Small Hydro – Mechanical Equipment

IEA Technical Report

IEA Hydropower Agreement

CANADA CHINA FINLAND FRANCE JAPAN NORWAY SPAIN SWEDEN UNITED KINGDOM

OVERVIEW OF THE IEA IMPLEMENTING AGREEMENT FOR HYDROPOWER TECHNOLOGIES AND PROGRAMMES

The Hydropower Implementing Agreement is a collaborative programme among nine countries: Canada, China, Finland, France, Japan, Norway, Spain, Sweden and the United Kingdom. These countries are represented by various organizations including electric utilities, government departments and regulatory organizations, electricity research organizations, and universities. The overall objective is to improve both technical and institutional aspects of the existing hydropower industry, and to increase the future deployment of hydropower in an environmentally and socially responsible manner.

HYDROPOWER

Hydropower is the only renewable energy technology which is presently commercially viable on a large scale. It has four major advantages: it is renewable, it produces negligible amounts of greenhouse gases, it is the least costly way of storing large amounts of electricity, and it can easily adjust the amount of electricity produced to the amount demanded by consumers. Hydropower accounts for about 17 % of global generating capacity, and about 20 % of the energy produced each year.

ACTIVITIES

Four tasks are operational, they are: 1. upgrading of hydropower installations, 2. small scale hydropower, 3. environmental and social impacts of hydropower, and 4. training in hydropower. Most tasks have taken about five years to complete, they started in March 1994 and the results will be available in May 2000. To date, the work and publications of the Agreement have been aimed at professionals in the respective fields.

UPGRADING

The upgrading of existing hydropower installations is by far the lowest cost renewable energy available today. It can sometimes provide additional energy at less than one tenth the cost of a new project. One task force of the Agreement is studying certain technical issues related to upgrading projects.

SMALL SCALE HYDROPOWER

Advances in fully automated hydropower installations and reductions in manufacturing costs have made small scale hydropower increasingly attractive. The small scale hydropower task force will provide supporting information to facilitate the development of new projects.

ENVIRONMENTAL AND SOCIAL ISSUES

For some hydropower projects the environmental and social impacts have been the subject of vigorous debate. There is a need to communicate objective information to the public, so that countries can make good decisions with respect to hydropower projects. The environmental task force will provide such information on possible social and environmental impacts and on mitigation measures.

TRAINING

The availability of well-trained personnel is a key requirement in the hydropower sector. The training task force is concentrating on training in operations and maintenance, and planning of hydro power projects.

THE INTERNATIONAL ENERGY AGENCY – IMPLEMENTING AGREEMENT FOR HYDROPOWER TECHNOLOGIES AND PROGRAMMES

SMALL HYDRO – MECHANICAL EQUIPMENT

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Trondheim, Norway

March 2000

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OTHER TECHNICAL REPORTS IN THIS SERIES

HYDRO POWER UPGRADING TASK FORCE (ANNEX 1)

Guidelines on Methodology for Hydroelectric Turbine Upgrading by Runner Replacement – 1998 (available to non-participants at a cost of US $ 1,000 per copy)

Guidelines on Methodology for the Upgrading of Hydroelectric Generators – to be completed in May 2000.

Guidelines on Methodology for the Upgrading of Hydropower Control Systems – to be completed in 2000.

SMALL SCALE HYDRO POWER TASK FORCE (ANNEX 2)

Small Scale Hydro Assessment Methodologies – to be completed in May 2000 (available to non-participants on request)

Research and Development Priorities for Small Scale Hydro Projects – to be completed in May 2000 (available to non-participants on request)

Financing Options for Small Scale Hydro Projects – to be completed in May 2000 (available to non-participants on request)

Global database on small hydro sites available on the Internet at:
www.small-hydro.com

ENVIRONMENT TASK FORCE (ANNEX 3)

Survey on Positive and Negative Environmental and Social Impacts and the Effects of Mitigation Measures in Hydropower Development – 2000 (available to non-participants on request)

A Comparison of the Environmental Impacts of Hydropower with those of Other Generation Technologies – 2000 (available to non-participants on request)

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Hydropower and the Environment: Present Context and Guidelines for Future Action
Volume 1: Summary and Recommendations
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Guidelines for the Impact Management of Hydropower and Water Resources Projects – 2000 (available to non-participants on request)

EDUCATION AND TRAINING TASK FORCE (ANNEX 5)

(All of the following reports are available on the Internet at www.annexv.iea.org Some reports may consist of more than one volume.)

Summary of Results of the Survey of Current Education and Training Practices in Operation and Maintenance –   1998 (available to non-participants on request)

Development of Recommendations and Methods for Education and Training in Hydropower Operation and Maintenance - 2000 (available to non-participants on request)

Survey of Current Education and Training Practice in Hydropower Planning – 1998 (available to non-participants on request)

Structuring of Education and Training Programmes in Hydropower Planning, and Recommendations on Teaching Material and Reference Literature - 2000 (available to non-participants on request)

Guidelines for Creation of Digital Lectures – 2000 (available to non-participants on request)

Evaluation of tests – Internet Based Distance Learning – 2000 – (available to non-participants on request)

BROCHURE

A brochure for the general public is available. It is entitled “Hydropower – a Key to Prosperity in the Growing World”, and can be found on the Internet (www.usbr.gov/power/data/data.htm) or it can be obtained from the Secretary (address on the inside back cover).

SMALL HYDRO
MECHANICAL EQUIPMENT

1 INTRODUCTION

Small hydro turbines have played a very important role during the development of hydropower around the world. The introduction of hydropower in developed countries started with small hydro for electricity production at the end of 18th century. As an example it should be noted that as late as at the end of World War II 2000 small hydro units with output less than one MW were still in operation in Norway, that has the highest hydropower production in Western Europe.

It should also be noted that small hydro will give only a supplementary production of clean renewable energy in developed countries, but it could play the main role in the electricity production in developing countries.

Also in remote valleys and coastal areas of mountainous countries small hydropower production may also have a positive impact on the development of local communities where young people may leave the farms because of low income from farming. The possibility of supplementary income from local electricity production with possibility to start small industry could be the goal for small hydro development in remote areas of developed countries as well as for developing countries.

Before going into the description of mechanical equipment for small hydro, we should look at the role of the total hydropower production in the global electricity supply. In 1997 the total global electricity production was 13 300 TWh/year of which 2 600 TWh/year was hydropower. (Ref. 1.) The main production came from thermal (not renewable) energy sources covering for 65 % of the consume while 19.5 % came from hydropower and nuclear power covered for the rest. Other renewable energy sources like wind power, solar energy, wave power and a negligible electricity production from bio-mass covered for less than 0.5 % in 1998. (Wind power alone covered for 0.1 % and even if it is increasing by a factor of 10 it will still play a negligible part of the production.) In countries with cold winter climate biomass production is a valuable energy source for heating, but due to high cost only a negligible part is used for electricity production. Also solar energy has so far mainly been used for heating. This is because of high cost and high-energy consumption in production of solar cells for electricity production.

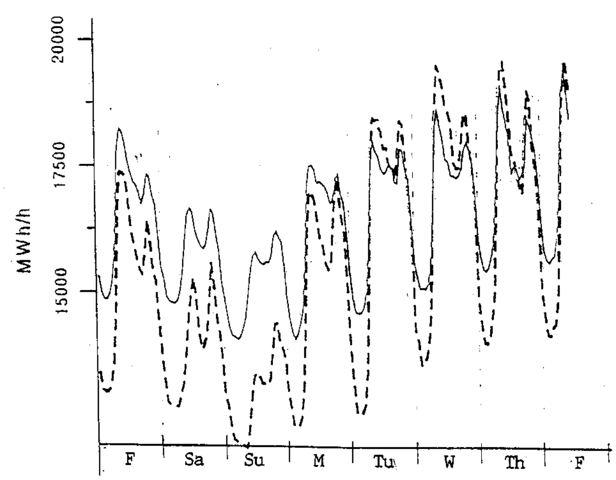


Fig. 1 Variation in Norwegian hydropower production (dotted bold lines) and the Norwegian consumes (full lines) during one week from 5. March 1999

Conventional hydropower from plants with large reservoirs is at the time being the only non-polluting source for electricity production with possibility of storing energy, which can be used for peak load production. The role of such hydropower production is illustrated in the one-week recording of the electricity production in Norway. From Fig. 1 it can be seen that the Norwegian hydropower (dotted lines) have a daily peaking of 5 000 MW and a weekly peaking of 10 000 MW. This peak production is larger than the variations in the Norwegian consumption (full lines) and a contribution of peak power is transferred to the Swedish system with electricity production coming from 50 % nuclear and 50 % hydropower mainly from low head river plants.

The role of small hydro will not be to support the peak load production because most of these plants will be run of the river plants. However, it will be possible to plan the production from knowledge of the river flow through the year and small hydro will not increase the need for peak power during the week in the same way as wind power (with unpredictable production). Thus small hydro will give a contribution of renewable energy which can be planned to fit into the electricity system even if the production will be decreased during winter or dry periods of the year. Another advantage is that the impact of the environment is very small and small hydro is normally accepted as a positive contribution of renewable energy.

Examples from the historical development of small hydro in a developed country maybe taken from Norway where the number of units at the end of World War II was approximately 2000. The role of micro units with output less than 100 kW played a negligible role in the total electricity production. However, the impact on local communities was large and this electricity production formed the root of local industry like saw mills, furniture production and flour mills for the farmers. Also the impact from electric lightning during the long dark winter should not be underestimated. (The national electric grid did not cover the whole country at that time.)

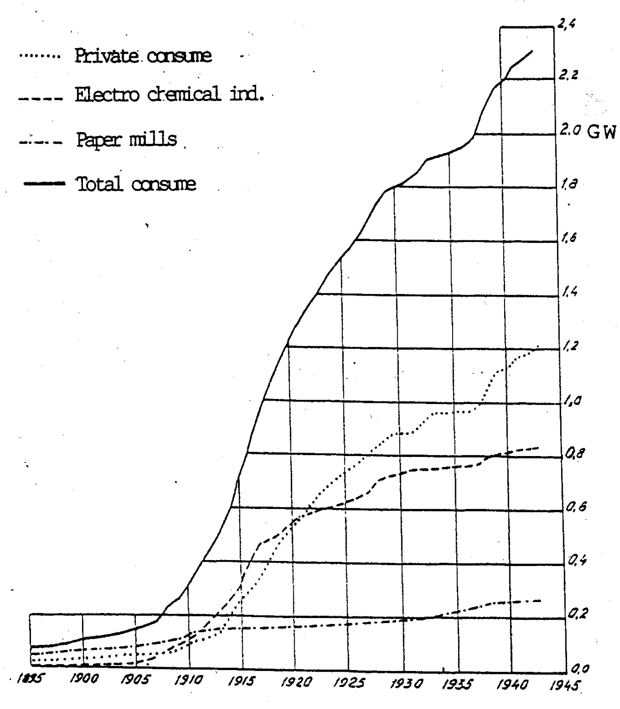


Fig. 2 Development of installed hydropower in Norway from 1895 to 1943

The electric power production from 1895 to 1943 is illustrated in Fig. 2, where the installed capacity of electric power was 2 300 MW only. During the period 1943 – 1995 the power production increased to 27 000 MW when the large hydropower plants were developed. From the available information following interesting figures can be found from the power production in 1943: 72.9 % of the total number of units had output of 100 kW or less, but the production was only 1.6 % of the total.

On the contrary only 9.5 % of the total number of units had output exceeding 1000 kW, but these units produced 93.1 % of the total production. Finally the main production came from units with output exceeding 10 000 kW with only 2.2 % of the total number of units, but with 73 % of the total power production.

From the history of small hydro following lesson may be learned.

- Micro turbines will only give a supplementary power production, but may give a contribution to the activities in remote parts of the countries in many cases.

- Mini turbines with output up to 1000 kW may give a contribution to the electricity supply without an environmental discussion about dams and large reservoirs. The production in mountainous countries will be larger and more predictive than wind power.

- Medium size and large small hydro units with outputs up to 10 MW operating in run of the river plants may be an acceptable alternative to larger plants for environmental reasons.

It is also of interest to compare the energy flux or the so-called energy density of the available supplementary renewable energy sources at present time. In the following table a comparison is made of the known renewable sources for electricity production (except solar energy).

Energy flux	Available (kW/m^2)	Utilized (kW/m^2)
Wind power (wind speed 15m/s)	2.2	0.7
Sea current (velocity 3 m/s)	13.5	6.0
Small hydro (net head 5 m)	485,-	413,-
Wave power on Norwegian coast	25 (kW/m)	12 (kW/m)

From this table it may be concluded that small hydro should be an economic alternative in mountainous countries like Norway.

2 CLASSIFICATION AND DESCRIPTION OF DIFFERENT TURBINE TYPES

This chapter of mechanical equipment does not include water wheels utilizing the gravity of water or the kinetic energy of water on wooden blades normal to the stream direction of the water. The reason for not describing water wheels is due to their low efficiency and low rotating speed, that is not suitable for conversion to electric energy by means of a high speed generator.

The turbines used for small hydro can be classified in two main groups:

- **Reaction turbines**
  In these turbines the runner of the turbine is completely filled with water and the pressure at the inlet of the runner is higher than at the outlet of the runner. About 50% of the energy drop through the runner are from pressure energy. Then an acceleration of the relative velocity occurs in the runner channel formed by the blades. This is the reason for the name REACTION TURBINE. Typical types of reaction turbines are: RADIAL TURBINES, RADIAL-AXIAL TURBINES LIKE FRANCIS TURBINES, AND AXIAL TURBINES LIKE PROPELLER TURBINES AND KAPLAN TURBINES.

- **Impulse turbines**
  In these turbines the total energy is transformed to kinetic energy at the runner inlet and there is no pressure drop through the runner. The energy transferred to the runner is caused by the impulse from changing direction of the water flow. In these turbines the geodetic head difference between runner and tail water

level is lost. Types of impulse turbines are: PELTON TURBINES, THE AXIAL TURBINES, TURGO TURBINES AND CROSS FLOW TURBINES.

Description of different types of turbines

For the highest heads Pelton turbines may be used. For small hydro fully speed-regulated turbines or turbines with control of the flow only are normally used by needle nozzle regulating systems. Synchronising can be made by a small needle opening set for a speed slightly above synchronising speed allowing for synchronising when the speed is slowly passing correct synchronising speed. Also Turgo turbines may be used in the same way.

Mini and micro turbines up to 6 jets may be used allowing for regulating the flow by closing one or more jet i.e. a stepwise control by 1/6 of full flow. In Fig. 3 an example of a small Pelton turbine with one jet is shown.

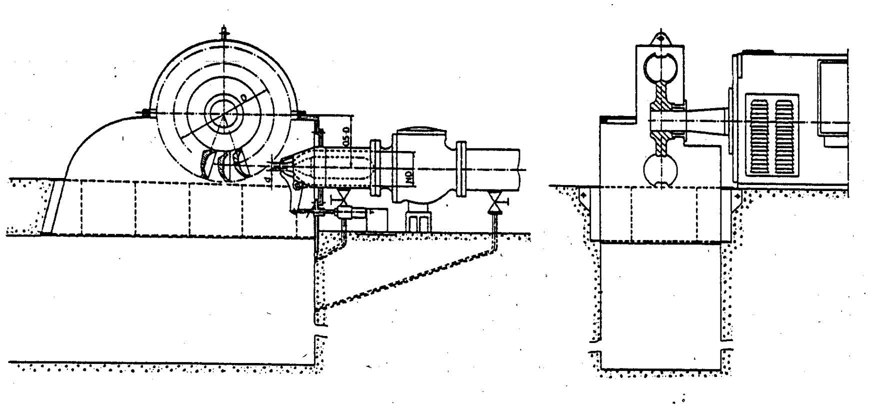


Fig. 3 A Pelton turbine for small hydro

A cross flow turbine is an impulse turbine with water flowing in on one side of the runner and out on the other side passing the buckets in two places on the periphery. The runner is running in air with loss of the head from the runner to the tailrace level and the turbine is because of this classified as an impulse turbine. The control of flow and speed is simple on this turbine type in the same way as for a Pelton turbine. The specific speed or speed number (explained later) is higher than for a Pelton turbine because of larger flow capacity.

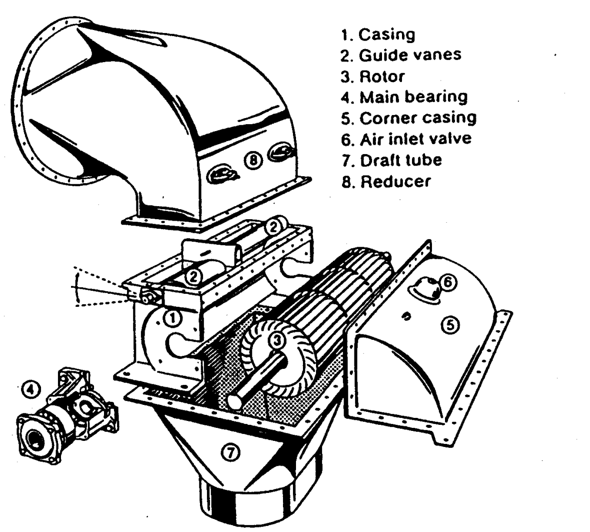


Fig. 4 Cross flow turbine exploded view

As described in the next chapter Francis turbines are used over a wide range of head up to 300 m for small hydro and 50-70 m for micro units. For micro turbines a simplified radial runner version may also be used.
Because of the complicity and price the guide vane regulating system may be omitted and substituted by positioning the guide vanes in steps for small hydro unless flow regulation is required. For mini turbines and especially for micro turbines a fixed guide vane cascade is normally installed. A possibility to adjust the fixed guide vane position to a smaller opening in dry season may be an option to stopping and starting the unit for water level control. In Fig. 5 a Francis turbine for small hydro is shown.

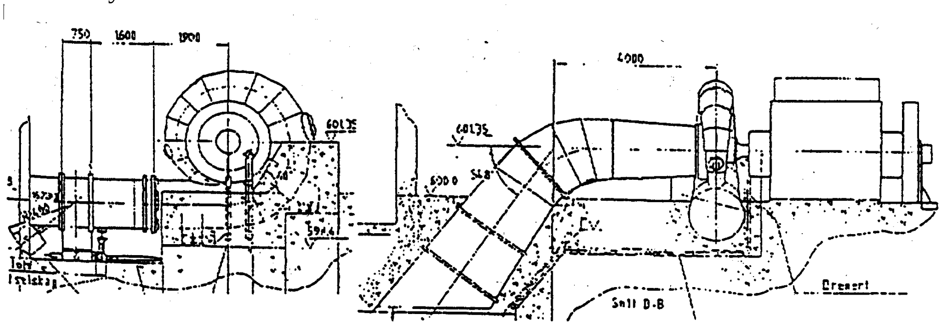


Fig. 5 A small hydro Francis turbine with fixed guide vanes

Propeller types and Kaplan types are used for the lowest heads. For the largest units with diameter up to 2.00 m movable blades on the runner may be used to avoid the sharp drop in efficiency at operation outside best efficiency of a fixed blade position.

For mini and micro turbines the blades may be adjustable when the unit is stopped in order to decrease the blade angles and increase the efficiency at part load during the dry period.

Also fixed guide vanes are normally used for micro and mini turbines. With a fixed guide vane cascade it is possible to use twisted guide vanes that makes it possible to obtain a wider range of high efficiency with fixed runner blades. For propeller type and Kaplan type of turbines it is convenient to use the so-called S shape design with horizontal shaft allowing for an arrangement with the generator and gearbox outside the turbine. In Fig. 6 an S-type small hydro unit is shown.

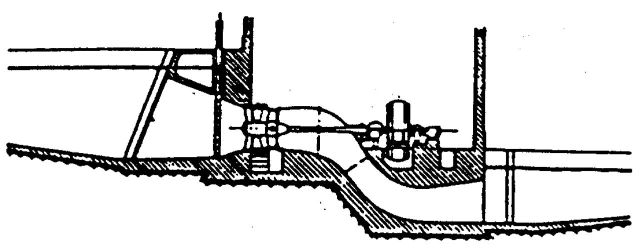


Fig. 6 S-type Kaplan turbine for small hydro

For micro and mini turbines the vertical unit is often used because the speed is often high enough for a direct coupling to the generator without a gearbox.

3 CHARACTERISTIC PARAMETERS FOR THE CHOICE OF TURBINE TYPE, SIZE AND SPEED

Duration curve
The choice of turbine type, size, speed and suction is based on the net head that must be based on maximum flow and best efficiency flow which must be determined by the river or stream where the turbine shall be installed.

Because small hydro power stations are normally built as run of the river plants, the maximum flow capacity of the turbines must be determined by means of the flow duration curve for the river or stream in question.

A duration curve is illustrated in Fig. 7 that show how many days in an average year the flow is equal to or larger than the value given for the regarded point on the curve.

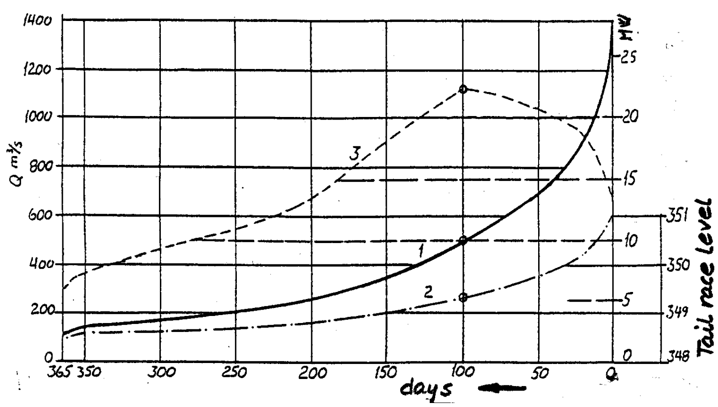


Fig. 7 Example of a typical flow duration curve of a river together with the variation of water level downstream of a possible dam for a large power plant.

Often the tailrace level may also rise with increasing flow and thus the net head is reduced.
The turbine output corresponding to the flow and net head that can be calculated. Estimated efficiency may also be available. An optimising of the price per kWh can be found by means of the price of the mechanical equipment and cost of operation including maintenance in addition to the cost of civil work versus the produced kWh as illustrated in Fig. 8.

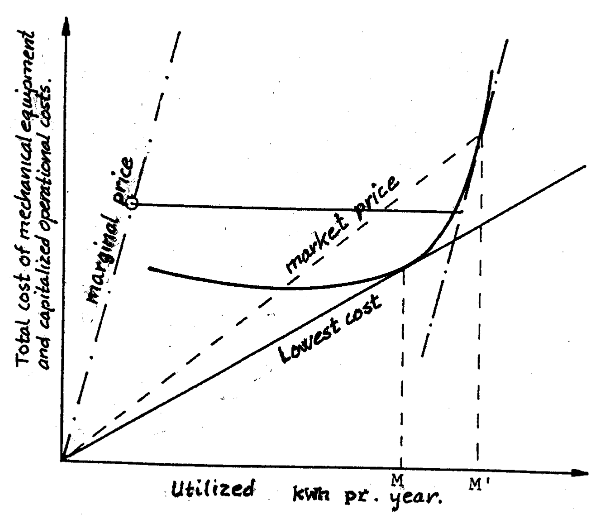


Fig. 8 Optimising of cost per kWh as function of installed capacity of turbines

Choice of turbine type
The basic parameters for the choice of turbine type, size and speed are net head H (m) maximum flow and best efficiency flow Q_n and *Q (m^3/s) respectively as well as the available net positive suction head $NPSH_A$ that includes barometric pressure and water temperature.

In general, the Pelton turbines and also the Turgo turbine that is an axial type of Impulse turbine cover the high-pressure domain down to 50 m for small hydro. The Francis types of turbines cover the largest range of head below the Pelton turbine domain with some overlapping and down to 10 m head for small hydro. Simplified radial turbines may also be used for micro turbines. The lowest domain of head below 10 m is covered by axial type of turbines i.e. propeller type with fixed blades or Kaplan type with movable blades. Runners for propeller turbines, with blades that can be adjusted when stopping the turbine as described in chapter 2, may also be used. For low heads and up to about 50 m head also the Cross-Flow impulse turbine can be used. This type of turbines is fully regulated, that is a great advantage. However, the distance between the runner and the tailrace level can not be utilised because the turbine is an impulse turbine that does not allow the runner to be filled with water which is necessary in order to obtain a suction pressure at the runner outlet.

The loss of head from runner to tailrace level is the reason for the low efficiency of Cross Flow turbines used for low heads compared with a Francis turbine or a Propeller turbine that utilises the total head from upstream level to downstream level.

An example of the range of operation for small hydro turbines is illustrated in Fig. 9. (Note micro turbines with power less than 100 kW is not covered in Fig. 9, which show examples of standardised turbines from a manufacturer of small hydro). Cross flow turbines that are normally used in the micro turbine domain are not included in Fig. 9.

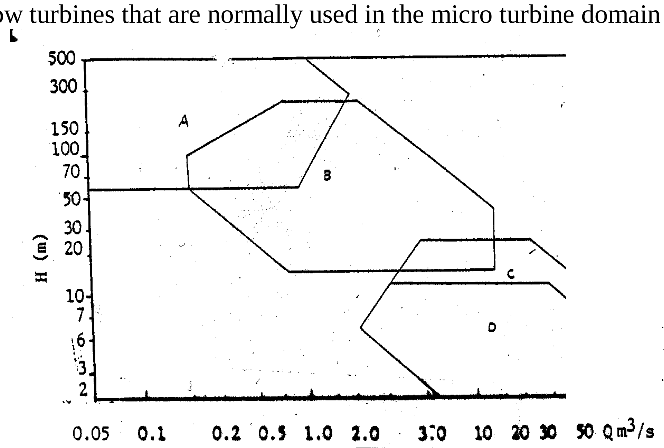


Fig. 9 Example of range of operation of different types of small hydro turbines.
A = Pelton turbines, B = Francis turbines, C = Kaplan- and Bulb or S type turbines including Propeller turbines.

Basic parameters for dimensional design of turbines
As described previously, the different turbine types covers a certain range of head and flow for mini-turbines and small hydropower plants. Micro turbines are normally built for heads below 200 m with a larger overlapping of types than shown for small hydro turbines in Fig. 9. In addition, also centrifugal pumps in reverse operation can be used overlapping multijet Pelton turbines and Francis turbines. Cross flow turbines and various kinds of more or less successful hybrids may cover the whole range of operation up to 200 m head.

This chapter only deals with guide lines for dimensioning of Pelton turbines, Francis turbines and Radial turbines as well as Propeller and Kaplan turbines based on best efficiency point (BEP) of operation.

The basic parameters for dimensioning the runner - the most important part - of the turbine are:

- The flow (or capacity) at best efficiency point *Q (m^3/s). Also the nominal flow at 100% output must be known = Q_n (m^3/s) (Q_n > *Q).
- The nominal design head (nominal head) H (m)
- The available net positive suction head $NPSH_A$ (m)

By means of the given parameters the specific speed or speed number of the turbine can be found.

According to the international norm IEC the equation of specific speed yields:

$$n_s = n\sqrt{Q_n} / E^{0.75} \qquad (1)$$

Here: n = (rev/sec), E = gH (m^2/s^2) = (J/kg) [F = ma (N = kg m/s^2) and (J = Nm = kg m^2/s^2)]

Another version of specific speed is THE SPEED NUMBER that refers to best efficiency point (BEP) where Q = *Q and the angular speed $\omega = {}^*\omega$ (rad/s) and the nominal head H that is also the head for best efficiency H = *H.

The equation for the speed number yields:

$$^*\Omega = {}^*\omega\sqrt{^*Q} /(2E)^{0.75} = {}^*\omega\sqrt{^*Q} /(2g\,^*H)^{0.75} \qquad (2)$$

The size of the turbine can be found by the capacity

$$^*\underline{Q} = {}^*Q / \sqrt{2g\,^*H} \quad (m^2) \qquad (3)$$

It is also convenient to introduce reduced velocities (dimensionless) for dimensioning of the various types of turbines:

$$\underline{c} = c / \sqrt{2gH} \qquad \underline{u} = u / \sqrt{2gH} \quad and \quad \underline{w} = w / \sqrt{2gH}$$

were c = absolute velocity u = circumferential speed and w is relative velocity. It is also convenient to introduce reduced circumferential speed that is not dimensionless $\underline{\omega} = \omega / \sqrt{2gH}$ (m^{-1}). The capacity is also the reduced flow $\underline{Q} = Q / \sqrt{2gH}$ (m^2) (see eq. (3)) and the speed number $\Omega = \underline{\omega}\sqrt{\underline{Q}}$ (dimensionless).

For the main dimensions of a turbine it is convenient to use following notations (see Fig. 10):

Inlet of turbine $_0$
Inlet of runner $_1$
Outlet of runner $_2$
Outlet of draft tube $_3$ (For Pelton turbines (and cross flow turbines) $_3$ is surface of tailrace level)

It is convenient to introduce the meridional velocity vector component and the tangential vector component of the absolute velocity c.

- The meridional component $c_m = c \cdot \sin(\alpha)$, where α is the flow angle versus tangential direction.
- The tangential component $c_u = c \cdot \cos(\alpha)$.

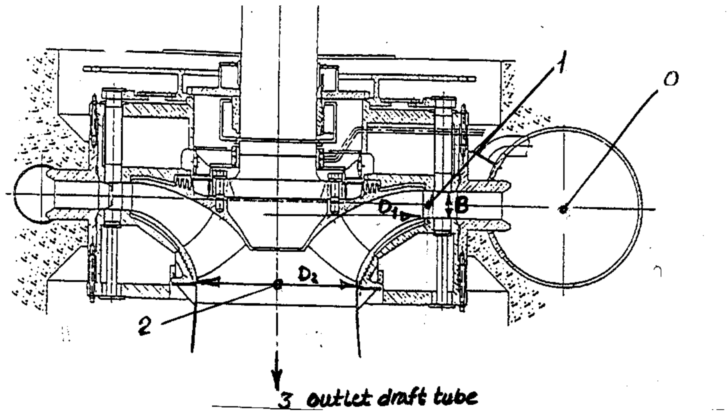


Fig. 10   Notation of positions in a Francis turbine

When studying the dimensions it is convenient to introduce the Euler turbine equation

$$gH\eta_h = u_1 c_u - u_2\ c_{u2} \qquad (4)$$

where η_h is the hydraulic efficiency taking into consideration the flow friction losses through the turbine. gH = E is the specific energy from inlet of turbine to outlet of turbine. Note that the draft tube outlet loss $(Q/A_3)^2/(2g)$ is not included in the head loss in the turbine. (A_3 = cross section of draft tube outlet.)

At best efficiency point (BEP) we have theoretically no swirl flow out of the turbine i.e. $\underline{c}_{u2} = 0$.
Thus the Euler turbine equation yields for best efficiency point:

$$g\ {}^{*}H\ {}^{*}\eta_h = {}^{*}u_1\,{}^{*}c_{u1} \qquad (5)$$

Now let us go back to the speed number eq. (2) and study the Francis turbine in Fig. 10.
We assume we have an ideal turbine with inlet velocity diagram and outlet velocity diagram as follows at best efficiency point where $c_{u2} = 0$. (See Fig. 11 where $c_{u2} \neq 0$ and Q < *Q).

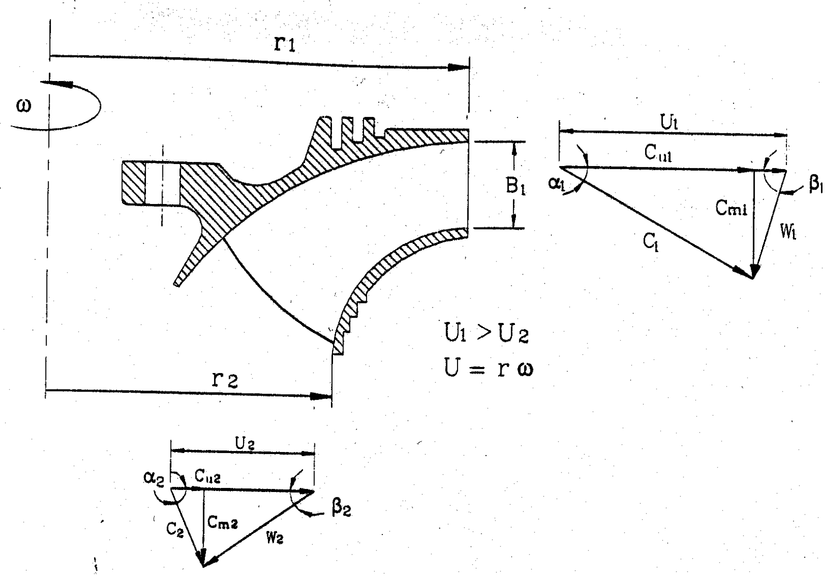


Fig. 11   Velocity vector diagram at inlet and outlet of a Francis turbine

The speed number can now be transformed to following equation:

$$*\Omega = {}^{*}\underline{\omega}\sqrt{\underline{Q}} = *\omega\sqrt{*Q}/(2gH)^{0.75} = *\omega\sqrt{\frac{\pi D_2^2}{4}c_{m2}}/(2gH)^{0.75}$$

or

$$*\Omega = \sqrt{\pi}\ \frac{u_2^{\ 3/2}}{(2gH)^{3/4}}\sqrt{\tan\beta_2} \qquad (7)$$

where β_2 is the blade outlet angle. This equation is valid for all turbines with axial outlet flow i.e. also Kaplan and Propeller types besides Francis turbines.

If we substitute for gH by means of the Euler equation we arrive at following interesting equations by substituting for $(u_2/u_1) = D_2/D_1$.

$$*\Omega = \sqrt{\pi}\left(\frac{\eta_h}{2}\right)^{0.75}\left(\frac{u_1}{c_{u1}}\right)^{0.75}\left(\frac{D_2}{D_1}\right)^{1.5}\sqrt{\tan\beta_2} \qquad (8)$$

This equation is valid for all turbines with axial outlet when assuming a uniform flow with C_{m2} to be constant over the cross section.

For a mini turbine with radial outlet we have

Q = $\pi\, D_2 \cdot B_2 \cdot c_{m2}$ instead of $Q = \pi\ D_2^2/4\, c_{m2}$ and the equation for the speed number can then be written as follows:

$$*\Omega = \sqrt{\pi}\ \sqrt{\frac{4B_2}{D_2}}\left(\frac{\eta_h}{2}\right)^{0.75}\left(\frac{u_1}{c_{u1}}\right)^{0.75}\left(\frac{D_2}{D_1}\right)^{1.5}\sqrt{\tan\beta_2} \qquad (9)$$

From eq. (7) and eq. (8) we find that various shapes of runners can be designed for the same speed number i.e. the same speed, flow and head. This is illustrated in Fig. 12.

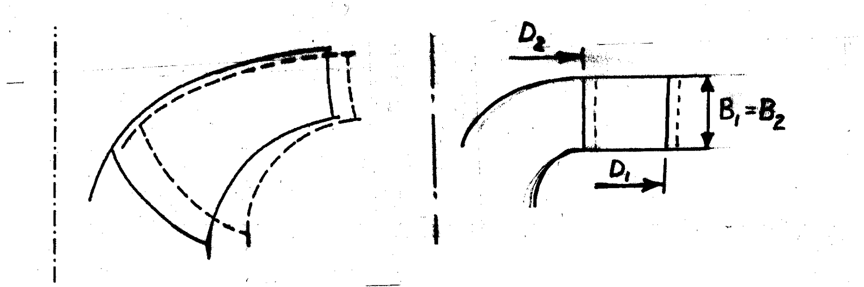


Fig. 12 Different shape of a Francis runner for the same specific speed or the same speed number left and radial turbine right

The designer has the choice of outlet angles (β_2) in the range of 12 - 20^0 normally with increasing angles for increasing specific speed. Variations of inlet angles can be compensated by the ratio (D_2/D_1) and the choice of u_1

noting that by choosing u_1 the value of c_{u1} must be calculated by means of the Euler turbine equation eq. (5) that is valid for $c_{u2} = 0$.
It is needed some experiences for the design because the inlet velocity ratio u_1/c_{u1} will also affect the reaction ratio and the inlet pressure, which may lead to inlet cavitation if the inlet pressure is too low for high specific speed turbines leading to inlet cavitation.

For a Pelton turbine the speed number can be written as a function of the jet diameter over pitch diameter ratio d_s/D as follows when substituting for the flow Q by $\sqrt{2gH} \cdot \pi\, d_s^2 / 4$ where $\sqrt{2gH}$ is the theoretical jet velocity. Here d_s = theoretical jet diameter (m) and D = jet tangential diameter of the runner (m).

Then

$$\Omega = \omega\sqrt{Q}\,/(2gH)^{3/4} = \frac{\omega D}{D}\sqrt{(\pi\, d_s^2/4)\,(2gH)^{0.5}}\,/(2gH)^{0.75} = \sqrt{\pi}\,\frac{\omega D}{2}\left(\frac{d_s}{D}\right)\frac{1}{(2gH)^{0.5}}$$

Further when substituting for the theoretically circumferential speed of the runner by $u = \frac{\omega D}{2} = \frac{1}{2}\sqrt{2gH}$, we arrive at following equation:

$$\Omega = \frac{\sqrt{\pi}}{2}\left(\frac{d_s}{D}\right) \tag{10}$$

The reaction ratio
When simplifying by assuming $\eta_h = 2 \cdot {}^*\underline{u}_1 \cdot {}^*\underline{c}_{u1} = 1.0$ the equation for the reaction ratio yields:

$$\frac{{}^*h_1 - {}^*h_2}{H} = 2\,\frac{{}^*u_1\,{}^*c_{u1} - \frac{1}{2}\,{}^*\underline{c}_{u1}^2}{2gH}$$

or when introducing reduced pressure *h/H = *$\underline{h}$ i.e.

$$ {}^*\underline{h}_1 - {}^*\underline{h}_2 = 2\,{}^*\underline{u}_1\,{}^*\underline{c}_{u1}\left[1 - \left(\frac{{}^*c_{u1}}{2\,{}^*u_1}\right)\right] = \left[1 - \left(\frac{{}^*c_{u1}}{2\,{}^*u_1}\right)\right] \tag{11}$$

This equation is developed by combining the Euler turbine equation and the energy equation at best efficiency point. Ref. 3.

Note that for Pelton turbines ${}^*c_{u1}/{}^*u_1 = 2$ and then ${}^*h_1 - {}^*h_2 = 0$ or ${}^*h_1 = {}^*h_2$.

4 DESIGN OF DIFFERENT TYPES OF SMALL HYDRO TURBINES, MINITURBINES AND MICROTURBINES

Small hydro 1000 kW - 10 000 kW
Because of the relatively cheap needle control of Pelton turbines this turbine type is normally equipped with governors. Fully regulated turbines of Francis types and Kaplan types - often made as horizontal
S-type - are used if operation on isolated load is required. If the units are connected to the main electric grid and water level control is required, the turbines must be equipped for guide vane control of the flow by a simplified water level control system.

If water level control is not required simplified turbines without movable guide vanes will be chosen. Simplified synchronising control by means of throttling the inlet valve will be necessary.

Mini hydro
For mini turbines of Francis or Kaplan type with output between 200 kW and 1000 kW control systems with guide vanes are omitted unless operation on isolated load or water level control is required.
Pelton turbines have needle control also for mini turbines either for speed control on isolated load or water level control if connected to the main grid.

Micro-turbines
Cross flow turbines with simplified control is often preferred instead of Pelton or Francis turbines for micro projects if the flow is large and/or the head is low. This because cross flow turbines covers a larger flow capacity overlapping the capacity of Francis turbines.

However, because cross flow turbines are impulse turbines the head between the runner and the tailrace level is lost as described earlier. Then the efficiency is lower than for reaction turbines like Francis or Propeller types.
For the smallest output less than 30 kW multijet Pelton turbines can be step controlled by closing one or more nozzles out of up to 6 nozzles.

Francis and Kaplan turbines should be made without guide vanes in order to reduce the price. Adjustable guide vanes and/or runner blades for Propeller turbines made during a stop for reduced power in the dry season is a favourable alternative. For Francis turbines an extra low capacity runner could be exchanged for operation during the dry season. In such cases some spilling over the dam must be accepted.

Standard pumps in reverse operation could also be used as micro turbines together as an alternative to the cheapest simplified radial or axial turbines.

However, in general, very little research has been made on micro turbine development and low efficiency and poor reliability in operation have often been reported.

Choice of turbine type, speed and main dimensions
The basic parameter for the choice of turbine type and dimensions will be the specific speed or speed number $^*\Omega$ referring to best efficiency point (see eq. 8).

The speed number can be calculated when the flow at best efficiency point (BEP) *Q is known in addition to the design head H (at best efficiency) when the speed is chosen.

The choice of speed is depending on the head by the speed number or the ratio D/d_s for Pelton turbines where D = runners jet tangent diameter and d_s = jet diameter. For heads from 50 m up to 500 m
$9 < D/d_s < 12$ is recommended (See eq. (10).

Smaller values than 9 should be avoided for 6 jet units because of interference between the jet. Many problems have been reported by choosing too small ratio of D/d_s for small hydro Pelton turbines.

For reaction turbines i.e. Francis- and Propeller types, the suction head must be taken into consideration when choosing the speed of the machine. This is because the circumferential speed of the outlet and the axial flow velocity out of the runner must be limited to avoid cavitation damage.

The required net positive suction head $NPSH_R$ may be expressed by following equation:

$$NPSH_R = \frac{u_2^2}{2g}\left(a \tan^2 \beta_2 + b\right) \tag{12}$$

where 1.0 < a < 1.15 and 0.05 < b < 0.1 and b = f $\left({}^{*}\Omega\right)$.

In eq. (12) β_2 = blades outlet angles and u_2 = circumferential speed of largest diameter at the runner outlet. The value of $NPSH_R$ for the turbine must be smaller than the available $NPSH_A$, which is a function of the suction head = Z_s (i.e. difference in geodetic height between runner and tailrace level), the outlet cross section of the draft tube and barometric pressure = h_b in (m WC) and the vapour pressure = h_{va} in (m W.C) (depending on temperature). Following equation of $NPSH_A$ yields:

$$NPSH_A = -Z_s + \frac{c_3^2}{2g} + h_b - h_{va} \tag{13}$$

$c_3 = Q_n/A_{dr}$ = outlet velocity from draft tube A_{dr} = outlet cross section.

It is a pity that testing of the real $NPSH_R$ or Thoma cavitation number σ = $NPSH_R/H$ is normally not made for small hydro turbines due to lack of model tests.

The reason for this is that many small manufacturers have no capacity of facilities to make such test. As a result many small hydro turbines has poor performance both in efficiency and cavitation. For safety reason the speed of the machine is also often chosen lower than necessary. On the contrary the speed of Pelton turbines has in many cases been chosen too high i.e. to small (D/d_s) ratio that leads to a low efficiency.

However, these turbines with poor performance are cheap and the low price often keeps the skilled manufacturers out of the market especially for micro turbines.

A general research programme will be necessary in order to obtain an improved quality of small hydro and in particular the quality of micro turbines without too high increase in price. A proposal for such research programme will be given at the end of this report.

As mentioned above the speed n and capacity ${}^{*}\underline{Q} = {}^{*}Q/\sqrt{2gH}$ is the basis for choice of specific speed or speed number of Pelton turbines and Francis turbines.

The cross flow impulse turbine may be used for all heads covered by Francis and Propeller turbines as described earlier and to some extent for Pelton turbines at low head. The weak point is fatigue problems for high heads and large capacities with long axial span of the vanes. In addition, as described earlier, the head loss from runner to tailrace level gives a low efficiency for low heads.

In Fig. 13 the range of speed number of different turbine types is shown. (The cross flow turbine cover the whole range from Pelton to propeller turbine, but is not shown.) Note that from eq. (8) we find the speed number of propeller and Kaplan turbines for $(D_2/D_1) = 1$.

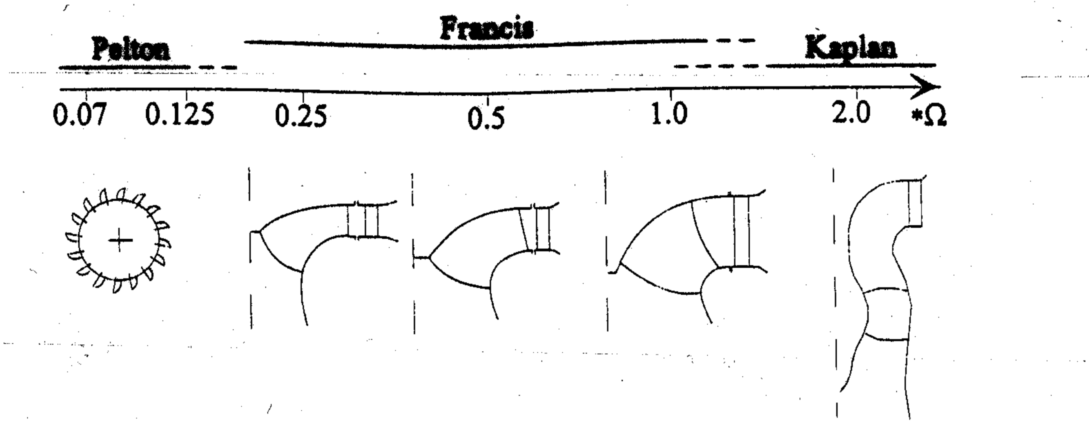


Fig. 13 Turbine types as function of speed number $^{*}\Omega$

5 RECOMMENCDATION FOR R&D ON SMALL HYDRO

5.1.1.1.1 General remarks

A systematically optimised design should be possible from the descriptions of the most important characteristic parameters used for the hydraulic design of small hydro turbines. This is not the case at present time because too many manufacturers have not the necessary education and facilities to design and test the turbines. On the other hand the prices are very low compared with products from manufacturers with experts on design and access to computerised design tools and laboratories for testing of models.

In order to improve the design and obtain a reliable turbine with an acceptable level of efficiency, a research programme should be addressed to both manufacturers and customers who want to buy machinery for small hydro and especially for mini turbines and micro turbines.

THE AIM FOR SUCH PROGRAMME IN ORDER OF PRIORITY, SHOULD BE:

- 1 Help the customer to chose the right economical optimised equipment for his plant and write contracts with specifications and performance guaranties that can be tested at site.
- 2 Work out textbooks for a general design of turbines. (Education on turbine design.)
- 3 Develop simplified testing procedures for acceptance tests of installed turbines at site.
- 4 Work out simplified theories on simplified control systems presented in textbooks.

Description of the four points in the research programme

• 1 Choice of equipment

The choice of equipment must be based on the flow duration curve as described in chapter 3.
However, for micro turbines the regulating equipment is often expensive and not included. However, the loss of energy by spilling over the dam can be reduced by choosing two or three units of different size or a cross flow turbine with loss of head and efficiency. Illustration of choice of 3 micro turbines or pumps in reverse operation as turbines without regulators is shown in Fig. 14. An economical optimizing of these alternatives should be made before the equipment is ordered.

A research in this field will be necessary in order to get the most economical solution for the owner. Also an evaluation of optimum penstock (steel, concrete or plastic) should be made taking into consideration water hammer problems and regulating stability versus price.

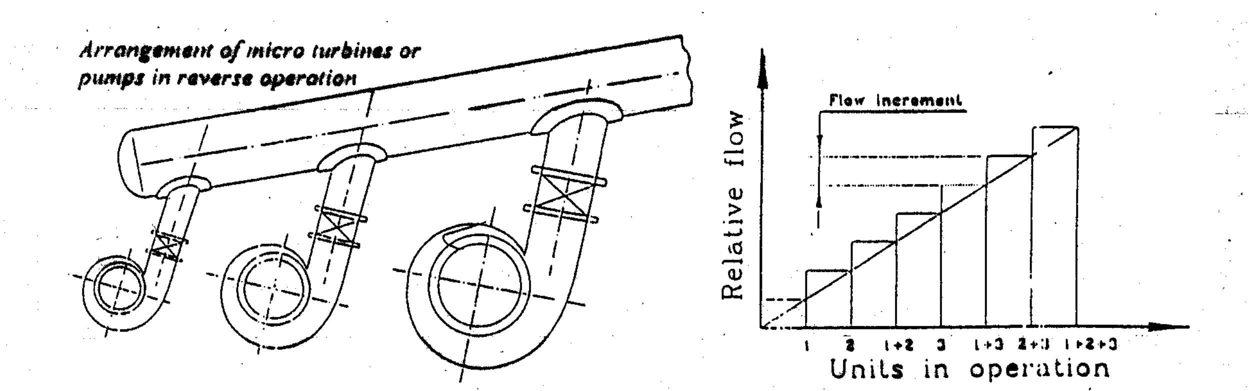


Fig. 14 Principle of on/off flow control of three micro turbines or three pumps of different size in reverse operation as turbines

• 2 Work out text book for general design of turbines

This book must be written by neutral experts on basis level with only the most important parameters for dimensioning as described in chapter 3. In addition, choice of materials, hydraulic forces, deformations, range of clearances and basic structural analyses must be presented. Simplified flow analysis to avoid too low efficiency and cavitation must be included. This research work will require a relatively large amount of work. A design of a simplified turbine for a make-it-yourself package may also be made and offered for a low price.

• 3 Develop simplified testing procedures as acceptance tests for small hydro turbines

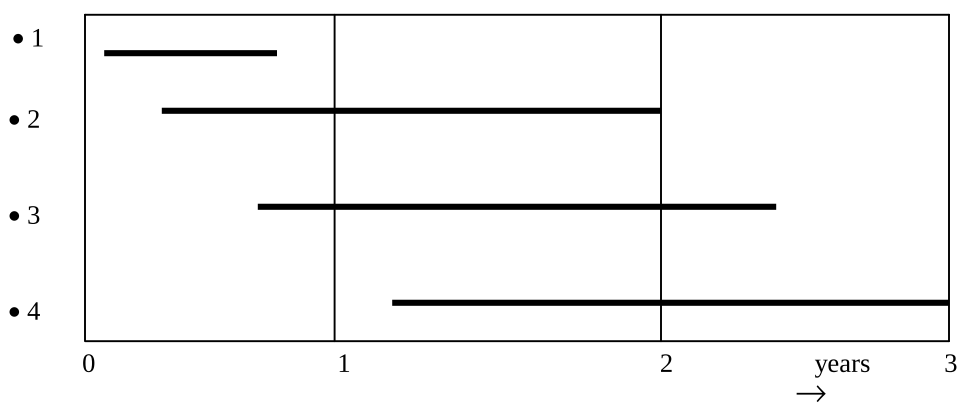
For micro-turbines and small hydro the IEC code for field acceptance tests is too complicated and is normally not used. A reliable cheap flow measurement by clamp on flowmeters on the pipes or simplified methods of thermodynamic efficiency measurement are possibilities that should be investigated in order to measure the efficiency with accuracy of $\pm$ 3%. The simplified test procedures should be available for all types of micro- and mini turbines. (This is because at present time turbines with efficiency of less than 65 - 70% efficiency has been produced and no turbines should have efficiency below 80%. Even micro-turbines should reach 85% efficiency.) For micro turbines test facilities could also be used in neutral laboratories for approval of series of turbines, i.e. a manufacturer may have tested and approved a design for delivery of turbines of this type with geometrical control only. A simplified acceptance NORM should be written in order to protect the customer from buying bad micro turbines.

• 4 Work out simplified theories on simplified control systems

This work must be based on basic governor theory, but it must be presented in a simplified form. A computer program may be used, but basic dimensioning equations must be available to avoid damage by water hammer and runaway speed. (It should be noted that a turbine runaway speed may damage a standard asynchronous generator besides causing rupture of the pipe and this must be avoided).

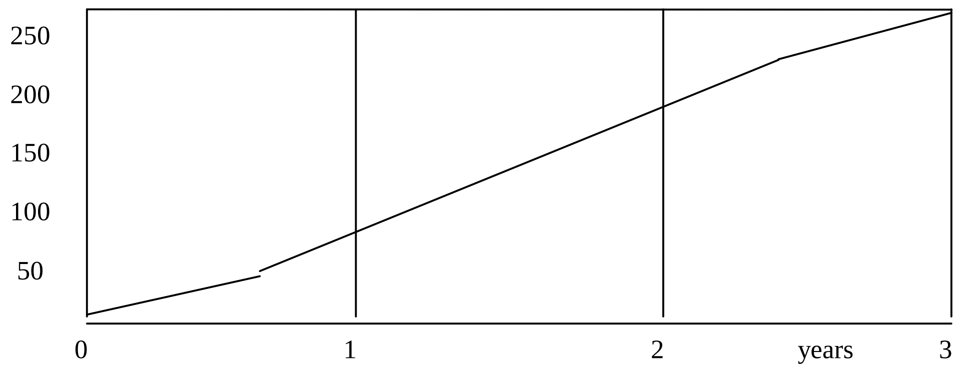
PROPOSAL FOR A POSSIBLE 3 YEARS RESEARCH PROGRAMME FOR THE WATERPOWER LABORATORY AT THE NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY IN ORDER TO IMPROVE SMALL HYDRO REFFERING TO THE SECTIONS •1, •2, •3, •4 IN THE RESEARCH PROGRAMME. (COLLABORATION BETWEEN UNIVERSITIES IS ALSO POSSIBLE)

ACTIVITY



GRAPH OF BUDGET US$ = 250 000 OVER THREE YEARS

US$ $\cdot 10^3$



Note, the budget includes test facilities and test equipment for field tests of US$ 60 000. Cost of travel for measuring in the field is not included in general, but only for a few selected plants in short travel distance from the University.

6 References:

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