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United Nations Industrial Development Organization

Distr.
LIMITED

ID/WG.468/3(SPEC.)
16 April 1987

ENGLISH

Expert Group Meeting and
Study Tour on Standardized
Small Hydropower Plants

Hangzhou, China
18-29 May 1987

EXPERIENCE IN THE STANDARDIZATION OF SMALL HYDROPOWER STATIONS*

Prepared by

OLADE** Secretariat

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** Organization Latinoamericana de Energia
(Latin-American Energy Organization)

V.87-84352

1. INTRODUCTION

In early 1980, the Latin American Energy Organization (OLADE) began to develop the Regional Program of Small Hydropower Stations, in order to have its 26 member countries achieve a joint, coordinated and rational use of the small hydro development sites which, according to various sources, existed in significant numbers in the region.

According to the evaluation undertaken by OLADE, Latin America's hydroenergy potential surpasses 800 000 MW, thus making the region one of the richest in the world in this source. However, this figure basically considers the assessment of medium- and large-scale hydroenergy developments, even though it is known that the possibilities for small projects are significant, not only due to the fact that some already exist but also because the financial requirements involved are more feasible for the overburdened Latin American economies.

Although at the beginning of this decade there was cumulative experience in Latin America dating back to the last decades of the nineteenth century, SHP development was characterized by sporadic actions that were not very systematic, primarily due to the advantages that at that time revived interest in the use of renewable sources of energy: among these hydroenergy, including small development projects, for the reasons mentioned above.

In the years since the initiation of the Regional Program of SHP, significant advances have been made. For example, hundreds of small plants have been installed and, as a result of the experience gained, it has been possible to reduce the cost of equipment and construction from US$ 4000-5000 per installed kW to US$ 1100-1200. Several countries have begun to produce different components for small plants and work is in progress to produce all of the necessary equipment locally.

The needs for intensive use of SHP on the one hand, and the need to reduce production costs on the other, mean that work is geared to standardizing the equipment used in small hydropower stations.

2. GENERAL ASPECTS

First of all, it is worthwhile to note that OLADE adopted a classification criterion responding to the installed power capacity of small hydro stations, as follows:

Micro hydropower stations	up to 50 kW
Mini hydropower stations	50 - 500 kW
Small hydropower stations	500-5000 kW

The term "small hydropower stations" is used generically for all of these, as well as for the group corresponding to the largest power range.

One important aspect in the design, manufacture and standardization of SHP is that they should not be treated as smaller-scale models of the large stations, because such treatment would entail excessive costs derived from the use of conventional technologies and unnecessary study methods. In other words, the application of SHP should be conceived of under the following criteria:

- previous simple studies to expedite subsequent work;
- simple civil constructions with widespread use of local materials;
- equipment built using non-conventional methods and preferably produced nationally; and
- participation of the local population in the stages of construction, maintenance and operation of the hydropower station.

Finally, with respect to standardization, it is useful for this to be done separately for the different parts of a PCH and not for the station as a whole, primarily because of the different degrees of development which the Latin American countries' national industries have currently. This criterion implies that, with the standardization of the different components, the intention is to cover the full range of utilization of SHP, with a view to making their use more flexible, unless technical or economic aspects impede this.

3. EQUIPMENT STANDARDIZATION

Taking into consideration the aforementioned aspects and the interest expressed by most of the OLADE member countries, the Organization decided to undertake the preparation of a series of manuals for the design of SHP equipment, which in all cases would include chapters on standardization. Progress has been made toward this goal through a contract signed between UNIDO and OLADE, by means of which the latter committed itself to elaborating a Manual for the Design, Standardization and Fabrication of Equipment for Small Hydropower Stations, to be composed of seven volumes covering turbines (3), speed regulators (3) and generators (1).

The principal aspects of these volumes are discussed below, insofar as standardization is concerned; and this will reflect OLADE's experience in this field.

3.1 Turbines

To date, OLADE has worked with the standardization of three types of turbines: Michell-Banki, Pelton and tubular ones. The procedure followed for development of the Michell-Banki series is explained herewith; and afterwards the results of the other two types are presented, since the procedure itself was similar in the three cases and, for the sake of time and space, will not be repeated here.

3.1.1 Michell-Banki Turbines

a) Standardization According to Hydraulic Criteria

In general, turbine standardization consists of designing an adequate number of turbines which complement each other in their range of application, so that together they will cover the full range of application of the type of turbine in question.

For standardization purposes, and attentive to the adequate hydraulic functioning of the turbine, it is possible to work on the basis of the expression for a specific number of revolutions, given by:

$$N_q = \frac{NQ^{1/2}}{H^{3/4}} \qquad (1)$$

where:

N_q : specific number of revolutions, which, in the case of Michell-Banki turbines, fluctuates between 18 and 60.

Q : design flow, m^3/s.

H : net utilizable head, m.

N : optimal number of turbine revolutions (rpm), with:

$$N = \frac{39.85\ H^{1/2}}{D_e} \qquad (2)$$

D_e : external runner or rotor diameter

By substituting (2) in (1) and solving:

$$\frac{Q}{\sqrt{H}} = \left(\frac{D_e\ N_q}{39.85}\right)^2 \qquad (3)$$

Expression (3) shows, first of all, that a given runner turbine with a diameter D_e could operate with any combination of head and flow for which the specific number of revolutions would remain constant; that is:

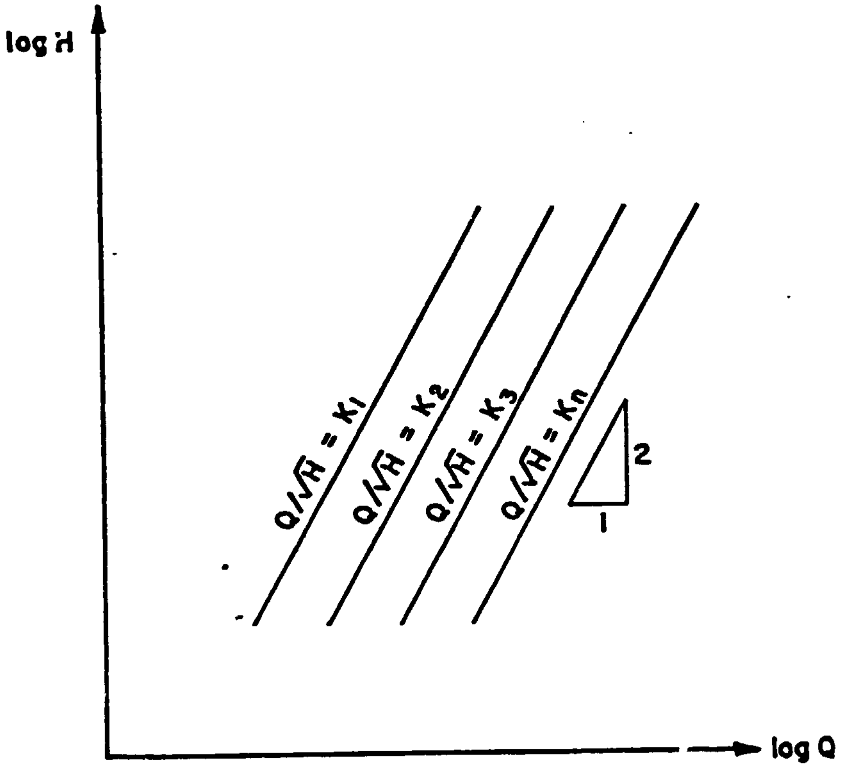


FIGURE 1

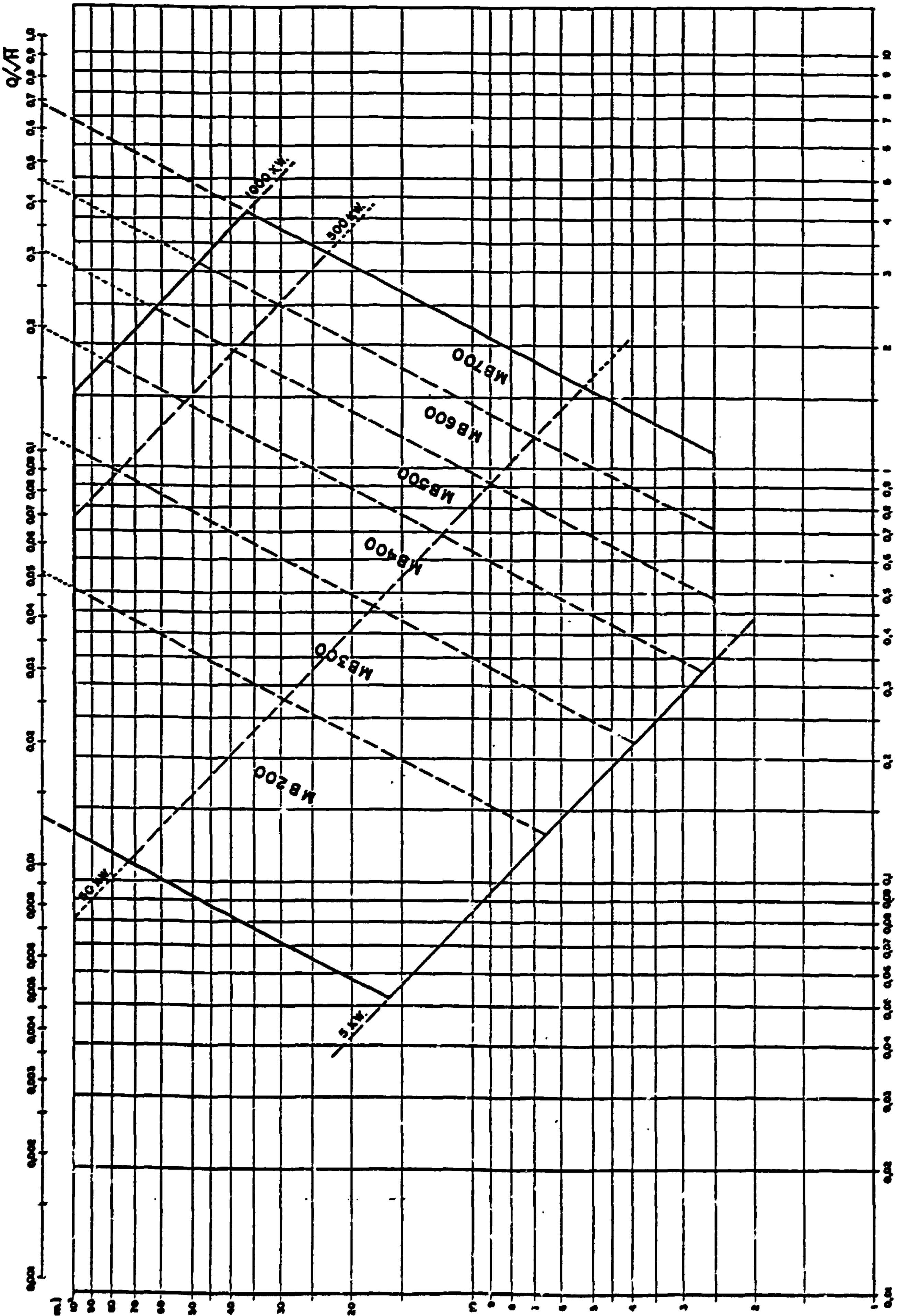

Q/√H
Q (m³/s)
H (m)
1000 kW
500 kW
50 kW
5 kW
MB700
MB600
MB500
MB400
MB300
MB200
1,0
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,09
0,08
0,07
0,06
0,05
0,04
0,03
0,02
0,01
0,009
0,008
0,007
0,006
0,005
0,004
0,003
0,002
0,001
10
9
8
7
6
5
4
3
2
1
0,9
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,09
0,08
0,07
0,06
0,05
0,04
0,03
0,02
0,01
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1

FIGURE 2

$$\frac{Q}{\sqrt{H}} = K \text{ (constant)} \qquad (4)$$

Now, knowing that for Michell-Banki turbines $18 \leq N_q \leq 60$, the substitution of those external values in (3) yields:

$$\frac{Q}{\sqrt{H}} = (0.204 - 2.267)\, D_e^2 \qquad (5)$$

This expression is of great practical value, since it makes it possible to establish the extreme values for $Q/\sqrt{H}$ for the application of each turbine of diameter D_e.

It is worth recalling the graphic interpretation for expression (4), shown in Figure 1.

On the basis of equation (5) and considering various values for the runner diameter, one arrives at the results shown in Table I, where it can readily be seen that there is ample overlapping in the field of application of the different runners. Furthermore, it is easy to demonstrate that the quotient $(Q/\sqrt{H})_{min}/(Q/\sqrt{H})_{max}$ is equivalent to the turbine's least favorable operating conditions at partial load P/P_{max}. All of the cases in Table I are between 8.8% and 9.2%, which prove excessively low and unfavorable for turbine efficiency in terms of the head produced.

TABLE I

D_e	$(Q/\sqrt{H})$min	$(Q/\sqrt{H})$max
0.25	0.013	0.142
0.30	0.018	0.204
0.40	0.033	0.363
0.50	0.051	0.567
0.55	0.062	0.686
0.60	0.073	0.816
0.70	0.100	1.111
0.75	0.115	1.275

In view of the aforementioned aspects, and the fact that the field of application of Michell-Banki turbines, as agreed by several authors, is for approximately $0.013 \leq Q/\sqrt{H} \leq 0.686$, one arrives at the conclusions in Table II, on the basis of which the graph in Figure 2 can be plotted, to summarize in simple fashion the standardization of Michell-Banki turbines, taking into account their adequate hydraulic functioning.

Table II shows that, considering that the turbine is designed for a final $(Q/\sqrt{H})$ and that it works with an initial $(Q/\sqrt{H})$, the effect of turbine efficiency only appears for diameters of 200 mm and 300 mm, and then only in small proportions.

TABLE II

D_e (mm)	$(Q/\sqrt{H})$	N_q	$(Q/\sqrt{H})$init./ $(Q/\sqrt{H})$final	efficiency (%)
200	0.013 - 0.051	22.7 - 45.0	0.25	76
300	0.051 - 0.111	30.0 - 44.3	0.46	79
400	0.111 - 0.198	33.2 - 44.3	0.56	80
500	0.198 - 0.309	35.5 - 44.3	0.64	80
600	0.309 - 0.445	36.9 - 44.3	0.69	80
700	0.445 - 0.686	38.0 - 47.2	0.65	80

b) Standardization According to Mechanical Criteria

As for the mechanical functioning of the turbine, it is necessary to consider two different aspects in order to arrive at the definitive standardization.

b.1) Aspect Related to Variation in Power

It has been established that for any combination of flow Q and head H so that the $Q/\sqrt{H}$ ratio remains constant, it is possible to use one single turbine, obtaining one same efficiency.

It is also known that there is a relation between the width of the injector (or the length of the runner) and the term $Q/\sqrt{H}$, expressed by:

$$B = \frac{0.96}{D_e} \frac{Q}{\sqrt{H}} \qquad (6)$$

so that it is evident that for each $Q/\sqrt{H}$ there is a corresponding runner B and only one, and vice versa.

Furthermore, it is known that the power which a hydroelectric station is capable of delivering is given by:

$$P = 9.81\, Q \,.\, H \,.\, \eta \qquad (7)$$

By making expressions (6) and (7) simultaneous:

$$P = 10.22\, B.D_e.H^{3/2} \,.\, \eta \qquad (8)$$

which establishes that the power output is directly proportional to the width of the runner. Then, in considering a $Q/\sqrt{H}$ different from the design value, a variation in the power to be attained will be accepted, in the same proportion in which a variation is permitted in $Q/\sqrt{H}$.

Proceeding inversely, i.e., admitting a maximum variation in power, an interval $(Q/\sqrt{H})$ in which it is possible to use one single turbine will be set.

Thus, on the basis of the lowest values for $Q/\sqrt{H}$ for each runner diameter D_e given in Table II, and accepting a maximum effect of 20% in the amount of power generated, i.e., an acceptable value from a practical standpoint, it is possible to define the different runner lengths shown in Table III for each runner diameter.

TABLE III

	200	300	400	500	600	700
1.	62.0	60.0	80.0	380.0	490.0	610.0
2.	75.0	73.0	97.0	475.0	594.0	757.0
3.	92.0	90.0	120.0	-	-	-
4.	112.0	110.0	145.0	-	-	-
5.	136.0	135.0	177.0	-	-	-
6.	165.0	165.0	215.0	-	-	-
7.	200.0	200.0	262.0	-	-	-
8.	-	245.0	320.0	-	-	-
9.	-	300.0	390.0	-	-	-

b.2) Aspect Related to Speed of Rotation

As has been indicated previously, the optimal speed of rotation for a Michell-Banki turbine is given by:

$$N = \frac{39.85\ H^{1/2}}{D_e} \qquad (2)$$

Now, from Figure 2, it can be seen that the turbines whose runners have a diameter of 200 mm would work with heads of up to 100 m; if these values are substituted in expression (2), N would be equal to 1992 rpm, which, even though this is mathematically acceptable, is not acceptable from a mechanical standpoint, since it has been possible to prove in practice that the maximum speed of rotation of these turbines is approximately 1000 rpm.

Taking N_{max} = 1000 rpm and using expression (2) yields the maximum value for head permitted in each runner, as shown in Table IV.

TABLE IV

Diameter, D_e (mm)	200	300	400	500	600	700
Maximum head, H (m)	25	55	100	100*	100*	100*

* Set according to these turbines' maximum permissible head.

c) Standardized Turbines

Taking into consideration all of the aspects analyzed above, one arrives at the results presented in Figure 3, where the symbols used are interpreted as follows: in the three-digit numbers, the first indicates the runner diameter and the second two the number of order.

Chart No. 1 gives the calculations of the principal elements of the standardized turbines.

3.1.2 Pelton and Tubular Turbines

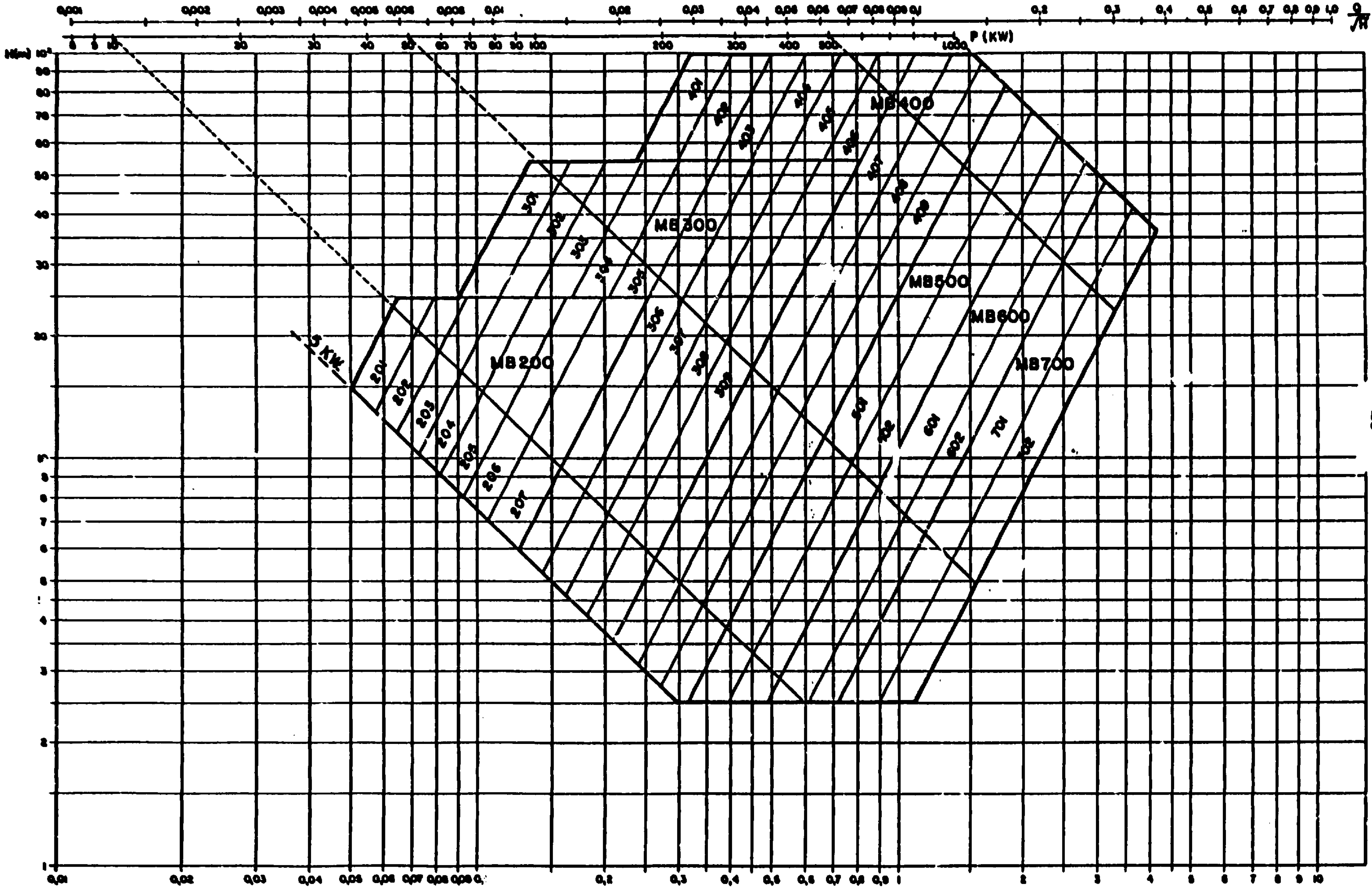
As indicated previously, a procedure similar to the one followed in the case of Michell-Banki turbines was applied for Pelton and tubular turbines. The results obtained are illustrated in Figures 4 and 5, respectively.

3.2 Alternators

In keeping with previous OLADE publications,the turbine-generator coupling considers mechanical transmission permitting different speeds in the turbine and in the generator, in the sizes adopted for SHPS, where the power to be transferred does not entail too high a transmission cost, and thus makes it possible to take full advantage of turbine and generator savings.

3.2.1 Standardization of Voltage and Power Factors

The power range foreseen in the OLADE Manual, of up to 1000 kW, may be suitably covered by two nominal voltages, one in the low-voltage category and the other in the so-called high voltages. Low voltages are understood to be those under 500 V, and this category includes the voltages for household and industrial use (210 and 380 V). For the power ranges considered, the distribution network could only be low-voltage, directly at the level at which it is used. However, normally the station is not close to the consumption center and transformation is necessary in order to raise the voltage to a more suitable level for transmission to the site where the load is located. In this case, the generating voltage should be higher in order to reduce the generator dimensions by limiting the currents to be handled.


H(m)
P (KW)
Q/√H
0,001
0,002
0,003
0,004
0,005
0,006
0,008
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,1
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1,0
5
10
20
30
40
50
60
70
80
90
100
200
300
400
500
1000
0,01
0,02
0,03
0,04
0,05
0,06
0,07
0,08
0,09
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
1
2
3
4
5
6
7
8
9
10
5 KW
MB200
MB300
MB400
MB500
MB600
MB700
201
202
203
204
205
206
207
301
302
303
304
305
306
307
308
309
401
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409
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502
601
602
701
702

FIGURE 3

CALCULATION OF THE MAIN COMPONENTS IN OLADE'S STANDARDIZED CROSS-FLOW TURBINES

ELEMENT / TURBINE	201	202	203	204	205	206	207	301	302	303	304	305	306	307	308	309	401	402	403	404	405	406	407	408	409	501	502	601	602	701	702
1. MAXIMUM DESIGN FLOW, $Q (m^3/s)$	0,064	0,078	0,096	0,117	0,142	0,172	0,208	0,139	0,169	0,208	0,233	0,313	0,383	0,464	0,568	0,655	0,333	0,404	0,500	0,604	0,736	0,866	1,092	1,333	1,604	1,803	2,089	2,434	2,728	3,062	3,577
2. MAXIMUM DESIGN LOAD, H (m)	25	25	25	25	25	25	25	55	55	55	55	55	55	55	55	55	100	100	100	100	100	100	100	100	93	83	72	62	54	48	42
3. MAXIMUM POWER, Pt (KW)	10,7	13,0	16,0	19,5	23,7	28,7	34,7	51,0	62,0	76,3	85,6	114,8	140,5	170,2	208,4	238,0	222,1	269,5	333,5	402,9	492,3	577,7	728,4	889,2	1000	1000	1000	1000	1000	1000	1000
4. MAXIMUM SPEED ROTATION, N (RPM)	996	996	996	996	996	996	996	985	985	985	985	985	985	985	985	985	996	996	996	996	996	996	996	996	971	726	676	523	486	394	369
5. SPECIFIC NUMBER, Nq minimum	22,3	24,9	27,6	30,5	33,6	36,9	40,6	18,2	20,0	22,2	24,6	27,3	30,2	33,2	36,8	40,6	18,2	20,0	22,3	24,5	27,0	29,8	32,9	36,4	40,2	35,4	39,6	36,9	40,8	37,9	42,3
6. SPECIFIC NUMBER, Nq maximum	24,9	27,6	30,5	33,6	36,9	40,6	45,4	20,0	22,2	24,6	27,3	30,2	33,2	36,8	40,6	44,6	20,0	22,3	24,5	27,0	29,8	32,9	36,4	40,2	44,5	38,6	44,4	40,8	44,6	42,3	46,9
7. INJECTOR WIDTH, B (mm)	62,0	75,0	92,0	112,0	136,0	165,0	200,0	60,0	73,0	90,0	110,0	135,0	163,0	200,0	243,0	300,0	80,0	97,0	120,0	145,0	177,0	215,0	262,0	320,0	390,0	380,0	475,0	494,0	594,0	610,0	757,0
8. MAXIMUM TORQUE WITH BLADE REGULATION, T (Kg-m).	1,36	2,42	2,98	3,63	4,40	5,33	6,45	8,39	11,66	14,34	17,39	21,39	26,42	32,00	39,16	47,83	41,29	50,10	62,00	74,90	91,84	111,10	135,41	165,89	191,44	234,60	275,04	364,04	372,87	463,36	[illegible]
9. DIAMETER OF BLADE SHAFT, d (mm)	12	13	14	15	16	17	18	20	21	23	25	27	29	30	33	35	33	35	38	40	43	46	49	52	55	60	62	67	69	74	76
10. RUNNER LENGTH, Br (mm)	62,0	75,0	92,0	112,0	136,0	165,0	200,0	60,0	73,0	90,0	110,0	135,0	163,0	200,0	243,0	300,0	80,0	97,0	120,0	145,0	177,0	215,0	262,0	320,0	390,0	380,0	475,0	494,0	594,0	610,0	757,0
11. NUMBER OF BLADES PER RUNNER	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
12. BLADE THICKNESS, e (mm)	2	2	2	2	2	2	2	2	2	2	2	2	2	3	4	6	3	3	3	3	3	4	6	6	6	6	6	6	6	6	6
13. BLADE WIDTH (LENGTH OF ARC), Le (mm)	39.8	39.8	39.8	39.8	39.8	39.8	39.8	59.9	59.9	59.9	59.9	59.9	59.9	59.9	59.9	59.9	79.6	79.6	79.6	79.6	79.6	79.6	79.6	79.6	79.6	99.5	99.6	119.5	119.5	139.4	139.4
14. THICKNESS END RUNNER DISKS, e' (mm)	12	12	12	12	12	12	12	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	16	16	18	18
15. FORCE ACTING ON BLADE, F (KG)	14,88	18,14	22,32	27,20	33,02	40,00	48,36	47,93	58,28	71,73	87,94	107,94	132,08	160,00	196,86	238,67	164,84	197,86	231,30	280,84	343,17	416,34	507,78	619,84	717,91	763,81	928,19	990,10	1032,17	1192,90	[illegible]
16. MAXIMUM STRESS ON BLADE, σ_{MAX} (KG/mm²)	0,61	0,90	1,35	2,00	2,96	4,34	6,37	0,91	1,34	2,04	3,06	4,60	6,89	7,02	8,03	8,07	1,49	2,19	3,35	4,89	7,29	8,29	8,30	6,34	6,95	5,96	7,97	6,08	7,67	9,04	7,07
17. THICKNESS INTERMEDIATE RUNNER DISKS, e'' (mm)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	10	10	10	10	10	10	10
18. RUNNER WEIGHT, Pr (KG)	6,8	7,1	7,3	7,6	8,0	8,4	8,9	16,9	17,2	17,6	18,0	18,6	19,3	22,3	26,6	35,0	31,2	32,0	33,0	34,1	35,6	40,5	51,2	66,3	72,6	101,4	112,0	160,0	173,5	241,1	264,2
19. TANGENTIAL RUNNER FORCE, Fr (KG)	104,6	127,1	156,5	190,7	234,8	280,7	338,3	336,2	408,7	503,0	617,0	756,8	926,2	1122,0	1373,8	1681,0	1066,0	1317,7	1630,7	1970,0	2405,1	2922,3	3561,6	4347,8	5015,4	5366,4	5783,3	6907,8	6683,0	7063,1	7940,6
20. MAXIMUM RUNNER BENDING MOMENT, M_{MAX} (KG-m)	1,1	1,6	2,4	3,6	5,2	7,7	11,3	3,4	5,0	7,5	11,3	17,0	23,8	32,4	56,1	64,1	14,8	21,3	32,6	47,6	71,0	104,7	152,3	231,9	326,0	330,9	456,3	541,3	666,9	716,8	852,1
21. MAXIMUM RUNNER TORSIONAL MOMENT, T_{MAX} (KG-m)	10,5	12,7	15,6	19,1	23,2	28,1	33,9	50,4	61,3	75,4	92,6	113,5	138,9	168,3	206,1	252,2	217,8	263,5	328,1	394,0	481,4	584,5	712,3	869,6	1003,1	1360,9	1440,8	1862,3	1993,9	2472,1	[illegible]
22. MINIMUM RUNNER SHAFT DIAMETER, dr (mm)	26	28	30	32	35	37	40	44	47	51	54	58	63	67	72	78	72	77	82	88	94	101	108	117	124	135	139	151	156	166	172
23. MAXIMUM RUNNER SHAFT DIAMETER, dr (mm)	65,6	65,6	65,6	65,6	65,6	65,6	65,6	98,4	98,4	98,4	98,4	98,4	98,4	98,4	98,4	98,4	131,2	131,2	131,2	131,2	131,2	131,2	131,2	131,2	131,2	164	164	196,8	196,8	229,6	229,6
24. SELECTED RUNNER SHAFT DIAMETER, d (mm)	35	35	35	35	45	45	45	55	55	55	55	70	70	70	80	80	85	85	85	105	105	105	125	125	125	145	145	160	160	175	175

CHART 1

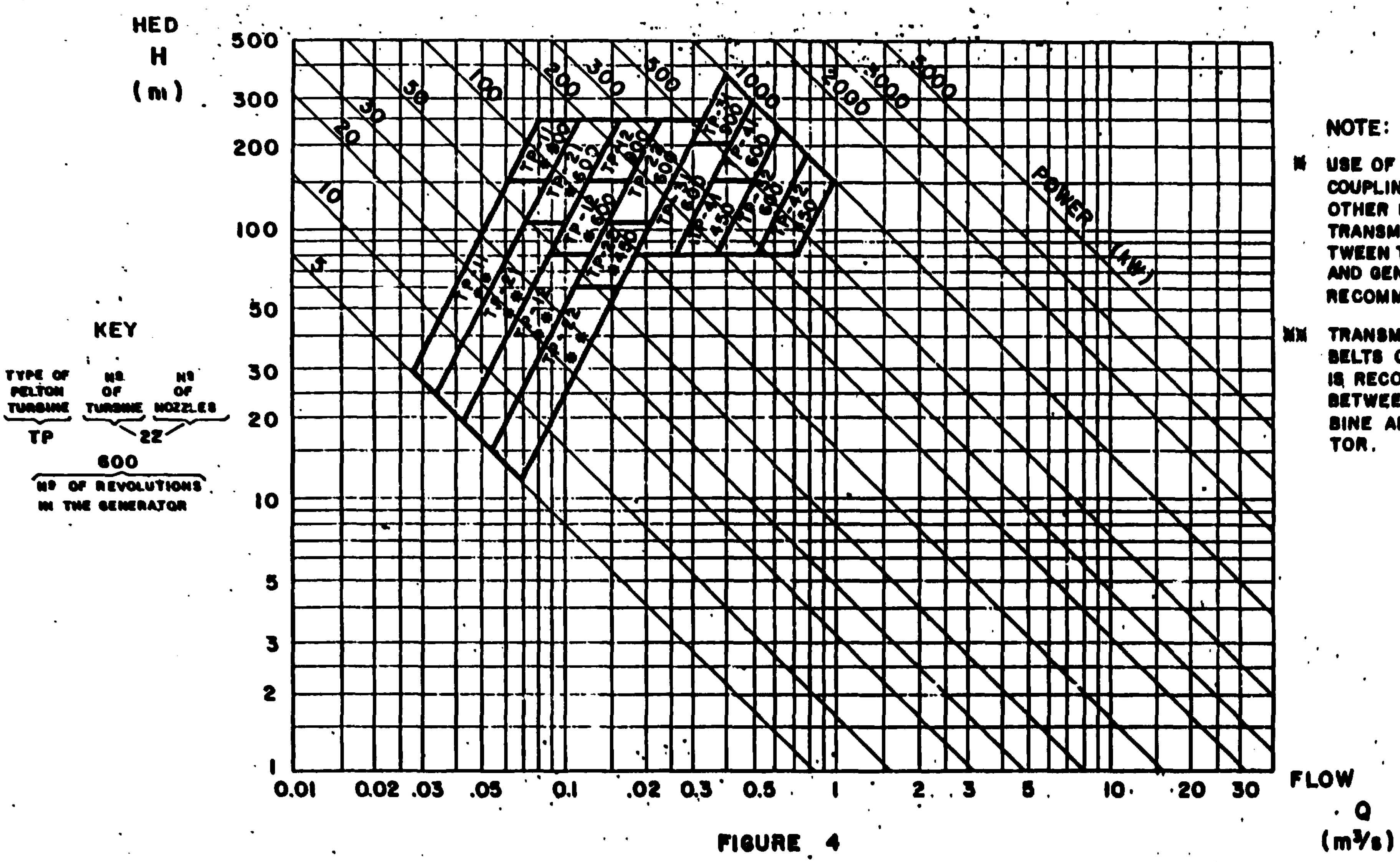


FIGURE 4

EXAMPLE OF TURBINE STANDARDIZATION CONSIDERING DIRECT COUPLING

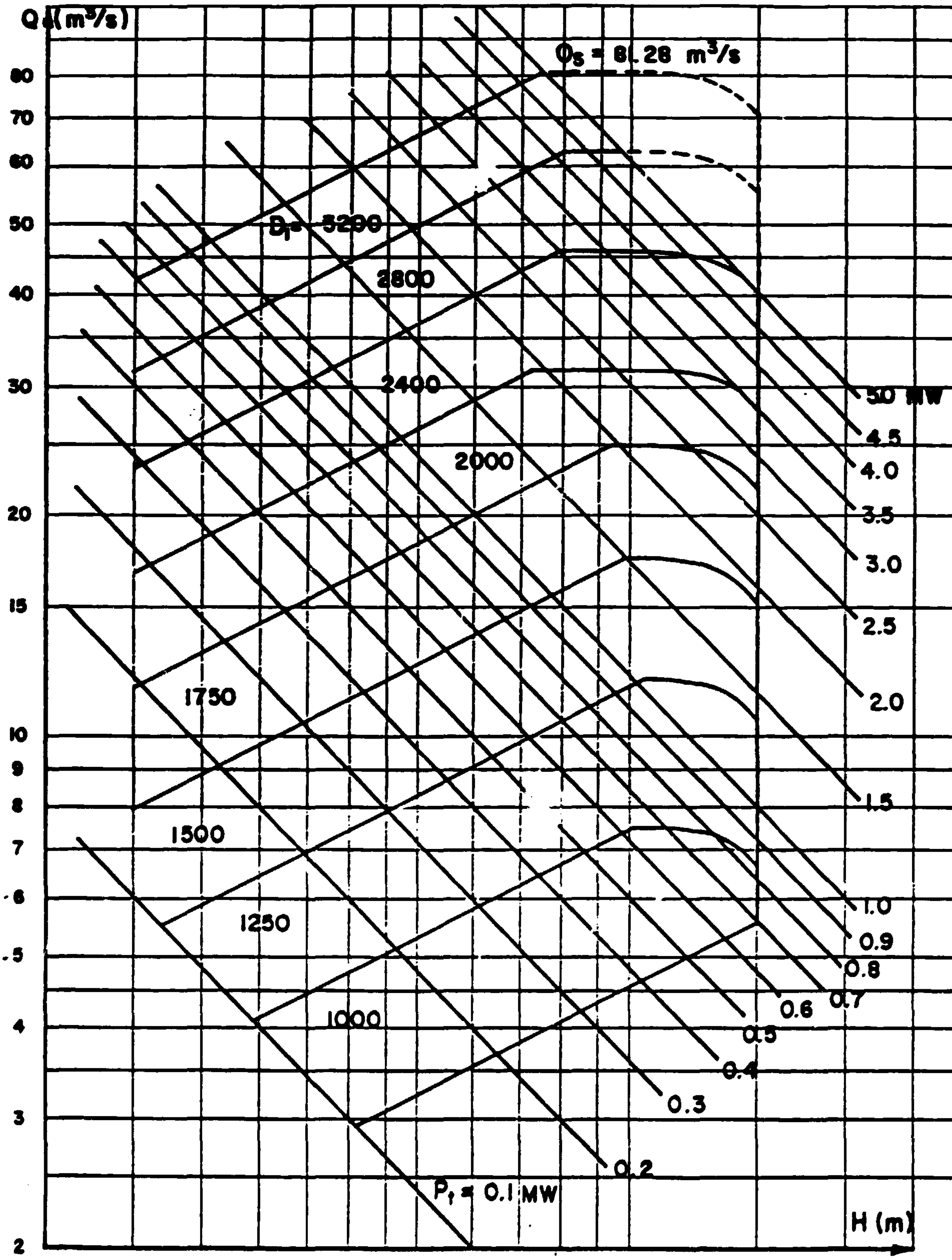
NOTE:

* USE OF DIRECT COUPLING OR SOME OTHER KIND OF TRANSMISSION BETWEEN THE TURBINE AND GENERATOR IS RECOMMENDED.

** TRANSMISSION BY BELTS OR GEARS IS RECOMMENDED BETWEEN THE TURBINE AND GENERATOR.

FIGURE 5

DIAGRAM FOR THE SELECTION OF TUBULAR TURBINES



On the basis of this consideration, 480 V are adopted for 60 Hz and 400 V for 50 Hz in the units having power ranges of up to half the maximum under consideration.

The units of over 500 kW justify a large generating voltage, considering the magnitude of the nominal current. The selected voltage may possibly serve as primary distribution, i.e., without additional elevation to be used in the distribution network, but with reduction transformers at the load sites. Naturally, this will be determined as a function of the distance at which the station is located.

The voltage which adequately combines the conditioning factors suitable for the level of generation and which, at the same time, is used in primary distribution is 4160 V; and it is therefore selected for standardization.

Furthermore, the value selected for the power factor should allow the generator to be self-sufficient with any type of load; for example, when feeding into a considerable percentage of induction motors. The value which meets all of these requirements and, for this reason, is suggested as part of this standardization is 80%. Without being overly low, this figure permits a 60% supply of the nominal power as reactive power.

3.2.2 Standardization of Speed

In general, the larger their nominal or rated speeds, all electric motors in one same power range call for smaller investments. This is particularly true in alternators, which require an increase in the number of poles in order to reduce speed.

Nonetheless, the synchronous speed corresponding to two poles does not prove convenient for a wide range of applications since 3600 RPM at 60 Hz or 3000 RPM at 50 Hz are speeds with which a transmission ratio of a maximum of 4 would only produce 900 or 750 RPM. If four poles are adopted, i.e., 1800 or 1500 RPM, with the same maximum transmission ratio, the minimum speeds attained would be 450 and 375 RPM at 60 and 50 Hz, respectively. In other words, with this number of poles, the generator could be coupled to a large number of turbines using primarily the material employed in the generator, thus calling for a relatively low investment in this equipment.

For this reason, a standardized 4-pole structure is adopted, i.e., 1800 RPM for 60 Hz and 1500 RPM for 50 Hz.

3.2.3 Standardization of Power

Generally speaking, the electrical equipment should consider nominal values as universal as possible, in order to have the associated devices be completely in line with each other, thereby avoiding figures that fall between the two preferred values, which would make it necessary to use equipment from the category immediately higher and hence raise the total cost. This must be kept in mind, for example, for cutting and handling equipment, instrument transformers, booster transformers, etc.

Considering the recommendations of the International Electrothermal Commission and the associated power factor, and adjusting the most common magnitudes for generator power, one arrives at the following suggested values: 125, 200, 320, 500, 630, 800 and 1000 kW.

Values below 125 kW were not taken since it was considered that in such small power ranges other solutions could be found, even without using the alternators which are the subject of this document.

For the suggested values, a one-phase structure is not adequate. Therefore, all of the examples have been geared to poly-phase machines and, more specifically, to three-phase systems, given their widespread dissemination and application.

3.2.4 Standardized Alternators

As an outgrowth of the summary analyses above, the volume on alternators within the Manual for Design, Fabrication and Standardization of Equipment for SHP provides detailed designs for eight standardized alternators, the technical data on which are presented in the following table.

ALTERNATORS DATA	1	2	3	4	5	6	7	8
Active power, kW	125	200	320	500	500	630	800	1000
Power factor	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Line tension, V	480	480	480	480	4160	4160	4160	4160
Frequency, Hz	60	60	60	60	60	60	60	60
Number of phases	3	3	3	3	3	3	3	3
Speed of rotation, rpm	1800	1800	1800	1800	1800	1800	1800	1800
Tripping factor	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8

3.3 Speed Regulators

3.3.1 Oleo-Mechanical Speed Regulators

The basic parameter for standardizing regulators is their work capacity, which, according to the foregoing, can be defined as the product of the maximum force generated by the servomotor times its stroke, i.e.:

$$A = F_{max} \cdot Yo$$

where:

A is the work capacity of the regulator, in kg-m.
F_{max} is the maximum force, in kg.
Yo is the stroke, in m.

In order to define a series of standardized regulators in the H-Q diagram, the regulator's work capacity should be expressed as a function of the flow and net head with which the turbine operates. Generally, it takes the following form:

$$A = K . Q . \sqrt{H}$$

where:

K is the constant which depends on the type of turbine with which the regulator operates and which takes into account some of its characteristic dimensions.
Q is the flow, in m^3/s
H is the net head, in m.

This expression can be obtained by analyzing the forces in the turbine's regulating mechanism for the regulator's most unfavorable operating conditions, i.e., for the position of the turbine distributor which provides maximum torque at its drive shaft.

To cite an example, for the case of the Michell-Banki turbine, the maximum torque in the regulating vane (distributor) shaft occurs in the completely-open position (full load) and has the following value:

$$T = 31\ D_e . Q . \sqrt{H}$$

where:

D_e is the diameter of the turbine runner, in m.

By analyzing the forces in this position of the regulating vane and taking into account the particular characteristics of the regulating mechanism of a Michell-Banki turbine with two-compartment injectors, one arrives at the following expression for the regulator's work capacity:

$$A = 155\ D_e . Q . \sqrt{H}$$

Then, for this particular case:

$$K = 155\ D_e$$

Considering the general equation for work capacity, it can be represented in an H-Q diagram like the one in Figure 6. It is important to note that, given the fact that the constant K depends on the type of turbine, and specifically on runner diameter, the capacity curve should be plotted by superimposing it on the graph for the corresponding standardized turbine series. Considering the capacity of a Michell-Banki turbine, the curve will take the shape of a saw.

This capacity represents the regulator's design conditions. However, it may work under conditions other than design conditions (smaller capacities), up to a minimum capacity "A_{min}", defined as follows:

$$A_{min} = (6.7 - 8) \cdot V \cdot P_{min}$$

where:

V is the servomotor's working volume, in lt.

P_{min} is the minimum operating pressure for the oil in the regulator, in kg/cm^2, the value of which may be on the order of 10 kg/cm^2 or more.

The plotting of "A_{min}" in the H-Q diagram, which will be the design value for another regulator that follows in the series, will make it possible to define the area of application in keeping with the indications of Figure 7.

Thus, one can define an adequate number of regulators to cover the range of application of water turbines for small hydropower stations.

3.3.2 Electric-Electronic Speed Regulators with Positive Flow Control

As possible system characteristics on which standardization may be based, the following may be mentioned:

1. Average variation in useful load.
2. Precision of desired regulation.
3. Type and power capacity of the turbine-generator set.

In relation to the first point, it is useful to do the following analysis:

It has been shown that, given an initial configuration of the basic regulator, a change in the control scheme does not entail a major price increase. Therefore, in this type of regulators, without major changes in the electronic part, it is possible to define the optimal regulator, i.e., the one which performs best under a given condition for useful load. In other words, if the control scheme does not change drastically, the scheme proposed in the OLADE Manual, which is very similar to the type used for

FIGURE 6

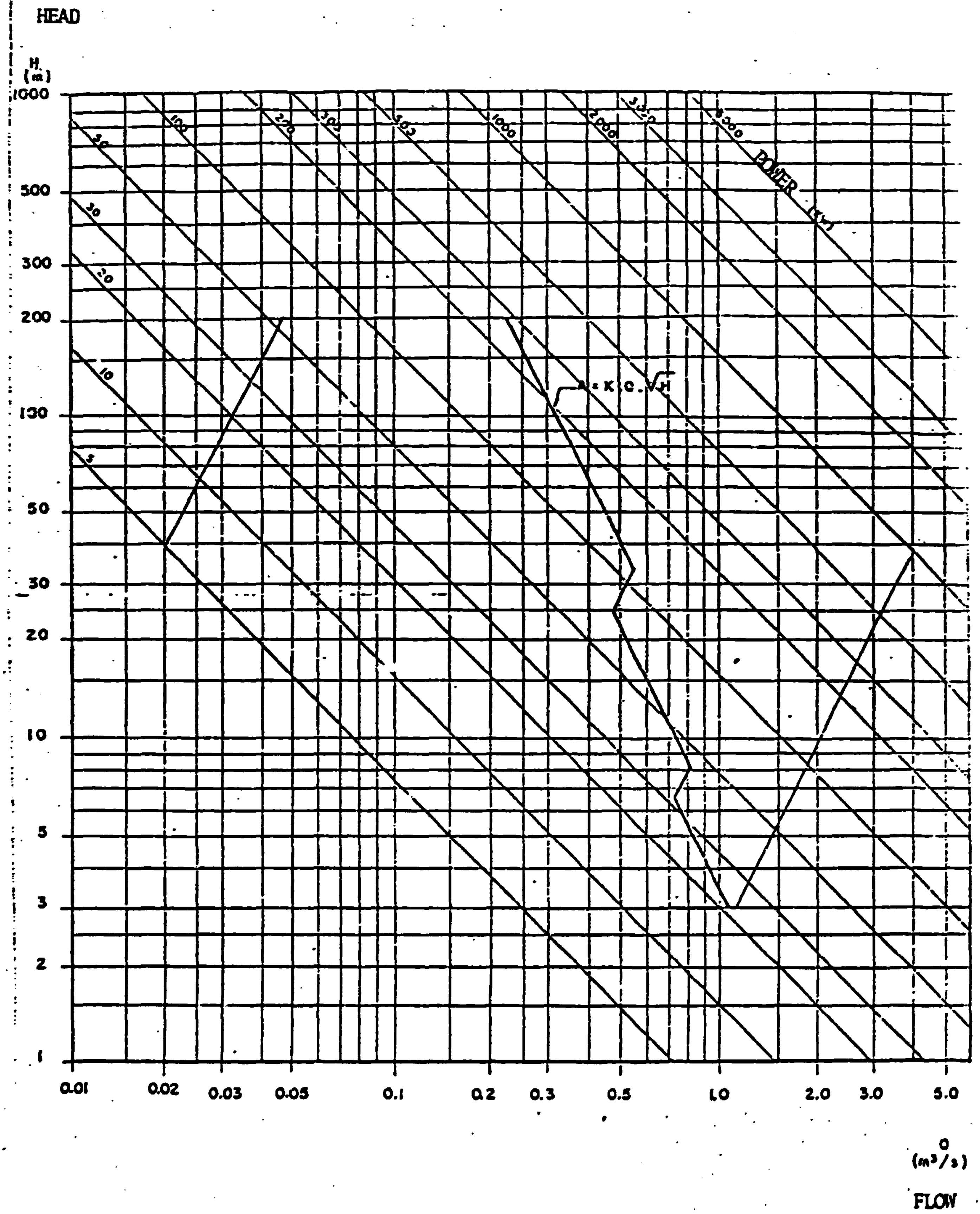
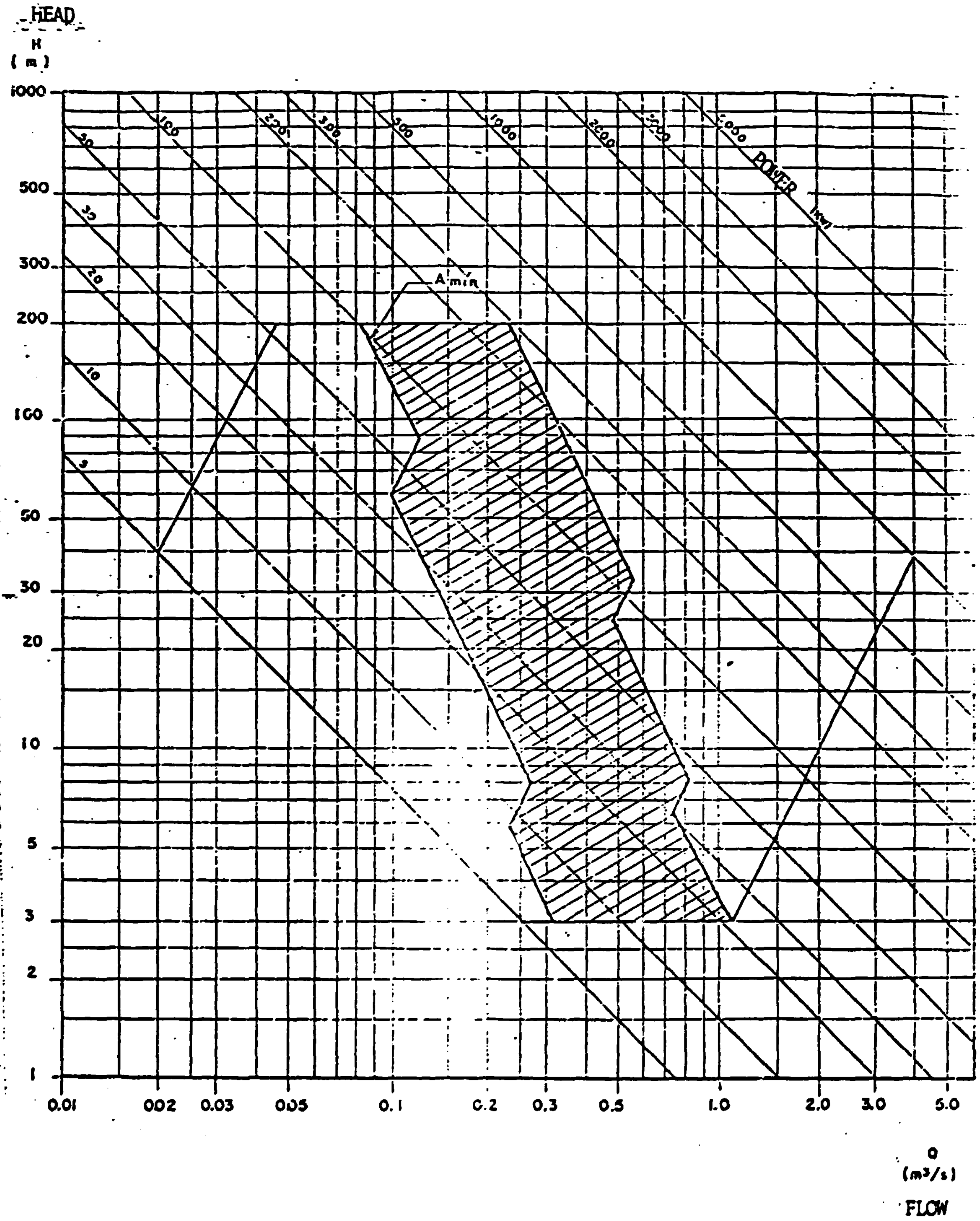

HEAD
H
(m)
1000
500
300
200
100
50
30
20
10
5
3
2
1
0.01
0.02
0.03
0.05
0.1
0.2
0.3
0.5
1.0
2.0
3.0
5.0
Q
(m³/s)
FLOW
50
30
20
10
5
100
200
300
500
1000
2000
3000
5000
POWER (kW)
P = K.Q.√H

FIGURE 7


HEAD
H
(m)
1000
500
300
200
100
50
30
20
10
5
3
2
1
0.01
0.02
0.03
0.05
0.1
0.2
0.3
0.5
1.0
2.0
3.0
5.0
Q
(m³/s)
FLOW
50
30
20
10
5
100
200
300
500
1000
2000
3000
5000
POWER (kW)
A min

hydropower stations, offers a certain quality of optimal regulation which cannot improve much more. Thus, the "average variation in useful load" characteristics would not be very suitable for use as a basis for standardization.

It is worthwhile to note that the arguments given in the analysis were obtained using a procedure for calculating speed regulators based on slight variations in the variables with respect to their nominal values. This is very close to reality for the case of large hydropower stations where, given their size, the average variation in useful life is very low. In small hydropower stations with low power capacities (less than 100 kW), this is not true because there can be large variations in average load. Thus, during the early hours of the evening, many homes and businesses could simultaneously require energy and this would lead to large variations in useful load, given the size of the station. For these cases, an analysis based on the calculation of slight variations in the variables would not be correct and it would be useful to do an experimental theoretical study in order to shed more light on the subject. On the basis of this study, it could probably be concluded that the average variation in useful load could turn out to be a parameter to be taken into account for the standardization of the group of small hydropower stations with a very small power capacity. For this case, the standardization of speed regulators should consider how to provide the greatest possibility for variation in the parameters K_p, K_i, etc. (in the electronic part), so that the regulators can adapt to the large variation in load.

On the basis of the arguments given in the preceding analysis, it is possible to see that the control scheme proposed here may also achieve optimal regulation precision, which it would be possible to attain without drastic changes in the control scheme and without substantially altering prices. In this regard, the characteristic regulation precision would not be useful to consider in standardization (if one accepts the calculation based on slight variations in the variables with relation to their nominal values).

In relation to the third characteristic "type and power capacity of the turbine-generator set," it is worthwhile to do the following analysis:

It is important to recognize that a electric-electronic speed regulator with positive flow control is composed of three basic parts. The first is the purely electronic part which is almost in its entirety an information processer which does not consume power. This part may be common to all standardize speed regulators since it would be independent of the size of the small hydropower station.

The second part of the speed regulator considered in this paper is the electric part, which is made up of the small electric motor. To a certain extent, its size depends on the power capacity of the small hydropower station. However, with sound standardization criteria, it could be overdimensioned insofar as power capacity refers and could thus work for most or even all of the group of small hydropower stations.

The third part of the regulator is the power section constituted by the pilot and power hydraulic servomotors. This part is highly dependent on the power of the turbine-generator set, so that it cannot be unique for all the group of small hydropower stations.

From this analysis, it can be seen that if speed regulators of the type proposed in the OLADE Manual are built, the electric and electronic parts could be universal for all SHP and the power part could be designed and constructed in standardized groups, depending on the power range.

The method for standardizing the power part can be developed taking as a basis the criteria provided in 3.3.1.

3.3.3 Electric-Electronic Speed Regulators with Load Dissipation

In a way similar to that used for regulators with positive flow control, in the present case the possible system features for standardization are as follows:

1. Average variation in useful load.
2. Precision in the desired regulation.
3. Type and power of the turbine-generator set.

The manual prepared by OLADE for the design, standardization and fabrication of electric-electronic regulators with load dissipation recommends that these be used only for power ranges lower than 150 kW, since otherwise the costs of construction and operation would be very high.

It is worthwhile to mention that the studies for system design permit variation in the useful load from one extreme to the other, i.e., from zero kW to the maximum power capacity implemented. This means that standardization is based solely on the third point of those mentioned above.

The regulator is composed of three basic parts: the first is the part to detect variables and process information, with a minimum energy consumption, and it is conceived so as to common to all standardized regulators.

The second part is comprised by the power or trigger circuit for the electronic relays (thyristors or triacs); and the third part, by panels of auxiliary load resistors. Both are dependent on power.

The OLADE Manual presents the design of this type of regulators for three power variants: 20 kW, 50 kW, and 100 kW, the first of which uses triacs in the power circuit, with thyristors in the two remaining ones.

4. SHORT- AND MEDIUM-TERM OUTLOOK

The interest shown by various OLADE member countries with respect to developing national production in most, if not all, of the areas of equipment for small hydropower stations justifies OLADE's interest in continuing to prepare other volumes of the Manual for Design, Standardization and Fabrication of Equipment for SHP, and even in broadening its scope so that it will not consider only equipment but also field study methods, etc.

Among others, it is considered worthwhile to prepare the following Manuals:

1. Francis Turbines
2. Standardized Michell-Banki Turbines (Detail Design)
3. Hydraulic and Structural Design of Civil Structures
4. Control Panels
5. Transformers
6. Asynchronous Generators (Applications)
7. Electrical Transmissions and Distribution Systems
8. Mechanical Connection Systems for Turbine-Generator Sets
9. Design and Costs of Hydroenergy Inventories in Small Basins
10. Evaluation of the Physical Medium: Hydrology, Topography and Geology
11. Evaluation of Demand and Economic, Financial and Social Analyses for Projects

5. CONCLUSIONS

As noted at the beginning of this paper, it has been based on the Manual for Design, Standardization and Fabrication of Equipment for SHP and it summarizes the different criteria for standardization expressed therein, since this provides an approximate picture of the level of development of this field in OLADE. However, it cannot be assumed that this paper could substitute for the use of the Manual itself, which, given its breadth and level of detail, is a much richer reference source.