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EXCITATION SYSTEM COMMISSIONING PROCEDURES

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16. ABSTRACT

Many hydrogenerator powerplants operated by the Bureau of Reclamation are being uprated and modernized. As a part of this effort, Reclamation is installing new excitation systems. Typical excitation system commissioning tests, performed by Reclamation's Electric Power Branch on these new systems are presented. An outline of the tests is developed and each test is explained in detail. Recent improvements of Reclamation's procedures for testing power system stabilizers are included.

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by

J. C. Agee

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Electric Power Branch
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Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR ★ BUREAU OF RECLAMATION

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PREFACE

This report is one of a series of reports prepared by the Bureau of Reclamation's Electric Power Branch, Controls and Automation Section, to document excitation system performance. The section personnel participate in the alignment and testing of excitation systems on new or uprated synchronous machines. They also encourage and perform periodic realignment of these control systems and conduct tests on excitation systems that field or regional personnel suspect are malfunctioning.

The Controls and Automation Section participates in WSCC (Western Systems Coordinating Council) affairs by way of several working groups. The section staff provide data from field tests to WSCC for use in digital computer stability studies. The staff participates in establishing industrial standards for excitation systems by being active in the Institute of Electrical and Electronic Engineers.

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INTRODUCTION

Excitation system commissioning tests are performed on all new excitation systems installed by the Bureau of Reclamation. In many cases, the system manufacturer is responsible for these tests; however, The Bureau of Reclamation must ensure that these tests are performed satisfactorily. Also, the excitation system parameters must be adjusted for proper power system operation. Equipment manufacturers do not provide this service. The Controls and Automation Section (in the Electric Power Branch) provides these functions for Reclamation. In addition, the section provides a service for periodic realignment of these systems as recommended by WSCC (Western Systems Coordinating Council) and IEEE (Institute of Electrical and Electronic Engineers). Currently, the recommended excitation system realignment interval is 5 years.

This report lists the steps in the excitation test procedures that are performed by Reclamation's Controls and Automation Section as a part of the commissioning program or realignment service. It is intended as a reference for engineers who are interested in excitation system testing. The test sequence is not absolute; however, some tests must be performed before others. The sequence presented in this report is based on several field tests. It has led to timely completion of commissioning tests and realignments for equipment provided by several different manufacturers. Additional discussion of excitation tests is contained in the references.

In addition to these tests, power system simulations should be conducted for all plants with new excitation systems. These simulations can predict the performance of excitation systems for various unusual circumstances such as line outages and faults. The simulations should be executed before the commissioning tests so any special parameter adjustments can be incorporated into the tests.

CONCLUSIONS

The procedures documented in this report have been used successfully for testing excitation systems provided by many manufacturers. Of course, more detailed procedures that are specific to each manufacturer's equipment should be developed before each test. However, the procedures in this report provide an excellent guide for the experienced field test engineer to use in designing more detailed procedures. The IEEE series of excitation system standards—series 421 standards—should be used with this guide [1,2,3].

EXCITATION TESTS OUTLINE

Always develop an outline summary of the excitation tests. It serves as a checklist for the test engineer, as well as a tool to inform others of schedules, sequences, etc. Limit the outline to one page—if possible. Include estimated times for the various tests. The following is a sample outline:

I. **Preparation** (4 hours)
  - A. Connect excitation transformer to separate source
  - B. Disable field flashing, reference presets, autoregulator transfer, etc.
  - C. Record all settings
  - D. Obtain calibration data
  - E. Connect test instruments

II. **Initial Voltage Application** (4 hours)
  - A. Field ground detector test
  - B. Short-circuit saturation test
  - C. Voltage buildup

III. **Off-Line Tests** (8 hours)
  - A. Normal voltage application
  - B. Manual, d-c, regulator step response
  - C. Balance, transfer, and autotracking functional checks
  - D. Automatic, a-c, regulator step response
  - E. A-C regulator bias and range adjustment
  - F. A-C regulator frequency response tests
  - G. V/Hz (ratio) limiter test
  - H. V/Hz (ratio) relay test
  - I. Normal voltage application — a-c regulator
  - J. Exciter overvoltage relay tests
  - K. Automatic start sequence tests

IV. **On-Line Tests** (12 hours)
  - A. Check phasing and calibration of CT circuits
  - B. Current compensation test
  - C. Load rejections
  - D. Underexcitation limiter tests
  - E. A-C regulator step and frequency response tests
  - F. Overexcitation limiter tests
  - G. Regulator transfer protection test
  - H. D-C regulator bias and range adjustment

V. **PSS Alignment** (if equipped — 8 hours)
  - A. PSS circuit checkout
  - B. Open-loop compensation adjustment
  - C. Gain selection test/damping determination
  - D. Final adjustments

VI. **Denouement** (2 hours)
  - A. Disconnect test instruments
  - B. Record final settings

TEST PROCEDURES

The following sections explain the excitation system tests in more detail. A generalized approach has been taken, but can be modified easily for application to most excitation systems.

Preparation

Connect Excitation Transformer to Separate Source.—For commissioning tests, feed the exciter from a separate power source if the normal feed is from the generator or motor terminals. Then, the regulator circuits can be tested before the synchronous machine is energized and machine voltage can be built up from low levels. Coordinate this step with plant personnel before arriving at the powerplant. This step is not necessary for systems fed from station service or for 5-year realignment tests. However, this method provides a way to verify limiter settings before operating the generator during realignment tests.

Disable Field Flashing, Reference Presets, Autoregulator Transfer, etc.—For commissioning tests, disable field flashing and use a separate source for initial voltage application. Disable the reference setter presets and set the references to their level points. Lower the manual, d-c, regulator bias and range so the synchronous machine can be energized at a low field current level.

Disable the automatic, a-c, regulator transfer switch so the synchronous machine cannot be placed under automatic regulator control until the voltage has been built slowly and the regulator has been tested. Also, disable any automatic field breaker closure, such as from a speed switch.

For systems using a rotating exciter, it may be desirable to connect the SCR (silicon-controlled rectifier) bridge output voltage as a feedback quantity to the d-c regulator for the initial tests. This will prevent overexcitation if the exciter leads are connected incorrectly. Five-year realignment tests do not require this step.

Record All Settings.—Before beginning any excitation commissioning or realignment test, record all parameter values. Devise a table with initial and final settings.

Obtain Calibration Data.—The following machine ratings and excitation system calibrations should be recorded:

Generator Ratings

MV·A .... ____________
Power factor .... ____________
Voltage .... ____________
Phase current .... ____________
Rated MW .... ____________
Rated MVAR .... ____________
Field resistance .... ____________
Obtain capability curve and saturation curve data.

Excitation System

PT ratio/rating ... ____________ / ____________
CT ratio/rating ... ____________ / ____________
Field voltage transducer calibration .... ______
Field current transducer calibration ...... ______
Terminal voltage transducer calibration ... ______
Ceiling voltage/transformer
secondary voltage .... ______ / ______

If a rotating exciter is involved, the following data also are necessary:

Rotating Exciter

Field resistance .... ______
Exciter field voltage transducer calibration . ______
Exciter field current transducer calibration . ______
Obtain exciter saturation curve data.

Connect Test Instruments.—Connect the three-phase voltage transducer directly to the regulator PTs at the cubicle terminal blocks. Set the transducer to the proper voltage (110–115–120). Also connect the digital frequency transducer to the PTs at this point.

Select a proper field voltage isolation amplifier and divider network to withstand the exciter ceiling voltage. Connect this amplifier directly to the exciter output bus (generator field). Connect another isolation amplifier across the main field shunt for measuring current. The gain of this amplifier should be selected for easy data interpretation (typically 30, 50, or 100).

If a rotating exciter is present, additional isolation amplifiers will be necessary to measure exciter field voltage and exciter field current. Follow the same guidelines for scaling as were used with the main field quantities.

Identify the input, output, and intermediate values of interest in the voltage regulator. Install a test cable to permit easy connection to these points. Calculate per unit bases for these quantities. These bases will be confirmed later by measurements.

By:____________________ Date:______________ Project:__________________________

Apparatus:__________________________

Cable	Wire	Signal
A	1 - Black	
	2 - White	
	3 - Red	
	4 - Green	
	5 - Blue (shield)	
B	1 - Black	
	2 - White	
	3 - Red	
	4 - Green	
	5 - Blue (shield)	
C	1 - Black	
	2 - White	
	3 - Red	
	4 - Green	
	5 - Blue (shield)	
D	1 - Black	
	2 - White	
	3 - Red	
	4 - Green	
	5 - Blue (shield)	
E	1 - Black	
	2 - White	
	3 - Red	
	4 - Green	
	5 - Blue (shield)	
F	1 - Black	
	2 - White	
	3 - Red	
	4 - Green	
	5 - Blue (shield)	
G	1 - Black	
	2 - White	
	3 - Red	
	4 - Green	
	5 - Blue (shield)	
H	1 - Black	
	2 - White	
	3 - Red	
	4 - Green	
	5 - Blue (shield)	

Figure 1. — Test cable wiring form.

Install the megawatt and megavar transducers, and connect a test cable for future use. Mark and document all cables on a test cable wiring form like shown on figure 1.

Initial Voltage Application

Field Ground-Detector Test.—Test the field ground detection system by connecting a resistor (about 1000 ohms) from one of the field slip rings to ground. It may be necessary to close the field breaker, start the machine, or jumper some relay contacts to activate the field ground detection device.

Short-Circuit Saturation Test.—Sometimes the generator manufacturer will execute a short-circuit saturation test before any other tests. Typically, a copper bar is connected directly across the synchronous machine terminals for this test. Therefore, a separate power source must be connected to the excitation system if it is normally fed from the machine terminals.

Field current, field voltage, and armature current data will be recorded by a generator manufacturer representative during this test. Normally, the procedure involves raising the excitation current to a high level and then reducing it in steps. The manual, d-c regulator should be used for this test.

Voltage Buildup.—During commissioning tests, the voltage should be built up gradually the first time excitation is applied to a new winding. Shaft runout, bearing isolation, and vibration should be checked as voltage is increased. Usually, plant personnel perform these functions. Phase rotation of the excitation transformer may need to be checked. A separate power source should be used for excitation systems that are fed from the machine terminals as explained in the **Test Procedures** paragraph under *Preparation* — Connect Excitation Transformer to Separate Service.

Two options can be investigated if a separate source is not readily available. In one option, for excitation systems employing a rotating exciter, it may be possible to drive the exciter field with a separate portable power supply. This will permit a slow buildup of machine voltage for initial PT (potential transformer) phase rotation checks, exciter polarity checks, and voltage regulator phasing checks. If this option is not possible, the generator or exciter field can be "flashed" from the station batteries with the excitation system disabled. This will provide temporary voltage for initial checks. Then, the excitation system should be enabled with all presets and limiters at reduced levels.

Build voltage using the manual, d-c regulator. Record terminal voltage, field voltage, and field current as the excitation is increased in steps. Then, construct the actual saturation curve and calculate the field resistance of the synchronous machine. If the excitation system includes a rotating exciter, record the field voltage and current in this device. Rotating exciter polarity may need to be verified. The SCR bridge voltage can be used as a feedback quantity to the d-c regulator to test this polarity.

Upon completion of this test, set the manual regulator adjuster to minimum. Then, adjust the manual regulator bias to produce about 80 percent of rated terminal voltage. Next, remove the excitation (by opening the field breaker or operating the excitation stop switch) and stop the synchronous machine. Reconnect the normal excitation supply and enable field flashing.

Off-Line Tests

Normal Voltage Application.—Enable the excitation system—by closing the field breaker or operating the excitation start switch—with the manual, d-c regulator in control and its setpoint at 80 percent. Record the voltage buildup. Suggested quantities to record are terminal voltage, field voltage, field current, and a regulator quantity. For systems having rotating exciters, record the exciter field voltage and possibly the exciter field current.

Note that if internal regulator transducers are used, they may not function properly at low levels of terminal voltage due to inadequate power supply.

Observe the voltage buildup and decide on the adequacy of the field flashing level. Most systems require 20 to 30 percent terminal voltage before the SCR firing circuits function reliably. After a successful buildup to 80 percent has been obtained, repeat this test with the manual, d-c, regulator setpoint increased to 100 percent.

Manual, d-c, Regulator Step Response.—Apply a step input of about ±1 percent to the manual, d-c regulator that typically controls either main field voltage or main field current. Adjust the response of this regulator so the controlled quantity has a moderate response time and no overshoot when the step is applied. This regulator should be slower than the automatic, a-c regulator. If parameter changes are made, repeat the normal voltage application to verify satisfactory large-signal performance. The minimum level of the manual, d-c, regulator adjuster can be set now; however, the range cannot be adjusted until the excitation requirement for full load is determined.

Balance, Transfer, and Autotracking Functional Checks.—Test the regulator balance circuit with the unit running off-line in manual, d-c, regulator mode.

Movement of the a-c adjuster should result in unbalance of the regulator balance meter. Perform the test by unbalancing to the right and the left and then rebalancing to center.

After the balance indication has been verified, voltage control can be transferred to the automatic, a-c regulator. Verify stable operation by observing a chart recorder monitoring terminal voltage, field voltage, and other quantities of interest. Verify the operation of all indicating lights when control is transferred to the automatic, a-c regulator.

If the excitation system has automatic setpoint tracking, this feature should be check. A unit breaker auxiliary relay may need to be enabled before this function will operate. If so, jumper the relay and verify that the automatic tracking system operates. Observe changes in both directions.

Automatic, a-c, Regulator Step Response.—Apply a step input of about ±1 percent to the automatic, a-c regulator. Record the response on a chart recorder. Adjust the regulator for proper operation. Typically, a response with 15 percent overshoot followed by rapid damping indicates adequate performance. However, system studies should be consulted for insight into proper tuning for each specific plant.

A-C Regulator Bias and Range Adjustment.—The automatic, a-c, regulator adjuster is normally adjusted to provide a control range of 90 to 110 percent of rated terminal voltage. Cam switches for light indication and preset positioning are often included. Make these adjustments now. Plant operating staff should have input into the range and operation of these controls.

A-C Regulator Frequency Response Tests.—Frequency response tests should be performed to verify the regulator response. Also, these responses will aid in excitation system parameter identification for simulation studies. An overall system closed-loop response with the unit off-line is essential. In addition, responses of each transfer function block are helpful for parameter identification. If the excitation system includes a rotating exciter, measure the transfer function from exciter field voltage to main field voltage.

V/Hz (Ratio) and Overvoltage Limiter Test.—The V/Hz limiter should reduce the terminal voltage of the unit whenever the frequency is lowered. It should operate in coordination with the V/Hz relay. Typically, the relay is set to operate if the V/Hz ratio exceeds 115 percent of nominal, so the limiter is usually adjusted to maintain a ratio of 110 percent of nominal. The limiter can be tested easily by increasing the voltage of the synchronous machine to 110 percent while decreasing the speed. Record the voltage and frequency simultaneously, and calculate the limiter ratio for several different values of speed (commonly 48 to 60 Hz). Devise a table containing this information.

If the unit has an overvoltage limiter, tests of this device can be easily incorporated into the V/Hz limiter test sequence. The limiter with the smoothest limit-cycle operation should be set with the lowest ratio. Usually, the V/Hz limiter has this characteristic; therefore, in most cases the V/Hz limiter will be the primary terminal voltage limiter. The overvoltage limiter should be set about 2 percent above the primary (V/Hz) limiter.

V/Hz (Ratio) Relay Test.—The V/Hz relay can be tested by disabling the V/Hz limiter (and overvoltage limiter) and repeating the procedure in the preceding subparagraph. If a unit lockout is not desired, the trip wire from the relay can be lifted. However, the excitation should be removed at the time when the lockout would have occurred to prevent damage from the V/Hz condition. Record the voltage and frequency when the relay operates and calculate the V/Hz ratio.

Normal Voltage Application — A-C Regulator.—Since the a-c regulator has been previously tuned and the V/Hz and overvoltage limiters have been set, the voltage can now be built using the a-c regulator. First, turn the excitation off using the excitation stop switch or field breaker (whichever is applicable). Then, wait for terminal voltage to decay to near zero. When this occurs, turn the excitation on while recording terminal voltage, field voltage, and any other desired excitation quantities.

Exciter Overvoltage Relay Tests.—Normally, two types of exciter overvoltage relays are installed—both are connected to the generator lockout relay. Instantaneous relays should be set above the normal ceiling forcing voltage of the exciter. This is typically at least 150 percent of the full-load rated field voltage. Timed exciter overvoltage relays are usually connected through time delay relays and should be set at a value about 120 to 130 percent of normal full-load excitation voltage. The time delayshould be about 25 to 40 seconds—depending on the setting level. These relays must be coordinated with the maximum excitation limiter functions.

The overvoltage relays can be tested easily during voltage application when the exciter reaches its ceiling voltage. Normally, this ceiling level can be controlled by limiting the voltage regulator output. Set the relays to appropriate levels and then test them by controlling the exciter voltage. If the exciter voltage cannot be controlled easily, set the relays and thoroughly test them with a relay test set.

Perform a functional test of the connection to the lockout relay, and set and verify any time delay relays present.

Automatic Start Sequence Tests.—Test the generator automatic start sequence while recording frequency, terminal voltage, and field voltage. Use this test to verify that the excitation system is energized at the correct speed and that it has adequate large-signal performance under dynamic conditions.

On-Line Tests

Check Phasing and Calibration of CT Circuits.—When the unit is first loaded, verify the phase relationship of the CT (current transformer) signal for the PSS (power system stabilizer), reactive current compensation, and underexcitation limiter circuits. Also check the calibration of this signal.

Current Compensation Test.—Reactive droop compensation will be needed if more than one generator or motor is connected to a single step-up transformer. This compensation is necessary for the units to share vars properly. Reactive droop compensation causes the regulator to control voltage at a point inside the synchronous machine terminals. The location of this point is determined by the amount of reactive droop compensation. Typically, about 10 percent internal compensation is needed. This can be tested by operating the parallel synchronous machines at the same megawatt and megavar loads. Then raise the voltage (vars) on one unit and observe the reaction of the other. Normally, the reacting unit should decrease its var output by one-half to two-thirds of the amount by which the var output of the other unit was raised.

In some cases, line-drop compensation may be needed for generators that have high-impedance step-up transformers or long transmission paths. This type of compensation is the opposite of reactive droop compensation. It can be tested by comparing the magnitude of a step response without compensation to the magnitude of a step response with the compensation in service. The step magnitude (and var output change) with compensation should be larger than the step magnitude without compensation.

Load Rejections.—Before a new or uprated generator can be operated at full load, a series of load rejections is usually performed. Normally, load rejections are executed from 25, 50, 75, and 100 percent load. The 100-percent load rejection should be performed at rated power factor overexcited. An additional 100-percent load rejection initiated by the lockout relay may be necessary to test field demagnetization if the regulator is removed from service when a lockout occurs. In this case, the field may be demagnetized by a field discharge resistor, fixed phase back circuitry, or a combination method.

Record speed (frequency), terminal voltage, field voltage, and any other excitation quantities of interest during the load rejections. Typically, mechanical engineers will simultaneously record gate position, penstock pressure, shaft run-out signals, and other mechanical quantities. Also record the field current required to produce rated power factor operation at full load for future reference.

Underexcitation Limiter Tests.—The underexcitation limiter operates to increase the excitation of the synchronous machine before an out-of-step condition or overloading occurs by way of underexcited vars. This limiter must operate in coordination with the loss-of-field relay. Test the limiter by operating the generator at various real power settings and decreasing the excitation until the limiter operates. Underexcitation limiter tests can be easily combined with the load rejections. Record a table of real and reactive power levels, terminal voltage, and field current. Then, construct a graph of the generator operating points as shown on figure 2.

A-C Regulator Step and Frequency Response Tests.—The on-line step response test indicates the speed and stability of the generator and power system combination. In some cases, a control system with excellent off-line response characteristics may produce oscillations when the generator is connected to the power system. Therefore, the on-line step response is a valuable test that must be performed.

For the on-line step response test, operate the unit at full load and unity power factor. Apply a step input of about ± 1 percent to the automatic, a-c regulator. Adjust the regulator for proper power system operation based on field data and power system simulation results. If the regulator settings are modified: off-line step response, frequency response, and large-signal performance tests will need to be repeated.

An overall frequency response of the voltage regulating control system should be performed to verify the on-line regulator performance. If the generator has PSS, this response also will be used for PSS tuning.

Overexcitation Limiter Tests.–Usually, two types of overexcitation limiting are provided: (1) instantaneous overexcitation limiting is provided at 150 to 200 percent of full-load field current, and (2) timed overexcitation limiting is provided as an inverse–time curve below the instantaneous level. Normally, the

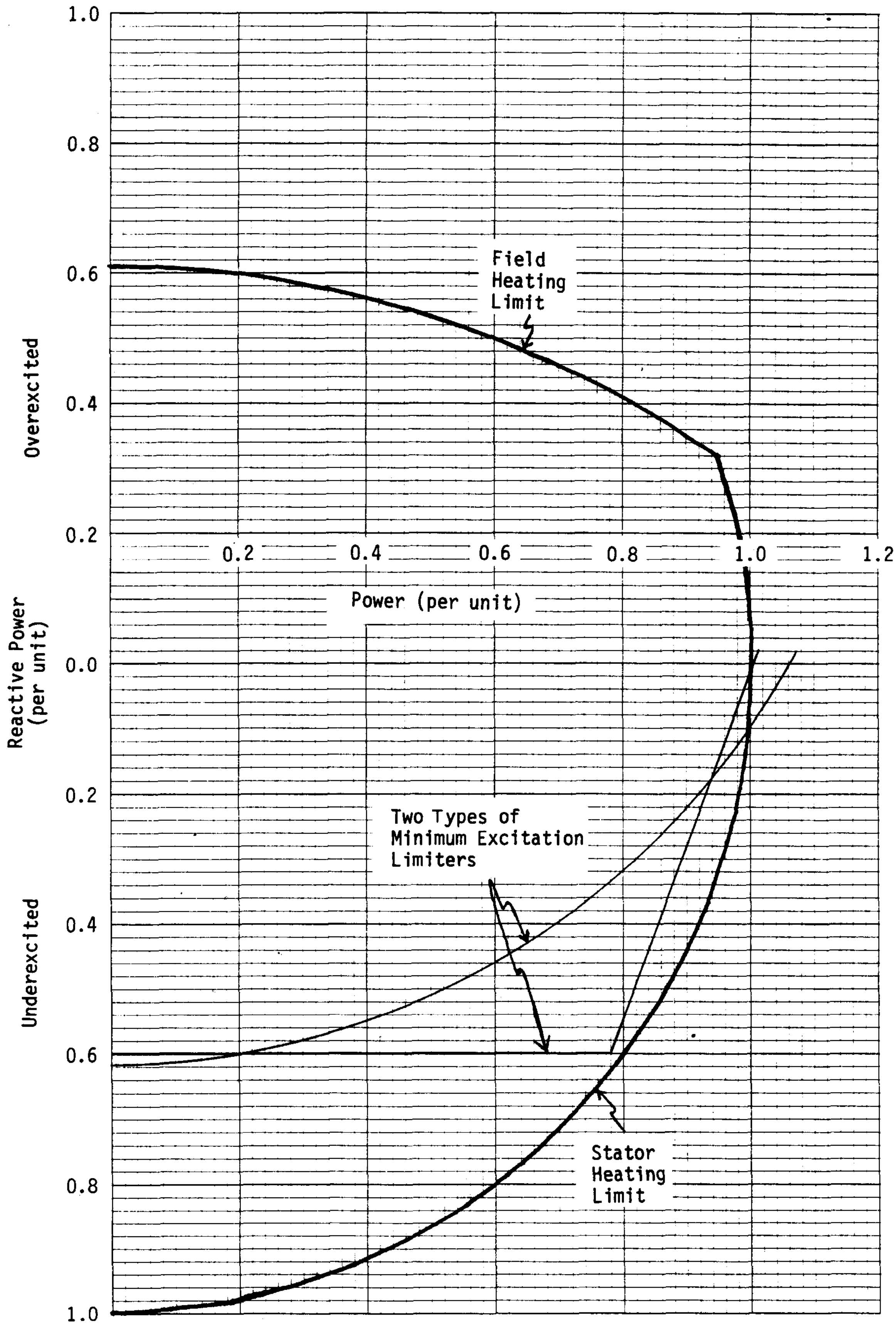

Figure 2. — Generator capability curve showing minimum excitation limiters.

instantaneous limiter is tested at a reduced level—then, returned to its proper setting. Also, the timed overexcitation limiter is typically tested at a reduced setting. These tests are performed by placing a large step into the voltage regulator and observing the excitation levels on a chart recorder. The inverse-time curve of the timed limiter can be verified by testing the instantaneous limiter at several values and timing the return to the timed limiter setting. After the tests, the pickup point for the timed limiter should be set at the field current required to produce rated output (overexcited) from the generator (100% of full-load field current). Since this level is asymptotic to the inverse-time curve, the time delay at this point should be infinite.

Normally, these limiters must be coordinated with protective devices that may transfer regulator control to the manual, d-c regulator or trip the unit by way of the lockout relay. These protective devices may have an inverse-time characteristic, but will probably have a fixed voltage pickup and time delay. Therefore, the coordination between the overexcitation limiters and these protective devices must be done wisely. Figure 3 shows typical:

- Short-time overload capability of the generator (from [4]),
- Typical overexcitation limiter curves, and
- Typical coordinated overexcitation protection curves

If the overexcitation protection devices are overvoltage relays, a hot field temperature of 75 °C should be assumed when converting from field voltage to field current since the overload curve is based on field overheating. If the field winding starts cold, it can be forced harder and longer without being damaged.

Regulator Transfer Protection Test.—If the excitation system has a device that transfers control from the automatic, a-c regulator to the manual, d-c regulator upon sustained field overvoltage (or overcurrent), this device should be tested at a reduced level. The test is much like an overexcitation limiter test. Reduce the pickup level of the device to approximately the field current required to operate the generator at rated load and unity power factor. Then raise the excitation slightly above this level. The device should operate at its predicted time delay and transfer control to the d-c regulator. Then return the device to a level that coordinates with the overexcitation limiter.

D-C Regulator Bias and Range Adjustment.—After the field current required to produce full-load, rated power factor operation has been determined, set the d-c regulator to produce this value at its maximum setpoint. The minimum value for the d-c regulator adjuster is typically set to 80 percent of rated terminal voltage with the unit off-line—but it may be set lower. The minimum value must, however, be high enough for the SCR bridges to fire correctly and any cooling fans to run properly.

PSS Alignment

If the excitation system includes a PSS (power system stabilizer), it should be aligned as a part of the commissioning (or 5-year realignment test) procedure.

PSS Circuit Checkout.—Check all stages of the PSS for functionality and accuracy of parameter adjustments. Check gain and time constant potentiometer at several values against manufacturer's curves. Test the PSS frequency transducer for gain and bandwidth if it is a new type that has not been tested before. This bandwidth test is accomplished by using the VCF (voltage-controlled frequency) input of a signal generator and the FRA (frequency response analyzer). In addition, investigate the control circuits for turning the PSS on and off for proper fail-safe operation if the PSS malfunctions.

Open-Loop Compensation Adjustment.—After the PSS circuits have been checked, the PSS compensation can be set. The traditional WSCC (Western Systems Coordinating Council) [5] PSS tuning procedure advocates placing the PSS lead time constants at the frequency where the overall automatic voltage regulator on-line frequency response passes through 90 degrees. (Refer to the **On-Line Tests** paragraph under *A-C Regulator Step and Frequency Response Tests*.) The PSS lag time constants are then selected to be 8 to 10 times smaller than the lead time constants. This is a good initial estimate; however, this method often results in undercompensation at the local mode.

To examine the PSS compensation, the frequency response of the PSS lead-lag circuits should be added to the overall automatic voltage regulator on-line frequency response. An overplot of these signals may be useful. The peak phase advance (60 to 100 degrees) of the PSS should occur near the local mode for optimum local mode damping and minimum noise. In many cases, the lead and lag time constants will need to be increased from their initial estimates to obtain this characteristic. The ratio should be maintained at 8 to 10.

Gain Selection Test/Damping Determination.—The traditional WSCC method for selecting PSS gain consists of increasing the gain until sustained oscillations occur and then reducing the gain to one-third of this value. Better insight into PSS operation

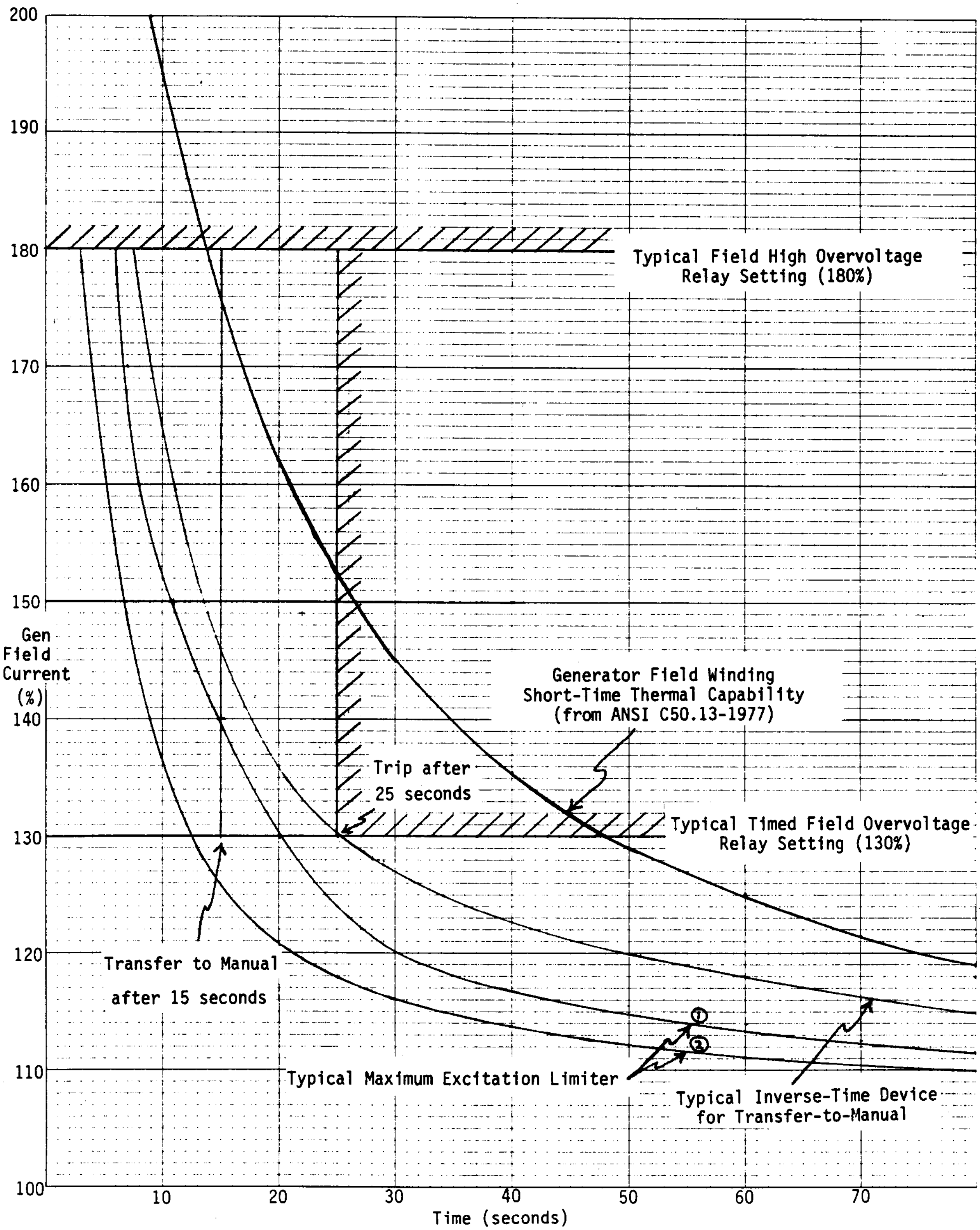

Figure 3. — Generator field winding protection coordination diagram. Overexcitation protection coordination curves are shown.

can be obtained by raising the PSS gain in small steps and executing an impulse test (or step test) at each gain value. Then, the responses can be characterized with damping ratios and oscillation frequencies and plotted on a root-locus diagram. (The appendix provides assistance for this step.) The operating gain should be selected with the best damping ratio. Large generators should be operated with gain as high as possible to aid system damping. Smaller machines (generators and motors) can be operated with lower gain as long as the local mode is well damped. Information obtained from system simulation studies also should be considered in the PSS tuning process.

Systems with rotating exciters may not be able to improve local mode damping significantly. In this case, damping improvement should be concentrated on the interarea modes which range in frequency from 0.2 to 0.7 Hz. Systems with static excitation should be able to damp local mode oscillations as well as the interarea modes.

Final adjustments.—Adjust the PSS output limits to permit approximately ±8 percent changes in terminal voltage. This may differ in some cases due to system constraints. The PSS reset time constant should be set to 30 seconds. Usually, these two settings dictate the adjustment of the PSS failure detection circuits. These circuits should be set to allow normal operations such as starting or stopping the synchronous machine. However, failure of the PSS circuitry should be detected. If PSS undervoltage/overvoltage cutoff circuits are present, they should be set to ±10 percent of nominal terminal voltage.

Denouement

Sometimes reaching the denouement, ". . . the outcome or resolution of a doubtful series of occurrences . . ." of excitation tests is a struggle.

Disconnect Test Instruments.—Ensure that the disconnecting process is done safely. Shut down the synchronous machine unit to remove field transducers, if necessary.

Record Final Settings.—Record final settings on the same form as the initial settings. Comments on any changes should be captured while they are still "fresh."

REFERENCES

[1] *IEEE Standard 421.1-1986*, "IEEE Standard Definitions for Excitation Systems for Synchronous Machines," Institute of Electrical and Electronic Engineers, 345 East 47th Street, New York, NY 10017.

[2] *IEEE Standard 421.2-1990*, "IEEE Guide for Identification, Testing, and Evaluation of the Dynamic Performance of Excitation Control Systems," Institute of Electrical and Electronic Engineers, 345 East 47th Street, New York, NY 10017.

[3] *IEEE Tutorial Course*, "Power System Stabilization Via Excitation Control," Course Text 91EH0175-0PWR, Institute of Electrical and Electronic Engineers, 345 East 47th Street, New York, NY 10017.

[4] American National Standards Institute C50.13-89, Rotating Electrical Machinery — Cylindrical-Rotor Synchronous Generators (Supersedes ANSI/IEEE C50.13-77, 16 pp., DOD Adopted Locator Code A-47-25).

[5] *Western System Coordinating Council*, System Control Work Group, "Test Procedure for Coordination of Excitation Supplementary Control for Power System Damping and Acquisition of Data for Refining Representation of Excitation Systems," University of Utah Research Park, 540 Arapeen Drive, Suite 203, Salt Lake City, UT 84108 (tele. 801-582-0353), 1971.

APPENDIX A

Characterizing the Damping of Time-Domain Waveforms

The damping of time-domain waveforms can be characterized easily if one assumes that the response was produced by a second order system. The following methods make this assumption. If multiple roots are present in the actual system being studied, errors will result. The size of the errors depends on the influence of the other roots. Many times, these errors are negligible, but sometimes they are not. As in many engineering problem, exercise judgment when evaluating the results.

How to Use the Damping Curves

1. For any two peaks, find the magnitude of the change from the previous zero crossing.
2. Determine the ratio of these magnitudes (smaller value over larger).
3. Use the damping curves (figs. X1 and X2) to find the value of ξ, the intersection of the ratio with the number of cycles between chosen peaks.
4. Measure duration of cycle (period), using peak-to-peak or zero crossing-to-zero crossing.
5. Calculate the resonant frequency ω_r, the natural frequency ω_n, and the attenuation σ.

$$\omega_r = \frac{2\pi}{\text{period}} \qquad \omega_n = \frac{\omega_r}{\sqrt{1-\xi^2}} \qquad \sigma = \xi\omega_n$$

6. Plot σ and ω_r on the s–plane.

How to Find the Values Without Using Curves

1. For any two peaks, find the magnitude of the change from the previous zero crossing.
2. Determine the ratio of these magnitudes (larger value over smaller).
3. Find the natural logarithm of the ratio.
4. To find σ, divide this value by the time elapsed between the chosen peaks.
5. Measure duration of cycle (period), using peak-to-peak or zero crossing-to-zero crossing.
6. Calculate the resonant frequency ω_r, the natural frequency ω_n, and the damping ratio ξ.

$$\omega_r = \frac{2\pi}{\text{period}} \qquad \omega_n = \sqrt{\sigma^2 + \omega_r^2} \qquad \xi = \frac{\sigma}{\omega_n}$$

7. Plot σ and ω_r on the s–plane.

Symbols

ξ = damping ratio
ω_n = natural frequency
ω_r = resonant frequency, frequency of oscillation; imaginary part of complex pole
σ = attenuation, time constant of decay; real part of complex pole
s = LaPlace operator

Characteristic Equation

$$s^2 + 2\xi\omega_n s + \omega_n^2 = s^2 + 2\sigma s + \sigma^2 + \omega_r^2$$

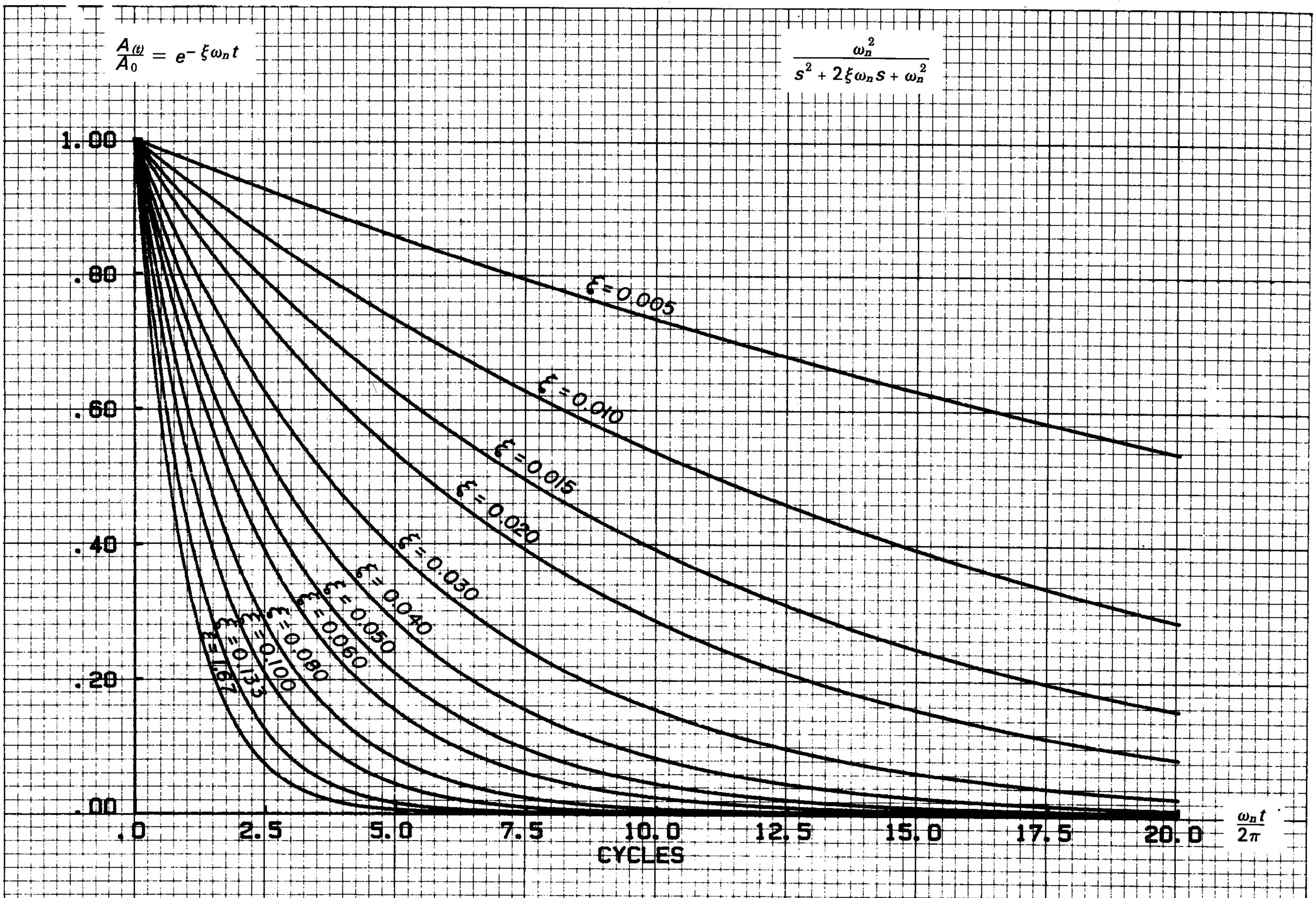

Figure X1. — Decrement of oscillation as a function of damping factor.

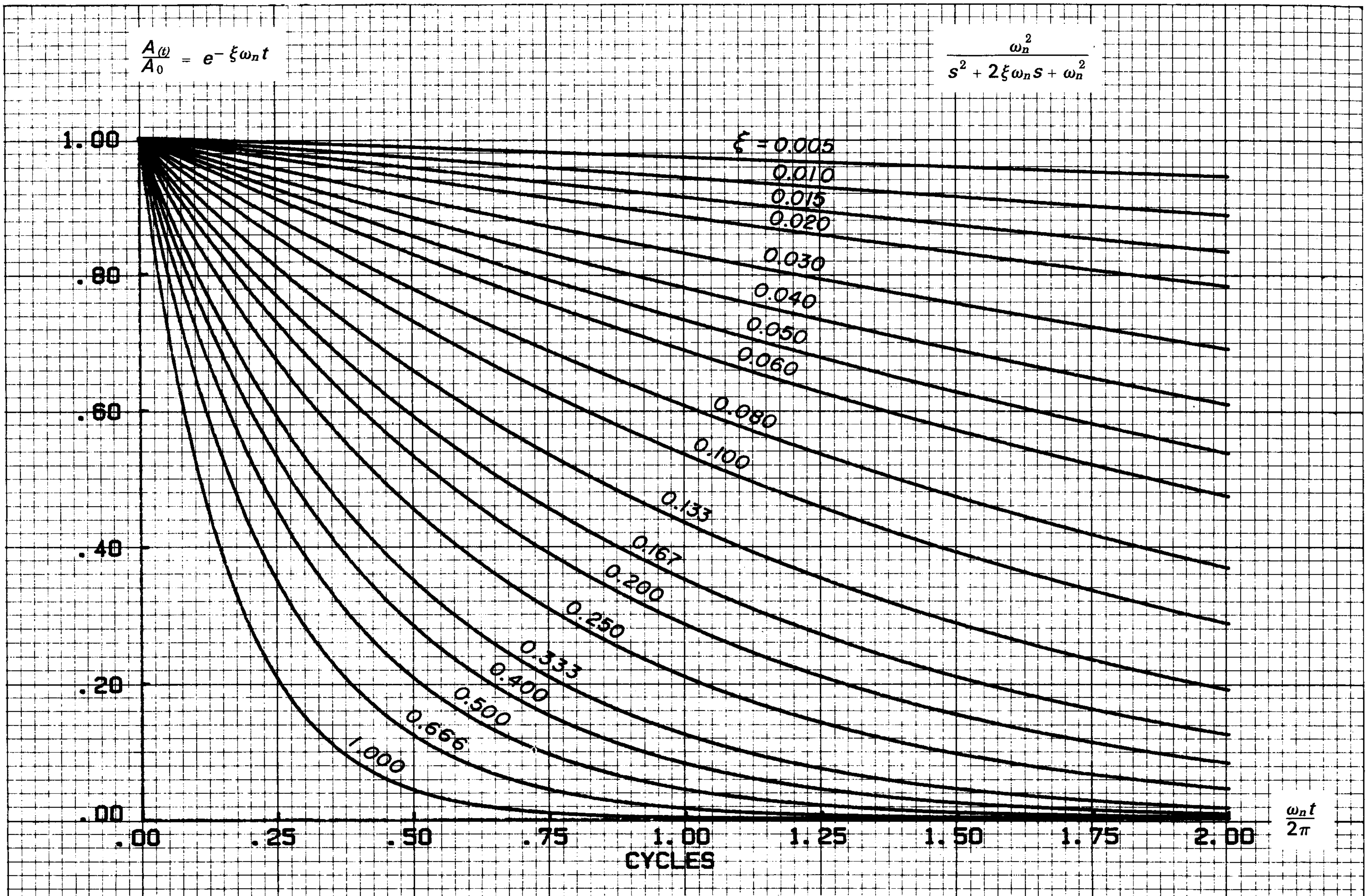

Figure X2. — Decrement of oscillation as a function of damping factor.

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Mission of the Bureau of Reclamation

The Bureau of Reclamation of the U.S. Department of the Interior is responsible for the development and conservation of the Nation's water resources in the Western United States.

The Bureau's original purpose "to provide for the reclamation of arid and semiarid lands in the West" today covers a wide range of interrelated functions. These include providing municipal and industrial water supplies; hydroelectric power generation; irrigation water for agriculture; water quality improvement; flood control; river navigation; river regulation and control; fish and wildlife enhancement; outdoor recreation; and research on water-related design, construction, materials, atmospheric management, and wind and solar power.

Bureau programs most frequently are the result of close cooperation with the U.S. Congress, other Federal agencies, States, local governments, academic institutions, water-user organizations, and other concerned groups.