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A FREQUENCY DOMAIN METHOD FOR TUNING HYDRO GOVERNORS

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Abstract - A frequency domain method to determine the optimum values for the parameters of a PID governor is presented. The method readily handles detailed models of turbine-penstock, gate dynamics and other system components. The main advantages of the method are that it is computationally simple, does not involve any iterations and that the designer can prespecify a speed response for load rejection.

INTRODUCTION

Optimum adjustment of the proportional, integral, and the derivative gains of a PID governor is crucial for the stability and satisfactory transient behavior of hydroturbine units. Simple empirical rules usually evolve for specific units as a result of numerous simulation studies and operating experience. These rules, however, cannot be extended readily to other units which have considerably different values for the basic parameters, such as, water starting time, T_W, wave time, T_e, and mechanical starting time, T_M. A general, streamlined method to determine optimum governor parameters is therefore highly desirable.

Attempts have been made [1-4] to establish generalized stability boundaries for the PID parameters. Hagihara, et al [3], in fact, provide a simple general recipe for obtaining parameter values for the governor. Unfortunately, the above investigators have used simplified models for the turbine-penstock. Furthermore, gate dynamics have been neglected. The contention has been that the parameter values from these studies can serve as a starting point.

The following example illustrates how unsatisfactory the parameter values as given by the recipe in Ref. [3] can be. The hydro unit is represented by the block diagram in Fig. 1. In this figure, V(s) represents the gate and T(s) represents the turbine-penstock transfer function. The basic parameters, T_W, T_e, and T_M are assumed to be 2, 1, and 8 seconds respectively. For these values, the formula in Ref. [3] gives:

$$K_P = 3.2,\ K_I = 0.48,\ \text{and } K_D = 2.16$$

In arriving at these values, it is assumed that V(s) = 1.0 and that the turbine is ideal, lossless, and at full load with the first order transfer function:

$$T(s) = \frac{1 - 2s}{1 + s} \qquad (1)$$

Neglecting the load self regulation factor,

$$P(s) = \frac{1}{8s} \qquad (2)$$

The system in Fig. 1 has been simulated for a 10% step load rejection using the above controller parameters and the simplified component transfer function, T and V. The corresponding speed response, as given by the solid curve in Fig. 2, does appear to be satisfactory.

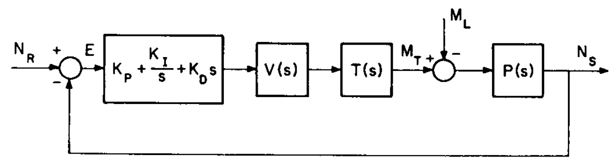

Fig. 1 BLOCK DIAGRAM OF A HYDRO UNIT

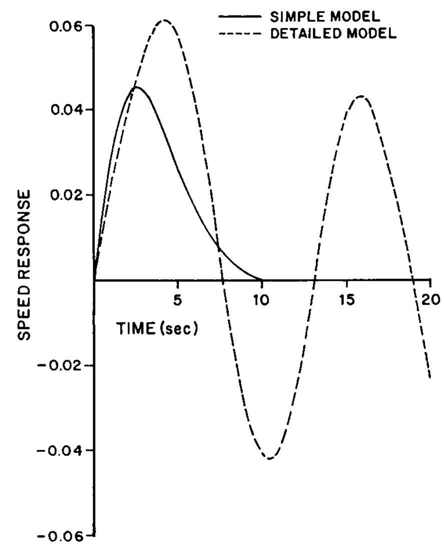

Fig. 2 COMPARISON OF SPEED RESPONSES

Now consider a more accurate approximation of T(s) as given in [5]:

$$T(s) = \frac{1 - 1.986s + 0.3606s^2}{1 + 0.9932s + 0.3606s^2} \qquad (3)$$

and a realistic gate transfer function [12]:

$$V(s) = \frac{1}{(1 + 0.1s)(1 + 0.15s)^2} \qquad (4)$$

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Using these transfer functions, the system in Fig. 1 is again simulated for a 10% load rejection. The resulting speed response is given by the dotted curve in Fig. 2. It is obvious that the governor parameters are unsatisfactory.

Simultaneous optimization of the three parameters for a realistic system model can be accomplished via the well known gradient method [6], direct search methods [7], or via the age old trial and error method. When the initial guess is poor, however, all of these methods will require a large number of iterations involving model simulation at each iteration.

The method presented in the following section allows the designer to prespecify a satisfactory reference response, similar to the solid curve in Fig. 2. The controller parameters are then determined (without any trial and error) such that the closed loop system response matches the chosen reference response. The method readily accommodates detailed transfer functions for the various components.

TUNING METHOD

The block diagram in Fig. 1 may be represented more generally as shown in Fig. 3, where the plant component transfer functions, G_1 and G_2, are known and the controller transfer function, $G_c(s)$, is to be determined. Let a reference model A(s) be specified as in Fig. 4.

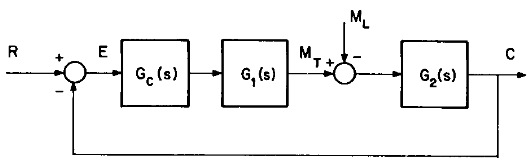

Fig. 3 GENERALIZED BLOCK DIAGRAM

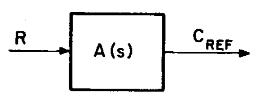

Fig. 4 REFERENCE MODEL

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

$$G_c(s) = \frac{A(s)}{[1 - A(s)]G_1(s)G_2(s)} \qquad (5)$$

Eq. (5) is generally known as the synthesis equation. Its use in controller design dates back several decades [8,9]. The main problem with the technique is that when the plant component transfer functions are of high order, the resulting expression for the "ideal" $G_c(s)$ in eq. (5) will be unsuitable for practical implementation.

For controller design purposes, it is found that a low order approximation of the ideal $G_c(s)$ which is accurate in the critical low frequency band, is sufficient. The frequency response of $G_c(s)$ can be generated readily from eq. (5) for any elaborate expression for $G_1(s)$ and $G_2(s)$. From the frequency response information a low order transfer function $G_c(s)$ is synthesized.

Since for a step change in M_L, (see Fig. 1) the steady state value of E must be zero, it is clear that $G_c(s)$ must contain a pole at the origin. Therefore, the frequency response of:

$$K(s) = sG_c(s) \qquad (6)$$

is used for controller parameter optimization. This isolates the enormous effect of the pole (at the origin) at low frequencies and thereby, a considerable enhancement in the accuracy of the reduced order controller is realized.

SELECTION OF THE REFERENCE MODEL

Selection procedure is illustrated for the system considered earlier. It is clear from eq. (3) that T(s) is a nonminimum phase transfer function. Therefore, it is necessary that A(s) must retain exactly the same RHP zeros as those of T(s). If not, $G_c(s)$ will turn out to be unstable. This is explained further in [10].

The pole locations for A(s) are somewhat arbitrary. However, A(s) must have at least four poles. This will become clear soon. Let two pole pairs be chosen such that they each have a damping factor of 0.707:

CASE - 1: $s = -0.3 \pm j\ 0.3; \quad -1.0 \pm j\ 1.0$

This leads to the following reference model:

$$A(s) = \frac{(1 - 1.986s + 0.3606s^2)(1 + as)}{(1 + 4.333s + 9.389s^2 + 7.222s^3 + 2.778s^4)} \qquad (7)$$

The additional term, (1 + as), in eq. (7) 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 A(s). This is to ensure that the 'implied' closed loop system corresponding to A(s) will have two poles at the origin (one for P(s) and the other for the controller). Hence, (a - 1.986) = 4.333 and therefore, a = 6.319. Note that if a load regulation factor is included in P(s), the additional term will not be necessary.

Thus, the numerator of A(s) must be at least of degree 3. Therefore, the denominator of A(s) must at least be of degree 4, to make A(s) a proper transfer function.

Before accepting the above reference model, it must be ascertained that its load rejection behavior is satisfactory. To simulate load rejection, Fig. 4 is transformed to Fig. 5 in which:

$$B(s) = \frac{A(s)}{[1 - A(s)]G_2(s)} \qquad (8)$$

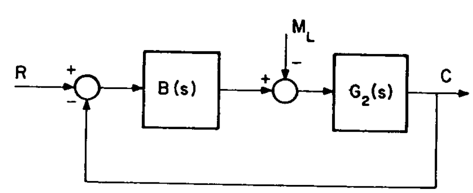

Fig. 5 MODIFIED REFERENCE MODEL

Using eq. (7) and (8):

$$B(s) = \frac{(1 - 1.986s + 0.3605s^2)(1 + 6.319s)}{s(2.697 + 0.5553 + 0.3473s^2)} \qquad (9)$$

Fig. 6 gives the speed response of the reference model for a 10% load rejection.

Similarly, for the sake of comparison, a second, more sluggish reference model has also been selected with its poles at:

CASE - 2: $s = -0.2 \pm j\ 0.2; \quad -0.75 \pm j\ 0.75$

The corresponding A(s) and B(s) are given in eqs. (10) and (11):

$$A(s) = \frac{(1 - 1.986s + 0.3605s^2)(1 + 9.653s)}{(1 + 7.667s + 27.611s^2 + 42.223s^3 + 22.223s^3} \qquad (10)$$

$$B(s) = \frac{(1 - 1.986s + 0.3605s^2)(1 + 9.653s)}{s(5.8026 + 4.8428s + 2.778s^2)} \qquad (11)$$

The speed response for a 10% load rejection for Case-2 is shown in Fig. 7.

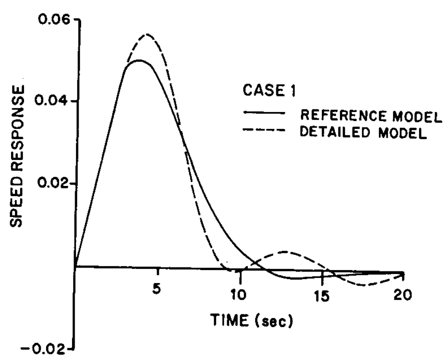

Fig. 6 COMPARISON OF SPEED RESPONSES - CASE 1

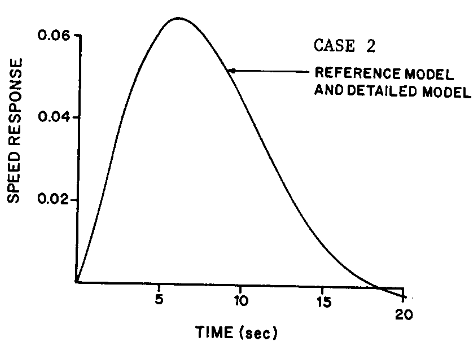

Fig. 7 COMPARISON OF SPEED RESPONSES - CASE 2

RESULTS

The frequency responses of K(s) of the ideal controllers for Cases 1 and 2 have been determined by means of eqs. (5) and (6). They are shown in Fig. 8. These frequency responses have been matched using a simple expression:

$$\hat{K}(s) = K_I + K_P s + K_D s^2 \qquad (12)$$

Note that K_I is the limit of $K(j\omega)$ as $\omega \to 0$, and it is evaluated readily using eqs. (5) and (6). Therefore, K_I is constrained to this value while obtaining the optimum values of K_P and K_D. Optimization is carried out by minimizing the mean square error between $K(j\omega)$ and $\hat{K}(j\omega)$ using the algorithm in [11].

For the two cases cited above, the optimum governor parameters are:

CASE - 1: $K_I = 0.37$, $K_P = 2.7$, $K_D = 2.916$

CASE - 2: $K_I = 0.1723$, $K_P = 1.776$, $K_D = 0.8985$

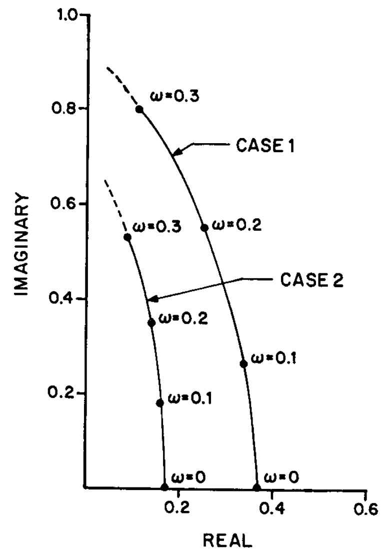

Fig. 8 FREQUENCY RESPONSE OF K(s)

Using the above parameters for the PID controller, the hydroturbine unit has been simulated with P(s), T(s), and V(s) as given by equations 2, 3, and 4 respectively. The speed responses for 10% step reduction in load are shown in Figs. 6 and 7 respectively. The responses do match the prespecified reference responses quite well.

SUMMARY OF COMPUTATIONAL STEPS

The computational procedure described above gives an effectively streamlined approach to obtain optimum governor settings. The steps involved are:

(1) Estimate the basic plant parameters (T_W, T_M, etc.), the turbine partials, and the time constants for gate dynamics.

(2) Derive a detailed transfer function for the turbine-penstock (involving the tanh function) and obtain an accurate reduced order model employing the method described in [5].

(3) Construct a reference model similar to that in eq. (7) and simulate its load rejection behavior using the block diagram in Fig. 5. Choose a specific reference model with satisfactory response.

(4) Obtain the frequency response K(s) of the "ideal" controller given by eqs. (5) and (6). See Fig. 8.

(5) Approximate K(s) in the form of $\hat{K}(s)$ as given by eq. (12). Determine the optimum value of K_I as the value of $K(j\omega)$ as $\omega \to 0$.

(6) Freezing the value of K_I to the one obtained above, determine the optimum values of K_P and K_D by matching the frequency response of $\hat{K}(s)$ with that of K(s). For this, the method in [11] or any other complex curve fitting method may be employed.

(7) Simulate the closed loop hydro-turbine model to compare its response with that of the reference model.

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NOMENCLATURE

A	T.F. of the reference model
B	T.F. associated with A as defined in eq. (7)
C	System response
G_1	Product of gate and turbine-penstock T.F.'s
G_2	Same as P
G_c	Controller (governor) T.F.
K_D	Derivative gain of the governor
K_I	Integral gain of the governor
K_P	Proportional gain of the governor
K(s)	Defined as $sG_c(s)$
M_L	Load torque
M_T	Developed torque in the turbine
N_R	Reference speed input
N_s	Turbine speed
P	Turbo-generator T.F.
s	Laplace transform variable
T	T.F. of turbine-penstock
T_e	Wave time
T_M	Mechanical starting time
T_W	Water starting time
V	Gate T.F.

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In 1968, Dr. Sanathanan joined the University of Illinois at Chicago where he was promoted to the rank of full professor in 1972 in the Department of Electrical Engineering and Computer Science. His research has encompassed a variety of disciplines, such as, power plant control, oil reservoir modeling and production policy assessment, computer automation of industrial plants/processes, and adaptive control of multivariable systems. Dr. Sanathanan has over fifty major publications.