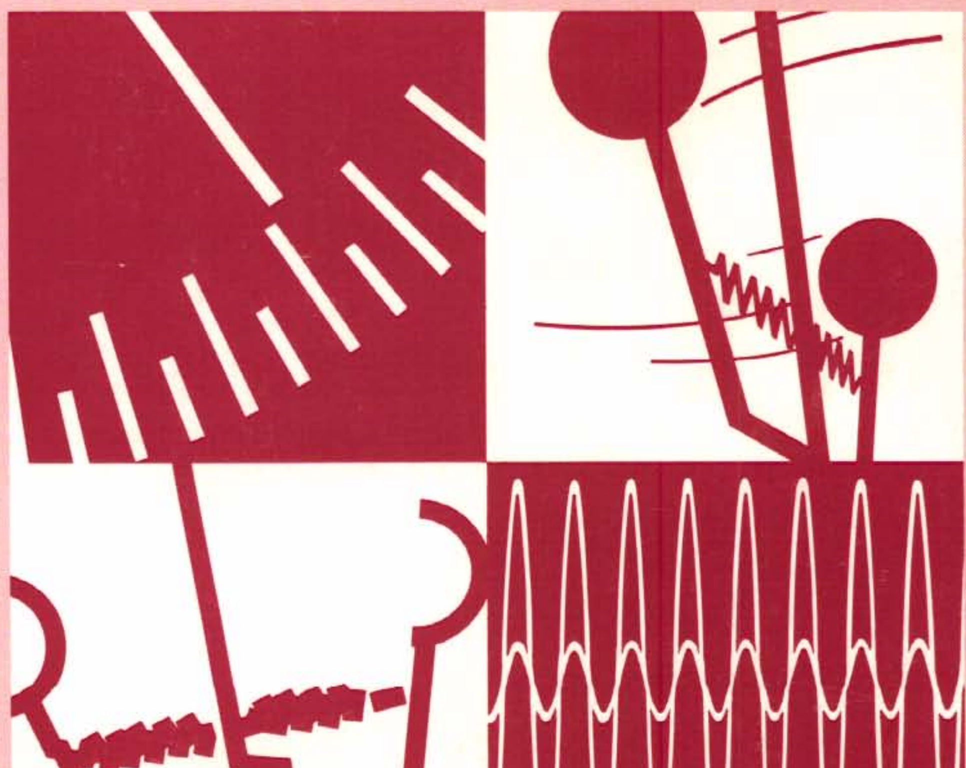
Harnessing Water Power on a Small Scale

Volume 8

Governor Product Information

Gerhard Fischer / Alex Arter
Ueli Meier / J.-M. Chapallaz



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Acknowlegment

Financed by HELVETAS, work on the development of simple speed governors took place at Balaju Yantra Shala (BYS) in Nepal, in collaboration with the Swiss Federal Institute of Technology (ETHZ), as early as 1977. Under professor Chaix of the Institute for Fluids Technology, Anton Kilchmann, then assistant at the institute, and Helmut Scheuer, a research engineer with previous working experience at Butwal Engineering Works (BEW) in Nepal, worked on the development of a simple, water-hydraulic speed governor for local fabrication. This governor was later successfully adapted to being manufactured at BYS, and was consecutively used in several small hydropower projects.

Supported by GTZ/Energy Division, H. Scheuer continued work on this governor in Germany in collaboration with the Hydraulics Institute of the University of Stuttgart, with the objective to standardize the design and make it more universally applicable.

It was later recognized that whatever new and appropriate governing device is developed will not be generally applicable in all situations. It was clearly felt, that a more comprehensive approach is necessary. Dr. Peter Baz and Klaus Rudolph of GTZ/GATE, with the help of Wulf Boje and Martina Kress of Projekt Consult and J.-M. Chapallaz, therefore organized a seminar on governing of small hydropower schemes in September 1988. More than 30 experts participated and it was concluded, that in order to be able to solve the question of adequate governing in each specific situation, information on existing concepts and products would have to be made available, ideally to enable design engineers to specify particular governing requirements in each situation and to select the adequate concept and ultimately the appropriate device or product as a part of the overall system.

The present product information on governors is the result of the preceding history outlined above and the authors would like to thank all individuals and institutions who were involved in one way or another. In addition, our thanks go to all who contributed with material on governing, both in the form of theoretical articles and advice, product descriptions and specifications. We especially also thank the contributors for the kind permission to use and reprint the materials provided.

We are grateful to GTZ/GATE for financial support for this publication and especially to Prof. Dr.-Ing. G. Lein of the University of Stuttgart, for his prompt and critical advice on some of the theoretical material. Finally, our thanks go to Silvia Ndiaye for the proof-reading and to Werner Fuchs, head of publishing at SKAT, who again has edited, designed and in general shaped the material into a superb printing job.

The authors

St. Gallen, 22 September 1990

Harnessing Water Power on a Small Scale

Governor Product Information

Contents

PREFACE

As early as 1920, the small hydropower station of Sundarijal supplied the residences of the nobility in Kathmandu with electricity.

A little story of that time is quite to the point and starkly summarizes the issue of control in small hydropower stations.

It runs thus: As happened sometimes, there was no electricity in the palace on the evening of a birthday party hosted by the Maharaja and ruler of the Kingdom. The elderly statesman was quite upset because he could not show off with the sparkling electrified chandelier in the great ballroom. To no avail, there was no electricity that night!

Still angry the next day, the Maharaja demanded to see the chief operator of the power plant in the early morning. ''I hold you responsible for what happened and shall punish you. What do you say to your defense?'' the operator was greeted.

The operator replied: ''Forgive me Highness, it was not my fault. The governor in the power house was out of order and did not do his duty.'' ''I shall not accept such misbehaviour a second time and for this time shall issue a strong warning letter to him'' said the Maharaja.

To this day, governing small hydropower stations has remained difficult and is very often a weak point in the operational reliability of the generating equipment. Full featured mechanical governors tend to have an excessively high price tag in relation to the cost of turbine and generator. Cheaper models, on the other hand, are subject to break down from wear and tear and all mechanical governors must be carefully selected and properly tuned in order to function well.

A modern alternative to mechanical speed governing is electronic load control, which has distinct merits and demerits. Load control - although the new trend - is not a valid concept in all situations and with the advent of such alternatives having become available, the issue of selection has become more complex.

The theory of automatic control and governing is not simple but is a necessary prerequisite for generating system design. Specialists are usually not available to design or review all details of a small plant. The micro hydro design engineer is often required to specify the governing concept all by himself. The present handbook attempts to provide assistance in this task, by discussing a number of issues and problems and by providing information on various controller and governor products which are commercially available, by way of example.

The authors hope to be able to make a further contribution in small renewable energy implementation. SKAT is continuing to document experience in micro hydropower development with the present handbook. It represents volume 8 in the series ''Harnessing Water Power on a small Scale''.

St.Gallen, June 1990

Chapter 1: Introduction

Governing of small water turbines, that is controlling manually, semi-automatically or fully automatically the operation of one or several water turbines as a function of load connected and/or water available, is a demanding and sometimes a very complex task, due to the existence of a variety of possible operating conditions. For the project engineer, responsible for the selection of the optimal governing device, it is essential to have an intimate knowledge of the requirements of control of a hydro plant already at the design stage, in order to be able to properly specify governor features as a condition for its procurement.

1.1 Aim of the handbook

This handbook is a practical guide on how to select and specify a governing concept for a micro hydro station. Since the selection of an appropriate governor is no simple task and requires a good deal of understanding, an attempt is made to give an overall introduction to the problem of governing and to show and explain the fundamentals of governed systems.

➪ **The handbook gives an overview of:**

- basic tasks of governing
- types of governors
- important specifications for the selection of the governor or controller
- reputed governor manufacturers

➪ **The handbook simplifies the access to:**

- further detailed information (literature, publications)
- organizations and experts who can give further support

1.2 The steps required

-Conditions for the pre-selection of governors:

The design concept of the micro hydro plant as well as the use of the produced energy determine the choice of the appropriate types of governor. A good knowledge of the working principles and the relevant data of the MHP-system are important for the pre-selection of the governor.

-Collection of data required for the specification of governors:

For a successfully operating MHP-plant, a careful collection of the important technical data is of great importance. This can only be done if the whole context of the different elements of the plant are understood. Manufacturers have therefore normally a questionnaire and in this publication we attempt to explain the importance and the meaning of a variety of questions to be answered for a specific case.

-List of manufacturers:

In chapter 6 there is a list of selected manufacturers. This list is not complete and is limited to such manufacturers who were known to us and who have answered our call for information for this product information handbook.

-Selection of the best governor from offers received:

The aim of this information is to enable the reader to understand the complex problem of governing as far as it is required. The ability to answer the questions of the governor manufacturers and to evaluate their offers, are mandatory to select the most suitable governor for a specific application.

Chapter 2: Different possibilities of governing

2.1 Basics of regulation

2.1.1 What is regulation?

Regulation is the automatic adaptation of a system to specified conditions of operation. Figure 1 shows the principle of a regulated system with its two main elements: the controlled system and the governor. The system works in the following way: the regulated parameter x is affected by a disturbance z, but is kept within a certain limit of deviation by the governor. To achieve this, the parameter x must be measured and it must be compared with a reference value w. By means of a control value y, adjustment takes place, until the difference x-w is within a determined limit.

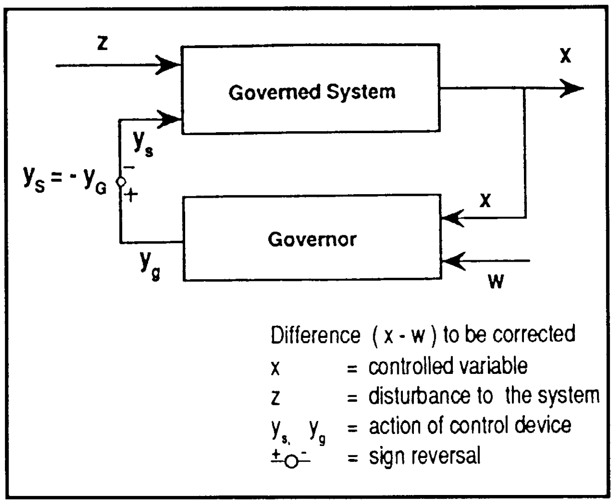


Figure 1: Elements of a governed system

In nature there are many examples of regulated systems. Analyzing such systems we will find the elements shown schematically in figure 1. Figure 2 shows a practical example: the light reaching the eye is changing over a great range. Each cloud z interrupts the direct sunlight. The iris opening y of the eye regulates the amount of light x reaching the sensitive background of the eye. The light sensitive nerves function optimally with the brightness w. The difference x-w is measured and if too much light enters the eye (x-w >0) the iris is closed (y<0) and if too little light is entering the eye (x-w < 0) the iris is opened (y>0). This means also a sign reversal for the control element (more light - less opening). This regulation you can observe yourself standing in front of a mirror and changing the light intensity with the hand and seeing the response of the iris of your eye.

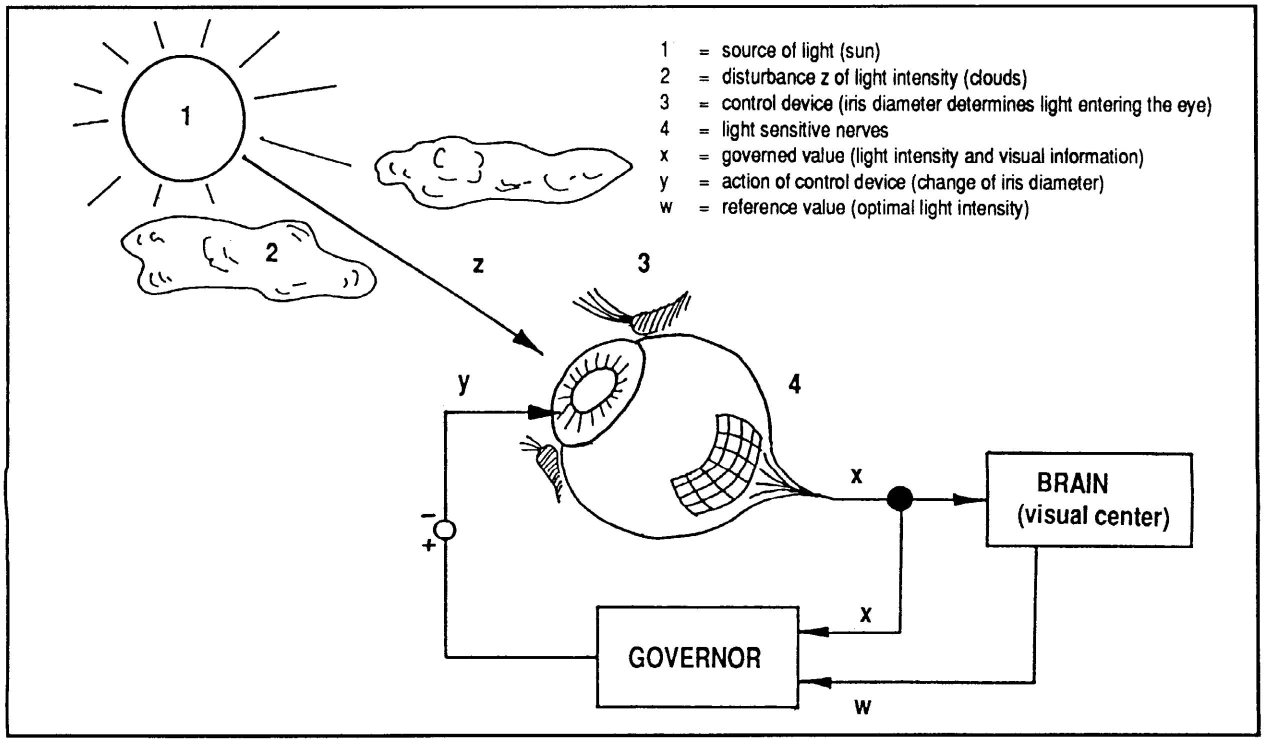


Figure 2: Natural governed system: Regulation of light intensity in the human eye

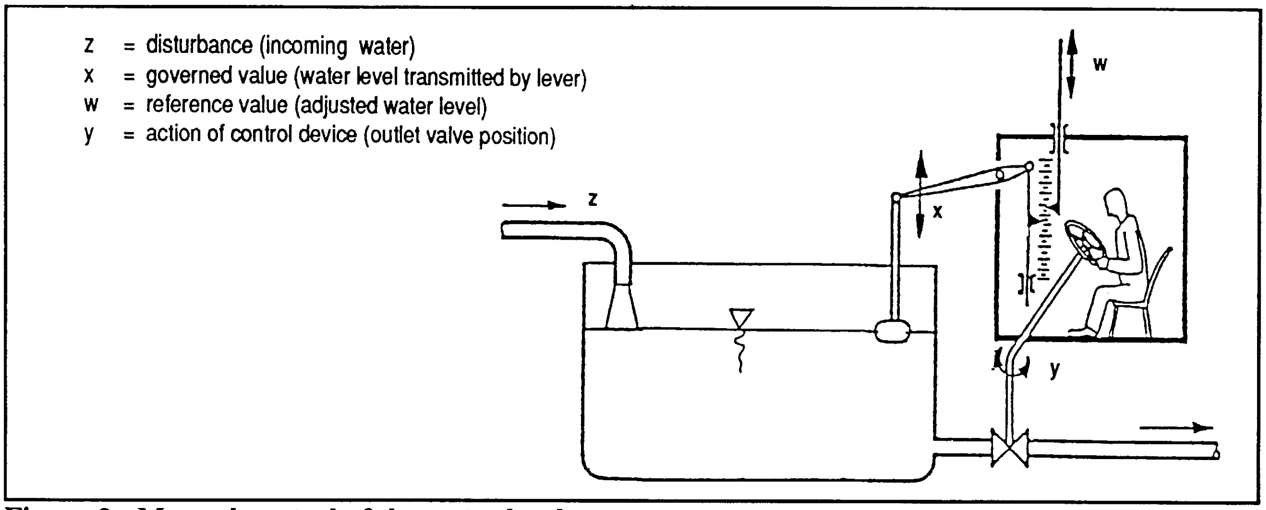


Figure 3: Manual control of the water level

Figure 3 shows an example of hand regulating the water level in a storage tank. The water level **x** should be kept constant at the reference value **w** by means of the control valve **y**. We see clearly that the governor (operator) works independent from the type of the controlled value (see fig. 3 and 4). He can operate in a closed room, not knowing whether speed, water level, temperature, etc. is being controlled. Only the response of the pointer on the indicator dial is of interest. When the water level falls, the operator has to close the valve to bring the pointer back to its reference value (nominal water level **w**). The governor/operator classifies the governed system according to its behavior **x(t)**, after a change of the control device **y**. Size and timing of the disturbance **z** are also important. The response of the system determines the characteristics of the governor needed for stable control of the system.

Imagine you are the operator. It will be more difficult to keep the water level on its nominal value if the following parameters change:

➪ **System parameters**
- smaller storage tank
- quick and significant variations of water flow **z** (or of the nominal water level **w**)

➪ **Governor parameters**
- sensitivity of valve response **y**
- sensitivity of display of the water level **x**
- reaction of operator (who may be sleepy or not taking an interest)

Figure 5 shows the main elements of an isolated MHP plant with speed control without connections to a grid.

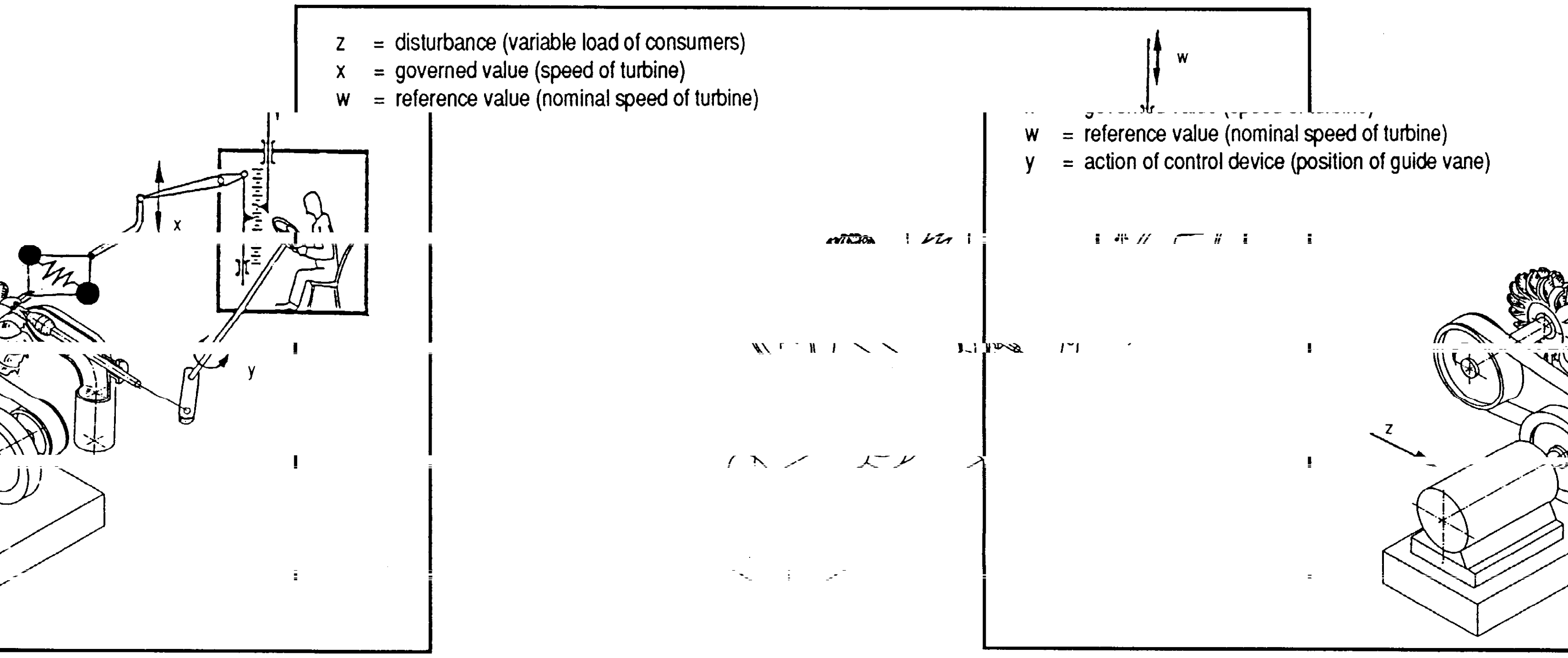


Figure 4: Manual control of a water turbine

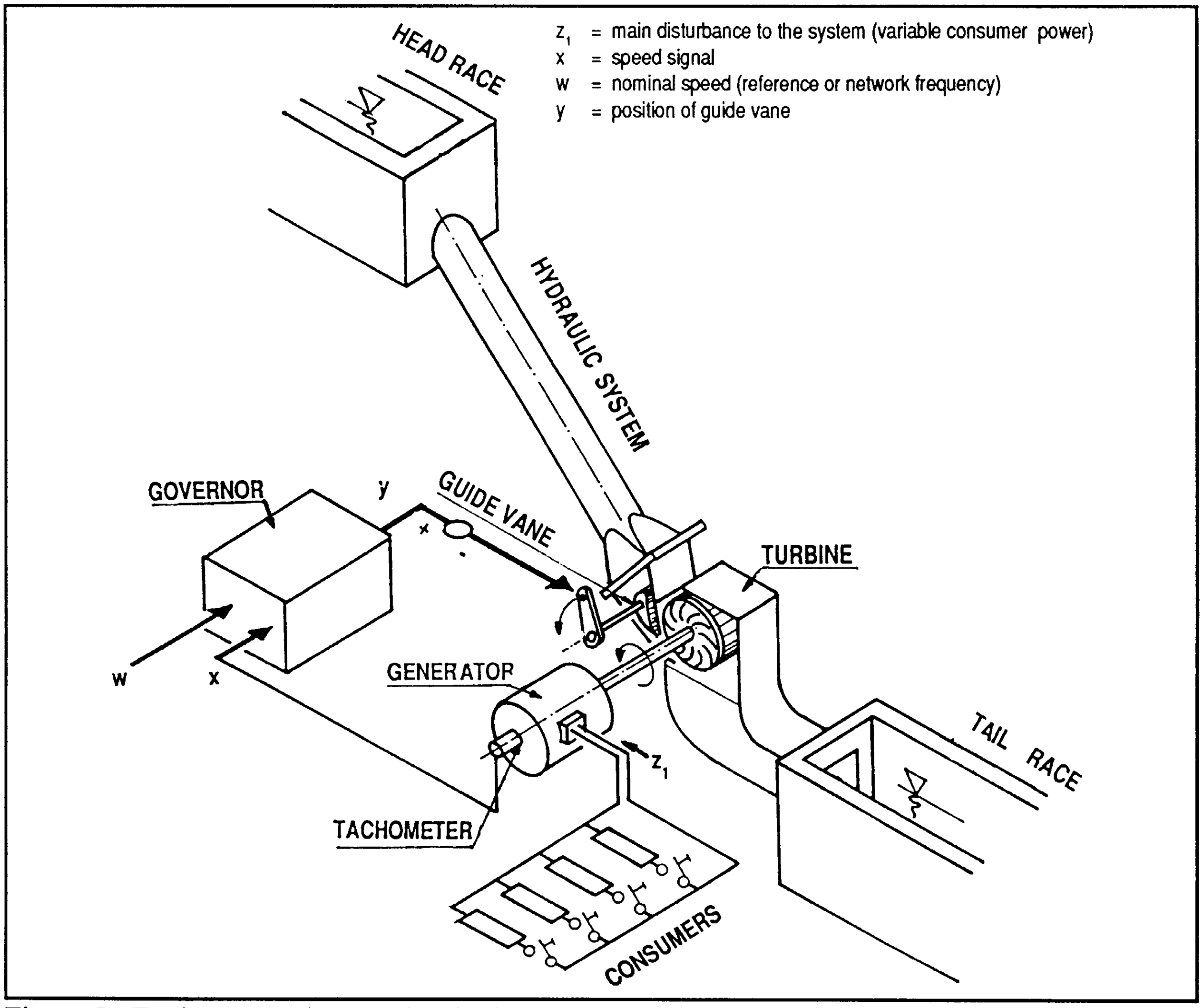


Figure 5: Typical MHP installation for isolated operation with its important elements of control

2.1.2 Why is regulation needed in MHP installations?

If a MHP scheme is operated without governor in isolated operation, its speed is only correct at nominal load. Decreasing load means increasing speed. For each constant load, the system will stabilize itself at another speed. This speed depends on the behavior of the turbine, the generator as well as of the consumers. The speed at very small load, is near the runaway speed of the turbine. The consequences of this are:

-the turbine and generator as well as direct driven mechanical consumers may not work properly or may even be damaged due to excessive centrifugal forces and/or overvoltage.

-voltage and frequency are related to the turbine speed. **The majority of the consumer devices however, need constant voltage and frequency** and cannot withstand large deviations of voltage and frequency.

Figure 6 shows the typical load-speed behavior of a governed and ungoverned MHP-system.

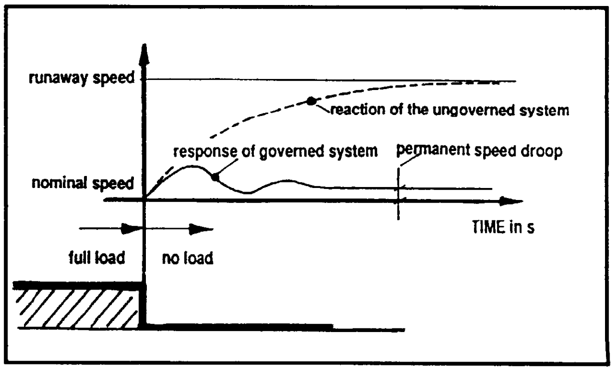


Figure 6: Behaviour of governed and ungoverned MHP-system

SUMMARY: BASICS OF REGULATION

Regulation is the automatic adaptation of a system to specified conditions of operation. In nature there are many examples of regulated systems. The characteristic elements of such a system are:

z = disturbance
x = governed value
w = reference value
y = action of control device

The need to govern MHP plants arises as the majority of the electrical consumer devices need constant voltage and frequency.

2.2 The self-regulated plant without governor

It is possible to operate a MHP plant without governor. Under normal conditions, such a plant would operate at different load levels with a speed determined mainly by the following parameters:

-Type of turbine

Each turbine has a specific load/speed characteristic. The speed of the unregulated turbine will reach runaway speed in case of no load. Figure 7 provides the specific runaway speed ratios for different turbine types.

TURBINE TYPE	$\frac{n_{max}}{n_N}$
Pelton	1.8 - 1.9
Crossflow	1.8 - 2.0
Francis	1.6 - 2.3
Propeller/Kaplan	2.0 - 3.0
reversed pumps	1.4 - 2.3

$$\frac{n_{max}}{n_N} = \frac{\textbf{runaway speed}}{\textbf{nominal turbine speed}}$$

Figure 7: Ratio runaway speed/nominal speed for different turbine types

-Design of the plant

The hydraulic design of the plant is also an important parameter. The friction losses in pipes rise with the increase of flow and therefore reduce the head and hence the speed of the turbine. Sudden changes of load cause changes of the turbine speed and depending on the turbine type, this may affect the flow through the turbine. It is also known that in long penstocks, changes of flow may cause pressure fluctuations (water-hammer effects).

-Type of consumers

The speed/consumption characteristic of the consumers may be very different.

For example:
-Directly connected mechanical consumers:
The important characteristic for the regulation may be expressed with the self-regulation factor of the consumers (see annexe A4). If this factor is high, the load of the consumers rises with the speed and therefore stabilizes the ungoverned operation.

Figure 8 shows the influence of self-regulation. We compare a turbine driving two centrifugal or two volumetric pumps. The torque of a volumetric pump is almost independent of its speed. The torque of a centrifugal pump on the other hand, rises with the second power of the speed. The operating points of the two systems if one or two pumps are working are shown. The response of the system if suddenly one of the pumps is disconnected is also shown. It shows, that the centrifugal pumps have a higher self-regulation factor (less speed fluctuation).

-Electrical generator connected to the turbine:

The type of generator and its internal voltage and current regulator have a great influence on its output/speed characteristics. The combination of the characteristics of generator, transmission line and consumer may be expressed with the self regulating factor of the grid (see annexe A4). If this factor is high, the load of the consumers rises with the speed and therefore stabilizes the ungoverned operation as already explained.

Practical application :
The combination of a centrifugal pump and a generator driven by the same turbine allows operation without governor. Such a plant works without great speed deviations, provided the generator output fluctuations due to the consumers are small in relation to the power demand of the pump (refer to figure 9).

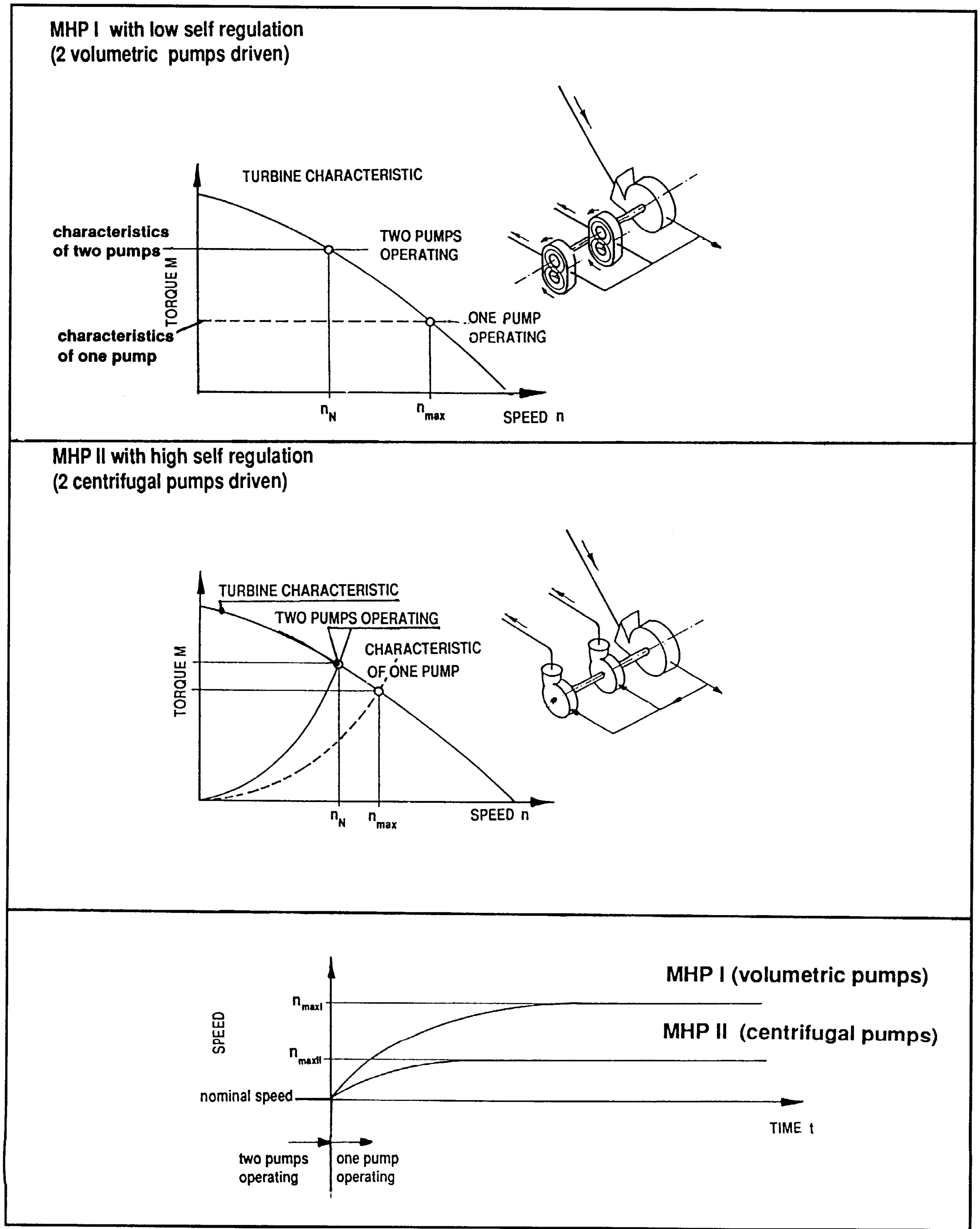


Figure 8: Influence of the turbine and consumer characteristics on the speed/load characteristics of the uncontrolled system (self-regulation)

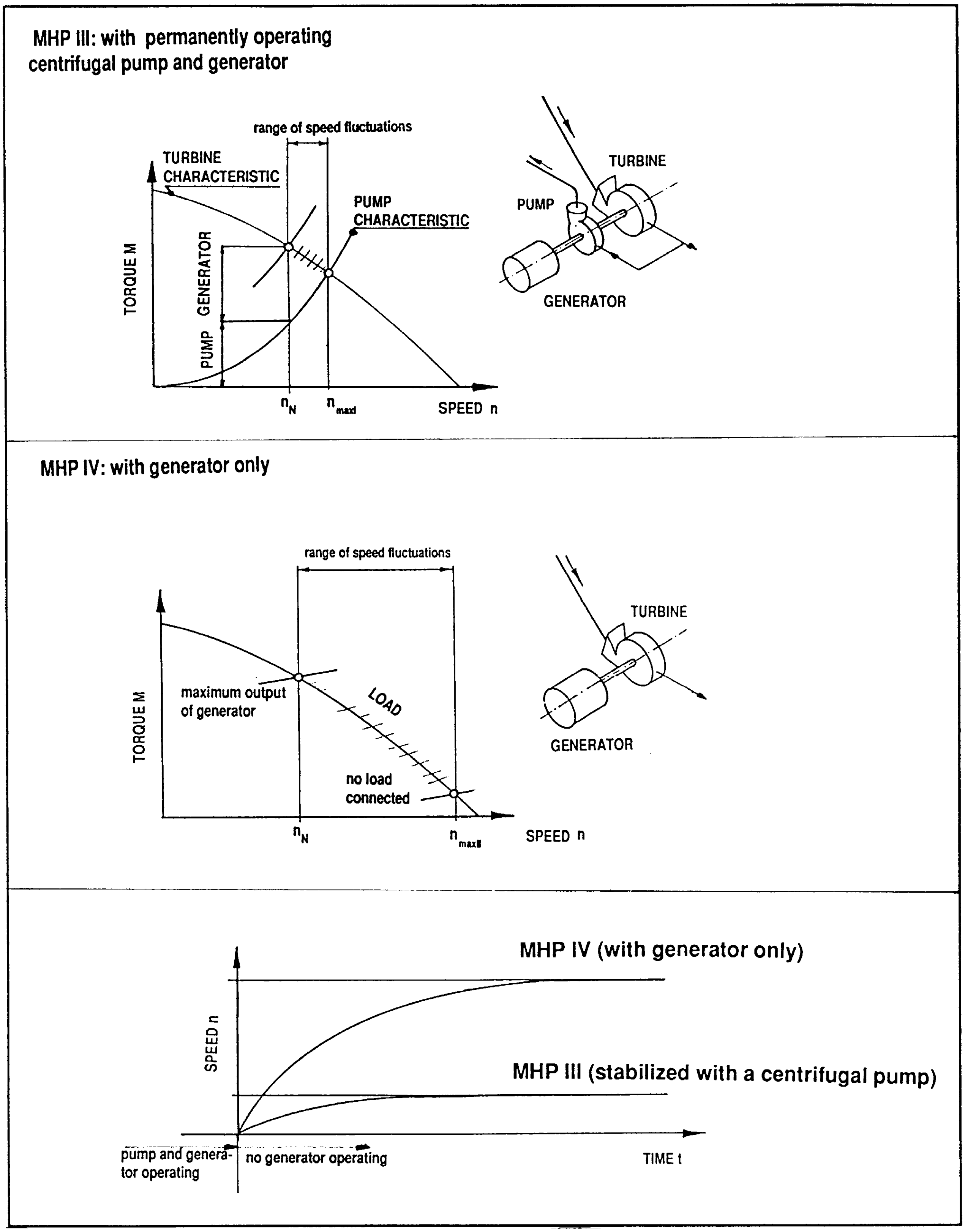


Figure 9: Reducing the speed fluctuations if the load changes by connecting permanently a consumer with good self-regulation

SUMMARY : THE SELF-REGULATED PLANT WITHOUT GOVERNOR

The self-regulated, ungoverned MHP scheme is only possible if all connected consumers can withstand the runaway speed in case of load rejection. If too much load is connected, the consumers also must withstand a lower-than-nominal speed. The MHP plant should have a good self-regulation characteristic to keep the speed/frequency changes small.

2.3 The hand-regulated plant

A hand-regulated plant is a scheme manually governed by an operator. The operator interferes as soon as the turbine speed or other parameters are exceeding specified limits. The rest of the time, the plant operates like the self-regulated plant without governor. This method is appropriate for mechanical machines and small electricity generating units with fairly constant load and low sensitivity to over- and underspeed. The entire equipment and all consumers must be able to withstand sizeable deviations of speed, voltage and frequency. The manual adjustment of the speed under all operating conditions is simpler for systems with large self-regulation factors of the consumers. Under certain conditions, it may be impossible to adjust the nominal speed by hand. Such critical, unstable operating conditions occur if the consumer and turbine characteristic are such, that two stable operating points exist for one turbine opening. The speed will be stable either at a too high or at a too low speed if no permanent accurate control is incorporated.

Figure 10 shows such a critical case in a plant with a Pelton turbine, a synchronous generator with constant voltage regulation, and only resistive consumers. Stable operation at the operating point 2 is very difficult because a small change of load leads to a collapse of the system stability. The system tends to operating point 1 or to an increase of speed to point 3. In this plant, it was only possible to adjust the inlet opening manually to either get 45 Hz or 55 Hz, but there was no way to manually adjust the turbine to get a frequency of 50 Hz.

In governed systems such an effect may destabilize the whole plant and cause large oscillations because the operating point of the governor changes between point 1 and 3. This effect is known as " HUNTING" or " SAWING" due to the particular shape of the speed/time diagram (see figure 11).

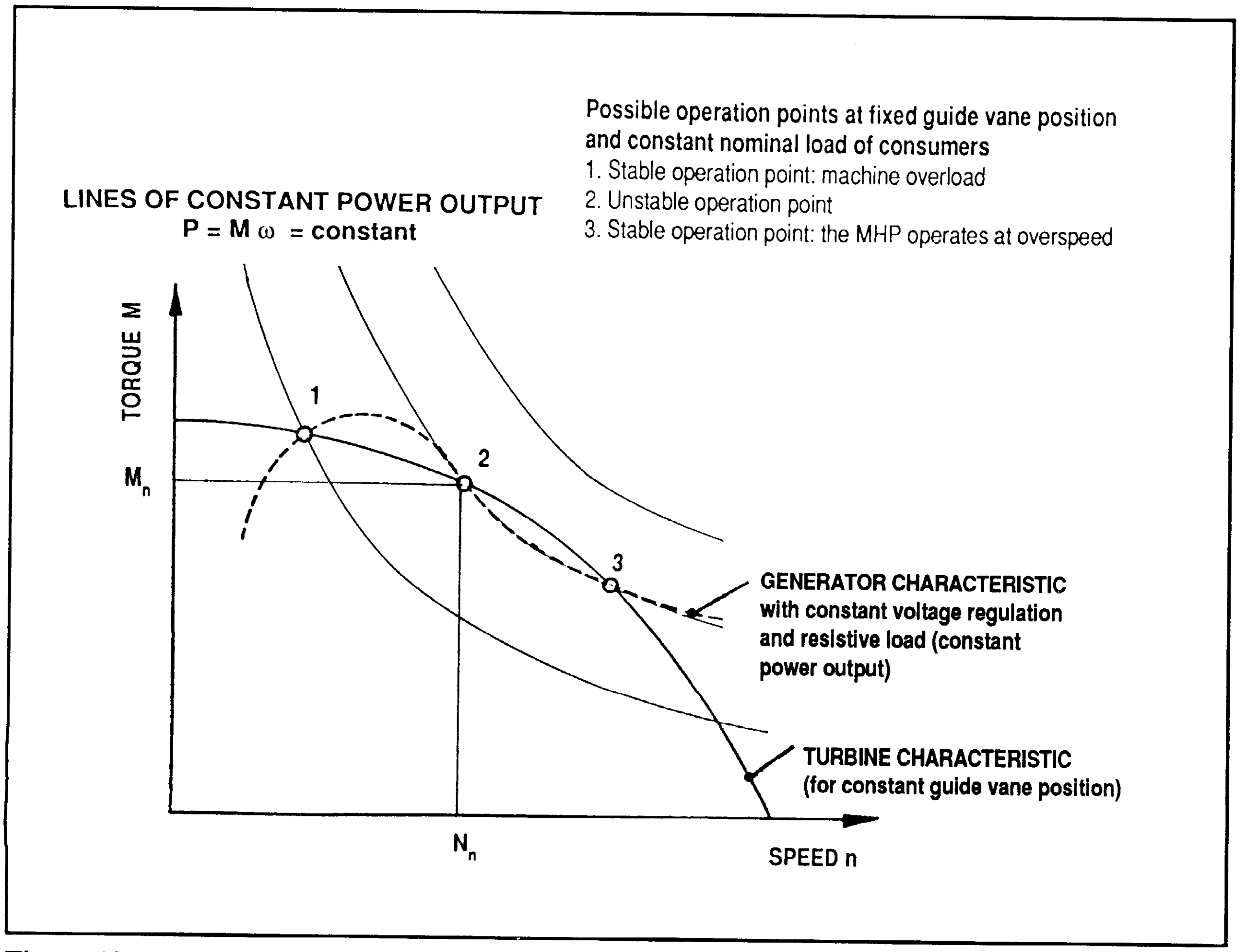


Figure 10: Critical case of instable control

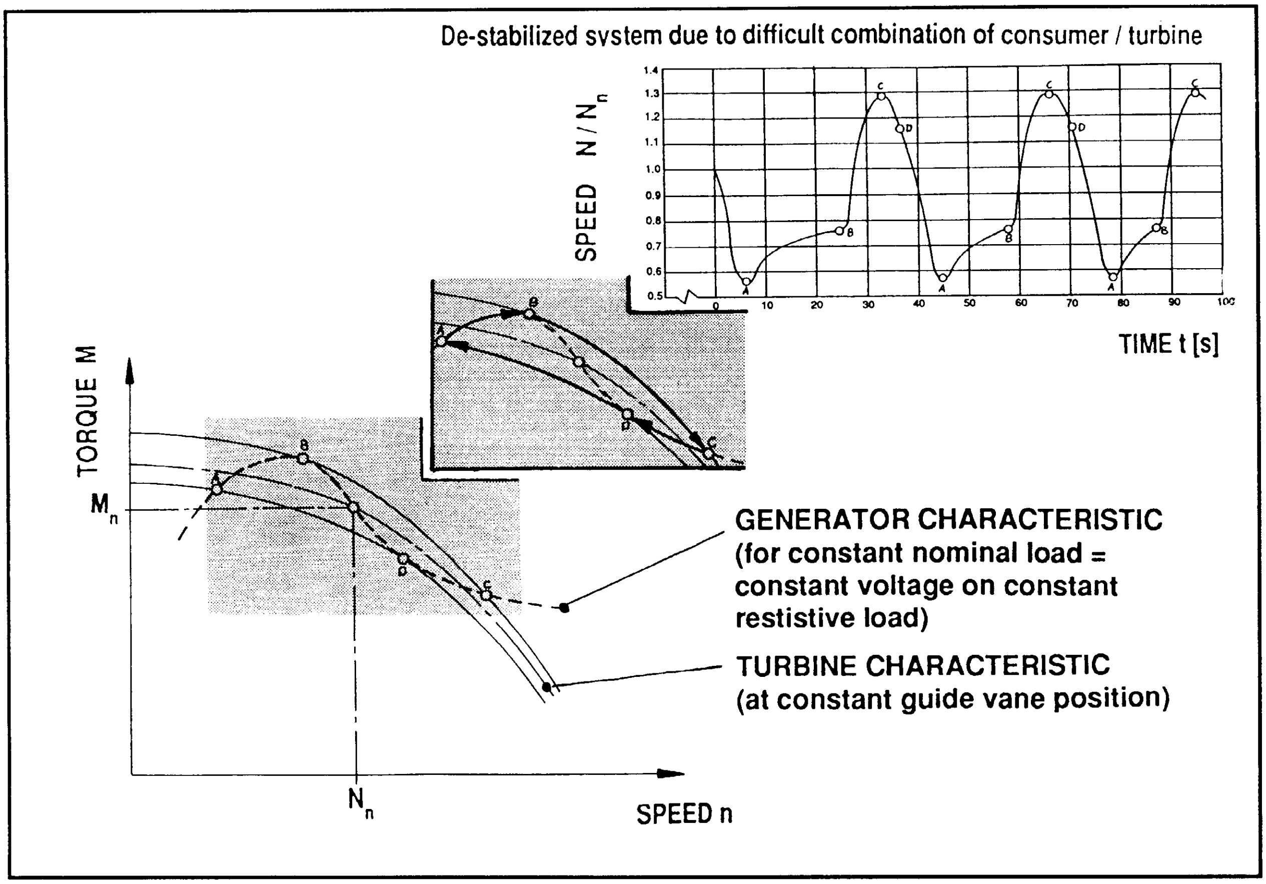


Figure 11: Unstable combination of turbine and consumer. (Pelton turbine with a voltage regulated synchronous generator loaded with resistive load)

SUMMARY: THE HAND-REGULATED PLANT

The hand-regulated MHP plant is an option only if all connected consumers can withstand the runaway speed at least for a short time. If load is increased, it is possible that the speed drops to a level from which the system will not recover without disconnecting load again. The hand-regulated MHP plant should have a good self-regulating characteristic to keep speed changes small and to allow for simple adjustments of the speed. The operator must be present in case of significant load changes.

2.4.Plants operating in parallel with a grid

2.4.1Definition of parallel operation and general remarks

We discuss here a MHP plant operating in parallel with a grid which has a much greater capacity than the power output of the turbine. Therefore, the frequency of this grid is independent of the power output of the plant. This simplifies the governing problem considerably.

The speed of the generating-set is determined by the grid frequency. No permanently acting governor is needed in the plant itself.

However, the following functions are still possible:

-Speed control

The grid keeps the speed constant. However, there may still be a need for a governor to synchronize the turbine set with the grid if a synchronous generator is used or to operate in isolated mode in the case of grid-failure.

-Flow / output control

It may be useful to adapt the produced power to the available water for optimal energy production. This can be done with a slow acting simple governor, adjusting the inlet gate of the turbine according to the water level (refer also to paragraph 2.4.2.4).

-Safety

There is a need for an automatic safety device to shut down the plant in case of grid-failure: The generator must be disconnected from the grid for electrical safety, and the turbine must be shut down to avoid overspeed. In case of lack of water: The output of the turbine is too small to drive the set with nominal speed and the generator will be acting as a motor, consuming energy instead of producing it. Therefore it must also be disconnected.

2.4.2 Energy production with asynchronous generators in parallel operation with a grid

2.4.2.1 General description of the asynchronous generator

Asynchronous generators have the same working principle as induction motors. These machines are generally cheaper than synchronous generators due to their simple construction. In small installations, standard low cost induction motors may also

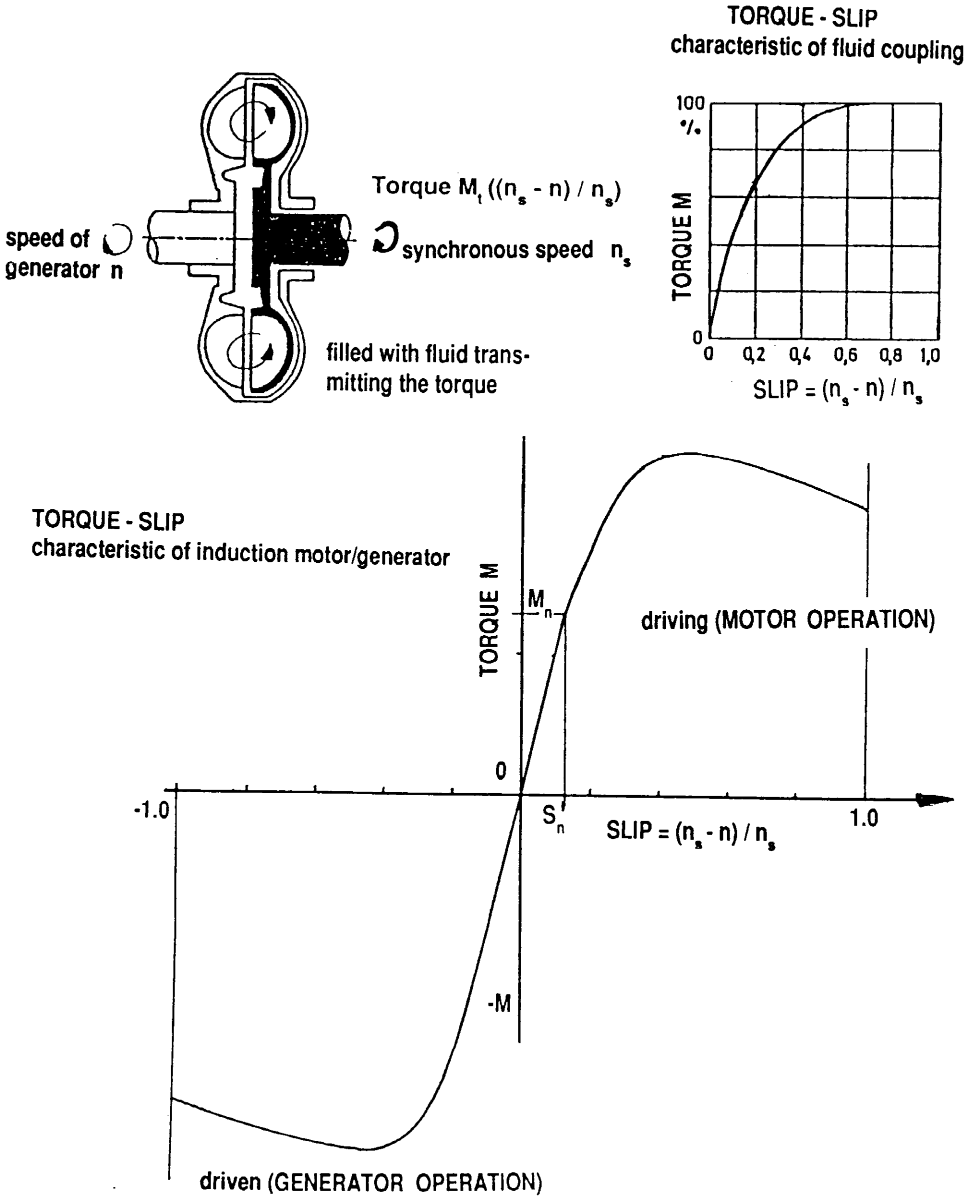


Figure 12: Mechanical equivalent for an asynchronous generator; connecting a large grid and the turbine with a hydraulic clutch

be used as generators (see annex A7, literature). The principle is the following: the machine is connected to a grid with constant frequency and voltage. If the machine is driven by the turbine with a speed higher than the synchronous speed of the grid (negative slip), it will operate as a generator. If the machine is operating with lower speed (positive slip) it will act as a motor. Therefore, the speed is controlled through the grid within a limit of +4 to -4% for nominal power out/input. To give a mechanical equivalent, we can imagine, that the generator is connected with a hydraulic clutch to the grid. The magnitude and direction of the torque of such a clutch corresponds to the slip of an asynchronous generator (see figure 12).

The feature of induction (asynchronous) generators is, that they require external excitation energy (reactive power) delivered by the grid. The drawback is the increase of the line current. To reduce reactive power consumption, capacitors are usually connected parallel to the generator.

2.4.2.2 A simple system for parallel operation with regard to synchronisation and safety

Small units with asynchronous generator connected to a grid may be operated in a manual mode. In this case, the turbine gate is opened and its speed is manually adjusted to slightly under the corresponding grid frequency. The generator is then switched to the grid as a motor and the turbine is opened according to the available water. The following problems may occur in this mode:

- In the case of grid failure the turbine will accelerate to runaway speed and the grid may still be fed by the generator set if capacitors are still connected parallel to the generator (self-excitation). Therefore, a relay must immediatly disconnect the generator and the capacitors from the grid in such a case, and the turbine gate (or safety valve) must be simultaneously shut down to avoid overspeed.

- If the capacitors are disconnected, short circuiting with a resistor should take place, because charged capacitors are dangerous (electrocution).

- The grid failure is detected by: over and under voltage relay, frequency relay, lack of one phase.

- A meter measures the energy supplied to the grid. The reactive power used by the generator itself (for excitation), is usually also metered to estimate line current (high reactive power increases line current, that means increased losses in the grid).

A simple electrical layout of such a system is shown in figure 13.

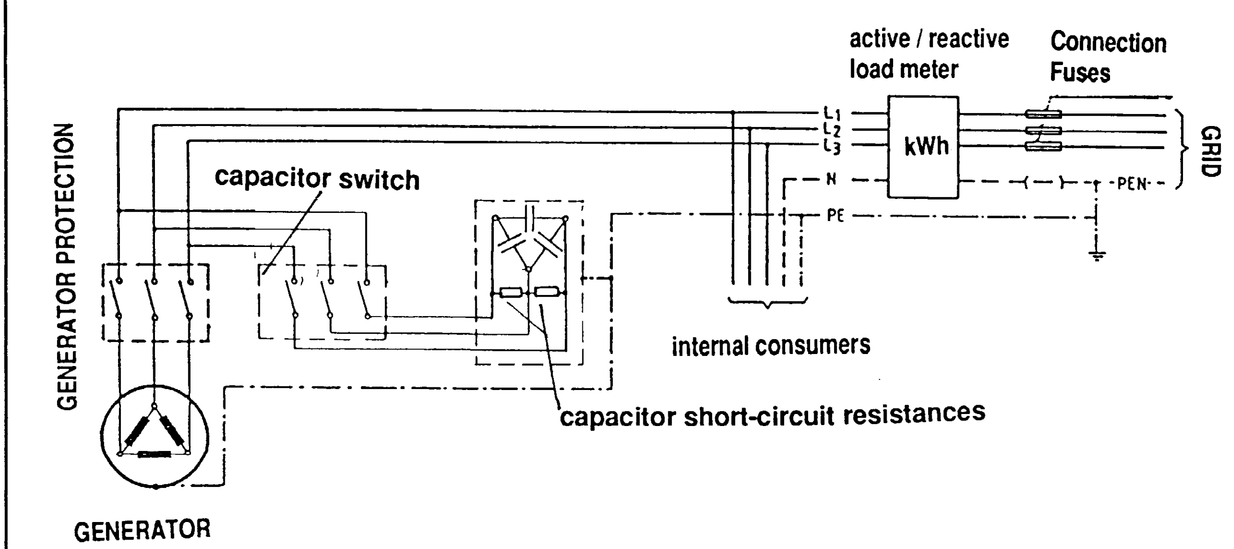


Figure 13: Electrical layout of an installation for parallel operation of an asynchronous generator with a grid.

2.4.2.3 Output regulation

Output regulation is used for example in storage schemes. It enables the control of the power output of the plant to get full output during peak demand periods. This is important for the management of large grids. In small grids it allows to allocate power to a single big consumer. In MHP installations connected to a national grid, output regulation does not make sense and water level control should be used, unless it is intended to cover peak loads with stored water.

2.4.2.4 Water level control

To use all available water for energy production in plants where the design flow is not always available, water level control may be introduced. The gate opening of the turbine is adjusted so as to maintain a constant water level at the forebay basin. To achieve this, the water level is measured and the signal is transmitted to the governor controlling the gate opening of the turbine. Water level control allows to maximize the power output and therefore the energy produced.
Figure 14, 15 and 16 show different systems incorporating water level control.

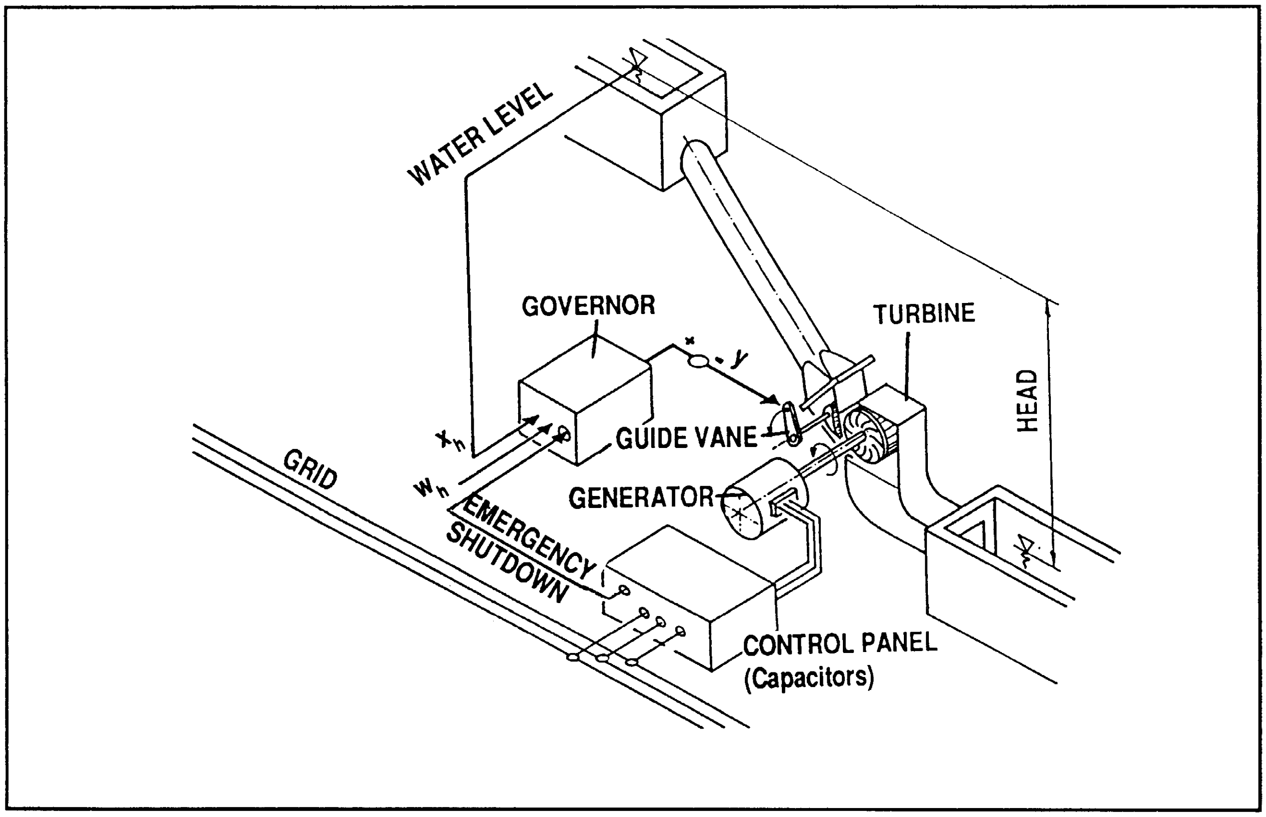


Figure 14: Water level control
Simple system without speed controller: only for operation in parallel with a grid

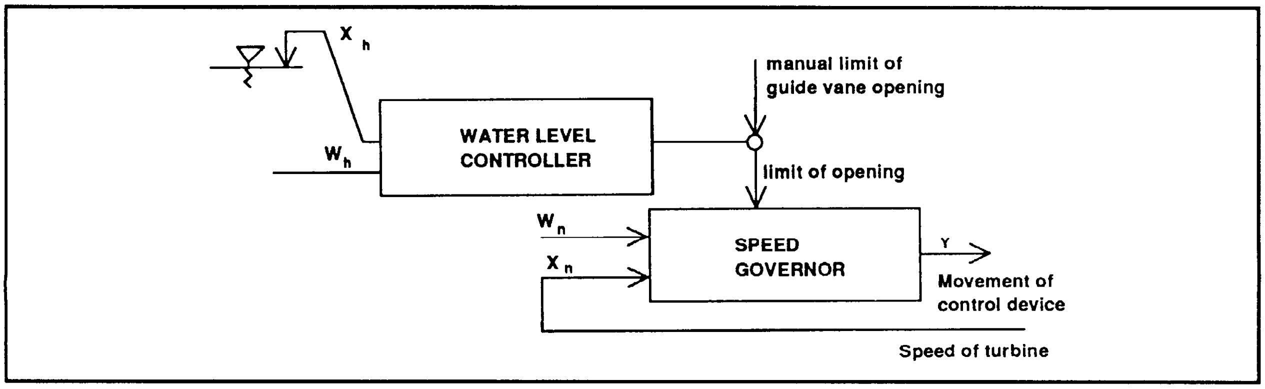


Figure 15:
Combined system of water-level and speed control: the water level is controlling the opening of the turbine gate. The speed governor operates in standby mode for the case that the grid fails. The turbine output is either set to its maximum by the water level or may be adjusted automatically by the governor maintaining the nominal speed.

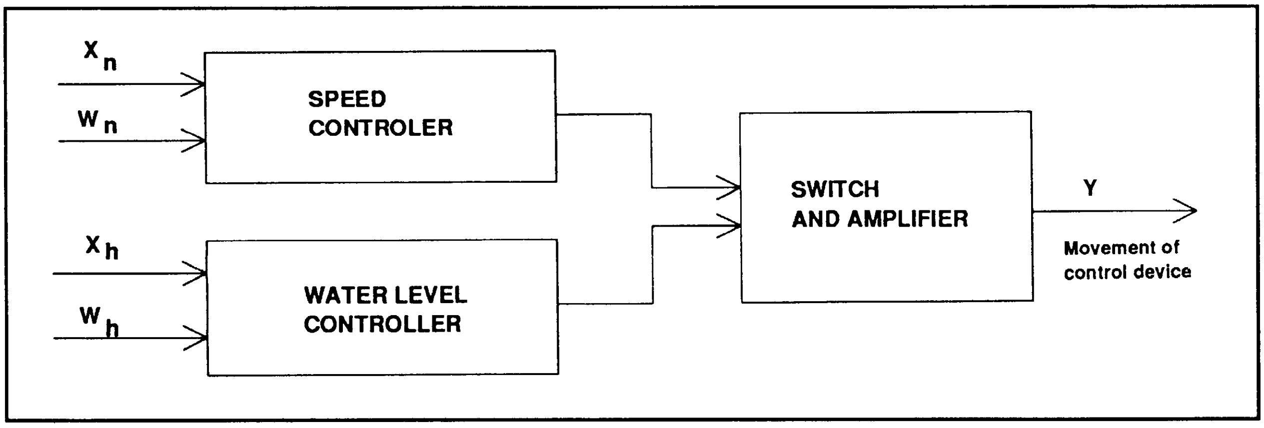


Figure 16: Stand-by system: if the grid fails, the governor is switched to speed control

2.4.3 Combination of mechanical drive, turbine and grid

A simple, cheap and a commonly used method in mills or workshops is to combine a turbine, an asynchronous motor/generator connected to the grid and mechanically driven machines. Figure 17 shows such a scheme, where the motor has at least the same capacitiy as the turbine and all simultaneously driven machines. If no mechanical power is needed, speed is approximately 3-4% higher than the synchronous speed and all energy produced is fed into the grid. If the turbine output is smaller than the power required by mechanically connected machines, speed will drop to below synchronous speed, and the asynchronous machine operates as a motor and supplies power to the machines together with the turbine. For system safety, this simple system needs an automatic shut down device or a hand regulator and an automatic disconnecting relay in the case of grid failure .

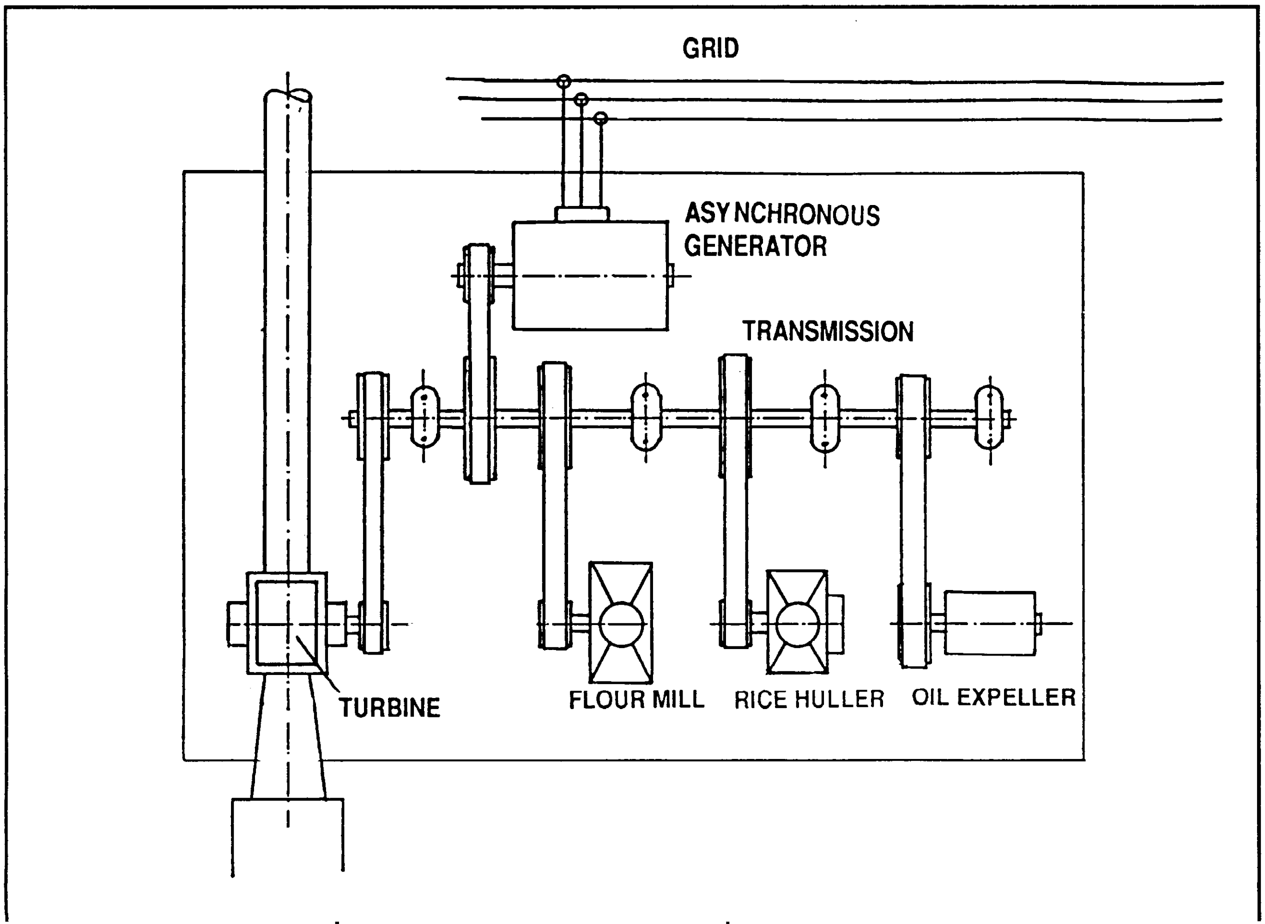


Figure 17: Mill installation stabilized by an asynchronous machine connected to the grid

2.4.4 Energy production with synchronous generators in parallel operation with the grid

2.4.4.1 General description of the synchronous generator

Synchronous generators are commonly used in plants which are able to work in isolated operation. Excitation is provided from an external DC source (battery or DC-generator) connected to the brushes of the rotor, or without brushes from the stator through a rotating rectifier. The delivered frequency is exactly the synchronous speed (slip = 0). The voltage is usually regulated with an automatic voltage regulator (AVR). As the reactive power is not delivered from the grid, the excitation current is adjusted to control the power factor.

Figure 18 shows an example of the connection of a synchronous generator with the grid..

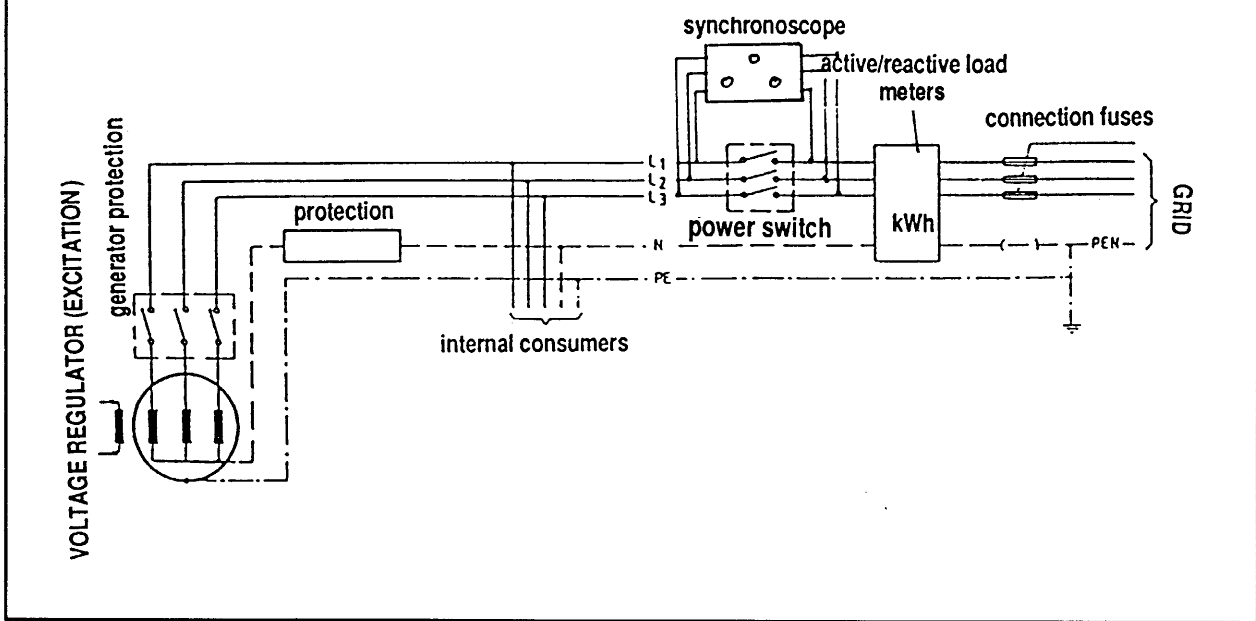


Figure 18: Example of the connection of a synchronous generator to the grid

2.4.4.2 The synchronization

Due to its electrical design a synchronous generator must be synchronized if it works in parallel with a grid. To give here also a mechanical equivalent, we may imagine that the generator and the grid are connected with a specially designed spring loaded gear clutch as shown in figure 19.

Engaging such a clutch is only possible, if both sides rotate with the same speed, the teeth have the same size and the proper position in relation to each other. Similary this means that the following conditions must be fulfilled at the moment of connecting the generator to the grid:

- **Generator and grid must have the same voltage (adjusted with the excitation; measured with volt meters) [teeth size].**

- **Generator and grid must have the same frequency (adjusted with the guide vane of the turbine or with the governor; compared with lamps or synchronoscope, or measured with frequency meters) [same speed].**

- **Generator and grid must have the same phase angles (checked by lamps or synchronoscope) [teeth in proper position].**

- **Generator and grid must "rotate" in the same direction (this is tested after installation before commissioning the plant with a field measuring instrument). Changing the sense of rotation is possible by interchanging the phase wires [same direction of rotation of clutch gears].**

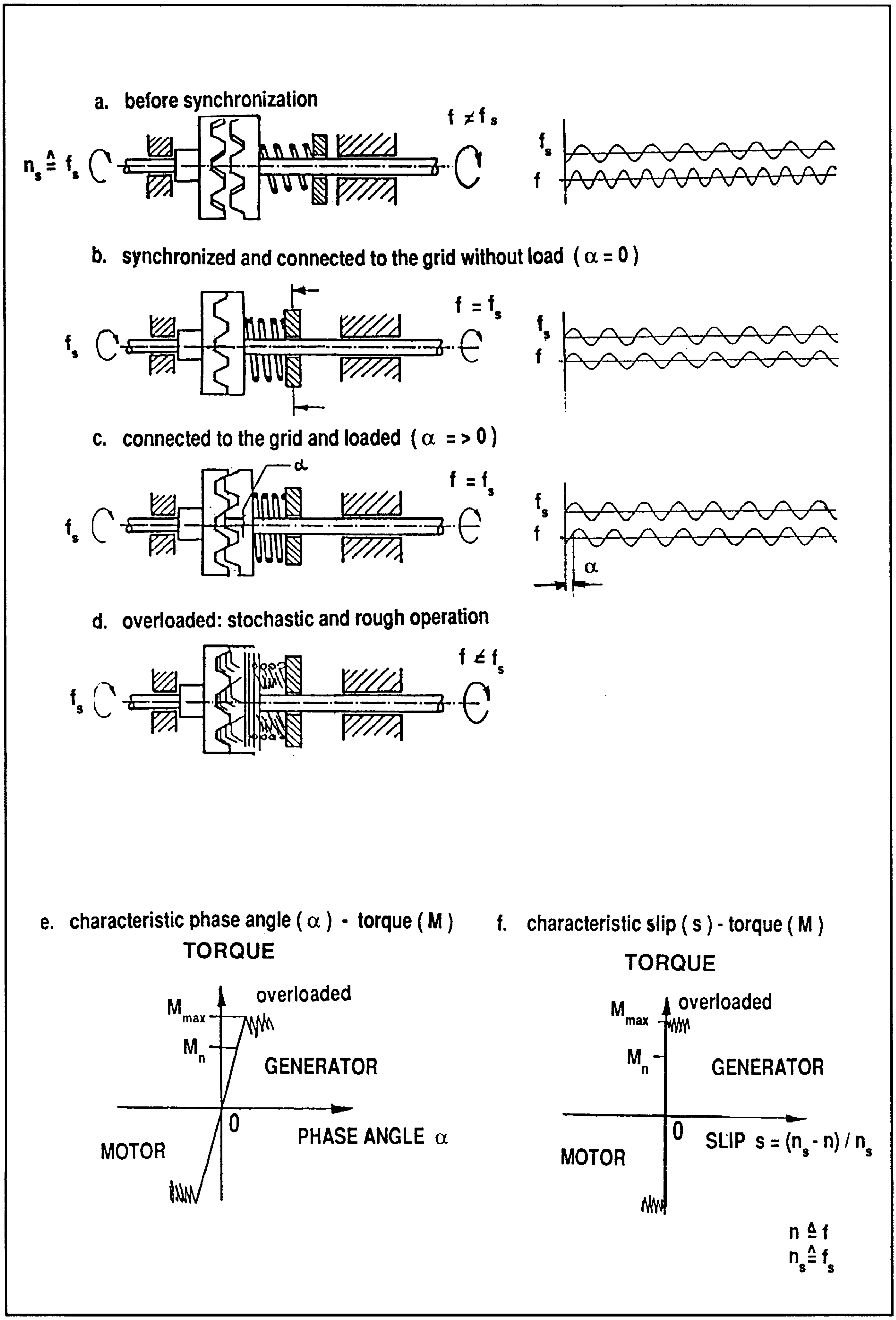


Figure 19: Mechanical equivalent for a synchronous genereator: connecting grid and turbine with a special gear clutch

Instruments for synchronization:

The instruments for synchronization use the physical effect of a beat frequency which results if two sinus curves of different periods are superimposed, see figure 20.

A modern synchroscope is shown in figure 23.

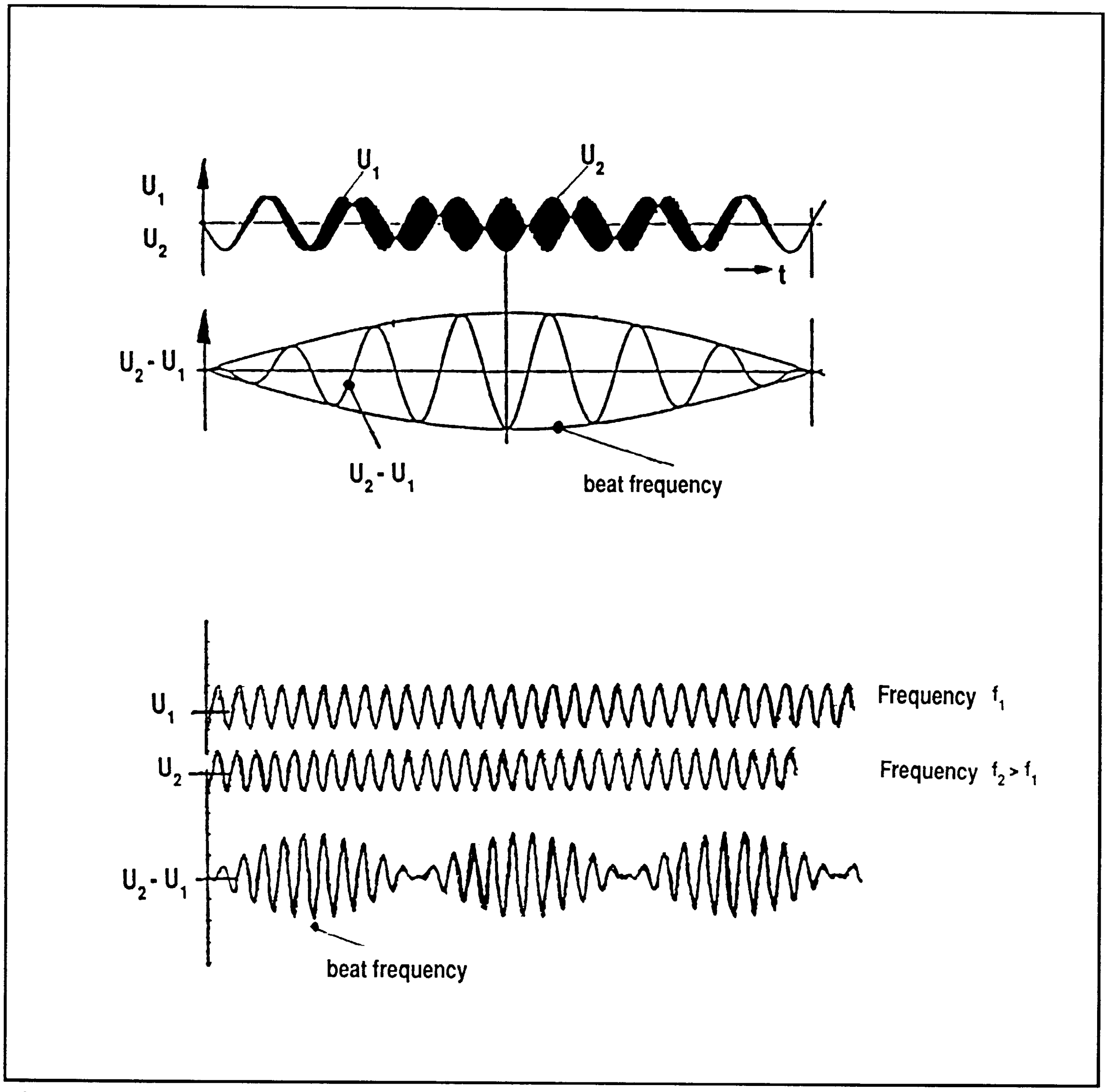


Figure 20: Formation of a beat frequency beween two separated lines with different frequencies

Figure 21 illustrates the process of synchronizing with lamps in "light off "-connection: If both frequencies of the two grid (generators) are equal the lamps will slowly change between dim and bright. If all lamps are dimmed completely, the frequency is equal and the lines can be connected.

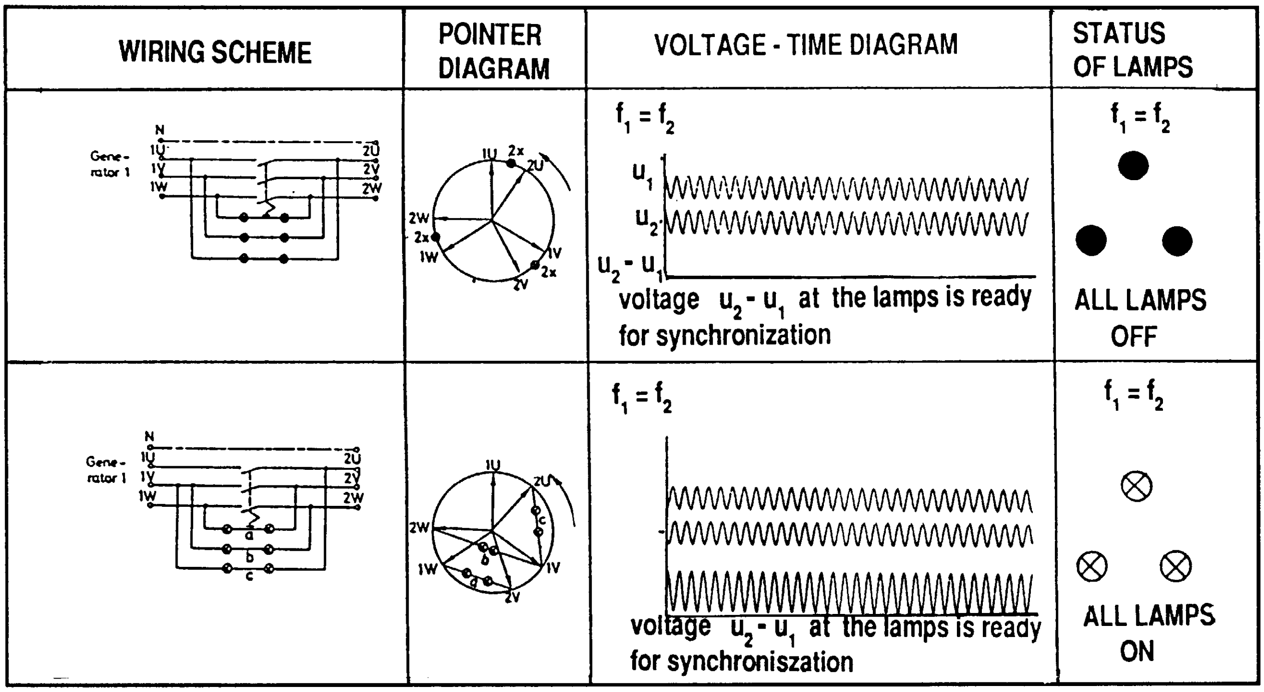


Figure 21: Synchronizing with lamps in "light-off" or "light on"-connection

Figure 22 shows the process of synchronizing with lamps in "rotational"-connection: If both frequencies of the two grids (generators) are almost equal, the single lamps will slowly turn dim and bright in such a way, that the light seems to rotate. The direction of the rotation shows whether the generator is rotating too fast or too slowly in relation to the grid. If rotating stops and all lamps are either completely dimmed out, or fully on, depending on the mode of connection, the frequency is equal and the lines can be connected.

Remark: There are two standard 220 volt lamps connected in series because the voltage during synchronization will be higher than 220 volts.

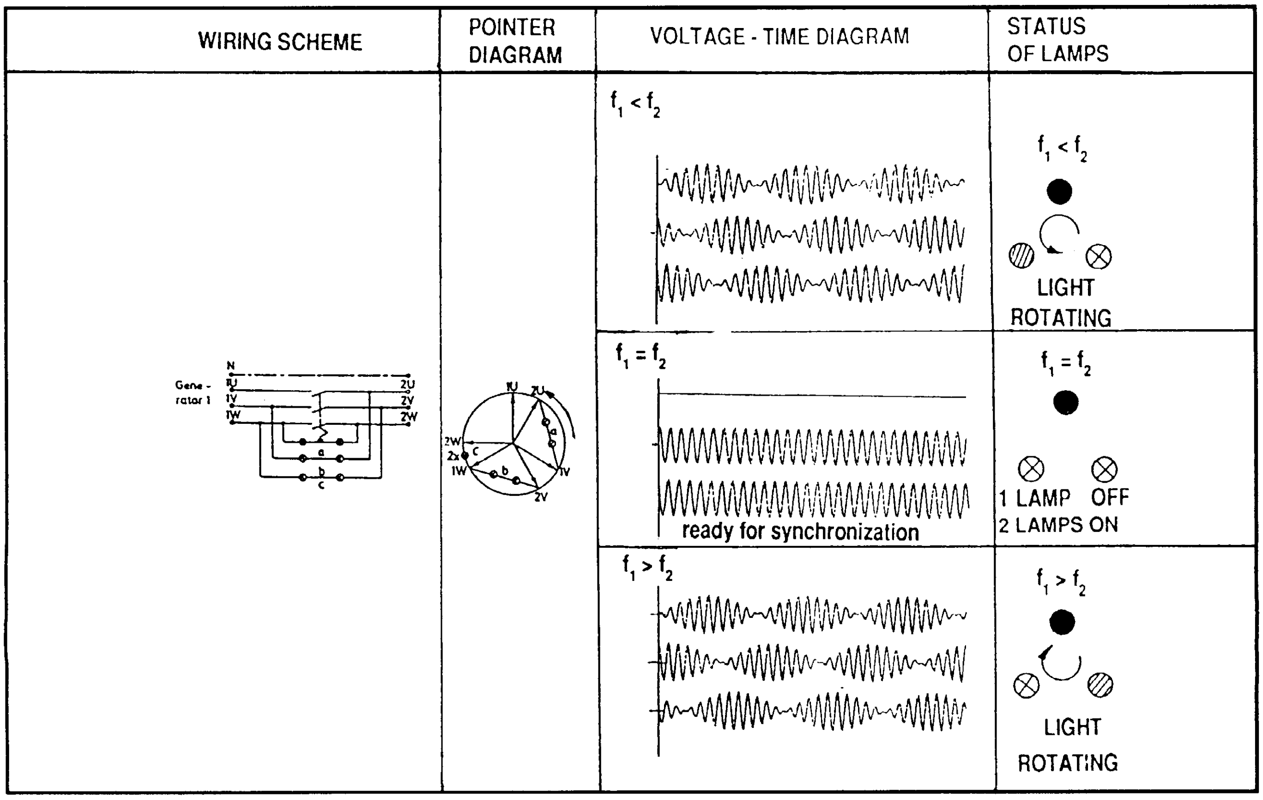


Figure 22: Synchronizing with lamps in "rotational"-connection

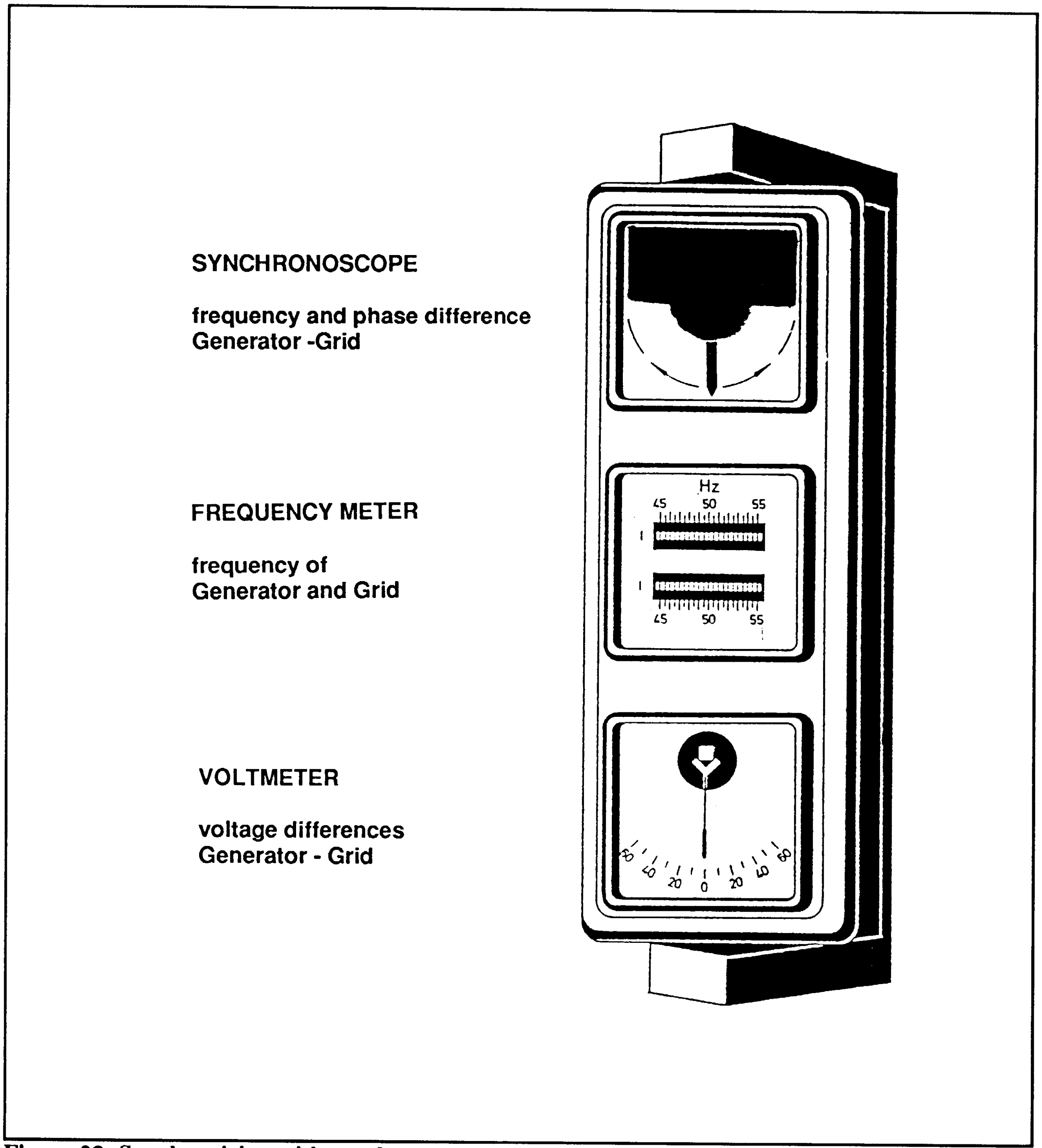


Figure 23: Synchronizing with synchronoscope: a synchronoscope shows the frequency differences, the two frequencies as well as the voltage difference between unconnected lines

SUMMARY

Parallel operation with a grid offers good possibilities for cheap and reliable control, because the speed will be regulated by the grid frequency. In the case of a grid failure, the generator must be disconnected from the grid, and the turbine must be shut down to avoid runaway speed. There must be a protection to avoid motor operation of the generator if there is no turbine output. Compared to synchronous generators, asynchronous ones require simpler devices and controls for synchronization and operation. To make maximum use of the available water, manual or automatic water level control is advisable.

2.5 Isolated operation, Flow control, Load control

2.5.1 Definition of isolated operation

A MHP plant is running in isolated operation if it is the only plant delivering energy to the connected consumers. The power output of the plant must therefore be higher than the power demand of all simultaneously connected consumers, in order to avoid an overloading condition.

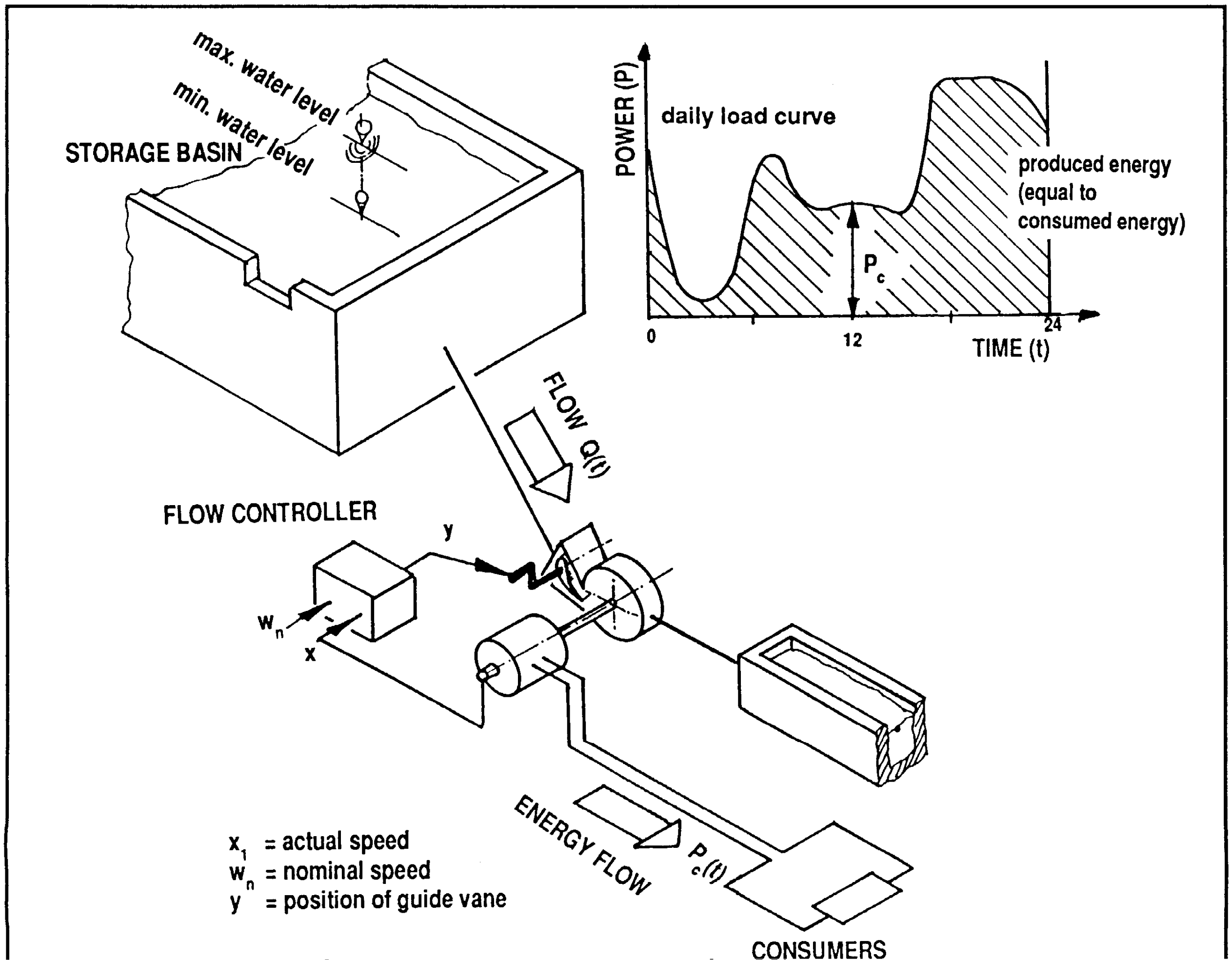
2.5.2 Flow control

To keep the speed of the turbine and the frequency of the supplied distribution network constant, it is a commonly used method to control the turbine with a governor actuating the distributor of the turbine. The distributor adjusts the water flow to the required amount, which is determined by the power requirement. Figure 24 shows the schematic design of a flow regulated MHP plant.

The advantage of flow control is the economy of the water used. Water saved may be used to cover peak loads if it is stored in a tank or basin. The design output of the scheme may be higher than the permanent discharge of the river depending on the load curve of the consumers.

The following is to be considered:

- A disadvantage is the more demanding design of the scheme and consequently high investment costs
- The regulation of flow is a very sensitive dynamic process
- Many parameters of the plant and the consumers have to be considered carefully
- Moving the inlet gate needs a certain force and work to be done. This depends on the size and construction of the turbine. Usually a hydraulic amplifier and a servo cylinder will be required.



CONSUMERS

load of the produced energy

Figure 24: Design of a flow controlled MHP plant with

2.5.3 Load control

Another method is to keep the turbine output constant and independent of the actual power consumed. An electronic governor keeps the turbine speed constant by diverting the excess power to resistors. This controller can react very fast and accurately to load changes without modifying the operating conditions of the plant on the turbine side. The design of the scheme is simple, because the dynamics of the hydraulic system and the turbine/generator set have no influence on the stability of the governing process. Load control is in a way similar to parallel operation, the grid having the function of the frequency controller and ballast resistors. In low-cost schemes, the flow is adjusted manually to less than the momentary river discharge. An emergency shutdown device should be incorporated in the system to avoid the dangerous operation under runaway speed conditions. Figure 25 shows schematically a load controller scheme. Although the load controller works very fast, the generating unit may have to be equipped with a flywheel to allow the starting of large electrical motors.

Another problem may arise from parasites induced by the power switching components (thyristor) and which may disturb radio, T.V. or computers.

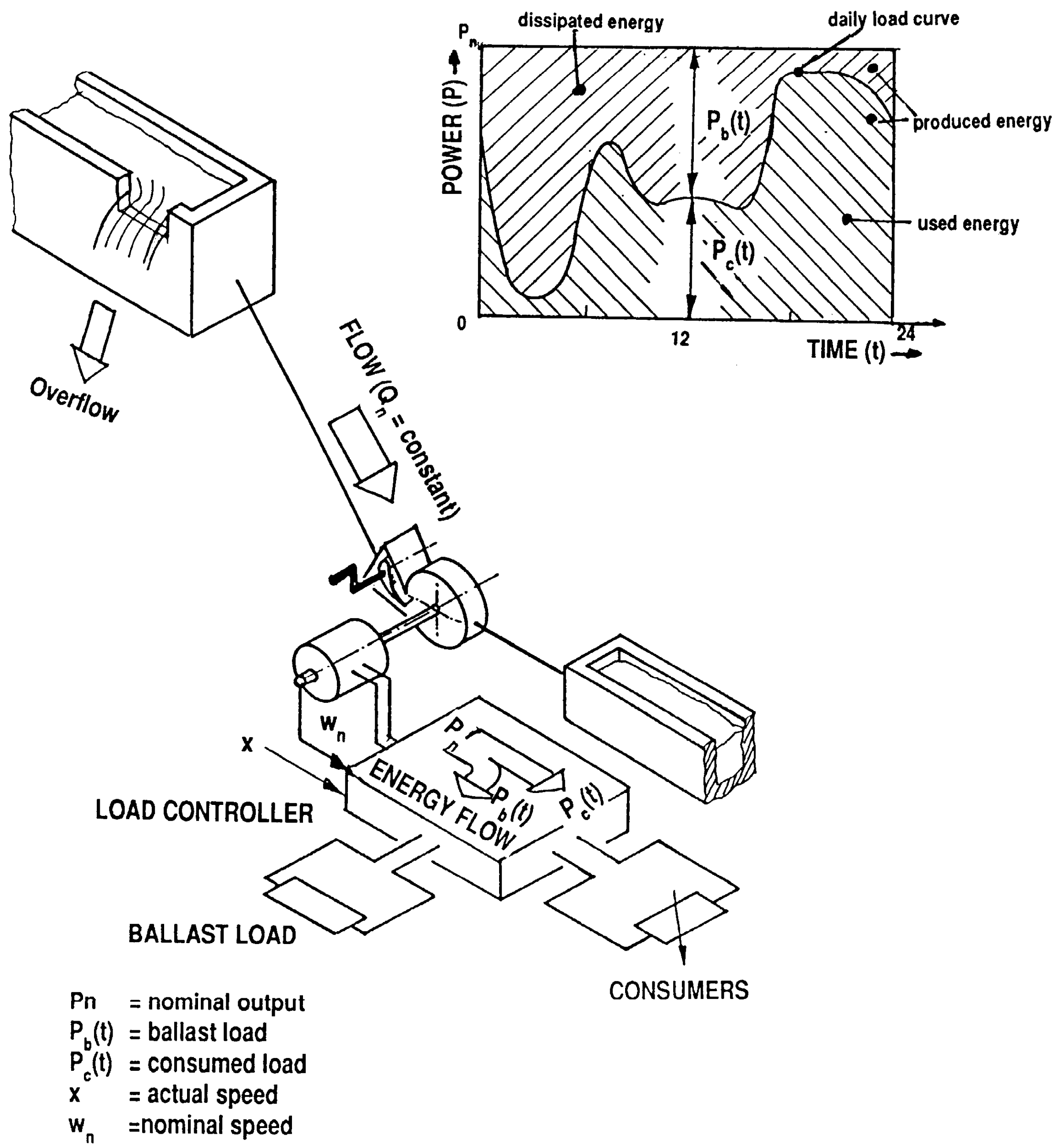


FIGURE 25: Basic schematic layout of a load controlled MHP scheme with load curve and produced / consumed energy

SUMMARY : Isolated operation, Flow control, Load control

Flow control: Speed governing by means of the turbine flow is a complex process. The turbine flow must be adjusted continuously and quickly to the load. The inertia of the water column in the penstock does however allow only a limited speed of the adjusting process of the control device of the turbine (water-hammer). A flywheel increases the stability and quality of the governing process. To achieve stable control of a MHP plant, a governor with a defined dynamic behavior is required.

Load control: A load controller operates a MHP plant with a constant load. The changes of load on the consumer side are compensated with electronically controlled resistors. This control action is free of any inertia effects and therefore possible with quick response and high accuracy. However, due to the increased transient power requirements during the starting phase of electrical motors, a flywheel may be needed to provide an additional moment of inertia.

2.6. Small grids

2.6.1 Definition

In a small grid we have the situation that two or more generators supply a number of consumers in a remote area without connection to the national grid. We want to describe shortly some typical governing problems related to small grids.

2.6.2 Two water turbines supplying a small grid (load sharing)

This is a common case. The turbines may be in one or different plants. The governors have to provide at least for one of the machines an output dependent, permanent speed droop. Otherwise the operation may be instable and one turbine may rhythmically close while the other one is opening. The two governors are normally able to control the turbines in isolated operation. If both turbines are in operation, load sharing between the two turbines may be adjusted by changing the nominal speed of one turbine. To achieve this, the reference speed of the turbine taking less of the connected load must be increased.

Figures 26a to f graphically illustrate the different cases of load sharing among two units, depending on their governor setting (with or without permanent speed droop).

A) Single unit in isolated operation

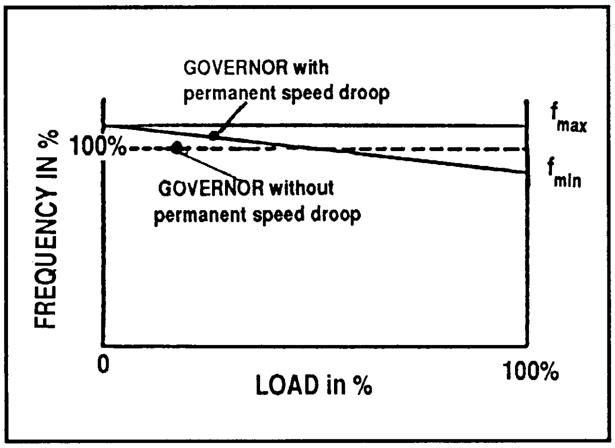


FIGURE 26a

Stable operation with permanent speed droop. Each output of the MHP plant is related to a certain speed, frequency. It may be possible to operate the plant with a PI governor without permanent speed droop.

B) Two units A and B of identical output; identical permanent speed droop, identical reference speed:

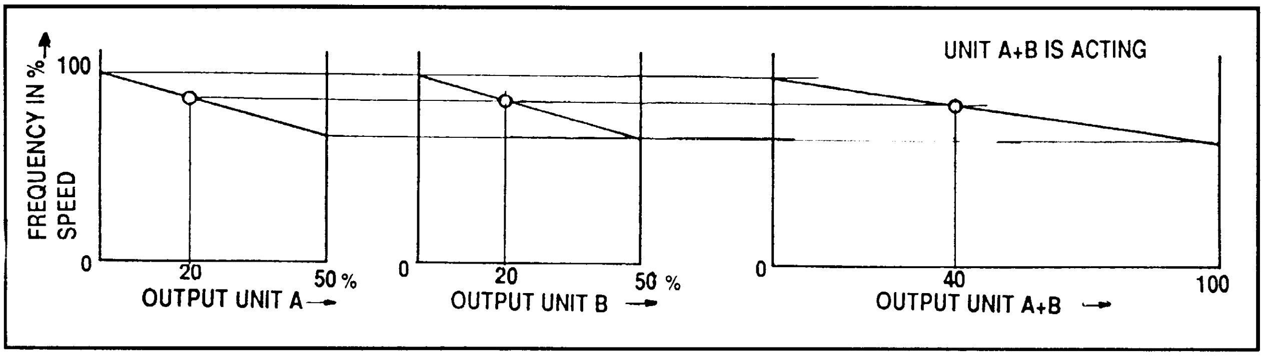


Figure 26b

Both units are governed in such a way, that each produces half of the needed output. The frequency is related to this output.

C) Two units A and B of identical output; identical permanent speed droop, different reference speed:

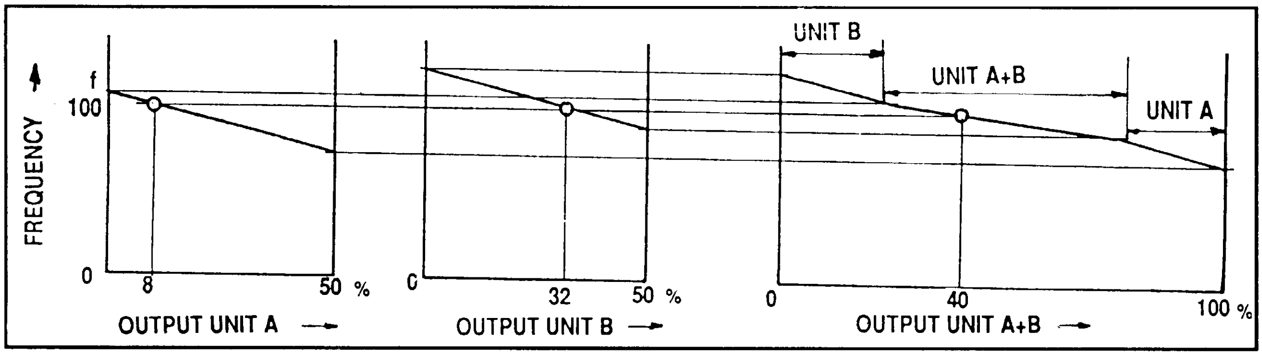


Figure 26c

Both units are governed in such a way, that they produce a certain ratio of the needed output. In the given example one can find:

40% total output:
Output: A = 8% B = 32% ; Frequency = f

D) Two units A and B of identical output; one with and one without permanent speed droop, different reference speed, at full load:

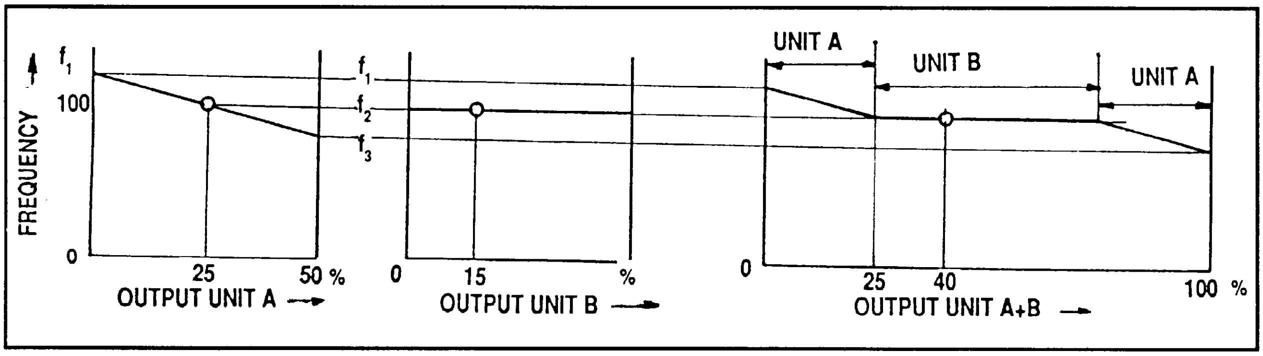


Figure 26d

Both units are governed in such a way, that they produce a certain ratio of the needed output. In a certain range however only one unit is governing the whole changes of the load at a constant frequency if it is governed without permanent speed droop. In the given example one can find:

Range: 0 - 25% output (only A governed):
Output: A = 0 - 25% B = 0%
Frequency: f2 < f <f1

Range: 25% - 75% output (A = 25% only B governed)
Output: A = 25% B = 0 - 50% ;
Frequency: f = f2

Range: 75% - (100)% output (B = 50% only A governed)
Output: A = 25% - 50% B = 50% ;
Frequency: f2 < f <f3

E) two units A + B with different output

The nominal speed of unit B is adjusted to the grid frequency. The output of unit A may be adjusted to

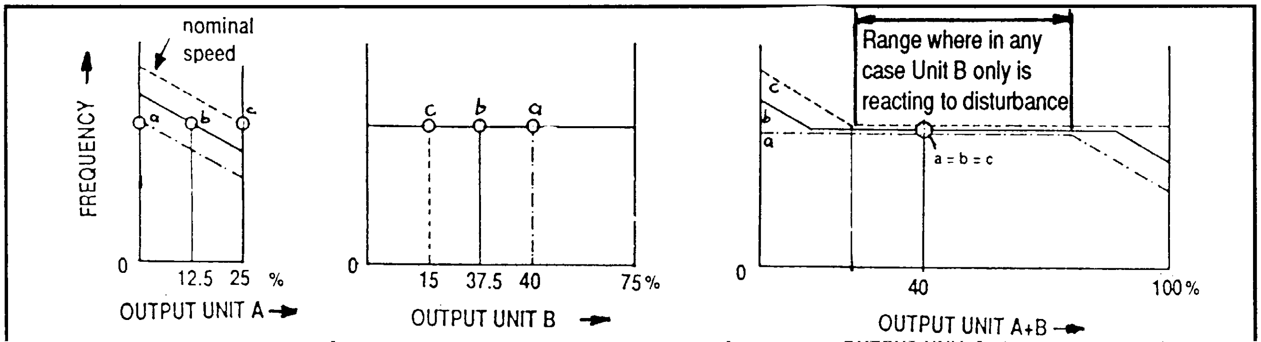


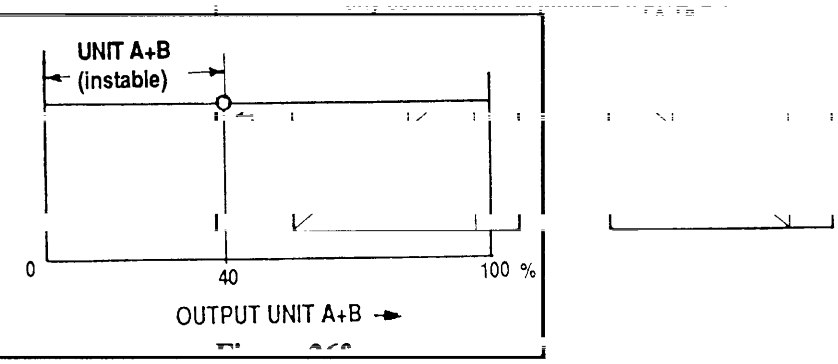
Figure 26e

constant x% by changing its reference speed. If changes of ou
they will be compensated from this unit at constant frequen
the one of unit A, we have the case of parallel operation of unit
by unit B.

tput within the nominal output of unit B occur
cy. If the output of unit B is much larger than
A with the grid with frequency determined

F) Two units A and B of identical output; without permanent speed droop, identical reference speed

nent speed droop, identical reference speed



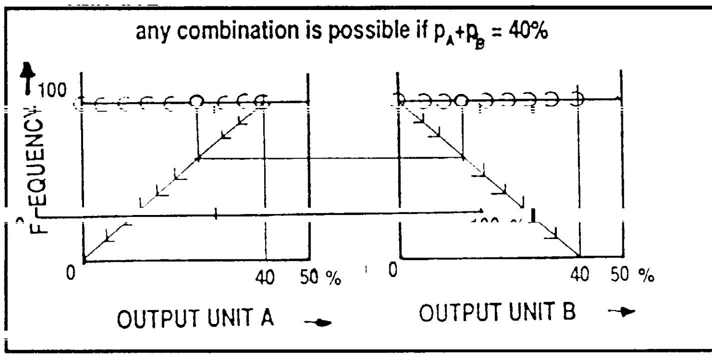


Figure 26f

The undefined distribution of the load creates the dange
from one machine to the other.

r of unstable operation and power oscillations...

Note: these considerations are also true for load controllers

s working in parallel.

2.6.3 A water turbine and a diesel generator supplying a small grid

This case is also very common. The diesel generator may be used as standby, if the turbine output is too small (for example in the dry season or if load peaks in the grid occur for evening lighting etc). For economic operation, the turbine should supply the base load and operate with maximum output corresponding to available flow. The diesel unit should only supply excess demand, its output should be minimized to save fuel.

The diesel governor is the leading unit, and regulates the output as long as the consumption exceeds turbine output. If the consumption drops to below turbine output, the diesel unit works at idling speed and the turbine governor controls the frequency.

The turbine governor may be put automatically into operation by a signal indicating minimum power of diesel unit (idling position of fuel valve) or by setting its reference frequency higher than the one of the diesel governor.

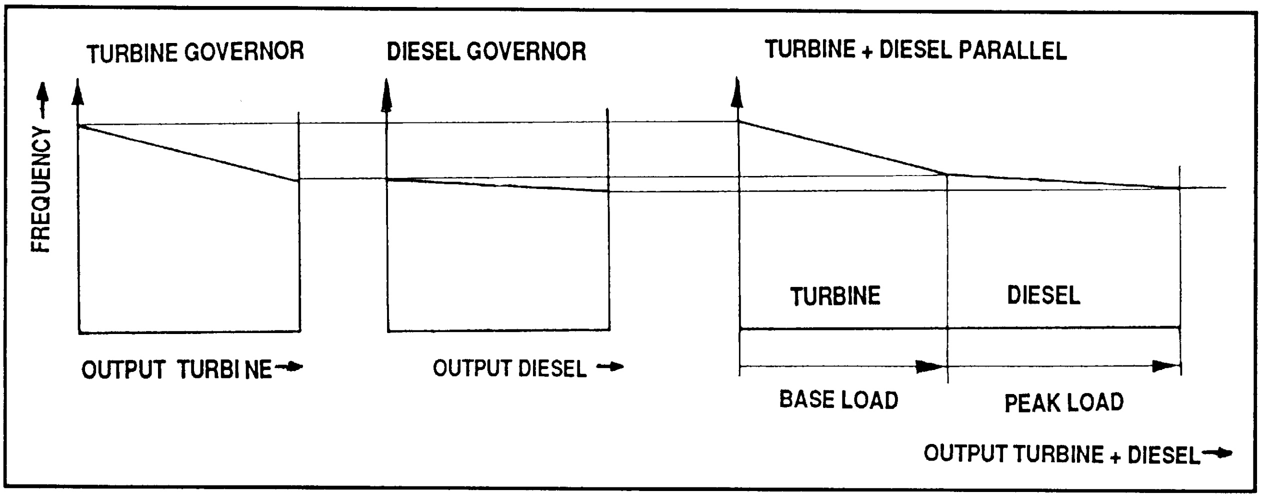


Figure 26g

SUMMARY : Small grids

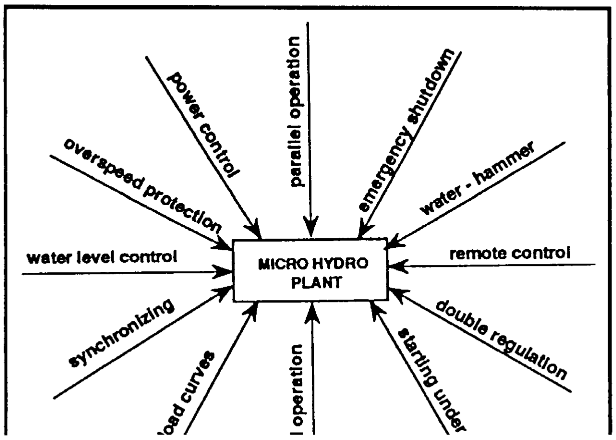
In small grids with two governed generating units (water turbine, diesel generator) a stable operation is obtained if at least one group has a governor with permanent speed droop. Choice of reference frequency and speed droop allows to determine the degree of load sharing between the units.

Chapter 3: Pre-selection of the governor

3.1. General

Studying chapter 2 it becomes clear that a number of principal choices concerning the governing concept are possible. Consequently a few basic decisions must be made when pre-selecting a governor.

Figure 27 illustrates the variety of operating conditions a MHP plant may have to cope with.



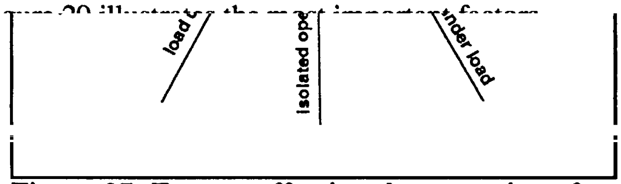


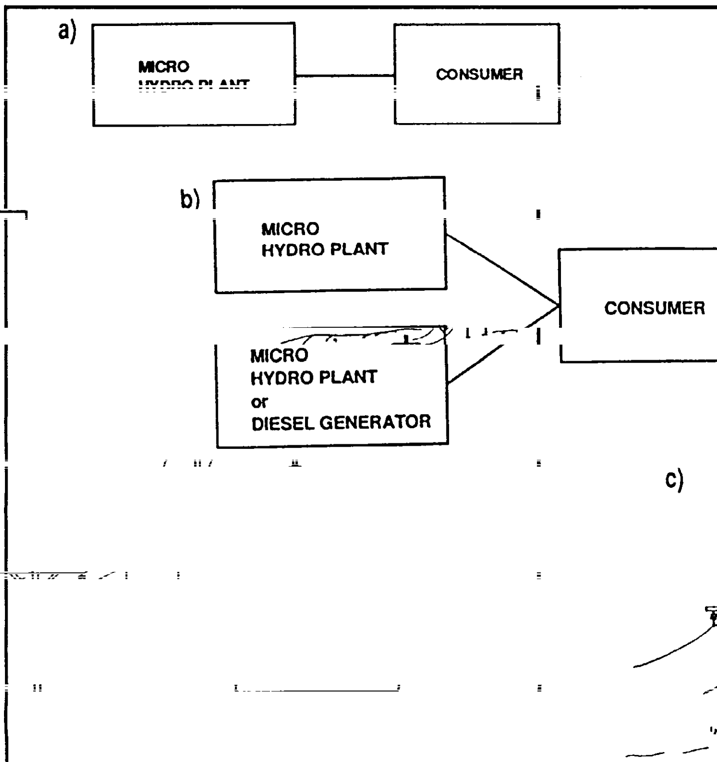
Figure 27: Factors affecting the operation of MHP plants

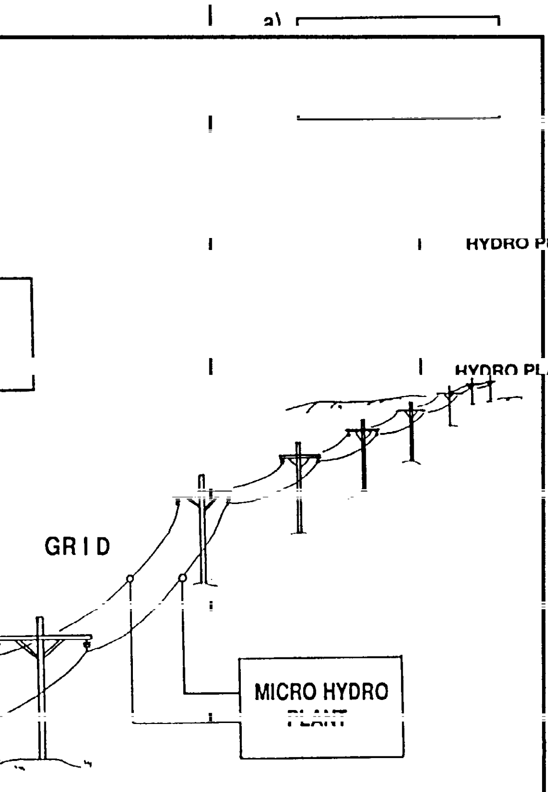
There are different ways to control a MHP plant. A plant may either operate isolated as the sole energy producer or together with other turbines/ generators, e.g. in a national grid, as shown in figure 28.

The complexity of different systems of governing varies considerably. It is for example much simpler to work out the specifications of a load controller than of a mechanical flow governor controlling the turbine speed in isolated operation.

A load controller is operating with constant turbine output and does not influence the hydraulic system as the flow controlling governor does, when the turbine is opened or closed. As a consequence, the selection of the governor type determines which parameters are to be studied carefully.

gure 29 illustrates the most important factors mining the feasible governor type.





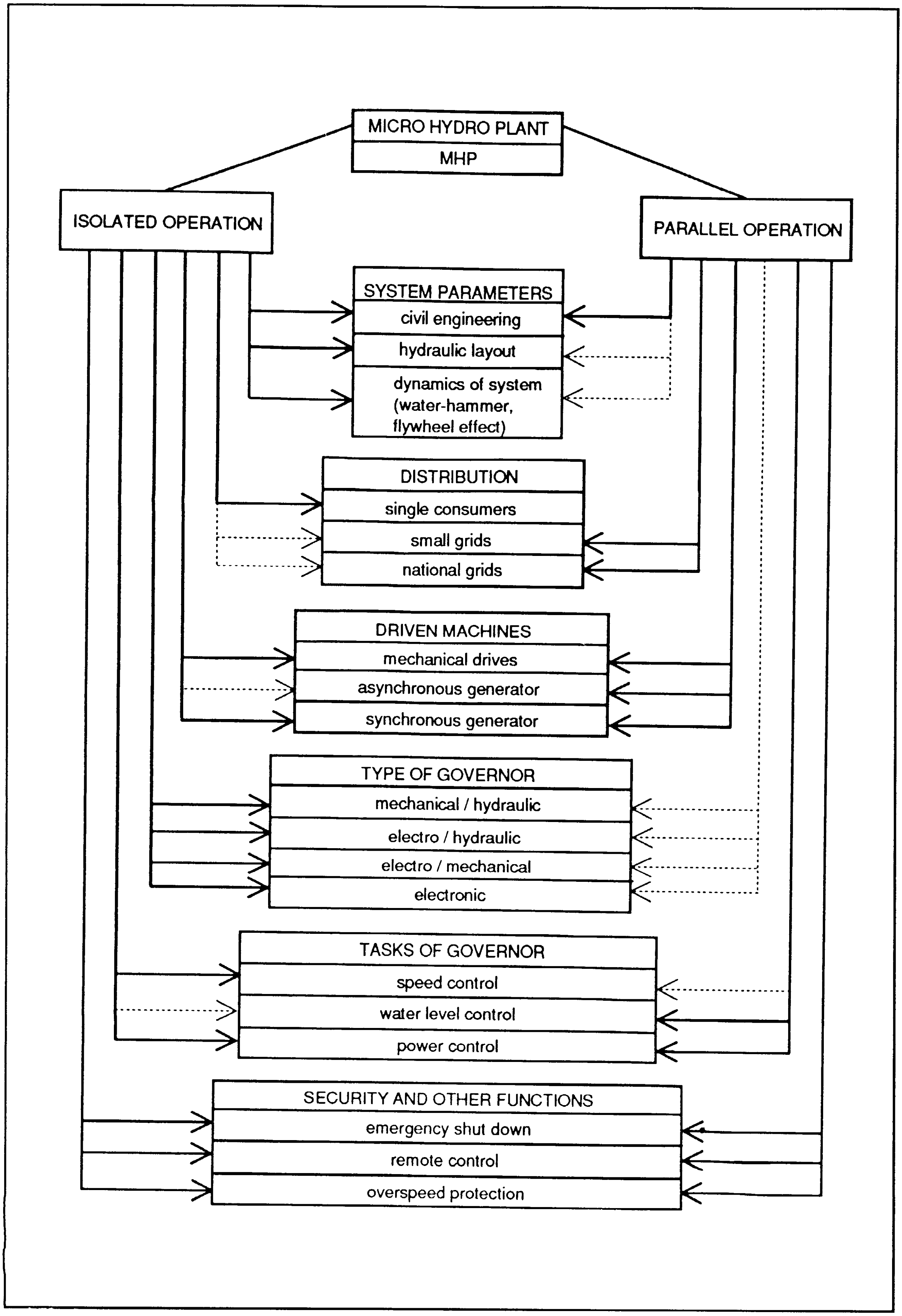


Figure 29: Different important parameters for the control of a MHP plant

Depending on the mode of operation (isolated or in parallel), a number of parameters are mandatory and others are optional. In addition, a governor is also to handle start-up and shut-down of the plant. Safety functions and emergency shut-down may also be incorporated (refer also to paragraph 4.3.5).

3.2. Pre-selection procedure

We have a choice of three main concepts:

a. Unregulated / hand regulated

- low investment and few planning problems
- perhaps higher manpower input for operation
- rough operating conditions for turbine and consumers

b. Load controller

- medium investment costs
- low manpower input for operation and maintenance
- only applicable in connection with electricity production
- for outputs up to 200 kW
- reliable but may be sensitive to disturbances of the grid (lightning, motor starting, type of consumers etc.)
- easy planning process

c. Flow controlling governors (oil hydraulic, electro-hydraulic, electro-mechanical)

- high investment costs
- low manpower input for operation
- optimal water management possible
- reliable if properly maintained
- demanding planning procedure
- skills of the level "automotive mechanics" needed for operation and maintenance. For sophisticated governors, even higher qualifications are needed.

Each concept has its own merits and limitations defining its range of application.

Using the present manual, a stepwise approach is possible as shown in figure 30. The ultimate result is the final selection of a suitable governor.

A) The concept of hand regulation is applicable if:

- the plant output is less than 20 to 30 kW
- the penstock length is less than 200 m
- the power produced is either for direct mechanical drive or for lighting only but not to drive electric motors
- connected equipment resists runaway speed as well as heavy underspeed and/or undervoltage conditions
- the permanent presence of an operator can be guaranteed

If one of the above conditions is not fulfilled do not consider hand regulation as an option.

B) The concept of load controller is applicable if:

- accurate frequency has to be ensured
- the plant output is less than 200 kW
- the discharge of water through the turbine can be constant as there is no need to save it
- electric motors are to be driven on the consumer side
- isolated and parallel operation with the grid or other units is needed

C) The concept of flow controlling governors is applicable if:

- accurate frequency has to be ensured
- the plant output is more than 20 kW
- electric motors are to be driven on the consumer side
- the discharge of water through the turbine must be economized whenever possible (storage scheme)
- the lifespan of the plant is to be longer than 20 years
- isolated and parallel operation with the grid or other units is needed

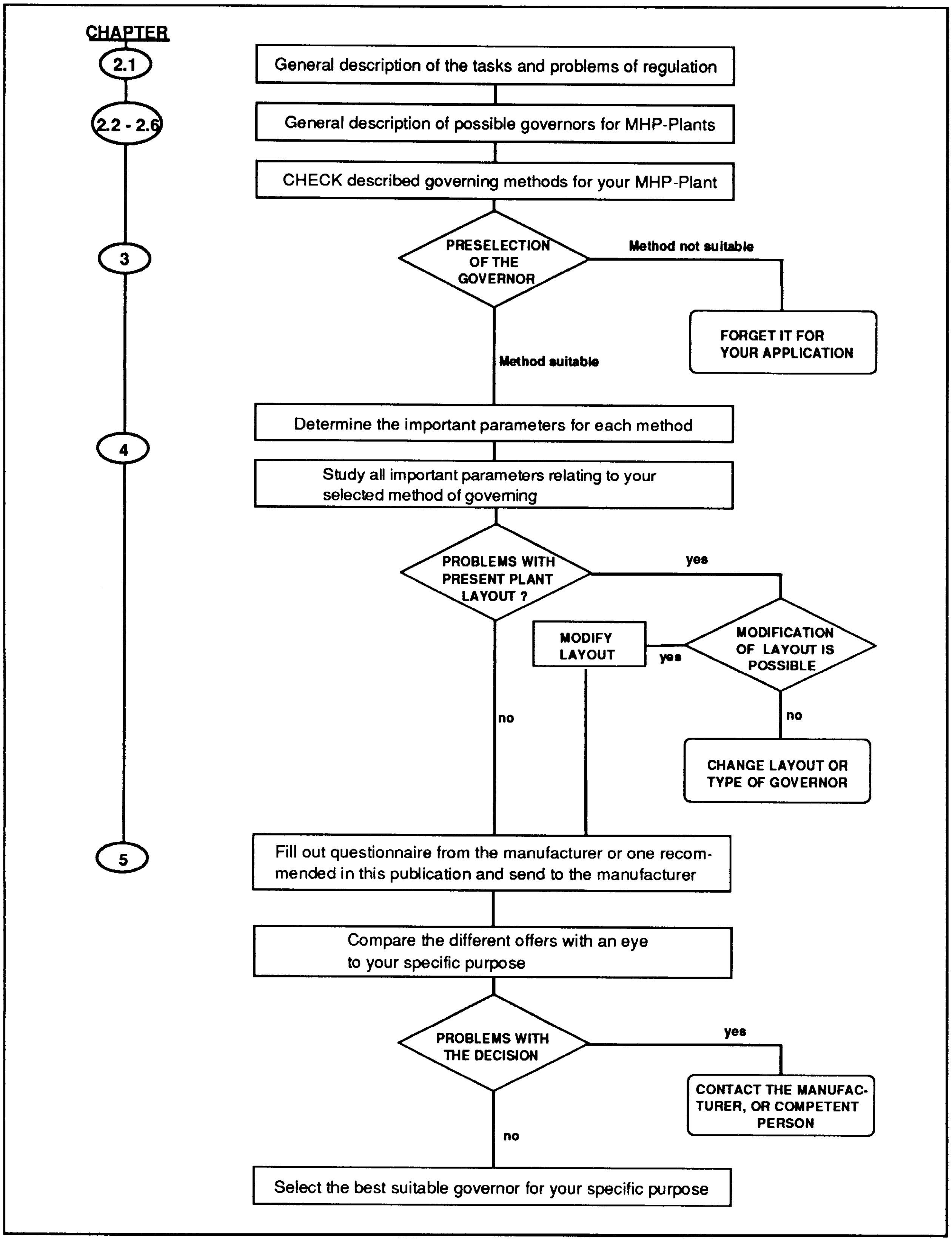


Figure 30: Flow chart for governor selection

Summary: Different possibilities of governing

The different possibilities of governing reflect different qualities and different tasks of control. The appropriate choice of the suitable governing concept largely depends on what is needed. Each concept, be it hand regulation, load or flow control has its own characteristic advantages and limitations. These provide the criteria for the pre-selection of the concept.

Chapter 4: Important parameters for regulation

4.1 General

Governing small MHP plants is not a simple task. The technical problem is the same as for large schemes but the limited amount of investment does not allow the same solutions. In small installations we have often to overcome relative high sudden load changes. A motor of 10 kW represents more than 50% of the nominal load in a 20 kW scheme whereas the same consumer in a plant of 1000 kW represents only 1% . In a small installation we also have to study carefully the problem of relatively high starting currents of motors.

It is a common misunderstanding to think that the governor is only a part of the turbine. The successful and smooth operation of the governor is only guaranteed if all the parameters of the scheme are carefully considered. Not only the turbine is controlled, but the entire dynamic system including the water column in the penstock, the generator and the consumers (see figure 31).

The governor and all other elements have a certain static and dynamic characteristic. We attempt to give with this handbook a basis not only for the selection of a suitable governor for a plant but also for the design of the plant with regard to the specific governing requirements. Properly defined specifications will enable suppliers to provide a governor which fulfills its task reliably.

SUMMARY

Governing MHP plants is technically sometimes as complex as governing big hydro plants. The governor must always be regarded as a part of a complex system. Required governor features must be properly specified to enable suppliers to provide a reliable governing device.

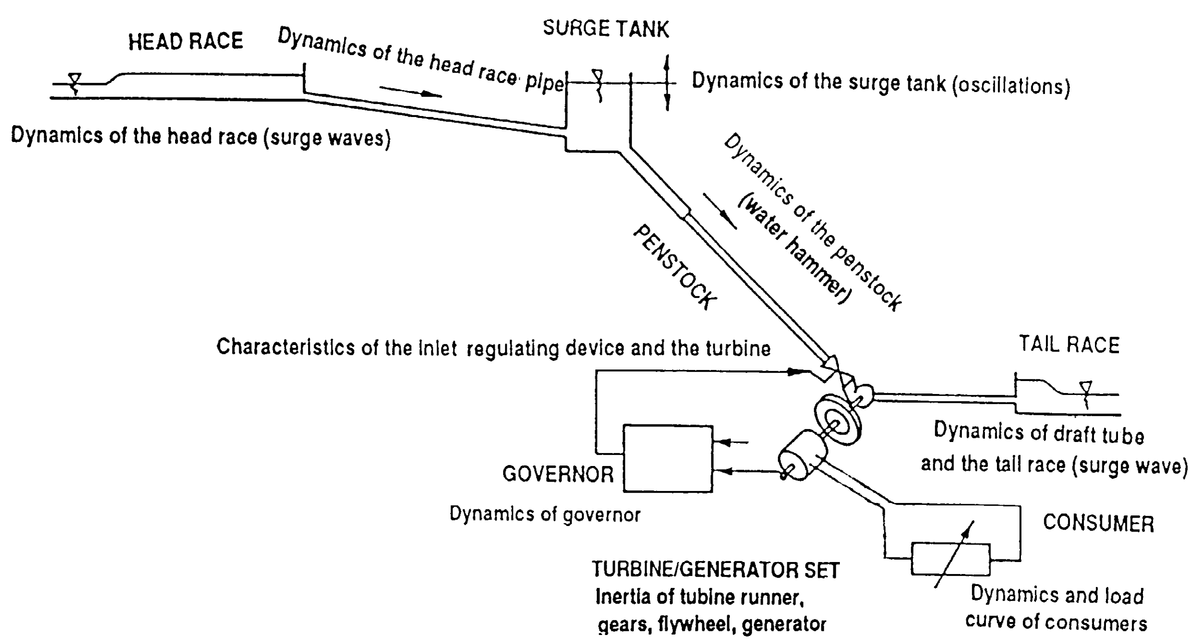


Figure 31: Main influences and parameters of the governed MHP system

4.2 Parameters of the generating system

4.2.1 Parameters of the hydraulics of the plant

If we consider the inertia of mass it is obvious that flow control will be affected by the design of hydraulic structures. The governor changes the flow through the turbine, causing a change of the speed of water within the water way system.

When the distributor of the turbine is closed, a dynamic pressure wave called water-hammer (see fig. 33) is produced. This pressure surge travels with the wave propagation speed into the hydraulic system, is reflected at the boundaries and returns - mostly with reversed sign - to the turbine. There it is superimposed to the newly arising waves. The amplitudes of the resulting pressure oscillations decrease gradually due to friction losses. Under certain conditions, such pressure oscillations may damage the penstock and plant. In installations with head race canals, the induced surge waves may overflow the canal embankments and also cause damage. Especially plants with a long penstock may produce a high pressure rise if the turbine is closed too quickly. This may result in rupture of the penstock and subsequent damage to the entire plant (see fig. 34).

Another negative influence of this phenomenon is the de-stabilization of the governing process. The governor closes the turbine to reduce the output. While closing the inlet regulator, the pressure rises and the output may also rise momentarily. The oscillating pressure induces an oscillating turbine output. We see clearly the connection between the flow control governor and the hydraulic design of the system.

The following parameters of the hydraulic design are important (see fig. 32):

- length of penstock, **L**
- diameter of penstock, **D**
- material, Young modulus and wall thickness of the penstock (if the penstock is divided into different sections these data are needed for each section), **E, s**
- length, dimensions and slope of the channel (headrace),**L**, $\mathbf{A_c}$
- dimensions of the surge tank (eventually sectional elevation drawings), $\mathbf{A_s}$
- scaled profile of the scheme with geodetic head shown, **H**

For a rough evaluation of the hydraulic design one may define the characteristic time T_w of water acceleration (see annex A2).

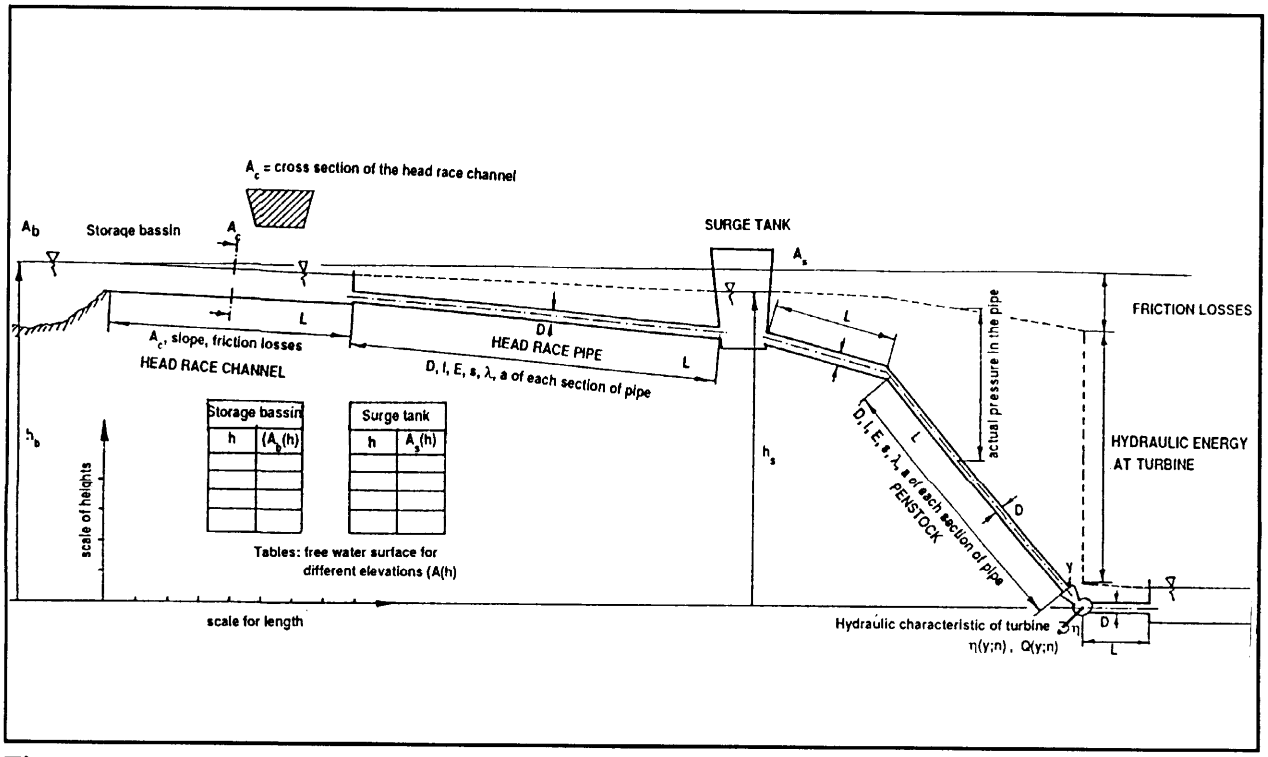


Figure 32: Parameters of the hydraulic system

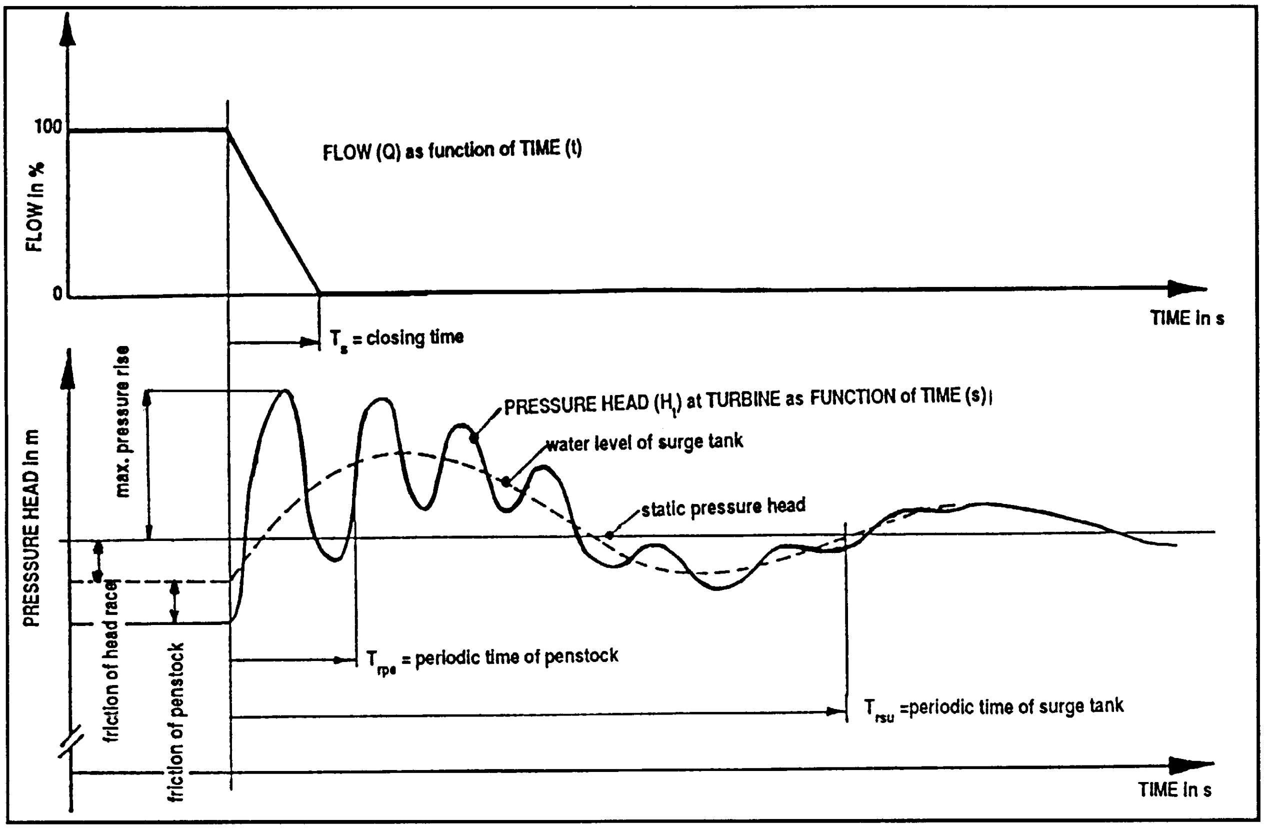


Figure 33: Reaction of the hydraulic system described in fig.32 if the turbine is closed down from nominal flow to no flow (water-hammer)

4.2.2 Parameters of the turbine / generator set

The type and design of the turbine determine its characteristic behavior. Important for the governing process are:

- **The characteristic of the inlet regulating mechanism (distributor, or -for turbines with fixed guide vanes - valve)**
- **flow and output as a function of the guide vane position**
- **forces necessary to move the inlet regulator (friction and hydraulic forces as a function of the guide vane position)**
- **effect of the turbine speed on the flow in the penstock**
- **inertia of the turbine, transmission arrangement, flywheel and generator rotor.**

Figure 34: Destroyed penstock due to water-hammer
Photo by: W. Roth

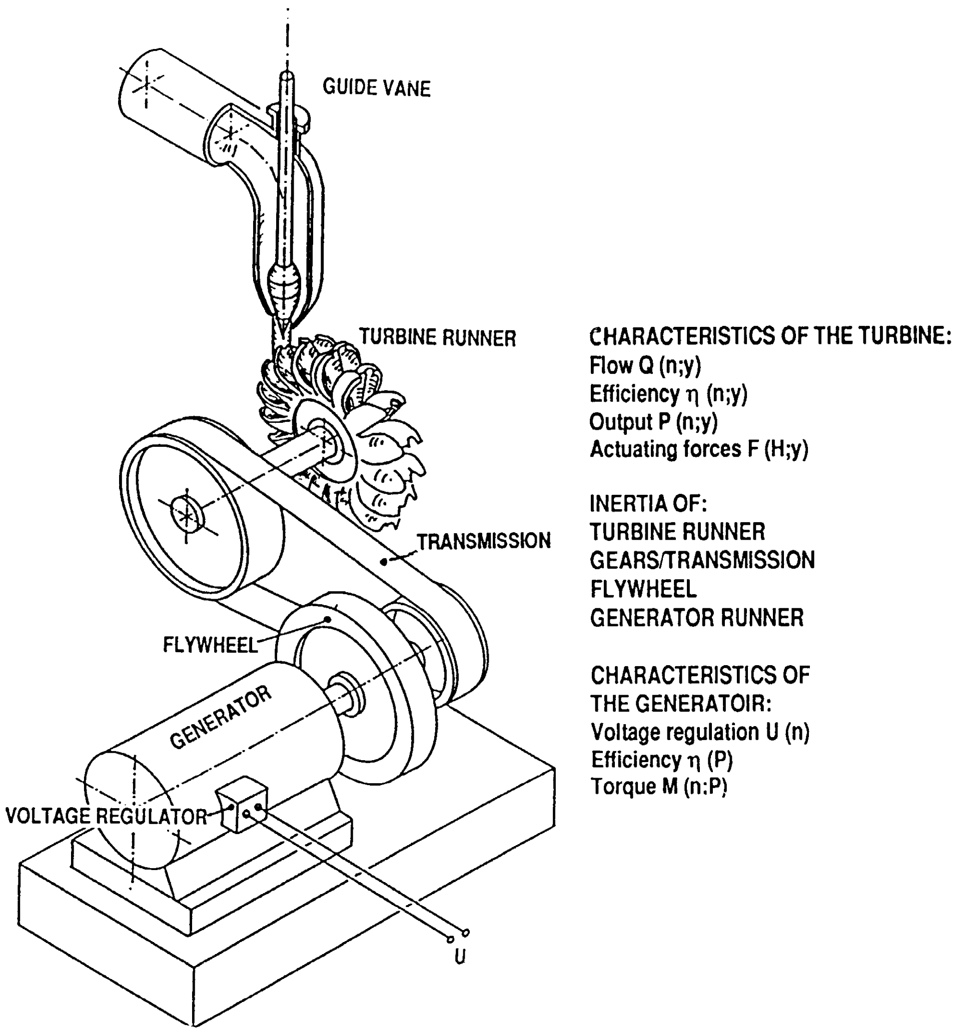


Figure 35: Parameters of the turbine-generator set

4.2.3 Parameters of the consumers/ grid

The connected consumers represent important parameters for the governor design. The resulting characteristic is either determined by the driven machines or the generator with its electrical consumers.

The main parameters are:

-Load curves of the consumers over time (see figure 38). The management of large fluctuations of output in a short time is a challenge for the governor. The knowledge of the maximum sudden load change may be expressed by load curves (load as a function of time). The load curves of grids with many small consumers may be determined statistically. In grids with big consumers or if only one machine is connected to the turbine, it is important to know their dynamic behavior and the timing of their operation. Especially if big motors are used, their starting current may be upto 5 to 6 times the nominal current.

-Change of power demand as a function of the turbine speed. These parameters may be expressed with the self-regulation factor of the consumers (refer also to paragraph 2.2 and figure 8).

SUMMARY :

Especially important for flow governors are the static and dynamic behavior of the MHP system. These include hydraulic structures, the turbine, the generator and the consumers. The governing process may cause dangerous problems like water-hammer and surge waves in canals.

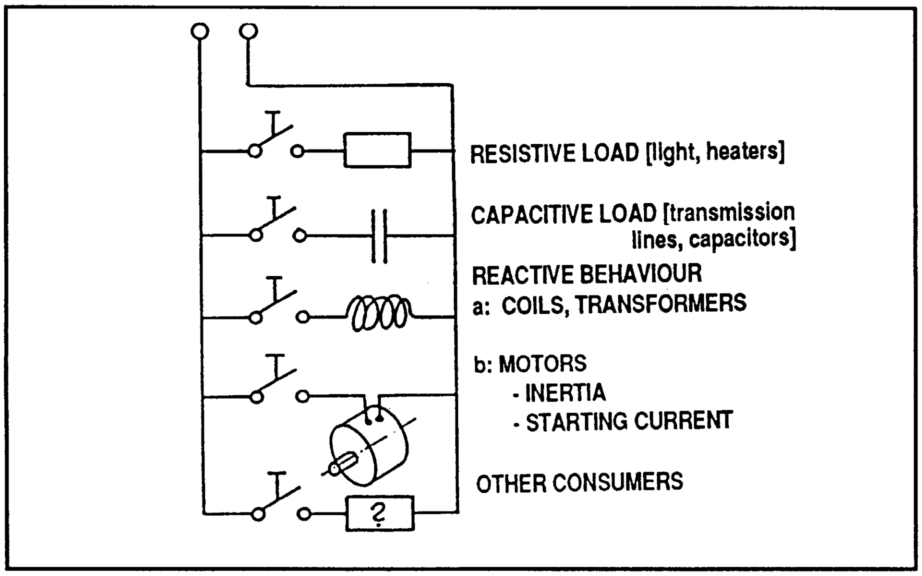


FIGURE 36: Parameters of consumers: types of consumers

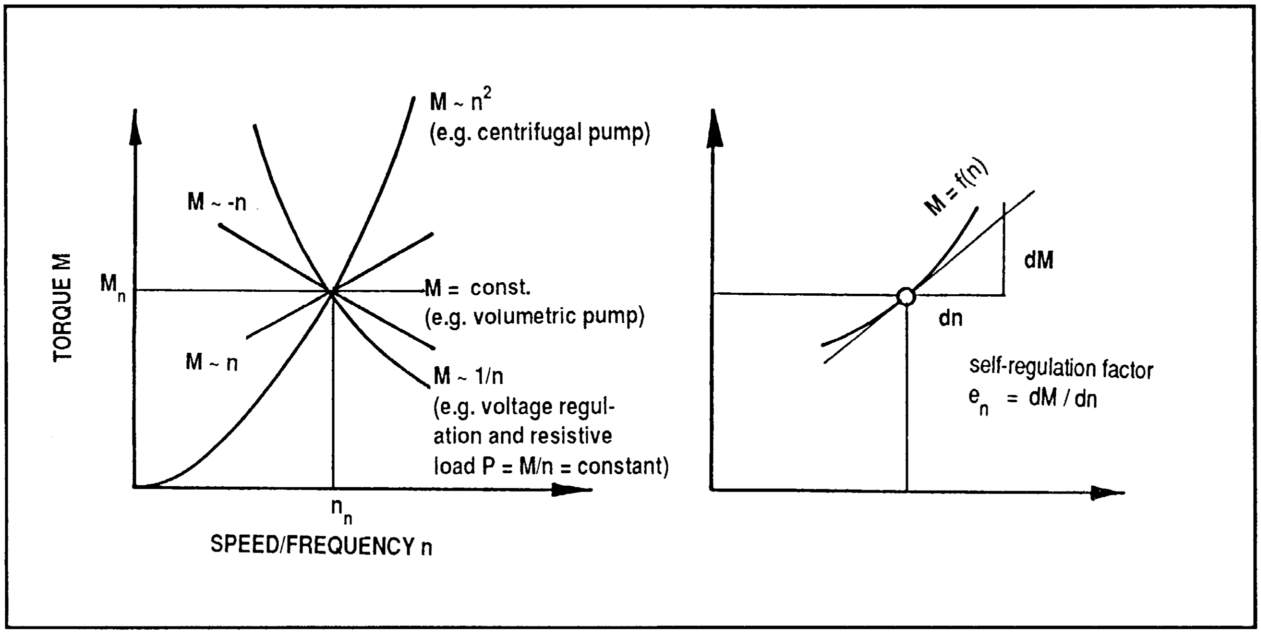


Figure 37: Parameters of consumers, SPEED TORQUE characteristics (self-regulation)

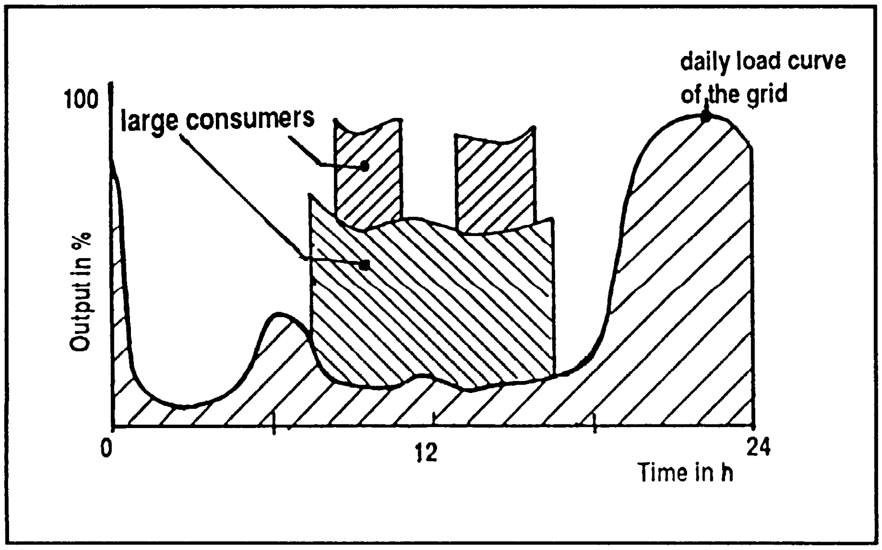


Figure 38: Parameters of consumers: DAILY LOAD CURVE

4.3 Parameters of speed control governors

The following description concentrates on speed governors controlling the speed of the machine set; control movements lead to a change of the flow of the turbine. Electronic load controllers are operating with constant or only slowly changing load of the turbine set. Working out requirements of load controller functions is therefore much simpler for the designer of a scheme.

4.3.1 Components of the governor

- **the sensing device**: the value which is controlled must be measured and the information about its actual size x must be fed to the governor. This is done in mechanical governors by means of a centrifugal pendulum. Electronic governors may use a tacho-generator, a counter or a frequency meter measuring the frequency of the synchronous generator.

- **the comparator**: at the governor one can adjust the reference value w which is desired for the controlled value. In the comparator this reference value w is compared with the actual value x. The governing difference (x-w) is the information for the governors action to correct the system.

The reference value may be supplied from a spring in a mechanical governor or from a quartz cristal oscillator in an electric governor.

- **the governor's behavior**: the governor has to react to each disturbance z in the system, which causes a governing difference (x-w) <> 0. The response of the governor may show different static and dynamic behaviors.

- **the correction device**: the governor has to have a feedback y to the governed system. This is done with the correction device. In a turbine, this is normally the distributor of the turbine. Due to the big forces required for the operation of the distributor an oil hydraulic amplifier of the governor signal is usually needed (servomotor).

4.3.2 The static and dynamic behavior of the governor

The static and dynamic behavior of the governor required to control the MHP plant may be ideally described with simplified mathematical models for small correction movements. The static values occur in a steady state operation, which means that all variables of the controlled system are at rest. The unit is operating under constant load and head.

The dynamic behavior is important if the governor has to respond to changes of operation like power or head fluctuations.

A good behavior is characterized by the systems return to a steady state condition without unreasonable deviation or time interval. The new operation point should be reached with a minimum of swinging (adequate damping) and the turbine operation should be within predictable limits for any operating condition. As already mentioned, we have to consider also the mode of operation if the governing system reaches its limits.

There are two possible ranges of operation:

- **The changes are sufficiently small** that none of the governing system elements reach their limits. Then the correction movements are according to the adjusted governor parameters and can be predicted more or less accurately by the linearized mathematical models. This mode is most important for the stability of the system. This means that the system can under all conditions reach a steady point of operation without permanent oscillations.

- **The changes are substantial**, causing the governing system to reach its limits. Such a limit is the maximum velocity of the servomotor determined mainly by the allowable water-hammer. An other is the maximum opening of the distributor determined by the flow available. Whenever such a limiting factor takes effect, the system response is different from the normal situation. Linear behaviour according to a linearized mathematical model is reached not before the control system is within the normal operating range again.

There are a number of **additional limiting factors** defining the range of governing capabilities, such as:

- the working range of the speed sensing device

- the maximum servo cylinder stroke defining full opening of the distributor

The maximum servomotor velocities are limited by the permissible pressure changes and speed changes.

Figure 39 shows graphically the parameters the governing system has to cope with.

The art of designing a sound governing concept is to shape the parameters in such a way that the governor can adequately act. Ill selected parameters lead to an unstable governing concept, e.g. never ending hunting of the system.

We first study the behavior of the governor independent of other system components as far as its response of the distributor y to a sudden change x of speed is concerned. Figure 40 is a schematic arrangement to study and test a governor. The governor (black box) is separated from the turbine and driven with variable speed. The response of the distributor is registered if the speed is changed suddenly. This reaction is often represented in block diagrams to specify the dynamic behavior of the system.

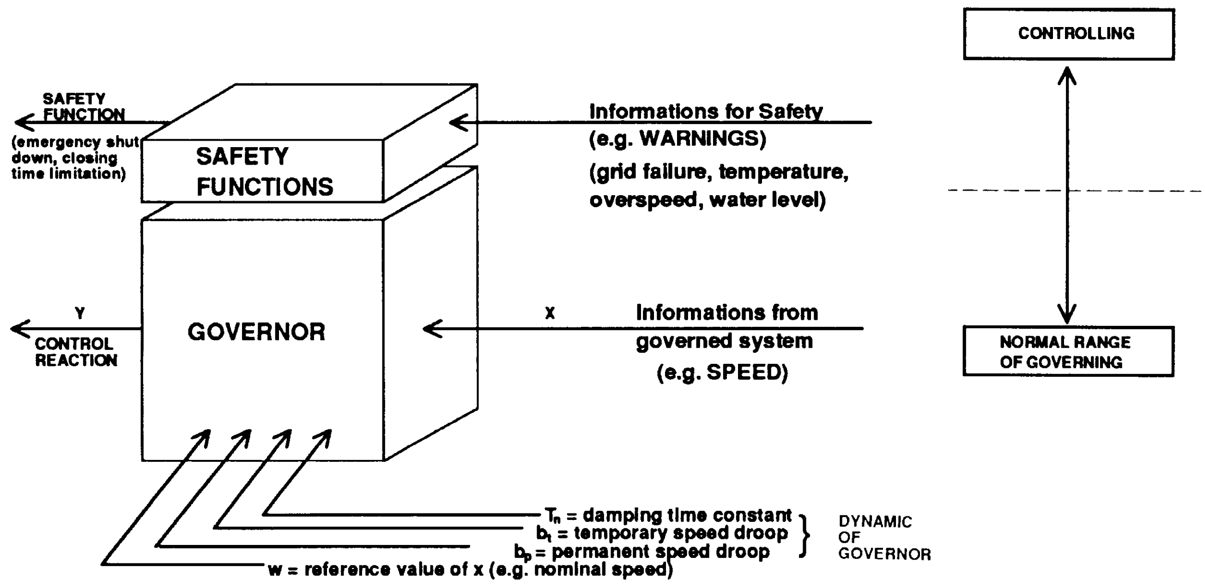


Figure 39: Parameters of the governor

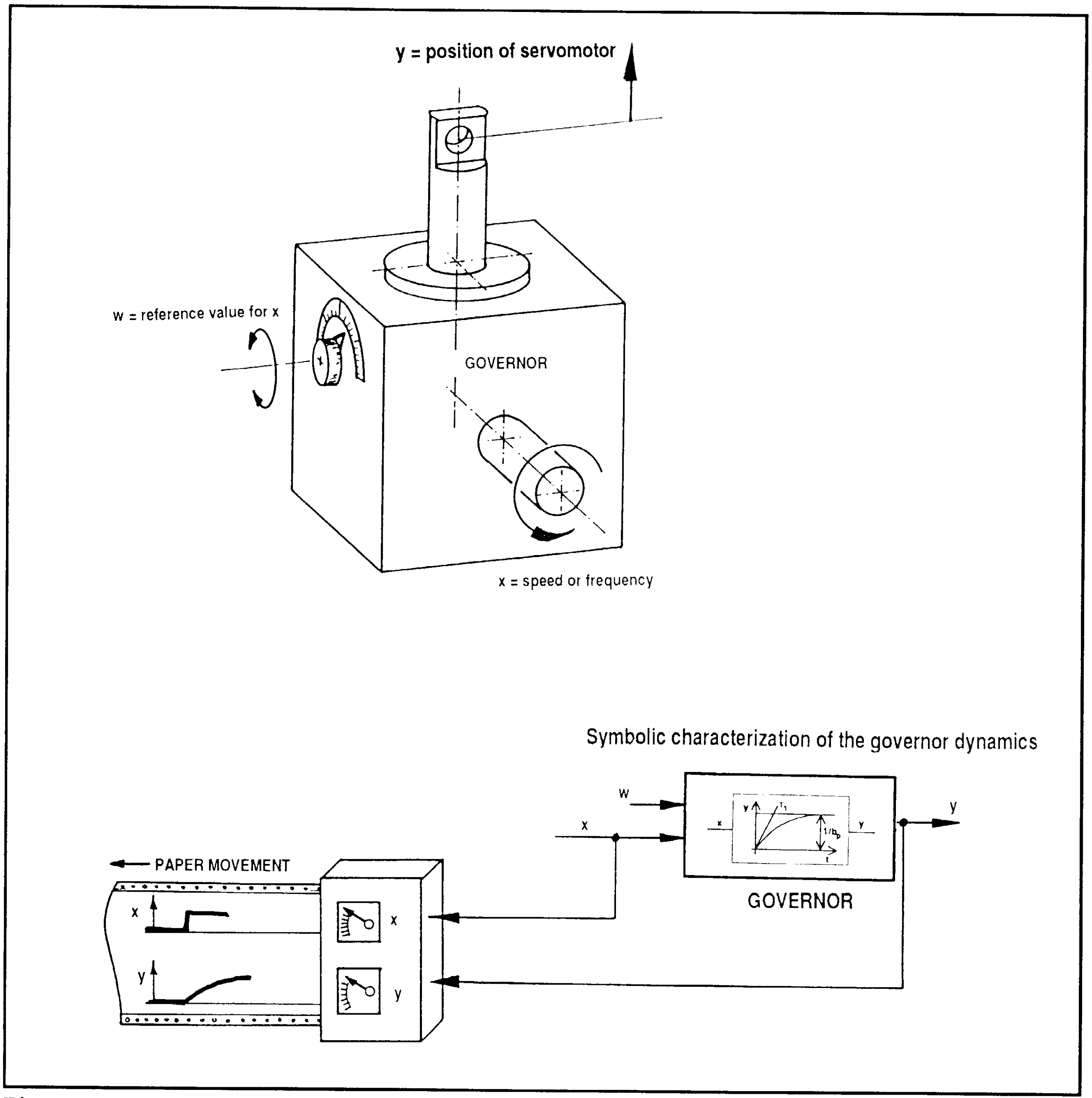


Figure 40: Measuring the dynamic behavior of a governor

➩ Proportional P-behavior:

The simplest governor is that with proportional (P-) behavior. In the ideal case it will respond to each change of the controlled value immediately with a proportional movement of the correction device. This means for steady operation, that each value x is corresponding to a certain proportional value y. The simplest example is a lever. Real systems however will always show a time delay of the response. We find therefore a P-T1 characteristic if we consider the friction and elasticity and a P-T2 characteristic of the governor's response if we also consider the inertia of masses (refer to figure 41). When - starting from a steady state operation point - a new stable operation point has been reached, the deviation of control device position y is proportional to the deviation x of the controlled variable.

In other words: the speed deviation **x** is proportional to the deviation of the servomotor position **y** and therefore, since output is proportional to the servomotor position, the P-governor will show an output proportional to speed.

A change of load from no-load to full load will cause a drop of speed of **x** ≈ $\mathbf{b_n}$, which is the so called permanent speed droop (refer also to annex A1).

A turbine speed governor with direct operation of the guide vane, as shown in figure 42, requires a large centrifugal pendulum to develop sufficient operating force. Satisfactory performance is achieved only with a relatively large permanent speed droop, and a good self-regulating factor of the system.

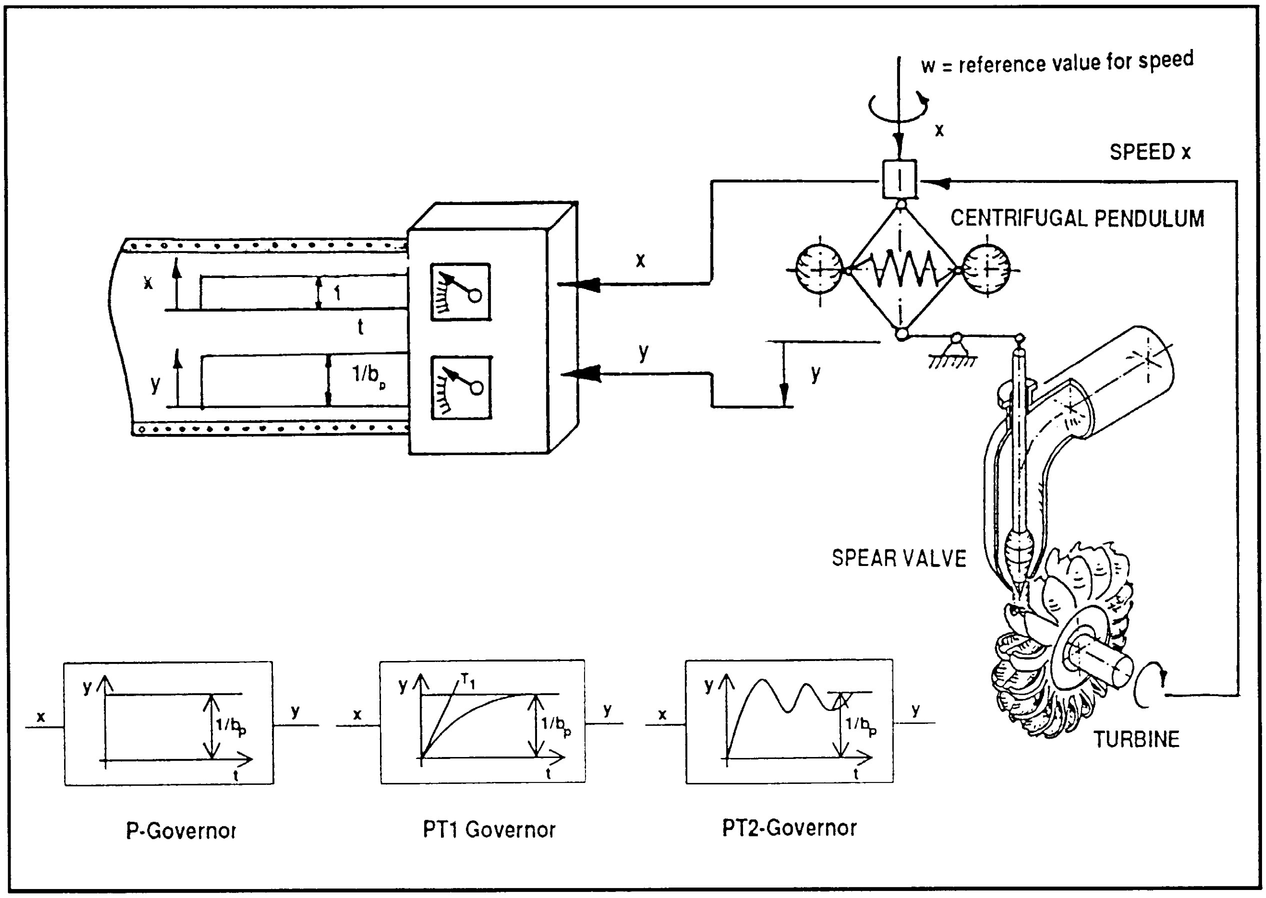


Figure 41: Response of a P-governor

⇨ **Integral I-behavior:**

In the ideal case, an I-governor will respond to each change of the controlled value with actuation of the control device with a velocity proportional to the change. Under stable operating conditions, such a governor will exactly adjust the nominal value of the controlled variable for all conditions.

In the example of a turbine speed governor, (refer to fig. 42), the pendulum controls a valve which in turn operates a hydraulic cylinder (servomotor). The speed of the servomotor piston is proportional to the value (w-x) due to the characteristic of the valve. Such a governor reacts too slowly for speed control. Its performance can be considerably increased by combining it with a proportional element.

⇨ **Proportional and integral PI-behavior** (refer to fig. 43):

This is the combination of proportional and integral behavior. Initially the control device will jump to a position proportional to the value (w-x). Subsequently it acts proportionally to the value (w-x). Under stable operating conditions, such a governor will adjust the nominal value of the controlled variable for all conditions exactly.

To obtain a PI-behavior, an elastic compensation device is used in a mechanical governor. A simple possibility is shown in fig. 43.

⇨ **Proportional and integral PI(P)-behavior with permanent speed droop** (refer to fig.44):

This is the most commonly used governor type for the control of water turbines. It combines the good dynamic behaviour of the PI-governor with the static behaviour of the P-governor. This enables the governor to operate in small grids together with other units as described in chapter 2.6.

Normally it is sufficient to have a PI-behavior with permanent speed droop as shown in fig. 44. In large powerstations, so called PID-governors, containing proportional, integral and derivative portions, may be installed as well as very complex electronic devices for demanding governing tasks. However, such governors are not subject of this publication.

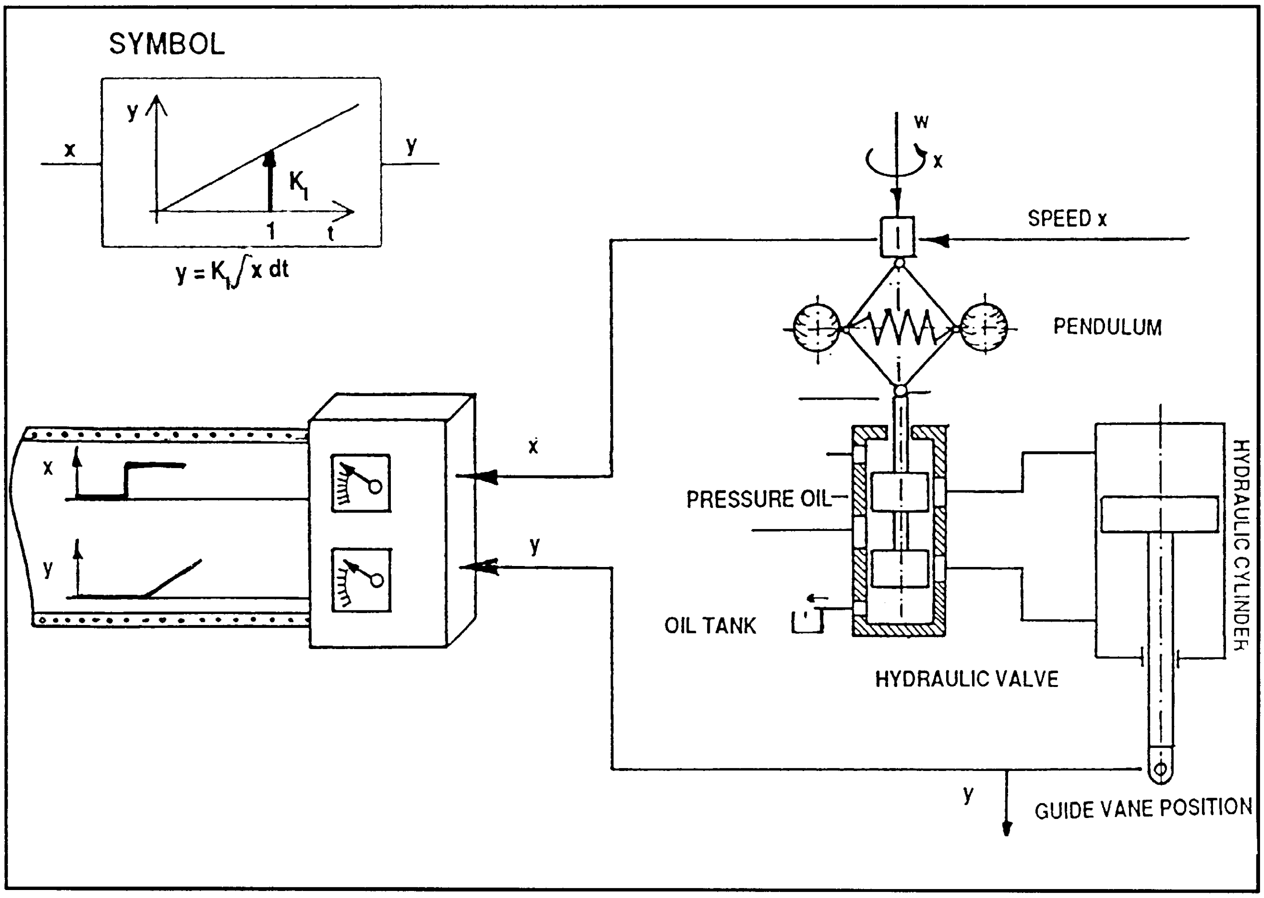


Figure 42: Response of a I-governor

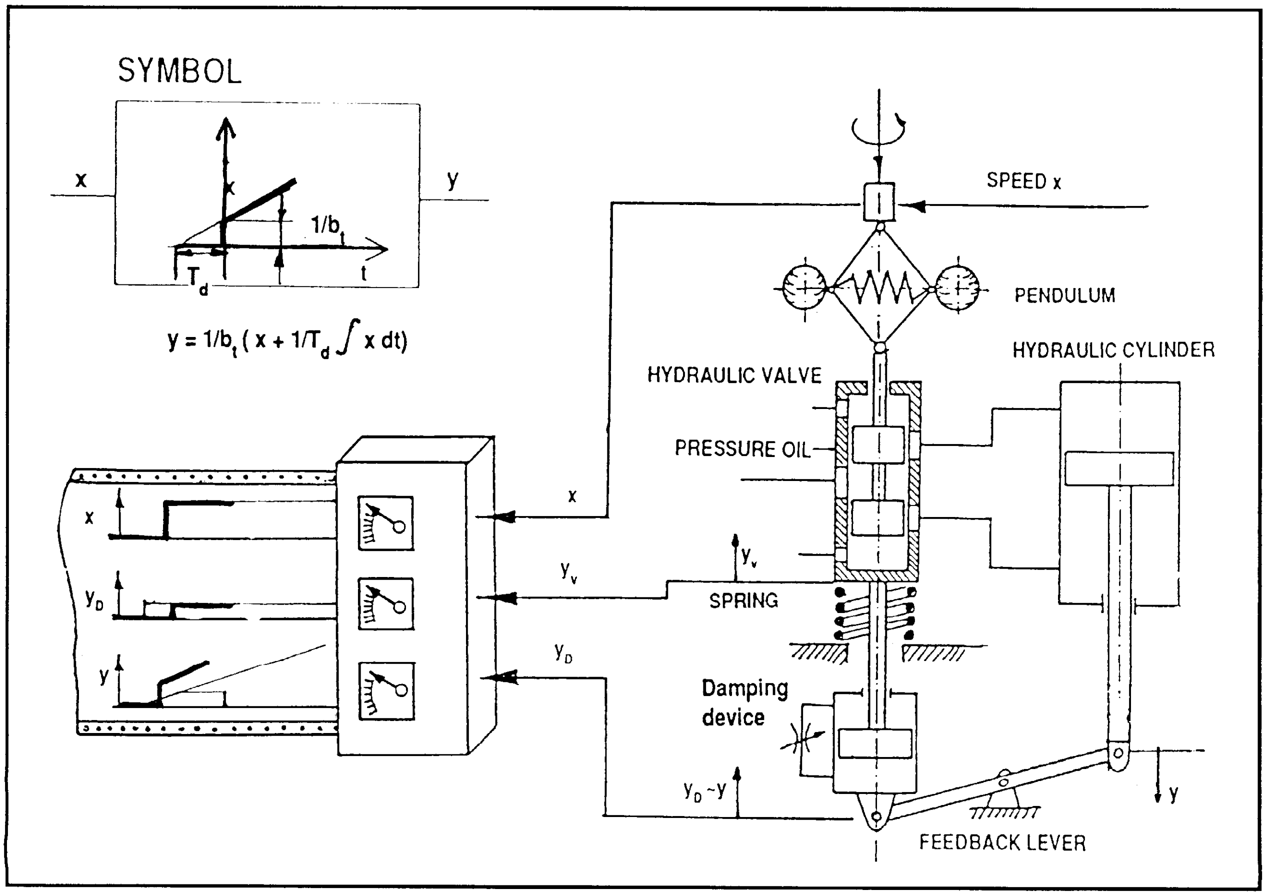


Figure 43: Response of a PI-governor

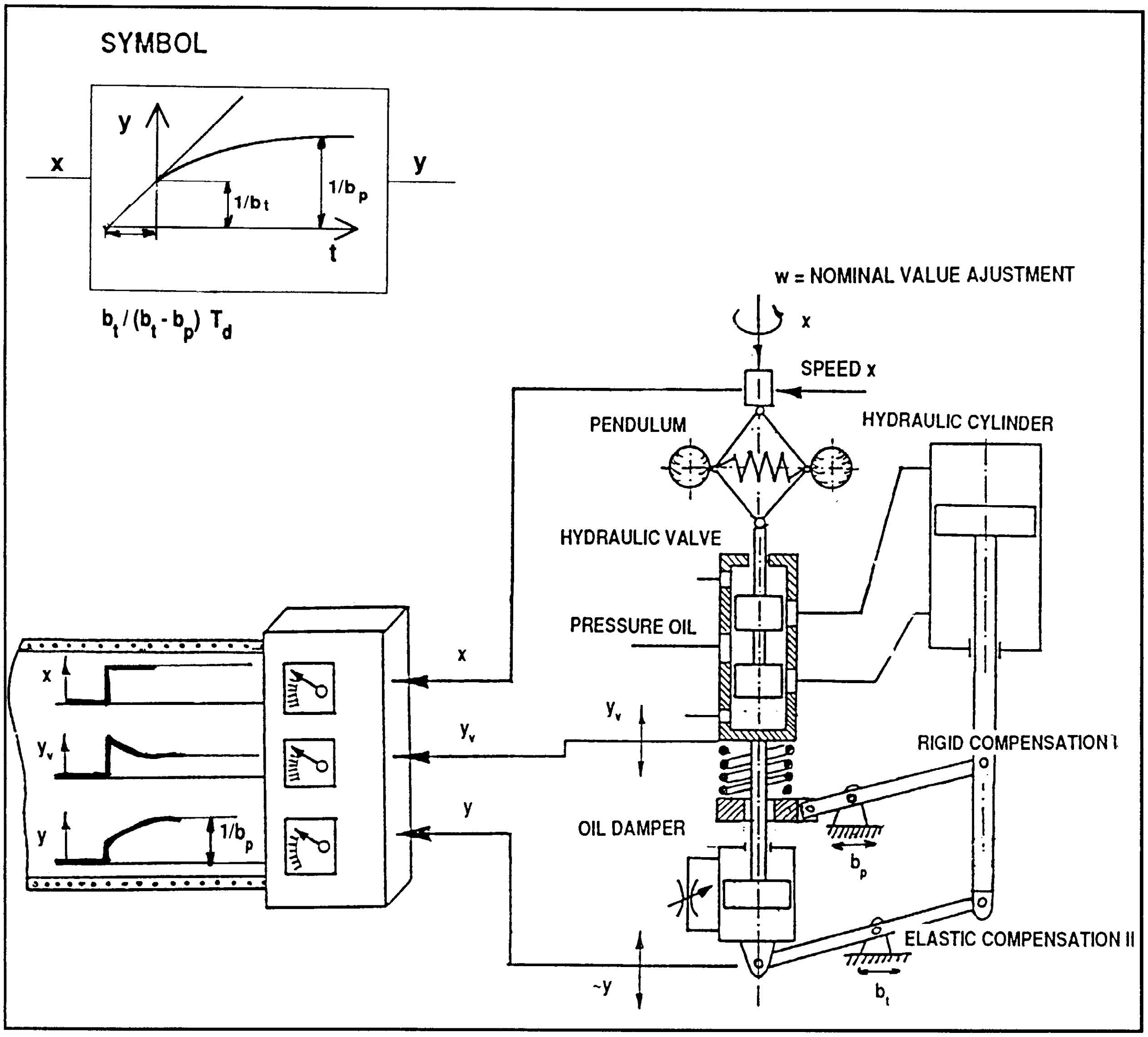


Figure 44: Response of a PI(P)-governor

4.3.3 Energy capacity of the governor

The output signal of the governor is normally not strong enough to actuate the distributor. Mechanical governors usually have an oil hydraulic amplifier. A hydraulic cylinder moves the inlet gate of the turbine. The working capacity must be high enough to move the distributor under all conditions with the required speed (refer to figure 45). The distributor and actuating levers must be designed to cope with the maximum force of the servo motor. If the energy capacity of the servo motor is too large, the distributor and levers must be overdesigned and this should therefore be avoided. The movement of the governor working shaft must be transmitted to the turbine distributor by means of a lever arrangement.

4.3.4 Dead times, delay of the governor

An important parameter of mechanical governors is their insensitivity. Due to friction and tolerances in bearings and lever linkages, the governor will not respond within a certain range of speed deviation. The magnitude of this insensitivity is one half of the so called dead band as shown in figure 46. The acceptable width i_x of the dead band depends on the governing task and is further specified in chapter 5. Another important value is the time delay of the governor response.

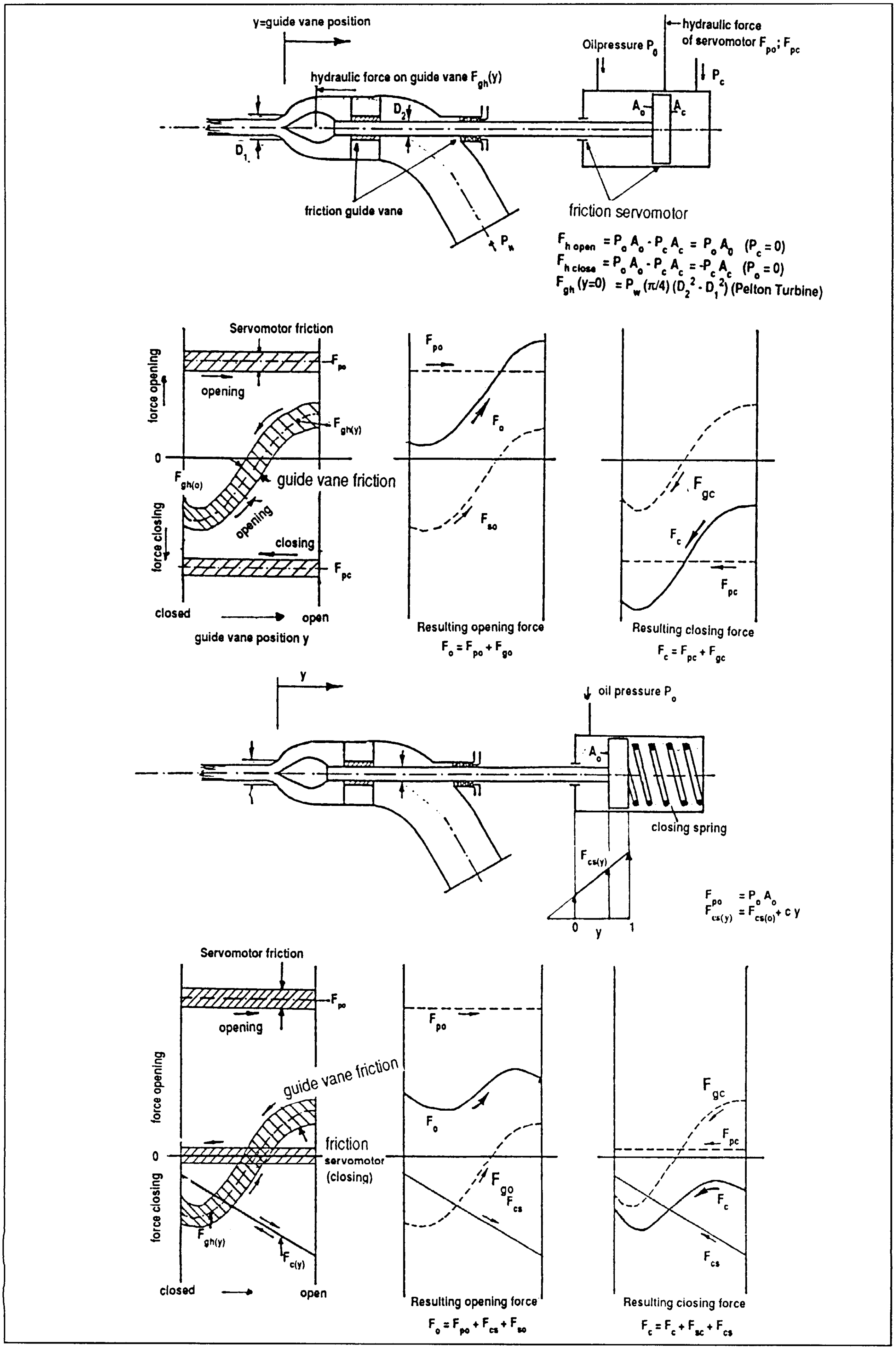


Figure 45: Work capacity of the governor

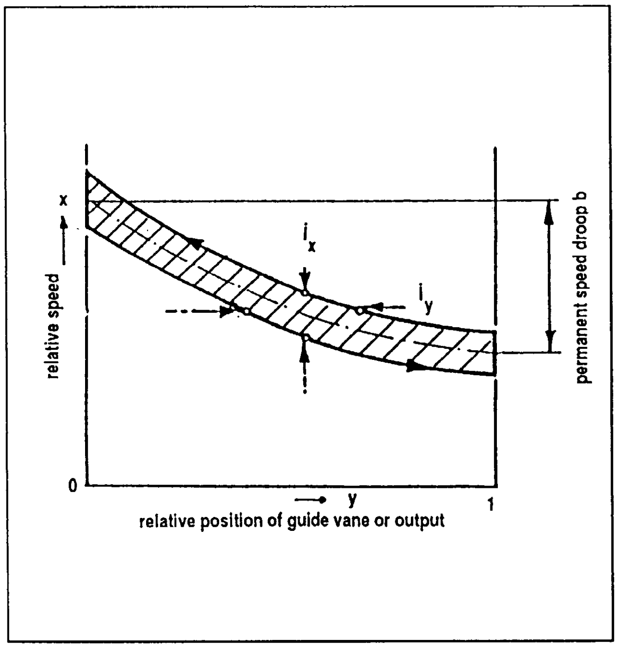


Figure 46: DEAD BAND of the governor

4.3.5 Safety functions of the governor

Different safety functions may be integrated in the governor and may be activated if certain critical situations occur.

⇨ Mechanical governors:

- turbine should close if governor drive (belt or motor) fails or if no oil is available
- warning if oil filter is clogged
- emergency stop in case of over- or underspeed (voltage) or if grid fails in schemes working in parallel with a grid .

⇨ Electronic governor (load controller)

- automatic disconnection by relays if grid fails
- automatic shut down of the turbine if component of controller, generator or turbine fails, refer to figure 47.

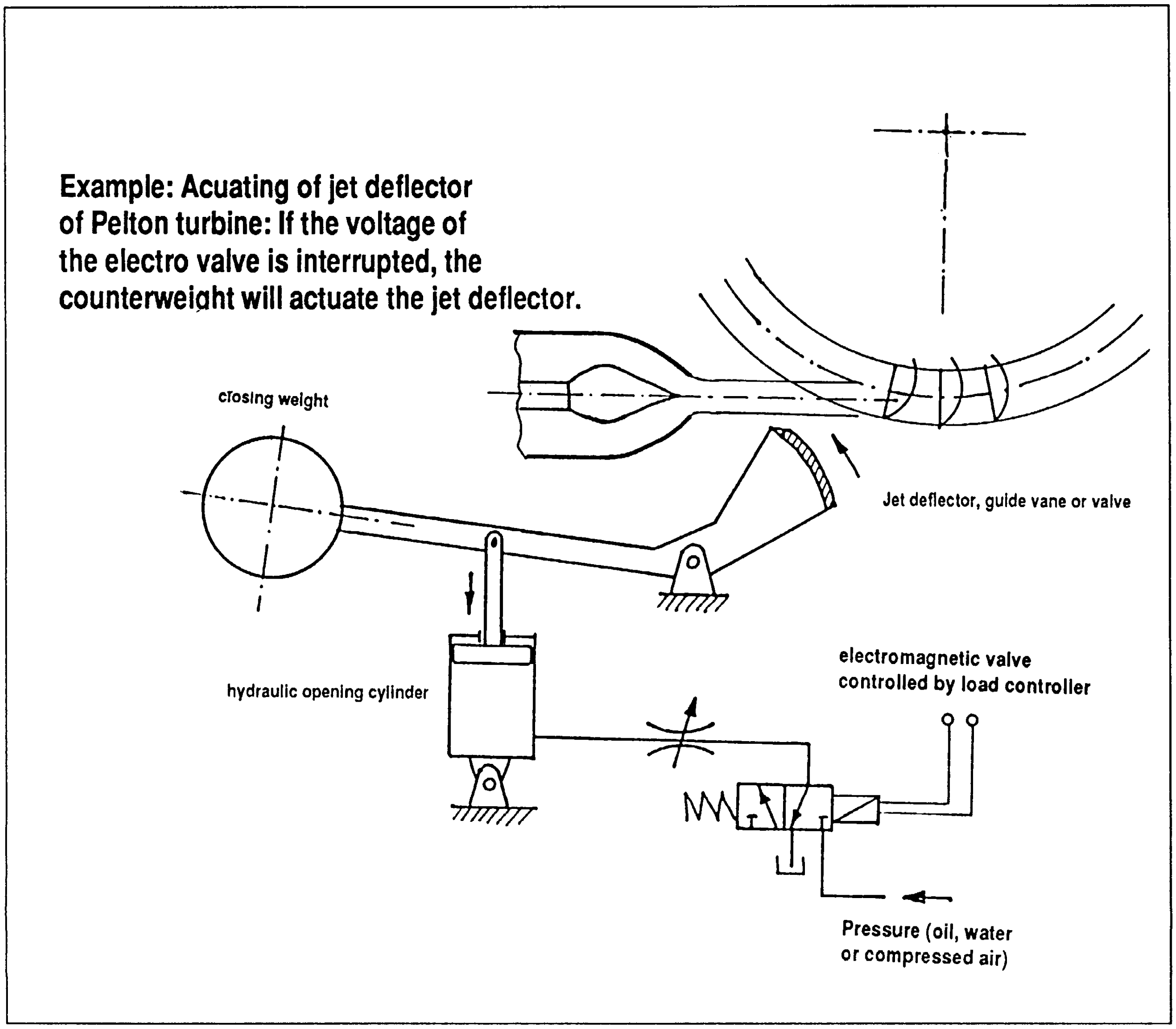


Figure 47: Safety functions of load controllers

SUMMARY: Parameters of speed control governors

Speed control governors: the dynamic and static behavior of the governor is of central importance especially for speed control systems. It must be adapted to the governed system. As an exact prediction of all parameters in MHP plants is not possible the governors must have possibilities to be adjusted during commissioning of the plant.

The governors should have a PI characteristic with a permanent speed droop. Such a governor is characterized by the following values:

b_p = ***permanent speed droop***
b_t = ***temporary speed droop***
T_d = ***time constant of damping device***

4.4 The dynamic behavior of the governed system and its importance for speed control

As already mentioned, dynamics of the system depend on many parameters. A precise mathematical analysis is beyond the scope of this handbook. We therefore have to reduce the complexity of the problem to practically applicable parameters.

The following characteristic values are used to describe the system (refer to annex A2 for formulae):

4.4.1 The hydraulic system

- **Starting time of water masses T_w:**

The inertia of the water in the pipe is expressed with the acceleration time of the water masses T_w. This is the fictitious time which is necessary to accelerate the water column in the penstock to nominal velocity under nominal head.

- **Reflection time of pressure waves T_r :**

The reflection time of pressure waves T_r determines the penstock characteristic: T_r is the time needed for a pressure wave to run from one end of the penstock to the other and back.

4.4.2 Dynamics of the turbine/generator set and consumer units

- **Unit acceleration time T_a of turbine/generator set (inertia of turbine, flywheel and generator):**

T_a is the time which is necessary to accelerate the turbine/generator set from zero to nominal speed if the nominal torque is acting. The inertia of consumers like motors may be difficult to estimate and is usually neglected. There is however a positive effect on the stability of the governor due to consumers with significant inertia.

The latter may be expressed with the load acceleration constant T_b. This is the time which is necessary to accelerate the rotating masses of the consumers from zero to nominal speed if the equivalent nominal torque is acting.

- **Self regulation of the system** (consumers and turbine):

e_n expresses the increase / decrease of the turbine speed if the plant output is changed at a fixed inlet gate position. It is the equivalent of the angle between the characteristics of the turbine and the consumers in the speed/torque diagram (see fig. 37 and in the annex fig. A27).

4.4.3 The dynamic behavior

The dynamic behavior of an entire MHP plant can be determined more accurately mathematically, if all relevant data are known. Literature on these methods is abundant.

The dynamic behavior of an entire scheme may also be analyzed in operation. Figure 48 shows the use of a data recorder which writes all important values on a moving paper strip. Such diagrams give an impression of the behavior of the system after a certain disturbance, e.g. if a consumer is connected or disconnected. We want to study some reactions to sudden load changes for a simple scheme for several types and adjustments of the governor, as shown in figure 49.

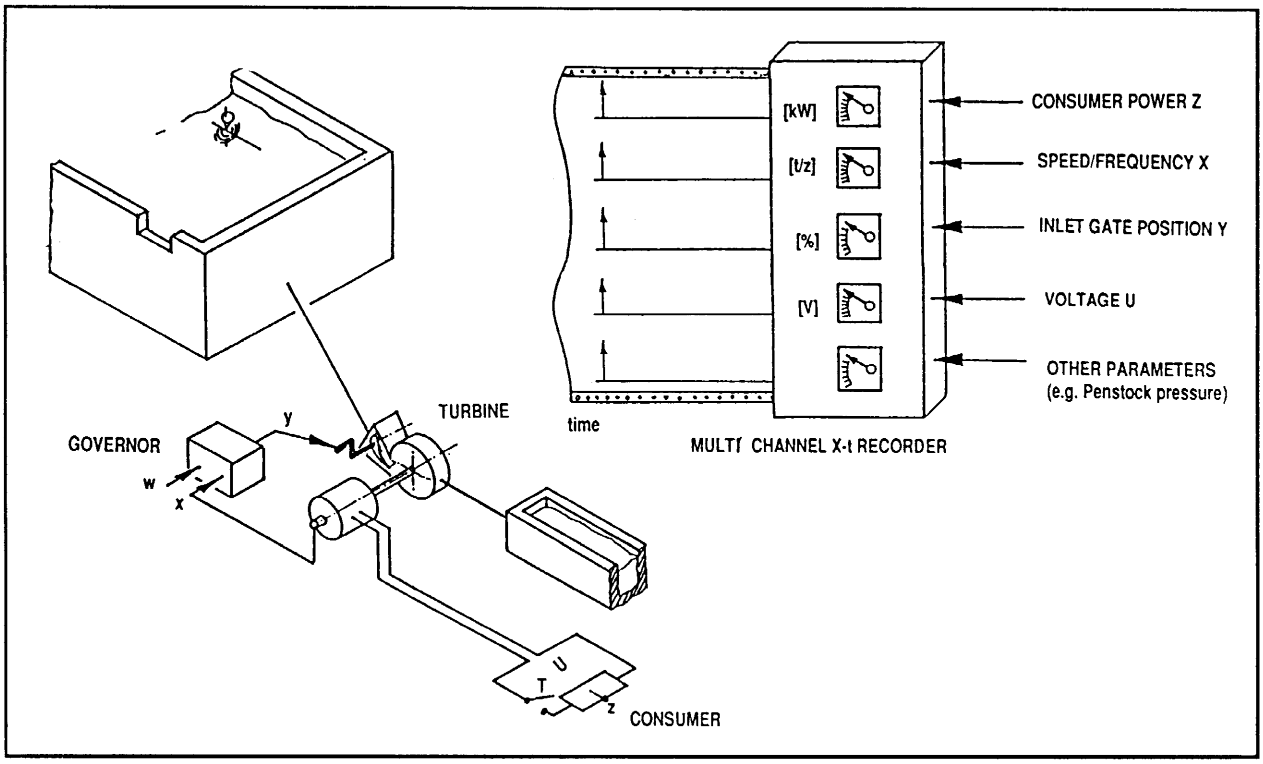


Figure 48: Measuring method for the response of the system to sudden load changes

Figure 49a shows characteristic curves of a P-governor:

- -0- Uncontrolled system without governor: speed goes up and reaches a steady state according to the static turbine characteristic for the load connected (runaway speed at no load).
- -1- setting of governor is insensitive with large permanent speed droop $\mathbf{b_p}$: speed deviation is high and quickly at a steady state.
- -2- improved sensitivity of the governor with moderate speed droop $\mathbf{b_p}$: best possible setting of the governor in question. Speed deviation is relatively small and quasi stable operation is achieved.
- -3- high governor sensitivity with small speed droop $\mathbf{b_p}$: governor reaction to small load change is quick. However, this is at the cost of stability. Speed oscillates with increasing amplitude.

In figure 49b, characteristic curves of a PI(P)-governor are shown:

- -4- optimal temporary speed droop $\mathbf{b_t}$ and blocked damping device ($b_p = b_t$): the system reaches a steady state at a relatively high level of speed deviation.
- -5- a degree of permanent speed droop $\mathbf{b_p}$ is maintained, according to which a point of permanent speed deviation is reached, timewise determined by the time constant of the damping device T_d.
- -6- setting as a PI-governor without permanent speed droop ($b_p = 0$). The system reaches steady state at nominal speed after a short period of transient speed deviation.

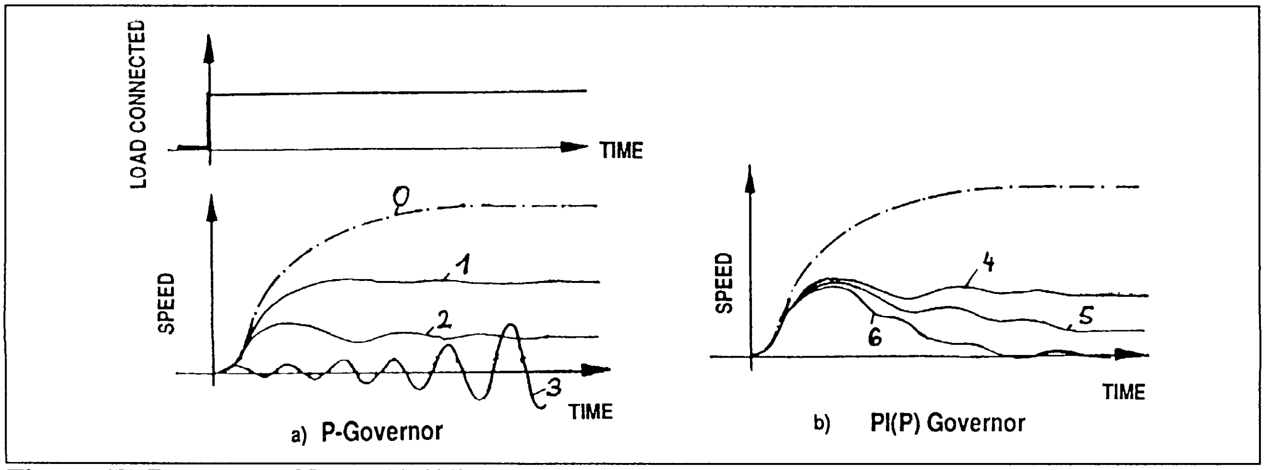


Figure 49: Response of P- and PI(P)-governor

In figure 50 the effect of different settings of the time constant T_d of the damping device is shown:

-7- the value set for T_d is very small: the system stabilizing effect of the temporary speed droop does not take place.

-8- optimized setting: the system reaches steady state operation after a short time period with relatively small and decreasing oscillations. The operating speed attained is near to nominal speed (b_p).

-9- the time constant is set at a high value: the time required to reach steady state operation is excessive. In systems with a low self-regulation factor, this may cause instability. If a large load is connected, a total speed collapse may occur.

Conclusion

Stability in PI(P)-Governors is determined by the settings of **temporary speed droop b_t** and the **time constant T_d** of the damping device. Steady state speed deviation on the other hand, is determined by the value set of the **permanent speed droop b_p**.

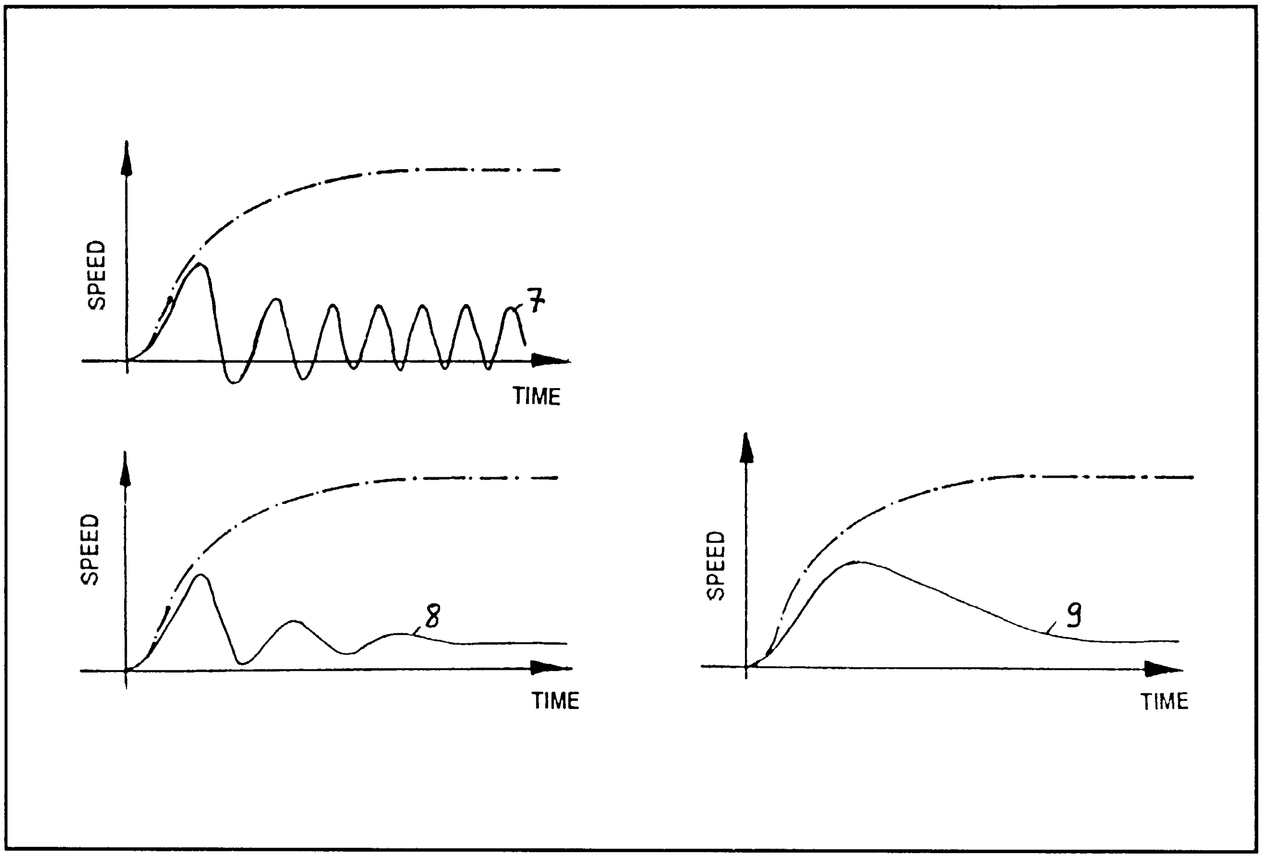


Figure 50: Response of PI(P)-governor with different settings of T_d

Figure 51 shows various diagrams recorded in a plant with a Cross-Flow turbine of 8 kW under a head of 2.5 m. The occurence recorded was switching of 60% of nominal load.

Figure 51a shows the response of the system without flywheel, set as a P-governor with permanent speed droop $b_p = 8\%$. Steady state operation is attained after speed oscillations have ceased, at different levels of speed, depending on the load.

Figure 51b shows the performance of the same system configuration, but with a setting of the temporary speed droop $b_t = 25\%$, and a damping device time constant $T_d = 9$ seconds, to work as a PI(P)-governor. It is remarkable, how fast speed oscillations cease and steady state operation is attained.

In figure 51c finally, the system performance is shown with a flywheel: The P-governor was set to a permanent speed droop $b_p = 3\%$, resulting in a speed characteristic of good quality due to the flywheel effect. The flywheel effect becomes obvious when comparing the guide vane characteristic curves in figure 51a (without flywheel), where the guide vane oscillates along with the speed oscillations. Load switching results in a much smaller speed deviation (due to the flywheel) in figure 51c, which in turn results in guide vane movement. The latter oscillates a few times, without however affecting speed. The flywheel absorbs/delivers the excess/shortage of energy caused by transient excessive/insufficient gate opening.

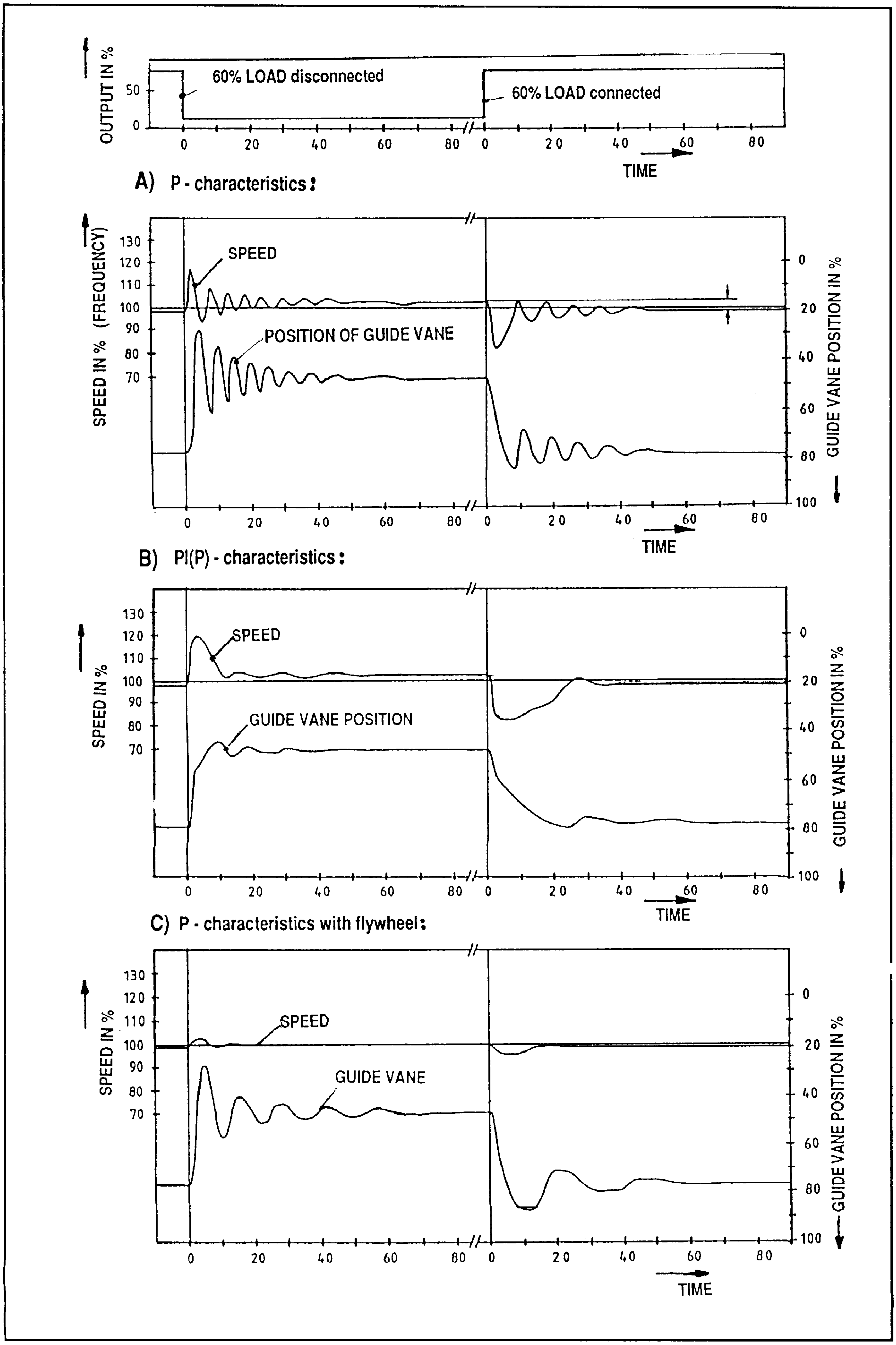


Figure 51: Response of a plant to 60% load switching

SUMMARY: Dynamic behaviour of the governed system

The behaviour of a governed system must be stable under all operation conditions. The transient and permanent speed, frequency and voltage deviations must be within acceptable limits and must reach steady state again. Under constant operating conditions without load changes, the governor must keep the system steady; no permanent oscillations (hunting) should occur.

Recommended adjusting range for the governor

4.5.1 Speed control governors

Precise pre-setting of a governor is difficult and usually not possible. A governor must therefore allow a certain range of adjustment for different parameters. For flow control governors, this provision of adjustment is recommended in DIN standards 4321 as follows:

- permanent speed droop b_p = 0 - 6%
- temporary speed droop b_t = 0 - 150%
- time constant of the damping device T_d = 0.1 - 20 s
- Range of speed adjustment w = +6% to -10%
- Closing time of inlet gate : T_s = 3 -20 s determined from the hydraulic system
- Opening time of inlet gate : as above (note: sometimes the closing speed is reduced for small openings of the inlet gate to avoid water-hammer effects.)
- Dead band:
- speed regulation: (high precision necessary) $Ix/2 < 2*10^{-4}$ for sophisticated systems $Ix/2 < 2*10_{-3}$ for low demands (governor must react if a speed change of 0.2% occurs)
- water level control: $Ix/2 < 1*10^{-2}$ (governor must react if a change of water level of 1% occurs).

These recommendations may be achieved only with precise and relatively complex governors. In MHP plants however, one may make some compromise as far as the quality of governing and the possible adjustment range is concerned. Experience however shows, that governors with insufficient accuracy cannot control a system with satisfactory stability.

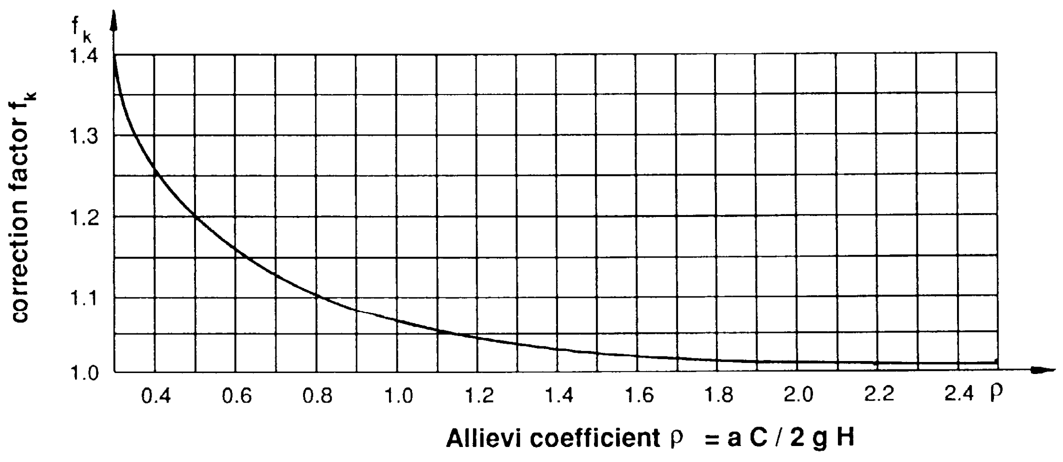


Figure 52: For high heads the correction factor for the governor adjustment is determined from the Allievi coefficient ρ = aC/2gH

Recommended adjustment for a PIP-governor

Recommendations for the probable optimal adjustment using the simple parameters as described above are given by Stein (annex A6, 2.2). This enables us also to see whether our governing problem is difficult or not.

- permanent speed droop b_p = 0 - 6% (depending on application)
- temporary speed droop $b_t = 1.8 * T_w/T_a * f_k$
- time constant of the damping device $T_d = 4\ T_w\ f_k$
- f_k = correction factor for penstock characteristics, expressed by the ALLIEVI coefficient (see figure 52)
- closing time of servomotor T_s = maximum servomotor speed for opening and closing is determined by the maximum permissible pressure rise. The servomotor speed and its working capacity determine the size of the servomotor and of the oil-hydraulic system (pump, pressure, storage tank volume etc.)
- acceleration time of the turbine/generator set T_a = 3 to 6 seconds, which may be determined from figure 53. In MHP-installations however, higher values may be feasible (T_a may reach 30 seconds and more).

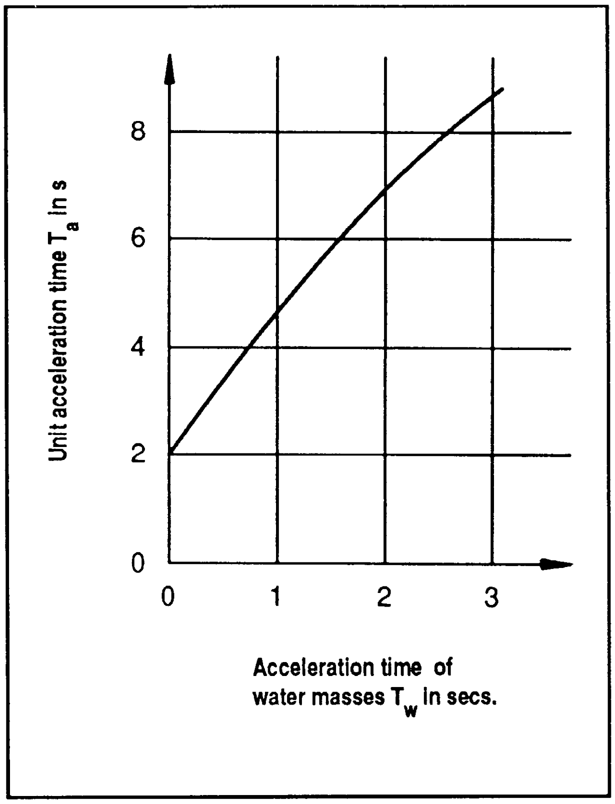


Figure 53: Unit acceleration time T_a as function of the acceleration time of water-masses T_w.

A criterion for satisfactory adjustment of a governor in isolated operation may be, that the speed oscillations after load changes are reduced to 10% of their highest amplitude after the passage of two oscillations (see fig. 54). No permanent oscillations should occur during normal operation.

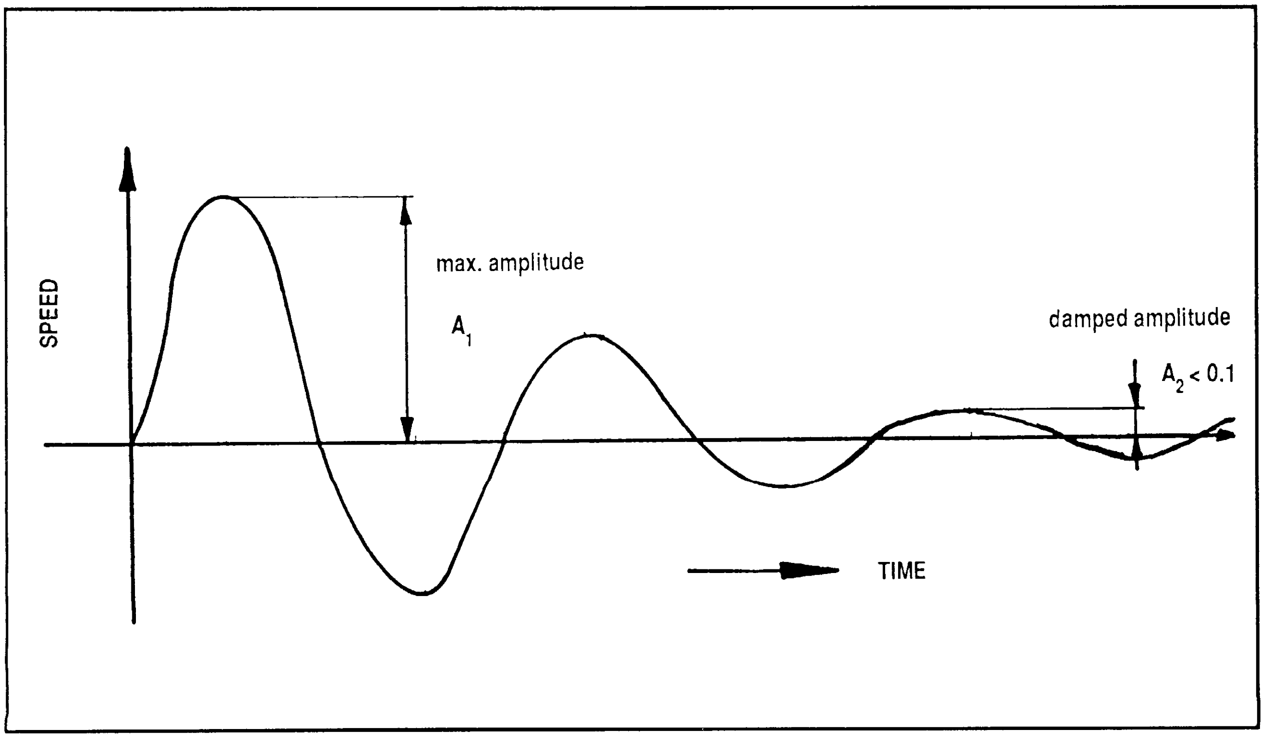


Figure 54: Speed/time diagram: criterion for governor adjustment

4.5.2 Electronic load controllers

Electronic load controllers are simple and precise to adapt to each dynamic behavior, as long as they do not interfere with the turbine flow. Adjustments may be necessary due to the voltage regulator of the generator (AVR), consumer type and load sharing for parallel operation.

SUMMARY: Recommended adjusting range

Flow controlling governors: The final fine-adjustment of flow controlling governors should be made at site during commissioning. There are standards such as DIN 4321 for the range of adjustment of governors. However, to comply with international standards in case of MHP plants can be an expensive issue.

Load controllers: the system is not influenced because load controllers operate under constant generator output. The adjustment of governing parameters in the plant is usually not necessary and if required, is simple. Nevertheless, if two units with load controller operate in parallel, the speed droop and reference frequency should be adjustable to obtain the desired load sharing.

4.6 Summary: Parameters of regulation

Table 1 below lists the relevant parameters as well as the chapters in this publication providing the respective explanatory remarks.

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Chapter 5: Required data for the specification of the governor

5.1 General

In the preceding part of this publication we have tried to provide the basic tools to understand the governing process. It is now seen, that the specification of the governor needs a clear definition of the relevant parameters of the plant. The importance of those parameters depends essentially on the governing concept.

The specification of governors must carefully consider the dynamic processes in the installation like water- hammer, overspeed of turbine generator set, size of flywheel, hydraulic forces on the inlet gate, etc.

The specification of electronic load controller systems is simpler than the one of a flow controlling governor. The electronic devices are not concerned by inertia of masses and can simply and precisely act according to the actual needs. One important fact must be mentioned: planners and engineers are often not aware that the governor is only an element of a complex system including the hydraulic design of the plant, the management of the load, the characteristics of consumers and the construction of the turbine. High demands on the quality of control and the specification of difficult operation conditions as well as an inappropriate design of the plant can cause excessive costs, as well as unnecessarily complicated and demanding specifications of the governor. Sophisticated governors often have to compensate design errors. The consequences are high costs, difficult maintenance as well as unnecessary sources of failure and flaws. The governor manufacturer should therefore give his feedback as regards the proposed plant design. This cooperation saves money and avoids trouble. It is therefore important to give the governor manufacturer all data concerning the governed system at an early stage of project planning.

5.2 Data required by the manufacturer to offer a governor

Some manufactures have detailed questionnaires. After having studied the important parameters of the governed system, we will understand the meaning and importance of these questions more clearly.

We will find 4 groups of questions:

- turbine
- waterway (storage bassin, forebay, channel, surge tank, penstock, draft tube)
- consumers (driven machines, flywheel effects of generating-set)
- specific control features

5.2.1 Turbine related questions

Type and design of the turbine and the hydraulic operation data have the following consequences:

- Capacity of servomotor (if a hydraulic cylinder is used this will determine the stroke, diameter, pressure, oil volume) necessary to actuate the flow control device.
- Type and construction of turbine determine the number of servomotors and the forces to actuate them. Kaplan turbines and Pelton turbines may be equipped with double regulation. In big machines the inlet gate may be operated with more than one servomotor.
- Hydraulic performance characteristics of the turbine determines its response to servomotor movements.
- The turbine output as a function of the inlet gate position should be as linear as possible. The length of the stroke required determines the speed of the servomotor.
- The part load efficiency of the turbine determines the economy of water management.

5.2.2 Questions related to hydraulic structures (incl. penstock and draft tube)

These data represent the dynamic and static behavior of the hydraulic system. They impose limitations on the servomotor speed together with the above mentioned turbine characteristics. Speed limitations may be necessary to prevent surge waves in channels and water-hammer effects in closed pipes. It is advisable to prepare a profile of the complete hydraulic installation with all dimensions of channels, surge tank (sectional elevation drawing), penstock sections (diameter, length, wall thickness and material). The designer of the plant should check the effects of these parameters:

- High dynamic pressures (water-hammer) can destroy the pipes
- Surge waves in channels may spill over its sides
- The surge tank volume and its free surface may be too small with the consequences of flooding the tank and air injecting into the penstock.
- The oscillation of pressure de-stabilizes the governed system and may come to resonance if the governor parameters are wrongly selected.

5.2.3 Governing task as related to generator, distribution and consumers

Flow controlling mechanical and electro/mechanical governors:

These data represent the dynamic and static behavior of the consumers. They determine together with the data of the hydraulic system the necessary parameters of the flow controlling governor to operate smoothly. The self regulation factor can indicate problems to regulate the system.

The minimal speed changes after sudden load changes and the possible quality of the governing process is a result of all these parameters. This means it may be necessary to change some of the parameters if a certain quality of governing is needed. It is a common misunderstanding that the quality of governing is only a matter of the governor.

In fact it is influenced by:

- Mode of operation (parallel with national or small grids, isolated, flow or load control)
- Load curve of consumers (what maximum load fluctuations can occur and with which timing)
- Type of the consumers (speed/power characteristic, starting behavior, reactive power demand)
- Flywheel effects of the turbine/generator or turbine/working machine.
- Generator characteristic
  - overload current and torque
  - voltage/ frequency characteristic
  - dynamics
  - cos ϕ at load fluctuations

Electronic load controllers:

The questions about the consumers and electrical machines are very important, because not all types of load controllers are able to control induction motors. If an electronic load controller is ordered one must add a list of all connected devices and machines. Sensitive electronic devices like radio, television, video and computers etc. must be specified to avoid disturbances from radio interference and other problems.

Also important for the specification of the load controllers is the type of wiring as well as the voltage and frequency of the grid. Lightning protection of the grid and controller is mandatory.

It is useful to have one supplier for all electrical components like generator, controller and ballast resistors. To avoid compatibility problems the following must be respected:

- Try to find one supplier of load controller and generator
- If this is not possible the load controller manufacturer should specify generators (list of types and manufacturers) which are compatible with his load controller.

5.2.4 Scope of supply: governor specifications and accessories

These data represent the dynamic and static behavior of the governor. They include the necessary safety devices like overspeed protection and additional functions as for example remote control and displays.

SUMMARY

The manufacturer knows the features and qualities of his governor. You know the planned Micro Hydropower plant. To offer you a suitable governor the manufacturer needs all relevant information influencing the operation of the offered governor. An information exchange is very important. It can help in selecting an appropriate governor and to modify the MHP plant design according to the needs of the selected governor to obtain a smooth operation of the plant at reasonable cost.

5.3 Typical questionnaire for procuring governors

since

1905

Question-Form concerning Governor for Water Turbine

For calculating the size of the governor and the other governor data we require the following statements concerning your water power plant. Please attach a sketch or a drawing of the whole plant to the filled-in form, if possible.

Jahns-Regulatoren-Gesellschaft

Com. No. | Ref.

Firm:

Address:

Phone:

A Turbine

Please fill in carefully, cross out that which does not apply

This column is filled in by us

Stamp of arrival

1. Manufacturer
2. Year of construction
3. Turbine shaft horizontal / upright
4. Turbine single, double, treble
5. One governor for 1, 2,.. turbines
6. Fall H = ms / ft
7. Water stream for each turbine Q = m³/s
8. max. power of each turbine N = PS
9. Speed of the turbine n_o = r. p. m.

$n_q = n\sqrt{Q}/H^{5/4} =$ min^{-1}

10. Francis Turbine yes / no
11. Runner wheel diameter mms.
12. Kaplan Turbine yes / no
13. Height of guide wheel mms.
14. Runnerwheel adjustable yes / no
15. Guide wheel adjustable yes /no
16. Open installation / spiral housing
17. Outside regulation / inside regulation

A_T = Kpm je Turbine

18. Free jet turbine yes /no
19. Number of nozzles 1/2/3/4
21. Inside ⌀ of stuffing-box mms.
20. Diameter of the nozzle mm
23. Runner wheel ⌀ mms.
22. Lifting of needle mms.

A_T = Kpm je Turbine

24. Streaming-through turbine yes / no
25. Runner wheel diameter mms.
26. Width of the runner wheel mms.
27. Number of the chambers 1 / 2 / 3

A_T = Kpm je Turbine

28. Desired energy kpm

If this energy cannot be indicated, we determine it according to our experiences, however without guarantee.

A_R = Kpm

B Piping (enclose piping plan, if possible)

$c_s \sim$ m/s

$c_s \cdot L \sim$ m²/s

29. Length of suction pipe mms.
30. Diameter above , below , mms.
31. If the piping has different diameters, please indicate them, too, in the opposite table with the concerned lenghts. Instead of the diameters you can also indicate the surface if cross sections are irregular.

partial piece	lenght (m)	diameter (mm)	surface [m²]	c [m/s]	c·L [m²/s]
at the inflow					
at the turbine					
Total lenght		X	$\Sigma_D\ c \cdot L =$		

32. Mean diameter of the spiral housing mms.
33. Maximal water stream Qmax = m³/s, if the turbine alone is at work
34. Maximal water stream Qmax = m³/s, if all turbines joined to the pipes are running.

$T_{oL} = \frac{\Sigma\ c \cdot L}{g \cdot H} =$ s

$\bar{c} = \Sigma\ c\ L/\Sigma\ L =$ m/s

$\bar{a} \sim$ m/s

35. Material of the pipes: steel / cast iron / concrete / asbestos cement / synthetic material/wood

$T_L \sim \Sigma\ L/\bar{a} \sim$ s

36. wall thickness

partial piece	at the inflow			at the turbine
mms.				

$\rho = \frac{\bar{a} \cdot \bar{c}}{g \cdot H} =$

37. Which increase of pressure is admissible at the turbine after cutting off the full load?

△H / H = % △H = m column of water

If this increase cannot be indicated, we set in a corresponding value according to our experiences. In no case we hereby assume a guarantee for an admissible strain of the pipes.

$\zeta = \triangle H/H =$

$T_L / T_{ys} =$ $\varkappa =$

$T_{ys} =$ s

$T_{y\ddot{o}} =$ s

C Driven Machine, Task of governing.

38. The turbine drives a generator for direct current, alternating current, threephase current, transmission, sawmill, mill and

39. synchronous alternator / asynchronous alternator   40. Tension regulator yes / no

41. Parallel working / island working, factory network, local network

42. Parallel working with steam engine / turbine / motor continously / at times

43. Electric parallel working with super power station / works network continuously / at times

44. Which temporary speed variations are to be observed?

Alteration of load $\Delta N/N_o$	± 25%	± 50%	± 100%
Speed variation $\Delta n/n_o$	+ — %	+ — %	+ — %

45. Which offset (proportional band) do you want?

max. %, min. %

46. Existent flying masses: G → weight [kp] D → rim diameter [m]

n_o					r. p. m.
G					kp
D					m
GD²					kpm²

47. which shaft can admit additional flying masses?

Turbine n_o = r.p.m. | transmission gear n_o = r.p.m. | Generator n_o = r.p.m.

This column is filled in by us

T_{ys} = s $T_{yö}$ = s

x = $\Delta n/n_o$ %

erforderlich T_{aT} = s

T_{aL} = s X_p = %

erforderlich T_{aT} = s

Gleichwertsteuerung ja / nein

gewählt:

T_{aT} = s X_p = %

$n_{o,red}$ = U/min

$$GD^2 = \frac{10^6}{3{,}73} \cdot \frac{T_{aT} \cdot \max N}{n_o^2{}_{,red}} [Kpm^2]$$

GD^2_{red} = kpm²

vorhanden

GD^2_{red} = kpm²

zusätzlich anordnen

GD² = kpm² auf

der Welle n_o = U/min

D Erection, Accessories, Extent of Offer.

48. Speed of the shaft that drives the governor n = r. p. m.

49. Speed control in service ± 6% yes / no ± %

50. Speed control additionally by electromotor yes / no

51. Simple water level regulation by means of float and wire rope yes / no

52. Electric distant regulation of water level yes / no

53. Electric adjustment of opening yes / no

54. Quick-closing magnet yes / no   55. Speed indicator yes / no

56. Governor as water level governor with overspeed releasing device (turbine stop) only for asynchronous plants yes / no

57. Is a double governor required? yes / no

58. Is an air-chamber governor required? yes / no   59. Drawings attached:

Piping	Turbine	Building	Plant
No.	No.	No.	No.

Must drawings be returned? yes / no

60. Mounting Fig. No.   according to general sheet WTM 61

Filled in (date):	Signature	Bearbeitet am	Name

Note:

It is beside the point to use the above questionnaire for the specification of an electronic load controller. Generally speaking, the dynamic behaviour of the plant is less and electrical specification of the system are more important in the case of an electronic load controller. Typical questions arising are:

- type and make of the generator
- excitation system specifications
- specifications of the AVR (automatic voltage regulator)
- tripping points of safety devices (such as voltage level of undervoltage relays)
- details on anticipated consumer loads, especially the kind and the size of the largest single load (resistive, capacitive or inductive)
- possible uses for dissipated energy
- emergency shut-down system, if any.

We suggest to ask for a specific LC-questionnaire at the time of calling for offers.

5.4 Summary: Data for governor specification

TABLE 2: FULL GOVERNOR SPECIFICATIONS SUMMARIZED

Chapter 6: Governor suppliers

6.1 General remarks

In this chapter a few governor suppliers and their products are described. The few selected have been chosen for one or several reasons listed below:

- the authors know the company and their product due to their own working experience in the field of governing.
- the technical information supplied has been found comprehensive.
- the company addressed has shown a problem solving attitude and is believed to be cooperative.

However, no preference is to be given to the few described over those listed in paragraphs 6.3.4 and 6.4.6. Furthermore we would like to make it very clear that there are without any doubt many other governor manufacturers equally qualified not even listed in this publication.

At the risk of exposure by the choice made, we believe that this publication gains value for the user by briefly describing a few actual governors.

6.2 A few recommendations when dealing with governor suppliers

- Aim to establish a long standing relationship, try to establish personal contacts.
- Make sure someone speaks the language you understand.
- Do not give top priority to prices when comparing quotations.
- Provide as much information as possible to the supplier and do not hesitate to tell clearly what you do not know or do not understand.
- Request the supplier to quote for recommended spare parts as well.
- Ask about training possibilities for your operators.
- Insist on getting an instruction manual, preferrably in your own language.
- Make sure the supplier of the governor, the supplier of the turbine and the supplier of the control panel stay in contact with each other. Ideally you have a competent project manager coordinating them and carrying the overall responsibility.
- Allow the governor supplier to alter your specifications, in many cases more sensible and more economic solutions than stipulated in your tender document are possible.
- Request the supplier also to comment on your civil engineering structures. Certain modifications (for instance on your forebay design), may be necessary.
- Permit the chosen supplier to charge for consultancy, in almost all cases this is very well invested money.

6.3 Suppliers of electronic load controllers

6.3.1 G.P. Electronics

G.P. Electronics was founded 25 years ago. Developing ELC's was started in 1973 and many units are continuously running in 35 countries. In case of enquiries the person to be contacted is:

Mr. Gerry Pope
G.P. Electronics
Bovey Tracey
Devon TQ13 9DS, U.K.
Phone No.: U.K. 0626 83 26 70

G.P. Electronics have a rich experience and will certainly advise you on how to choose the appropriate alternator size, whether you shall choose a single or three phase system, on how to select a suitable ballast load, etc.

To give you an impression of the kind of hints you can expect from them see their notes on hydro systems using G.P. Electronic Load Controllers concerning the voltage regulator below:

Quote: "**Voltage regulators**:

The frequency of the hydro plant is controlled by the Load Controller and the voltage is controlled by the alternator's own voltage regulator. Nearly all of the problems associated with hydro electric plants are due to voltage regulators. There are many designs and variations but they can be split into two basic types, the STATIC type consisting of current transformers, chokes, diodes and resistors and the ELECTRONIC type. The static type is the most reliable and stable, the diodes being the only parts which usually ever break down. The voltage regulation is quite adequate for use with a Load Controller because there is always a constant load.

The ELECTRONIC type offers very good regulation but is less reliable. This type is nearly always fitted to brushless machines, they are usually designed to work with engine driven alternators where the load is subject to large changes and where good regulation is required. Consequently they need to be very sensitive. This high sensitivity can sometimes cause hunting in a load controlled hydro system. If hunting occurs look to see if the voltage is changing with the hunt, if the voltage is changing then it shows that the voltage regulator is not doing its job properly. If this is the case, try turning the "stability control" of the voltage regulator, this may stop the hunting, if not then the regulator is too sensitive. The sensitivity may be reduced by adding resistance in series with the output leads of the regulator where they enter the alternator - usually marked "X" and "XX". Connect a resistor of about 30 ohms 20 W or preferably a variable one (rheostat 0-100 ohms) in one of these leads and increase the resistance until the system is stable and the voltage is still correct at full load. Voltage regulators which are mounted inside the alternator should be removed and mounted in a separate box away from heat and vibration." (end of quote)

The G.P. Electronics ELCs are available in standard sizes, the units use phase controlled thyristors and are designed to run continuously under tropical and high altitude conditions.

As a sample, the data sheet and indicative prices are given for STAR Connected 380/415 V 3 Phase Electronic Load Controllers below:

<u>CONTROLLED VARIABLE</u>
Frequency (50 Hz or 60 Hz). With automatic phase balance.

<u>CONTROL METHOD</u>
Integral or proportional, using phase controlled thyristors.

<u>CHARACTERISTICS</u>
On sudden application or removal of full load (integral control).
Transient frequency deviation, better than 0.2 Hz.
Recovery time, better than 0,5 sec.
Constant frequency maintained for all input powers up to maximum.

<u>METERING</u>
One line voltmeter, one frequency meter, three alternator ammeters and three ballast voltmeters (analogue type).

<u>TERMINATIONS</u>
Alternator Input (4 wire), Main Load Out (4 wire), Ballast Load Out (4 wire). Bottom cable entry via gland plate.

<u>MAX. AMBIENT TEMPERATURE</u>
55 degrees centigrade, no altitude restriction.

<u>DIMENSIONS</u> (approx) all powers
800 mm high, 600 mm wide, 300 mm deep (steel enclosure).

<u>TRIPS & CONTACTOR</u> (optional)
Frequency trip, adjustable from 0 up to + or - 3Hz from set frequency. Contactor disconnects the main load only (not Ballast) when frequency goes outside set limits. Contactor must then be manually reset by push button on front panel. Stop push button on front panel opens contactor and disconnects main load. Two front panel lamps indicate status of frequency trip and contactor.

<u>POWER HANDLING</u>
Main Load: 4 wire, 220/240V line-neutral delta with PF better than 0.8.
Ballast load: 4 wire resistive.

ELC Power	Main Load upt to (max.)	Ballast Load upt to (max.)	Weight approx.	Terminals size	Current PF=0.8
21 kW	21 kW	24 kW	45 kg	M6 studs	38 Apms
30 kW	30 kW	35 kW	55 kg	M6 studs	57 Amps
60 kW F	60 kW	70 kW	65 kg	M6 studs	114 Amps
90 kW F	90 kW	105 kW	70 kg	M8 studs	171 Amps
150 kW F	150 kW	172 kW	90 kg	M10 studs	284 Amps

Units marked with F use fan cooled heat sinks

THREE PHASE STAR 389/414 VOLT 50 OR 60 HZ

DESCRIPTION			PRICES		
ELC POWER RATING	APPROX. WEIGHT (STAND.)	STEEL ENCLOSURE SIZE mm	COMPLETE STANDARD UNIT	LESS TRIP & CONTACT.	LESS TRIP METERS & CONTACT.
21 kW	45 kg	300x800x600	£ 1270	£ 1030	£ 850
30 kW	55 kg	300x800x600	£ 1533	£ 1263	£ 1063
60 kW	65 kg	300x800x600	£ 2294	£ 1974	£ 1775
90 kW	70 kg	300x800x600	£ 2877	£ 2537	£ 2337
150 kW	90 kg	300x800x600	£ 3390	£ 2950	£ 2750
225 kW and above			Details on application		

6.3.2 THES Small Hydro Controls

THOMSON AND HOWE ENERGY SYSTEMS INC. is a small company located in Kimberley B.C. Canada. T.H.E.S. has been dedicated to providing small hydro electronic control equipment for eleven years now. They concentrate on plants of capacity from 1kW to 5000kW, with an average size of about 70 kW. Their equipment is used on more than 350 hydro sites at the current time, and this number is currently increasing at the rate of almost 2 per week. About 30 % of their manufacturing output is now destined for 50 HZ applications, the rest for use at 60 Hz.

With some minor exceptions, all their equipment is based on micro-processor technology, but integrated into the equipment such that the equipment remains simple to understand, troubleshoot, or repair. For instance, most of their digital governors have all the logic built into one easily replaced plug-in module. T.H.E.S. designs and manufactures its own circuit boards to maintain highest reliability and ruggedness.

Their major product area currently is for hydro governors incorporating load control, where they have eight different product lines for use on systems as small as 12 kW, or as large as 5000 kW, with or without load management capability, with or without water management capability. List prices start at about $ 500.00 U.S. They are currently dominating the governor market in North America for hydro plant governors under about 300 kW.

Complimentary to their governing equipment, they also offer a complete line of custom built switchgear, heater tanks, and also load management equipment for small hydro systems. Load management equipment is often essential to prevent plant overloading, or to obtain maximum plant factor in order to improve return on investment.

They also have application specific control packages for synchronous and induction plants to be interconnected with utilities for co-generation purposes.

Their shipments during 1989 have included the following sites:

Sweden	70 kW	Vermont	10 kW
Wyoming	10kW	Montana	10 kW
Hawaii	20 kW	California	20 kW
Ohio	5 kW	Sweden	25 kW
Zaire	15 kW	California	10 kW
Marocco	100 kW	Bolivia	150 kW
Korea (2 x)	500 kW	Canada	25 kW
Mass.	100 kW	Canada	5 kW
Alaska (2 x)	500 kW	Chili (2 x)	5 kW
California	12 kW	Canada	300 kW
California	12 kW	Canada	12 kW
Ohio (2 x)	5 kW	Canada(4 x)	2 kW
Sweden	5 kW	Canada(2 x)	250 kW
Canada	15 kW		

Person to be contacted:

B. Thomson, F. Howe
THOMSON AND HOWE ENERGY SYSTEMS INC.
Site 17, Box 2, S.S. 1
Kimberley, British Columbia / CANADA
Phone: (604) 427-4326
Fax: (604) 427-7723 or (604) 427-4326

LOAD CONTROLLERS

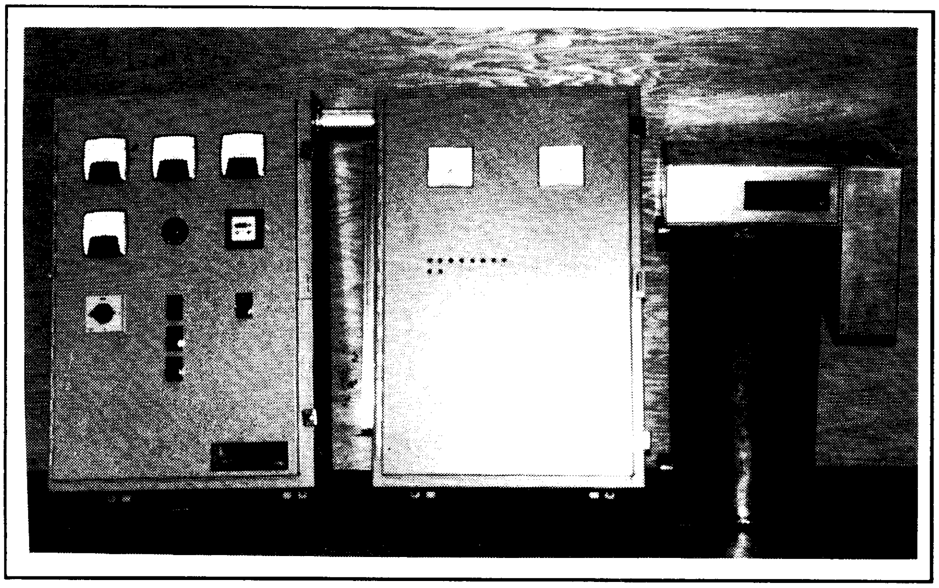


Figure 55: Complete wallmount switch-gear, governor and one surplus load tank for plants from 50 to 150 kW.

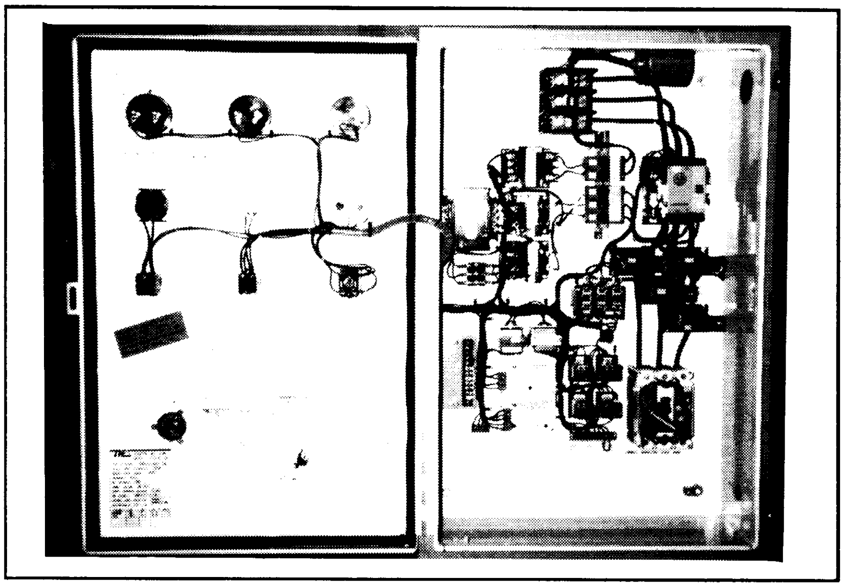


Figure 56: Switchgear cabinet typical of what is supplied for hydro plants of 50 to 150 kW . Includes generator/turbine protection, voltage regulation, metering.

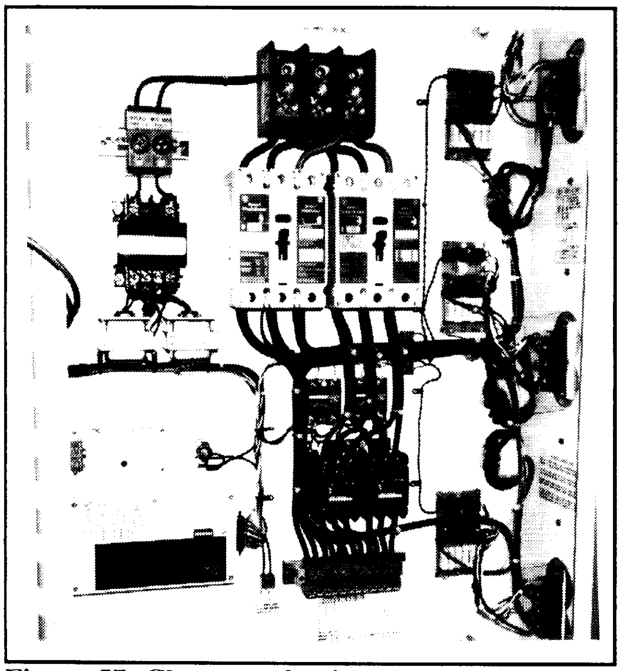


Figure 57: Close-up of switchgear

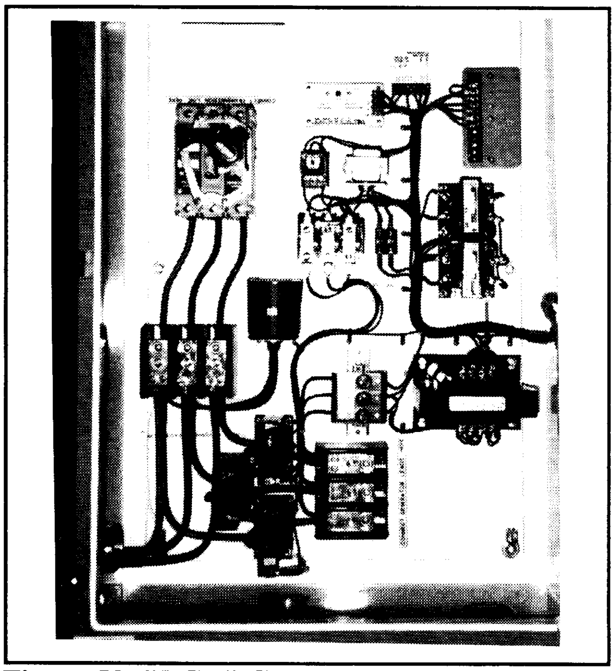


Figure 58: "LCX" Governor capable of up to 120 kW of load control at 400 Volts 3 phase.

6.3.3 IREM

IREM is an industry which has been active in the electromechanical and electronic sector for 40 years.

Their ECOWATT Electronic Regulators are of modular construction and at present the maximum adjustable power of any element is equal to 2 or 10 kW. Hence, the number of necessary regulators depends on the plant capacity and the kind of electricity distribution (single / three phase 220 V or three phase 380 V).

Each electronic regulator has 15 regulation steps of 133 W or 666 W respectively. Therefore the regulation curve is a ''broken'' one (refer to figure 59 below) but can of course be approximated by a straight line. In case of a higher number of regulation steps this approximation becomes even more accurate.

As the reaction time is very short - the regulator goes from 0 to 100 % of the regulated power in about150 milliseconds - the incorporation of a fly-wheel on the turbine/generator side is unnecessary, furthermore the recovery time is independent from the number of regulators installed.

Each electronic regulator is set, during tests, at a normal operation threshold of +/- 5 % of the nominal voltage and frequency (which corresponds to +/- 11 V and +/- 2,5 Hz). In case of specific requirements this threshold can be increased or decreased. The regulators are protected against overvoltage and radio frequency interference, they must be grounded.

The person to be contacted in case of enquiries:

Mr. Alberto Bonini
IREM SPA - SEDE / Head Quarters
Via Vaie 42
I-10050 S. Antonino / ITALY
Phone: (011) 96 49 133
Telex: 212134
Fax: (011) 96 49 933

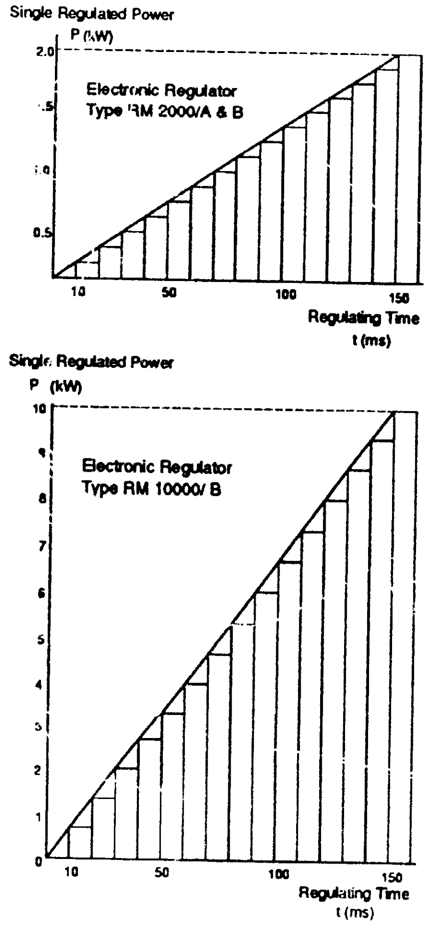


FIGURE 59 : Caracteristic curve of ECOWATT electronic regulators

6.3.4 List of further suppliers of load controller

Mr. N. Smith
Dept of Electrical Engineering
Trent Polytechnic
NOTTINGHAM U.K.

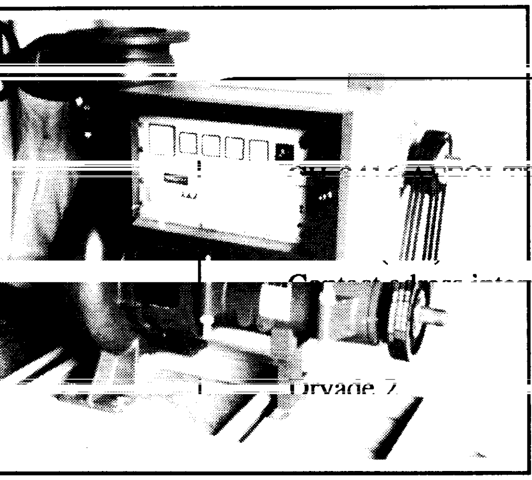
Würtenberger & Haas
H.P. Roth
Bannwaldallee 44-46
D-7500 KARLSRUHE / Germany
Phone: (0721) 55 10 22 or 55 10 23
Telex: 7826 823
Fax: (0721) 55 71 54

ITDG
Railway Terrace
RUGBY CV 213HT, United Kingdom
Phone: (0788) 60631
Fax: (0788) 540 270

Hydro Power, V. Schnitzer
D - 6901 BAMMENTAL
Germany

GUGLER Gesellschaft m.b.H. & CO KG
A - 4085 NIEDERRANNA 41, Austria
Fax: (07285) 62 42
Telex: 116 540

H. Kobel
Elektro-Apparatebau
CH-3416 AFFOLTERN i.E.
Switzerland
Phone: (034) 75 14 13
Contact adress international:
J.M. Chapallaz
Dryade 2
CH-1450 STE.CROIX, Switzerland



" by V. Schnitzer, mounted on gen-set.

6.4. Suppliers of mechanical speed control governors

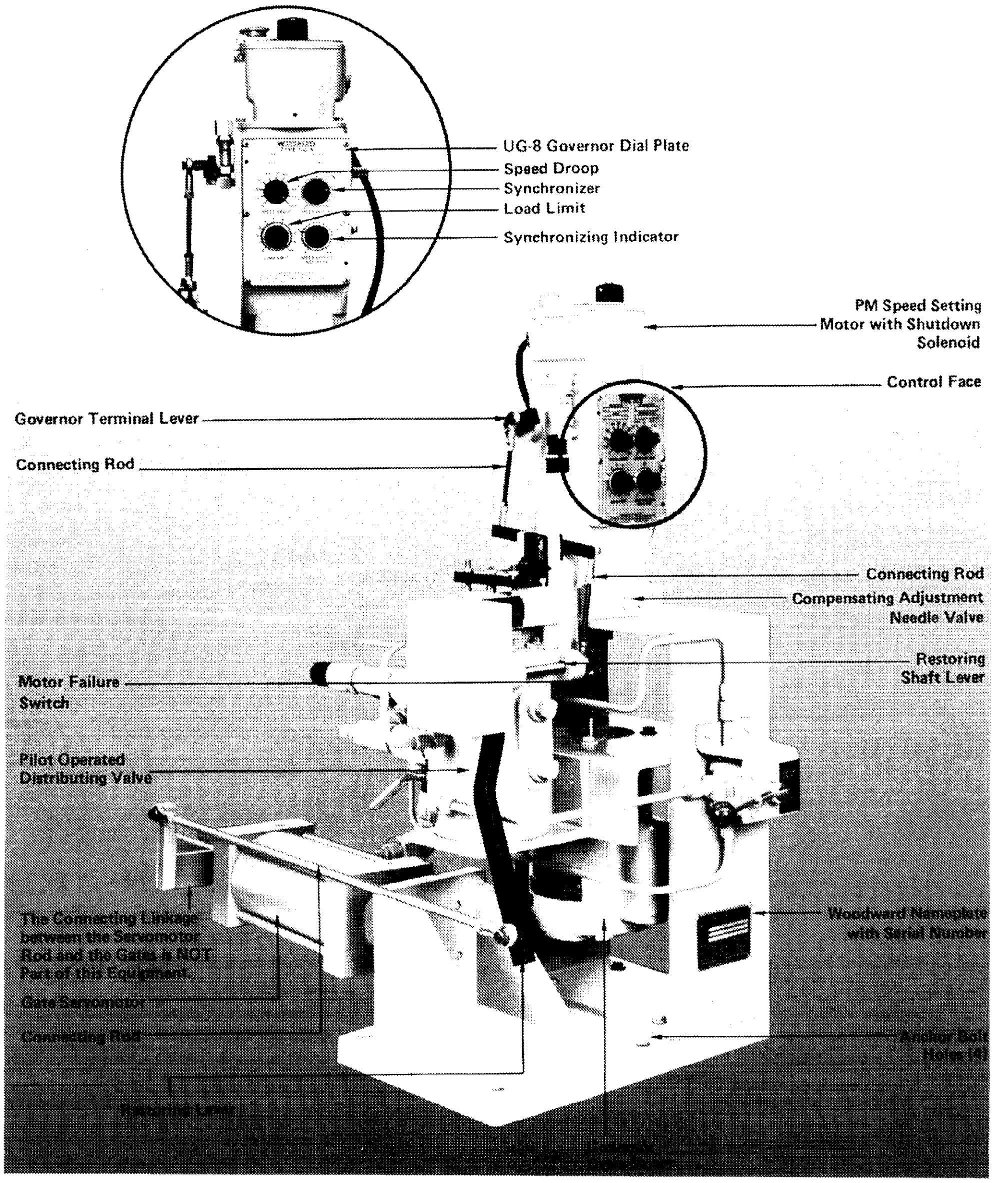
6.4.1 WOODWARD governor GmbH

Woodward produces for Mini and Micro Hydro the UG-HT or the MC control, offering a hydro-mechanical or digital governor. If the whole package is economically not possible, the customer can select components which can be advantageously locally produced.

Absolutely outstanding is the technical documentation of the Woodward products and one example of this is reprinted in detail in annex A6 with the kind permission of WOODWARD. It describes the operation of the UG 8 governor in minute detail. In case of problems related to governing, Woodward has proven in countless cases to be a competent partner. The Woodward quality assurance reflects a total commitment of providing their customers and all users of their equipment with the highest quality products and field support.

Person to be contacted:

Mr. R. van Heuvelen
WOODWARD GOVERNOR GmbH
P.O.Box 34
2130 AA Hoofdorp
The Netherlands
Phone: (02503) - 1 32 41
Telex: 74508
Fax: (02503) - 3 65 29



6.4.2 E F G

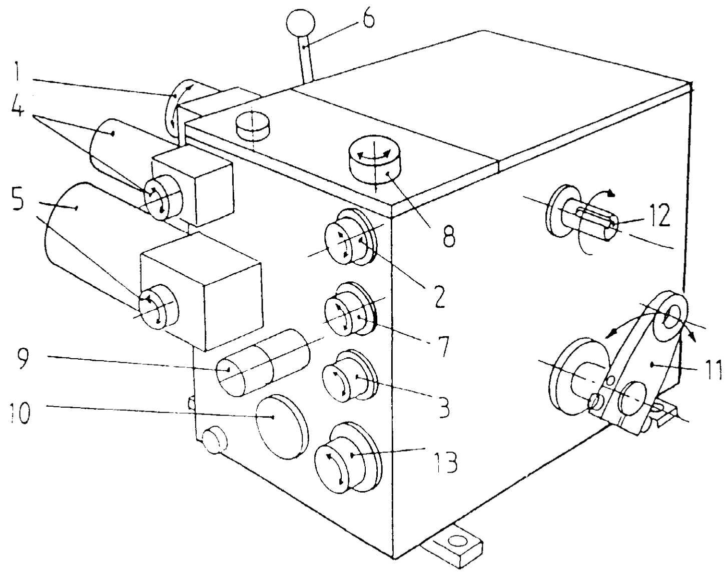
EFG have an interesting background. A number of power plant owners felt that sometimes they were more experienced to solve encountered problems in running, maintaining and uprating their power stations than specialised companies. They further made the experience that it can be very economical to join hands among each other, finally they established their own company, the present EFG P (Ltd). Beside their broad practical experience they have excellent design capabilities and an innovative attitude when solving problems. Further, their helping attitude when dealing with less experienced customers is to be mentioned.

In case of enquiries the person to be contacted is:

Prof. B. Buchelt
EFG Energieforschungs- und Entwicklungs-
GmbH & Co. KG.
Untere Tiebelgasse 16
A-9560 FELDKIRCHEN / AUSTRIA
Phone:04276 4670
Telex:422 896 butta-a
Fax: 04276 46703

The information on page 62 is an excerpt from their sales literature. (An interesting capability of EFG not mentioned in their sales literature is to repair and recondition old oil-hydraulic governors of virtually any type.

Low-cost versatile PID governor for closing times from 0.1 seconds (Pelton) upto 30 seconds (Cross Flow or Francis turbines), and with a maximum work capacity of 1000 Nm.



1) I-scale adjustment possible during operation either manually or with an optional remote control electric motor
2) Manual P-scale (speed droop) adjustment possible during operation
3) D-scale adjustment (compensation) possible during operation
4) Synchronization of speed either manually or with an optional electric motor
5) Manual, or optionally by a remotely controlled electric motor, black start feature
6) Optional starting pump
7) Oil pressure adjustment
8) Adjustment of compensation leverage ratio possible during operation
9) Adjustment of servo-valve stroke
10) Adjustment of closing spring pre-tension
11) Governor operating lever (on both sides of the housing)
12) Governor drive shaft [0.3 kW (on both sides of the housing)] sense of rotation must be specified when placing the order
13) Adjustment of the servo motor stroke

Figure 61: Relatively simple full-scope governor suitable for local production

THE EFG GOVERNOR PROGRAM

EFG R 2 Precise and fast governor for the actuation of the jet deflector of Pelton turbines. Closing time 0.15 s at strokes of 150 mm and acting forces up to 2000 N. The high reaction speed of this governor enables operations without flywheels in many cases.

EFG R 3A Precise and fast governor for the actuation of jet deflectors of Pelton turbines but using an intermediate amplifier between a Woodward UG 8 governor and an EFG amplifier which brings in additional features to those of the Woodward UG 8. Closing time below 0,5 s at 120 mm stroke and actuating forces up to 5000 N.

EFG R 3B Precise governor for fast and slow regulations suitable for Francis- and Crossflow Turbines. It consists of a Woodward UG 8 governor and an EFG amplifier. The closing time ranges between 2 s and 20 s. It is stepless adjustable during turbine operation. The power output stroke is 120 mm max. and the max. actuating force is 12 kN.

EFG R 3 C Precise governor for the regulation of the guide vanes and the counterdependent regulation of the runner vanes of Kaplan turbines. Data similar to those of the R-3B.

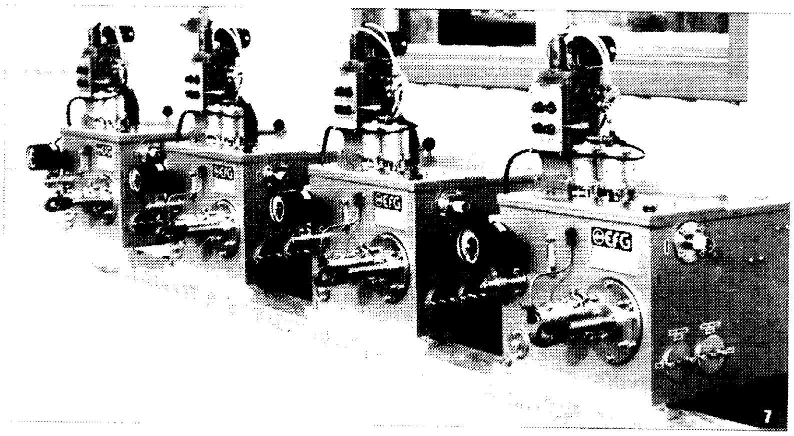
General about EFG governors.

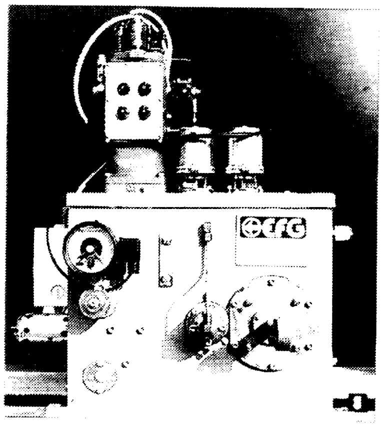
All EFG governors are suitable for network and island operation, have a highly developed accuracy in maintaining the required turbine speed and have a redundancy of shut off safety. EFG governors are modern examples of the hydraulic mechanical principle, designed in a new compact manner. EFG governors might be handled either manually or fully remotely controlled by means of up to four electric motors mounted on to the housing (R-3B). The optional electronic supplementation is kept in the background and might be integrated in the overall electric panel of the power station. The electronic control unit (EC) can be delivered by EFG too. The spear valve regulation of EFG Pelton turbines happens by means of electro-mechanical units, modell 'auma' of the Riester KG company in Germany. The top water level controls the position.

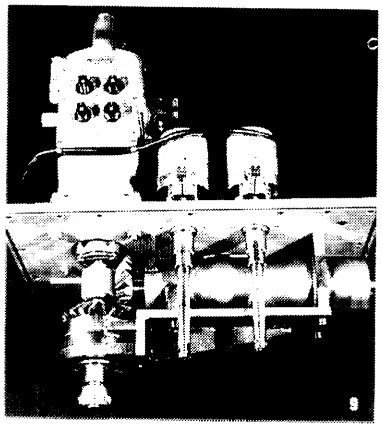
All EFG R-3 models use a **Woodward UG 8** governor as the heart-piece combined with an EFG amplifier which brings in additional features to those of the UG 8. It should be mentioned, that Woodward not only produces big size water turbine governors but is also the worldwide leading company in the field of aircraft gas turbine governors. Woodward has also a well organized worldwide service network.

EFG R-3 governors have the following features:

- Adjustable speed droop (UG 8)
- Adjustable load limitation, important for island operation (UG 8) Three shut off possibilities on the UG 8 for various reasons (overspeed, bearing over temperature etc.) and one emergency shut down switch on the EFG amplifier, all switches servicable manually or automatically.







- Stepless adjustment of the oil pressure (output force).
- Stepless adjustment of the compensation during turbine operation.
- Stepless variation of the actuation velocity during turbine operation.
- The velocities are adjustable differently into the closing direction and into the opening direction.
- Adjustable stroke range of the hydraulic servomotor
- Electric motor driven auxiliary oil pump (beside the turbine driven main oil pump) for automatic black starts and as a third oil pump a manually actuated oil pump for manual starts.
- Optional pressurized oil connections for hydraulically actuated main penstock valves.
- Electric indication of governor amplifier oil pressure and oil level (optional feature).

Fig. 7
Governors EFG R-3B - ready for export to Malaysia. The R-3 is suitable for automatic network and island operation.

Fig. 8
Governor EFG R-3B
All parameters are adjustable during turbine operation.
These governors have a redundancy of shut off safety.

Fig. 9
Governor EFG R-3B with Woodward UG 8 Subassembly:
Bevel gear-switch motors

Geschäftsführer
Manager of Business
Ing. Günther Eder
Ing. Armin Buttazoni

Konstruktion/Design
Dipl.-Ing. Benno Buchelt
EFG-Konstruktionsburo
Design Office
10-Oktober-Straße 14
A-9560 Feldkirchen/Austria
Tel. 04276/4670

EFG-Buro Wien/Vienna Office
Univ.-Prof. Dr. W. Lengyel
Jacquingasse 13
A-1030 Wien/Austria
Tel. 0222/833280
Telex 112009 bile-a

6.4.3 Geppert

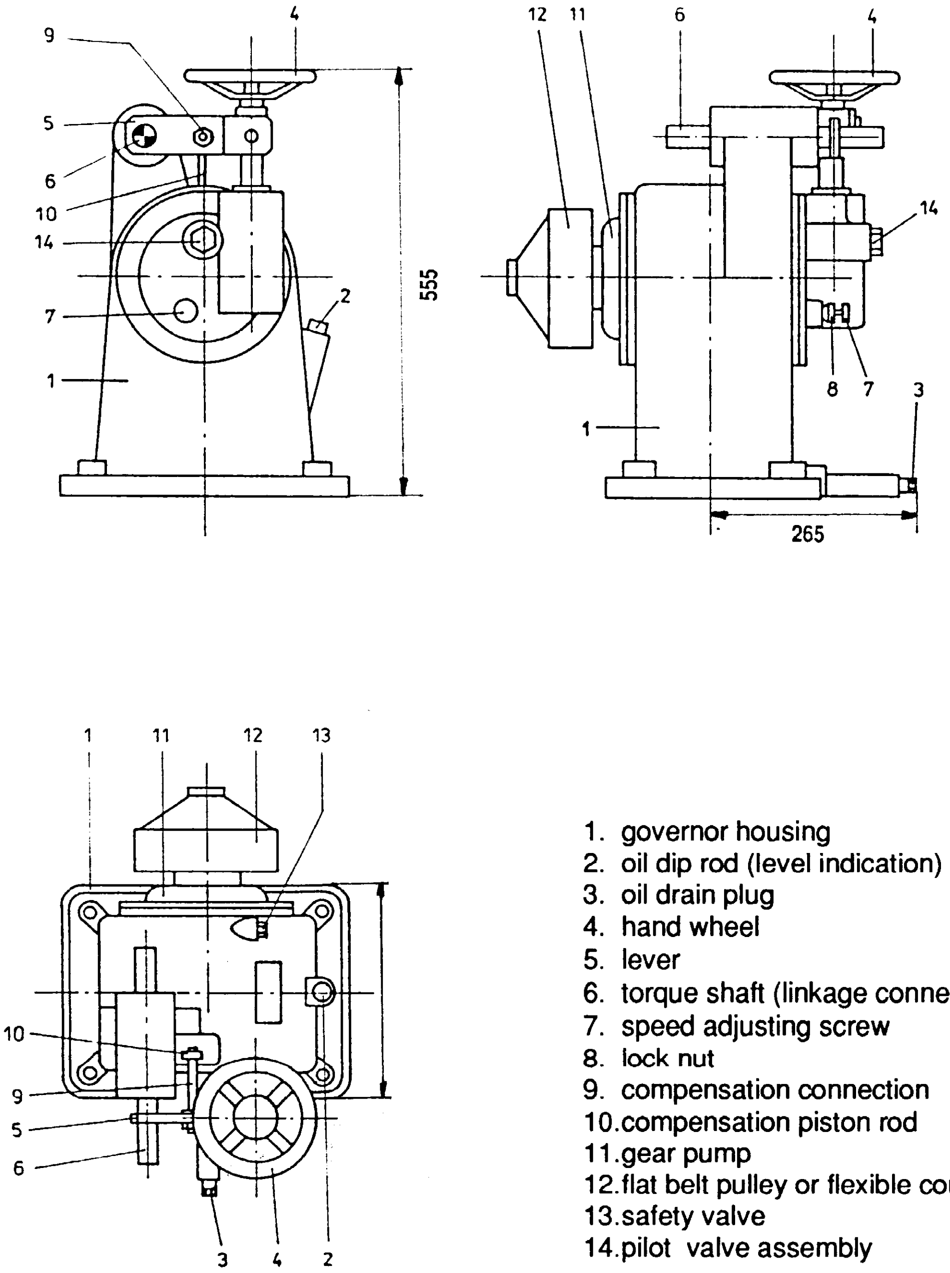
Geppert Company was established in 1896. Already in the early days they produced Francis turbines. Today Francis and Pelton turbines as well as oilhydraulic governors are their well established products. Nearly 2000 mechanical turbine governors have been produced.

The governors suitable for micro hydro plants produced by Geppert are the two models R2/70 and R2/100. The two models are basically identical, whereas the model R2/70 has a servomotor capacity of 200 Nm and the R2/100 a capacity of 400 Nm.

The price for the governor type R2/70 is in the range of US$ 6000.-, the type R2/100 costs about US$ 6300.- ex factory. The weight of the governor (without oil) is approx. 90 kg.

The person to be contacted in case of enquiries:

Mr. Josef Geppert
Breitweg 8 - 10
6060 Hall in Tirol
Austria



1. governor housing
2. oil dip rod (level indication)
3. oil drain plug
4. hand wheel
5. lever
6. torque shaft (linkage connection)
7. speed adjusting screw
8. lock nut
9. compensation connection
10. compensation piston rod
11. gear pump
12. flat belt pulley or flexible coupling
13. safety valve
14. pilot valve assembly

Figure 62: Schematics of GEPPERT governors R2/70 & R2/100

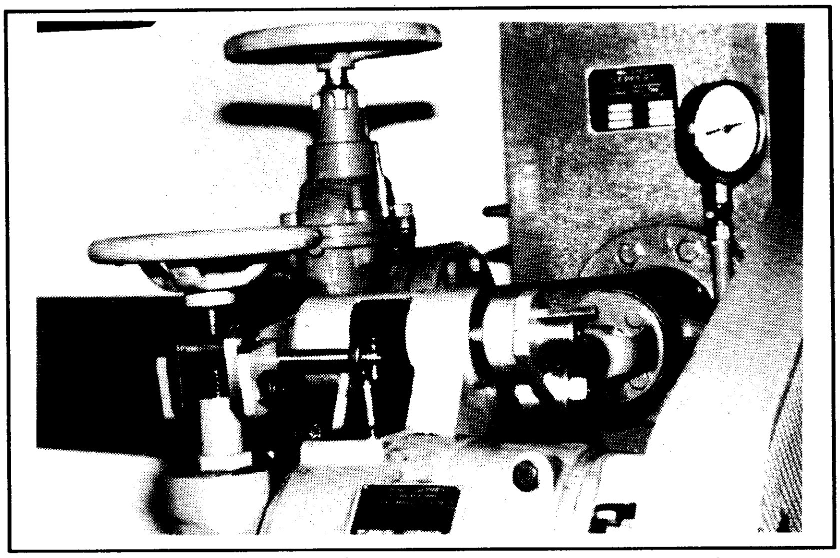


Figure 63: GEPPERT R2/70 mounted on a Pelton turbine

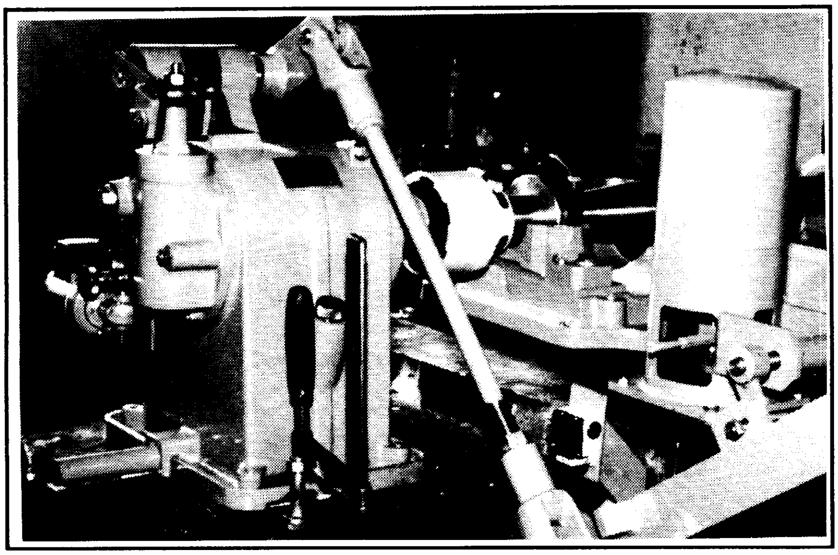


Figure 64: GEPPERT governor on the test bed

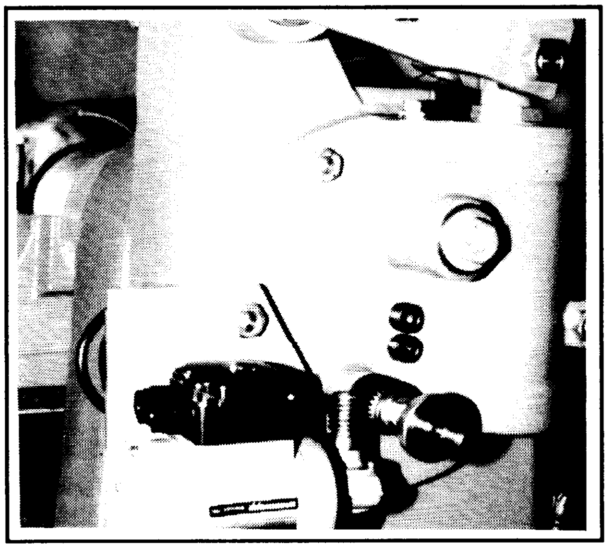


Figure 65: Electric speed setting motor with worm drive

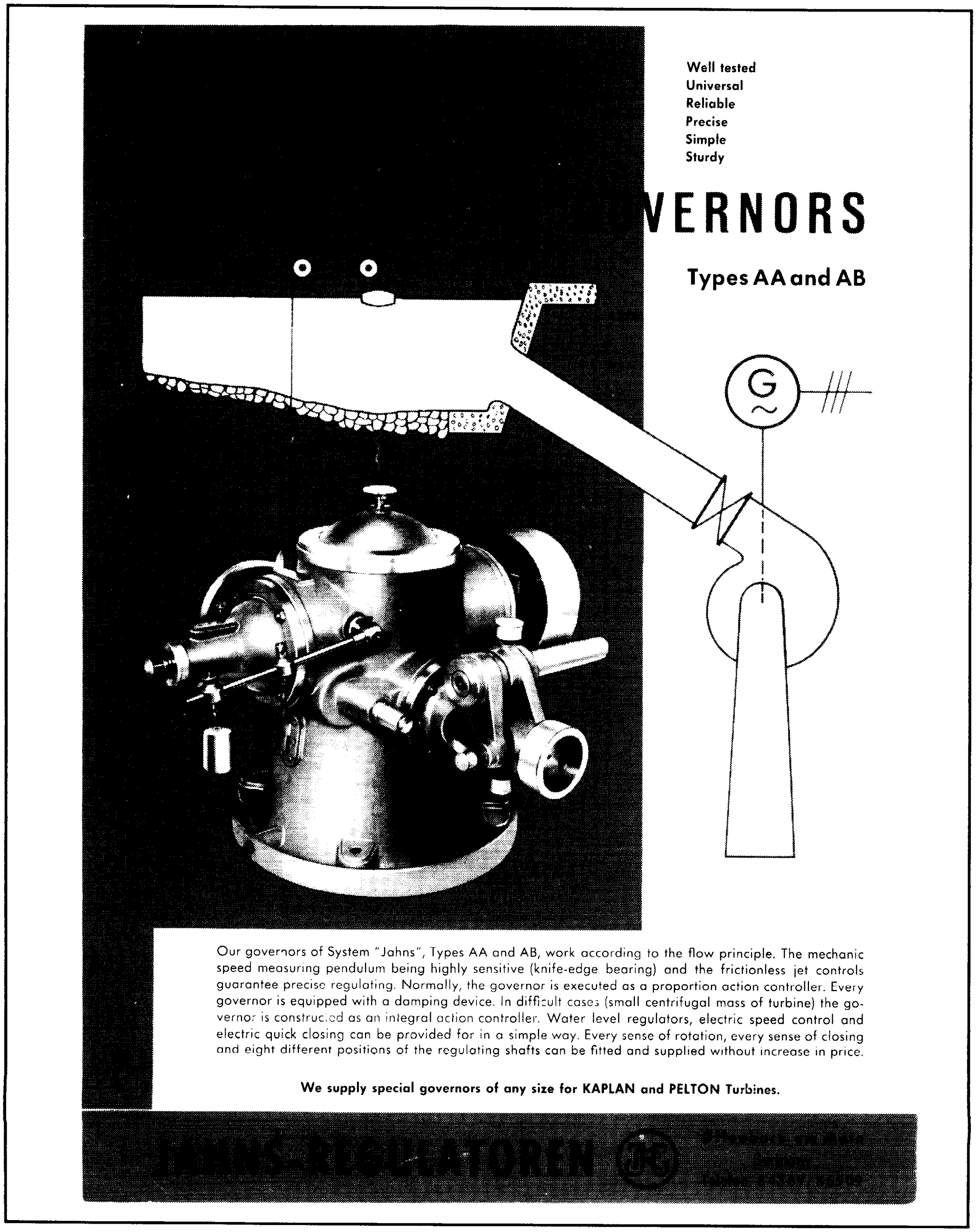
Photos by: U. Meier

6.4.4 Jahns

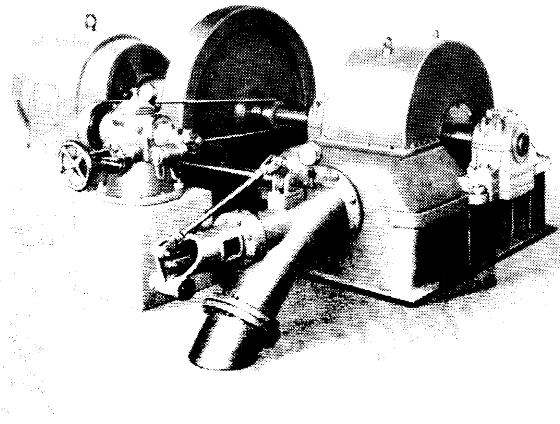
Jahns Company is an old reputed governor manufacturer, further details are given from the excerpt of their sales literature.

The person to be contacted in case of enquiries:

Mr. K. Johannes
Jahns-Regulatoren GmbH
Spendlinger Landstrasse 150
6050 Offenbach / M., Germany
phone: (069) 83 10 87 or 83 10 86
telex: 4152778, fax: (069) 83 70 59



Since 1920 our governors have been experienced a thousand times. Whether it be a Pelton, a Francis or a Kaplan Turbine, shaft construction or spiral casing, vertical or horizontal turbine shaft, the "Jahns" Governor can always be adapted easily to the kind and construction of the turbine. We are quite disposed to submit you a proposal for mounting. Please write to us. Your plant will become modern and economic with the aid of "Jahns" Governors.

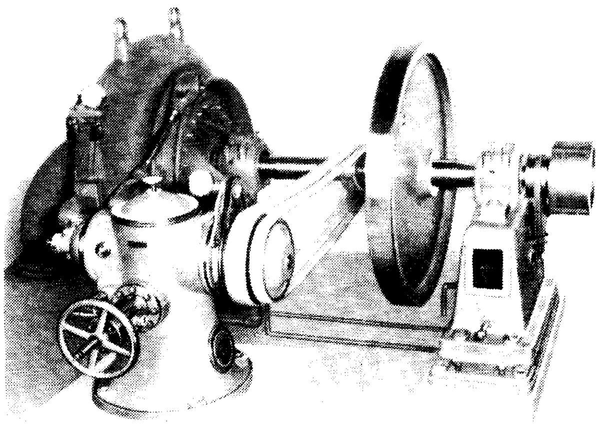


Governor AA 3, energy 64 kpm with electric setpoint adjustment, regulates a free jet turbine.

H = 221 m Q = 148 l/s
N = 280 kW n 1200 r.p.m.

Workshop picture

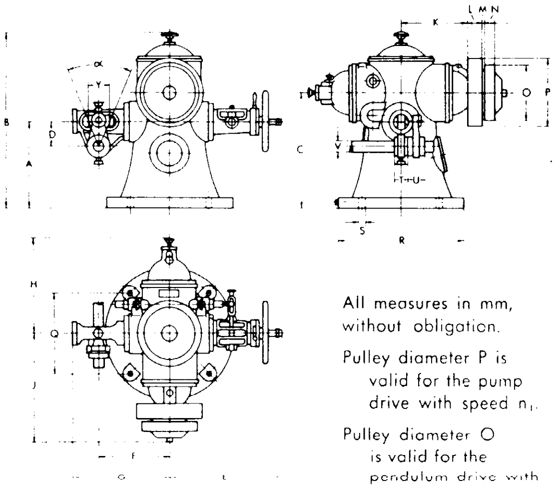
Little attendance, reliable action and precise frequency of the water turbines are guaranteed by the inexpensive "JAHNS" Governors in small and large plants. For calculating the data of the governors we need, apart from the details as to the turbines, the measures of the pipes (as far as they are existent). Please write for a query-sheet. Our experiences will help you in obtaining a plant that is economic and works in a satisfactory manner.



Governor AB 4 - energy 125 kpm - regulates a Francis Turbine.

H 50,7 m Q 1000 l/s
N 410 kW n 1200 r.p.m.

Workshop picture



All measures in mm, without obligation.

Pulley diameter P is valid for the pump drive with speed n_1.

Pulley diameter O is valid for the pendulum drive with speed n_2.

The governors are supplied according to our Figures 106 to 153. Please write for a special leaflet. The governors from AA 1 to AB 4 can be executed also without regulating lever. (See special leaflet).

No. [kpm]	AA 1 16	AA 2 32	AA 3 64	AB 4 125	AB 5 250	AB 6 500
A	175	200	265	455	510	560
B	410	480	575	900	1010	1130
C	250	290	365	600	675	745
D	75	90	101	125	165	200
E_{max}	380	435	535	640	750	1060
F	215	245	300	365	445	525
G	295	335	405	500	625	740
H	310	325	410	490	575	625
J	300	330	395	545	655	690
K	200	220	280	350	390	430
L	55	70	85	80	100	120
M	—	—	—	10	10	10
N	—	—	—	50	55	60
O	—	—		320	390	450
P	180	220	250	385	425	500
Q	210	243	300	405	465	528
R	350	400	500	650	750	850
S	18	18	18	27	28	35
T	40	45	55	70	95	130
U	50	55	60	90	120	150
V	30	35	40	60	80	100
α°	45°	45°	45°	45°	45°	45°
Y	60	68	80	100	125	160

6.4.5 VOLK

Volk is a manufacturer of turbines and governors with great experience in micro hydro. He has delivered several complete installations to Third World countries. Volk has developed its own mechanical governor with relative high working capacity for isolated, flow controlled installations. This governor is of reliable and solid construction, designed for operation under rough conditions. The adjustment range of the parameters are the following:

- permanent speed droop: b_p = 1 - 6 %
- transient speed droop: b_t = 10 - 50 %
- T_n, T_c, T_o adjustable to specified values
- working capacity A = 500 up to 3000 Nm

The governor is equipped with a closing spring and closes automatically if the oil pressure is failing. It may be equipped with remote control of speed and opening limitation.

The price is in the range of DM 28'000 up to DM 50'000 (Jan. 1990). For small working capacities Volk recommends governors manufactured by Jahns.

Person to be contacted:

Manfred Volk
Wasserkraft Volk GmbH
Turbinenfabrik und Ingenieurbüro
Gefäll 45,
D-7809 Simonswald / Germany
Phone: (07683) 844
Fax: (07683) 805
Telex: 772668 iraim d

6.4.6 List of further suppliers
(for mechanical and electro-mechanical speed control governors)

DISAG
Dieselmotoren AG
CH - 7320 SARGANS, Switzerland
Phone: (085) 2 21 81)
Fax: (085) 2 78 34
Telex: 855 597

OSSBERGER
Turbinenfabrik GmbH & Co.
Otto-Rieder-Str. 7
D - 8832 WEISSENBURG, Germany
Phone: (091) 41 40 91
Fax: (091) 417 05 22
Telex: 624 672

F. HEINZMANN GmbH & Co.
Staufenstr.18
D- 7321 ALBERSHAUSEN, Germany
Phone: (07161) 3 2091
Fax: (07161) 3 4074

KOESSLER GmbH
A - 3151 ST: GEORGEN, Austria
Phone: (02746) 8272
Fax: (02746) 2626
Telex: 015 652

BIWATER HYDROPOWER
Millers Road
Warwick, CV34 5AN / United Kingdom
Phone: (0926) 411740
Fax: (0926) 410740
Telex: 317473 BWaterG

H. Kobel
Elektro-Apparatebau
CH-3416 AFFOLTERN i.E.
Switzerland
Phone: (034) 75 14 13
Contact adress international:
J.M. Chapallaz
Microhydro Engineering
Dryade 2
CH-1450 STE.CROIX, Switzerland
Phone: (024) 61 10 42

Würtenberger & Haas
H.P. Roth
Bannwaldallee 44-46
D-7500 KARLSRUHE / Germany
Phone: (0721) 55 10 22 or 55 10 23
telex: 7826 823
fax: (0721) 55 71 54

Annex

Technical Notes and Definitions

General:

In the theory of regulation relative values are commonly used. With the example of the speed the advantage is clearly seen. The relative speed deviation x is the same value never mind whether we determine it from the turbine, generator speed or from the frequency of the produced electricity (mechanical and electrical slip neglected).

Some of the following definitions are in accordance with IEC 308 (guideline for governing hydraulic turbines) and IEC 41 (field acceptance tests of hydraulic turbines).

A1. Parameters of the governor

Speed	n	rev/min
	ω	rad/s

The speed of rotation n of turbine

{A-1.1} $$\omega = \frac{\pi}{30} \cdot n$$

Nominal speed / guarantee speed	n_N or n_r	rev/min
	ω_N or ω_r	rad/s

The speed for which the turbine is ordered

{A-1.2} $$\omega_N = \frac{\pi}{30} \cdot n_N$$

Speed deviation	Δn	[rev/min]

At a considered instant, the difference between the actual speed of rotation and a reference speed (e.g. the nominal speed)

{A-1.3} $$\Delta n = n - n_N$$

Relative speed deviation	x	-

Speed related to the nominal speed

{A-1.4} $$x = \frac{\Delta n}{n_N} = \frac{\Delta \omega}{\omega_N} = \frac{\Delta f}{f_N}$$

Slip	s	-

Relative deviation of the turbine-generator speed n from the synchronous speed n_s

{A-1.5}

$$s = \frac{n_s - n}{n_s}$$

Frequency	f	Hz

Frequency of the electric voltage: in a MHP equipped with a synchronous generator it is proportional to the generator speed.

{A-1.6}

$$f = \frac{p}{60} n$$

with p = number of generator pole pairs.

Relative load / guide vane opening / distributor position	y	-

The relative position of the guide vane y is the position of the guidevane (distributor) Y related to the rated guide vane position Y_r. If the guide vane position is proportional, the output P is equal to the relative load P/P_r

{A-1.7}

$$y = \frac{Y}{Y_r} \mathrel{\hat{=}} \frac{P}{P_r}$$

Maximum stroke speed droop	b_s	100%
Permanent speed droop	b_p	100%

The permanent speed droop b_p is the slope of the speed droop/load (or guide vane opening)-graph at a specific point of steady operation.

{A-1.8}

$$b_p = -\frac{dx}{dy}$$

The turbine output is related to the guide vane position y. A flow controlling governor with permanent speed droop adjusts the guide vane. Y however is proportional to the actual speed x. Therefore, such a governor will show approximately an output proportional speed. A change of load from no load to nominal load will cause a droop of speed of approximately b_s•100%.
b_s is the maximum stroke speed droop which under ideal conditions is equal to the permanent speed droop b_p.

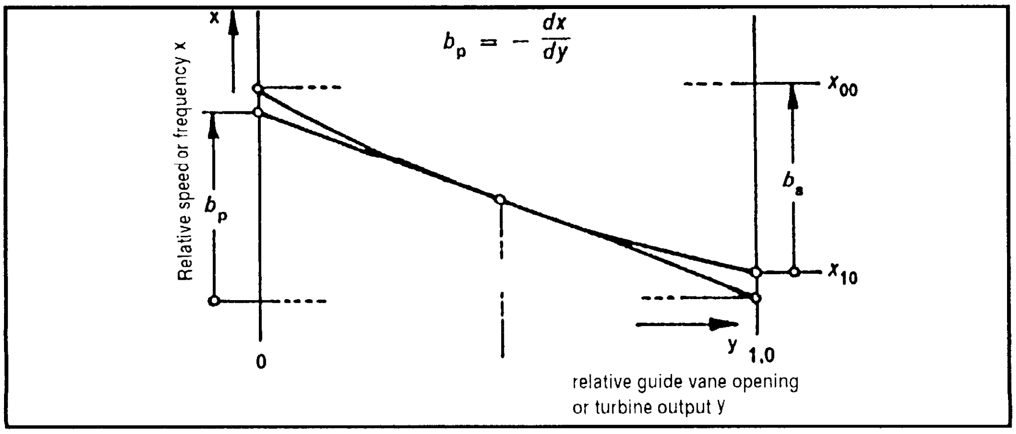


Figure A1: Permanent speed droop in the output/speed graph (static operation)

Temporary speed droop	b_t	100%

The temporary speed droop b_t is the slope of the speed droop graph at a specific point of steady operation if the permanent speed droop is inactive. This would occur if the damping device is blocked. Blocking the damping device transforms the governor into a P-governor with permanent speed droop (see figure 42 - 44).

$$b_t = -\frac{dx}{dy} \qquad \text{\{A-1.9\}}$$

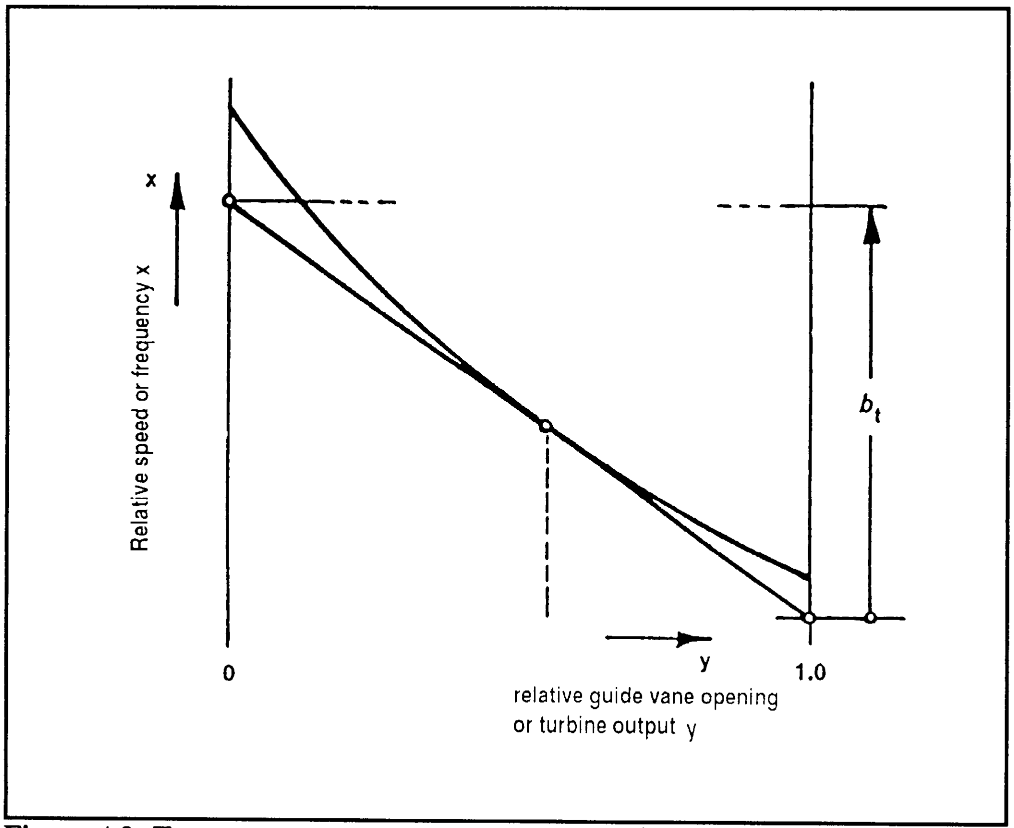


Figure A2: Temporary speed droop in the output/speed graph (damping device blocked)

Amplification	$\frac{1}{b_p}$	-

This is another definition for the speed droop and expresses more obviously the fact, that the relative speed deviation is more or less amplified to operate the control device Y. A small permanent speed droop needs a high amplification of the speed deviation.

$$K_p = \frac{1}{b_p} \qquad \text{\{A-1.10\}}$$

Time constant of damping device	T_d	s

A time constant which describes the delay of the feedback signal from servomotor position, caused by the damping device.

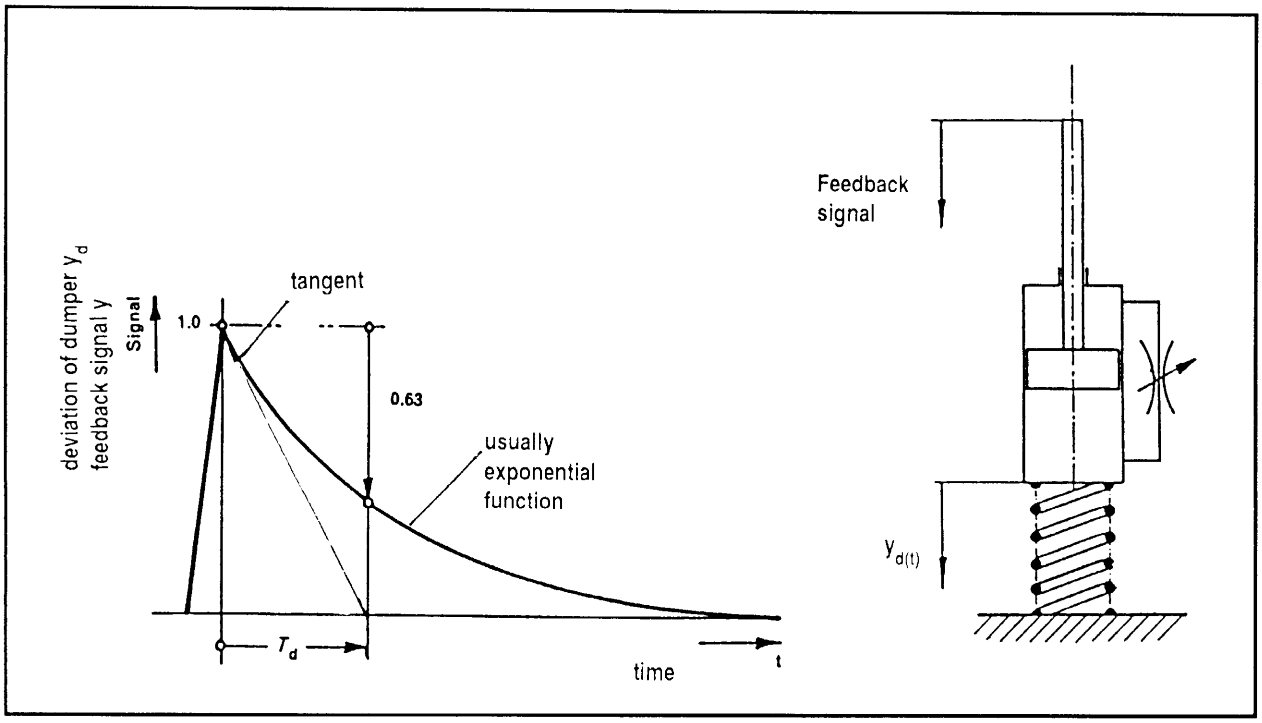
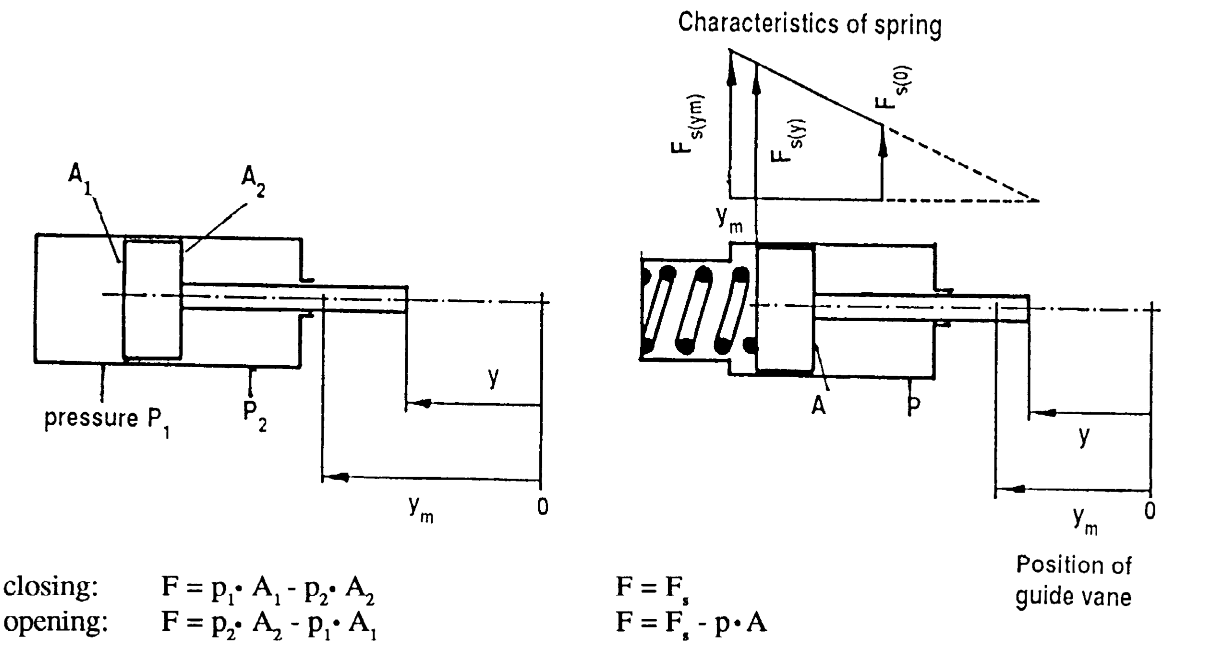


Figure A3: Time constant of damping device in the time deviation diagram of the damping device

Energy capacity of the governor	A	Nm

The energy capacity is the product of the nominal force F of the servo-motor and its nominal stroke y_r.

{A-1.11} $$A = F \cdot y_r$$



closing: $F = p_1 \cdot A_1 - p_2 \cdot A_2$
opening: $F = p_2 \cdot A_2 - p_1 \cdot A_1$

$F = F_s$
$F = F_s - p \cdot A$

DIFFERENTIAL HYDRAULIC CYLINDER   SIMPLE CYLINDER WITH CLOSING SPRING

Figure A4: Energy capacity of the governor

Attention:

- Too high servomotor cross section or too high oil pressure produce big forces. All elements of the guide vane must be dimensioned to stand these forces.

- In the case of a guide vane ring acting on a number of vanes, excessive load may occur if one vane is blocked mechanically. It may be neccessary to protect the mechanism from damage by means of design measures (weak component that may slide or even break).

Servomotor force	F	Nm

The net opening and/or closing force generated by the servomotor when supplied with oil at a minimum specified pressure p.

For spring operated servomotors it is the net force exerted by the servomotor when the spring is at its maximum extended position.

Minimum servomotor closing time	T_f	s

The elapsed time for one closing servomotor stroke at maximum closing velocity.

Minimum servomotor opening time	T_g	s

The elapsed time for one opening servomotor stroke at maximum opening velocity.

Cushioning time	T_h	s

The elapsed time during which the rate of servomotor travel is retarded beginning at a specific servomotor position to the closed position. The use of this method is to reduce the water-hammer and at the same time to avoid high speed rises in plants with a long penstock.

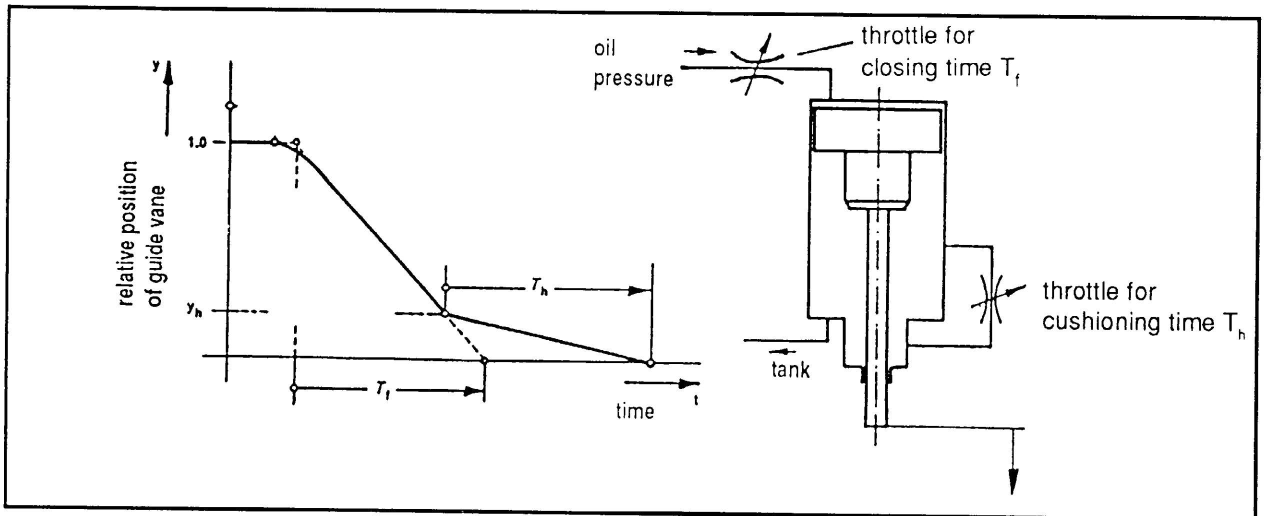


Figure A5: Time / speed graph of the servomotor

Speed dead band	i_x	-

The maximum band i_x between two values of the relative speed x within which governing action does not occur. The command signal is assumed constant. One half of the speed dead band $i_x/2$ is termed the speed insensitivity.

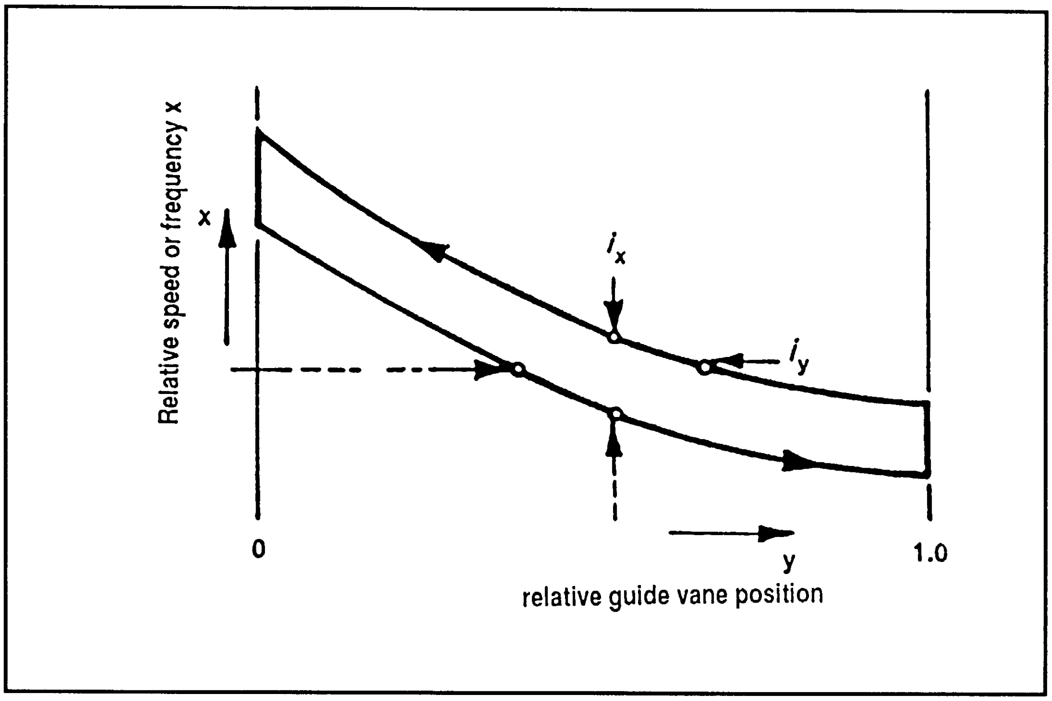


Figure A6: Dead band and inaccuracy of the governor

Governor inaccuracy	i_y	-

Maximum variation between the extreme relative position of the servomotor for a constant speed and a fixed command signal for a specified speed droop.

A 2. The hydraulic system

Acceleration time of the water masses	T_w	s

The inertia of the water in the pipe is expressed with the acceleration time of the water masses T_w. This is the fictitious time which is necessary to accelerate the water column in the penstock to nominal velocity v_r under nominal head .

{A-2.1}

$$T_w = \frac{Q_r}{g H_r} \sum^{i} \frac{L_i}{A_{di}}$$

where

Guarantee discharge, rated discharge	Q_r	m^3/s
Guarantee head, rated head	H_r	m
Cross section of penstock section	A_d	m^2

$A_d = \pi/4 \; D_i^2$; where D_i = internal penstock diameter of section

Example A2.1: Calculation of acceleration time of water masses for a Pelton turbine scheme as shown in figure A7:

Pelton turbine installation:

Nominal Head: $H_r = 44$ m
Nominal Flow: $Q_r = 28$ l/s
Length of penstock: $L = 210$m
Internal diameter $D_i = 0.2$ m
Area of penstock : $A_d = 0.031$ m²
$g = 9.81$m/s²

$$T_w = \frac{0.028}{9.81 \cdot 44} \cdot \frac{210}{0.031} = 0.43 \text{ s}$$

⇨ Acceleration time of water: $T_w = 0.43$ s

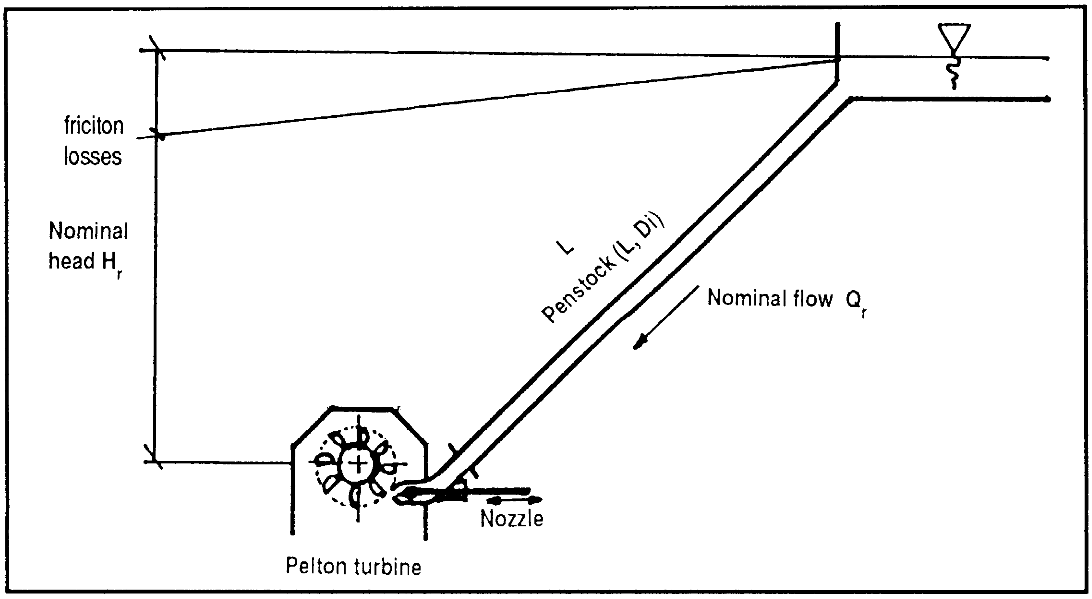


Figure A7: Pelton turbine scheme

Reflection time of pressure waves	T_r	s

The reflection time T_r is the time needed for a pressure wave along the penstock and back. This means the wave has to travel with the wave propagation speed two lengths of the penstock.

{A-2.2}
$$T_r = 2 \sum^{i} \frac{L_i}{a_i}$$

Length of penstock section	L	m

If the penstock is not uniform over its total length, each section must be described separately (dimensions, material, nominal pressure)

Velocity of wave propagation	a	m/s

The wave propagation speed in a closed conduit depends mainly on two values. These are the compressibility of the fluid and the elasticity of the conduit.

{A-2.3}
$$a = \frac{1}{\sqrt{\rho \left(\frac{1}{e_w} + \frac{D_i}{e_p\, e} \right)}}$$

where : ρ = specific mass of fluid, ρ water = 1000 kg/m^3
e = wall thickness of pipe [m]
D = internal diameter of pipe [m]
e_p = Young modulus of pipe material
e_p steel = 2.1 10^{11} N/m^2
e_p cast iron = 1.2 to 1.7 10^{11} N/m^2
e_p plastic = 0.1 to 1.1 10^9 N/m^2

e_w = Young modulus of fluid , e_w water = 2 10^9 N/m^2

Example A2.2: Calculation of the reflection time of pressure waves T_r for a pump scheme as shown in figure A8:
As the pressure pipe of the pump scheme consists of a lower section made of cast iron with an internal diameter D_i = 86mm and an upper section made of PE plastic pipe with an internal diameter D_i = 55mm the velocity of the wave propagation must be calculated section wise.
Data for the *upper section* (Index 1):

L_1 = 360 m
D_{i1} = 0.05 m
e_1 = 0.01 m
e_{p1} = 1.1 10^9 N/m^2
e_w = 2 10^9 N/m^2
ρ_w = 1000 kg/m^3

wave propagation velocity a_1

$$a_1 = \frac{1}{\sqrt{1000\left(\frac{1}{2\ 10^9} + \frac{0.055}{1.1\ 10^9\ 0.01}\right)}} = 426 \text{ m/s}$$

Data for the *lower section* (Index 2):

L_2 = 1880 m
D_{i2} = 0.086 m
e_2 = 0.006 m
e_{p2} = 1.5 10^{11} N/m^2
e_w = 2 10^9 N/m^2
ρ_w = 1000 kg/m^3

wave propagation velocity a_2

$$a_2 = \frac{1}{\sqrt{1000\left(\frac{1}{2\ 10^9} + \frac{0.086}{1.5\ 10^{11}\ 0.006}\right)}} = 1296 \text{ m/s}$$

Calculation of the reflection time of pressure waves T_r

$$T_{r1} \text{ (upper section)} = 2\frac{L_1}{a_1} = 2\ \frac{360}{426} = 1.7 \text{ s}$$

$$T_{r2} \text{ (lower section)} = 2\frac{L_2}{a_2} = 2\ \frac{1880}{1296} = 2.9 \text{ s}$$

$$T_r = 2\ \sum^{i} \frac{L_i}{a_i} = T_{r1} + T_{r2} = 1.7 + 2.9\ = 4.6 \text{ s}$$

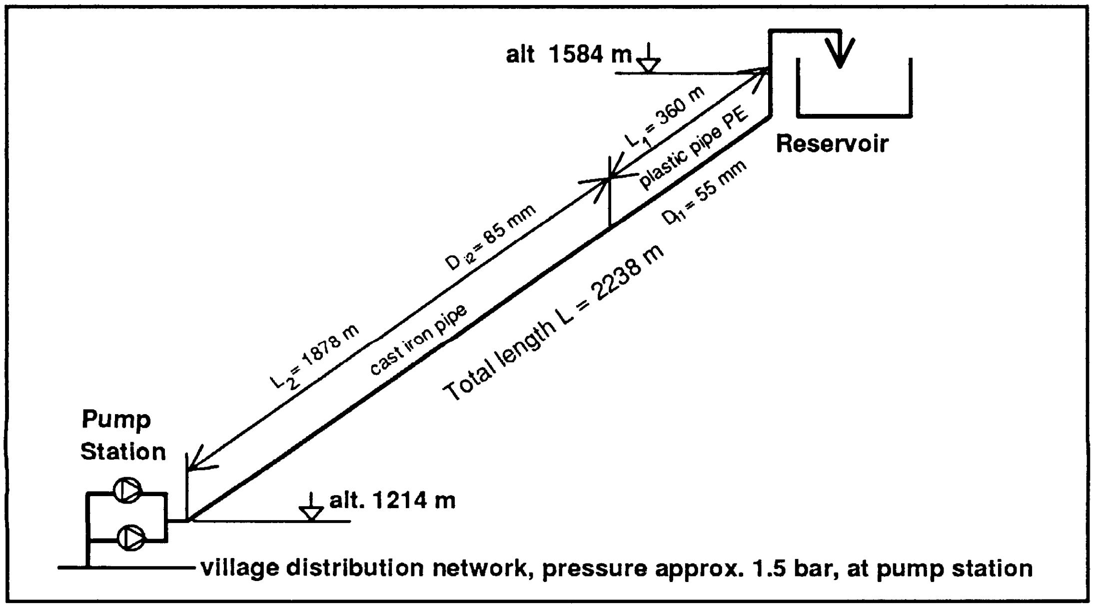


Figure A8: Pumping scheme

Allievi constant (penstock parameter)	h_w or ρ	-

The Allievi constant (water-hammer number) is the ratio of water inertia time T_w to penstock reflection time T_r under specified conditions.

{A-2.4}

$$h_w = \frac{T_w}{T_r} = \frac{a\,Q_r}{2\,g\,H_r\,A_d}$$

Relative shutdown time (valve operation parameter)	t_f or θ	-

This is a parameter needed for the determination of the water-hammer with the Allievi method. It is the total closing time of the valve / guide vane related to the travel time of a pressure wave from one penstock end to the other (T_r /2).
Linear closing characteristic:

{A-2.5}

$$t_f = \frac{T_f}{T_r} = \frac{T_f}{2\,\Sigma\,\frac{L}{a}}$$

Non-linear closing characteristic:
The Allievi method is based on a linear closing law for the valve flow. In practice this characteristic is not linear but may be approximated in the following way to estimate the maximum possible water-hammer (see Figure A9).

{A-2.6}

$$t_f = \frac{T_{f\&}}{T_r} = \frac{T_{f\&}}{2\,\Sigma\,\frac{L}{a}}$$

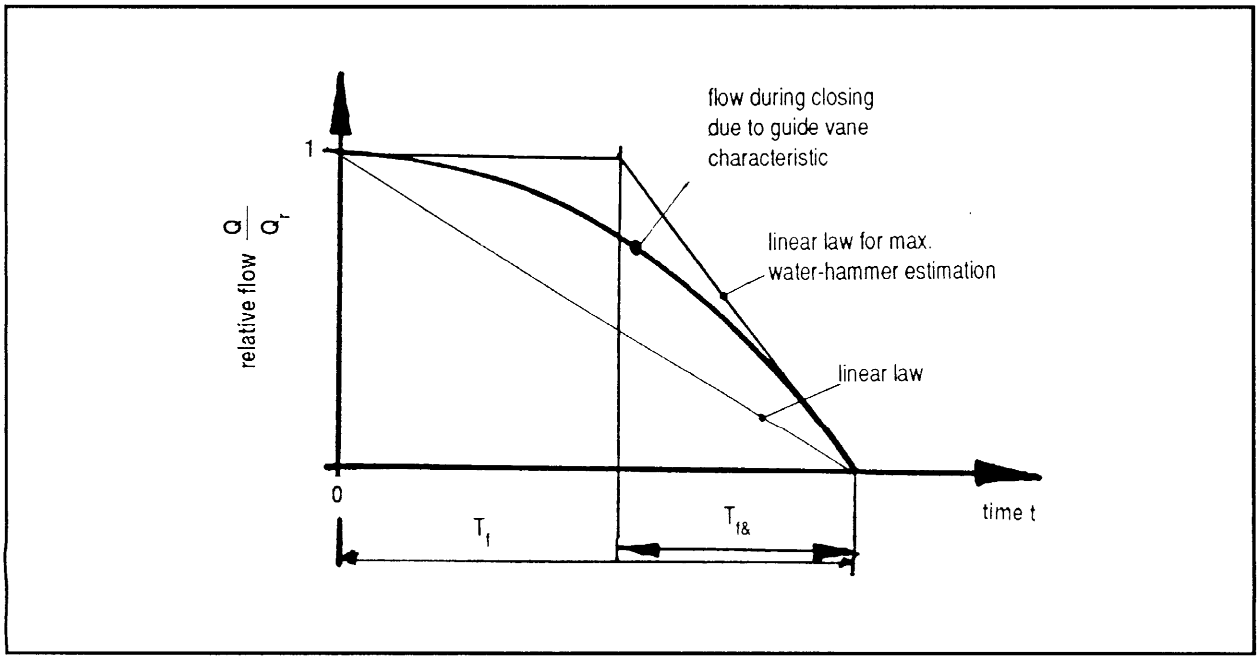


Figure A 9: Approximating a non-linear closing characteristic

Non-dimensional transient head factor	Z^2	-

Using the previously defined values and the Allievi diagram one can find the non-dimensional transient head factor and the corresponding transient pressure H_{max} is calculated.

$$Z^2 = \frac{H_{max}}{H_r} \quad \text{\{A-2.7\}}$$

In this method, the influence of friction losses is neglected. In penstocks with high friction losses they can be added to the maximum head H_{max} for a safe estimate.
For more details it is recommended to refer to the literature and especially to chapter 2.2.9 in the HYDRAULICS ENGINEERING MANUAL of SKAT [3.8] and the SKAT-working paper WATER-HAMMER PROBLEMS IN SPECIFIC SHUT-DOWN SITUATIONS [3.9].

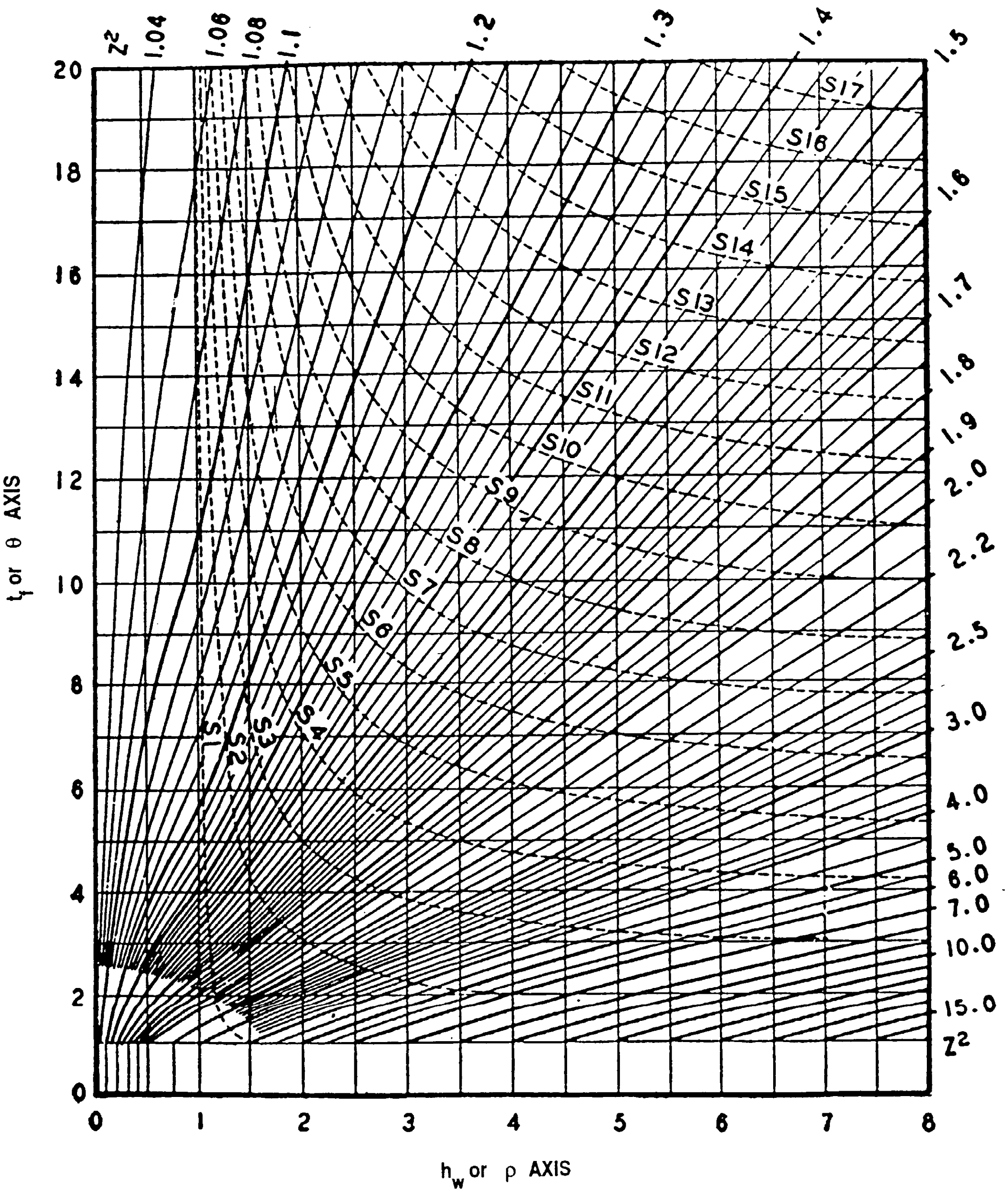


Figure A10: Allievi Chart for linear shutdown of a penstock (friction neglected)

A3. Dynamics of the turbine/generator/consumer system

Unit acceleration time turbine/generator	T_a	s

T_a is the time which is necessary to accelerate the turbine/generator set from zero to nominal speed if the nominal torque is acting (inertia of turbine, flywheel and generator).

{A-3.1}

$$T_a = \frac{I\,\omega_N}{M_r} = \frac{I\,\omega_N^2}{P_r \cdot 1000}$$

where

Moment of inertia	I	kgm^2
Rated torque at turbine	M_r	Nm
Rated output of turbine	P_r	kW

The moment of inertia determines the torque needed to accelerate a mass around a rotating axis. This value may be given from manufacturers of generators, motors, flywheel and other rotating parts of the plant. If not, it may be calculated approximately using the formula for a full disk:

{A-3.2}

$$I = \frac{1}{2}\, m \cdot r^2$$

where: m = mass of disk = $\rho\, \pi\, b\, r^2$ in kg
r = radius of disk in m
ρ = specific mass of disk material in kg/m^3

Sometimes the moment of inertia is given as :

$GD^2 = 4\,I$ in kgm^2

where: G = rotating mass in kg
D = Diameter of inertia. This is the diameter where the mass may be theoretically concentrated to have the same inertia effect.

If different rotating parts are situated on axes with different speeds , they must be transformed to the same reference axis and are to be added. We use the following relation:

{A-3.3}

$$\frac{I\,\omega^2}{2} = \text{kinetic energy} = \text{const.}$$

To calculate the unit accelleration time of a given arrangement the following steps are neccessary:

1. Step: Choose reference axis -> normally generator axis
2. Step: Calculate or ask inertia of all rotating components
3. Step: Calculate inertia referred to same reference axis and sum them up.

4. Step: Determine torque acting on reference axis and nominal speed of the axis
5. Step: Calculate T_a
6. Step: If T_a is too small for the application in question the needed inertia and size of an additional flywheel have to be calculated, and are then added to the system.

Example: Calculating the unit acceleration time T_a of a Pelton Turbine arrangement:

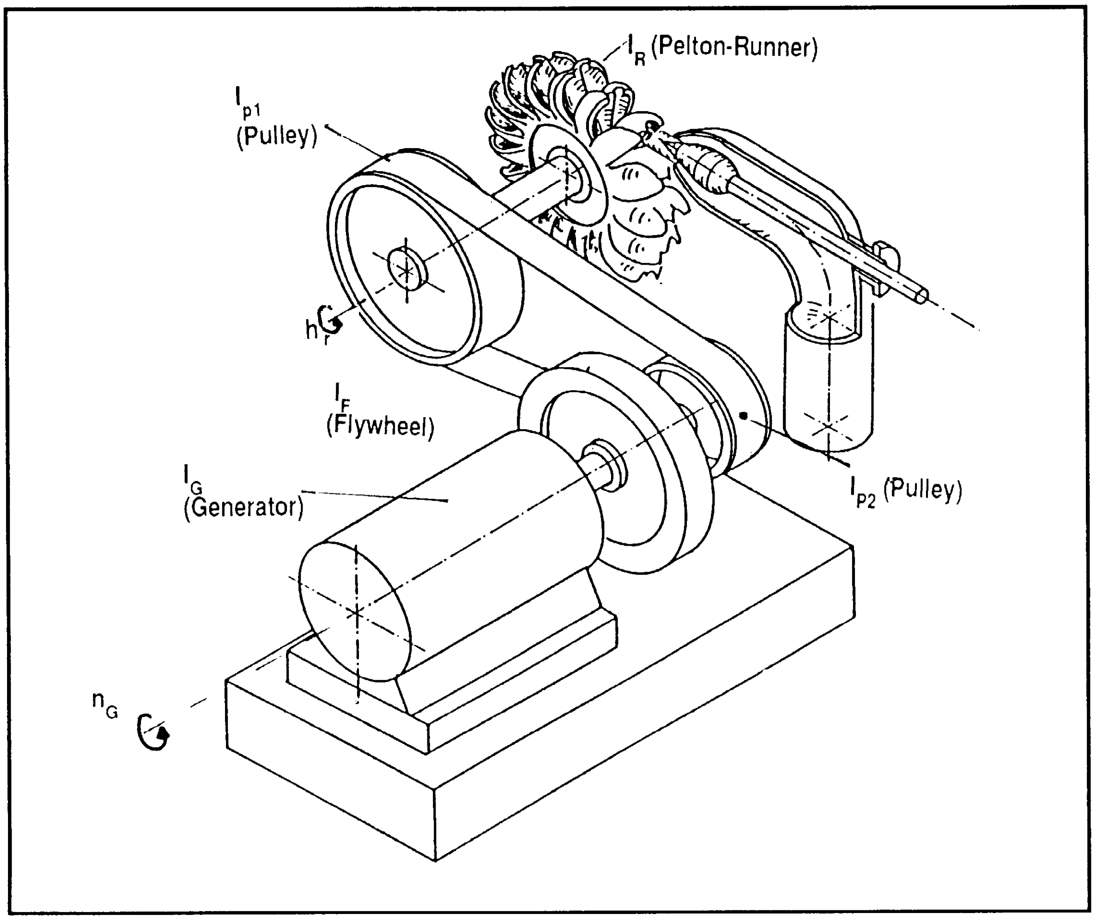


Figure A13: Pelton turbine arrangement

Data and calculation:

Pelton turbine output

Nominal Head: $H_r = 44$ m

Nominal Flow: $Q_r = 28$ l/s $= 0.028$ m^3/s

Nominal efficiency of turbine $\eta_t = 0.8$

Nominal efficiency of pulley transmission $\eta_p = 0.98$

--> nominal output at generator shaft :

$$P_{gen} = \eta_t\ \eta_p\ \rho\ g\ H_r\ Q_r = 9.5\ \text{kW}$$

--> nominal torque at generator shaft :

$$M_{gen} = 30 / \pi / n_{gN}\ P_{gr} = 60.5\ \text{Nm}$$

Turbine shaft

Nominal Speed $n_{tN} = 544$ 1/min

Pelton runner $I_r = 3.8$ kgm^2 (manufacturer data)

Pulley $I_{p1} = 10$ kgm^2 (manufacturer data)

---->Turbine shaft total $I_{nt} = 13.8$ kgm^2
(related to turbine shaft $I_{ntg} = 1.81$ kgm^2)

Generator shaft

Nominal Speed n_{gN} = 1500 1/min
Generator I_g = 1.5 kg m^2 (from manufacturer)
Pulley I_{p2} = 0.6 kg m^2 (from manufacturer)
Flywheel I_f = 5.6 kg m^2 (calculated)

----> Generator shaft total I_{ng} = 7.7 kg m^2

The calculated inertias for the turbine- and generator shaft can not be added without considering the fact, that they rotate with different speed:

----> Turbine/generator total (related to generator shaft)

{A-3.3a}
$$I = I_{ng} + I_{nt} \left(\frac{n_{tN}}{n_{gN}}\right)^2$$

I = 9.4 kg m^2

----> Acceleration time of Turbine/generator/flywheel set

$$T_a = \frac{\pi\, n_{gN}\, I}{30\, M_{gen.}} = 24.7 \text{ s}$$

(without flywheel T_a = 10.1 s)

Calculation of the Flywheel:
The flywheel is divided into disk (cylinder) elements:

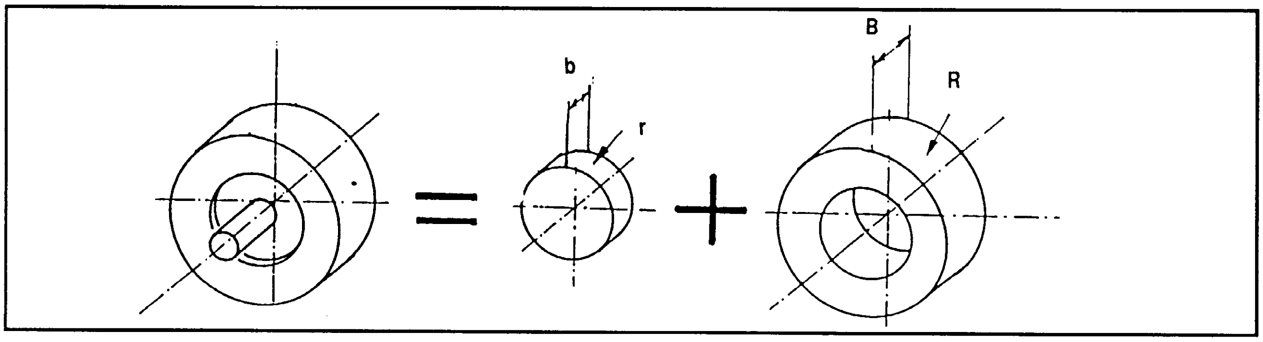


Figure A14: Elements for calculating the inertia of a flywheel

Disk:

external radius r = 0.24 m
width b = 0.025 m

{A-3.4}
$$m_d = \rho_m\, \pi\, r^2\, b$$ = 35.3 kg

{A-3.5}
$$I_d = \frac{1}{2} \cdot m_d \cdot r^2$$ = 1.02 kgm^2

Cylinder:

external radius $R = 0.29$ m
internal radius $r = 0.24$ m
width $B = 0.10$ m

{A-3.6}
$$m_c = \rho_m \pi B (R^2 - r^2)$$
$= 65$ kg

{A-3.7}
$$I_c = \frac{1}{2} \cdot m_c (R^2 - r^2)$$
$= 4.6$ kg m^2

Total flywheel:

--> $m_f = m_d + m_c$ $= 100$ kg
--> $If = I_d + I_c$ $= 5.6$ kg m^2

Load acceleration time constant	T_b	s

The inertia of consumers like motors may be difficult to estimate and is usually neglected. They have, however, a positive influence on the stability of governing. It may be expressed with the load acceleration constant T_b.
The load acceleration T_b is the time which is necessary to accelerate the rotating masses of the consumers from zero to nominal speed if the equivalent nominal torque is acting.

The acceleration time of the unit and the load may be measured as described in IEC 308.

Maximum speed rise of turbine generator set	n_{max}	%

The maximum speed rise occurs after full load rejection. It depends on the acceleration time constant of the turbine generator set and the characteristic of the hydraulic system. Depending on the turbine type, this transient process of closing down the turbine will also produce a water-hammer effect. Therefore an accurate determination of the maximum speed rise is complex. However we want to give some simplified methods to calculate this important value using different mathematical models of the system.

Case 1:
Speed rise after a full load rejection of an idealized, not governed Pelton Turbine:

Assumptions:

- flow of turbine is independent from speed (no water-hammer)
- run-away speed $= 2\ n_r$
- no guide vane or jet deflector activated
- linear torque-speed characteristic
- torque law of turbine accelerating the turbine if load decreases to zero:

{A-3.8}
$$M(\omega) = \left(2 - \frac{\omega}{\omega_N}\right) \cdot M_r$$

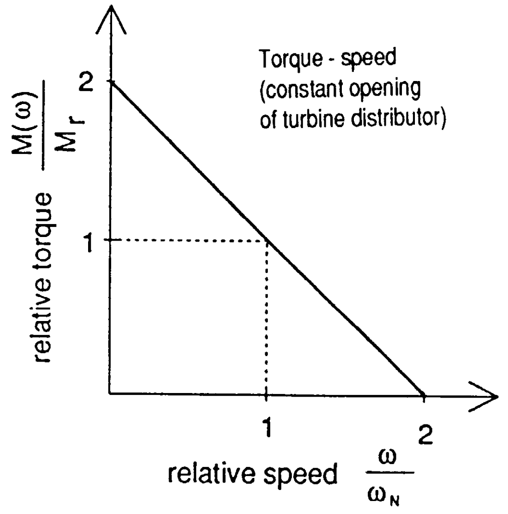


Figure A15:Estimated torque charateristics, case 1

Acceleration of the set:

{A-3.9}
$$M(\omega) = I \cdot \frac{d\omega}{dt}$$

If the full load is switched off, the torque M(ω) will accelerate the turbine/generator set up to the run away speed. And we find:

{A-3.10}
$$\frac{1}{2 \cdot \omega_N - \omega} \cdot d\omega = \frac{1}{T_a} dt$$

where $T_a = \omega \frac{I}{M_r}$

Integrating this, one finds the speed/time curve :

{A-3.11}
$$\omega_{(t)} = \left(2 - e^{-\frac{t}{Ta}}\right) \omega_N$$

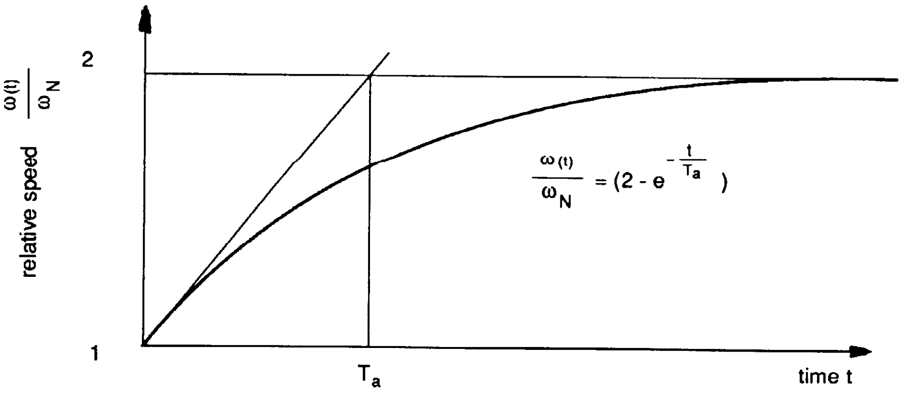


Figure A16: Speed/time curve of idealized, ungoverned Pelton turbine after full load rejection

Case 2:
Speed rise after a full load rejection of an idealized governed turbine:

Assumptions:

- idealized, linear guide vane position/flow characteristic
- torque of turbine is proportional to flow
- torque of turbine is independent of speed
- water-hammer neglected

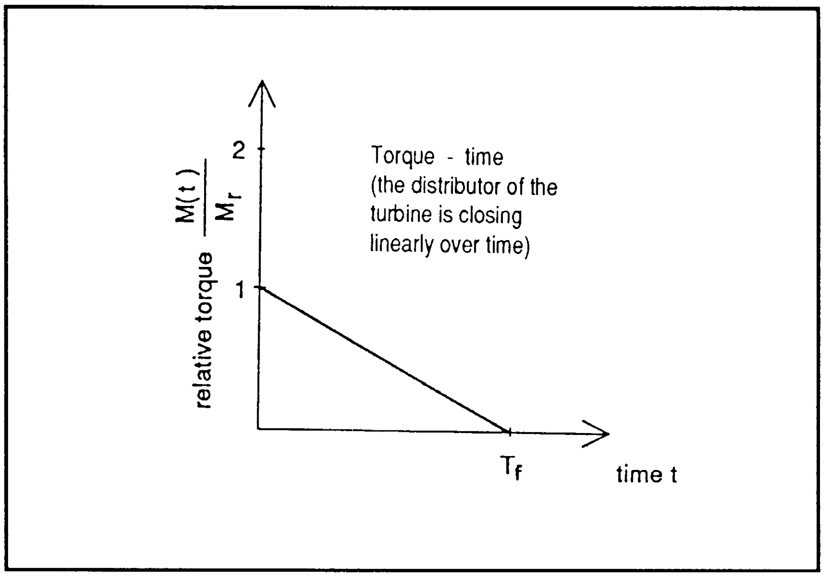


Figure A17: Estimated torque characteristics, case 2

Under these idealized conditions an average acceleration torque can be calculated during the time T_f of closing down.

{A-3.12} $$M_{(t)} = M_r \left(1 - \frac{t}{T_f}\right)$$

{A-3.13} $$d\omega = \frac{M_r}{I} \left(1 - \frac{t}{T_f}\right) dt$$

Integrating this over the closing time one finds the maximum speed:

{A-3.14} $$\omega_{max} = \left(1 + \frac{1}{2} \cdot \frac{T_f}{T_a}\right) \omega_N$$

$$\omega_{max} = \omega_N + \frac{T_f}{2} \cdot \frac{M_r}{I}$$

where $T_a = \omega_N \dfrac{I}{M_r}$

Case 3:
Speed rise after a full load rejection of an idealized Pelton Turbine closing with jet deflector (may be also valid for other turbine type with negligible water-hammer) :

Assumptions:
- no water-hammer effect
- flow of turbine is independent of speed (no water-hammer)
- idealized, linear torque-speed characteristic

{A-3.15}
$$M_{(\omega)} = \left(2 - \frac{\omega}{\omega_N}\right) M_r$$

- runaway speed is constant for all deflector positions.

{A-3.16}
$$\omega_R = 2 \cdot \omega_N$$

- jet deflector closes linear in the time T_f. This causes a linear torque/time characteristic of the turbine at constant turbine speed.

{A-3.17}
$$M_{(t)} = \left(1 - \frac{t}{T_f}\right) M_{(\omega)}$$

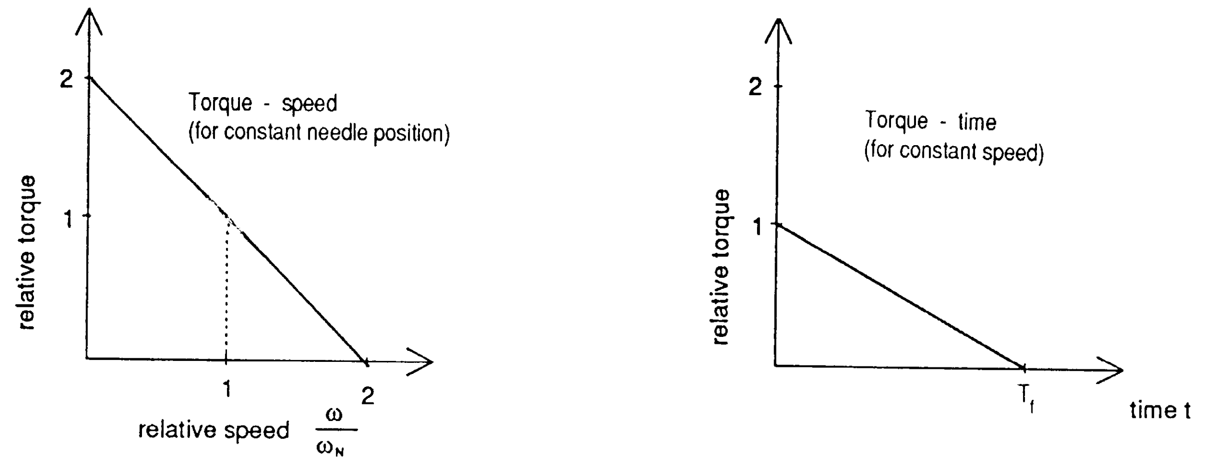


Figure A 18: Estimated torque charateristics, case 3

Under these idealized conditions an average acceleration torque can be calculated during the time T_f of closing down the jet deflector.

{A-3.18}
$$M_{(\omega,t)} = \left(1 - \frac{t}{T_f}\right)\left(2 - \frac{\omega}{\omega_N}\right) M_r$$

From this we can calculate the speed/time curve as already done :

{A-3.19}

$$\omega_{(t)} = \left(2 - e^{\left(\frac{t^2}{2 T_f T_a} - \frac{t}{T_a} \right)} \right)$$

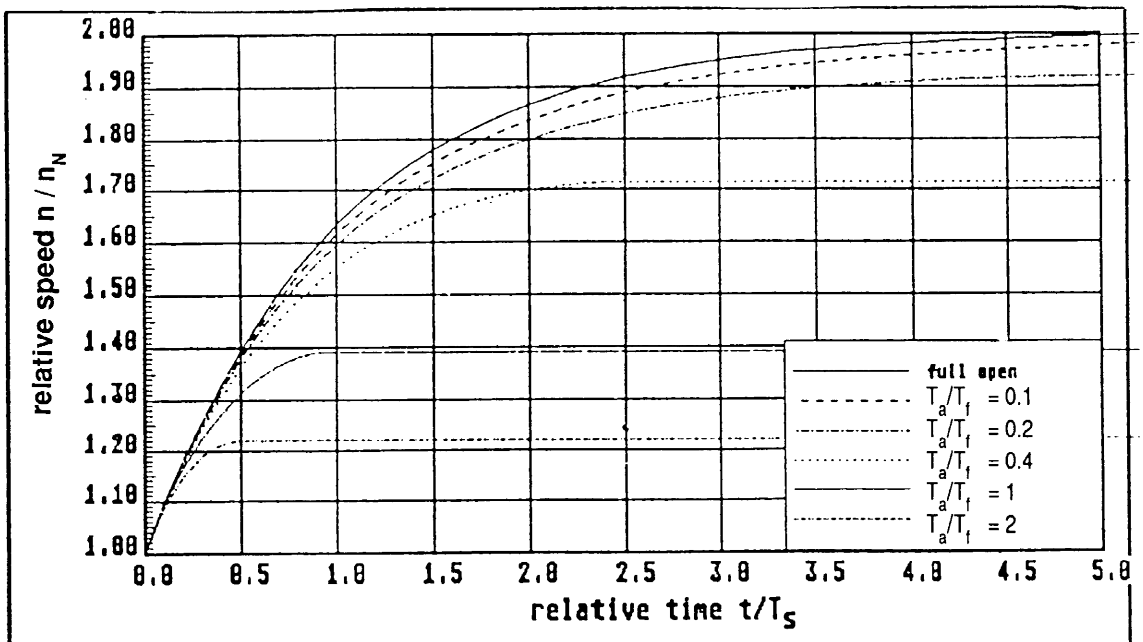
(valid for $0 < t < T_f$)

The maximum speed rise will occur when the deflector (distributor) is closed ($t = T_f$):

{A-3.20}

$$\omega_{max} = \left(2 - e^{-\frac{1}{2} \frac{T_f}{T_a}} \right) \omega_r$$

It can be seen, that the speed rise is under these simplified conditions a function of the closing time T_f and the unit acceleration time, according to figure A19



Transient speed rise following a full load rejection (idealizes conditions)

Figure A19 : Speed rise for idealized turbine as function of time, closing time and unit acceleration time.

Case 4:
Speed rise after a partial load rejection of idealized turbines with regard to turbine characteristic and transient pressure rise:

This case is based on case 3 with the following additional assumptions:

- a partial load rejection P smaller than nominal load P_r can be considered by correcting the unit acceleration constant T_{ap}

{A-3.21}
$$T_{ap} = \frac{P_r}{P} T_a$$

Transient pressure rise

- a transient pressure rise ΔH can in the worst case increase the turbine output during the closing time:

{A-3.22}
$$P_{\Delta h} = P \left(1 + \frac{\Delta H}{H_r}\right)^{3/2}$$

The runaway speed ω_R will also increase due to higher head to ω_{Rh}

{A-3.23}
$$\omega_{Rh} = \left(1 + \frac{\Delta H}{H}\right)^{1/2} \omega_R$$

Speed / torque characteristic

- the speed/torque characteristic of different turbine types is approximated as shown in figure A 20

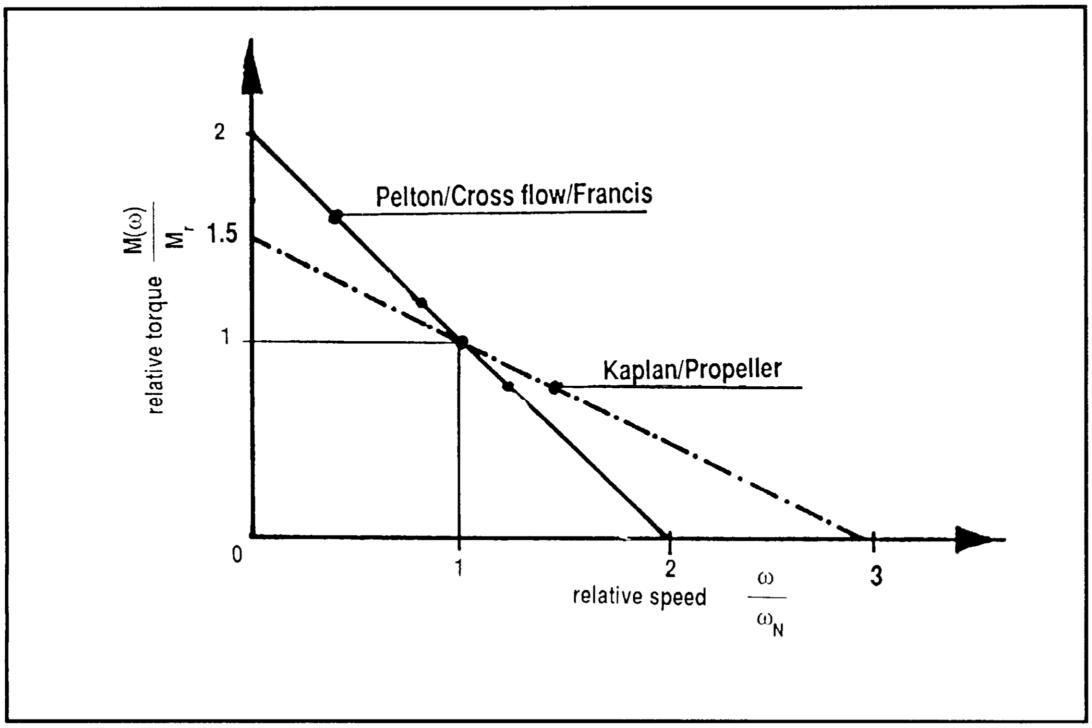


Figure A20 : Roughly approximated torque characteristics

With these assumptions one can calculate the diagram in figure A21 - 22
For a quick approximation of the speed rise on sudden load rejection from the nominal point of operation, the following steps are neccessary:

1. step: calculate the relative time factor

{A-3.24}
$$\text{Relative time factor} = \frac{T_a}{T_f} \frac{P_r}{P}$$

2. step: calculate transient pressure rise $\Delta H/H_r$ 100% (e.g. with Allievi method)
3. step: determine the maximum speed rise for the turbine type used from figure A21-22

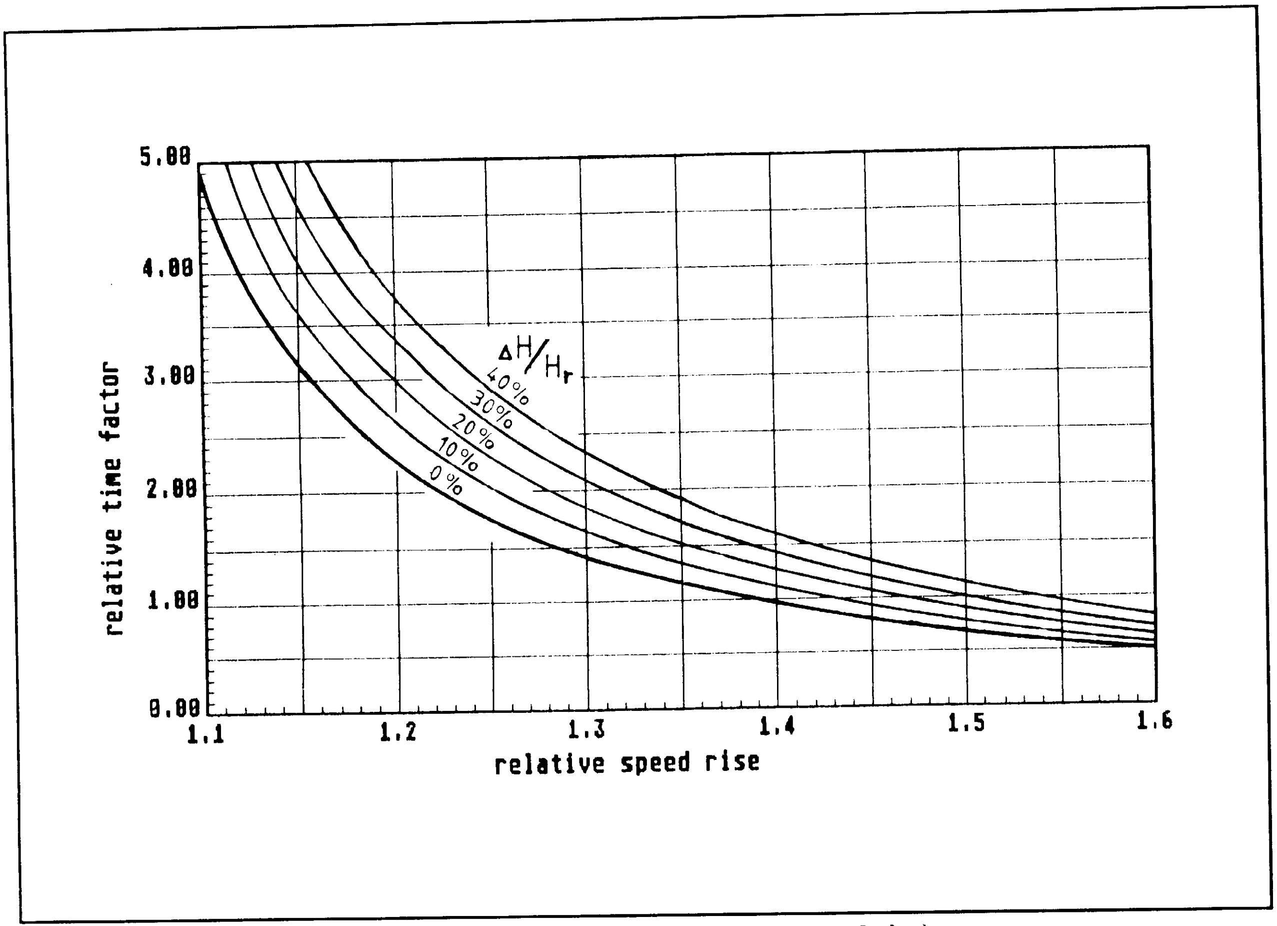


Figure A21a: Pelton / Cross flow / Francis turbines (relative speed rise)

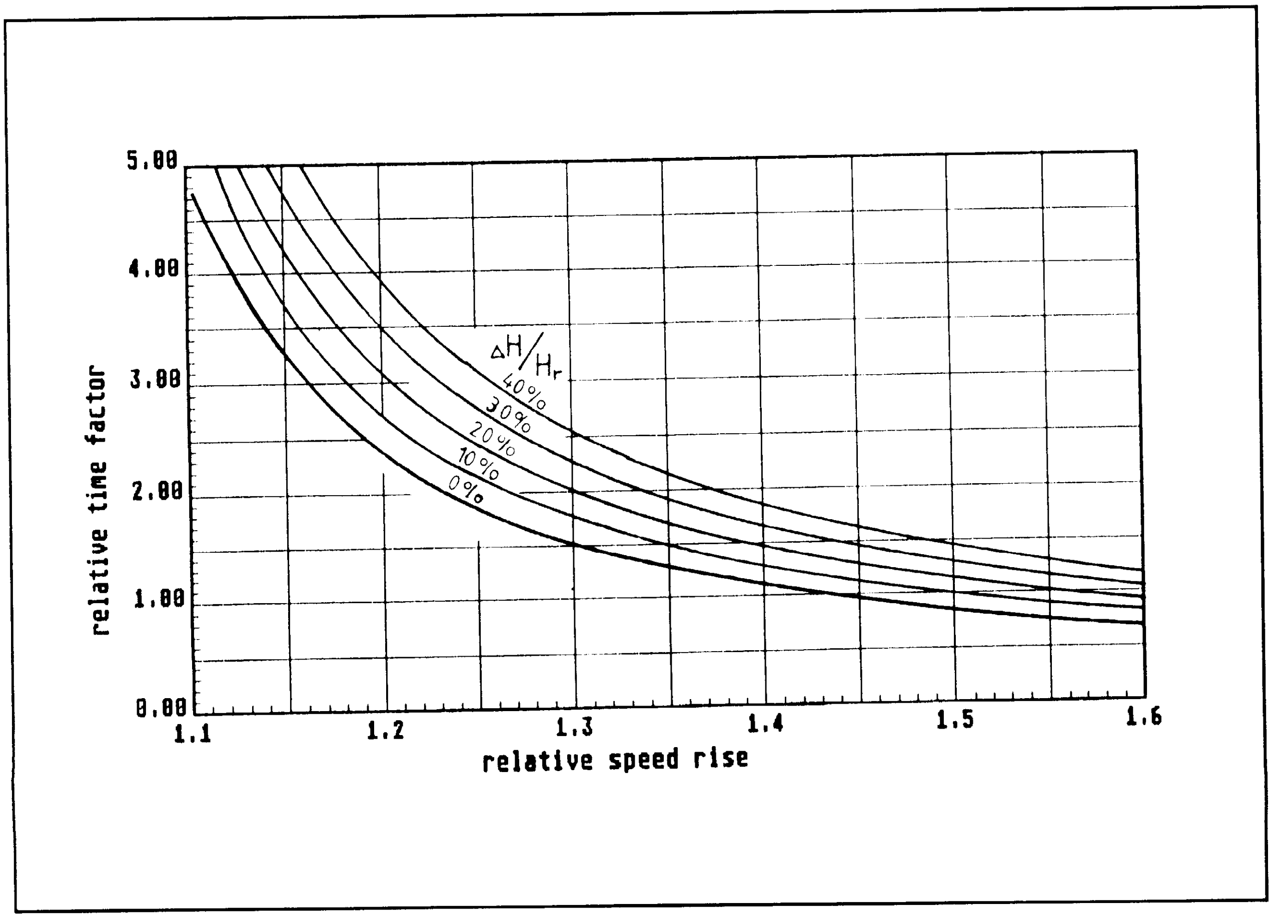


Figure A21b: Kaplan / Propeller turbines (relative speed rise)

case 5:
Speed rise after a full load rejection under real conditions according to Lein [2.1].

As already mentioned the accurate calculation of the speed rise is too complex to be shown here. However, another practicable estimation method is shown from G. Lein to calculate the speed rise following full load rejection with regard to the water-hammer and the turbine characteristic. The estimated water-hammer is valid for a steel penstock and includes closing within one reflection time period T_r. The worst case - opening from closing position in 1 T_r and immediately closing in the following T_r - has to be considered seperately. If opening and closing time are equal the maximum pressure rise in this case is approximately two times the maximum pressure drop. The method is described shortly and should be studied in detail in the source text:

1. Step:
Calculation of the Penstock Parameters
Reflection time T_r
Acceleration time T_w

2. Step:
Determination of the allowed maximum relative dynamic pressure rise (water-hammer)

$\Delta H/H_r$ = depending on penstock nominal pressure

3. Step:
Calculation of the minimum possible closing time T_f of the turbine determined from penstock data, permissible water-hammer and turbine type:

{A-3.25}
$$T_f = K_c \cdot \left(\frac{T_w}{\frac{\Delta H}{H_r}} + \frac{T_r}{2} \right)$$
valid for $T_f > 3\ T_r$

where: K_c = correction factor for turbine type

Pelton turbine	$K_c = 3.7$
Francis turbine	depends on the specific speed, $K_c = 1.45$ is a value on the safe side
Kaplan turbine	$K_c = 1.35$ for calculating the distributor closing time T_{fdi} (the closing time of the runner blades, T_{cru}, can be chosen from $T_{fru} = 1\ T_{fdi}$ to $2\ T_{fdi}$)
Cross flow turbine	K_c factors for cross flow turbines are not known, as a safe approximation of values of Pelton turbines should be assumed

4. Step:
Calculation of the maximum speed rise following full load rejection

{A-3.26}
$$\frac{\omega_{max}}{\omega_r} = \sqrt{\left(1 + k\, T_f\, \frac{1 + \frac{\Delta H}{H_r}}{T_a}\right)}$$
valid for $\frac{\omega_{max}}{\omega_R} < 1.5$

where k = correction factor for speed rise

Pelton turbines	k = 0.9 (for turbines with jet deflector T_f is the deflector closing time)
Cross flow turbines	k = 0.9 (assumed)
Francis turbines	k = 0.8
Kaplan turbines	k = 0.8, if $T_{fru} = T_{fdi}$ k = 0.7, if $T_{fru} = 2\ T_{fdi}$

Note: **When calculating parameters in an approximative way, compute the values using the different available methods and compare**

Maximum speed decrease	n_{min}	%

The maximum speed decrease occurs if the maximum specified partial load is suddenly added at a certain point of operation. Its determination is more complex than the maximum speed rise following a full load rejection, because additional parameters are the self regulation of the grid and the actual point of operation.

Hence we want to give a simplified method to estimate this important value. The approximation formulae for the maximum speed rise and speed drop are only valid if the servomotor velocities reach their maximum values. Especially at part load rejections or part load acceptances the governor may decelerate the servomotor velocities; in this case speed deviations are greater.
We use the following assumptions to show a simplified method of calculation:

- assumed, linear guide vane position/flow characteristic
- torque of turbine is proportional to flow
--> torque is therefore proportional to guide vane opening and to the opening time
- torque M_t of turbine is independent of speed (self regulation $e_t = 0$)
- water-hammer neglected
- torque M_l of the load is independent of speed (self regulation $e_l = 0$)
- self-regulation of the system = 0

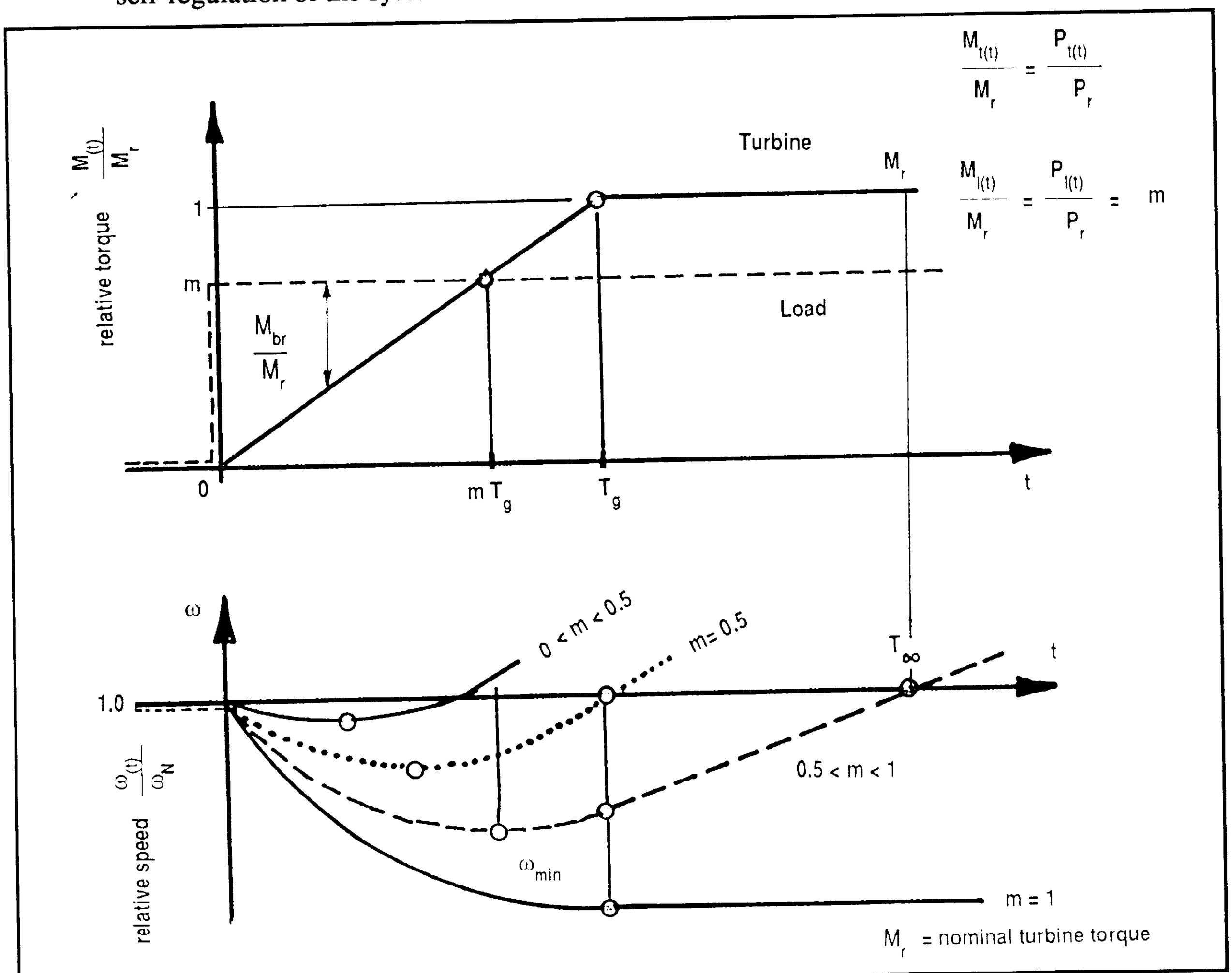


Figure A22: Estimated torque charateristics and calculated speed decrease

Under these conditions the braking torque M_{br} can be calculated during the time T_g of opening.

{A-3.27}
$$M_{t(t)} = M_r \cdot \frac{t}{T_g}$$

{A-3.28}
$$M_{br} = M_{t(t)} - M_L = I \cdot \frac{d\omega}{dt}$$

We introduce the load ratio **m** = M_l/M_r:

{A-3.29}
$$d\omega = \frac{M_t}{I\ T_g} \quad (t - m\,T_g)\,dt \qquad \frac{d\omega}{\omega_N} = \frac{1}{T_a\ T_g} \quad (t - m\,T_g)\,dt$$

Integrating this over the time t one finds the speed time curve

{A-3.30}
$$\omega_{(t)} = \left(1 + \frac{t^2}{2\,T_a\,T_g} - \frac{m\,t}{T_a}\right)\omega_N$$

For t = m T_g one finds the minimum speed

{A-3.31}
$$\omega_{min} = \left(1 - \frac{m^2}{2}\ \frac{T_g}{T_a}\right)\omega_N \qquad \left(\frac{\Delta\omega}{\omega}\right)_{min} = \frac{m^2}{2}\ \frac{T_g}{T_a}$$

where $\frac{\Delta\omega}{\omega_N}$ is the so called speed droop ratio

For t = T_g one finds the speed at the end of opening

{A-3.32}
$$\omega_{(Tg)} = \left(1 + \left(\frac{1}{2} - m\right)\frac{T_g}{T_a}\right)\omega_N \qquad \left(\frac{\Delta\omega}{\omega_N}\right)_{T_g} = \frac{T_g}{T_a}\ \left(m - \frac{1}{2}\right)$$

- if m < 0.5 :

Turbine reaches nominal speed before the guide vane is fully open
The time T_{oo} when the turbine reaches again nominal speed is

{A-3.33}
$$T_{\infty} = T_g\ 2\ m$$

- if 0.5 < m < 1 :

Turbine is still running with a speed lower than nominal speed if the guide vane is fully open. It will be accelerated with the constant torque M = M_r (1-m). The time T_{oo} when the turbine reaches again nominal speed is

{A-3.34}
$$T_{\infty} = \left(1 + \frac{m - \frac{1}{2}}{1 - m}\right)T_g$$

Example: m = 0.9 --> T_{oo} = 5 T_g

- if m = 1 (full load is suddenly connected):

Turbine doesn't reaches nominal speed. It will remain at the speed calculated for the fully open guide vane, because no torque is left to accelerate the set. 100% load connection is even theoretically not possible. Turbine output must be larger than the connected load (m<1).

-The sudden connection of loads causes a speed decrease ω_{min} depending on:

load ratio	m	>	causes a higher speed decrease
opening time	T_g	>	higher speed decrease
load acceleration time	T_b	>	higher speed decrease
unit acceleration time	T_a	>	smaller speed decrease
system self regulation	e_n	>	smaller speed decrease

- The time T_{oo} until the turbine reaches the nominal speed again depends mainly on (for m>0.5):

load ratio	m	>	causes a very long time T_{oo}
opening time	T_o	>	longer time T_{oo}
load acceleration time	T_b	>	longer time T_{oo}
system self-regulation	e_n	>	shorter time T_{oo}

- A sudden connection of full load is practically not possible.
For low self-regulation a sudden load increase may cause a collapse of the speed and the turbine may operate continuously with too low speed (see also chapter 2.3). This can damage the generator and should be prevented with an underspeed protection.

- It may take a long time until the set reaches again nominal speed if a load greater than 50% is connected. (This time is independent of flywheel size).
- It is not reasonable to expect more than 50% sudden load connection in an isolated operating MHP scheme. Provision must be there to connect the consumers stepwise.

Summary:

The approximation formulae for the maximum speed rise and speed drop described in this annex are only valid if the servomotor velocities reach their maximum values. Especially at part load rejections or part load acceptances the governor may decelerate the servomotor velocities; speed deviations resulting are greater.

The sudden connection of relatively high loads cause a speed decrease in speed control governing systems. Under difficult conditions the set may operate a long time (or even constantly) at underspeed. Rotating masses of consumers must be initially accelerated with the energy of the inertia of the turbine/generator set or the inertia of other consumers.
Therefore it is important to describe the load connection conditions exactly to the governor supplier.

Load controllers can easily accept the connection of high resistive load without a speed decrease. Connection of big motors however causes also a speed decrease and must be compensated by a flywheel.

A4. Static behavior of the turbine/generator/consumer system

Self-regulation factor of the system	e_n	-

At the speed considered, the slope of the graph relating the total torque to the speed at a specified servomotor position and a specified load condition of the network. The torque is to be referred to nominal speed ω_N.

{A-4.1}

$$e_n = e_g - e_t$$

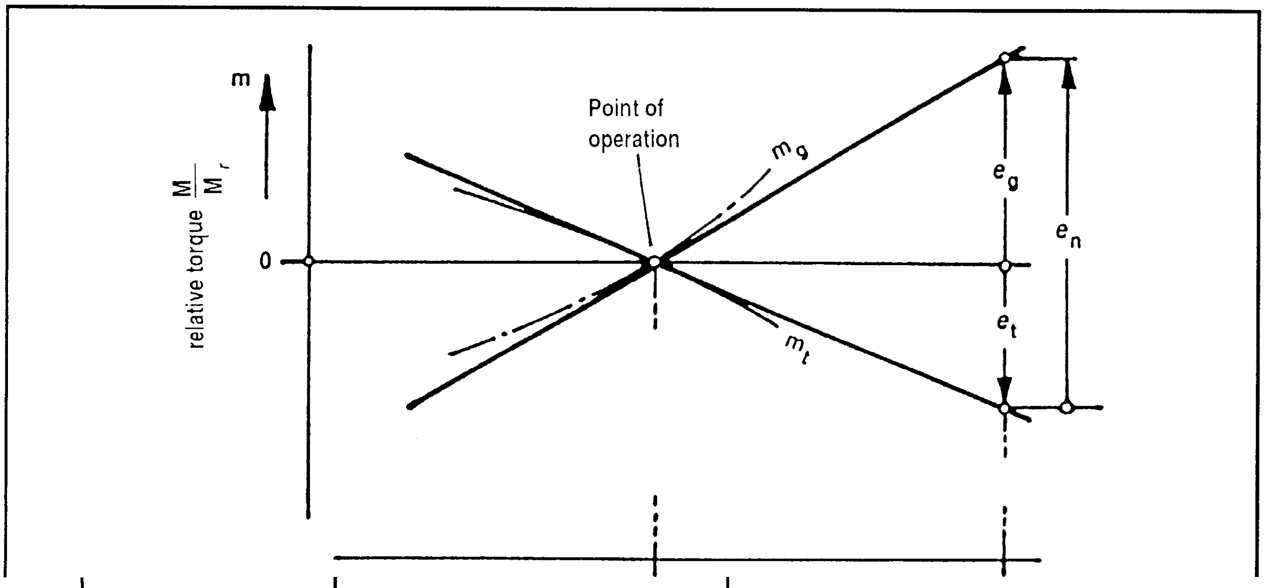


Figure A23: Self-regulation factor e_n

The self-regulation of the system can be determined in the fielc
and by causing a change in output by a certain amount. The
d by blocking the guide vane at a certain output
self-regulation can be determined:

{A-4.2}

$$e_n = \frac{\frac{\Delta P}{P_r}}{\frac{\Delta\omega}{\omega_N}} \quad - 1$$

Turbine self-regulation factor	e_t	-

The component of e_n due to the turbine. It is the slope of the speed/torque graph at a certain point of operation.

{A-4.3}

$$e_t = \frac{\text{change of Torque}}{\text{change of Speed}} = \frac{dmt}{dx}$$

Typical values:

Pelton / Cross flow	e_t = -1
Francis (normal)	e_t = -1
Francis (low spec. speed)	e_t = -1.1
Kaplan/Propeller	e_t = up to -0.6

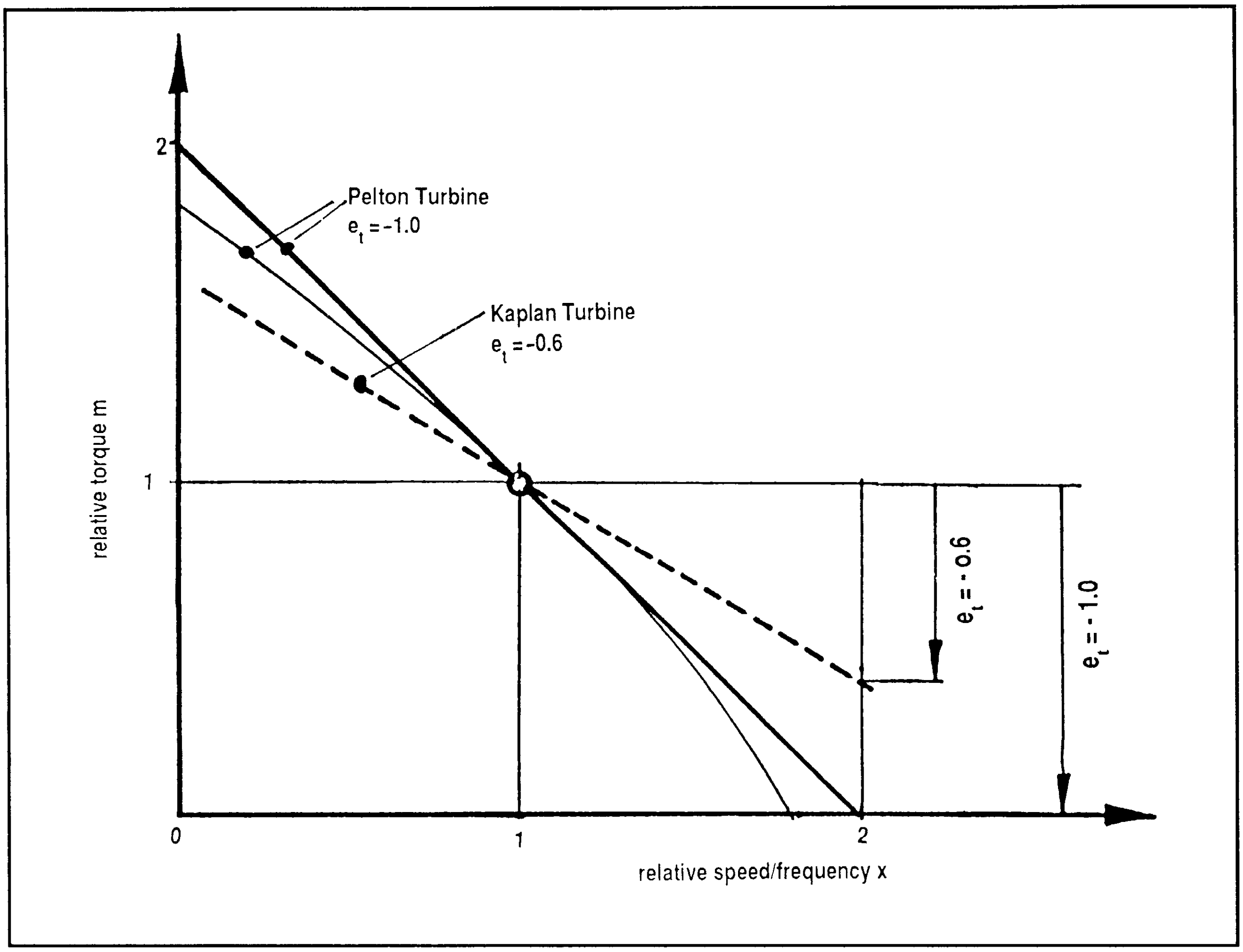


Figure A24: Self-regulation factor of turbines

Kaplan and propeller turbines with high specific speed can reach a low self-regulation e_t = - 0.6 and are therefore sometimes difficult to govern.

Load self-regulation factor	e_g	-

The component of e_n due to the load:

{A-4.4} $$e_g = \frac{dm_g}{dx}$$

Typical values:

Load with torque independent of speed (for example direct drive of a volumetric pump): $e_g = 0$

Generator supplying resistive load (for example electric heating, light bulbs, boilers etc.
Generator with voltage regulation $e_g = -1$
(P = M/n = const.)
(a voltage regulator with a voltage speed droop increases the self-regulation and is recommended)

Generator without voltage regulation $e_g = +1$ to $+4$

Direct driven machines: volumetric pump $e_g = 0$
centrifugal pump, ventilator $e_g = 2$

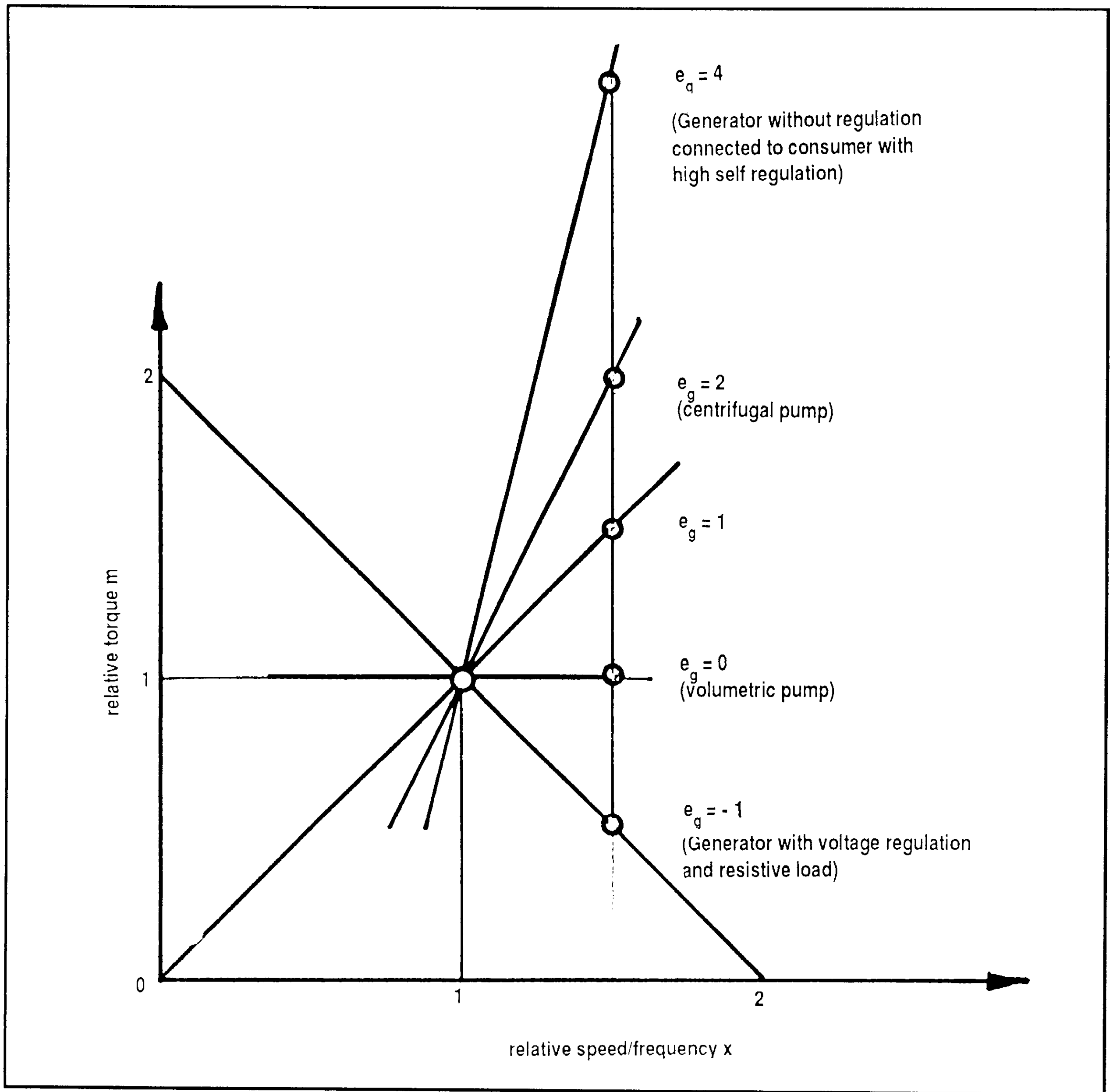


Figure A25: Self-regulation factor of various loads

Examples :

a. High self-regulation (see figure A26)

Pelton turbine ($e_t = -1$) driving a centrifugal pump ($e_g \approx 2$)
This results in a self regulation factor $e_n = 3$. The system is simple to regulate.

b. Low self-regulation (see figure A27)

Kaplan turbine with high specific speed ($e_t = -0.6$) driving a generator with voltage regulation ($e_g = -1$).
This results in a self regulation factor $e_n = -0.4$. The system is very difficult to regulate.

c. Grid of a town

The self-regulation is the result of the statistic diversification of the connected consumers and varies daily and seasonally. In Paris for example this value is typically:

$e_n = 1.5$ to 2.5

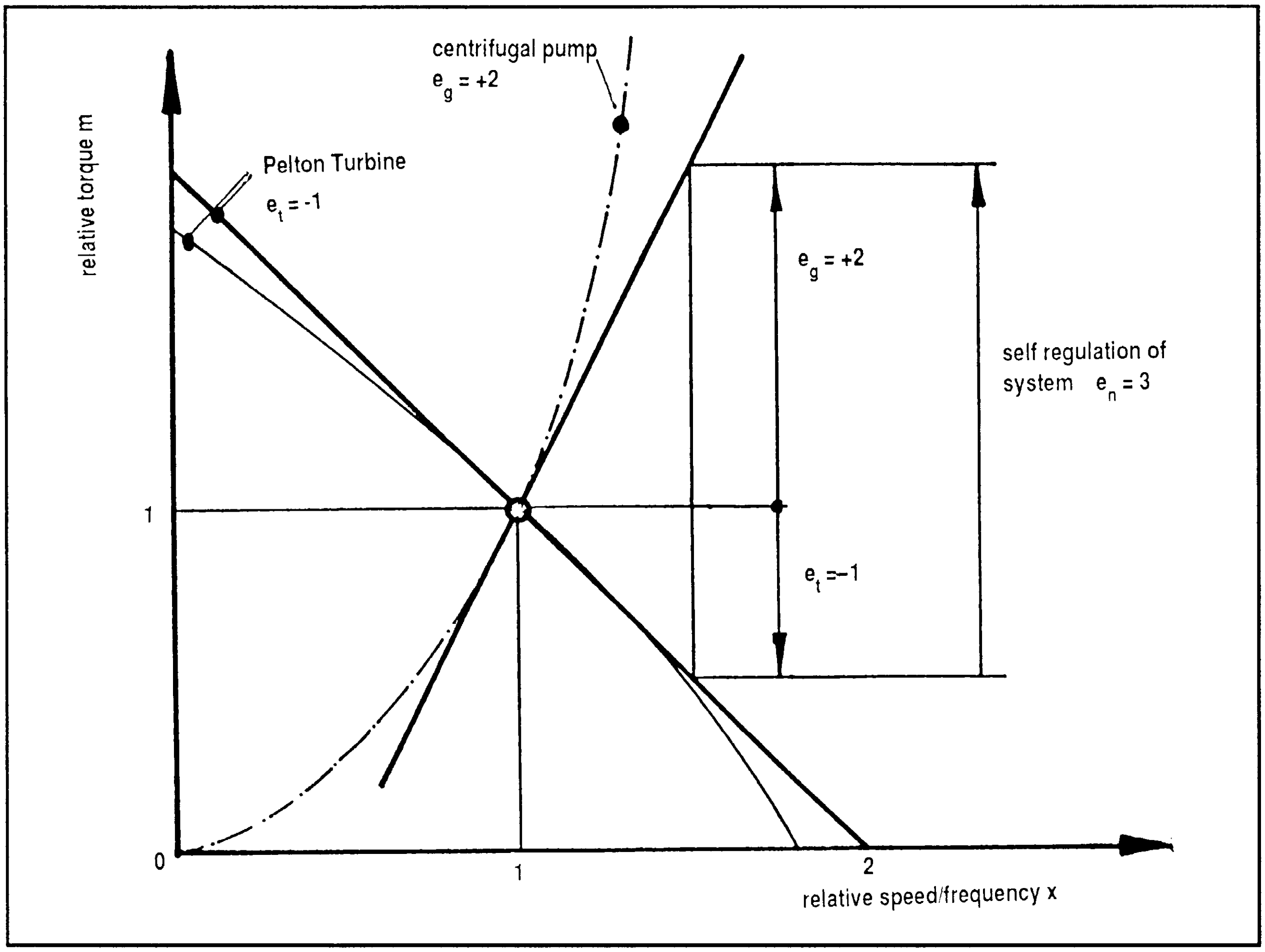


Figure A26: Low self-regulation factor

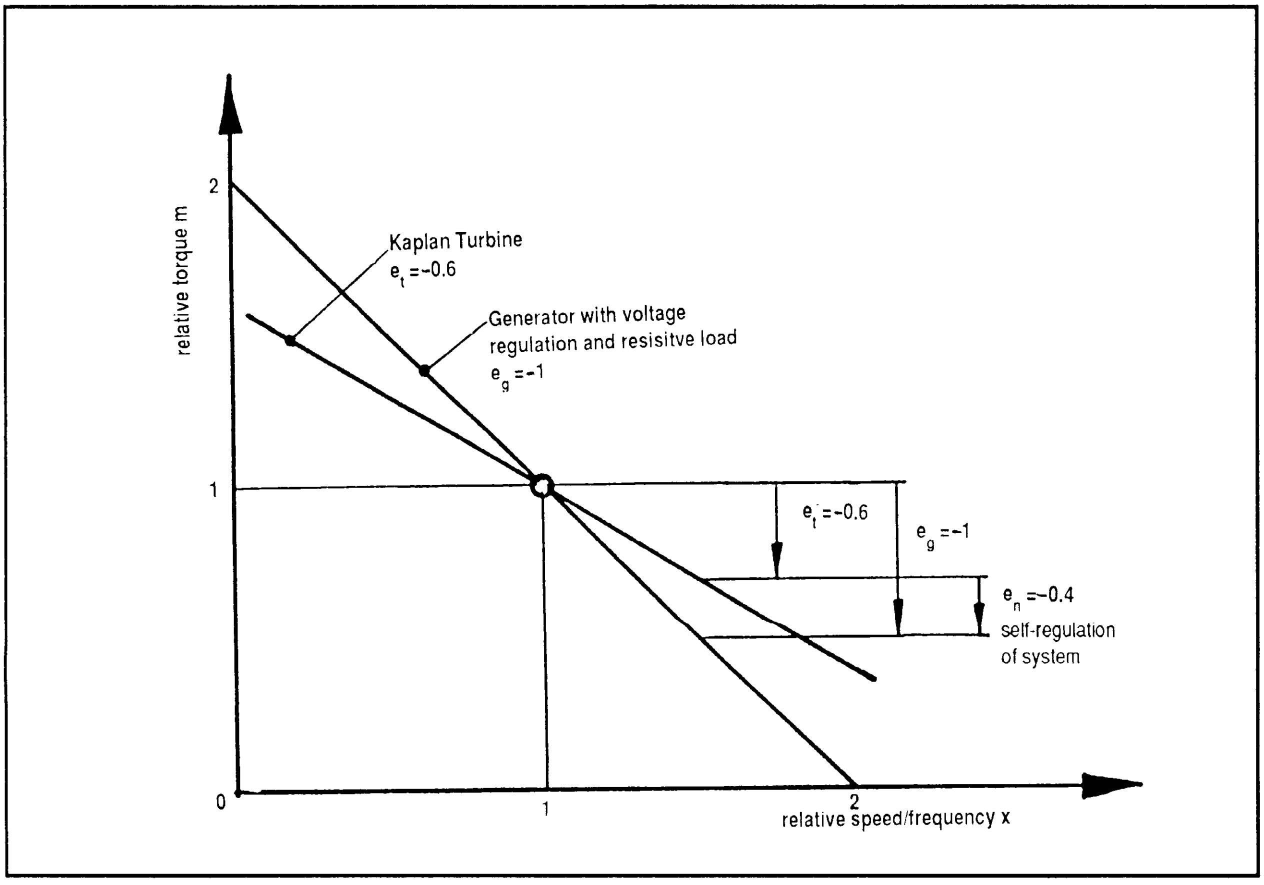


Figure A27: High self-regulation factor

A5. Examples for layout of governed systems:

5.1 Layout of a pelton turbine generator set without jet deflector:

Three possibilities of the layout for the turbine / generator set with different unit acceleration times T_a are compared. Two layouts with and without flywheel are compared with a direct coupled generator:

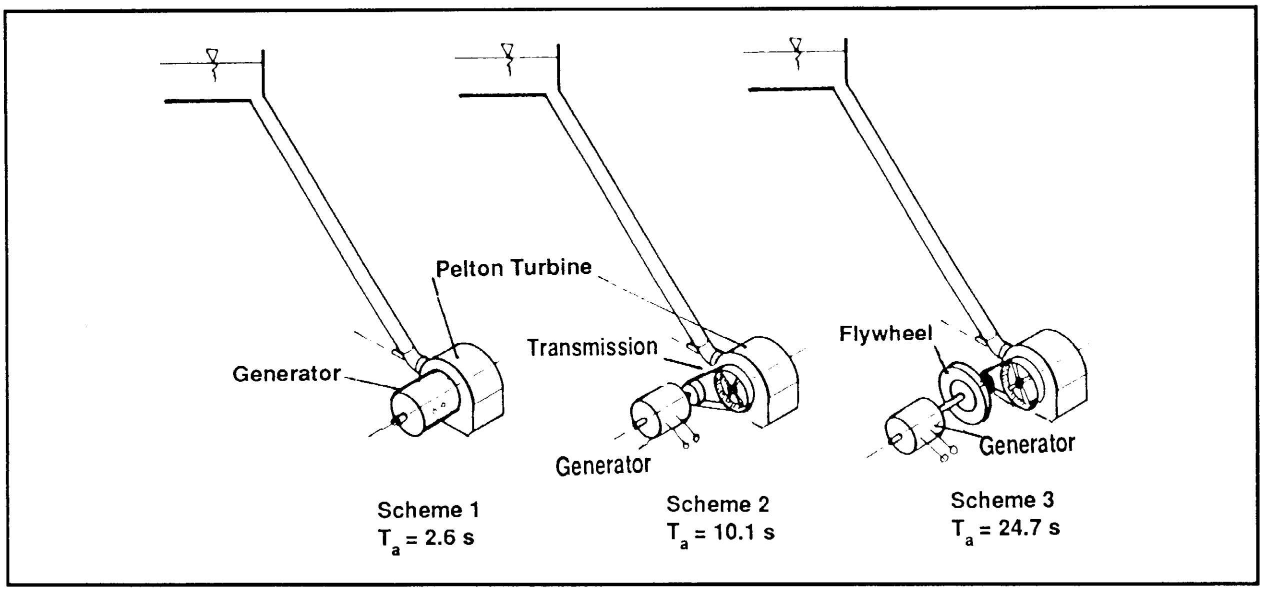


Figure A 28: Different layouts (scheme 1, 2 and 3)

Nominal head:	$H_r = 44$ m
Nominal flow:	$Q_r = 28$ l/s = 0.028 m^3/s
Nominal output :	$P_r = 9.5$ kW
Nominal turbine speed:	$n_{tN} = 750\ min^{-1}$

Scheme 1: Direct coupled turbine runner on the generator shaft

Nominal generator speed	$n_{gN} = 750\ min^{-1}$
Nominal torque :	$M_r = 121$ Nm
Generator	$I_g = 2.5$ kg m^2 (data from manufacturer)
Turbine	$I_{p2} = 1.5$ kg m^2 (data from manufacturer)
Unit acceleration time :	$T_a = 2.6$ s

Scheme 2: Belt drive between turbine and generator without flywheel:

Nominal generator speed	$n_{gN} = 1500\ min^{-1}$
Nominal torque :	$M_r = 60.5$ Nm
Unit acceleration time :	$T_a = 10.1$ s

Scheme 3: Belt drive between turbine and generator with flywheel (see also page 81 and 82):

Nominal generator speed	$n_{gN} = 1500\ min^{-1}$
Nominal torque :	$M_r = 60.5$ Nm
Unit acceleration time :	$T_a = 24.7$ s

Data	Scheme 1	Scheme 2	Scheme 3
Turbine:			
type	Pelton	"	"
static head H_r	44m	"	"
nominal flow Q_r	$0.028 m^3/s$	"	"
unit acceleration time T_a	2.6s	10.1s	24.7s
Penstock:			
material	Plastic	"	"
diameter d_i	0.200m	"	"
wave propagation speed a	400 m/s	"	"
length L	210m	"	"
maximum transient pressure rise $\Delta H/Hr$ 100%	30%	"	"

Calculations (according to case 5, page 90)			
acceleration time of water column T_w	0.44s	"	"
reflection time of pressure wave T_r	1.05s	"	"
minimum closing time (steel pipe; safe estimate) T_f	7.4s	"	"
maximum relative speed rise ω_{max}/ω_N 100%	>160%	136%	116%

Calculations (according to case 4, page 87 and 88):			
1. step: calculate the time factor T_f	7.4 s	7.4 s	7.4 s
relative time factor = T_a/T_f P_r/P	0.32	1.36	3.3
2. step: calculate transient pressure rise (closing down within T_f) $\Delta H/H_r$ 100%			
$t_f = T_{f\&}/T_r$, where $T_{f\&} = 0.75\ T_f$	5.3	"	"
h_w	0.42	"	"
Z^2	1.12	"	"
$\Delta H/H_r$ 100%	12%	"	"
3. step: determine the maximum speed rise for the turbine type used (figure A21)			
ω_{max}/ω_r 100%	>160%	134%	116%

	Scheme 1	Scheme 2	Scheme 3
Calculations related to maximum speed decrease:			
minimal opening time T_o	7.4s	"	"
needed load ratio m	0.3	"	"
minimal speed ω_{min}/ω_N 100%	86%	97%	99%
min time until set reaches nominal speed T_{oo}	4.4s	4.4s	4.4s
m = 0.6 : ω_{min}/ω_N 100%	(45%)*	87%	95%
T_{oo}	9.3s	9.3s	9.3s
m = 0.8: ω_{min}/ω_N 100%	(9%)*	76%	91%
T_{oo}	18.5s	18.5s	18.5s
* not acceptable			
Recommended governor adjustments according to Stein [2.2]			
Correction factor f_k	1.24	1.24	1.24
Temporary speed droop $b_t = 1.8\ f_k\ T_w/T_a$ 100%	37%	9.7%	4%
Time constant of damper $T_d = 4\ f_k\ T_w$	2.2s	2.2s	2.2s

Comments:

Scheme 1

Stability may be a problem because the system is very sensitive. Speed-control governing is not recommended. If speed-control is a requirement, precise governor adjustment and a sophisticated governor are needed. Sudden load connection is limited to about 30% (2.8 kW). In the case of full load rejection, overspeed will amount to almost 70%, which is close to runaway speed.
Load-control is recommended. If electric motors need to be started, a flywheel may be necessary.

Scheme 2

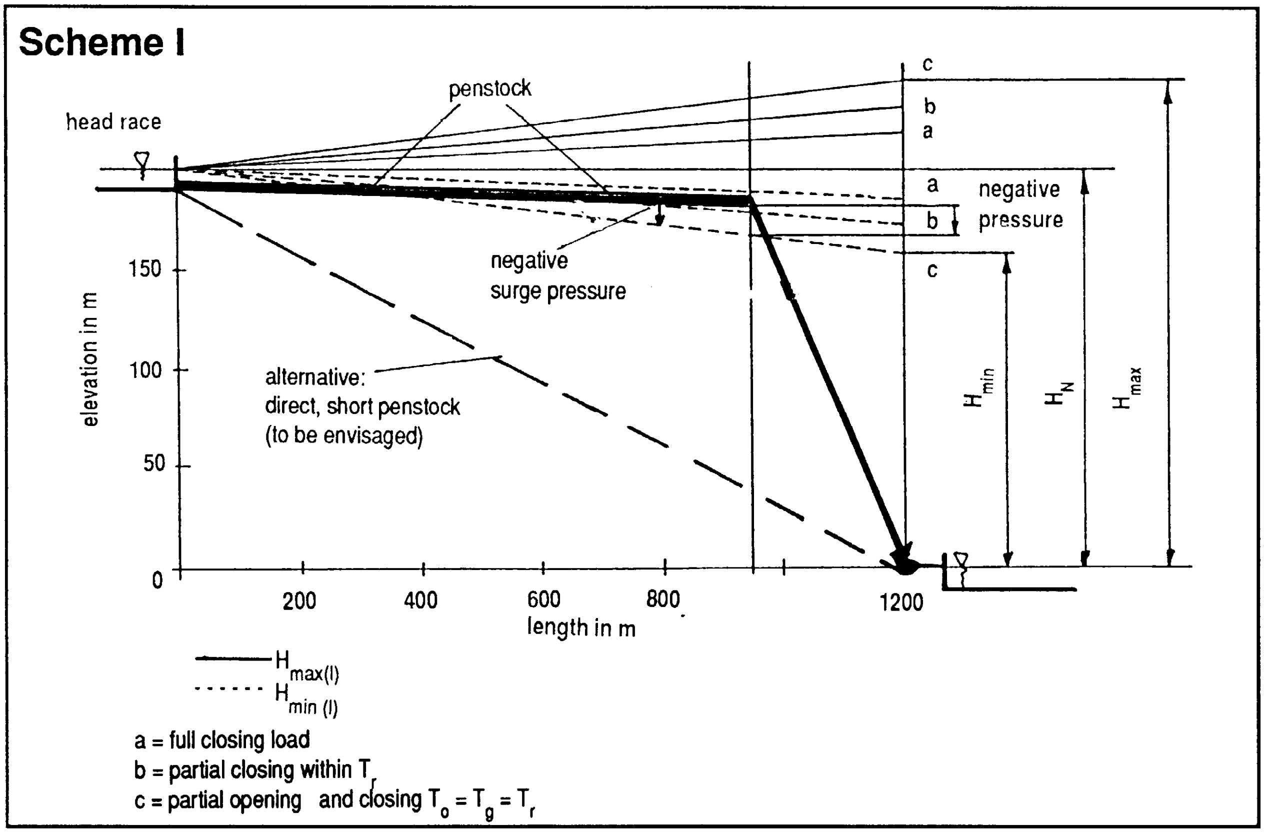
Flow-control is possible if the self-regulation of the system is high. For good stability, a PI-governor is required. Sudden load connection of 60% (approx. 5 kW) will result in a speed decrease of 13%, which is not generally acceptable. Transient speed increase after full load rejection will be around 40%. Therefore, a flywheel is recommended.
A load controller would be a good choice. Most likely, the maximum size of an electrical motor that can be started is limited to about 3 kW (approx. 50% of plant capacity), but this should be verified with the controller supplier.

Scheme 3

This represents the optimized system from the point of view of ease of governing, either by flow-control or by load-control.
For flow-control, a simple P-governor with a permanent speed droop of 6% will do, if the self regulation characteristic of the system is fairly high. Major load switching may be controlled without big speed variations. Full load rejection will cause a speed rise of less than 20%. Connection of 80% of the load will result in a transient speed decrease of about 10%. However, if self-regulation is low, e.g. due to electronic voltage regulation in the alternator and resistive consumer loads, problems may occur when connecting more than 50% of the load suddenly.
When using a load-controller, no problem is likely to occur; the flywheel will assist in the event of switching on big motors. The limiting factor of the size of electric motor that can be started is the starting current admissible for the alternator in both load- and flow-control.

5.2 Pelton turbine installation with different hydraulic designs

Two possible hydraulic penstock designs are compared: Scheme 1, with a long penstock and corresponding long acceleration time T_w and reflection time T_r, and scheme 2, where a surge tank is added to reduce the effective penstock length, resulting in shorter time values T_w and T_r.



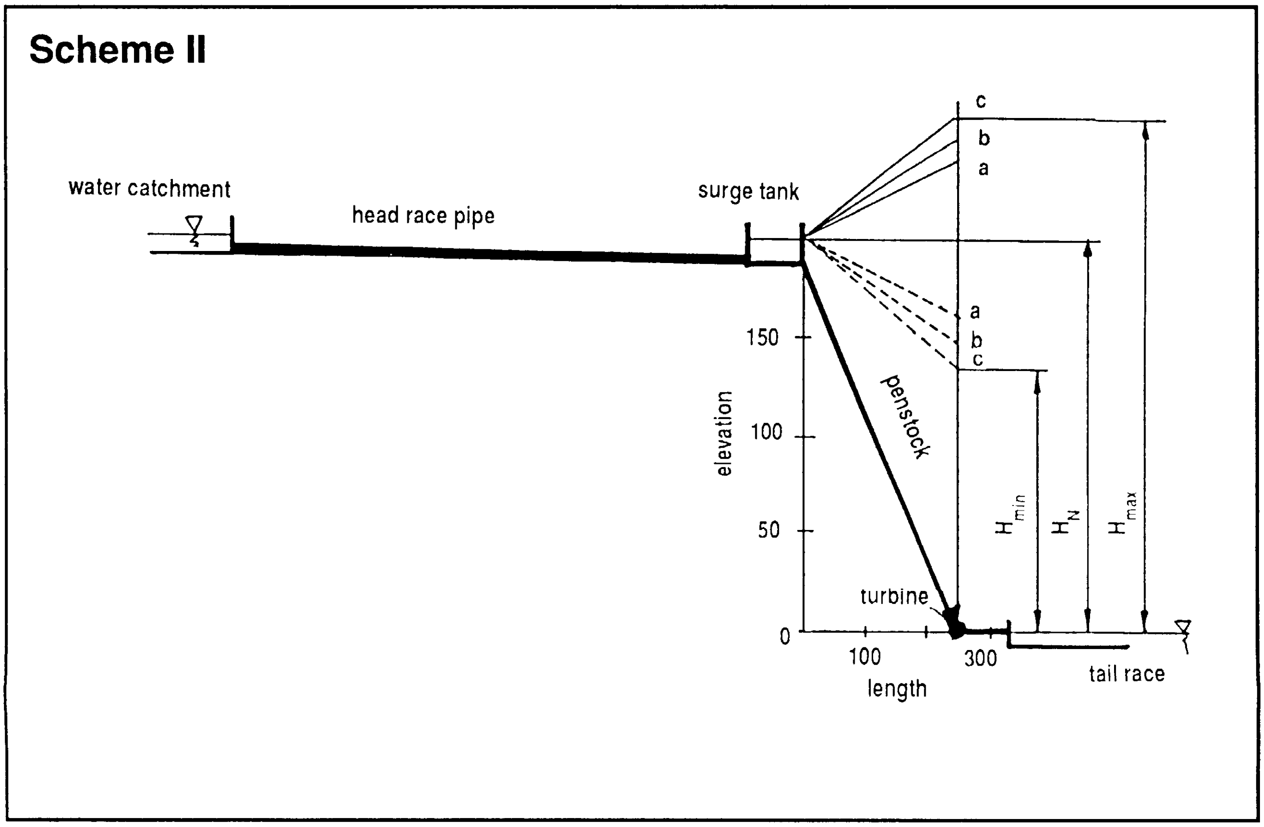


Figure A29: Two possible layouts for a Pelton turbine installation

Data	Scheme I	Scheme II
Turbine:		
type	Pelton	Pelton
static head H_N	200m	"
nominal flow Q_r	$0.06 m^3/s$	"
unit acceleration time T_a	5s	"
Penstock:		
material	cast iron	"
diameter d_i	0.253m	"
wave propagation speed a	1175 m/s	"
length L	1200m	260m
maximum admissible transient pressure rise $\Delta H/H_N$ 100%	30%	"
(normal pressure rise during operation: 10%)		

Calculations (according to case 5, page 90)		
acceleration time water column T_w	0.81s	0.14s
reflection time of pressure wave T_r	2.05s	0.44s
minimum closing time T_f	13.9s	2.4s
maximum speed rise ω_{max}/ω_N 100%	>160%	124%

Calculations (according to case 4, page 87 and 88)			
1. step:	calculate the time factor		
	T_f	13.9s	2.4s
	Flywheel relative time factor = $T_a/T_f \, P_r/P$	0.36	2.1
2. step:	calculate transient pressure rise $\Delta H/H_N$ 100%	10%	10%
3. step:	determine the maximum relative speed rise for the turbine type used from figure A21 ω_{max}/ω_N 100%	>160%	124%

	Scheme I	Scheme II
Calculations related to maximum speed decrease:		
minimal opening time T_o	13.9s	2.4s
needed load ratio m	0.3	"
minimal speed ω_{min}/ω_N 100%	88%	98%
minimal time until set reaches nominal speed T_{∞}	8.3s	1.4s
m = 0.6		
ω_{min}/ω_N 100%	(50%)*	91.4%
T_{∞}	17.4 s	3 s
m = 0.8		
ω_{min}/ω_N 100%	(11 %)*	84.6%
T_{∞}	34.8s	6.0s
* not acceptable		
recommended governor adjustments according to Stein [2.2]		
Correction factor f_k	1.3	1.3
Temporary speed droop b_t	38%	6.6%
Time constant of damper T_d	4.2s	0.8s

Comments:

Scheme I

Due to a relatively long penstock, a long closing time and time constant of the damper are required. In combination with a high temporary speed droop, large velocity deviations will occur even at minimum levels of load switching. If the self-regulation of the system is low, elevated levels of load switching and resulting water-hammer effects may destabilize the system. Possible governing concepts could be:

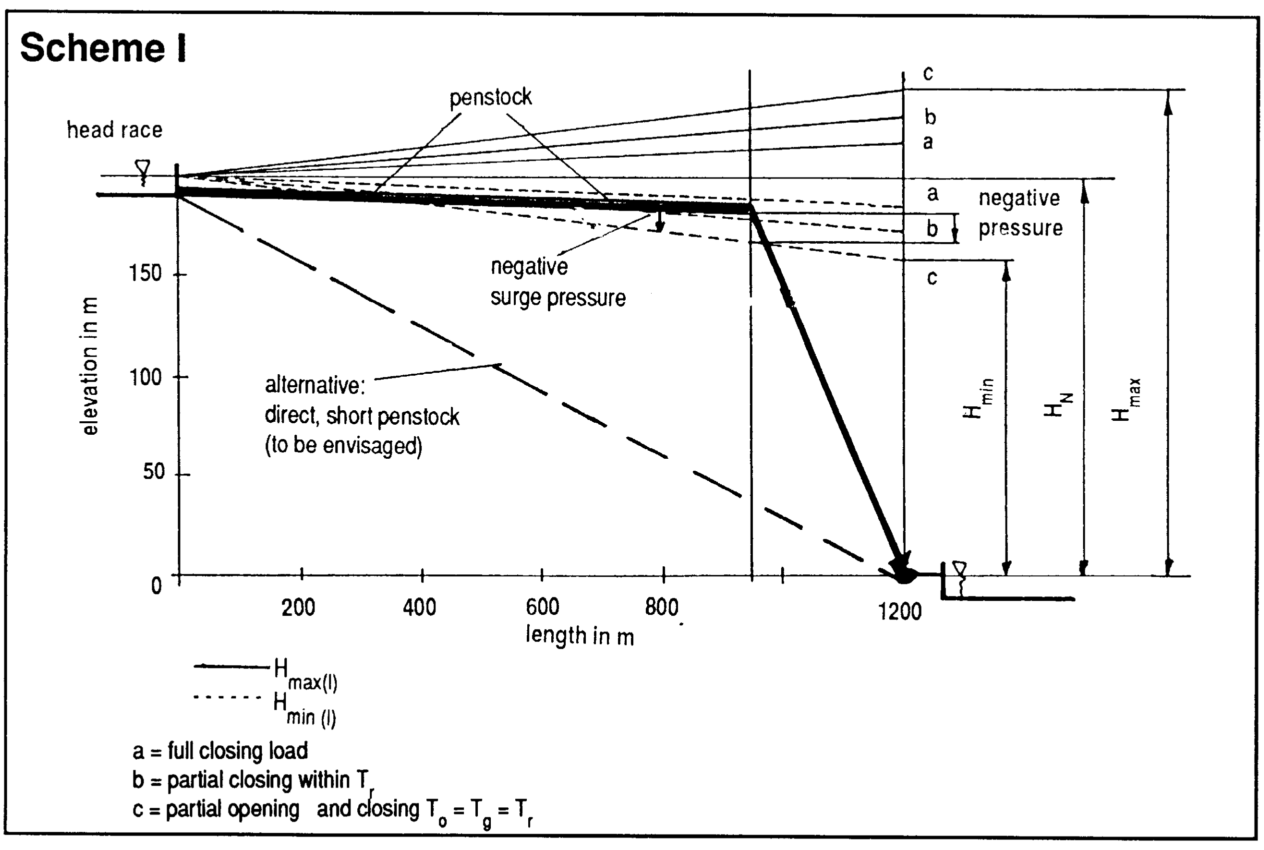
- A load controller with stepped, slow speed needle adjustment for water level control and activation of the jet deflector for emergency shutdown. Flow and thereby maximum load may also be set manually. The concept is applicable in isolated as well as in grid connected schemes.

- Speed-control would require a sophisticated PID-governor with regulation of the spear valve and the jet deflector. Speed control is not recommended in this case because in addition to the complex governor, there is a problem with negative pressure surge in the penstock.

- If the scheme is operating in parallel to the grid, jet deflector regulation is feasible for synchronisation and shutdown in the case of grid failure. In addition, water level control may also be done as described earlier.

5.2 Pelton turbine installation with different hydraulic designs

Two possible hydraulic penstock designs are compared: Scheme 1, with a long penstock and corresponding long acceleration time T_w and reflection time T_r, and scheme 2, where a surge tank is added to reduce the effective penstock length, resulting in shorter time values T_w and T_r.



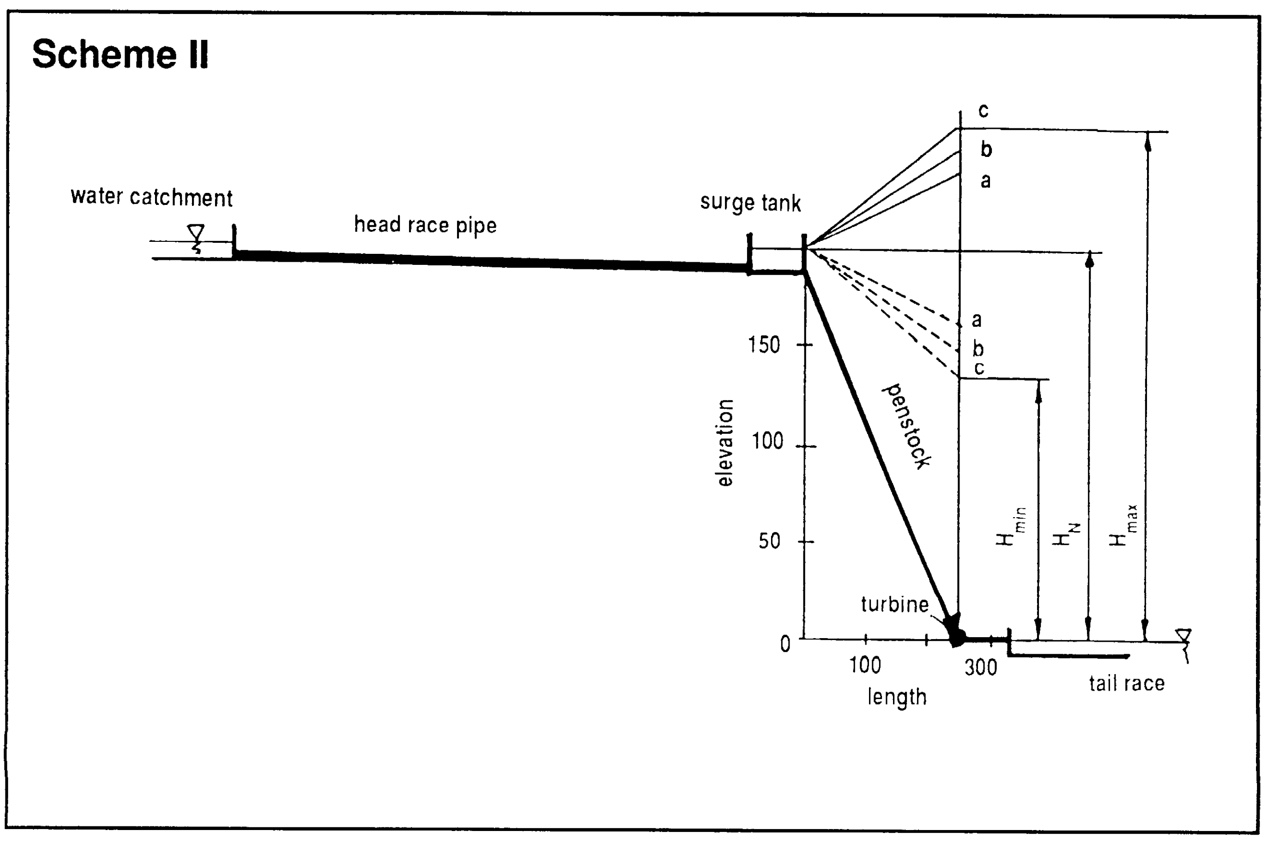


Figure A29: Two possible layouts for a Pelton turbine installation

Scheme II:

The hydraulic design of the scheme with a surge tank results in less complex and difficult control requirements but higher investment for civil structures. Several concepts are feasible:

- load-control as described for scheme I.
- Speed-control is feasible with a PI-governor. The following points should be discussed with the governor manufacturer:
    - in an isolated scheme, the consumer load curves must be studied. There is a limit on the maximum size of load that may be connected. If this is exceeded, a bigger flywheel is required.
    - A larger diameter of the penstock will decrease the acceleration time of the water column. This results in a lower temporary speed droop and shorter damper time. The system stability will increase.

Conclusion:

To identify the optimal governing concept requires the study of the overall system in the planning stage. The description of the Pelton turbine installation with different hydraulic design (page 101 to 104) shows the interaction of the layout of the waterways and the governing concept.
Scheme II with head race pipe, surge tank and speed control governor may turn out to be more expensive than scheme I having a direct but still long penstock and load control.
Scheme I would be optimal for a run of the river power plant provided that the river discharge is sufficiently large to cope with peak demand.
Scheme II is to be preferred if a storage scheme is envisaged to cover peak load demand (available river discharge lower than peak turbine flow). In case of parallel operation with a grid, scheme I is recommended.

A6. Operation of WOODWARD Governor Type UG8

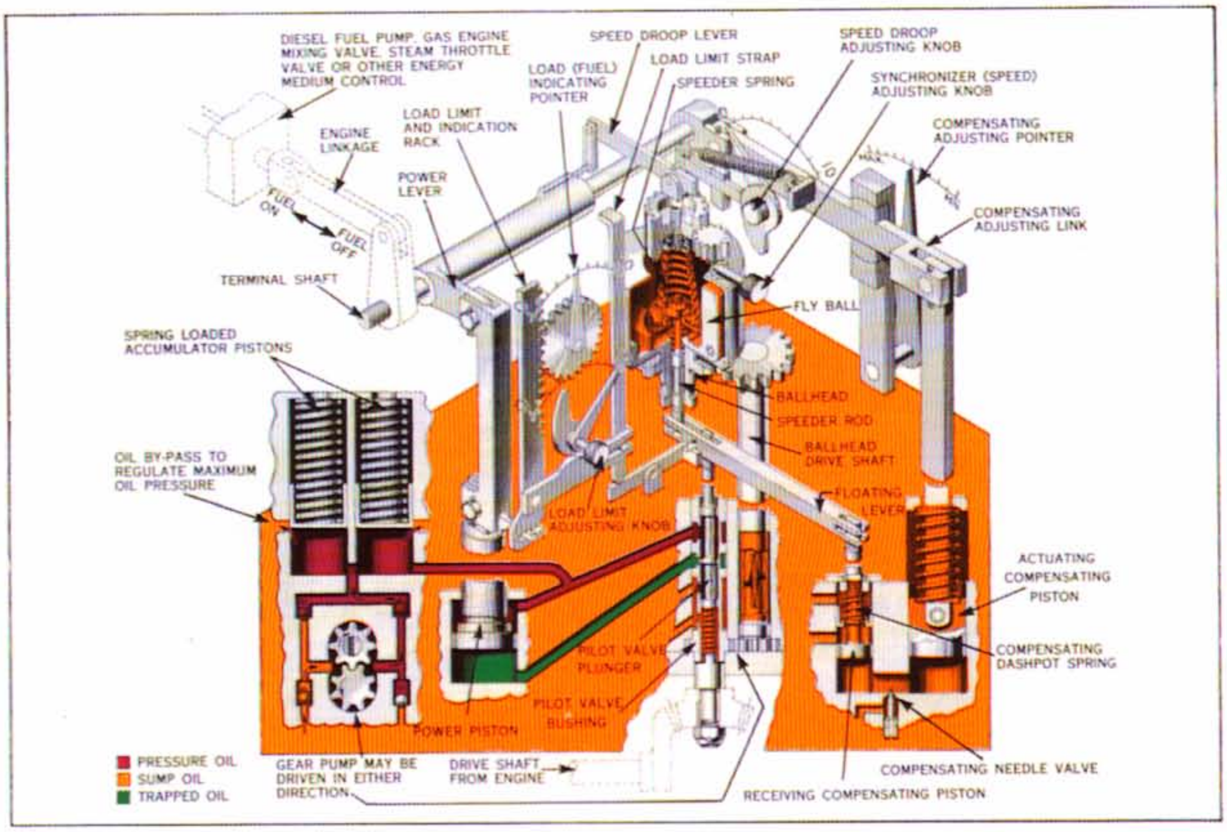
WOODWARD

SCHEMATIC DIAGRAM: The schematic diagram shows a UG8 dial control governor without auxiliary equipment. A differential type of servomotor is used in this governor. There is always full accumulator oil pressure on the top area of the power piston (regardless of pilot valve position) which will turn the terminal shaft in the direction to shut off fuel if there is no pressure (or low enough pressure) on the bottom area of the piston. The pilot valve will supply this same oil pressure to the bottom area of the power piston if the valve is moved down. Due to the difference of areas on the top and bottom of the piston a greater force on the bottom will then overcome the force on the top side and will move the piston turning the terminal shaft in the direction to increase fuel.

If the pilot valve is moved up the area under the piston is opened to sump, reducing the force exerted on the bottom of the piston. The force exerted by the oil pressure on the top will then be greater and will move the piston, turning the terminal shaft in the direction to decrease fuel.

The spring under the pilot valve supports the weight of the pilot valve, floating lever, etc., and has no effect in the operation of the governor.

The spring above the compensating actuating piston acts to eliminate lost motion in the compensating linkage and has no effect in the normal operation of the governor.



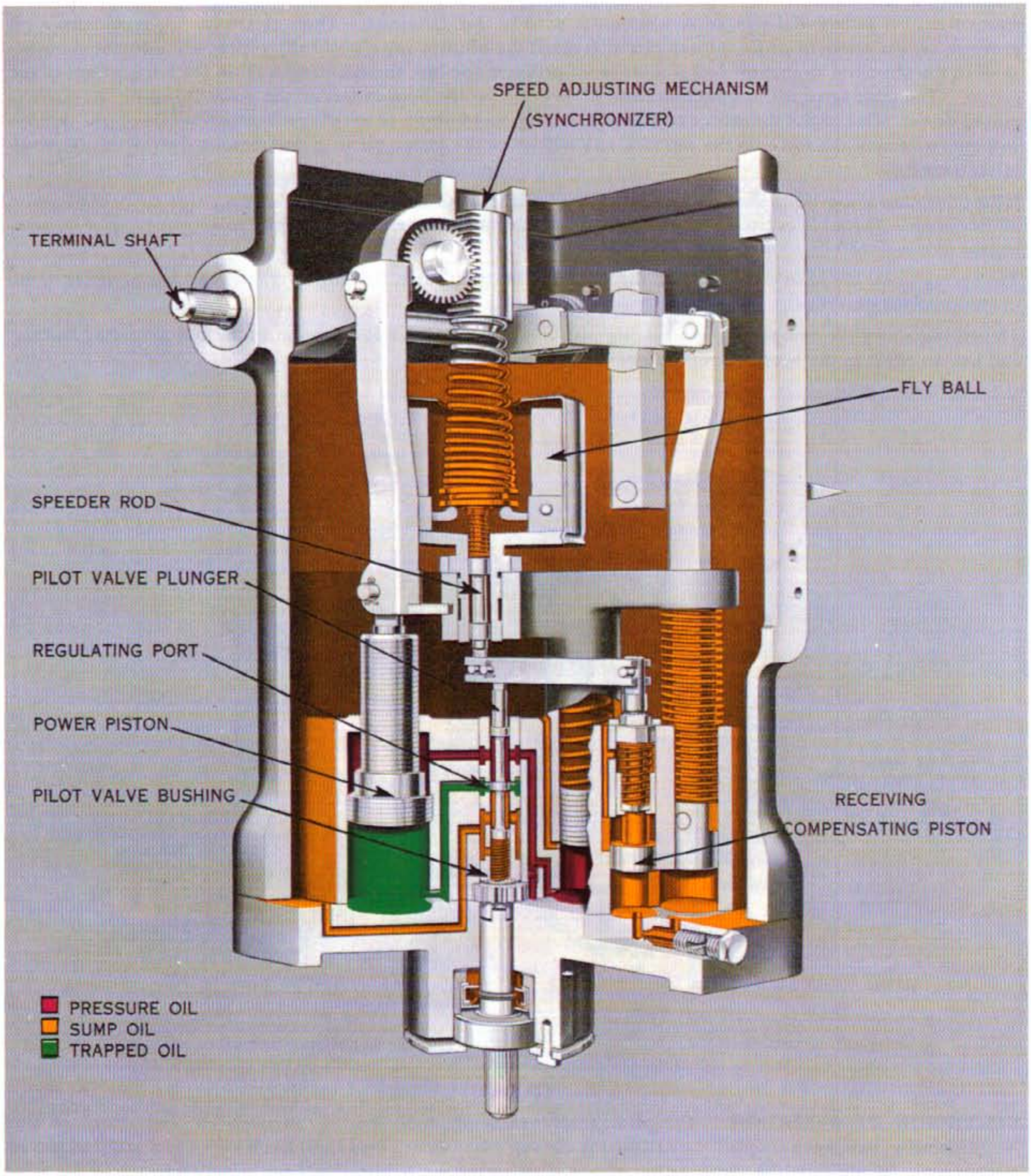
Cut No. 3

DESCRIPTION OF OPERATION: The photographs showing operation of the governor, Cuts No. 4 to Cut No.10 inclusive, have been simplified by removing the top cover, panel, load limit mechanism, and load indicating mechanism. In addition, the synchronizer or speed adjusting mechanism has been simplified.

Speed changes as a result of load changes have been considered, but the same sequence of governor movements would occur if a difference between actual governor speed and governor speed setting is produced by turning the synchronizer adjusting knob (Speed Adjustment).

Movements of the operating parts of the governor are actually proportional to the amount of speed change, but have been greatly exaggerated in the photographs to make them more visible.

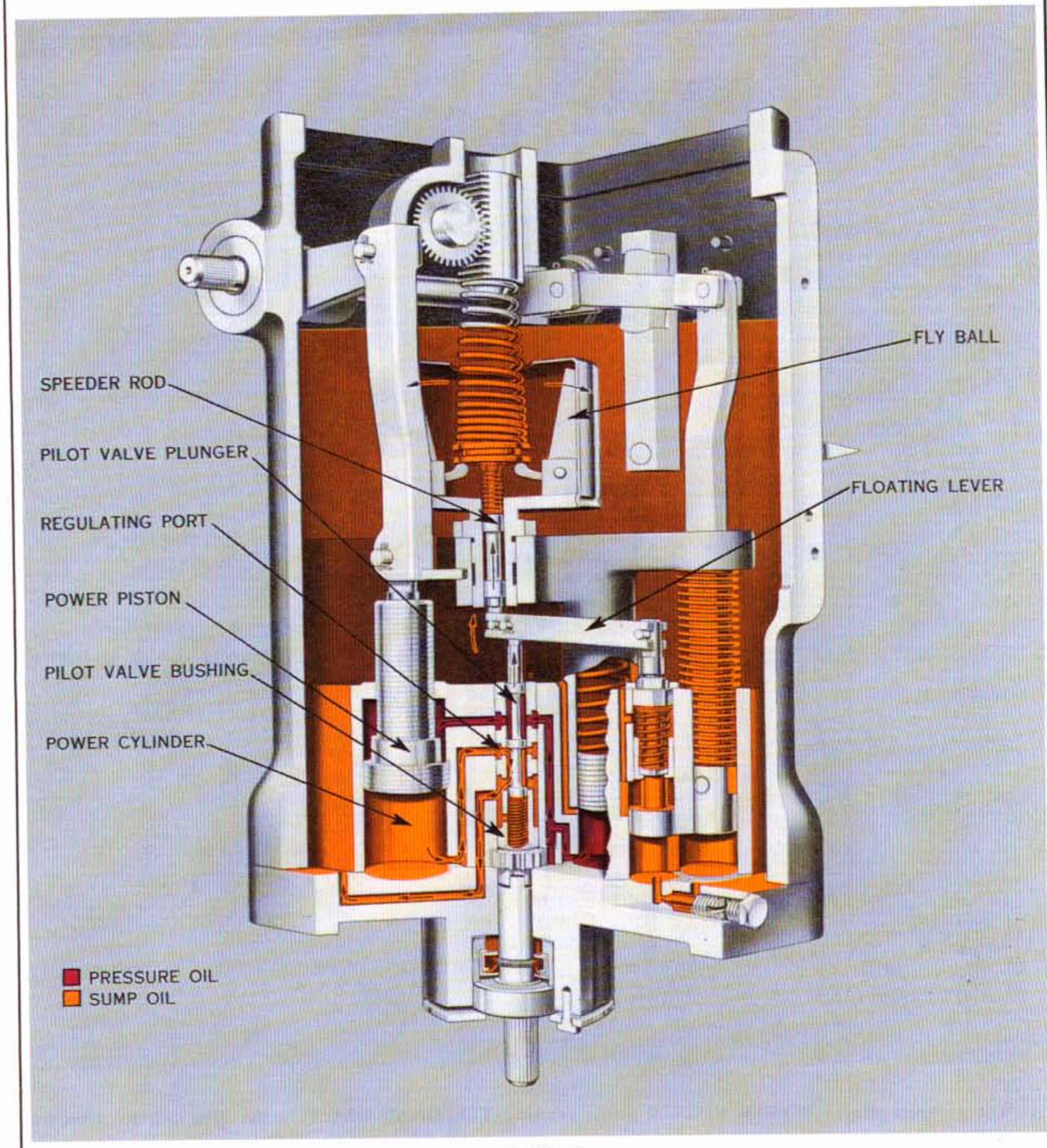
WOODWARD



Cut No. 4

1. Engine is running at normal speed under steady load.
2. FLYBALLS, SPEEDER ROD, PILOT VALVE PLUNGER, and RECEIVING COMPENSATING PISTON are in normal positions; REGULATING PORT in PILOT VALVE BUSHING is covered by land on PILOT VALVE PLUNGER.
3. POWER PISTON and TERMINAL SHAFT are stationary.

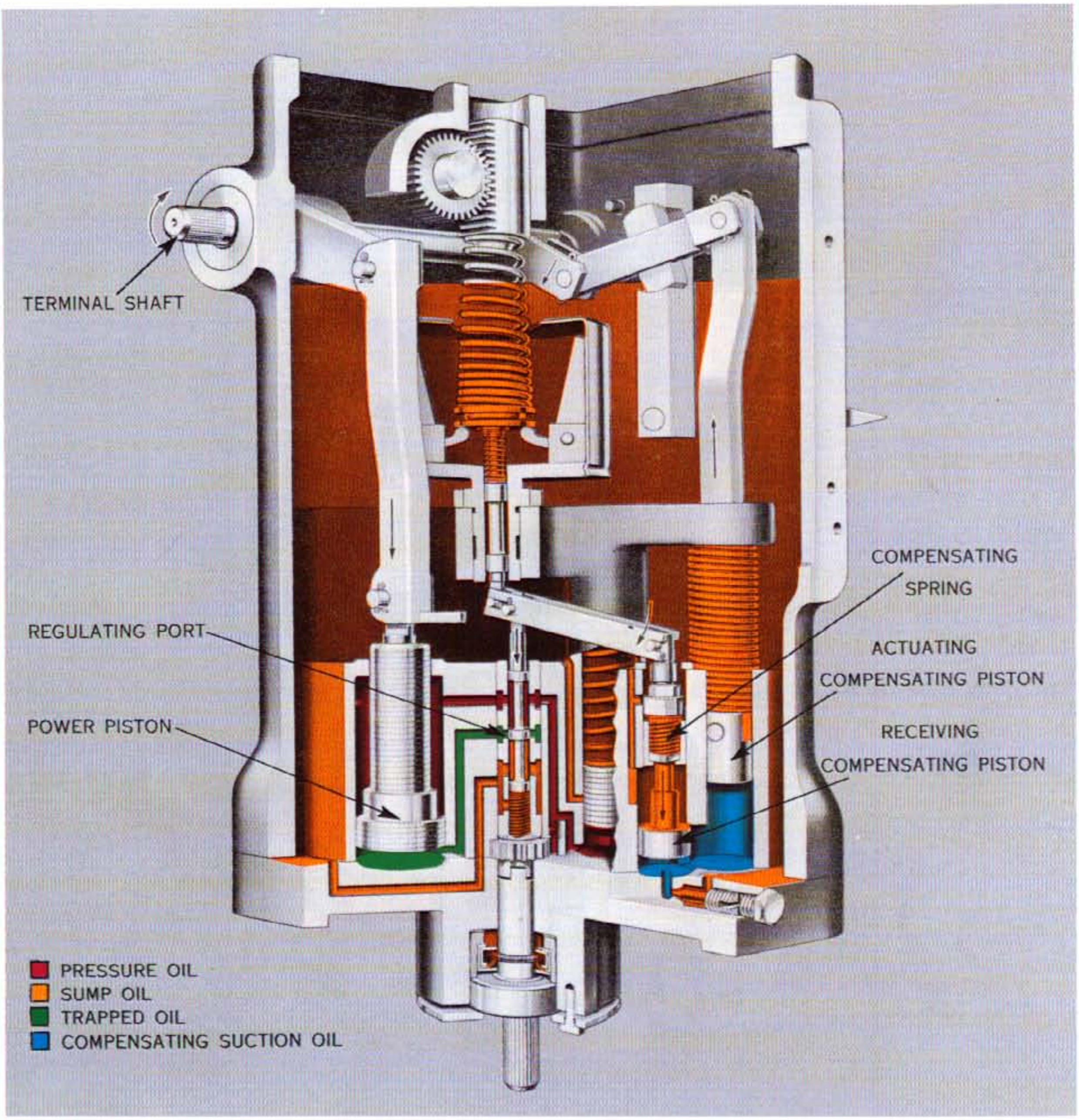
WOODWARD



Cut No. 5

LOAD REDUCTION:

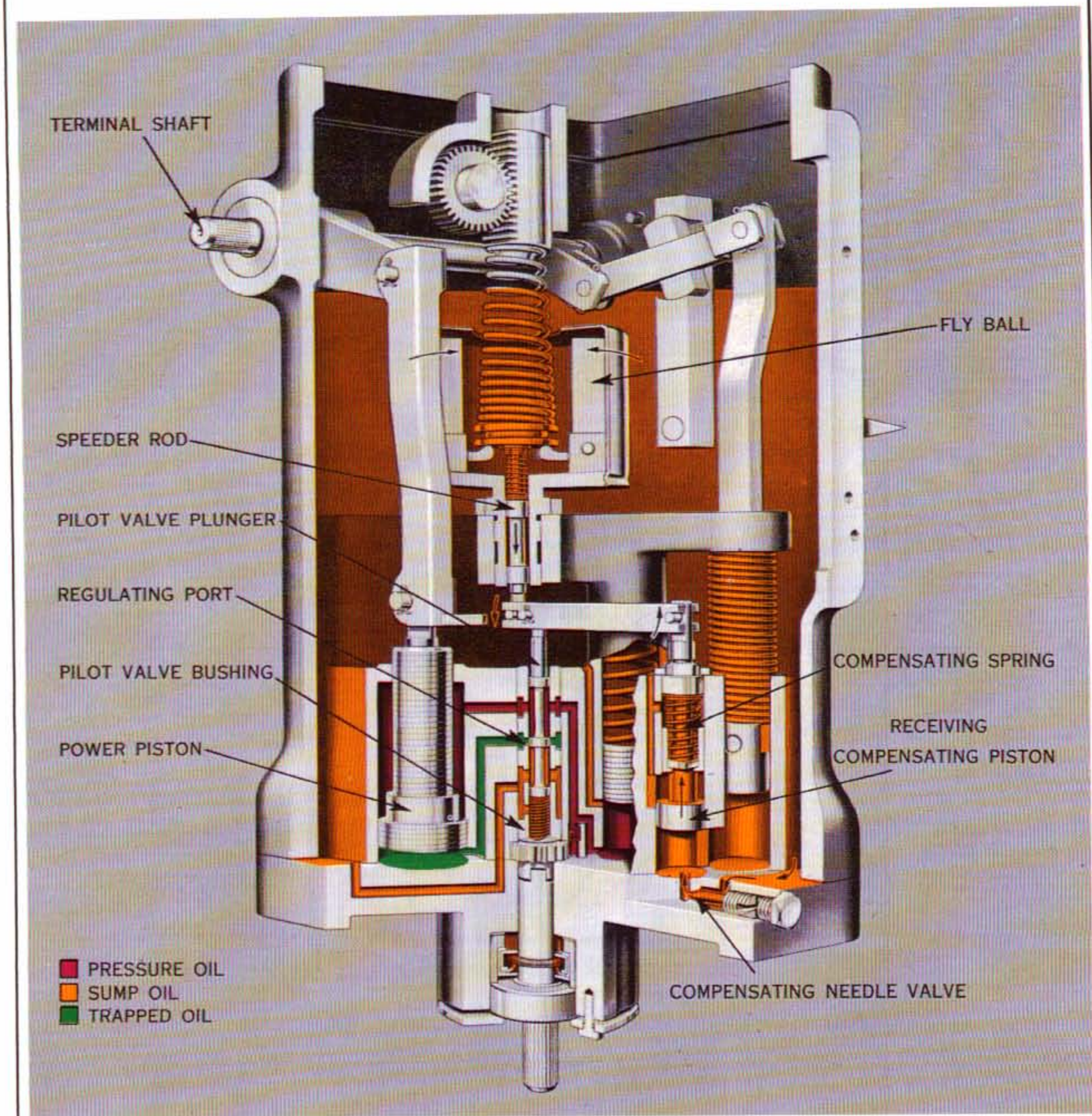
1. Load is decreased and speed increases.
2. As speed increases, FLYBALLS move out raising SPEEDER ROD and inner end of FLOATING LEVER, thus raising PILOT VALVE PLUNGER and uncovering REGULATING PORT in PILOT VALVE BUSHING.
3. Uncovering of REGULATING PORT opens bottom of POWER CYLINDER to sump and will allow oil pressure in top of POWER CYLINDER to move POWER PISTON down.



Cut No. 6

1. Oil pressure moves POWER PISTON down rotating TERMINAL SHAFT in the direction to decrease fuel.
2. As POWER PISTON moves down, ACTUATING COMPENSATING PISTON moves up and draws RECEIVING COMPENSATING PISTON down compressing COMPENSATING SPRING and lowering outer end of FLOATING LEVER and PILOT VALVE PLUNGER.
3. Movement of POWER PISTON, ACTUATING COMPENSATING PISTON, RECEIVING COMPENSATING PISTON and PILOT VALVE PLUNGER continues until REGULATING PORT in BUSHING is covered by land on PLUNGER.
4. As soon as REGULATING PORT is covered, POWER PISTON and TERMINAL SHAFT are stopped at a position corresponding to decreased fuel needed to run engine at normal speed under decreased load.

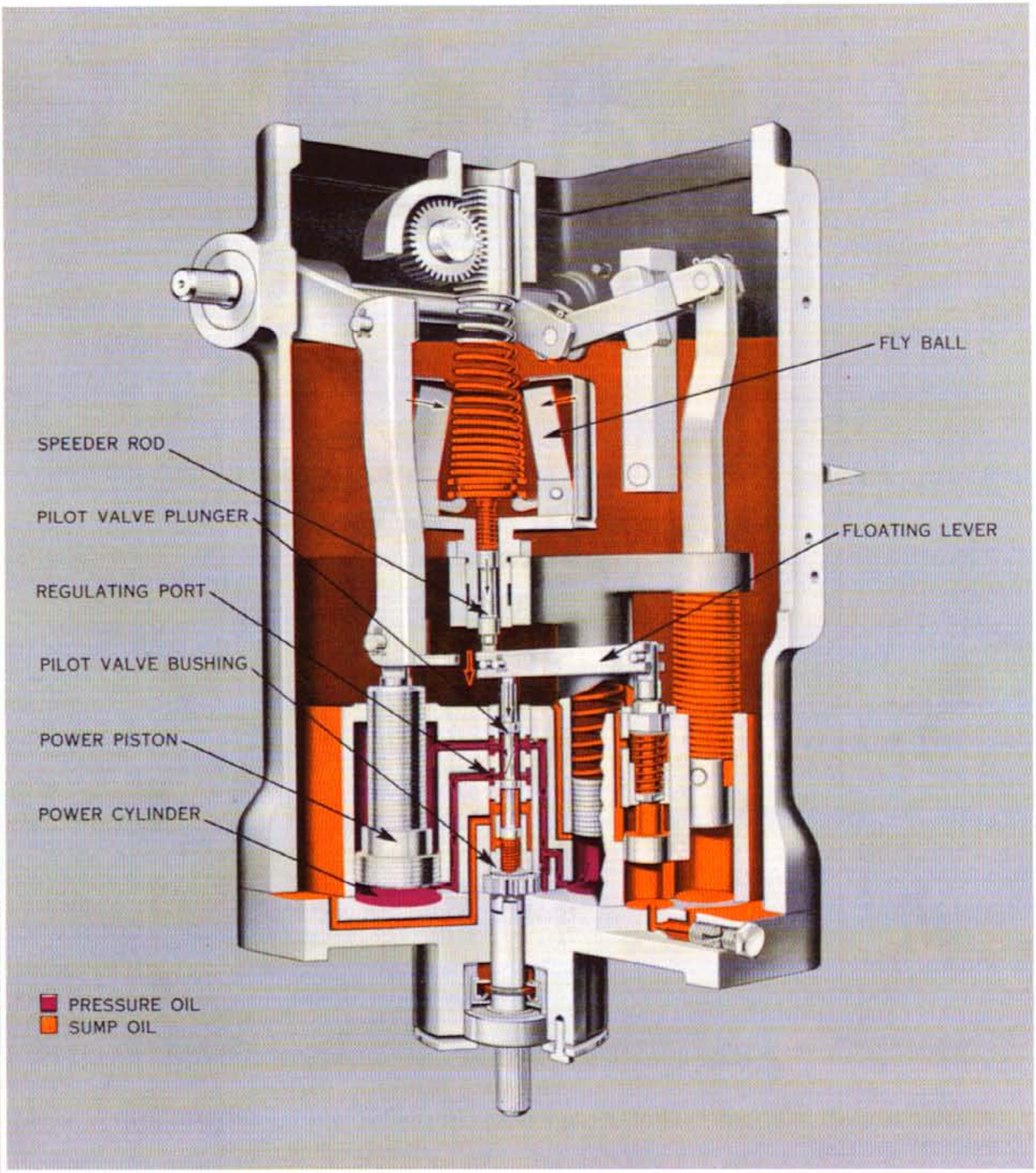
WOODWARD



Cut No. 7

1. As speed decreases to normal, FLYBALLS return to normal position lowering SPEEDER ROD to normal position.
2. RECEIVING COMPENSATING PISTON is returned to normal position by COMPENSATING SPRING at the same rate as SPEEDER ROD thus keeping REGULATING PORT in PILOT VALVE BUSHING covered by land on PILOT VALVE PLUNGER; flow of oil through COMPENSATING NEEDLE VALVE determines rate at which RECEIVING COMPENSATING PISTON is returned to normal.
3. At completion of cycle, FLYBALLS, SPEEDER ROD, PILOT VALVE PLUNGER, and RECEIVING COMPENSATING PISTON are in normal positions; POWER PISTON and TERMINAL SHAFT are stationary at a position corresponding to decreased fuel necessary to run engine at normal speed under decreased load.

WOODWARD

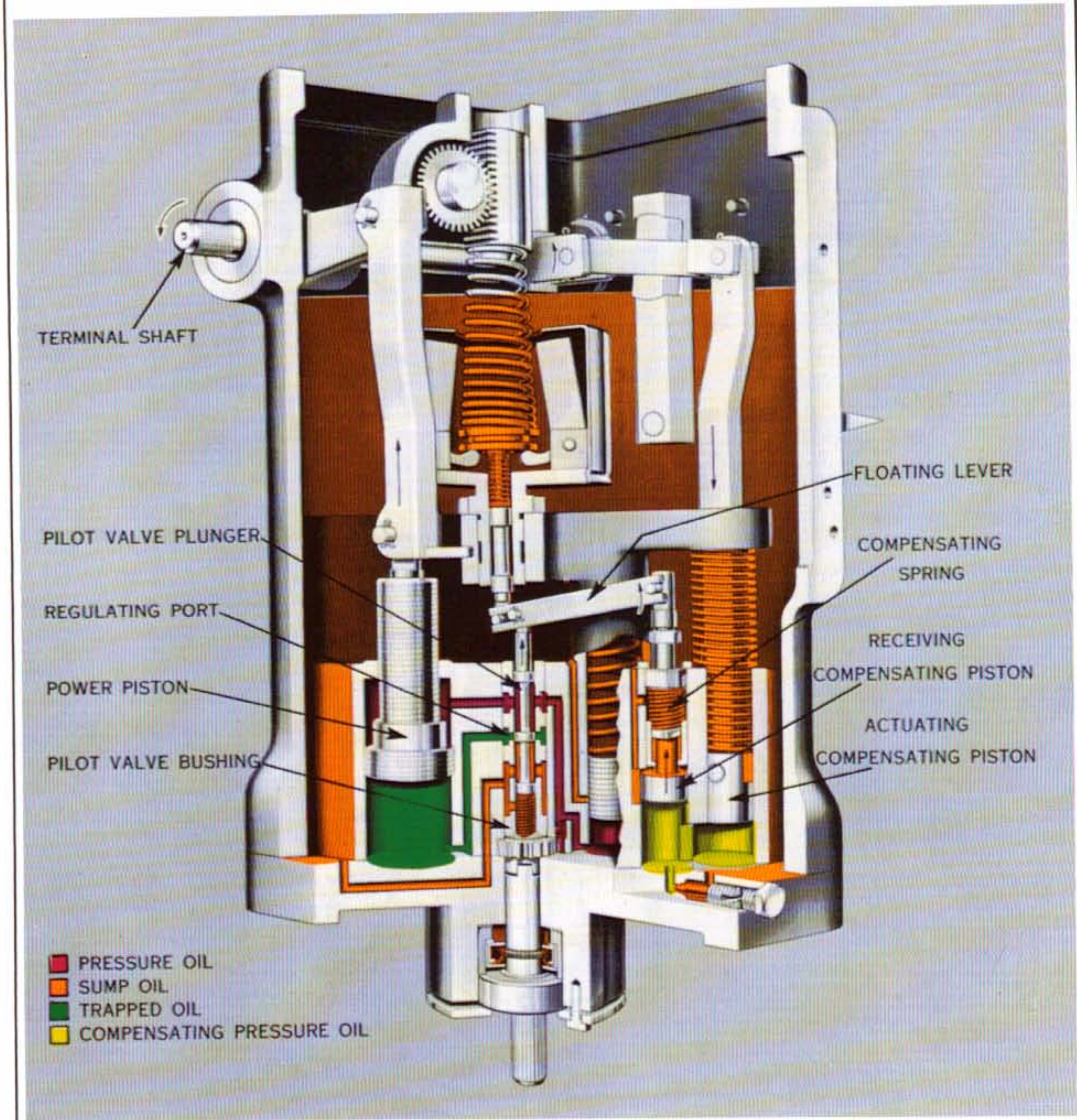


Cut No. 8

LOAD INCREASE:

1. Load is increased and speed decreases.
2. As speed decreases, FLYBALLS move in lowering SPEEDER ROD and inner end of FLOATING LEVER, thus lowering PILOT VALVE PLUNGER and uncovering regulating port of PILOT VALVE BUSHING.
3. Uncovering of REGULATING PORT admits pressure oil to bottom of POWER CYLINDER; since bottom area of POWER PISTON is greater than top area, oil pressure will move PISTON up.

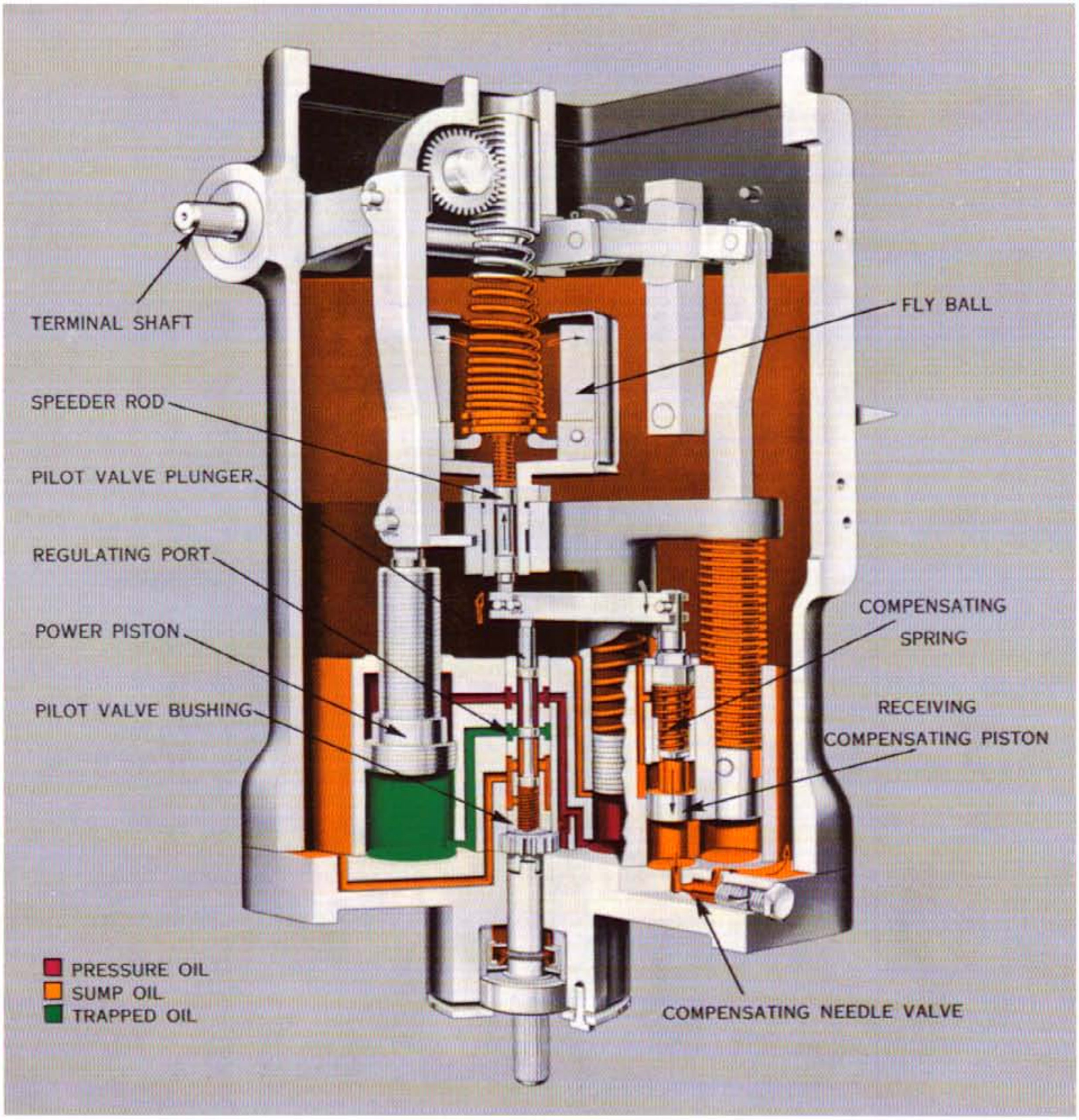
WOODWARD



Cut No. 9

1. Oil pressure moves POWER PISTON up and rotates TERMINAL SHAFT in direction to increase fuel.
2. As POWER PISTON moves up, ACTUATING COMPENSATING PISTON moves down and forces RECEIVING COMPENSATING PISTON up compressing COMPENSATING SPRING and raising outer end of FLOATING LEVER and PILOT VALVE PLUNGER.
3. Movement of POWER PISTON, ACTUATING COMPENSATING PISTON, RECEIVING COMPENSATING PISTON, and PILOT VALVE PLUNGER continues until REGULATING PORT in PILOT VALVE BUSHING is covered by land on PLUNGER.
4. As soon as REGULATING PORT is covered, POWER PISTON and TERMINAL SHAFT are stopped at a position corresponding to increased fuel needed to run engine at normal speed under increased load.

WOODWARD



Cut No. 10

1. As speed increases to normal, FLYBALLS return to normal position raising SPEEDER ROD to normal position.
2. RECEIVING COMPENSATING PISTON is returned to normal position by COMPENSATING SPRING at the same rate as SPEEDER ROD thus keeping REGULATING PORT in PILOT VALVE BUSHING covered by land on PILOT VALVE PLUNGER; flow of oil through COMPENSATING NEEDLE VALVE determines rate at which RECEIVING COMPENSATING PISTON is returned to normal
3. At completion of cycle, FLYBALLS, SPEEDER ROD, PILOT VALVE PLUNGER, and RECEIVING COMPENSATING PISTON are in normal positions; POWER PISTON and TERMINAL SHAFT are stationary at a position corresponding to increased fuel necessary to run engine at normal speed under increased load.

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Volume 8 in the series "*Harnessing Water Power on a Small Scale*" with the title GOVERNOR PRODUCT INFORMATION reflects the conclusion that in order to be able to solve the question of adequate governing in each specific situation, information on existing concepts and products should be made available, ideally to enable design engineers to specify particular governing requirements in each situation and to select the adequate concept and ultimately the appropriate device or product as part of the overall system.

This handbook gives a synopsis of the basic tasks of governing, the types of governors as well as important specifications for the selection of the governor or controller.

A list of governor manufacturers and bibliographical references simplify the access to relevant literature as well as to organizations and experts who can give further support.