Whatever the approach, it should be noted that the optimum determined for the characteristic of previous analysis ($\beta = 0$) does not necessarily represent desirable settings for either low or high head machines, as reference to Fig. 15 will show.

Summary and Conclusions

It has been shown that as far as reaction turbines are concerned the turbine of the standard text is the exception rather than the rule. It has been further shown what effect the speed dependence of turbines has on the pressure-quantity and pressure-torque relationships and that while the effect varies from turbine type to type it can at any gate be defined accurately by a single parameter—the slope of the unit quantity-unit speed curve at that gate.

The effect of the speed dependence of the turbines on stability and response has also been examined and found to be at least as significant as that of the most basic parameters—the machine and water column inertias—and should not therefore be neglected in any analysis.

It has been further shown by reference to real characteristics that the relationship between quantity, torque, and gate is such as to make the relative changes in quantity and torque at rated output smaller (often significantly so) than the corresponding change in gate. In order to be able to deal with this effect, the concept of effective gate should be introduced. This in turn leads to the reappraisal of the effective value of temporary droop, always provided that the governors used have high sensitivity.

Finally, it has been shown that in the bulk of the installed water turbines the run of the river units are significantly easier to stabilize and have potentially better response than the turbines of conventional theory and only the high head Francis machines present a problem greater than the conventional approach would lead one to expect.

The obvious drawback of the present approach lies in the need for dealing with particular installation at a given gate rather than turbines in general, and no doubt this can and will be rectified in time, either by the use of charts or by more far reaching analysis of the problem than it was possible to give here.

Acknowledgment

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References

4. Ibid., p. 79.

M. Leum

The author has made an excellent contribution to the literature now available concerning the simulation of the hydraulic turbine-governor combination. The discussor's company employs a system for predicting stability and evaluation of overall performance which is believed to be equivalent to the author's.

The starting point of the analysis is with the turbine characteristics. Normally, during the design stage, the only information available is the turbine model data. Here, the author is correct in stating that model data is often in an awkward form for deriving the turbine equations. The preferable form is to plot or tabulate torque as a function of speed and discharge as a function of speed for various wicket gate openings from zero to fully open.

Thus, for the model turbine

\[ M_1 = M_1(N_1, Y_1) \]

\[ Q_1 = Q_1(N_1, Y_1) \]

When studying response to small disturbances, equations (30) and (31) can be linearized to obtain

\[ m_1 = \frac{\partial m}{\partial n} n_1 + \frac{\partial m}{\partial y} y_1 \]

\[ q_1 = \frac{\partial q}{\partial n} n_1 + \frac{\partial q}{\partial y} y_1 \]

Here, \( m_1, n_1, \) and \( y_1 \) represent per unit variations of torque, speed and gate for the model.

Representation of the prototype is obtained by using similitude relations which on a linearized basis are:

\[ q_1 = q - \frac{Q_0}{2Q_0} h \]

\[ m_1 = m - \frac{M_1}{M_0} h \]

\[ n_1 = n - h/2 \]

where \( m, n, \) and \( y \) represent per unit variations of torque, speed and gate for the prototype.

Elimination of model variables \( q_1, m_1, \) and \( n_1 \) from (32) and (33) result in

\[ m = \frac{\partial m}{\partial n} n + \frac{\partial m}{\partial y} y + \left( \frac{M_1}{M_0} - \frac{1}{2} \frac{\partial m}{\partial n} \right) h \]

\[ q = \frac{\partial q}{\partial n} n + \frac{\partial q}{\partial y} y + \frac{Q_0}{2Q_0} - \frac{1}{2} \frac{\partial q}{\partial n} \]

Equations (37) and (38) correspond to the author's (2) and (8) and represent the turbine operation in a small region around a chosen operating point.

Assuming incompressible flow, the pipeline can be represented by

\[ -h = T_w \frac{dq}{dt} \]

The total inertia of the rotating parts is represented by

\[ T_M \frac{dn}{dt} = m - m_0 \]

where \( m_0 \) represents the per unit torque loading on the rotating shaft.

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Combination of (37), (38), (39), (40), and (19) then allows a study of stability of the turbine governor combination. It must be recognized that the external load on the unit represented by \( m_g \) has a significant effect upon the transient behavior of the hydro unit. This term has a different form for the various types of conditions encountered in practice. For example, the generator may be supplying power to an isolated resistive load, or to a d-c transmission line, or synchronized to an infinite bus. In each case, the dynamic effect is different and should be considered.

The temporary droop governor, equation (19), is basically a proportional plus integral controller as the author has shown in equation (21). Field experience by the discussers and documentation by Schiott has indicated superior transient performance of the three term controller: that is, proportional plus integral plus derivative with about a 30% reduction in the speed error for a step load change. It is often stated that this improvement in response is not important since practically all hydro units are tied to an infinite bus; however, another performance criteria should be taken into account which is the time delay between a change of command signal and the achievement of the new power level. Schiott has stated that this time is approximately

\[
300 \frac{T_w}{T_M} \text{ seconds}
\]

for the conventional temporary droop governor and for the PID hydro governor

\[
67 \frac{T_{p_d}}{T_M} \text{ seconds}
\]

This represents better than a four to one improvement.

Because of the response improvements reported, it is believed that the author should review his figures which depict stability limits and regions of critical damping.

Additional References

18 Schiott, F. R., and Butes, C. G., “Governing Characteristics for 820,000 Horsepower Units for Grand Coulee Third Powerplant,” IEEE paper No. 70 TP527-PWR.

Author’s Closure

The author wishes to thank Mr. Leum for his discussion and especially for showing that those who are concerned with the problem of stability and of the evaluation of transient response of hydroelectric installations recognize the need to represent the turbine characteristic in substantially more detail than it would appear to be customary from study of the literature on the subject.

It is appreciated that in addition to the turbine characteristic the characteristic of the external load and of the governor play a significant part in determining the transient response of a hydro-electric unit. In the present context however the former has been dealt with adequately in terms of a coefficient of self-regulation of the load, which has been allowed for in formulating the equation of motion of the system, and the latter has been the subject of sufficient studies [11, 13, 14] to require no further discussion here, where a plea for the inclusion in the analysis of the relevant turbine parameters is being made. Nevertheless it would be amiss, once the subject has been broached not to mention briefly the question of time delay between a change of command signal and the achievement of the new power level. In both the P.I. and P.I.D. type of governor this is determined by the “on load” time constant and is given by

\[
\frac{(b_i + b_p)T_d}{b_p}
\]

It is agreed that a high value of the “on load” time constant is often an embarrassment and it has been so stated in the text.

It is further agreed that a properly adjusted P.I.D. governor will give a lower value of this time constant than a P.I. governor.

However in practice, most units operate on a grid and the high values of governor parameters are seldom required. As a result of this in some modern controllers of both types the magnitude of the several parameters determining the “on load” time constant is varied automatically.

When the unit is coupled to a grid pre-set low values of \( b_i \) and \( T_{d} \) are used.

Should the response of the unit be too lively protection which is provided automatically switches on the normal large values of the appropriate parameters. These are also used for start up prior to synchronizing. Thus the optimisation of the governor settings for the “on” and “off” grid conditions is carried out separately and one does not affect the other.

In the above context an improvement of four to one in the magnitude of the “on line” time constant while useful can often be improved upon even with a P.I. type controller. It will also be obvious that in the case of a P.I.D. type controller a combination of governor parameters determining the “on line” time constant most appropriate for mixing with an acceleration signal in the presence of an isolated load would not necessarily be the best combination for a unit operating in conjunction with a grid.

At this stage it would be unadvisable to argue further the merits of the various solutions, especially as governors of diverse origins have all their own idiosyncracies, but it is hoped that the discussion has shown that the characteristics of governors and turbines alike affect the problem of stability and of response and while it is not proposed, at least for the present to take up Mr. Leum’s challenge and extend the analysis to P.I.D. type governors, the analysis, such as it is, has shown the need to consider the relevant turbine data, and that is all that was intended.

Such experience as is available with P.I.D. type controllers shows that the need to represent the turbine characteristic accurately is no less acute when these are used as otherwise any desk study of the transient response of the unit bears little resemblances to the real problem.