

Validation of Mechanical Governor Performance and Models Using an Improved System for Driving Ballhead Motors

J. C. Agee, Member

George K. Girgis, Member

Bureau of Reclamation
Denver, CO

Abstract—The Bureau of Reclamation has developed new equipment and procedures for testing mechanical-hydraulic governors for hydroelectric generators. The test equipment generates a three-phase voltage that will drive the governor ballhead motor at variable speed. Most traditional governor tests can be completed with the generating unit unwatered using this equipment. In addition, frequency response testing and other detailed analytical tests can be performed to validate governor models using this equipment.

KEYWORDS: Speed Governing, Power System Dynamic Performance, Transient Stability Models, Field Test.

INTRODUCTION

As reported by others, testing of mechanical-hydraulic governors for hydroelectric generators can be accomplished easily with the main generating unit shut down and the penstock unwatered if the ballhead motor can be driven by a separate source.^{1,2} Hovey employed a Ward-Leonard drive system for this application as early as 1963.¹ The Bureau of Reclamation has constructed an improved device for driving ballhead motors, which has been used successfully in several powerplants over a wide range of ballhead frequencies and voltages.

The device consists of a variable voltage and frequency three-phase sine-wave generator and three industrial grade audio power amplifiers. It is known as a PMG (Permanent Magnet Generator) Simulator because it is designed to operate like a typical PMG. That is, the voltage and frequency increase or decrease together as a function of speed. In the

case of the PMG Simulator, the desired simulated generator speed deviation is entered on the front panel of the simulator and the corresponding voltage and frequency are produced at the output terminals.

Typical governor tests as described by Hovey and Schleif can be conducted using the PMG Simulator with only minor modifications to the test procedures.^{3,4} However, overall frequency responses and step responses have proven even more valuable in determining the transfer function and parameters of the governor under test.

EQUIPMENT DESIGN

The PMG Simulator was designed to produce frequencies from 0 to 80 hertz and voltages from 0 to 180 volts. Nominal PMG frequency and voltage for the unit under test are input into the signal generator by thumbwheel switches. Another set of thumbwheel switches is provided to facilitate step variations of simulated speed. This input affects frequency and voltage by the same percentage. Both positive and negative steps are possible.

Analog inputs for frequency, voltage, and deviation from nominal simulated speed (modulation) are also provided. In addition, the simulator is equipped with an automatic ramping feature that provides "soft" starting and stopping of the ballhead motor.

The frequency setpoint signal is multiplied by the deviation, modulation, and ramp inputs, and then routed to a voltage-to-frequency converter. The output of this converter drives a counter that operates the address lines of three ROMs. The ROMs are programmed with digitally represented sine waves of proper phase to create a three phase set of voltages exactly 120 degrees apart when routed to digital-to-analog converters. The output of the D/A converters is multiplied by the voltage setpoint as modified by the deviation, modulation, and ramp inputs. A simplified block diagram of the signal generator is shown in Fig. 1.

The power amplifiers of the simulator are connected as a three-phase, grounded-ye source which is connected directly

94 SM 374-9 EC A paper recommended and approved by the IEEE Energy Development and Power Generation Committee of the IEEE Power Engineering Society for presentation at the IEEE/PES 1994 Summer Meeting, San Francisco, CA, July 24 - 28, 1994. Manuscript submitted December 30, 1993; made available for printing April 18, 1994.

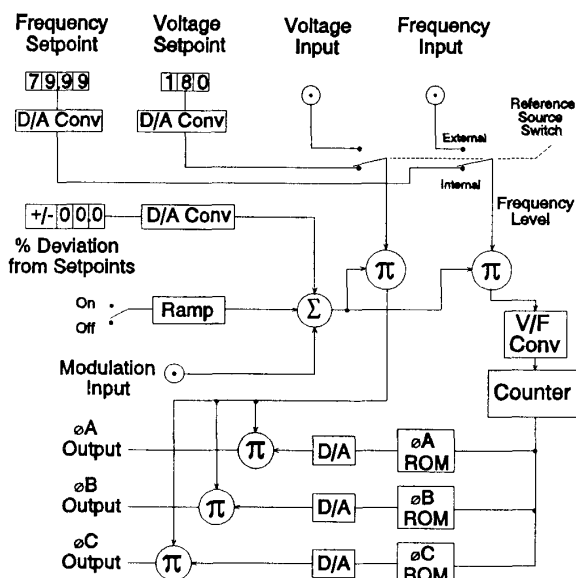


Fig. 1 - PMG Simulator Signal Generator

to the delta-connected ballhead motor with the normal PMG disconnected. This connection provides greater line to line voltage for the ballhead motor while retaining low line to ground voltages across the power amplifier output devices. The governor tachometer and electric speed switches can also be driven and tested by the simulator power amplifiers.

To produce the full 180-volt output, three stereo power amplifiers are operated in "push-pull" or "bridged" mode. Each amplifier circuit common is disconnected from case ground, and isolation amplifiers are used to drive the amplifiers. Two stereo amplifiers are used for units requiring less voltage by merely connecting the signal generator outputs to the amplifier inputs. This arrangement reduces the weight of the system and provides a spare amplifier.

TEST PROCEDURES AND ANALYSIS

The PMG Simulator is typically used after a generating unit is uprated or in conjunction with a governor overhaul. Normal tests include measuring and setting the permanent droop, the temporary droop, the range of speed adjustment control, the restoring ratio, and the dashpot time constant. Other tests can be incorporated as needed.

The tests are accomplished by shutting down the generating unit, unwatering the penstock, disconnecting the normal PMG, and connecting the PMG Simulator output to the ballhead motor. After resetting or blocking the governor shutdown solenoid, the wicket gates can be opened with the gate limit. Then, the PMG Simulator is started and the

wicket gates will respond to ballhead frequency. Typically, the maximum rate of wicket gate travel is adjusted at this time.

Tests with Disabled Dashpot

The performance and model representation of the forward path elements of a mechanical-hydraulic governor; the ballhead, pilot valve, main valve, main servomotor, and associated linkages; can be verified easily by disabling the dashpot feedback. This can be accomplished by opening the needle valve wide (several turns). In early tests, the input plunger was disconnected from the restoring linkage feedback and spacers were installed to hold the plunger in a fixed position, but opening the dashpot needle valve was found to be just as effective. This procedure leaves only the permanent droop, a constant, as a feedback element.

The permanent droop, R_p , can be measured readily with the dashpot function inactive by decreasing the frequency of the PMG Simulator in one percent steps and recording the corresponding gate position at each frequency. The permanent droop is then calculated as:

$$R_p = \frac{\frac{\Delta \text{Frequency}}{\text{Base Frequency}}}{\frac{\Delta \text{Gate Position}}{100\%}} \quad (1)$$

Linearity of droop as a function of gate position, speed adjustment setting, and ballhead frequency can all be investigated using the PMG Simulator. Typical field test data used to determine droop, where only ballhead frequency was varied, is shown in Fig. 2. Droop is the slope of the curve and varies with frequency and gate position because of the nonlinearities of mechanical linkages; however, droop is generally approximated as a constant in power system transient stability models. The average slope should be selected for this constant.

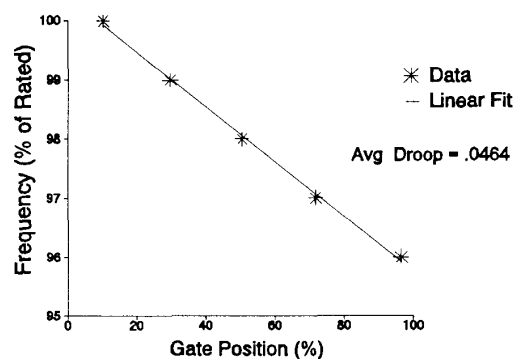


Fig. 2 - Droop Characteristic Curve

The speed adjustment range and calibration can be verified by removing the dashpot from service as described above and operating the flyball motor at rated frequency. Next, the speed adjustment setting is increased in one percent steps and the corresponding gate position is recorded at each setting. A graph of gate position vs. speed adjustment setting such as Fig. 3 can be used to verify the linearity and calibration of the speed adjustment. This type of graph is useful when tuning multiple governors for identical response to load control or Automatic Generation Control inputs.

The dynamic response of a governor with a disabled dashpot can also be obtained with the simulator. This response gives insight into the condition of the governor and allows measurement of the forward path elements used in typical governor models.^{5,6,7} Worn or binding linkages can be detected and the pilot valve time constant, T_p , and main servo gain, Q , can be determined using this test.

The dynamic response test is performed with the dashpot disabled as described above. Then, the output of the PMG Simulator is suddenly changed by one percent. The response of gate position is recorded and examined. Any irregularities indicate worn or binding linkages. These irregularities should be fixed at this time because adding the dashpot would only compound the problems.

Analysis of this dynamic response to determine T_p and Q can be performed by comparing the actual response to the calculated response of a mathematical governor model without a dashpot. This model is obtained by removing the dashpot block, limiting functions, and additional Gate Servomotor time constant from the mechanical-hydraulic governor model described in Reference 7. This results in the block diagram shown in Fig. 4. Since the droop was measured in the previous test, only T_p and Q remain to be determined.

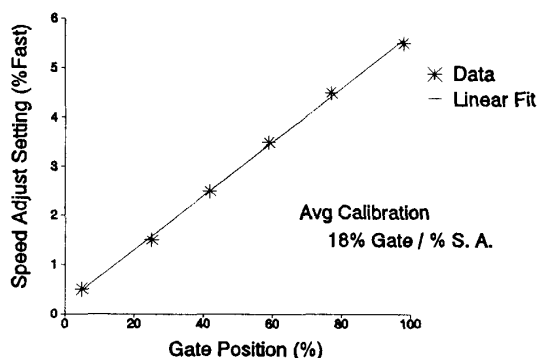


Fig. 3 - Speed Adjustment vs. Gate Curve

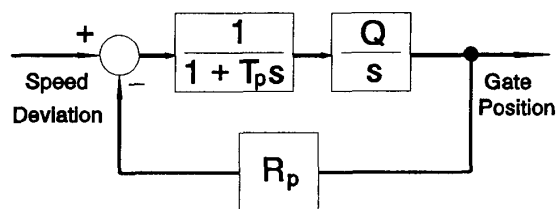


Fig. 4 - Governor Model with Dashpot Removed

Combining the blocks in Fig. 4 results in the following transfer function:

$$H(s) = \frac{\frac{1}{R_p}}{1 + \frac{s}{QR_p} + \frac{T_p s^2}{QR_p}} \quad (2)$$

Many techniques, ranging from hand calculations using inverse LaPlace Transforms to sophisticated computer programs, are available to compute the time domain response of this transfer function for various parameter values. Plots of this time domain response for $R_p = 0.05$ and several values of T_p and Q are shown in Fig. 5. Model data for T_p and Q can be obtained by comparing the field test results to curves similar to those in Fig. 5. Additional plots with more specific values of T_p and Q can be generated easily at the test site using a portable computer or programmable calculator.

Many times, the field data obtained from governors of large hydroelectric generators cannot be represented by this second order system. In these cases, adding a simple pole outside the loop to represent additional lag in the servomechanisms and ballhead improves the model fit. A portion of this additional lag is caused by components inside the servoloop, such as nonlinearities in the valves. The remainder is from components outside the loop, such as spring constants in the ballhead.

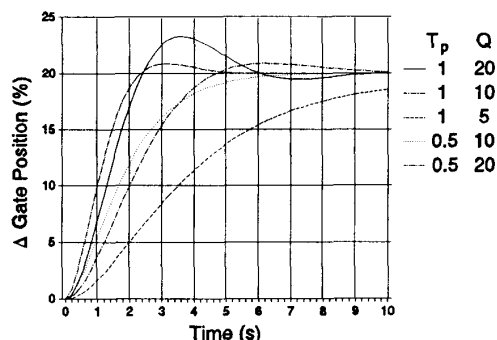


Fig. 5 - Computed Step Response of Governor with Disabled Dashpot for 1% step change in frequency with $K_p=0.05$ and various values of T_p and Q

Provision for this additional pole is included in Fig. 8 by restoring the additional Gate Servomotor time constant described in Reference 7. The time constant of this pole can be derived by comparing the actual response to the time-domain response of the following transfer function, or by using frequency response techniques as described below.

$$H(s) = \frac{1}{R_p} \frac{1}{\left(1 + \frac{s}{QR_p} + \frac{T_p s^2}{QR_p}\right)(1 + T_g s)} \quad (3)$$

This time-domain method is often cumbersome because three parameters must be determined from slight visual differences. Therefore, frequency response methods, which enable isolation of the simple pole more readily, are preferred. The PMG Simulator makes it possible to investigate the dynamic response of a governor with a disabled dashpot in the frequency domain.

A frequency response analyzer connected to the modulation input is used to vary the simulated PMG speed by about one percent peak-peak, and a gate position signal is fed back to the analyzer. A Bode plot of the transfer function from modulation input to Gate Position is then made as shown in Fig. 6. Graphical or computer techniques can be used to determine T_p , Q , and the additional time constant, T_g . Field test data for several different restoring ratio (RR) adjustments are shown in Fig. 6.

The performance of the governor, and the parameters T_p , Q , and T_g can be changed by adjusting the restoring ratio of the governor. The restoring ratio indicates the amount of movement of the main distributing valve necessary to move the bushing (or spool) of the pilot valve enough to stop oil flow to the main valve servomotor. Thus, if the restoring ratio is 40:1 the main valve will move 40 times farther than the pilot valve.

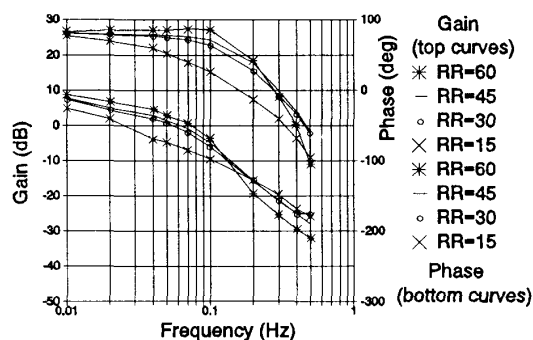


Fig. 6 - Frequency Response of a Governor with a Disabled Dashpot

Naturally, as the restoring ratio is increased, the main servo integration gain, Q , increases. In addition, the pilot valve time constant, T_p , and the additional time constant, T_g , increase as the restoring ratio increases based on analysis of the data in Fig. 6. Table I lists computed values of T_p , Q , and T_g for the data used in Fig. 6.

Table I - Governor Model Parameters Corresponding to Several Restoring Ratio Adjustments

Restoring Ratio	T_p	Q	T_g
15:1	0.89	3.29	0.245
30:1	0.906	9.29	0.318
45:1	0.922	15.4	0.65
60:1	1.064	20.26	0.80

The parameters in Table I were selected for the best fit to the gain curve, because the gain and phase curves could not be fit simultaneously with the model of Fig. 4 (even with the additional simple pole). A more accurate representation could be obtained by fitting the phase curve and applying a nonlinear gain block for Q to model the main relay valve port area as a function of displacement; however, this model complexity is not warranted for the small additional increase in accuracy. A frequency domain comparison of field data and model data is shown in Fig. 7.

Reclamation's general criteria for setting restoring ratio results in a time domain response of a governor with a disabled dashpot that is as fast as possible while maintaining less than 5 percent overshoot. However, for plants with long penstocks where the dashpot time constant and the temporary droop are large, it may be necessary to detune the restoring ratio to prevent fast oscillations of gate position.^{4,8,9}

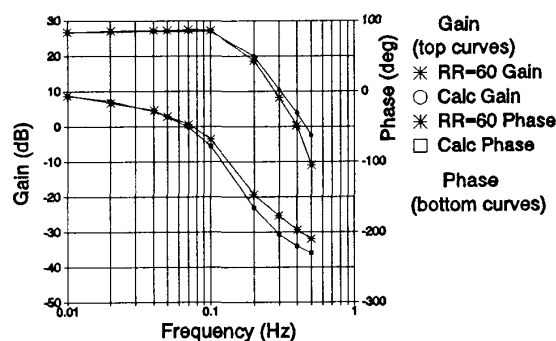


Fig. 7 - Comparison of Field and Model Data for a Governor with a Disabled Dashpot

Tests with Dashpot in Service

After satisfactory response is obtained with the dashpot disabled, the dashpot is returned to service by adjusting its needle valve. Then, target values for the dashpot time constant, T_R , and the temporary droop, R_t , are selected by using the Paynter, Hovey, or Schleif criteria and an approximate time domain step response is generated by portable computer or programmable calculator using the complete governor model shown in Fig. 8.^{10,3,4}

With the additional Gate Servomotor time constant, the transfer function of this block diagram is:

$$\frac{\frac{1}{R_p}(1+T_R s)}{(1 + \frac{[1+QT_R(R_p+R_t)]s + (T_p+T_R)s^2 + T_p T_R s^3}{QR_p})(1+T_g s)} \quad (4)$$

After the target response is chosen, the dashpot and compensating crank are adjusted to make the actual step response match the calculated time-domain waveform. Dashpot needle valve adjustments change the time constant of the response, and compensating crank adjustments affect the size of the initial cusp. Defective dashpot pistons or linkages can be detected by aberrations in the response.

A typical field test response curve and the corresponding calculated curve are shown in Fig. 9. Calculated parameters for this case are $T_p = 0.922$, $Q = 15.4$, $T_g = 0.53$, $R_p = 0.0464$, $R_t = 0.29$, and $T_R = 8.96$. The difference in T_g when compared to the case with the dashpot disabled and the difference in oscillation frequency during the initial transient are both attributed to the nonlinear valve port gains. These nonlinear gains were also apparent when the input signal amplitude was varied during frequency response tests. Advanced computer techniques are being examined to develop better models from field data. Evaluation of the dynamic response of the overall governor can also be performed in the frequency domain as described in the previous section. Bode plots of the complete governor model using the parameters listed above and field test data from the actual apparatus are shown in Fig. 10 for a restoring ratio of 45.

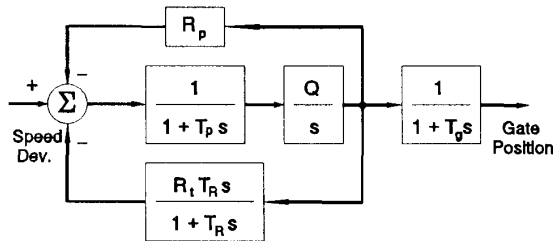


Fig. 8 - Complete Governor Model

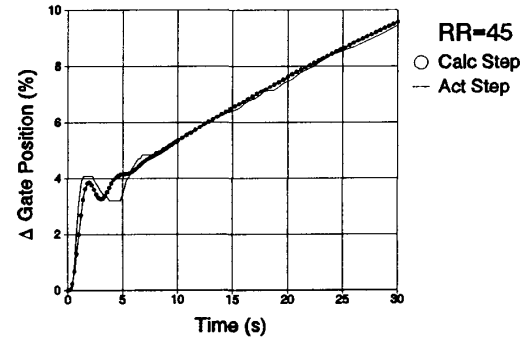


Fig. 9 - Actual governor step response compared to calculated response

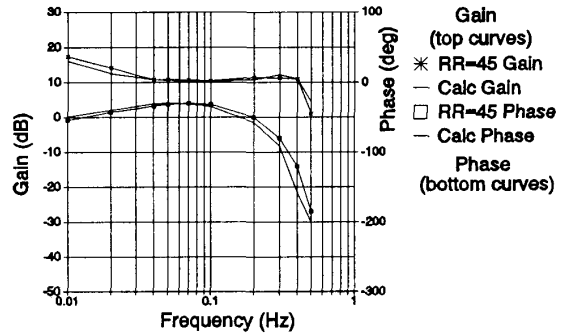


Fig. 10 - Frequency Response Comparison of Actual System and Calculated Model

Generators with long penstocks will have large values for the dashpot time constant, T_R , and the temporary droop, R_t . If the restoring ratio is adjusted for optimum response, the gates may have a tendency to oscillate as shown in Fig. 11. Reducing the restoring ratio in these cases will eliminate the oscillation without seriously affecting the performance of the governor.⁴ The phase lag of the governor at the point of control system crossover (less than 0.1 Hz for this case) is only a few degrees larger with reduced restoring ratio, but the resonant peak, which can interact with other power system resonances, is much smaller as shown in Fig. 12.

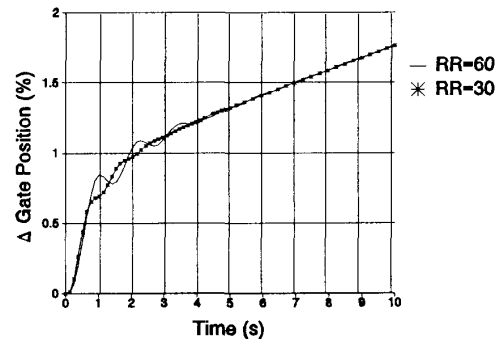


Fig. 11 - Computed Step Response with Large T_R , Large R_t , and
1) Large Restoring Ratio, 2) Reduced Restoring Ratio

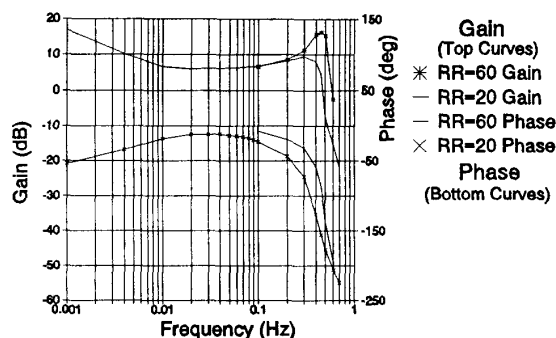


Fig. 12 - Computed Frequency Response with Large T_R , Large R_p , and
1) Large Restoring Ratio, 2) Reduced Restoring Ratio

Additional Tests

Tests to determine dashpot bypass time constant settings can be accomplished easily by energizing the solenoid bypass. Simulated load rejections can be performed to determine if the governor will satisfactorily close the gates for overspeed conditions. In addition, all tests can be executed at any gate position to determine the effects and calibration of the gate limit mechanism, gate feedback transducers, shutdown solenoid linkages, etc.

CONCLUSIONS

The PMG simulator has provided a means to verify proper operation, adjust parameters, and validate models of mechanical-hydraulic governors for hydroelectric generators. Methods employed result in direct retrieval of the parameters used in most power system transient stability governor models and assist in verification of these parameters at the test site. Field test data indicate that an additional gate time constant, as shown in reference 7, is necessary to improve modeling of governors for large hydroelectric generators. In addition, these tests can be performed at any gate position and speed to aid troubleshooting unusual problems.

ACKNOWLEDGEMENTS

Special thanks to Bill Duncan, who provided insight into how mechanical things work, helped develop test procedures, and wouldn't let us quit until we got it right; and to Lee Matuszczak, who designed and constructed the simulator.

APPENDIX

Definitions of Model Symbols

T_p	Pilot Valve Time Constant
Q	Main Servo Integration Gain
R_p	Permanent Droop
R_t	Transient (Temporary) Droop
T_s	Additional Time Constant (Ballhead, Servo, etc.)
T_R	Dashpot Time Constant or Reset Time

REFERENCES

- [1] L. M. Hovey, "Adjustment of Hydro-Governor Characteristics Using Separate Drive for the Speed-Sensing Element," *Transactions of the ASME, Journal of Engineering for Power*, January, 1965, pp. 13-18.
- [2] Karl H. Fasol, "Economical Dynamic Governor Tests in Power Stations," *Water Power*, April, 1973, pp. 129-134.
- [3] L. M. Hovey, "Optimum Adjustment of Hydro Governors on Manitoba Hydro System," *Transactions of the AIEE on Power Apparatus and Systems*, Vol. 81, Part III, Dec., 1962, pp. 581-587.
- [4] F. R. Schleif and A. B. Wilbor, "The Coordination of Hydraulic Turbine Governors for Power System Operation," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-85, No. 7, July, 1966, pp. 750-758.
- [5] D. G. Ramey and John W. Skooglund, "Detailed Hydrogovernor Representation for System Stability Studies," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-89, No. 1, January, 1970, pp. 106-112.
- [6] IEEE Task Force on Overall Plant Response, "Dynamic Models for Steam and Hydro Turbines in Power System Studies," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-92, No. 6, pp. 1904-1915.
- [7] IEEE Working Group on Prime Mover and Energy Supply Models for System Dynamic Performance Studies, "Hydraulic Turbine and Turbine Control Models for System Dynamic Studies," *IEEE Transactions on Power Systems*, Vol. 7, No. 1, February, 1992, pp. 167-179.
- [8] J. M. Undrill and J. L. Woodward, "Simulation Studies of Hydro Governing with A.C. and H.V.D.C. Interconnections," *N. Z. Engineering*, December 15, 1965, pp. 512-520.
- [9] P. L. Dandeno, P. Kundur, and J. P. Bayne, "Hydraulic Unit Dynamic Performance under Normal and Islanding Conditions - Analysis and Validation," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-97, No. 6, November/December, 1978, pp. 2134-2143.
- [10] H. M. Paynter, "The Analog in Governor Design, I, a Restricted Problem," *A Palimpsest on the Electronic Analog Art*, George A. Philbrick Researches, Inc., Boston, MA, 1960, p. 228.

J. C. Agee received his BSEE degree from Rose-Hulman Institute of Technology in 1979. Upon graduation, he joined the Bureau of Reclamation as a power systems engineer. He is currently employed in the Research and Laboratory Services Division as a technical specialist in the fields of governor control, excitation control, and power system stability. His research interests include feedback control systems, microprocessor control, and power system stability analysis.

George K. Girgis graduated from the University of Colorado at Denver in 1983 with a BS degree in electrical engineering. He began working for the Bureau of Reclamation as a design engineer, transferring to the Research Division in 1986. Currently, he works with excitation systems, speed governors, and computer-based data acquisition systems.