Governing turbines for transient loads

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Governors developed for Francis turbines are commonly used with Kaplan or bulb-type turbines; this may not always be satisfactory, particularly during instantaneous load acceptance or rejection. However, simple modifications can greatly alleviate the problem. The author discusses the relevant factors and describes a practical application.

THE POSSIBILITY of using Kaplan or bulb type turbines as exclusive prime movers for generators supplying isolated communities or industries depends (among other factors apart from the governor) on their ability to maintain frequency and accept or reject relatively large loads instantaneously without an adverse effect on external load or power station auxiliary services. Here we shall investigate only the ability of a unit to absorb or reject instantaneous loads; the small perturbance stability criteria will not be touched upon, as these are amply documented elsewhere. All subsequent reasonings are based on the assumption that the values selected for acceleration time T_a and water acceleration time T_w of the unit satisfy the small perturbance stability requirements and ensure that during a full power load rejection the stipulated velocity limit is not exceeded.

The load absorbing capacity of a unit under these assumptions depends mainly on the opening speed of the runner blades since both flow and torque are practically a linear function of blade angle provided the unit is on-cam, (see Fig. 1) the maximum deviation (for a certain unit) being +2.5 per cent for torque and 1.5 and −0.7 per cent for discharge. The deviation from the best straight line is still better: ±0.8 per cent for both quantities.

Off cam the turbine has a double nature as illustrated by Figs. 2 and 3. Fig. 2 shows the turbine discharge as function of distributor opening (a_0) with runner blade angle (α) as parameter, while Fig. 3 shows the turbine torque (M) for the same variables. From Fig. 3 particularly, one can understand that whenever the distributor opening is less than the on-cam value, the machine behaves as a Francis turbine, ie, torque and flow are

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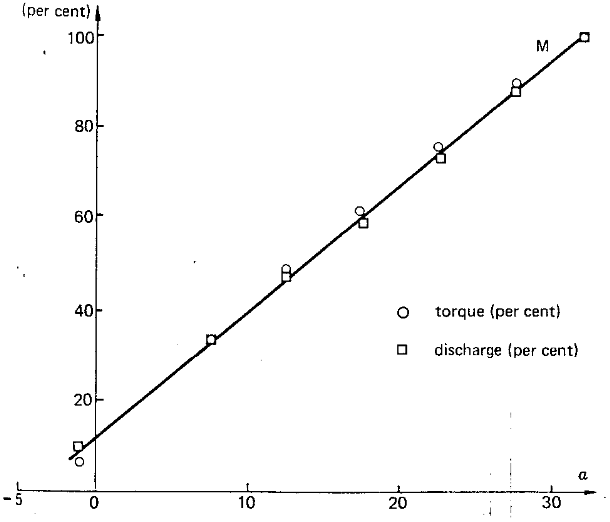

Fig. 1. Flow and torque of a small unit are virtually linear functions of the blade angle (α) under conditions defined in the text.

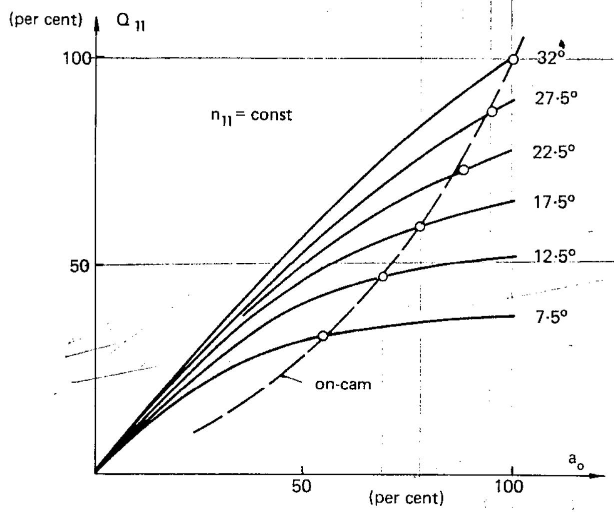

Fig. 2. Turbine discharge as a function of distributor opening (9_o) where the runner blade angle is α.

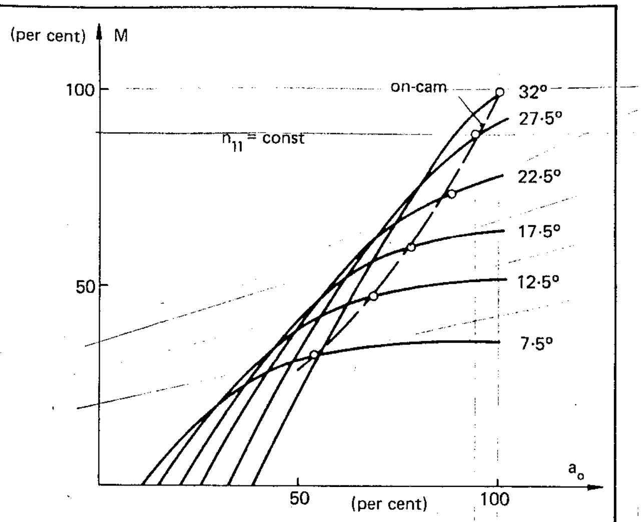

Fig. 3. Turbine torque (M) as a function of distributor opening (9_o) where the runner blade angle is α.

roughly proportional to distributor opening, while whenever the distributor opening is greater than the on-cam value, the distributor has little influence, especially on torque, at least in relation to the on-cam torque for the runner blade angle in question. Thus, a turbine with long runner blade opening time would stall even for a 10 per cent step-increase of an arbitrary stationary load.

The properties of Kaplan turbines discussed above indicate directly the optimum relationship between the distributor and runner blade timing. High loading capacity requires that the runner blades could be opened very fast, thus, if the opening time of the distributor is 6 s and an even loading velocity ($\Delta P/\Delta t$ const) is desired, the opening time of the runner blades should be about 9-12 s, depending on the maximum value of $\Delta\alpha/\Delta a$. However, if for the same turbine it is required that the turbine should open on cam in 6 s, the necessary opening time of the runner blades must be around 3-4 s.

The closing speed of the distributor is limited by the maximum allowable pressure surge in the spiral case and the maximum allowable depression below the head cover. The closing speed of the runner blades is less critical but one should keep in mind that the maximum speed rise during a load rejection is greatly influenced by this value. Fig. 3 clearly indicates that for an arbitrary runner blade angle, the difference between distributor opening corresponding to the on-cam point and the one yielding zero torque is fairly independent of the runner blade angle and unit speed within the normal operating range. Thus the greater the difference between the distributor and runner closing speeds, the sooner the unit will reach zero torque with a consequently lower speed rise.

Also the effect of excitation of the generator on the turbine speed is of great importance. As an illustration of the influence of the voltage regulator properties on unit

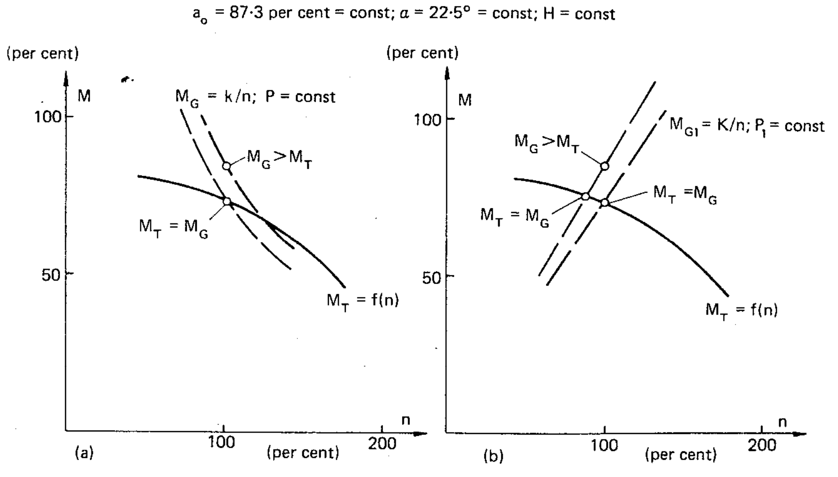

Fig. 4. The influence of the voltage regulator properties on the unit stability where: (a) the generator voltage regulator is assumed to be very fast and the load resistive; and (b) the voltage regulator maintains excitation independently of speed and the load is resistive.

stability, two cases are presented, both based on the same self-regulating characteristics, ie, $M_T=f(n)$ (with $a=\text{constant}$ and $\alpha=\text{constant}$)) of the turbine. In Fig. 4a the generator voltage regulator is assumed to be very fast and the load resistive:

$$M_G=k_1(U^2/R)/n, \text{ and since}$$

$$U^2/R=\text{constant}, \ M_G=k_2/n$$

a hyperbolic relationship. It is apparent that for these conditions the unit is inherently unstable because once a small load increment disturbs the momentary equilibrium, no new equilibrium can be reached. In Fig. 4b it has been assumed that the voltage regulator maintains excitation independently of speed and the load is resistive. Thus:

$$M_G=kU^2/Rn \text{ and since } U^2/R=(nU_0)^2/n_0^2R$$

$$M_G=k_3n$$

here the torque of the load will vary linearly with speed yielding an essentially stable system.

It is not uncommon that governors developed for Francis turbines are used to control the speed of Kaplan or bulb type turbines with the addition of a mechanical hydraulic or electronic combinator device to control the runner blades. Governors intended for Francis turbines are ones which derive the stabilizing signals (or temporary speed droop, time delay) from the distributor, a practice fully justified for Francis turbines since the distributor opening of these is roughly proportional to turbine torque. But this is not quite the case for Kaplan or bulb turbines, at least not on-cam (see Fig. 5) or during an opening when the distributor opens faster than the blades. On the other hand when the distributor opening is at least a bit less than the opening corresponding to the on-cam point and downward, the turbine torque varies almost linearly with the distributor opening, fairly independently of the runner blade angle.

From these properties a number of simple rules can be deduced, which describe what conditions are necessary for stable operation of Kaplan or bulb type turbines supplying isolated loads where considerable instantaneous load variations are expected.

- either the opening velocity of the runner blade should be high enough, or the opening velocity of the distributor should be low enough, for on-cam opening of the unit;
- the temporary speed droop should be proportional to variation in torque, thus it is different within different power ranges of the unit and also different for opening or closing motions, since closing is usually done off-cam; and,
- the voltage regulator of the generator should ensure—at least during the first seconds of a considerable load change—a kind of constant torque or constant excitation type of loading, especially if the load is mainly resistive or incandescent lighting. With later developments which change the characteristics of the load, changes in voltage regulator parameters could be justified.

It has to be emphasized that these conditions as already

Notations

a_0 = Wicket gate opening
b_t = Temporary speed droop
e_p = Permanent speed regulation
k_1 = Constants
n = Speed
n_0 = Synchronous speed
t = Time
D = Runner diameter
H = Head
M_G = Generator torque
M_T = Turbine torque
P = Generator power
R = Resistance
T_A = Unit acceleration constant
T_C = Closing time
T_D = Damping time constant
T_O = Opening time
T_W = Water inertia time
U = Generator voltage
α = Runner blade angle

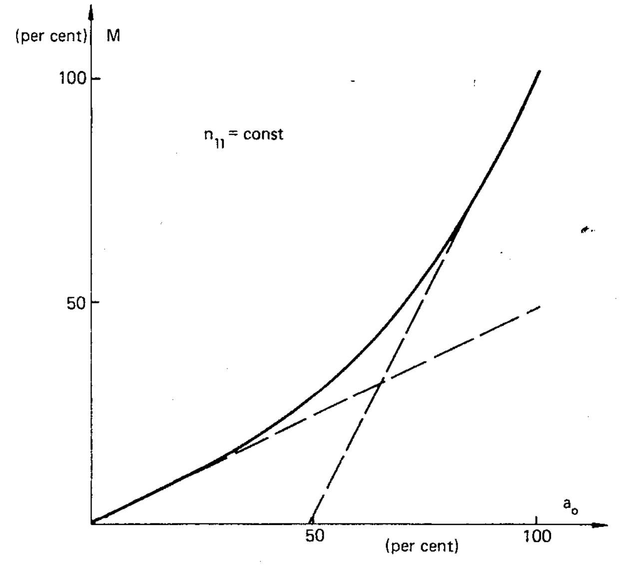

Fig. 5. For Kaplan on bulb turbines the distributor opening is not directly proportional to turbine torque when the distributor opens more quickly than the blades.

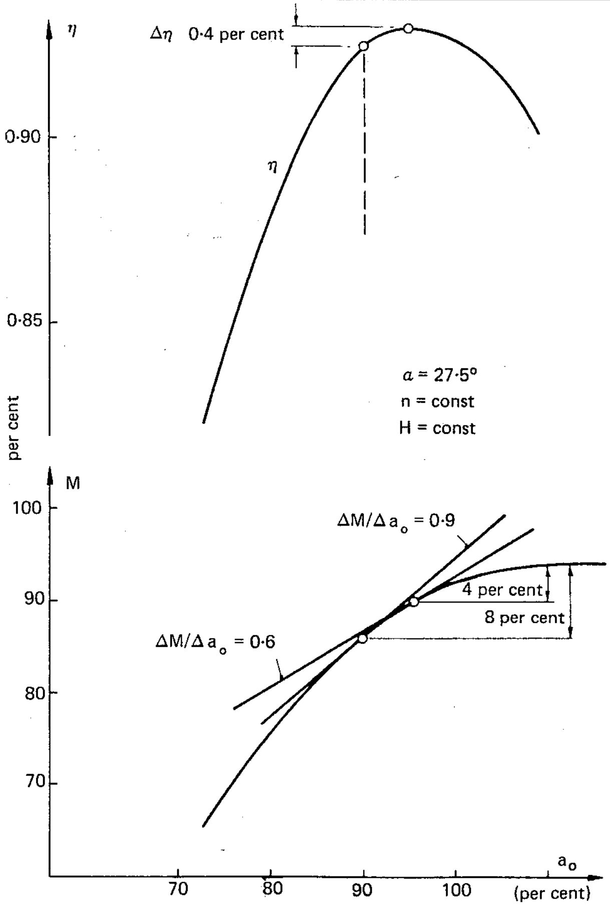

Fig. 6. At a runner blade angle of 27.5°, shifting the distributor opening from 95 to 90 per cent will reduce the efficiency by only 0.4 per cent, but will increase torque response by 50 per cent and off-cam overload capacity by 100 per cent.

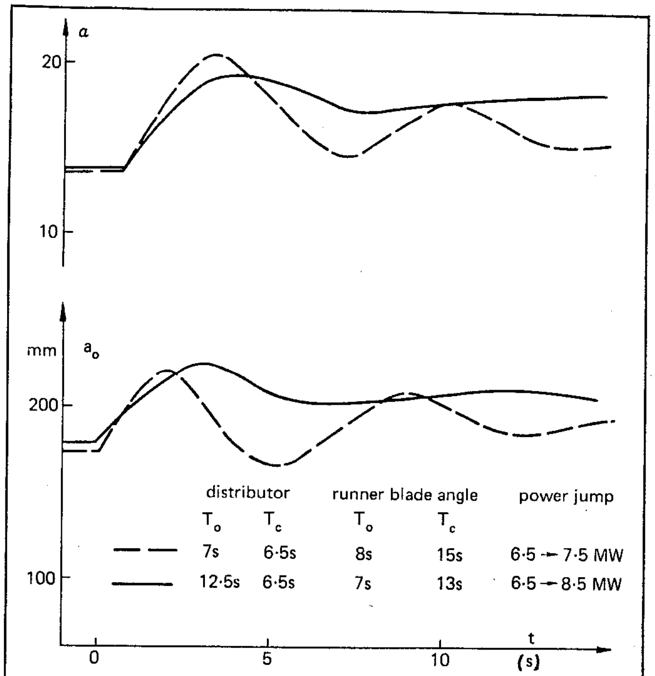

Fig. 7. New timing for the unit supplying Curuá-Una gives more stable operation.

mentioned are additional to the ones required for small perturbance stability and load rejection speed rise limitation.

On existing units these ideal conditions are not always easy to satisfy. Servomotor size, pressure oil unit size often limit the maximum runner blade servomotor velocity. The modification of temporary feedback over the operating range can be difficult to achieve by mechanical governors. In such cases the only way to improve the ability of a unit to accept considerable load changes is to change the relationship of distributor opening (a_0) to runner blade angle (α), to a lower a_0-value for the same α-angle. Fig. 6 illustrates the consequences of such a change. For the turbine in question at a runner blade angle of 27.5° the shifting of the corresponding distributor opening from 95 to 90 per cent will reduce the efficiency only by 0.4 per cent, but will increase torque response by 50 per cent and off-cam overload capacity by 100 per cent.

The recommendations put forward in this article (apart from theoretical considerations) are mainly based on experience gained in different power stations, where the principles, in part, have also been tested with satisfactory results. Before going into the presentations of the special solutions and achievements some words should be said about the governor.

The governors used were ASEA electronic-type QRVV 103 or 104 ones, together with the Nohab Tampella hydraulic part type NEH-A. The electronic part is a conventional PID governor where the stabilising terms (b_t, T_d) are derived from the motion of the distributor. The combinator device is mechanical/electronic, the runner blade and distributor controls are also electronic/hydraulic. The use of an electronic runner blade regulator was fortunate because this simplified the shifting of the turbine operating point on the cam curves without much inconvenience.

An interesting feature of the hydraulic part is that there is no actuator, the position of which in a conventional system is usually copied by the main servomotor with the aid of the main distribution valve and restoring linkage. So as to have a good frequency response, the position of the electro/hydraulic transducer is amplified and then directly transferred to the main distribution valve while the restoring signal—which is a pure electronic one in automatic operation—is led directly to the electronic governor position input. Thus, all inaccuracies, overlap-

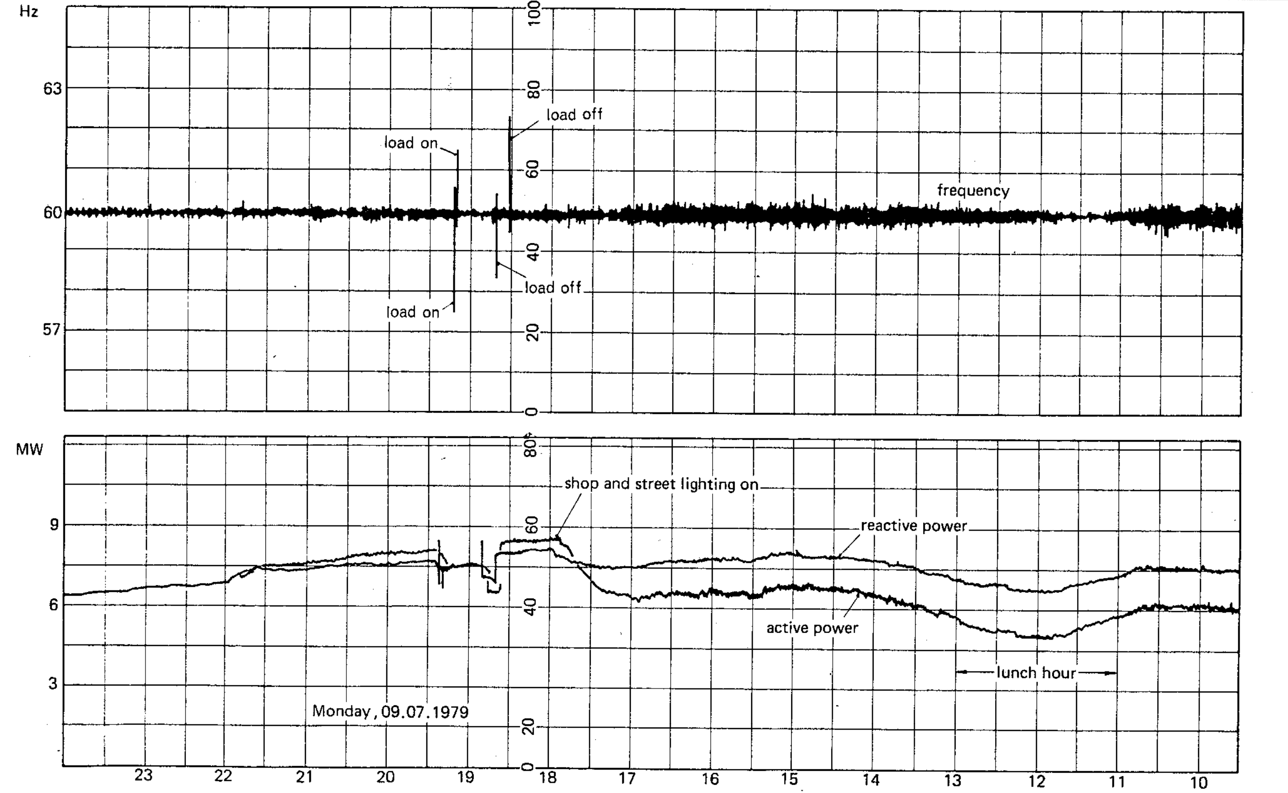

Fig. 8. Frequency (top) and power (below) variations for the town of Curuá Una during one day in 1979. Note the small variation of frequency variation following disconnection or reconnection of a sector of the town between 18.40 and 19.20.

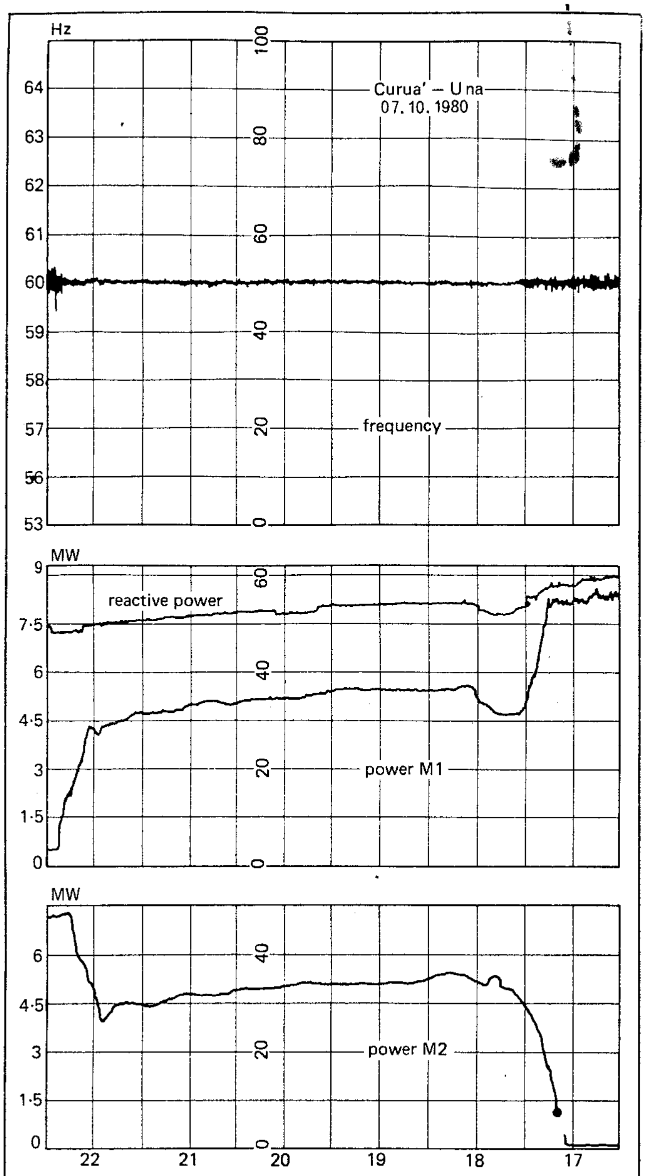

Fig. 9. Improved response to load variations at Curuá Una using two units with different speed droops.

ping, backlash, etc, are within the main restoring loop, giving an extremely fast response. For emergency hand operation there is a simple restoring wire. The possible drawback of the system is that adjustments which require movement of the distributor can be made only with the intake gates set and the unit dewatered, or when the pressure is the same on both sides of the wicket gates.

With this equipment, two Nohab-Tampella turbines (P=10.3 MW, H=21.7 m, n=200 rev/min, D=3.1 m) are operating in the Curuá-Una, power station built on a small tributary of the Amazonas near Santarém, Pará, Brazil, about 800 km upstream from the sea. The town itself is supplied through a single line. The local distribution is handled at the town sub-station dividing the town into—for the moment—four sectors.

To indicate the conditions which could be encountered in isolated grids the station record of power and frequency of 09.07.1979 showing the daily routine of the town is reproduced in Fig. 8. It is interesting to observe the repeated disconnection and reconnection of a town sector between 18.40 and 19.20; also the small value of subsequent instantaneous frequency deviation.

The fuzzy part of the recording is the consequence of connecting and disconnecting heavy machinery in the local saw-mills. During the weekend, the frequency is maintained at 60 Hz with a deviation better than ±0.1 Hz.

In the beginning the distributor and runner blades stroke times were set conventionally:

	distributor	runner blades
T_0	7 s	8 s
T_c	6.5 s	15 s

These values gave good load absorbing abilities in the lower power range but above 50 per cent load, exaggerated distributor and runner blade motions were observed with stepwise changes of load of 1-2 MW.

Later considerations, especially the necessity to be able to reject or take on substantial loads (as, for example, whole town sectors) near the limit of unit rating made resetting of this timing desirable. The new timing is:

	distributor	runner blades
T_0	12.5 s	7 s
T_c	6.5 s	13 s

With this new timing a very stable operational form has been achieved. Although the unit is now a bit sluggish in the low-power range, it can still absorb a power jump from 2 MW to 7 MW in a single step without dropping out, and the behaviour above 6 MW has improved significantly. As the recordings show, the motion of the distributor and runner blade has been greatly reduced, leading to a reduction in oil consumption. By introducing a two-speed opening law, further improvements could be made.

Before the readjustment of distributor and runner blade timing it was necessary to advance the runner blade angle by 3° (with the results shown in Fig. 6). With the new settings, this value could be reduced to around 1°, compensating for the time delay in the runner system.

When the units are in parallel, the leading unit has zero permanent speed droop, $e_p=0$ and the so called ancillary unit is adjusted to $e_p=2$ per cent. Thus, both units participate in the maintenance of frequency with a difference in speed droop large enough to eliminate power transfer between the units but small enough to avoid motoring with all its consequences to the leading unit in case of failure of one or two major sectors or the town itself. Since the governors are equipped with power feed-back, the operators are instructed to adjust the power reference value for the ancillary unit at intervals to about 50 per cent of the total instantaneous station load.

Fig. 9, showing the station frequency record and the unit power records during peak hours shows the quality of frequency control with the two units in parallel.

To safeguard against permanent overload in case one of the units should fail when the station load exceeds the capacity of one unit, time delayed under-frequency relays are envisaged to cut out the least important consumers.

Conclusions

By carefully selecting the closing and opening times of the distributor and the runner blade servomotor, it is possible to achieve excellent step-load handling capability of Kaplan and bulb type turbines, provided the unit acceleration time T_a and water acceleration time T_w satisfy the conditions necessary for small perturbance stability and speed-rise limit during full power load rejection. In existing units where control actuator timing is limited by pressure oil unit capacity etc, some improvements can be obtained by shifting the cam towards a higher runner blade angle. ☐

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WESTERN SIMULATION COUNCIL GOVERNOR REPRESENTATION

$$Z = \frac{K_1 (1 + T_2 s)\, n}{(1 + T_1 s)(1 + T_3 s)}$$

OUR TRANSFER FUNCTION FOR THE MECH-HYDRAULIC TYPE GOVERNOR IS:

$$Z = \frac{(t_r D + 1)}{t_s t_r D^2 + (t_s + \delta t_r + \sigma t_r) D + \sigma}$$

WHERE:

δ = TEMPORARY DROOP
σ = PERMANENT DROOP.
t_r = DASHPOT RESET TIME (SECONDS)
t_g : GATE TIME (SECONDS)
t_s = 1/GOV. OPEN LOOP GAIN (βt_g)

β = SPEED DEVIATION REQUIRED TO SATURATE THE DISTRIBUTING VALVE.

THE ABOVE EXPRESSION CAN BE WRITTEN:

$$Z = \frac{1}{\sigma} \; \frac{(t_r D + 1)}{\frac{t_s t_r}{\sigma} D^2 + \frac{[(\delta + \sigma) t_r + t_s]}{\sigma} D + 1}$$

WHICH CAN BE REDUCED TO THE DESIRED FORM AS FOLLOWS:

LET $T_A = \frac{t_s t_r}{\sigma}$ AND $T_B = \frac{(\delta + \sigma) t_r + t_s}{\sigma}$

THEN.

$$T_1, T_3 = \frac{T_B}{2} \pm \sqrt{\frac{T_B^2}{4} - T_A}$$

AND $T_2 = t_r$

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PLM