TUNING OF SPEED-GOVERNING SYSTEM FOR KALAYAAN PUMPED STORAGE POWER PLANT

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Abstract---*Changes in system frequency are caused by any imbalance between load and generation. To control these, a speed governor is usually provided. The change in frequency may be either stable or unstable depending on the values of the parameters of the plant and governor. This paper describes a simple analytical procedure of tuning electro-hydraulic P.I.D. governors for the units of Kalayaan Pumped Storage Power Plant. Mathematical analysis is carried out using MATLAB simulation software, while validation through time simulation is performed using Power System Simulator/ Engineering (PSS/E). Optimum gain settings were found both during isolated and grid operations. Although actual plant testing was not possible, the result of the study is seen as an improvement from the usual trial-and-error approach which is currently being practiced.*

INTRODUCTION

Generating units operating synchronously in parallel in a power system must have a means of controlling their speed by automatically adjusting their mechanical power to maintain balance between load and generation. Such is the function of a speed-governing system or speed governors.

Synchronous operation implies a common electrical speed or frequency among the generators and the rest of the system. Imbalances between load and generation are reflected by proportionate changes in system frequency. A frequency below nominal value is a sign that the load exceeds the generation while a frequency above nominal indicates otherwise. Using speed or frequency as input, speed-governors respond by adjusting the power output of the generating units to restore the balance and correct the frequency errors.

System components such as steam turbines are sensitive to frequency changes due to severe vibrations which cause cumulative metal fatigue and loss-of-life. To minimize exposure to below nominal frequency, especially during sudden loss of generation, underfrequency relays are installed on feeders to automatically drop customer loads. Although this has been a long accepted practice, it results in service interruption when frequency is poorly regulated.

Among the different types of generating plants, the hydroelectric units are very suitable for frequency regulation primarily due to their simple energy conversion process which are relatively easier to control. Modern hydro units, like those of the Kalayaan Pumped Storage Power Plant (KPSPP) of the National Power Corporation, are equipped with electro-hydraulic P.I.D. (proportional, integral and derivative) speed-governors which greatly facilitate tuning for improvement of response.

Early endeavors have been made with regard to governor tuning for speed control of hydro-generators. Attempts to establish a generalized guideline for the selection of control parameters were also considered. The work of Hovey [1] and Chaudry [2] investigated the stability of the hydraulic turbine-generating unit controlled by temporary droop governors. Thone and Hill [3] studied the stability region of a hydraulic turbine generating unit having a P.I.D governor. They showed the stability boundaries as a function of proportional and integral gains but no reference is made to the derivative gain. Dhaliwal and Wichert [4] analyzed the effect of derivative gain on the stability of a single machine supplying an isolated load. In the aforementioned, no attempts were made to define the stability boundary, until later, Hagihara, et al [5] expanded the works of Hovey and Chaudry to show the stability boundaries of a hydraulic turbine generating unit having a P.I.D. governor. Unfortunately, the above investigators have used simplified models for the turbine-penstock and water column.

Sanathanan [6] presented a frequency domain method to determine the optimum values for the parameters of a P.I.D. governor. The method readily handles detailed models of turbine-penstock, gate dynamics and other system dynamics.

The problem of tuning the speed-governing system of the KPSPP was considered in the SwedPower Report [10]. The unit test result showed that the unit has good automatic frequency regulating capacity but the P.I.D. governor parameters need to be adjusted in order to be coordinated with other units operating on free governor.

The purpose of this report is to introduce a simple analytical procedure of tuning P.I.D. speed governors for hydro units for optimum response during isolated and grid operations with due consideration for control stability. Thus, this paper presents a root locus and time domain method based on Guillemin-Truxal Design approach in tuning the P.I.D. governor of the KPSPP. There are two main advantages of the method namely, simple computations required and the designer can prespecify a speed response for load change.

ANALYTICAL INVESTIGATION

The analytical investigation, in an attempt to tune the speed-governing system for hydro-turbines, includes adequate representation of the speed governor, the gate dynamics, the hydro-turbine and water column, and the generator.

An examination of this problem shows that, for small disturbance analysis, a reduced-order model for the system is adequate in determining the response after the disturbance has occurred.

The reduced block diagram of the speed-governor is shown in Fig. 1.

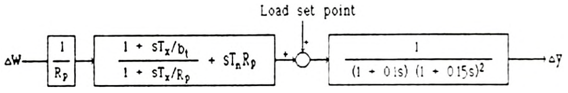

Figure 1. Reduced P.I.D. Controller Block Diagram

and a more realistic hydraulic system model:

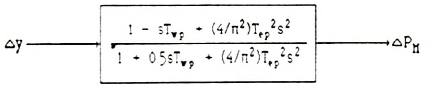

Figure 2. Hydraulic System Block Diagram Relating Turbine Mechanical Power Output and Gate Position Change

The generator and load model is shown in Fig. 3.

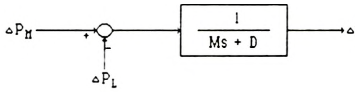

Figure 3. Reduced Rotating Mass-Load Block Diagram

The Hydro-unit Block Diagram

The complete speed control of the hydro unit is now represented by the block diagram as shown in Fig. 4.

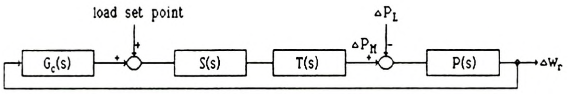

Figure 4. Block Diagram of Speed-Governing System

The component transfer functions derived from the model are defined by the following equations:

$$G_c(s) = \frac{T_n s^2 + \frac{T_n R_p + T_x / b_t}{T_x} s + \frac{1}{T_x}}{s + \frac{R_p}{T_x}} \tag{1}$$

$$S(s) = \frac{1}{(1-0.1s)(1+0.15s)^2} \tag{2}$$

$$T(s) = \frac{1-1.0304s+0.4601s^2}{1+0.5152s+0.4601s^2} \tag{3}$$

$$P(s) = \frac{1}{9.86s} \tag{4}$$

For frequency control studies, the block diagram can be reduced into the form shown in Fig. 5.

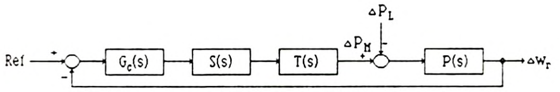

Figure 5. Reduced Hydro Unit Block Diagram

Let a reference model M(s) be specified as in Fig. 6.

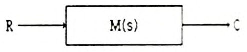

Figure 6. Reference Model

The central idea involved in this method consists of finding $G'_c(s)$ such that the time response of the closed loop transfer function, C/R, matches that of M(s). For this the required $G'_c(s)$ must satisfy:

$$G'_c(s) = \frac{M(s)}{[1 - M(s)]S(s)T(s)P(s)} \qquad (5)$$

This is known as the synthesis equation by Guillemin-Truxal Design approach.

For controller design purposes, it is found that the low order approximation of the ideal $G'_c(s)$ which is accurate in the critical low frequency band, is sufficient. The transfer function of $G'_c(s)$ can be generated readily from eq. (5) for any elaborate equation for S(s), T(s) and P(s). From this information, a low order transfer function $G'_c(s)$ is synthesized.

Since for a step change in ΔP_L, see Fig. 5, the steady state value of Δw_r must be zero, it is clear that $G'_c(s)$ must contain a pole at the origin.

Selection of the Reference Model

A selection procedure is carried out considering the units of Kalayaan Pumped Storage Power System parameters. From eq. (3), it is clear that T(s) is a non-minimum phase transfer function. Therefore, it is necessary that M(s) must retain exactly the same right-half-plane zeros as those of T(s) [13]. If not, $G'_c(s)$ will turn out to be unstable.

The pole locations for M(s) are somewhat arbitrary. However, M(s) must have at least four poles. This will become clear as the procedure continues. Using the **0.707** damping ratio as a design criterion, let two pole pairs of M(s) be chosen as:

$\mathbf{s_{1,2} = -0.3 \pm j0.3}$; $\mathbf{s_{3,4} = -1.0 \pm j1.0}$

This leads to the following reference model:

$$M(s) = \frac{(1 - 1.0304s + 0.4601s^2)(1 + as)}{(1 + 4.333s + 9.389s^2 + 7.222s^3 + 2.778s^4)} \qquad (6)$$

The additional term, (1 + as), in eq. (6) is chosen with an appropriate value for 'a' such that the coefficients of s^0 and s^1 are the same for the numerator and the denominator of M(s). This is to ensure that the implied close loop system corresponding to M(s) will have two poles at the origin (one for P(s) and the other for the controller). Hence, **(a - 1.0304) = 4.333** and therefore, **a = 5.3634**. Note that if a load regulation factor is included in P(s), the additional term will not be necessary.

Thus, the numerator of M(s) must have a degree of three. Therefore, the denominator of M(s) must at least be of degree four, to make M(s) appear as a proper transfer function.

To simulate step response, Fig. 6 is transformed into Fig. 7 in which:

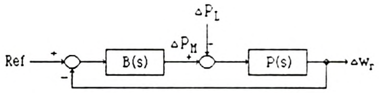

Figure 7. Modified Reference Model

$$B(s) = \frac{M(s)}{[1 - M(s)]P(s)} \qquad (7)$$

Using eq's. (6) and (7):

$$B(s) = \frac{(1 - 1.0304s + 0.4601s^2)(1 + 5.3634s)}{s(1.4661 + 0.4823s + 0.2817s^2)} \qquad (8)$$

Figure 8 gives the response of the reference model for a 10% load increase.

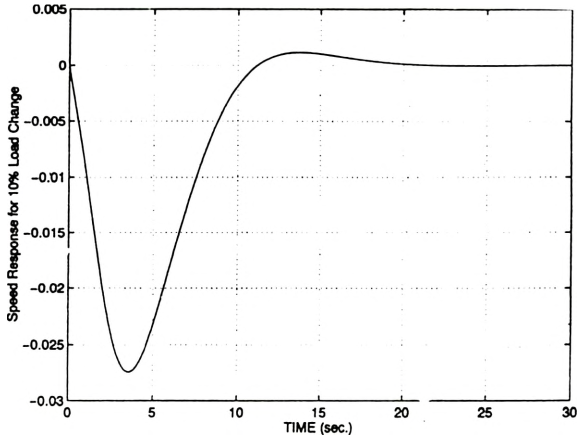

Figure 8. Speed Response of the Reference Model for a 10 Percent Increase in Load

The transfer function of $G'_c(s)$ of the ideal controller can be determined by means of eq's. (5) and (6). This transfer function was matched using a simple expression of the equivalent P.I.D. controller, eq. (1).

The value of Rp meanwhile is set to zero. Note that from eq. (1), $1/T_x$ is the limit of $G_c(s)$ using the final value theorem, and it is evaluated readily using eq's. (1) and (5). Therefore, T_x is constrained to this value while obtaining the optimum values of T_v/b_t and T_n. From eq. (5), applying the final value theorem, $G'_c(s)$ approaches 0.6821. Since the controllers of KPSPP units have discrete set points for parameter adjustment, the best value that matches this is $T_x = 1.65$ and the integral gain is forced to this value. Optimization is carried out using the mean square error of the time response between $G_c(s)$ and $G_c'(s)$. This is carried out using discrete values of T_x/b_t and T_n set points of the Kalayaan controller model.

For the case presented above, the optimum governor parameters setting are:

$\mathbf{T_x = 1.65;\quad T_n = 1.7;\quad T_x/b_t = 5.3}$

Using the above parameters for the P.I.D. controller, the hydro-turbine unit has been simulated with S(s), T(s), and P(s) defined by eq's. (2), (3) and (4), respectively. The speed responses for 10% load increase are shown in Fig. 9. The responses do match the prespecified response quite well. Figure 9 also shows the comparison of the speed responses using the gain values from the MATLAB simulation and the default setting obtained from the National Power Corporation (NAPOCOR) considering the effect of speed droop. The figure shows that an improved damping and settling time are achieved using the gains obtained by this technique.

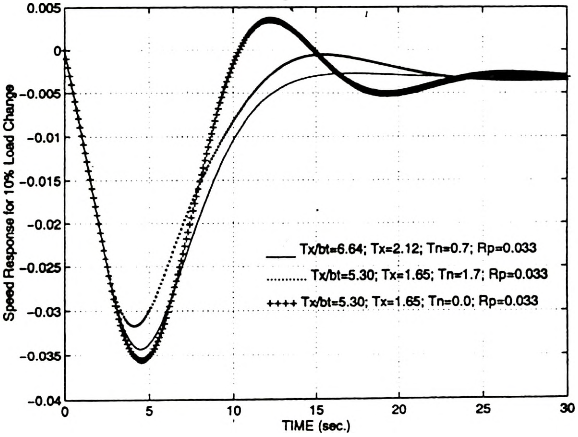

Figure 9. Comparison of Speed Responses with Speed Droop

PSS/E VALIDATION

The result of the analytical investigation is verified using the PSS/E software by simulating both the island and synchronous operations of KPSPP. The network data used for the study has been derived from the NAPOCOR in the form of PSS/E raw data.

Isolated Mode of Operation

The governor data is first verified by simulating the response of the individual units in isolation. This test simulates the response of the governing loops of all units, in isolation, to a step change in load. The KPSPP unit initial condition is set to 60% of the MW rating of one unit and a step change of 10% is applied.

Three different sets of P.I.D. parameter settings are used in the case of KPSPP. The two sets are the result of the analytical investigation while the other set is obtained from the NAPOCOR performance specifications. Figure 10 shows that the result of the analytical investigation is in close coordination with the result obtained from the PSS/E simulation.

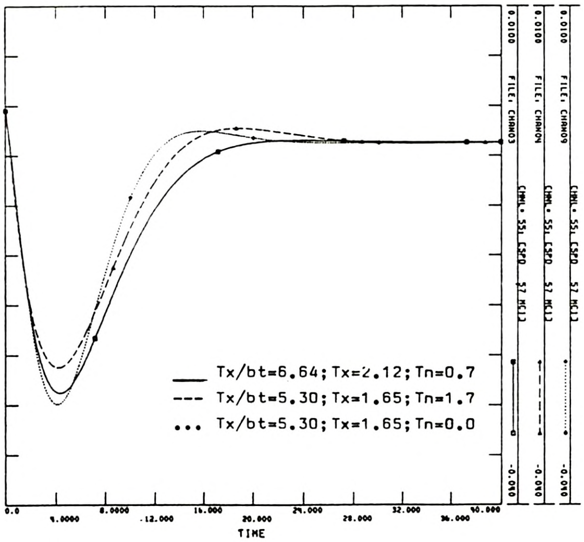

Figure 10. Comparison of Speed Responses

With the governor parameters set at $T_x/b_t = 5.30$, $T_x = 1.65$ and $T_n = 1.7$, a 10% load increase on this unit showed that the speed dropped to a certain minimum peak and then settled down without oscillation to a value just below nominal, as determined by the speed droop of 3.33 percent. Also the improvement in the undershoot is very noticeable.

Synchronized Mode of Operation

To determine the response of the speed governor when the units are connected for synchronous operation, simulation is performed for a case where frequency is controlled by a combination of seven (7) oil thermal units and one (1) hydro unit, the KPSPP. The mode of operation is to consider the system in normal synchronous operation and suddenly trip off one generating plant connected in the system. A total of 36 generating pants are considered connected in the simulated system. This test assumed that there is enough operating reserve and that it is capable of taking care of the generator tripping as applied in this test.

The same three sets of P.I.D. parameter settings are used for the electro-hydraulic governor of KPSPP unit while maintaining the same conditions for other plants participating in the frequency control. Figure 11 shows the speed responses of KPSPP for three cases considered. This figure reveals that an optimum performance is achieved for a condition where the P.I.D. parameters setting is,

$$T_x/b_t = 5.30; \quad T_x = 1.65; \quad T_n = 0$$

With the parameters tuned to these values, a faster and smoother response is achieved.

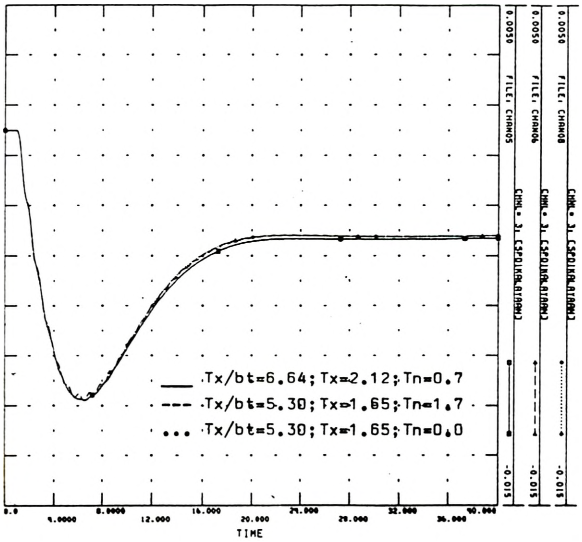

Figure 11. Comparison of Speed Responses

Figure 12 shows the electrical power response from the generator. The fluctuations in the first seconds are not caused by the governor system but are due to the oscillations between different generators. This can be found by comparing the electrical power response of Fig. 12 to the mechanical power response of Fig. 13. A somewhat less obvious but nevertheless perverse characteristic of the derivative action of the P.I.D. governor is its tendency to accentuate distortion of the gate movement, Fig. 13.

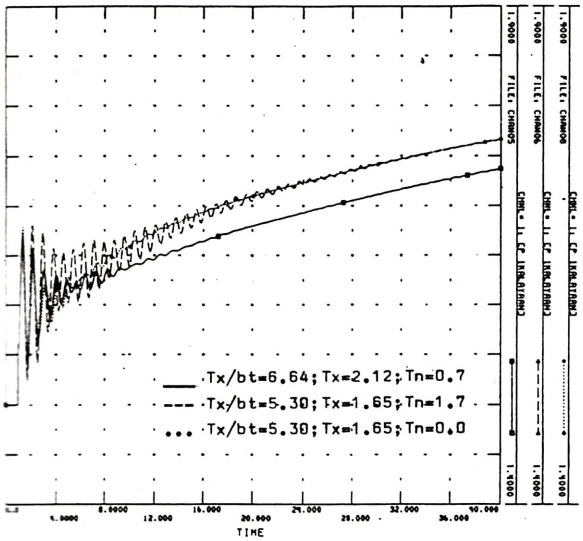

Figure 12. Electrical Power Output

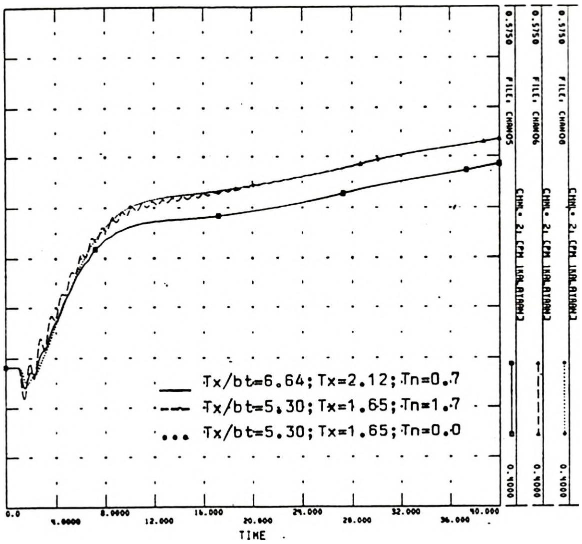

Figure 13. Mechanical Power Output

From Fig. 11, the period of speed transient of the KPSPP under synchronous operation lies between the respective periods of the speed transients of the individual units on isolated basis and is appropriately damped. Although the speed transient of the KPSPP under the synchronous operation is over in approximately 18 seconds, Fig. 13 shows that there is a continuous secondary readjustment of gate position. Following application of generator tripping, the faster of the units participating in the frequency control picks up the greater share of the generation change. Then, after the speed has been corrected, the units gradually shift load until it is divided according to their droop characteristics.

CONCLUSION AND RECOMMENDATIONS

The following important results and observations are listed in conjunction with the tuning of the speed-governing system of KPSPP for both isolated and synchronized operating modes.

*Frequency excursion can be easily controlled if frequency control is distributed to a large number of units with free governor operation.

*The step response test for the KPSPP reveals that a much improved performance is achieved if the governor parameters are tuned to $T_x/b_t = 5.30$, $T_x = 1.65$ and $T_n = 1.7$. This is verified by both the analytical investigation and the PSS/E software simulation.

*The stability of KPSPP under island operation is enhanced by appropriate derivative gain.

*Under synchronous operation, there is no need for the derivative function on the KPSPP governor unit. Its presence accentuates the noise due to interaction among the different generators connected in the system. The optimum performance is achieved when $T_x/b_t = 5.3$, $T_x = 1.65$ and $T_n = 0$.

*The above recommended setting allows the units of KPSPP to respond faster and take a greater proportion of the generation change.

*By eliminating the derivative function, a calmer regulation is obtained and thereby less maintenance will be required.

*A governor parameter setting for good speed regulation under an isolated condition also yields good regulation for system operation under normal condition after the derivative function is eliminated.

*Though actual plant testing was not possible, the result of the study is seen as an improvement from the usual trial-and-error approach which is currently being practiced.

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NOMENCLATURE

$1/b_t$	Coefficient of the proportional action
D	Load damping constant
$G_c(s)$	P.I.D. controller transfer function
M	Angular momentum of the machine
P(s)	Turbo-generator transfer function
ΔP_L	Change in electrical power
ΔP_M	Change in mechanical power
R_p	Permanent speed droop
S(s)	Actuator-servomotor transfer function
T(s)	Turbine-penstock transfer function
T_n	Time constant of the derivative action
T_v	Water starting time $= Z_p T_{ep}$
T_x	Time constant of the integral action
Δw	Deviation from the nominal frequency
Δw_r	Change in rotor frequency
Δy	Deviation from the servomotor stroke

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