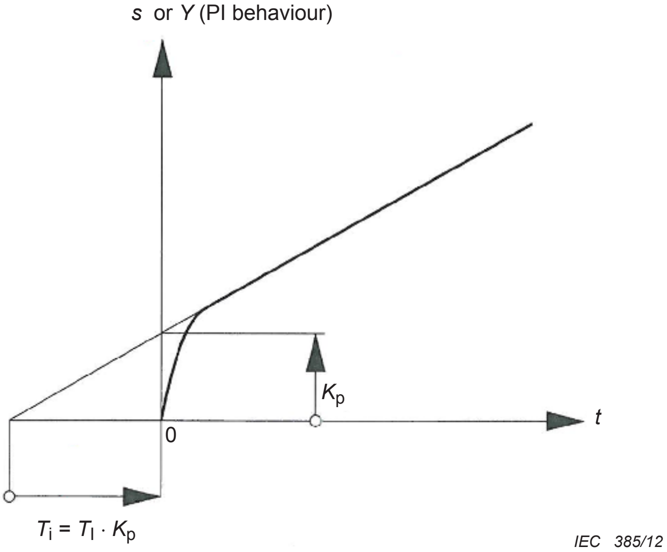


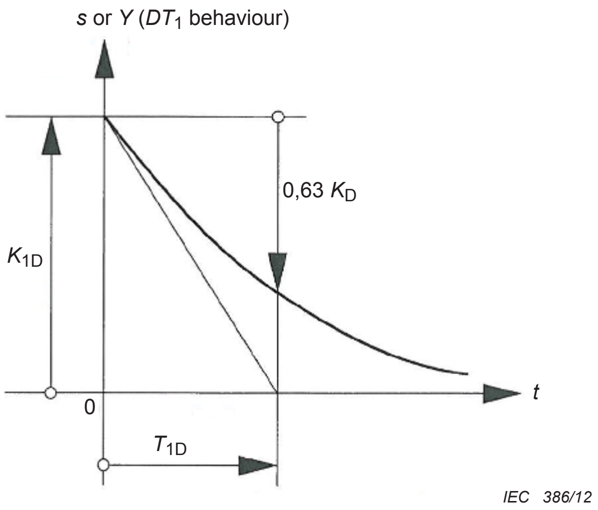
Figure 3 – Proportional action coefficient and integral action time

Sub-clause	Term	Definition	Symbol	Unit
3.6.10	**integral action time**[a]	time constant of the integral action of an idealized PID-controller. The reset time T_i in parallel structured PID-controllers is defined by $T_i = T_I \cdot K_p$ and K_p/T_i corresponds to the slope of the controller step response curve with $b_p = 0$, $K_D = 0$ and input signal $x = 1$ SEE: Figure 3	T_I	s
3.6.11	**derivative**[b] **action time**	time constant of the derivative action of an idealized PID-controller. The transfer function ($T_D \cdot p$) can practically be realized only approximately by a DT_1 transfer function, i.e. a derivative term multiplied by a first-order lag element[c] : $$\frac{K_{1D} \cdot T_{1D} \cdot p}{1 + T_{1D} \cdot p}$$ The step response of such a transfer function of an idealized PID-controller, the proportional and integral term being zero, is shown in Figure 4. For small values of T_{1D} the following approximation applies: $$T_D = K_{1D} \cdot T_{1D}$$	T_D	s

[a] Reset time can also be defined by $T_i = K_p/K_I$ with integral action coefficient $K_I = 1/T_I$ (see IEC 60050-351).

[b] Rate time is defined in parallel structured PID-controllers by $T_d = K_D/K_p$, with derivative action coefficient $K_D = T_D$ (see IEC 60050-351).

[c] Realization also by second-order lag element possible.



IEC 386/12

Figure 4 – Derivative time constant

Sub-clause	Term	Definition	Symbol	Unit
3.6.12	**dead band**	the maximum band between two values inside of which the variation of the controlled variable does not cause any governing action SEE: Figure 5	i_x	–
3.6.13	**insensitivity**	one-half of the dead band	$i_x/2$	–

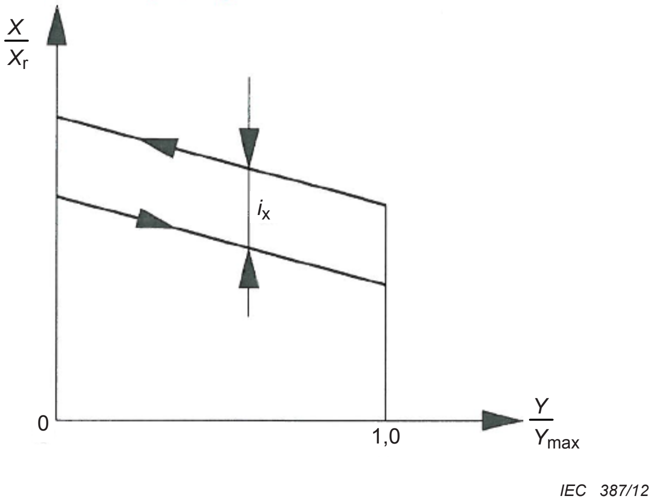
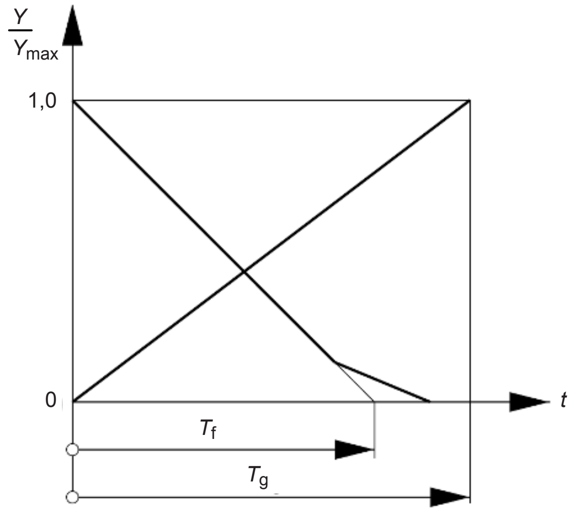


Figure 5 – Dead band

Sub-clause	Term	Definition	Symbol	Unit
3.6.14	**minimum servo-motor opening/ closing time**	the opening/closing time for one full servo-motor stroke at maximum velocity, cushioning times disregarded SEE: Figure 6 Note 1 to entry Minimum servomotor opening and closing times are the result of hydraulic transient calculations.	T_g, T_f	s

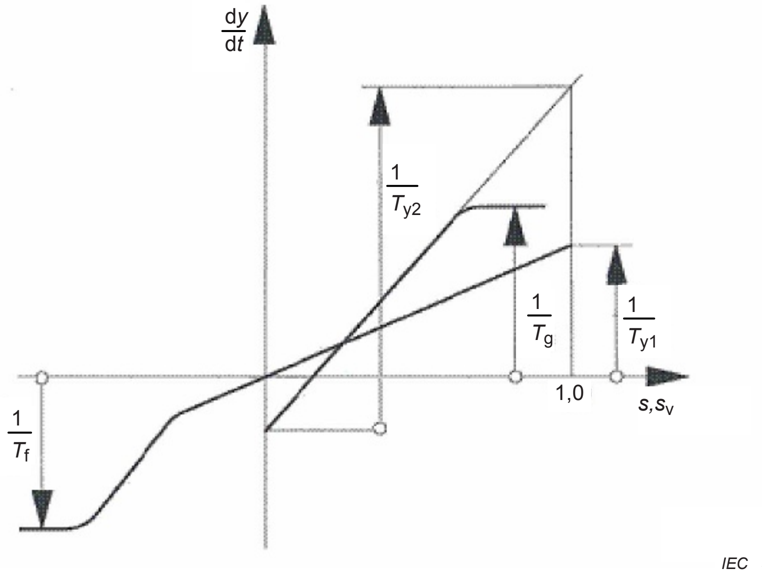


IEC 388/12

NOTE In case of stepped opening/closing velocities a diagram may be provided.

Figure 6 – Minimum servomotor opening/closing time

Sub-clause	Term	Definition	Symbol	Unit
3.6.15	**time constant of the servo-positioner**	the reciprocal value of the slope of the curve showing the servomotor velocity dy/dt as a function of the relative deviation of the position of the control valve, s, s_v , from the zero position related to s, s_v = 1 (s, s_v = 1 theoretical relative spool stroke in the absence of feedback) SEE: Figure 7	T_y	s



IEC 389/12

Figure 7 – Time constant of the servo-positioner

Sub-clause	Term	Definition	Symbol	Unit
3.6.16	**servo-positioner inaccuracy**	the maximum possible change in the servomotor position which can occur for a given constant value of the input signal of the servo-positioner SEE: Figure 8	i_a	–

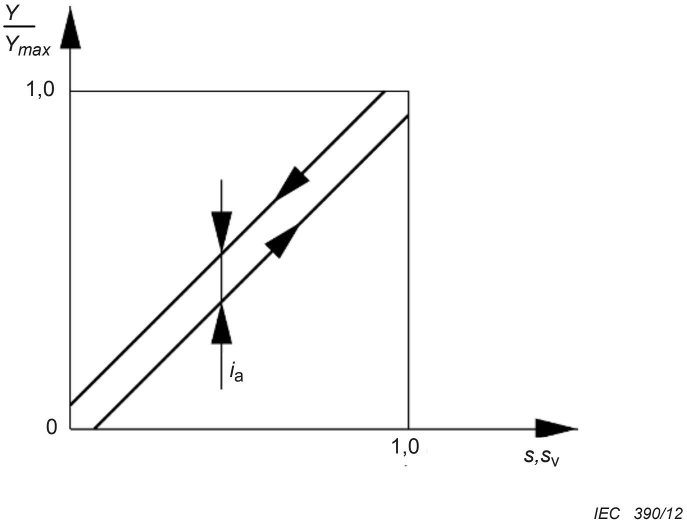


Figure 8 – Servo-positioner inaccuracy

Sub-clause	Term	Definition	Symbol	Unit
3.6.17	**control system dead time**	time interval between a specified change in speed or command signal and the first detectable movement of the servomotor SEE: Figure 9	T_q	s

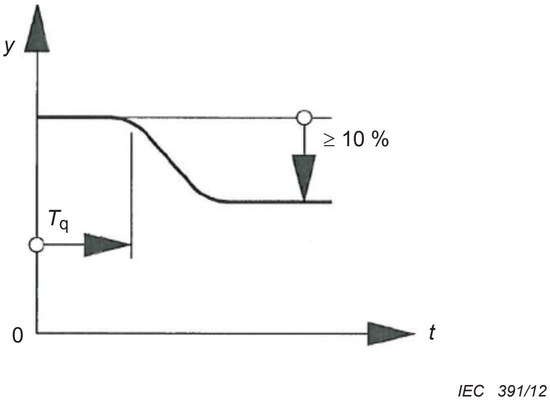


Figure 9 – Control system dead time

Sub-clause	Term	Definition	Symbol	Unit
3.6.18	**actuating energy**	required energy for one servomotor stroke under the minimum required pressure $p_R = E_R/V_S$	E_R	N · m
3.6.19	**servomotor volume**	oil volume of the servomotors	V_S	m^3
3.6.20	**tripping oil volume**	oil volume of the pressure tank at the tripping point (between p_T and p_R, see Figure 20)	V_T	m^3
3.6.21	**usable oil volume** (Figure 20)	usable oil volume between $p_{o\ min}$ and p_R	V_u	m^3
3.6.22	**residual (not usable) oil volume** (Figure 20)	oil volume of the pressure tank after a full-load shut-down from the tripping point	V_{res}	m^3
3.6.23	**design oil pressure**	design pressure of the oil pressure tank	p_D	Pa[a]
3.6.24	**operating oil pressure**	operating oil pressure under normal operating condition	p_o	Pa[a]
3.6.25	**tripping oil pressure**	when the tripping pressure p_T is reached a shutdown is released, this implies $p_R < p_T < p_o < p_D$	p_T	Pa[a]
3.6.26	**minimum required pressure**	minimum required pressure in the oil servo system	p_R	Pa[a]

[a] The unit bar is also used.

4 Control structure

4.1 General

In the hydraulic turbine control, various tasks can be specified with varying priority. Realization leads to certain typical control system structures and in turn to some basic rules to be adhered to.

Such typical arrangements are compiled for clarification.

4.2 Main control functions

4.2.1 General

In hydraulic turbine control, these major control functions can be distinguished:

- speed control;
- power output control;
- water level control;
- opening, and
- flow control.

In some systems, combinations of these control functions also occur.

4.2.2 Speed control

The purpose of the speed control basically is to maintain constant frequency. In the various modes of operation this means that:

- in the isolated network mode with only one unit (small network), the actual speed and therefore the frequency corresponds to the command signal setting; in the isolated network mode with more than one unit (medium network), the speed control contributes to the frequency control through the permanent droop avoiding oscillation between the units;
- in the operation on the grid, where the speed is determined by the network frequency, the speed control contributes to the network frequency control through the permanent droop and the dynamic characteristics of the controlled system;
- in the no load mode (before synchronization and after separation from the network), the actual speed corresponds to the command signal or the existing network frequency with some small deviation.

4.2.3 Power output control

The power output control with a separate power controller is applied with the unit connected to the grid, its purpose is to control the power output of the unit according to a power command signal irrespective of head variations. Any frequency variations influence the power level additionally via the permanent droop.

It is noted that in the cases where head variations can be ignored, a closed loop power output control, i.e., a power output controller, may not be necessary. In such a case, the calculation of the appropriate opening via a linearization may suffice (see 4.3.2). In this case also, any frequency variations influence the power level additionally via the permanent speed droop.

4.2.4 Opening control

The opening control serves to position the opening of the servomotor according to an opening command signal, either as a follow-up control in master control operations (for example speed control) or as a specific operating mode in grid control. In that last case, the usual configuration includes the permanent speed droop, which creates the relationship between the frequency of the grid and the opening of the servomotor, around the opening set-point from the unit control system; it is an alternative solution for power control with frequency influence, which is the preferred solution using modern digital controllers.

4.2.5 Water level control

For run-of-the-river hydropower plants, it is often required to control the water level of the upper part of the river, in order to keep it relatively constant or inside a specified range around a fixed value. The corresponding water level control is usually operated by an external controller of the power plant control system. But in some cases, it can also be managed by the turbine governing system itself, especially if there is no need of grid frequency control.

In the first case, by using an external water level control, the water level controller operates as a secondary controller. For that, it compares a water level measurement with a level set-point or level limit values, and by a specific algorithm, modifies the command signal of the main controller of the turbine governing system (speed or opening or power controller), in order to control the water level. Attention should be paid, in case of participation of the unit to the frequency control of the grid, that time constant of the water level control has to be enough long, in order to allow the action of the primary frequency control, with a duration as required by the TSO (transmission system operator) according to the corresponding grid code.

In the second case, the internal water level controller also compares the level measurement with the level set-point or level limit values, and modifies the command signal to the servo-positioners, or to the opening limiter of the speed controller. If there are several units in the power plant, a level-opening droop (see 5.3.2) has to be implemented in each governor, in order to fix the operating point of each unit.

4.2.6 Flow control

For run-of-the-river hydropower plants, especially in case of several cascade power plants along a river (see 5.16.4), it can be required to control the flow across the different turbines in operation in the concerned power plant. With that objective, a flow control system can be implemented in the power plant control system or inside the turbine governing system.

In both cases, the usual configuration is as following: the flow controller compares a flow "measurement" with a flow set-point, and by a specific flow control algorithm, modifies the command signal to the servo-positioners or to the main controller of the turbine governing system (speed or opening or power controller). The flow "measurement" is generally an indirect measurement, i.e. calculated using characteristic curves from the runner blade opening (in case of Kaplan or bulb turbines) or from the guide vane opening, if necessary with a dependency on the measured head.

For Pelton turbines, the flow can be calculated from the position of each needle and the measured head.

In case of participation of the unit to the frequency control of the grid, attention should be paid that time constant of the flow control has to be long enough, in order to allow the action of the primary frequency control, with a duration as required by the TSO (transmission system operator) according to the corresponding grid code. In this case, another solution could be to implement a flow controller directly in place of the opening or power controller, with a “frequency-flow droop” using the difference between the flow set-point and the "measured" flow (calculated as above).

4.3 Configurations of combined control systems

4.3.1 General

In combined systems, each control function can be assigned to a separate controller. However, the controllers all actuate the same main servo-positioner through the opening setpoint.

Thereby, a bump-free switch-over between modes requires attention. In case of separate controllers, parameters shall be set according to the respective control loop. Water level and power output control, etc, are often incompatible with the maintenance of speed in an isolated network. The speed controller always remains functional for safety reasons, e.g., to take over in the case of a load rejection.

4.3.2 Parallel structure

Two controllers are arranged in parallel and actuate one or several servo-positioners via a selector or a summing point. If a selector is applied, it often includes a max./min. function for the speed control loop to prevail in the case of a load rejection.

If a summing point is applied, the switching of signals is avoided, but the power output controller (or other controller) influences speed control additionally and shall be set to ensure stability.

The configuration according to Figure 10 is often used in peak-load power stations.

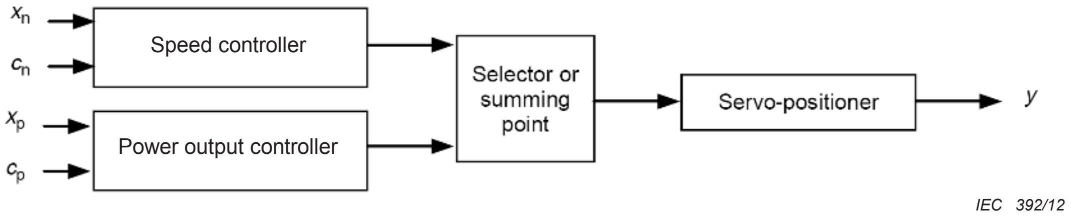


Figure 10 – Control system with speed and power output controllers in parallel

Figure 11 shows an arrangement with speed controller and power command signal in parallel according to 4.2.3.

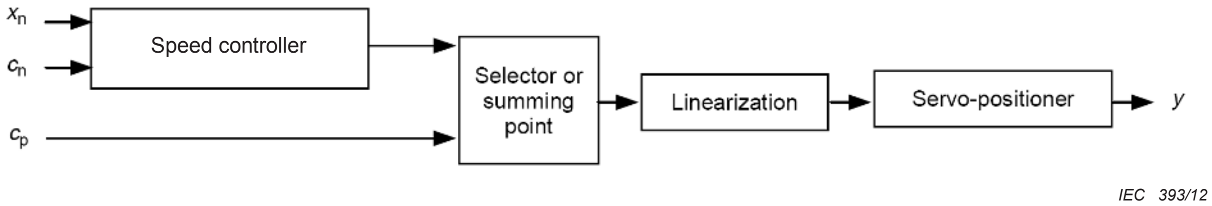


Figure 11 – Control system with speed controller and power command signal in parallel

Figure 12 shows a similar arrangement with water level controller.

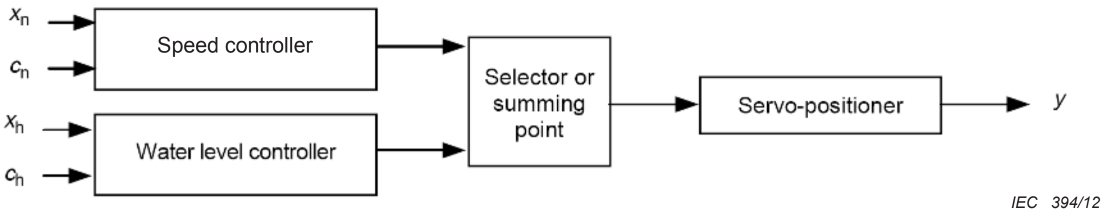


Figure 12 – Control system with speed controller and water level controller in parallel

4.3.3 Series structures

Power output controller or water level controller precedes the speed controller. They actuate the speed signal setter of the speed controller (Figure 13) or the opening limiter (Figure 14).

In Figure 13 the power output controller actuates the speed signal setter of the speed controller.

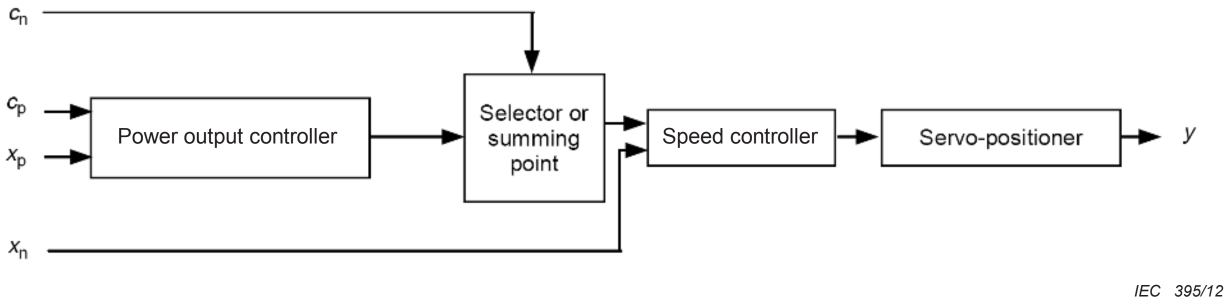


Figure 13 – Governing system with power output and speed controller in series

In Figure 14 the water level controller actuates the opening limiter of the speed controller.

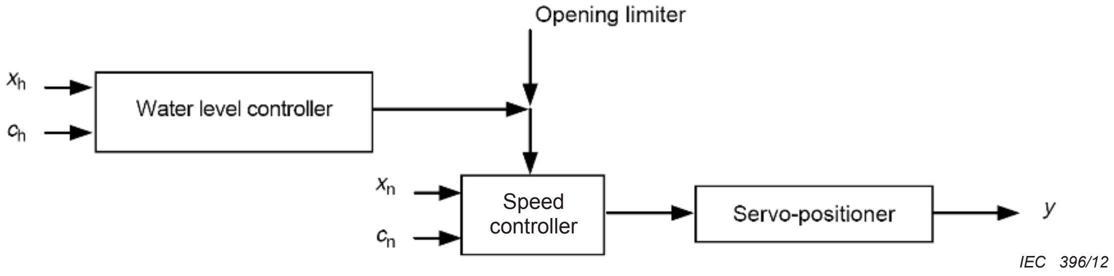


Figure 14 – Governing system with water level controller and speed controller in series

The configurations of Figures 13 and 14 are typical examples. However, there are also configurations with the power output controller acting on the opening limiter of the speed controller or with the water level controller acting on the speed signal setter. In the power output and the water level control mode, the speed controller acts essentially as a positioner.

The configuration as per Figure 14 is often used in base-load power stations.

4.3.4 Other configurations

4.3.4.1 Power output control via the speed controller (power output introduced as feedback signal)

Changeover between control modes is by switching from actual speed signal to the actual power output signal (see Figure 15).

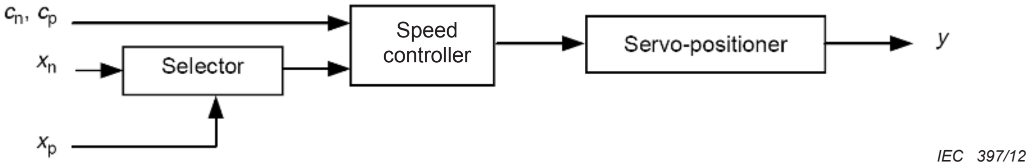


Figure 15 – Power output control via the speed controller

4.3.4.2 Water level controller without speed controller

In simple cases (for example in the case of induction units), the water level controller acts on the servo-positioner via a setter (see Figure 16).

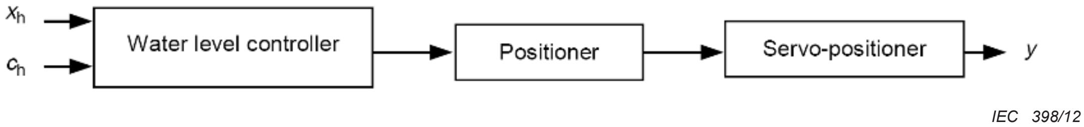


Figure 16 – Water level controller without speed controller

4.4 Configurations of servo-positioners

Depending on the actuating energy required, the main servomotor can be:

- directly actuated by an electro-hydraulic amplifier; the electronic feedback signal is fed back to the governor;
- actuated via a pilot servomotor; it positions a closed-loop hydro-mechanical follow-up system consisting of main control valve, servomotor and mechanical feedback;
- actuated via a piloted main control valve with parallel feedback signals from main control valve and servomotor, etc.

The type of configuration has a bearing on positioning accuracy and manual control options.

4.5 Multiple control

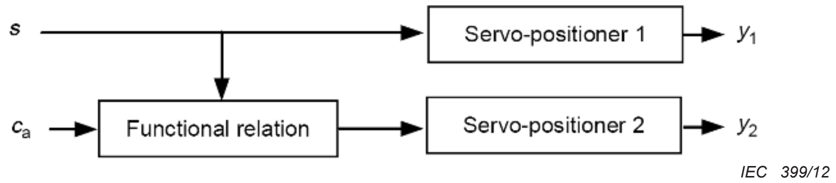
4.5.1 General

In case of multiple control elements (e.g. dual control of a turbine with controllable guide vanes and runner blades),

- parallel (see Figure 17) and
- series (see Figure 18)

arrangements are distinguished. The functional relationship can be defined non-linearly through a function generator. Frequently an additional signal is superimposed (e.g. the head can be used to influence the guide vane-blade angle relationship). In the case of more than two positioners (e.g. individual servomotor control), only parallel control is applied.

4.5.2 Parallel structure



Key

s output signal of the electronic governor

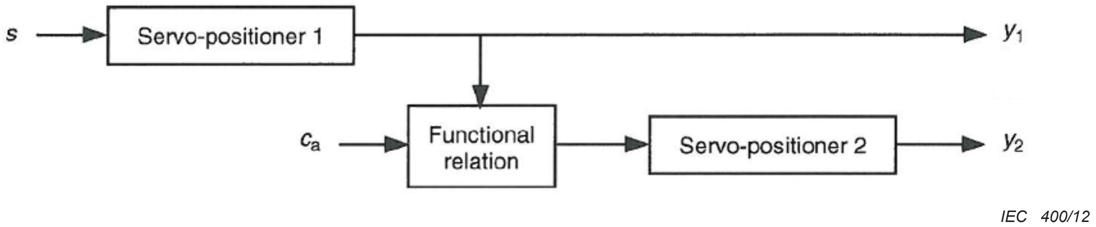
y_1 output signal of servo-positioner 1

y_2 output signal of servo-positioner 2

c_a input signal for the functional relation

Figure 17 – Parallel structure with defined functional relation and an additional signal superimposition

4.5.3 Series structure



Key

s output signal of the electronic governor

y_1 output signal of servo-positioner 1

y_2 output signal of servo-positioner 2

c_a input signal for the functional relation

Figure 18 – Series structure with defined functional relation and additional signal superimposition

5 Performance and components of governing systems

5.1 General

Clause 5 is concerned with the overall performance criteria for a governing system. As the performance of a turbine governing system will strongly depend on the characteristics of the individual controlled system, some guidance is offered first regarding its modelling and digital simulation.

After that, recommendations are given for the ranges of parameter settings for a PID configuration as the most common example for control algorithms in the governor. Other control strategies may be applied if suitable or desirable for superior performance in relation to PID-controllers.

Servo-positioners, requirements for signal transmitters and the actuating energy supply are also covered with the purpose of guiding the establishing relevant specifications.

5.2 Modeling and digital simulation

In the case of new hydropower schemes, a mathematical model of the total system is valuable for an optimization of the control, unless the system is straightforward and/or similar to existing plants. The same applies to the modernization of existing plants. The purpose of such computations can relate to three areas:

- physical dimensioning of components of the plants;
- demonstrating the dynamic behavior of the system (resonance phenomena, etc.);
- control system analysis and optimization.

These computations shall be based on a representative model of the system components, such as:

- the water passages;
- the turbine with its mechanism;
- the essential generator characteristics in the isolated network and the grid mode;
- the network characteristics;
- the governing system.

All the mentioned areas of interest can in principle be served by the same models while the mathematical approach can vary. Whilst physical dimensioning of components of the plant shall be based on computations in the time domain, the dynamic behavior of the total system can also be evaluated in the frequency domain. Control performance can be treated either

- in the frequency domain with respect to small deviations from the steady state, or
- in the time domain for large deviations where non-linearities are significant.

If mathematical investigations of the dynamic behavior in the frequency domain are applied, a suitable variable such as the guide vane opening shall be subjected to sinusoidal variations (frequency analysis). Thereby all frequency ranges shall be considered at which excitations, e.g. suction tube vortices in Francis turbines and/or resonances such as with natural frequencies of tunnel, penstock or the generator may occur. Thereby it should be noted that calculated natural frequencies of the hydro system may be inaccurate because the wave travel speed cannot be determined precisely.

For investigations with the aim of an optimization of the parameter setting of the governor, calculations in the time domain offer the advantage of considering non-linearities. Usually an integral criterion is applied, e.g.

$$\int |x - x_\mathrm{c}| \times \mathrm{d}t = \text{minimum}$$

or

$$\int t \times |x - x_\mathrm{c}| \times \mathrm{d}t = \text{minimum}$$

There are computer programs available which systematically vary the parameters and select a set of optimal values. By applying this method to the complete operating range, the setting of an adaptive governor may also be determined.

Optimization of the parameter setting of the governor in the frequency domain requires a linearized model. The set of optimal parameters can, for example, be determined by positioning the poles, i.e., the roots of the characteristic equation for optimal performance. This requires some experience.

The degree of detail in the modeling of a plant depends on the requirements with respect to controllability of the plant.

The effort even for smaller systems may be considerable and costly. The following may help to make a judgment as to how far the modeling should be carried in individual cases.

Water passages

- For the simulation of the water passages, the compressibility of the fluid and the elasticity of the penstock material shall be taken into account. For dimensioning and resonance studies, this should also be applied on tunnels and on galleries and shafts of surge tanks. If in the time domain, the length of a water column changes, then water and walls of this part are usually regarded as incompressible and inelastic.
- A separate analysis of the tunnel–surge tank section and the penstock–machine section is desirable to determine extreme values of the surgetank water level and maximum machine transient variables such as speed and pressure rises, respectively. System oscillations and control system behavior can only be reliably judged on the basis of the total system description.
- In surge tank calculations, energy dissipators such as throttles and the fluid inertia shall be taken into account.
- In low head plants, the inertia of water masses in the head and tailwater housings shall be taken into account while the elasticity can be neglected. Also surge phenomena in headwater canals can be relevant.

Turbine, generator, network

- The turbine characteristics should be defined in the investigation. The speed control of Pelton turbines may pose difficulties due to the lack of a negative torque and the non-linearities introduced by the deflector. For isolated network operation, controlled deflectors are needed.
- For investigations on resonances and the behavior of the unit connected to the grid the synchronization and damping factor of the generator shall be taken into account.
- The stability of frequency control in isolated networks depends on the type of load, such as resistor, motor or combined loads. The resistor type load is the most stringent requirement.

Control concept

It is to be expected that in the future, PID-controllers will remain in use for many plants for speed, power and water level control. Higher order algorithms, e.g., state control schemes will be used for the more complex system requirements. These control schemes, while necessitating more effort to implement, are justified where superior behavior with respect to the magnitude of deviations from steady state and its return to steady state can be achieved.

It is to be noted that the behaviour of an electronic PID-controller can also be enhanced considerably by readily available special means, such as disturbance superposition and the feedback of secondary variables.

This in turn justifies the intention of this guide to use the PID-controller as a basis and reference for recommendations relating to system control. The recommended ranges in parameter adjustment will suffice in all normal cases. Special conditions – extremely low inertias, extremely long penstocks – should in all cases be subjected to digital simulation and may require an extension of the recommended parameter adjustment range.

5.3 Characteristic parameters for PID-controllers

5.3.1 General

Subclauses 5.3.2 and 5.3.3 relate to the characteristic parameters of a PID-controller (analog or digital) with permanent droop. It does not cover relevant parameters for other higher algorithms or control strategies.

5.3.2 Permanent droop b_p

For units participating to the grid frequency control, the permanent droop establishes a defined relationship between the relative rotational speed variations (i.e. frequency variations), and the relative position of the servomotor or power output variations, in the steady-state condition, e.g.: $x_n + b_p \times y = 0$

- using the relative position of the servomotor, b_p is usually defined as “permanent speed droop” or “frequency-opening droop”;
- using the relative power output, b_p is usually defined as “power droop” or “speed regulation” or “frequency-power droop”.

Recommended minimum setting range of the permanent droop for frequency control: 0 % to 10 %.

For example, with a value of 5 % of power droop, a unit in a grid after a disturbance with a steady-state frequency deviation of -1 % (i.e. -0,5 Hz on a 50 Hz power system) will increase its power output by 20 % of P_{Gr}.

A principle functional scheme of such a permanent droop using the output power is given in the Figure B.1.

For units participating to a water level control (with a water level controller implemented in the governor), the permanent droop - defined as “level-opening droop” - establishes a defined relationship between the relative water level variations and the relative variations of the servomotor position, in the steady-state conditions, e.g.: $x_h + b_p \times y = 0$.

5.3.3 Proportional action coefficient K_p, integral action time T_I, and derivative action time T_D

The parameters K_p, T_I and T_D establish the transient response of the governor. The desired transient response can be achieved

- with parallel structure,
- with series structure, or
- with feedback structure of the elements.

The suitable adjustment of the parameters depends on the controlled system and shall be selected so as to provide a satisfactory transient response. Depending on the mode of operation, different adjustments may be necessary, e.g.

- with speed control:
  - in no load mode;
  - in an isolated network mode (required only for part load in some cases);
  - in operation on the grid (over the complete power range).
- with combined power output and speed control, Figures 10, 11, 13 and 15:
  - for speed control (with inoperative power output control);
  - for speed controller acting as positioner (with operative power output control).

Usually the same parameter selection can be applied for no load mode and operation on an isolated network; it may differ considerably from the suitable adjustment for grid operation.

If necessary an automated changeover parameter adjustment is to be provided (e.g., through generator breaker position, or by a detection criterion for the transition to isolated network operation, e.g. a large frequency variation or a power step).

a) Proportional action coefficient K_p (= reciprocal value of the temporary speed droop b_t)

Recommended minimum adjusting range:

- for speed controllers, between 0,6 and 10 [2];
- or power output controllers, between 0,2 and 1.

b) Integral action time T_I

Recommended minimum adjusting range: between 1 s and 20 s [2].

(For water level controlling considerably higher values may be applicable)

c) Derivative action time T_D

Recommended adjusting range: between 0 and 2 s.

where the relation $T_{1D}/T_D = 1/K_{1D}$ is generally between 0,1 and 0,2.

Minimum required range between 0 s and 1,4 s. 0 s means deactivation of derivative actions is possible.

5.4 Other parameters of the governing systems

5.4.1 Command signal adjustments for controlled variables (speed, power output, etc.) and load limiter

a) Command signal ranges

Recommended adjusting range:

- for speed controls: –10 % to +10 %.

b) Command signal setting times

The setting times (stroke times) shall be adjusted so as to exceed the shortest servomotor stroke times as defined by the limiting orifices (see also 5.4.3). Setting times should usually not be smaller than 20 s.

Recommended time setting range:

- speed setting: between 20 s and 100 s, normally between 30 s and 60 s;
- power output setting: between 20 s and 80 s;
- limiter: between 20 s and 80 s;

in each case for the full stroke of the servomotor.

5.4.2 Governor insensitivity $i_x/2$

Recommended limits:

- speed control: $i_x/2 < 2 \times 10^{-4}$
- power output control: $i_x/2 < 1 \times 10^{-2}$
- water level control: $i_x/2 < 1 \times 10^{-2}$ [3]
- flow control: $i_x/2 < 1 \times 10^{-2}$

In case of less stringent requirements relative to network frequency control, also $i_x/2 < 2 \times 10^{-2}$ is acceptable for the speed control function. This may, for example, apply for networks, in which larger frequency variations occur frequently, and also in cases where stability is critical.

---

[2] A range between 1,2 and 10 for K_p and 1 s and 5 s for T_I may be sufficient for many applications, e.g. rehabilitations without additional performance requirements.

[3] For level control deviating from Figure 5 the following definition applies: $i_x = \Delta X/(X_{max} - X_{min})$.

5.4.3 Parameters of servo-positioner

Input: electrical signal or position of the pilot servomotor.

Output: relative position Y/Y_{max} of the main servomotors.

For all servo-positioners, including those of double regulated turbines, the following applies.

a) Minimum servomotor opening/closing times T_g and T_f which are separately determined to satisfy waterhammer and overspeed limitations

NOTE 1 The limiting orifices or other suitable devices are dimensioned such that the actual stroke times in the presence of the highest supply pressure and the lowest required regulating capacity will not be lower than the allowable stroke time.

b) Time constant of the main servo-positioner T_y

This value is used for modeling and digital simulation of the system.

Recommended values for T_y*:*

- guide vane/needle servo: between 0,1 s and 0,25 s;
- runner blade servo: between 0,2 s and 0,8 s;
- deflector: between 0,1 s and 0,15 s.

Near the zero displacement, higher values of T_y prevail due to overlap and grooves (see T_{y1} in Figure 7).

NOTE 2 If the graph is stepped or if, in a frequency response measurement, the limit velocities of a servomotor are reached, an effective time constant (as a function of amplitude) can be used for computations.

c) Servo-positioner inaccuracy in follow-up arrangement, i_a

It has a major influence on the dead band i_x and shall be kept small.

Recommended value: $i_a < 0{,}4\ \%$ [4] for the complete servo-positioning system.

d) Governing system dead time T_q

The governing system dead time T_q results from a dead time in the electronic controller (sampling time in the microprocessor if applicable) and from an overlap in the control valve and/or from a series arrangement of several amplifiers.

Recommended value: $T_q < 0{,}20$ s [4].

e) Dynamic response of servo-positioner

The dynamic response is essentially determined by the time constant of the servo-positioner. In case of multiple-stage servo-positioners possibly with special transfer function (electronic positioning loop), the setting shall yield a response corresponding to a damping ratio D between 0,8 and 1,1, where critical damping is defined by $D = 1$ (see Figure 19).

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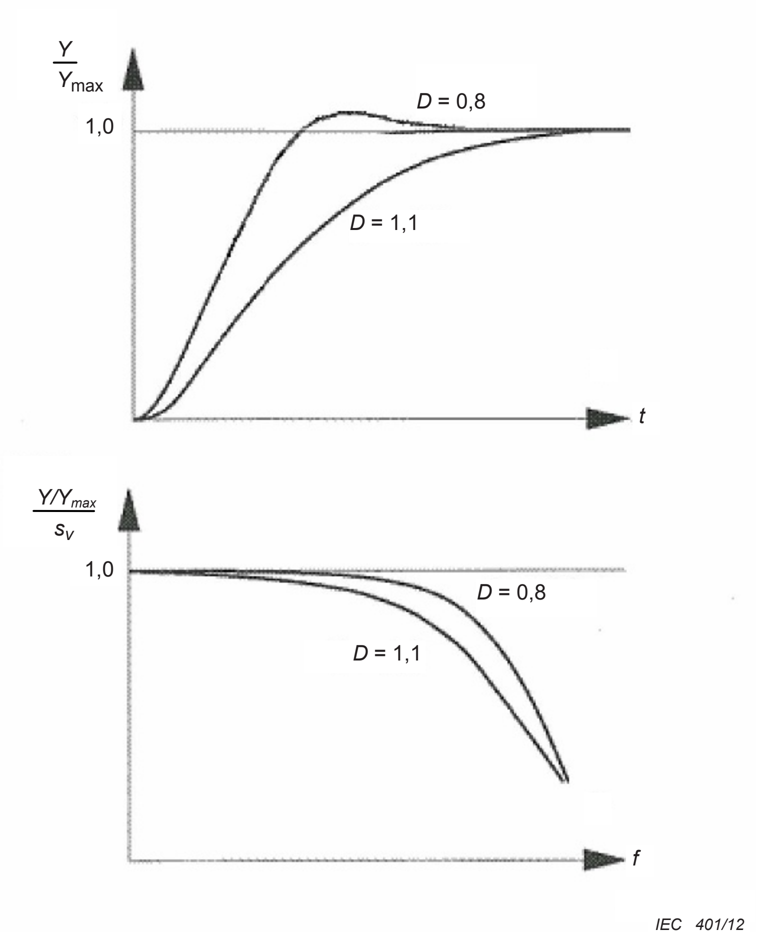
[4] In the case of small power stations, the values given may be increased to: $i_a < 0{,}6\ \%$, $T_q < 0{,}30$ s.



D < 1 periodically damped case

D > 1 aperiodic case

Figure 19 – Time step response and frequency response of the amplifier output Y/Y_{max} to a displacement input s_v

5.5 Functional relationship between servo-positioners

5.5.1 Dual regulation of turbines with controllable guide vane and runner blade angles

5.5.1.1 General

The functional relationship between guide vane and runner blade position is called cam relation. The following arrangements are distinguished:

- parallel control;
- follow-up control.

The head H can be arranged to influence the functional relationship additionally. In the follow-up control, either the guide vane or the runner blade servo can be in the lead.

5.5.1.2 Implementation

This can be implemented:

- electronically through function generators with and/or without the influence of head;
- mechanically by a cam, designed for the rated head (in the case of small head variations or reduced requirements);

- mechanically by a profiled cam which is shifted with varying head either:
  a) electrically as a function of head, or
  b) manually.

5.5.1.3 Adjustment

The defined functional relationship between guide vane and runner blade angle is generally based on specific or series model test results. The relationship may be verified or corrected on site by index measurements or measurements of the efficiency or other quantities.

5.5.2 Dual control of turbines with needles and deflectors

The deflector´s purpose is to limit the speed increase during load rejections and to control speed under isolated network operation when large perturbations occur. The control can be accomplished in the following ways:

- parallel control of needles and deflector;
- direct control of needles, control of deflector as follow-up control;
- direct control of the deflector, control of needles as follow-up control.

The follow-up control can be implemented:

- electronically by means of a function generator;
- mechanically by means of a cam in the forward path;
- mechanically by means of a cam in the feedback path.

5.5.3 Multiple control

It is applied in the case of individual guide vane and individual needle control. Individual servomotors are very often controlled in parallel.

5.5.4 Other relationships

The following examples are related to equipment according to 5.16.1 to 5.16.3:

- runner blade and guide vane angle and possibly the position of the servomotor of a draft tube gate following a load rejection to minimize surge;
- guide vane angle and the position of a bypass valve following a load rejection to limit dynamic pressure variations and speed increases;
- guide vane angle and bypass position in normal operation and following a load rejection in the case of combined operation of a power station with an irrigation scheme.

5.6 Actual signal measurement

5.6.1 General

For the various control tasks, essentially the following variables are measured:

- rotational speed;
- power;
- water level;
- pressure;
- stroke.

5.6.2 Rotational speed

5.6.2.1 Methods of rotational speed measurement for electronic governors

- Hall-generator or toothed disk (if a free shaft end is not available) with impulse transducer;
- speed measurement at the generator via transducers (utilizing the residual remanence);
- tachogenerators, especially if a free shaft end is available;
- others.

5.6.2.2 Methods of rotational speed measurement for mechanical-hydraulic governors

- Belt drive of the flyweight head (in simple or existing plants)

  Additional monitoring means are recommended to guard against breaking or slipping-off of the belt (belt guard).

- Motor drive of the flyweight head

  The governor head drive-motor is fed from

  a) a permanent magnet generator connected to the turbine shaft;
  b) an additional winding of the main generator;
  c) the winding of the main generator via a transducer.

In the cases b) and c) the governor head drive becomes effective only with the onset of excitation.

5.6.3 Power output

The power output is measured via a transducer. The input signal to the governor shall be sufficiently filtered, but with care in order to avoid the introduction of an inadequate delay.

5.6.4 Water level

The water level is measured electrically (e.g., via an electrode) or mechanically (e.g., via a float, a pressure transducer, a pneumatic transmitter or other sensors) and is transmitted to the water level controller.

5.6.5 Actuator position (stroke)

Position/motions (e.g. feedback signals) are picked up

- electrically (via rotational or linear transducers),

or

- mechanically (via linkage, cable, driving band)

With electrical transducers these items are important:

- freedom from backlash in the mechanical components;
- environmental resistance;
- adjustability.

In case of linkages, backlash and undue forces (e.g., in the case of overstroking) shall be avoided. In case of cables and driving band, sufficient pre-tension is important. The design of the system shall avoid resonance phenomena with suitable margins of safety.

5.6.6 Signal transmission from electronic transmitters

For the variables as per 5.6.2 to 5.6.5, usually 0 to 20 mA or 4 mA to 20 mA are used for signal transmission from the transmitter to the controller. Signals < 4 mA and > 20 mA are often used for signal monitoring. For signal transmission, shielded or twisted cables are required in order to suppress induction noise. The use of optical fibres may be opted for in the case where signals are transmitted in digital form.

5.7 Manual control

Manual control is understood as a means to set the turbine opening, using the positioning loop in the electronic governor or directly via the actuator(s). In any case, the unit's safety still rests at least with the overspeed protection.

Manual control may be desirable to allow a continuation of power generation in the case where the governor control loop or parts of it are out of order. Also manual control may be regarded as helpful in the commissioning phase of turbines and for maintenance activities.

Depending on the degree of impairment of the system, allowable manual control will be arranged to bypass an increasing number of functions. Costs rise as more functions are bypassed. Also, the use of a proportional setting incurs higher costs than an impulse type setting.

The following general possibilities can be implemented as manual controls.

a) Manual control using the positioning loop in the electronic governor

   The positioning loop for manual control is an integral part of the electronic governor, that means manual control is only available when the electronic governor functionality is not impaired. All supervision functions are active during operation of the turbine.

   If higher availability of the unit is required, a redundant configuration of the electronic governor can be used. After the failure of one of the systems, the redundant one will take the control keeping the complete functionality.

b) Manual control by electronic proportional positioning

   It sets the independent electronic positioning loop directly bypassing the governor control loop. The electronic positioning loop including the feedback is assumed to remain functional in this case. An independent power source and other redundancies can be arranged to enhance the system availability.

c) Manual control by integral or impulse positioning

   It may actuate the control valve electronically or the (pilot) servomotor directly via separate on-off valves. The electronic positioning loop, including the feedback function, is assumed to be out of order in this case.

d) Manual control by mechanical proportional positioning

   It positions the main control valve mechanically and requires a mechanical feedback. In cases where the amplifier arrangement does not include a mechanical feedback, it has to be provided for manual control purposes. The impact on costs should be considered.

5.8 Linearization

In some cases, it is advisable that a controlled variable follows the input signal linearly, e.g. the power output. The relationship between the input (setter) signal and the actuator stroke is non-linear in such a case.

Implementation:

- electronically via a function generator;
- mechanically via cams.

5.9 Follow-up controls

In case a bump-free transition from one operational mode into another is specified in combined control system configurations with selectors (Figures 10 to 13) the command signals of the control which is not on the line shall be made to follow the respective controlled variable and/or to correspond to it in the instance of change-over. In analog systems especially, follow-up controls incur additional costs.

Examples

- The power output controller command signal follows the actual power output signal in the speed control mode.
- The speed command signal follows the actual frequency signal in the power output control mode.
- The manual control set point follows the actual actuator position in the various control modes.
- To minimize start-up times (see 5.14.1) the pre-opening can be adjusted to varying heads or a separate control loop can be arranged for the start-up phase (e.g., acceleration control).
- In the case of remote control, the respective local controls shall be made to follow the respective command signals.

5.10 Optimization control

Special control configurations may be provided to optimize the system with respect to the overall plant efficiency, the running smoothness or other criteria by means of:

- a staggered control of multiple needles in Pelton-turbines;
- a load distribution among several units in a plant;
- others.

5.11 Monitoring parallel positioning of amplifiers

In the case of guide vanes or needles with individual servomotors, monitoring the parallelism of the positioning is recommended. For this purpose, the deviation of the position of each servomotor from the average of the total is monitored. When the deviation exceeds a given limit, a warning or a shut-down is initiated. Also the control deviation of the individual positioning loop can be monitored. If it does not return to approximately zero in a given time span a warning or a shutdown is initiated.

5.12 Provision of actuating energy

5.12.1 General

The necessary actuating energy is provided predominantly by oil hydraulics.

The minimum required pressure p_R follows from the required regulating capacity E_R [5] and the volume of the servomotors:

$$p_R = E_R/V_S$$

There are systems with and without accumulators to be distinguished.

---

[5] Friction included.

Systems with accumulators are preferred, where quick delivery of large amounts of actuating energy is called for (e.g., in the case of power output-frequency control or when stringent requirements in frequency control prevail).

5.12.2 System with an accumulator

5.12.2.1 Pressure tank (air/oil accumulator)

For maximum applicable pressure and calculation the respective rules apply (ASME, European Directives, etc.).

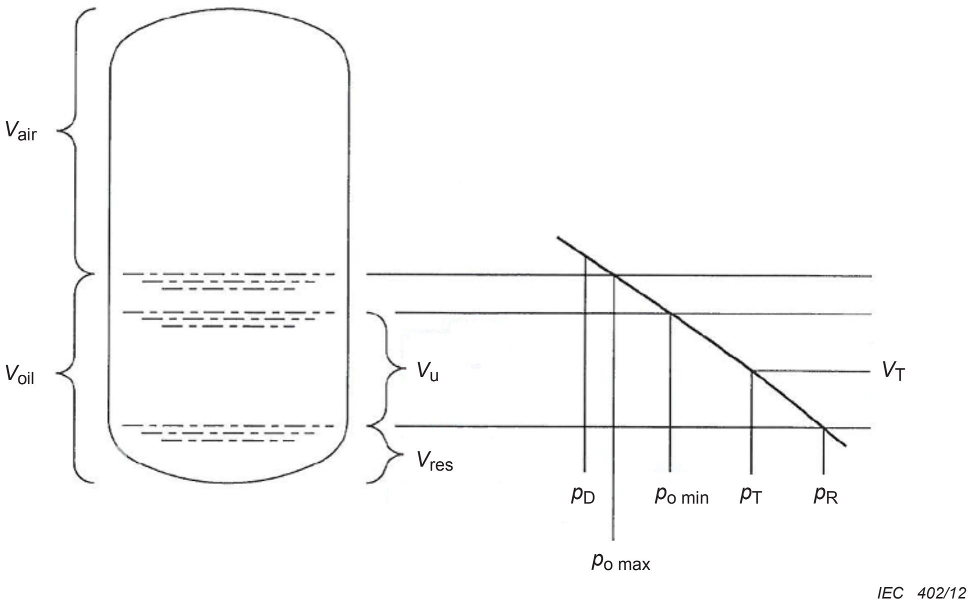


Figure 20 – Pressure tank content and pressure ranges

Design pressure, p_D

- Operating pressure range

  $p_{o\,max}$ to $p_{o\,min}$

  $p_{o\,max} = (0,85 \text{ to } 1,0)\ p_D$ [6]

  $p_{o\,min} = (0,80 \text{ to } 0,9)\ p_D$
- Tripping pressure (minimal pressure for emergency shutdown)

  p_T ($p_{o\,min} > p_T > p_R$) [7]
- Minimum required pressure

  $p_R = (0,58 \text{ to } 0,75)\ p_D$

Recommended usable oil volume

- Single loop control

  $V_u = 3\ V_S$
- Dual control

---

[6] When determining the maximum operating pressure, the rules concerning the opening and final pressure of the safety valve apply.

[7] p_T is chosen such that pressure after closure does not drop below p_R.

$V_u = 3\ V_{Sga} + (1{,}5 \text{ to } 2{,}0)V_{Sru}$

$V_u = 3\ V_{Sde} + (1{,}5 \text{ to } 2{,}0)V_{Sne}$

where

V_S is the oil volume of all servomotors;

V_{Sga} is the total volume of all guide vane servomotors;

V_{Sru} is the volume of the runner blades servomotor;

V_{Sde} is the total volume of all deflector servomotors;

V_{Sne} is the total volume of all needle servomotors.

In special isolated network operating conditions, higher values may be required.

Minimum usable oil volume

If isolated network operation is not required, the usable oil volume can be reduced to a minimum, which corresponds to the tripping oil volume V_T according to:

$$V_T = V_S + q_l \times t_l + V_{res}$$

where

q_l is the leakage of the whole oil supply system;

t_l is the time available up to ensuring a mechanical locking of the servomotors or closing time of inlet valve;

V_{res} is the volume reserve in the lower part of the pressure tank, including a safety margin and some volume to prevent air flowing into the system.

5.12.2.2 Piston accumulators

Commercial piston accumulators with a hermetic separation between oil and inert gas (mostly nitrogen) allow the application of higher pressures than those which national codes set as limits for air/oil accumulators. A residual oil volume and an automatic gas replenishment do not have to be provided.

For the design of the volumes of the piston accumulator system, the range of ambient temperature in the area of the accumulator has to be considered, in order to assure that extreme low or high ambient temperatures do not lead to situations related to the position of the piston, in which the closing safety of the turbine is not guaranteed.

Design pressure, p_D

- Operating pressure range

  $p_{o\,max}$ to $p_{o\,min}$

  $p_{o\,max} = (0{,}80 \text{ to } 1{,}0)\ p_D$ [8]

  $p_{o\,min} = (0{,}75 \text{ to } 0{,}9)\ p_D$
- Tripping pressure (minimal pressure for emergency shutdown)

  $p_T\ (p_{o\,min} > p_T > p_R)$ [9]
- Minimum required pressure

---

[8] When determining the maximum operating pressure, the rules concerning the opening and final pressure of the safety valve apply.

[9] p_T is chosen such that pressure after closure does not drop below p_R.

$p_R = (0,5 \text{ to } 0,75)\, p_D$

Recommended usable oil volume

- Single loop control

  $V_u = 3\, V_S$
- Dual control

  $V_u = 3\, V_{Sga} + (1,5 \text{ to } 2,0) V_{Sru}$

  $V_u = 3\, V_{Sde} + (1,5 \text{ to } 2,0) V_{Sne}$

5.12.2.3 Bladder accumulators

As in this case the oil/gas volumes cannot directly be supervised, bladder accumulators may not be used if the safe closing of the unit depends on the amount of storage energy in the accumulator. If closing of the turbine is guaranteed by other means (e.g. closing weight, closing spring) bladder accumulators can be allowed.

As a breakage of the bladder cannot totally be prevented, this case including the consequent transport of gas dissolved in the oil to the rest of the system has to be considered. In parts of the system with lower pressure levels the gas will be released in form of bubbles. The gas bubbles may collect in some points of the system or flow through valves and orifices. Both situations may lead to a malfunction of the positioning (instabilities, vibrations or irregular partially too fast movements of the servos). Therefore specially in case of critical configurations regarding water hammer (e.g. Pelton turbines with long penstocks) the use of bladder accumulators should be avoided or only be allowed after having carried out detailed investigations.

5.12.2.4 Other systems

For shutdown safety, weight or spring-loaded accumulators (low-head turbines) and water pressure taken directly from the penstock (high-head turbines) partly in combination with oil pressure systems (combined systems) are used.

These systems are to be dimensioned in such a way that the turbine can be shut down safely, i.e. also in the case of failure of the oil pressure supply in combined systems.

The opening is in most cases effected with oil pressure.

5.12.2.5 Pumps for accumulator systems

Two induction motor driven pumps are normally foreseen, each with a capacity of one combined servomotor volume of turbine per minute or with a capacity which can refill the oil volume ranging from $p_{o\ min}$ to $p_{o\ max}$ within one minute. As a general rule the smaller pump capacity of both criteria will be valid.

For combined oil hydraulic pressure units for both turbine and inlet valve, the combined capacity of both pumps shall allow to open the inlet valve within 1 min. Such oil hydraulic pressure units are safe, if the closing of the inlet valve is performed by a closing weight or by water pressure from the penstock.

In case of higher requirements regarding the starting time of the unit and/or the regulating activity bigger pumps should be used.

In special cases (e.g. to provide a start-up capacity without external supply), the drive of a second pump can be by d.c. motor, a small turbine in high head plants or by the turbine shaft.

In some cases, a pump to handle leakage losses and normal regulation only may be selected in addition to the main pumps, or instead of the second large capacity pump.

5.12.2.6 Oil sump tanks

The recommended layout is as follows:

- the sump tank shall be designed to allow drainage of the complete hydraulic system into the tank;
- it shall also be designed to allow a complete emptying for maintenance purposes and to remove dew-point water, e.g. by providing a slightly inclined bottom plate.

5.12.2.7 Auxiliary equipment

- Cooling and heating

  Cooling of the system oil is normally only required for large and medium size units in tropical zones and in the case of Kaplan turbines with servo-oil distribution through a shaft bearing.

  Cooling/heating can be desirable to limit oil viscosity variations.

- Oil mist exhaustion

  All tanks shall be equipped with at least a vent with filter insert and oil trap.

  Under unfavorable conditions (e.g. underground power stations with closed loop air conditioning systems), separate oil mist exhaust equipment is desirable.

5.12.2.8 Provision of pressurized gas

a) For pressure tank

   The pressurized air supply is usually provided by compressors. The design pressure of these shall be chosen to exceed the design pressure of the hydraulic system p_D. The capacity of the compressors shall be sufficient to achieve the desired loading times taking into account the resistance of the piping arrangement of the system.

   Recommended time for the first filling of the tank:

   - between 6 h and 12 h.

   Appropriate steps shall be taken to provide a drying of the air.

   An automatic air replenishing requires the following additional equipment:

   - a float switch in the pressure tank;
   - a pressure switch at the pressure tank;
   - a compressor-control module.

b) For accumulators

   Gas bottles and a special loading device are needed.

5.12.3 Systems without accumulator

5.12.3.1 Constant flow systems

These systems are characterized by the use of constant displacement pumps. In the steady-state condition, the excess oil is discharged via a pressure control valve or a bypass.

In order to reduce the system’s consumption, several pumps of different capacities may be used, especially in the case of large capacity hydraulic systems.

The hydraulic pumps shall have enough capacity to achieve the desired turbine opening and closing times in the presence of the respective leakage rates. In case additional accumulators are provided (combined systems) only the opening time applies. The dissipation losses shall be handled by the cooling system.

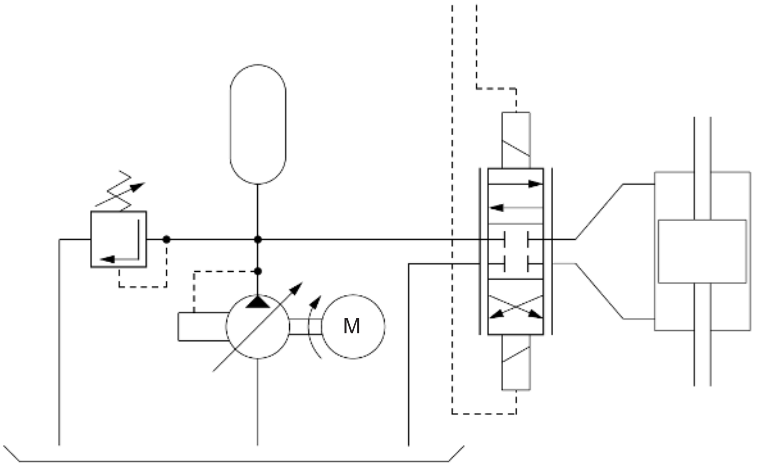
5.12.3.2 Variable flow systems

- Open-circuit systems

  In these systems (Figure 21) variable displacement pumps are used. The pump discharge in this case is adapted to the momentary flow requirement by means of a pressure control. Pumping power is therefore saved in comparison with a constant flow system. Also, cooling requirements are reduced. The pump capacity is determined according to 5.12.3.1.

  A small accumulator is recommended to avoid momentary pressure drops.

  A safety valve shall be provided.



IEC 403/12

Figure 21 – Open-circuit system

- Closed-circuit systems

  These systems are characterized by the fact that the pump flow and its direction are both controlled. The pump therefore combines the function of producing and distributing hydraulic energy. A control valve is not needed, as the pump is directly actuated by the positioning signal of the governor.

  Both servomotor sides shall be protected by safety valves which should preferably discharge into the opposite servomotor side.

  In order to cover internal leakages and/or to accommodate for servomotor area differences, means of replenishment via check valves shall be provided.

  These systems additionally require a small constant displacement pump to cover the need for pilot oil pressure.

5.12.4 Direct electric positioner

For small size turbines, guide vane operating systems driven by an electric servomotor are sometimes applied. Shutdown safety can in this case be provided by a parallel inlet valve closing circuit and/or by a separate power source.

5.12.5 Recommendation for hydraulic fluid selection

In water turbine installations, the same oil is sometimes used for both governor system and the lubrication of main and auxiliary machinery bearings.

The oil viscosity is selected to suit the type and design of the turbine and also the prevailing operating temperatures.

In normal cases an oil without additives is sufficient. Oils with additives are chosen in order to increase the lifetime specially in case of high operating pressures.

Concerning specifications, refer to ISO 3448.

5.13 Power supply for electronic control systems

The power package of the governor is to be connected to the station d.c. battery or an internal battery pack and to the station a.c. supply.

An automatic change-over in the case of a voltage drop in either system is recommended.

DC range: +10 % / –20 % [10]
AC range: +5 % / –10 % [11]

Fault monitoring is recommended.

5.14 Operational transitions

5.14.1 Start-up and synchronization

During the start-up phase (See Figure 22), the speed versus time curve is at first mainly determined by the characteristics of the installation such as the unit acceleration constant, the allowable guide vane or needle opening rate with regard to waterhammer, etc. Later, when approximately 80 % of rated speed is reached, the governor mainly determines the speed versus time curve. In this phase, its objective is to reach synchronization readiness within an acceptable time span. This time span may be considered to gauge a governor´s performance in this function. The performance of the synchronizer is not included in this consideration.

NOTE 1 Synchronization readiness is achieved, when the speed change rate dx/dt does not exceed a given value within the synchronization band.

NOTE 2 $t_{0,8}$ is the time at which 80 % of rated speed is reached.

NOTE 3 t_{SR} is the time at which synchronization readiness is reached.

NOTE 4 t_S is the time at which the generator is switched on line.

NOTE 5 Recommended values:

Synchronization band (0,995 to 1,01) $f_{network}$

Speed change rate for synchronization $dx/dt = 0{,}003\ s^{-1}$

$t_{SR}/t_{0,8}$ = 1,5 to 5,0

Steady state of network frequency is presupposed. The lower values of $t_{SR}/t_{0,8}$ apply to peak load power stations with favourable hydraulic conditions, the higher to base load installations. In the presence of pronounced surge tank influences and/or other hydraulic oscillatory phenomena, higher values are tolerated.

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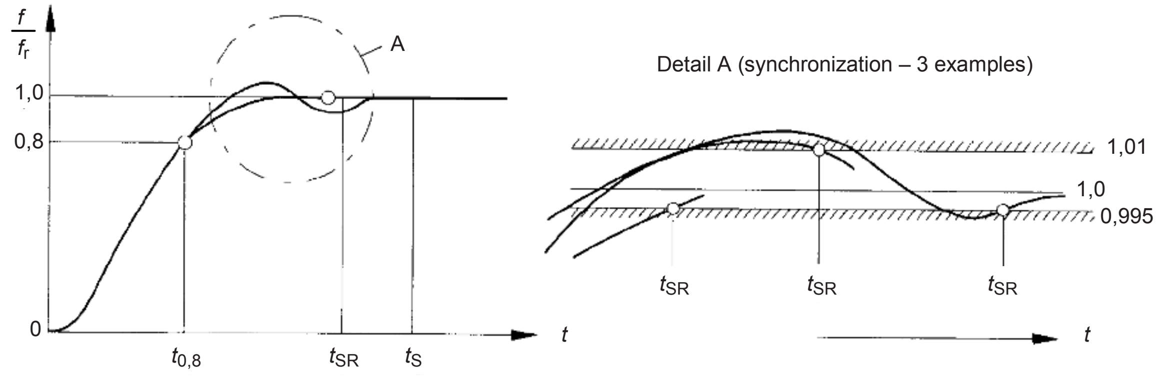
[10] –15 % can be specified by mutual agreement.

[11] For direct supply from the generator, these values may be higher.



IEC 404/12

Figure 22 – Start-up speed curve up to synchronization

5.14.2 Normal shutdown

Normal shutdown is activated in case of operational decisions. It is controlled with a command signal from the unit control system.

5.14.3 Sudden load rejection

The speed rise following a full load rejection (e.g. due to electrical disconnection from the grid) depends on the installation, e.g. on the allowable closing time with regard to the waterhammer and on the unit acceleration constant T_a etc. up to the beginning of the settling phase (see Figure 23). From that time on, the performance of the governor determines the speed vs. time curve[12].

NOTE 1	Regulating time t_E:	time, after which the speed deviation from the speed setpoint remains below ±1 %.
NOTE 2	Maximum speed n_{max}:	maximum speed after a load rejection (at t_M).
NOTE 3	Minimal speed n_{min}:	lowest speed after a load rejection.
NOTE 4	Recommended values:	t_E/t_M = 2,5 to 8 (in case of Pelton-units (free slow-down of unit) and high head, Francis turbines values of up to 15 may be reached).
		n_{min}/n_r = 0,85 to 0,95 (applies only in the case when the unit supplies the station service network after separation from the grid).

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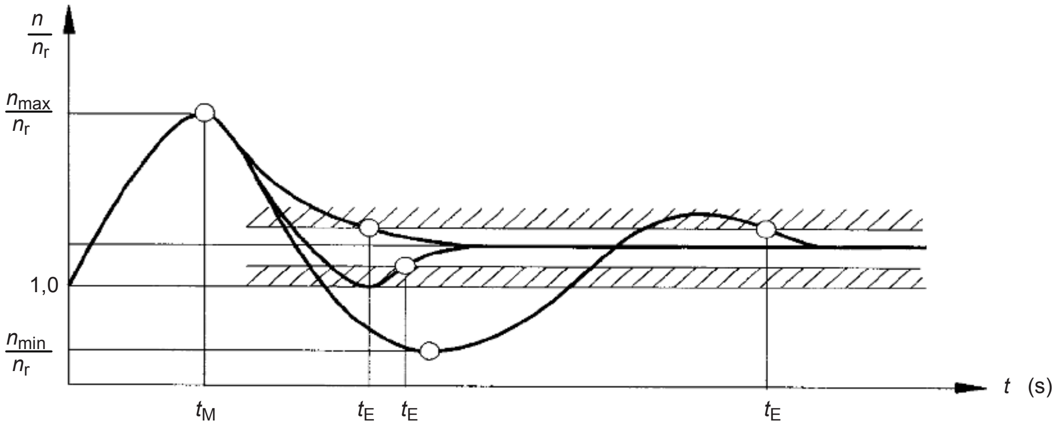
[12] Only in the case of low specific speed turbines, the discharge and torque characteristics may be of considerable influence.



IEC 405/12

Figure 23 – Load rejection

5.14.4 Other operational transitions

Various additional operational transitions result in case there are other operational modes provided besides the turbine mode. The different transition times shall be agreed upon.

5.15 Safety devices/circuits

5.15.1 General

The different types of shutdown sequences of the unit are in relationship with the unit control system and the protection system; therefore the operation of the turbine governing system and associated safety devices/circuits has to be in accordance with the corresponding requirements of this system.

5.15.2 Quick shutdown and emergency shutdown

5.15.2.1 General

For the definition of the tripping strategies for quick shutdown and emergency shutdown, tripping actions, servomotor shutdown initiating devices and tripping criteria have to be distinguished and combined:

5.15.2.2 Tripping actions

- Moving of the servomotor to the closed position
- Opening of the circuit braker

5.15.2.3 Servomotor shutdown initiating devices

- Turbine governor system
- Governor-independent shutdown valve

5.15.2.4 Tripping criteria

- Mechanical fault
- Electrical fault in the unit
- Serious fault in the governing system
- Emergency shutdown push-button pressed

5.15.2.5 Tripping strategies

There are several different tripping strategies widely used as common practice today depending on a combination of different tripping criteria, different servomotor shutdown initiating devices and the corresponding sequence of tripping actions.

The terms "quick shutdown" and "emergency shutdown" cannot be standardized at the time being, because the terms are used differently and contradictory today in the international community.

Annex C contains two different widely used strategies and emergency/quick shutdown definitions as examples.

5.15.3 Overspeed protection device

The following types are used:

- electrical speed contacts of a measuring system integrated with and monitored by the governor;
- electrical speed contacts of a measuring system independent of the governor;
- electrical speed contacts switched by a mechanical safety pendulum;
- oil hydraulic tripping device directly activated by mechanical safety pendulum.

5.15.4 Interlocks

- Electrical and/or hydraulic interlocks between the governing system and the main shut-off valve/gate to avoid erroneous control modes or dangerous conditions.
- Mechanical and/or hydraulic interlocks of the guide vane to protect against possible re-opening after quick or emergency shut-downs.
- Electrical interlock between needle control and braking (counter) nozzle.

5.16 Supplementary equipment

5.16.1 Measures to reduce pressure variations

To this effect, a bypass may be provided parallel to the turbine, which opens for a limited time span as a function of the closing movement and the closing speed of the main actuator.

In special cases, such devices may be used to maintain stationary flow (e.g., bypass cross connection to an irrigation scheme).

Additional measures shall be taken to guard against failure of such supplementary equipment, e.g. volumetric coupling between guide vanes and the supplementary equipment or provision for an extended closing time of the main servomotor in the case of a failure of the supplementary equipment.

The control of the supplementary equipment and its sensitivity shall be described and in accordance with the operational requirements.

Special care should be taken in the design of the water passages system (pressure pipe, surge tank, etc.).

5.16.2 Surge control

Surge control may be provided in low head installations. Its aim is to limit surge in rivers in the case of a load rejection by arranging for a continued flow through the turbine. For this purpose, the runner blade opening is brought to a certain position to provide a given flow rate after load rejection. The governor usually still acts on the guide vanes in such a case.

The following factors are of importance:

- tripping criteria (power drop or frequency deviation due to network failure);
- the lower flow rate limit, above which the equipment is activated;
- the allowable flow rate variation with the system activated;
- limits in head and flow rate;
- time span during which the system is activated;
- turbine speed;
- station service system supply.

5.16.3 Equipment and measures to lower the speed rise

In unfavorable cases such as in the case of low moments of inertia or a low allowable pressure rise in installations with long conduits, measures to reduce speed rise after load rejection may be necessary. The following may be introduced to this effect:

- bypass (according to 5.16.1);
- runner blades opening control (according to 5.16.2);
- resistors to absorb excess power (also for speed control in small hydro installations).

5.16.4 Central flow rate control in river power station systems

The input signal set manually or automatically through a central control station acts upon the opening setpoint resp. unit related flow setpoint of the local governor. The guide vane opening or the runner blades opening may be used as a flow rate feedback signal taking into account the characteristic curves of the turbine.

Central flow rate control aims at providing a given flow rate versus time function for a system of several cascade power stations along a river.

The following requirements apply:

- rapid start-up and synchronization;
- adaptation to varying heads;
- possibility to activate different opening limiter times.

5.16.5 Brakes

Brakes are used to shorten the slowdown time of the unit in the shutdown process.

While electric and mechanical brakes are usually not regarded as part of the governing system, in special cases hydraulic braking is implemented:

- in the case of Kaplan turbine, in the upper speed range by increasing the runner blades opening;
- in the case of Pelton turbines, by additional braking (counter) nozzles, which act on the back of the buckets.

5.16.6 Synchronous condenser mode of operation

In the synchronous condenser or phase shifting mode of operation, reactive power is produced. The generator is synchronized. Normally the guide vanes are closed and the runner rotates in air or the turbine is uncoupled. In addition synchronous condenser mode can be used to operate the unit as spinning reserve, capable to provide fast power reserve to the grid.

5.17 Environmental suitability of governor components

5.17.1 Vibration and shock resistance

Turbine-mounted transducers are often subjected to considerable levels of vibration and shall withstand such environmental conditions safely.

Head-cover or guide vane servomotor-mounted stroke sensors (transducers and transmitters) shall withstand the following vibration load without resonances in the relevant frequency range and without impairing the component function:

- vibration resistance: max. acceleration 5 g in the frequency range 10 Hz - 100 Hz (defined according to IEC 60068-2-6);
- shock resistance: max. acceleration 20 g (defined according to IEC 60068-2-27)

As the imposed vibration load depends on the type of turbine and on the location of the component, these requirements may be reduced in special cases.

5.17.2 Temperature and humidity

Specifications

Control equipment shall withstand, without impairing the component function, the following ambient conditions:

- temperature range: +5 °C to +40 °C;
- relative humidity: 85 % at 40 °C.

The actual range of temperature and relative humidity is to be agreed upon in each case. The dew-point shall not be reached. If necessary, special measures shall be taken (heating, air conditioning).

5.18 Electromagnetic compatibility

Relevant immunity tests shall be found in the IEC 61000-4-1; for emission tests CISPR 11 is applicable.

6 How to apply the recommendations

For practical purposes an appropriate selection of the requirements and properties as listed in Clauses 4 and 5 shall be made with respect to the type of installation concerned.

Thereby, it is necessary to distinguish between

- peak-load power stations;
- base-load power stations;
- power stations with induction generators.

In simple straightforward cases, unnecessarily stringent requirements shall not be imposed. Therefore in each of the three types of installation mentioned two kinds of requirements can be distinguished:

- minimum requirements;
- additional requirements.

Minimum requirements shall be fulfilled in all cases. They are normally sufficient in the case of power stations, which are to be run with a limited amount of monitoring and automation. Additional requirements may for example result from the integration of a power station into a network or a group of power stations. They may also result from requirements of navigation, irrigation, etc.

For each category of power station, recommendations should also be given for the parameter setting of the governors.

To facilitate the setting up of specifications, the following data sheets have been devised which shall be filled out. Data which should have been collected either by the purchaser or the supplier already during the enquiry phase are marked by double vertical lines at the left-hand side of the pages. All other data are needed only during contract finalization or in the course of contract implementation.

Water turbine governing system		Data page No. 6.1a
Customer:	Supplier:	Installation:
Date:		

Installation data

Type of turbine						
Number of units						
		Rated	Maximum	Minimum		
Specific energy or Net head	E or H				$m \cdot s^{-2}$ or m	
Flow per unit	Q				$m^3 \cdot s^{-1}$	
Power per unit	P				MW	
Rotational speed	n				rpm	
Head water elevation					m a.s.l.	[1]
Tail water elevation					m a.s.l.	[1]
Single control/dual control[2]			Runner blade	Guide vane		
			Needle	Deflector		
Individual servomotors, Guide vane / Needle				Number		

Water passage system[3]

Head water side		Channel		Conduit			[2]
Length in case of conduits						m	
Area in case of conduits						m^2	
Tailwater side		Channel		Conduit			[2]
Length in case of conduits						m	
Area in case of conduits						m^2	
Other data (e.g. about distributors, surge tanks, etc.)							
Maximum permissible pressure						m a.s.l.	[1]
Minimum permissible pressure						m a.s.l.	[1]
Measured at point							
Other limitations (e.g. surge, negative pressure, etc.)							

[1] Above sea level.

[2] Cross out if not applicable.

[3] Data may be supplemented by drawings.

Water turbine governing system		Data page No. 6.1b
Customer:	Supplier:	Installation:

Moment of inertia of generator $I = MD^2/4$						kg · m^2
Moment of inertia of turbine and additional rotating masses						
						kg · m^2
Permissible speed rise relative to rated speed when rejecting load from levels of						
P_G/P_{Gr}				100		%
$\Delta n/n_r$						%
Permissible speed decrease when rejecting load from levels of						
P_G/P_{Gr}						%
$\Delta n/n_r$						%
Operational modes			Isolated networks		Grid	[1]
Grid mode			Rated frequency			Hz
Frequency band					+/–	Hz
Isolated network						MW
Isolated network mode up to						MW
Largest power step change				+	–	MW
Permissible speed change $\Delta n/n_r$				+	–	%
Type of load (e.g. predominately resistance-, motor-, combined load, etc.)						
Regulating capacity	Guide vane					N · m
	Individual guide vane		Needle			N · m [1]
	Runner blade		Deflector			N · m [1]
Other data						

Limits of delivery

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[1] Cross out, if not applicable.

Water turbine governing system		Data page No. 6.2
Customer:	Supplier:	Installation:

Minimal requirements in case of peak load power stations

	Subclause
Manual start-up and synchronization 1)	
Automatic start-up and synchronization	5.14.1
Stable no load mode	
Manual shut-down 1)	
Automatic shut-down	5.14.2
Local opening limiter and speed setting at the governor	5.4.1
Remote opening limiter and speed setting with adjustable setting rates	5.4.1
Operation on grid with opening limiter or with speed setter and small damping time constant	5.3.3
Load rejection pressure and speed rises within permissible limits	5.14.3
Transitions between specified modes of operation	
Quick shutdown function	5.15.2
Emergency shutdown function	5.15.2
Overspeed protection	5.15.3

1) Without automatic function and remote control.

Water turbine governing system		Data page No. 6.3
Customer:	Supplier:	Installation:

Minimal requirements in case of base load power stations

	Subclause
Manual start-up and synchronization[1)]	
Stable no load mode	
Manual shut-down	
Local opening limiter and speed setting at the governor	5.4.1
Operation on grid with opening limiter	5.4.1
Load rejection pressure and speed rises within permissible limits	5.14.3
Quick shutdown function	5.15.2
Emergency shutdown function	5.15.2
Overspeed protection	5.15.3
[1)] Without automatic function and load control.	

Water turbine governing system		Data page No. 6.4
Customer:	Supplier:	Installation:

Minimal requirements in case of induction generator units

	Subclause
The governing system has no speed controller function	
Manual start-up[1]	
Manual switching-on to network[1]	
Manual shut-down[1]	
Load rejection pressure and speed rises within permissible limits	5.14.3
Local positioning of servomotor	
Water level controller (if it is included in the governor)	4.2.5
Quick shutdown function	5.15.2
Emergency shutdown function	5.15.2
Overspeed protection	5.15.3

[1] See data page 6.3.

Water turbine governing system		Data page No. 6.5a
Customer:	Supplier:	Installation:

Additional requirements for peak-, base-load and asynchron generator units1)

			Subclause	
Isolated network mode according to data page 6.1b				
Input and output for automatic and remote control				
Remote control of opening limiter			5.4.1	
Remote control of speed set point			5.4.1	
Automatic start-up			5.14.1	
Automatic shut-down			5.14.2	
Start-up without external supply of auxiliaries thereby energy supply by:				
Start-up opening as function of head			5.14.1	2)
Preadjustment of speed command signal				2)
Synchronization with synchronizer				
Manual control	with the electronic governor		5.7	
	with mechanical feedback			
	with electrical feedback			
	without feedback (e.g. impulse type)			
Power control				
Water level control				
Quick shutdown			5.15.2	
Emergency shutdown			5.15.2	
Additional overspeed protection	mechanical		5.15.3	
	electrical			
Interlocks			5.15.4	
Type of speed transducer			5.6.2	
Type of feedback			5.6.5	
Joint control of multiple units			5.10	
Optimization control (multiple turbines, needles, cells)				
Guide vane / runner blade relationship as function of head (Cam relation)			5.5.1	
Surge control			5.16.2	3)

1) Indicate if applicable.

2) Mainly for peak-load units.

3) Mainly for base-load units.

Water turbine governing system		Data page No. 6.5b
Customer:	Supplier:	Installation:

Other requirements		Subclause
For example		
Flow rate control		5.16.4
Condenser mode operation		5.16.6
Linearizations		5.8
Operational transition times[1]		

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[1] Mainly applicable for peak-load power stations.

Waterturbine governing system		Data page No. 6.6a
Customer:	Supplier:	Installation:

Parameter adjustment of governor

						Subclause	
Main operational mode with	Grid		Isolated network				1)
	Limiter		Speed setter				1)
	Power controller						1)
	Speed control		Power control				
	Grid	Isolated mode, no load mode					
Permanent droop b_p					%	5.3.2	
Proportional action coefficient K_p					-	3.6.9, 3.6.10, 3.6.11 and 5.3.3	
Integral action time T_I					s		
Derivative action time T_D					s		
Automatic switch-over to governor with adjustment						5.3.3	1)
by	grid mode		isolated network mode				
			Speed control	Power control			
Command signal setter	Adjustment range				%	5.4.1	1)
	Adjustment time				s		
Limiter adjusting time					s		
Closing time function (see Figure 6)	Guide vane				%	3.6.14 and 5.4.3	1)
	Needles				s		1)
	Total closing time				s		
	Adjusting range				s		
Closing time (see Figure 6)	Runner blades		Deflector		s		1)
Opening time function (see Figure 6)	Guide vane				%	3.6.14 and 5.4.3	1)
	Needles				s		1)
	Total opening time				s		
	Adjustment range				s		
Opening time (see Figure 6)	Runner blades		Deflector				1)
Synchronization readiness after t_{SR}					s	5.14.1	
Governor insensitivity $i_x/2$						5.4.2	
Overspeed protection	Electrical tripping at				%	5.15.3	
	Mechanical tripping at				%		

1) Cross out if not applicable.

Water turbine governing system		Data page No. 6.6b
Customer:	Supplier:	Installation:

				Subclause	
Surge control	activated at guide vane position		%	5.16.2	
	at surge speed n_s/n_r		%		
	at surge flow Q_s (fixed) or		$m^3 \cdot s^{-1}$		1)
	at surge flow Q_s/Q_r		%		1)
Other parameters e.g. with respect to a bypass, water resistor, …				5.16.3	1)

Provision of actuating energy

						Subclause	
Energy provision for	opening	by				5.12	1)
	closing	by					1)
		by					1)
							1)
							1)
							1)
Design pressure of servomotors	Guide vane				bar		1)
	Individual guide vane		Needles		bar		1)
	Runner		Deflector		bar		1)

Hydraulic pumps (constant and variable displacement)

					Subclause
	Main pump				5.12.2.5
Type					
Rotation speed				rpm	
Driven by					
Noise level				dB (A)	
Discharge					
Pressure				bar	
Power				kW	

---

1) Cross out if not applicable.

Water turbine governing system		Data page No. 6.6c
Customer:	Supplier:	Installation:

						Subclause
Accumulators						5.12.2 1)
Gas replenishing through						
Loading time					s	
					bar	
Safety valve opening pressure					%	
Final (maximum) pressure at full discharge rate of pumps and zero consumption					%	
Working oil volume	Minimum usable oil volume			V_T	%	
	Single servomotor control				x V_S	
	Dual control		x V_{Sga}		x V_{Sru}	
Oil sump tank						5.12.2.6 and 5.12.2.7
Level indicator						
Bypass filter						
Oil mist exhaustion						
Oil heater						
Oil cooling						
Water ingress warning						
Hydraulic fluid	mineral oil	/	synthetic oil			5.12.5
Viscosity at 40 °C					mm²/s	
Other data (e.g. on density, water separation and de-aeration capacity, corrosion protection properties, etc.)						

Other data

		Subclause
Type of brake		5.16.5
Parameters of the servo-positioner (e.g. inaccuracy, time constant, etc.)		5.4.3

		Principle	Maker/type	
transducers for	stroke			
	pressure			
	temperature			
	speed			

1) Cross out if not applicable.

Water turbine governing system		Data page No. 6.6d
Customer:	Supplier:	Installation:

Limit switches	Principle	Maker/type

Control valves		Maker/type					
Instruments							
	digital/analog						
	direct/indirect						1)
	size						
	accuracy						
	maker/type						
Status indication							
Fault indication							

Electrical power supply			
Station service network	+/–	V	Hz
Safe a.c. supply	+/–	V	Hz
DC supply	+/–	V	
		W	
Terminal wire cross-section up to			mm^2

	Type
Cable	type

---

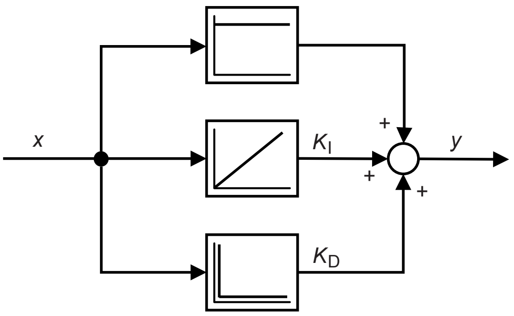
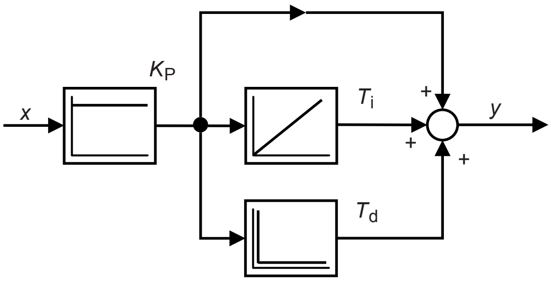
1) Via signal transducers.

Annex A
(normative)

Simplified differential equations and transfer functions of idealized PID-controllers

This guide uses as far as possible the terms and definitions of IEC 60050-351. For clarification, the simplified differential equations and transfer functions of the idealized PID-controllers as used in this guide are given below.

Two representations widely used in hydro turbine governors are shown in Figure A.1 and Figure A.2.

 IEC 406/12 **Figure A.1 – Idealized PID in pure parallel structure** Differential equations and transfer functions of an idealized PID-controller with – integral action coefficient K_I – integral action time T_I – derivative action coefficient K_D – derivative action time T_D – proportional action coefficient K_P	 IEC 407/12 **Figure A.2 – Idealized PID alternative representation** Differential equations and transfer functions of an idealized PID-controller with – reset time T_i – rate time T_d – proportional action coefficient K_P
x relative deviation of the controlled variable *y* setpoint for the relative displacement of the servomotor piston *t* time *s* complex variable of the Laplace transform Differential equation (controller without servo-positioner): $\frac{dy}{dx} = K_P \frac{dx}{dt} + K_I x + K_D \frac{d^2 x}{d t^2}$ integrated: $y(t) = K_P x + K_I \int x dt + K_D \frac{dx}{dt}$ resp. $y(t) = K_P x + \frac{1}{T_I} \int x dt + T_D \frac{dx}{dt}$	*x* relative deviation of the controlled variable *y* setpoint for the relative displacement of the servomotor piston *t* time *s* complex variable of the Laplace transform Differential equation (controller without servo-positioner): $\frac{dy}{dx} = K_P \times \left[\frac{dx}{dt} + \frac{x}{T_i} + T_d \frac{d^2 x}{dt^2} \right]$ integrated: $y(t) = K_P \times \left[x + \frac{1}{T_i} \int x dt + T_d \frac{dx}{dt} \right]$
Transfer function (controller without servo-positioner): $F(s) = \frac{y(s)}{x(s)} = K_P + \frac{K_I}{s} + K_D s$ resp. $F(s) = \frac{y(s)}{x(s)} = K_P + \frac{1}{T_I s} + T_D s$	Transfer function (controller without servo-positioner): $F(s) = \frac{y(s)}{x(s)} = K_P \times \left[1 + \frac{1}{T_i s} + T_d s \right]$

Annex B
(informative)

Grid frequency control

B.1 General

Annex B gives a brief description of the grid frequency control, which is generally described in the grid codes for the operation of large interconnected grids. Usually, such a grid frequency control is organized in a hierarchical structure: primary control, secondary control, etc, with a major role of some generating units.

The primary frequency control is essential for the equilibrium between the power demand and generation; it is automatically and locally operated by the governing systems of the units concerned.

The secondary frequency control is required for the restoration of the primary power reserves and power exchange programs, after a disturbance. It’s automatically operated, with modifications superimposed on the governing system power setpoints of the selected units; these modifications are generally sent by a remote control system.

B.2 Power equilibrium and grid frequency

B.2.1 Power equilibrium

In any electric power system, the active power has to be generated at the same time as it is consumed. Power generated shall be maintained in constant equilibrium with power demanded. Disturbances in this balance, causing a deviation of the grid frequency from its set-point value, will be offset initially by the kinetic energy of the rotating generating units and motors connected.

There is only very limited possibility of storing electric energy as such, so that the generation system shall have sufficient flexibility in changing its generation level, in order to restore the power equilibrium.

B.2.2 Grid frequency

The frequency f of a synchronous interconnected grid is a measurement for the rotational speed of the synchronised generators, which are rotating at the same “electrical speed” (calculated from the rotational speed by taking into account the number of pairs of poles of the generator).

After an increase in the total demand (or in case of loss of generation), the grid frequency (speed of generators) will decrease. Conversely, after a decrease in the demand, the grid frequency will increase.

B.3 Primary frequency control

B.3.1 Primary frequency control performed by generating units

In order to restore the balance between demand and generation, governing systems will perform automatic primary frequency control action, in relationship with a primary control reserve. The resulting transient frequency variation will be influenced by both the total inertia in the system, and the speed of primary control action of the governors. Therefore, the primary frequency control is performed by the action of the turbine governing system of the units involved in this control within a few seconds or tens of seconds, until a balance between power output and consumption of the global grid is re-established. The final contribution of a unit to the correction of a disturbance on the grid depends mainly upon the droop of the generating unit (see below), and on the primary control reserve of the concerned unit.

As soon as the balance is re-established, the grid frequency stabilizes and remains at a steady-state value, which may differ from the frequency set-point because of the droop of the generating units, which provides proportional type of action.

B.3.2 Droop of a generating unit

The droop of a generating unit is expressed as the following ratio (without dimension):

$$s_G = -(\Delta f/f_r)/\ (\Delta P_G/P_{Gr}).$$

It is directly linked with the permanent droop of the turbine governing system. A principle functional scheme of such a permanent droop using the output power is given in Figure B.1 (the same diagram could be drawn using $\Delta P_G + (1/b_p) \times \Delta f$ in front of the PID-governor).

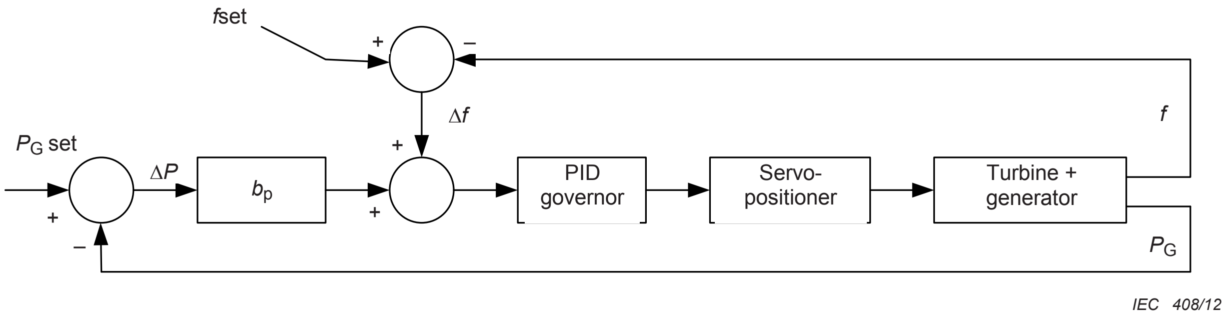


Figure B.1 – Example of principle schematic functional diagram of a unit with a turbine governing system using an idealized PID controller with a power droop

As an illustration, we now consider two interconnected generating units a and b with different values of droop under equilibrium conditions, but with identical primary control reserves.

Therefore, Figure B.2 presents the relationship between the power output of the units and the grid frequency. In case of a minor disturbance (final frequency offset $< \Delta f_b$), the contribution of unit a (which has the smallest droop value) to the correction of the disturbance will be greater than that of unit b, which has the greatest droop value. The frequency offset Δf_a at which the primary control reserve of unit a will be exhausted (i.e. where the power generating output reaches its maximum value P_{max}) will be smaller than that of unit b (Δf_b), even where both units have identical primary control reserves. It should be noted that if the governors on the interconnected units were adjusted for zero permanent droop, the units would not effectively share the system load. Differences in both the unit response times and in the governor calibrations would eventually result in one unit attempting to provide the whole load power, with the other unit delivering a very small power.

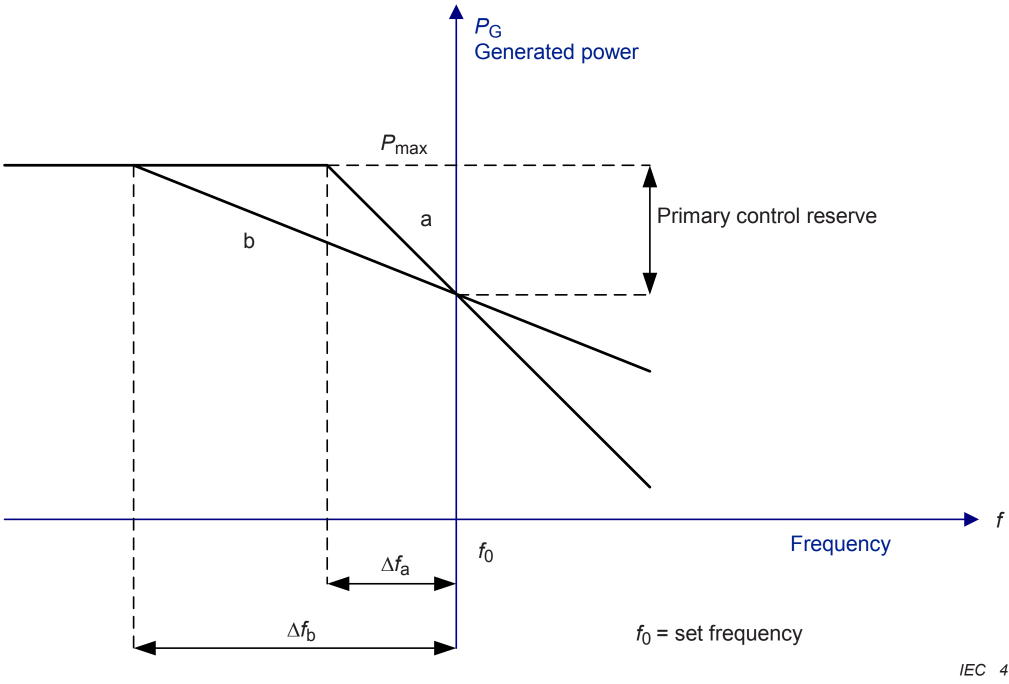


Figure B.2 – Behaviour of two units with different governor permanent droop values

B.4 Secondary frequency control

As mentioned above, in response to a sudden imbalance between power generation and consumption (e.g. as consequence of an incident) or random deviations from the power equilibrium, the primary control allows a balance to be re-established at a grid frequency value other than the frequency set-point value (i.e. at a steady-state frequency deviation Δf).

Furthermore, in case of different interconnected control areas within a large interconnected grid, since all control areas contribute to the frequency control process in the global interconnected system, an imbalance between power generation and consumption in any control area will also cause power interchanges between individual control areas to deviate from the scheduled values, or agreed values between companies.

The function of secondary frequency control (also known as load-frequency control or frequency-power control) is to keep or to restore the power balance in each control area and, consequently, to keep or to restore the grid frequency f to its set-point value, and the power interchanges with adjacent control areas to their programmed scheduled values, thus ensuring that the full reserve of primary control power activated will be made available again.

Secondary frequency control may make use of a centralised automatic generation control (AGC), modifying automatically the active power set points and producing adjustments of some generation units with corresponding secondary control reserves. This secondary frequency control operates for periods of several minutes, and is therefore timely dissociated from primary frequency control: both are operating in parallel.

Annex C
(informative)

Quick shutdown and emergency shutdown

C.1 General

As stated in 5.15.2.5 there are several different tripping strategies widely used as common practice today depending on a combination of different tripping criteria, different servomotor shutdown initiating devices and the corresponding sequence of tripping actions.

The terms quick shutdown and emergency shutdown cannot be standardized at the time being, because the terms are used differently and contradictory today in the international community.

Annex C contains two different widely used strategies and emergency/quick shutdown definitions as examples.

C.2 Alternative example I

C.2.1 General

The basic objective of this strategy is to limit the number of tripping cases in which the emergency shutdown device is activated and/or overspeed will occur, thus resulting in less stressing and wearing tripping procedures for the generating unit. In spite of that the required level on safety will be achieved.

C.2.2 Quick shutdown

C.2.2.1 Definition

Quick shutdown is activated in case of faults in the unit when the turbine governing system is still operative. The unit is shutdown within the shortest servomotor closing time by imposing a closing signal on the electronic governor and/or to an electro-hydraulic shutdown device.

C.2.2.2 Implementation

The electronic, electrical and if available the parallel electro-mechanical or electro-hydraulic devices are designed to provide an immediate and full displacement of the main control valve piston into its closing position.

C.2.2.3 Quick shutdown, mechanical faults (QSD-M)

In case of faults in the mechanical part of the unit (e.g. bearings, governor oil pressure, oil level, ...) and in order to not unnecessarily stress the unit as a consequence of overspeed, it is not required to trip the generator circuit breaker immediately. As long as the generator circuit breaker is closed, no overspeed will occur. The generator circuit breaker should be tripped with a delay (approximately in the no load position of the turbine guide vane opening, fully inserted deflector of Pelton turbines or at the moment when zero power output is reached).

C.2.2.4 Quick shutdown, electrical faults (QSD-E)

In case of faults in the electrical part of the unit (e.g. electrical part of generator) the generator circuit breaker is tripped immediately.

C.2.3 Emergency shutdown

C.2.3.1 Definition

Emergency shutdown is released in case of over-speed, serious faults in the turbine governing system or when the emergency shutdown push-button is activated. The governor and/or the speed sensing system are assumed to be inoperative. The unit is shutdown either by closing the guide vanes by overriding the governor and usually also some other elements of the unit control system and/or by closing the main shutoff valve or gate (if closable under flow).

Signals leading to emergency shutdown should be hardwired connected to a simple and robust emergency shutdown device, which is independent from the main unit control system, or to a fully redundant unit control system.

C.2.3.2 Implementation

The electro-mechanical or electro-hydraulic device closes the main servomotor by bypassing the governor. Additionally or alternatively closing of the spherical valve, the butterfly valve or intake gate (closable under flow) is initiated.

Provisions of emergency shut-down energy may be provided by:

- additional oil volume in the hydraulic energy supply system;
- a separate pressure oil supply;
- closing weight;
- pressure water servomotor (e.g. for the deflector in the case of high head installations);
- closing spring.

Tripping criteria are as follows:

- over-speed of the unit;
- serious governor failure (e.g. watchdog);
- certain special conditions of danger within the power plant (e.g. flooding);
- push-button emergency shutdown is pressed.

C.2.3.3 Automatic emergency shutdown (ESD-A)

The emergency shutdown is released automatically as a consequence of over-speed or serious faults in the governing system of the turbine. In order to not unnecessarily stress the unit as a consequence of over-speed it is not required to trip the generator circuit breaker immediately. As long as the generator circuit breaker is closed, no overspeed will occur. The generator circuit breaker should be tripped delayed (approximately in the no load position of the turbine guide vane opening, fully inserted deflector of Pelton turbines or at the moment when zero power output is reached).

C.2.3.4 Push-button emergency shutdown (ESD-PB)

The emergency shutdown push-button should be pressed in situations where the operator of the plant notices an abnormal situation leading to the decision to shutdown the unit. As in this case no information about the type of failure is available to the unit control system, the generator circuit breaker is tripped immediately.

C.2.4 Summary table and combined tripping cases

Table C.1 summarises the different cases for quick shutdown and emergency shutdown.

Provisions shall be taken that combined tripping cases lead to the right actions in order to assure the safety of the unit. Basic rules are:

- ESD has higher priority than QSD;
- the immediate tripping of the generator circuit breaker has higher priority than the delayed tripping.

Example: A combination of ESD-A with QSD-E shall lead to an emergency shutdown of the unit by overriding the governor and to an immediate tripping of the generator circuit breaker (the result is similar to ESD-PB).

Table C.1 – Alternative I – Summary of cases for quick shut-down and emergency shut-down

Tripping case		**Tripping criterium**	**Governor status**		**Actions**	
			Operative	**Inoperative**		
QSD-M	Quick shutdown, mechanical fault	Mechanical fault in the unit	X		Delayed tripping of the generator circuit breaker (no load opening or $P_G \approx 0$)	Shutdown within the shortest servomotor closing time by imposing a closing signal on the governor and/or electro/hydraulic shutdown device.
QSD-E	Quick shutdown, electrical fault	Electrical fault in the unit	X		Immediate tripping of the generator circuit breaker	
ESD-A	Automatic emergency shutdown	Over-speed, serious faults in the governing system		X	If possible delayed tripping of the generator circuit breaker (no load opening or $P_G \approx 0$, or latest when guide vane opening = 0 = closed)	Emergency shutdown by overriding the governor and other elements of the unit control system and/or by closing of spherical valve, butterfly valve or gate (if closable under flow)
ESD-PB	Push-button emergency shutdown	Decision of the operator	irrelevant		Immediate tripping of the generator circuit breaker	
Combined cases					ESD has higher priority than QSD. The immediate tripping of the generator circuit breaker has higher priority than the delayed tripping.	
It is recommended to operate QSD and/or ESD valves at the end of normal turbine stop. Alternatively a periodic functional test of QSD and/or ESD valves is advisable.						

C.3 Alternative example II

Some customers and suppliers implement the safety functions quick shutdown and emergency shutdown in an alternative less extensive way, by using a single shutdown valve that is activated in any case of fault. The effect of this shutdown valve overrides the governor actions.

In this alternative solution, there are only two tripping cases :

- quick shutdown (QSD), in case of mechanical fault, or serious faults in the governing system;

- emergency shutdown (ESD), in case of electrical fault or emergency shutdown push-button pressed by the operator.

Table C.2 summarises the different cases for quick shutdown and emergency shutdown for this alternative.

Table C.2 – Alternative II – Summary of cases for quick shut-down and emergency shut-down

Tripping case		**Tripping criterium**	**Governor status**		**Actions**	
			operative	**inoperative**		
QSD	Quick shutdown	Mechanical fault in the unit, or serious faults in the governing system	Irrelevant		Delayed tripping of the generator circuit breaker (no load opening or $P_{\mathrm{G}} \approx 0$)	Shutdown by overriding the governor and other elements of the unit control system and/or by closing of spherical valve, butterfly valve or gate (if closable under flow)
ESD	Emergency shutdown	Electrical fault in the unit, or Emergency shutdown push-button pressed by the operator	Irrelevant		Immediate tripping of the generator circuit breaker	
Combined cases					ESD has higher priority than QSD. The immediate tripping of the generator circuit breaker has higher priority than the delayed tripping.	
It is recommended to operate the shutdown valve at the end of normal turbine stop. Alternatively a periodic functional test of shut-down valve is advisable.						

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