Computer Representation of Electrical System Interaction with a Hydraulic Turbine and Penstock

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COMPUTER REPRESENTATION OF ELECTRICAL SYSTEM INTERACTION WITH A HYDRAULIC TURBINE AND PENSTOCK

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Abstract - In the design of a hydroelectric generating plant, the major engineering disciplines assume responsibility for various items of equipment. It is difficult to examine the dynamic relationships that may exist between the penstock, the turbine and governor, and the generator and electrical system. Computer models are available to represent hydraulic transient phenomena in detail, and separate detailed representations of the electrical system are also available.

This paper discusses a computer modelling approach that uses a high level computer language to represent hydraulic effects, including water hammer, concurrently with a detailed representation of the turbine, generator, controls and the electrical system.

INTRODUCTION

Hydraulic transient solution methods for digital computers are highly specialised and use complex computer codes for problem definition. Electrical models also tend to be specialised and oriented to the system. It may be difficult for the engineers responsible for the design of a hydroelectric plant to appreciate the possible interractions of the system components. The best known example of a troublesome interraction is the draft tube surge, which may excite either or both the penstock water column and the electrical system. Design choices may be required when the governing system, the excitation system and the generator are specified. A versatile method of simulating the generating station is required to make rational design choices.

An extension of analogue computer methods of handling hydraulic transient problems has been adapted for use on a digital computer. The method can be implemented using a high-level language such as CSMP (Continuous Systems Simulation Program). The resulting concise code can be readily modified so that an appropriate level of detail can be used. The CSMP approach is ideally suited to dynamic problems containing control loops and differential equations, as are encountered when describing a hydro-turbine generating plant connected to an electrical system.

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This approach is currently being applied in the following areas:

(a) To determine the response time of a hydro plant to supervisory load set signals, such as those originating from an automatic generation control centre.

(b) The design of a control loop to take a signal from the penstock or draft tube and use this to alleviate draft tube surge effects on the electrical system.

The paper describes the methods used, with a discussion of different levels of approximation that may be adopted for different purposes. An example of a simplified model is given to illustrate the methodology, and also a complete set of generator equations suitable for design work on excitation controls.

Computer Modelling Languages

Before the large scale introduction of digital computers, analog computers were used for simulating dynamic problems that can be represented using differential equations. Following the introduction of digital computers, the Fortran language became almost the universal language for engineers and scientists who wished to apply the computer. However, if this language is used to describe a problem of the complexity commonly encountered in real life dynamic situations, then the designer must become familiar with computer programming and numerical integration methods at a very detailed level. To improve the situation, computer languages were developed that allow an engineer familiar with analogue computers to formulate a model for a digital computer in similar terms. Two types of language are in current use:

(a) A block diagram oriented approach using a numbered network.

(b) An algebraic concept using time dependant variables linked using input-output dependancy statements.

The block diagram approach is most closely related to analogue computer methods and is easily learned. The algebraic approach is more concise and the available programs typically offer greater versatility. The algebraic version has been defined by committee[1] and compatible program versions are available from different sources. The algebraic approach has been used in the most recent work described in this paper. It has also been used by others for modelling electrical systems[2]. The program is documented by the original authors[3] and there is at least one excellent application oriented text available[4].

Hydraulic Transients

The most usual method of handling hydraulic transients on a digital computer is the method of characteristics[5]. This is an accepted and accurate method but must be implemented in Fortran, leading to a complex computer code that is best written or modified by specialists. The resulting model is not easily integrated with electrical system models.

A "classical" turbine-penstock transfer function is widely used for modelling the hydraulic part of a system model[6]. This accounts for the kinetic energy of the water column, but does not recognise compressibility. Examples can be found in the literature that clearly indicate that compressibility phenomena can be very significant[7,8]. While the "classical" transfer function can readily be incorporated into electrical system models, the result will not represent, for example, the storage of energy as a pressure wave in the penstock.

A transfer function oriented penstock model, taking account of compressibility, has been used on analogue computers[9], and more complete models have been proposed[10]. This model has been applied, using digital computers, to represent a hydroelectric plant with a complex penstock geometry including branches, area changes and a surge chamber[11]. This method is summarised in Appendix A.

Electrical Machine Model

General methods for modelling electrical machines are available in the literature[12]. Various levels of detail can be incorporated, depending on the purpose of the model[13]. Matrices can be used to develop equations that can be included directly into a computer model[14]. Equations are developed in Appendix B for a 5-coil synchronous generator, which have been used by the authors in recent studies to evaluate the feasibility of a generator stabiliser to dampen power swings caused by draft tube surges.

Control Loops

The principal control loops on an electrical generator are the governor and the voltage regulator. The governor should be of increasing interest as automatic generation control schemes are implemented. These schemes will usually rely on any hydro power in the system to take the fast adjustments to area generation. Modern governing equipment is greatly improved. It is now more sensitive to small frequency errors and capable of faster action. A block diagram for a 3-term electronic governor is given in Appendix C. This diagram also includes a feed-forward device which can be used to inject a supervisory signal directly to the unit. This allows fast response with respect to the supervisory system, while retaining stable settings for the primary frequency control loop. Feedforward features similar to the one illustrated can be provided by several suppliers of governing equipment.

Excitation System

In modern hydroelectric plants, the static excitation system is almost exclusively used. This can be represented in block diagram terms using the IEEE Type 1S model. For a high initial speed static exciter, a gain of 1 and time constant of zero is adopted. The regulator part consists of a high gain operational amplifier with local feedback.

It is usual, in modern practise, to use a power system stabilizer (PSS) to improve the dynamic performance. The design of the PSS is a current topic and a number of papers and design methods have been presented [15,16,17]. The PSS used in this model has two lead-lag functions, and is designed to compensate the generator and exciter phase lag at the frequency of interest. It is possible to choose from a number of different input signals such as power, shaft speed or frequency. System frequency deviation is an effective signal and has been widely used in practise.

Turbine Model

A representation of the hydraulic turbine model is given in Appendix E. Hydraulic head and turbine speed are input variables, and hydraulic flow and machine torque are output variables. The model also allows for gate position to be input. The equations are based on the "Hill Curve" representation of turbine model data. This is adequate for a conventional hydraulic turbine where reverse rotation is not encountered. While unit power or unit discharge data can be used, unit discharge data is more direct and works better in a numerical model. Alternate data structures may be more appropriate when dealing with a reversible pump-turbine[11,18]

RESPONSE OF A HYDRO PLANT TO SUPERVISORY SIGNALS

A computer model using transfer functions for the elements described above was used to investigate the design of an improved interface between a hydro unit and supervisory signals. The governor is used to control the unit output, and the traditional method has been to bias the speed set command. Depending on the setting of the speed droop, the unit would make some response to this bias. This worked well on the original, isolated systems. On more typical modern systems, however, the speed signal as sensed by the unit does not give any indication of a regional generation imbalance, since this is compensated for by power flows on tie lines to adjacent generation regions. The modern requirement, therefore, is to sense regional imbalance by tie line monitoring. A supervisory signal can then be sent to the generation chosen as the most suitable to accept the required adjustment. Typically, this is the hydro units on the system. Hydro governors, however, should be set with carefully chosen gains to give a compromise between fast response that tends to destabilise the system, and lower gains that will give stable response if isolated or have no destabilising influence on the on system operation[19]. If the more appropriate stable gains are used, the response to supervisory signals is slow.

Figure 1 is a simple representation using the "classical" penstock model and the traditional generator model used in swing angle analysis. Linear turbine characteristics are assumed. The governor is a 3-term electronic governor, and the gains are chosen based on temporary droop and dashpot relaxation time normally recommended for a conventional mechanical governor, except that the corresponding integral and proportional gains have been doubled to take advantage of the stabilising

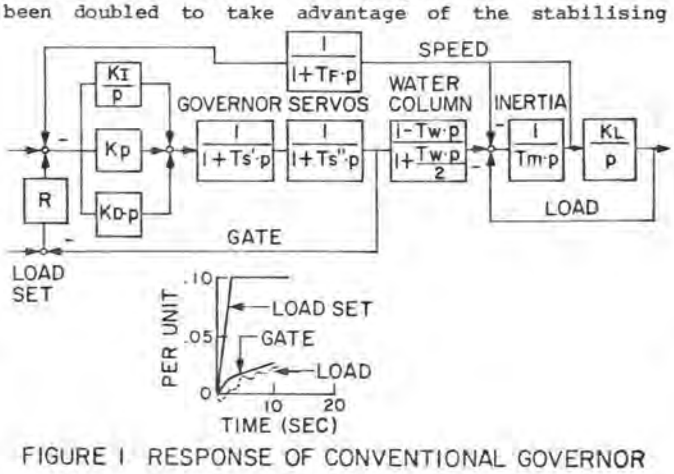


FIGURE 1 RESPONSE OF CONVENTIONAL GOVERNOR

effect of derivative action. The results clearly indicate that the response to a supervisory signal is very sluggish.

Figure 2 shows how the supervisory signal can by-pass the low-gain elements of the speed control loop. The result is that the unit tracks the supervisory signal with a delay determined only by the inertia of the penstock water column. This is a pronounced improvement over the normal arrangement, with no system stability penalty.

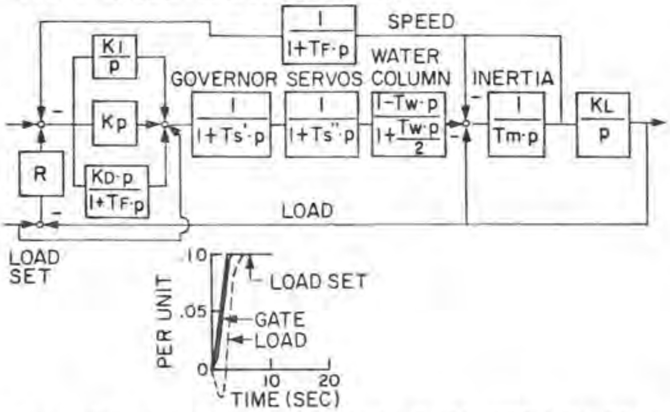


FIGURE 2 SUPERVISORY SIGNAL BYPASSES LOW GAIN ELEMENTS

The diagram includes a 1-second filter, which must be in the speed feedback loop through the derivative element to prevent an instability. This has been noted in field tests of derivative governors, and the instability is reproduced in the numerical model.

Since the work summarised in Figures 1 and 2, the modelling has been repeated using the penstock model described in Appendix A, and the detailed turbine model described in Appendix C. The behaviour has been essentially reproduced and the benefits of the feedforward arrangement have been confirmed.

More than one governor vendor can offer a feedforward device similar to the one modelled in Figure 2. The model demonstrates stability with a very direct relationship between load set and unit output. This suggests that the stringent stability requirements of the speed feedback loop do not apply. It is anticipated that the details of the circuitry can be varied significantly with no threat to unit stability.

APPLICATION OF A POWER SYSTEM STABILISER FOR DRAFT TUBE SURGE SUPPRESSION

The first four units at the Tarbela project were found to be susceptible to power swings[20]. In an attempt to determine the significant factors in this problem and to reduce the probability of the problem recurring in successive units, not yet installed, it was decided to use numerical modelling. An existing computer program was utilised[21], and additional coding was added to represent the penstock using impedance concepts described earlier. The results of this work indicated that there was no significant amplification of pressure surges in the complex penstock and manifold. It is possible that the complex branching and area changes helped to dissipate pressure surges. The cause of the power swing appeared to be a draft tube surge causing a forcing frequency close to the generator natural frequency. However, a Canadian design of power system stabiliser had been specified for the later units. The stabiliser used the system frequency as the input signal. It was included in the model and was found to be effective in damping the power swing effect. At the end of the study, it was felt that the prevention of draft tube surging by sound hydraulic design was the first priority, but the inclusion of a power system stabiliser gave an added margin of security.

The United States Bureau of Reclamation (USBR) has a long standing interest in draft tube surges (22,23), and supported work on an extension of the techniques applied on the Tarbela project. This work allowed the integration of a detailed generator model, hydraulic conduit model, turbine performance model and control loops as described earlier. These models were all implemented using a standard language, CSMP, again following the approach recommended earlier.

The principal objective of the USBR sponsored work was to explore the concept of taking a signal directly from the draft tube. This could then be modified and used to vary the excitation.

The study used data for the Grand Coulee III power plant. This plant is not different from other similar installations with respect to draft tube surges, but was chosen because good data was available from model tests and commissioning. This plant differs from the Tarbela plant in that there is a good separation between the draft tube forcing frequency and the natural frequency of the generator. The power swings observed at part load are much smaller, approximately 3 percent of rated power[24].

As part of the model validation process, the pressure swings observed in the prototype were supplied to the numerical model. The correspondance is shown in Table 1:

TABLE 1

COMPARISON BETWEEN COMPUTER SIMULATIONS AND PROTOTYPE TEST

Run No.		Prototype Test	Computer Simulation
1	Power Output, MW	280	280
	Gate, percent	45	41
	Penstock pressure surge, peak to peak, feet	18	18
	Surge frequency, Hz	.3	.3
	Power swing, MW+/-	11	12.5
2	Power output, MW	440	440
	Gate, percent	60	57
	Penstock pressure surge, peak to peak, feet	15	15
	Surge frequency, Hz	.33	.33
	Power swing, MW+/-	15	16

The model is now being used to compare the effectiveness of PSS signals taken from the system frequency with signals taken from the penstock or draft tube as well as other PSS signals such as frequency and power. It is anticipated that the study will confirm that the excitation system can be controlled so that the generator natural frequency is adjusted to avoid draft tube surge. However, it is not yet clear that the excitation system can attenuate the effect of draft tube surges on the electrical system. Clearly, it would be advantageous for the hydraulic turbine model test stand to give better data on the possibility of draft tube surge interracting with the penstock or generator. This implies extended scaling to obtain:

(a) Penstock wave return time. Plastic materials with a low modulus of rigidity may be useful here.
(b) Vibration energy storage capacity on the turbine shaft. This could be a rigidly coupled mass

driven by the turbine, connecting to the dynamometer by a flexible shaft. The dynamometer should have an inertia at least equal to the inertia of the turbine-driven mass. The shaft flexibility and the masses should be chosen to simulate the prototype natural frequency. Ideally, the test stand should be a complete scale model of the prototype electrical generator and controls.

Special efforts would be needed in the design of the test stand to ensure that pump or other pressure pulsations are eliminated so that any turbine draft tube pulsations are not obscured.

CONCLUSIONS

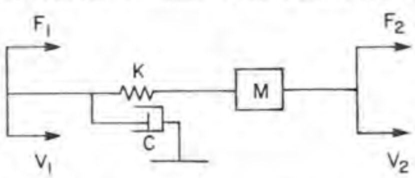
Mathematical modelling can be applied in any desired level of detail to analyse the behaviour of hydroelectric power plant and its associated control loops. This is a topic of current interest as automatic generation control schemes are implemented, often relying on hydroelectric generation capacity to provide fast initial response to the need for additional generation within an area. Mathematical modelling may also be used to improve understanding of unanticipated behaviour, such as the power swing problem at Tarbela or the pressure surge at Grand Coulee III. Since some aspects of the problem cannot be modelled mathematically, particularly the generation of draft tube surges, physical modelling still has an important role to play.

The possibility of resonance between a draft tube forcing frequency and the generator or penstock should be considered in the design stage. If necessary, this possibility can be evaluated using numerical modelling as described in this paper.

The behaviour of the numerical model suggests that the limit of stability improvement will respect to draft tube surging using a conventional single winding rotor, has been reached. It has been pointed out by others that stability gains can be obtained by the use of additional rotor windings (25,26). This may be an appropriate time to resume work on this concept.

APPENDIX A
HYDRAULIC CONDUIT MODEL

Electrical transmission line theory uses a series of four-terminal elements to represent the line. The following is a mechanical analog for a unit length of hydraulic conduit with linearized fluid friction.[11]



This analog can be used to develop a characteristic impedance function

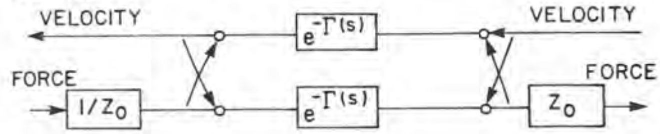
$$Z_0 \simeq \sqrt{MK} + \frac{C}{2}\sqrt{\frac{K}{M}}\cdot\frac{1}{S}$$

and

propagation function

$$e^{-\Gamma(s)} = \underbrace{e^{-s\cdot\ell\sqrt{\frac{M}{K}}}}_{\text{DELAY}}\cdot\underbrace{e^{-\frac{c\ell}{2\sqrt{MK}}}}_{\text{ATTENUATION}}$$

A four-terminal model for the hydraulic conduit can be written

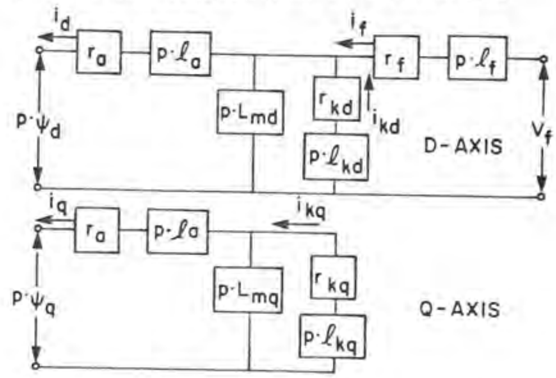


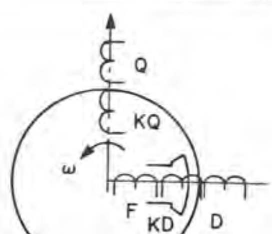
Units are as follows.

V = velocity
F = force
C = damping force per unit length, per unit velocity
M = mass of fluid contained in a unit length of line
K = effective bulk modulus times area of line
ℓ = length of line
S = Laplace operator

APPENDIX B
GENERATOR MODEL

The following D and Q axis equivalent circuits are used in the detailed generator model.[12]





5 WINDING MODEL

NOMENCLATURE FOLLOWS (12)

The flux linkages are defined by 5 equations.

$$\psi_f = \frac{1}{\omega_o}\cdot\left[X_f\cdot i_f - X_{md}\cdot i_d + X_{md}\cdot i_{kd}\right] \quad (1)$$

$$\psi_d = \frac{1}{\omega_o}\cdot\left[X_{md}\cdot i_f - X_d\cdot i_d + X_{md}\cdot i_{kd}\right] \quad (2)$$

$$\psi_{kd} = \frac{1}{\omega_o}\cdot\left[X_{md}\cdot i_f - X_{md}\cdot i_d + X_{kd}\cdot i_{kd}\right] \quad (3)$$

$$\psi_q = \frac{1}{\omega_o}\cdot\left[-X_q\cdot i_q + X_{mq}\cdot i_{kq}\right] \quad (4)$$

$$\psi_{kq} = \frac{1}{\omega_o}\cdot\left[-X_{mq}\cdot i_q + X_{kq}\cdot i_{kq}\right] \quad (5)$$

These equations can be written in matrix form

$$\left[\psi\right] = \frac{1}{\omega_o}\cdot\left[X\right]\left[I\right]$$

where

$$[\psi] = \begin{bmatrix} \psi_f \\ \psi_d \\ \psi_{kd} \\ \psi_q \\ \psi_{kq} \end{bmatrix}, \quad [I] = \begin{bmatrix} i_f \\ i_d \\ i_{kd} \\ i_q \\ i_{kq} \end{bmatrix}$$

$$[X] = \begin{bmatrix} X_f & -X_{md} & X_{md} & 0 & 0 \\ X_{md} & -X_d & X_{md} & 0 & 0 \\ X_{md} & -X_{md} & X_{kd} & 0 & 0 \\ 0 & 0 & 0 & -X_q & X_{mq} \\ 0 & 0 & 0 & -X_{mq} & X_{kq} \end{bmatrix}$$

Matrix [X] is inverted to obtain currents [I]

$$[I] = \omega_o \cdot [X]^{-1} \cdot \psi$$

where

$$[X]^{-1} = \begin{bmatrix} X_{11} & X_{12} & X_{13} & 0 & 0 \\ X_{21} & X_{22} & X_{23} & 0 & 0 \\ X_{31} & X_{32} & X_{33} & & \\ 0 & 0 & 0 & X_{44} & X_{45} \\ 0 & 0 & 0 & X_{54} & X_{55} \end{bmatrix}$$

Expanding

$$i_f = \omega_o \cdot \left[\psi_f \cdot X_{11} + \psi_d \cdot X_{12} + \psi_{kd} \cdot X_{13} \right] \tag{1a}$$

$$i_d = \omega_o \cdot \left[\psi_f \cdot X_{31} + \psi_d \cdot X_{32} + \psi_{kd} \cdot X_{33} \right] \tag{2a}$$

$$i_{kd} = \omega_o \cdot \left[\psi_f \cdot X_{31} + \psi_d \cdot X_{32} + \psi_{kd} \cdot X_{33} \right] \tag{3a}$$

$$i_q = \omega_o \cdot \left[\psi_q \cdot X_{44} + \psi_{kq} \cdot X_{45} \right] \tag{4a}$$

$$i_{kq} = \omega_o \cdot \left[\psi_q \cdot X_{54} + \psi_{kq} \cdot X_{55} \right] \tag{5a}$$

Flux linkages, voltages and currents are related

$$i_f = \omega_o \cdot \left[\psi_f \cdot X_{11} + \psi_d \cdot X_{12} + \psi_{kd} \cdot X_{13} \right] \tag{1a}$$

$$i_d = \omega_o \cdot \left[\psi_f \cdot X_{21} + \psi_d \cdot X_{22} + \psi_{kd} \cdot X_{23} \right] \tag{2a}$$

$$i_{kd} = \omega_o \cdot \left[\psi_f \cdot X_{31} + \psi_d \cdot X_{32} + \psi_{kd} \cdot X_{33} \right] \tag{3a}$$

$$i_q = \omega_o \cdot \left[\psi_q \cdot X_{44} + \psi_{kq} \cdot X_{45} \right] \tag{4a}$$

$$i_{kq} = \omega_o \cdot \left[\psi_q \cdot X_{54} + \psi_{kq} \cdot X_{55} \right] \tag{5a}$$

where ω is the per unit angular velocity of the rotor and ω_o is the synchronous angular velocity in radians per second (377 for a 60-Hz system).

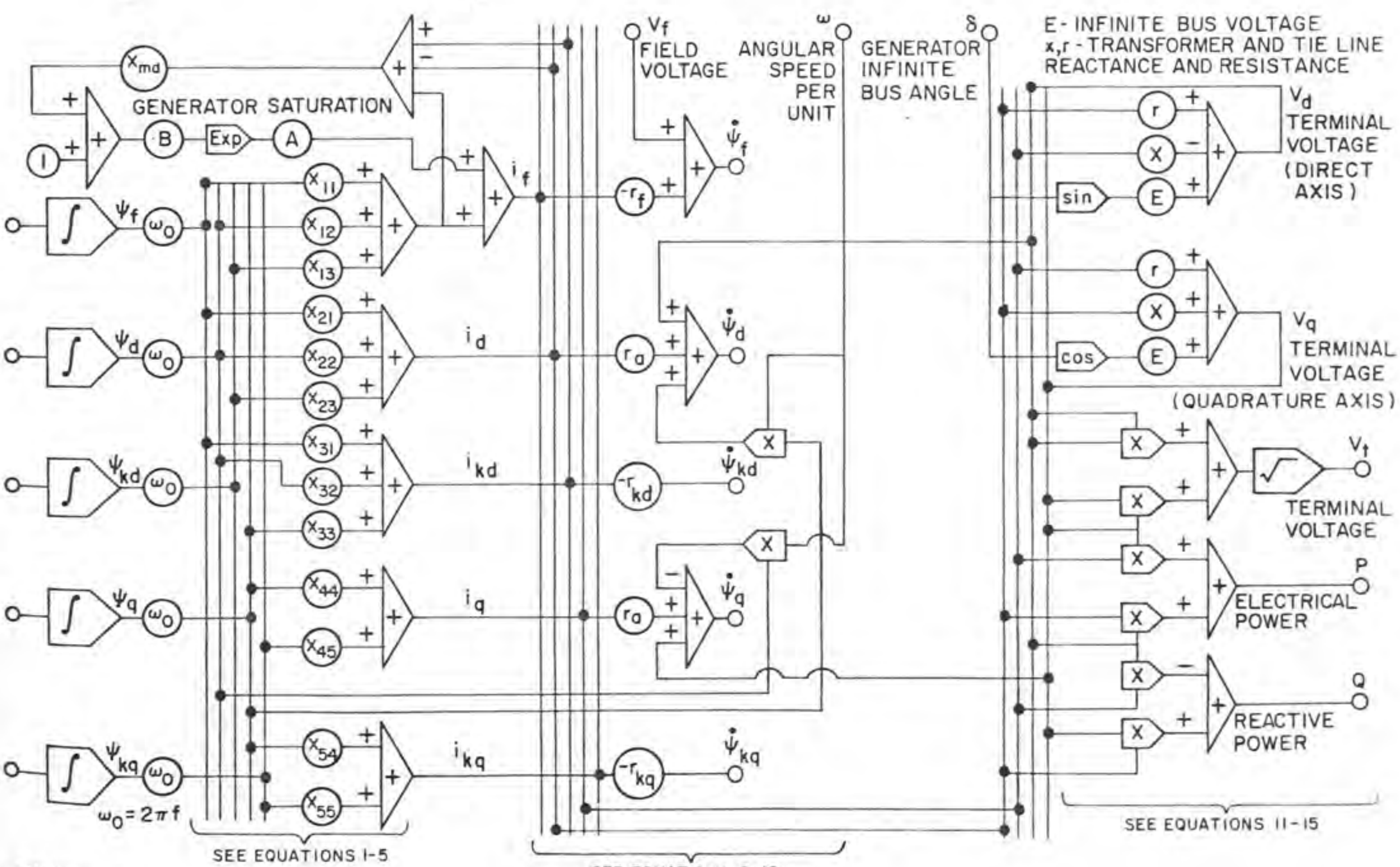
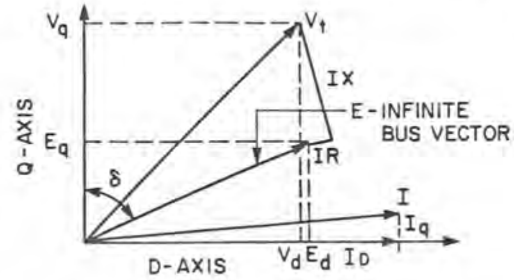


FIGURE B-1 GENERATOR MODEL

With reference to the following vector diagram



The relationships between the generator and infinite bus voltages and currents are given by

$$V_d = E \cdot \sin \delta + I_d \cdot R - I_q \cdot X \tag{11}$$

$$V_q = E \cdot \cos \delta + I_q \cdot R - I_d \cdot X \tag{12}$$

$$V_t = \sqrt{V_d^2 + V_q^2} \tag{13}$$

$$\text{Power} = \overline{V}_t \cdot \text{conj } \overline{I}$$
$$= (V_d + jV_q) \cdot (I_d - j \cdot I_q)$$

giving

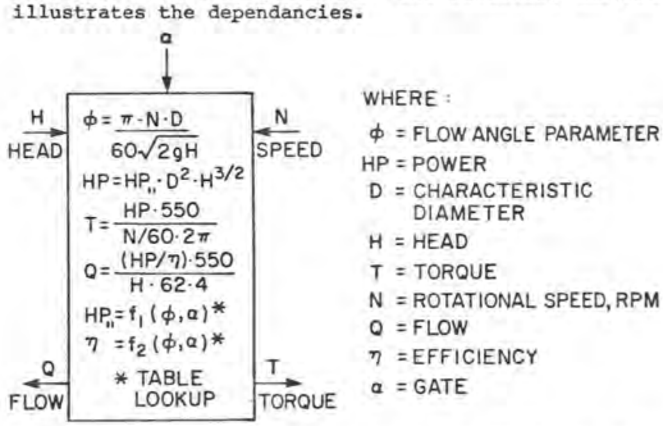
$$P = V_d \cdot I_d + V_q \cdot I_q \tag{14}$$

$$Q = V_q \cdot I_d - V_d \cdot I_q \tag{15}$$

Equations 1 to 15 are the basis of the numerical model used for the generator.

APPENDIX C
TURBINE MODEL

The most readily available form of turbine data is the hill curve. This gives either unit power or unit discharge, and turbine efficiency, as a function of flow angle and gate position. The following diagram illustrates the dependancies.

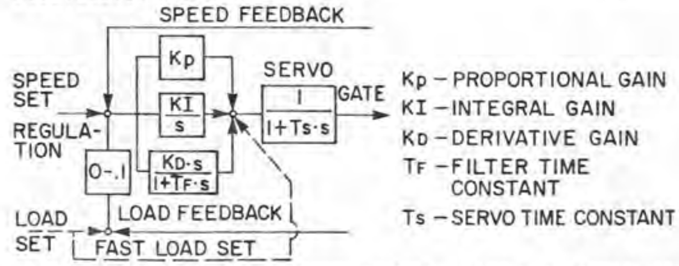


A similar scheme would be used if unit discharge data was available. Unit discharge is preferable if there is a choice since the estimate of flow is obtained more directly and the numerical model will be better behaved.

If the numerical model is to be used for reverse flow/reverse rotation situations, other methods must be used. [11, 18]

APPENDIX D
GOVERNOR MODEL

The modern electronic governor is usually built as a three-term or PID (Proportional, Integral, Derivative) controller.



Optional features are shown dashed. Load feedback is an alternate to gate feedback on the earlier mechanical governors. If derivative gain is to be used, a filter should be used in the speed feedback/derivative element loop to ensure stable operation.

Other forms of governor can be incorporated into a numerical model. However, the above configuration can be related to experience with mechanical governors using the relationships

$$k_p = 1/\delta_t$$

$$k_I = 1/(\delta_t \cdot T_r)$$

where

δ_t = Temporary speed droop

T_r = Dashpot relaxation time.

If the derivative effect is used, with a gain of approximately 1.0, then the values of k_p and k_I can approximately be doubled relative to the usually recommended gains [19].

APPENDIX E
EXCITER MODEL

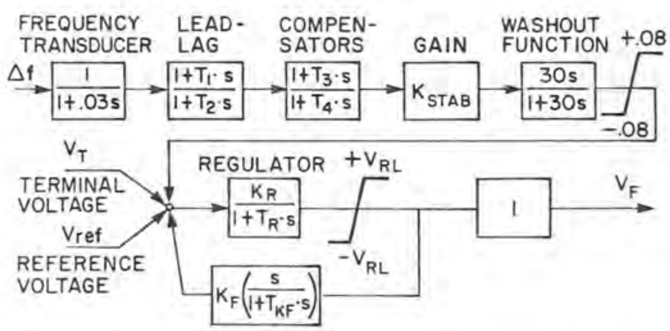


FIGURE E-1
STATIC EXCITER AND POWER SYSTEM STABILIZER

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