# Facilities Instructions, Standards, and Techniques - Volume 3-14

## Excitation Systems for Hydroelectric Units

U.S. Department of the Interior

Revision 1.0

**Cover Photo**
Bureau of Reclamation, excitation control cabinet, photo taken by Reclamation Employee

# Facilities Instructions, Standards, and Techniques - Volume 3-14

## Excitation Systems for Hydroelectric Units

Prepared by

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U.S. Department of the Interior
Bureau of Reclamation
Power Resources Office
Denver, Colorado

Revision 1.0

# Mission Statements

The U.S. Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; honors its trust responsibilities or special commitments to American Indians, Alaska Natives, Native Hawaiians, and affiliated Island Communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

## Disclaimer

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# Codes and Standards

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

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.

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.

IEEE Tutorial Course, "Power System Stabilization Via Excitation Control," Course Text 91 EHO175-0PWR, Institute of Electrical and Electronic Engineers, 345 East 47th Street, New York, NY 10017.

NERC Standards:

- VAR-001-5, Voltage and Reactive Control
- VAR-002-4.1, Generator Operation for Maintaining Network Voltage Schedules
- VAR-501-WECC-4, Power System Stabilizer (PSS)
- MOD-025-2, Verification and Data Reporting of Generator Real and Reactive Power Capability and Synchronous Condenser Reactive Power Capability
- MOD-026-1, Verification of Models and Data for Generator Excitation Control System or Plant Volt/Var Control Functions
- MOD-027-1, Verification of Models and Data for Turbine/Governor and Load Control or Active Power/Frequency Control Functions
- MOD-032-1, Data for Power System Modeling and Analysis
- PRC-005-6, Protection System Maintenance
- PRC-019-2, Coordination of Protection Systems for Performance During Faults
- PRC-024-3, Frequency and Voltage Protection Settings for Generating Resources

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.

# Reclamation Standards and Documents

| | |
|---|---|
| FAC 04-14 | Power Facilities Technical Documents |
| FIST 1-1 | Hazardous Energy Control Program |
| FIST 1-2 | Conduct of Power Operations |
| FIST 4-1B | Maintenance Schedules for Electrical Equipment |
| FIST 5-14 | Electrical Safety Program |
| PEB 54 | ECS2100 Excitation System Drawer-Type Bridge Defect |
| PEB 55 | FIST 4-1B Reconciliation |
| RCD 03-03 | Request for Deviation from a Reclamation Manual Requirement and Approval or Disapproval of the Request |

# Reclamation Forms

POM: POM Forms - All Documents (doi.net)
POM-226, FIST Revision Request
POM-300, FIST Variance Form

# References

Brushgear Maintenance Guide, Report No. T112700-0343B, CEATI International Inc.

Carbon-graphite and Metal-graphite Brushes, by the Research and Technical Staff of National Carbon Company[1]

Hunter-Brown, Carbon Brushes and Electrical Machines, A.M.I.E.E. published by the Morgan Crucible Company, Ltd., Battersea Works, London[1]

Commutator and Slip-ring Maintenance, by Ideal Industries, Inc., Sycamore Illinois[1]

Carbon Brushes and Commutator Maintenance (B-6150A), Westinghouse Electric Corporation[1]
Better Carbon Performance (GEA6688), General Electric Company[1]

[1] Reference material was used to develop appendix A. Much of this material was not extensive and is no longer available.

# Acronyms and Abbreviations

| | |
|---|---|
| A | ampere |
| ac | alternating current |
| AVR | automatic voltage regulator |
| BES | bulk electric system |
| CT | current transformer |
| dc | direct current |
| FCR | field current regulator |
| FIST | Facilities Instructions, Standards, and Techniques |
| FVR | field voltage regulator |
| HXL | volts per hertz limiter |
| HXP | volts per hertz protection |
| Hz | hertz |
| IEEE | Institute of Electrical and Electronics Engineers |
| $in^2$ | square inches |
| ISO | International Standards Organization |
| kV | kilovolts |
| $mm^2$ | square millimeters |
| MVA | megavolt-ampere |
| MVAR | megavolt-ampere reactive |
| MW | megawatt |
| NERC | North American Electric Reliability Corporation |
| OEL | over-excitation limiter |
| OEP | over-excitation protection |
| O&M | Operations and Maintenance |
| OVL | overvoltage limiter |
| OVP | overvoltage protection |
| psig | pounds per square inch gauge |
| PMG | permanent magnet generator |
| PPT | power potential transformer |
| PT | potential transformer |

| | |
|---|---|
| PRO | Power Resources Office |
| PSS | power system stabilizer |
| RPM | revolutions per minute |
| Reclamation | Bureau of Reclamation |
| SCL | stator current limiter |
| SCR | silicon-controlled rectifier |
| SNL | speed-no-load |
| SSG | speed signal generator |
| TSC | Technical Services Center |
| UEL | under-excitation limiter |
| V/Hz | volts per hertz limiter |
| WECC | Western Electricity Coordinating Council |

# Symbols

Reserved

# 1.0 Introduction

The Bureau of Reclamation operates and maintains hydroelectric powerplants, switchyards, pumping plants, water delivery equipment and associated facilities in the 17 western United States. These facilities house complex electrical and mechanical equipment that must be kept operational because they are critical to the electric power and water delivery systems relied on by many. Facilities Instructions, Standards, and Techniques (FIST) are technical documents that provide criteria and procedures that should be utilized by the offices involved in managing Reclamation facilities and assets.

This document establishes standard technical practices to ensure the safe, reliable, economic and efficient Operations and Maintenance (O&M) of Federal facilities by keeping related assets in good condition and ultimately protecting Federal investments. These technical practices provide a sufficient level of detail to ensure consistent application while providing flexibility for the use of innovative techniques and approaches. This document was developed with input from staff in Reclamation's Denver, regional, and area offices.

## 1.1 Purpose and Scope

This document is intended to promote uniformity in the manner that assets are managed, documented, and coordinated, and may be utilized by transferred facilities and other entities as appropriate. It establishes consistent procedures, minimum standards and O&M criteria for hydroelectric equipment and systems owned and operated by Reclamation. Other technical documents may provide additional electrical and mechanical maintenance information for the equipment or systems discussed in this document.

O&M requirements are based on industry standards and experience. Maintenance requirements vary based on equipment condition and past performance, and sound engineering practices and maintenance management should be employed for special circumstances. Manufacturer recommendations and instructions should be consulted for additional maintenance that may be required beyond what is stated in this manual.

This volume includes standards, practices, procedures, and advice on day-to-day operation, maintenance, and testing of excitation equipment in Reclamation facilities.

## 1.2 Reclamation Standard Practices

FIST manuals are designed to provide guidance for maintenance and testing on equipment in Reclamation's facilities. There may be multiple ways to accomplish tasks outlined in this document. Facilities may exercise discretion as to how to accomplish certain tasks based on equipment configurations and available resources.

Reclamation's regions, Power Resources Office (PRO), and the Technical Services Center (TSC) agree that certain practices are required to be consistent across all Reclamation facilities. Mandatory FIST procedures, practices, and schedules that appear in **{Red, bold, and bracketed}** or **[Black, bold, and bracketed]** text are considered Reclamation requirements for the O&M of equipment in power facilities. RM D&S FAC 04-14, Power Facilities Technical Documents, describes the responsibilities required by text designations: **{Red, bold, and bracketed}**, **[Black, bold, and bracketed]**, and plain text, within this technical document.

Refer to RM D&S FAC 04-14 for more details concerning technical documents.

## 1.3 Maintenance Tables

Maintenance tables for tasks described in this document are included in FIST 4-1B, Maintenance Scheduling for Electrical Equipment.

## 1.4 Manufacturer Recommendations

The information in this document is based on manufacturers' documentation and historic Reclamation practices. Due to the differences in equipment designs, owner's manuals and manufacturer's recommended maintenance should be consulted when developing job plans. Not following the manufacturer's guidance may void the warranty of new equipment. If there is a discrepancy between the FIST and the manufacturer's recommendations, the job plan must use the more stringent practice unless there is a reason that a less restrictive maintenance practice is warranted. Use of a less restrictive maintenance practice must be approved as outlined in RM D&S FAC 04-14 by either a deviation or a variance. A deviation may be granted in accordance with RCD 03-03 and POM Form 300.

## 1.5 FIST Revision Requests

The FIST Revision Request Form (POM-226) is used to request changes to a FIST document. The request will include a summary of the recommended changes and a basis for the revision or new FIST. These forms will be submitted to the Manager, PRO. The PRO Manager will keep a list of Revision Requests for each FIST and include these in the next scheduled revision unless the change is prioritized sooner.

## 1.6 Safety During Maintenance Activities

Safety is an essential part of excitation maintenance. Identifying the hazards involved with working on or near excitation systems is essential to create a safe working condition.

Personnel performing maintenance on excitation systems may involve work on rotating machinery, various types (i.e. ac and dc) and voltage potentials of electricity. Equipment may have high arc flash hazards and potential for stored energy requiring extra care and knowledge. It is important that all hazards be assessed prior to the start of work. All maintenance activities must be conducted in accordance with FIST Volume 1-1, Hazardous Energy Control Program (HECP), FIST Volume 5-14, Electrical Safety Program, and the Reclamation Safety and Health Standards (RSHS). A job hazard analysis (JHA) must be conducted as well.

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# 2.0 Fundamentals

Large hydroelectric power and pumping plants use synchronous machines as their primary energy conversion devices. When operating as generators (alternators), these machines convert mechanical energy into electricity. Conversely, when operating as motors, they convert electrical energy into mechanical energy. Synchronous machines operate on the principle of interacting magnetic fields with one magnetic field produced in the rotating coils of the field (or rotor) winding and the other field produced in the stationary coils of the stator (or armature) winding.

To generate electricity with a synchronous machine, mechanical power is applied to the shaft to rotate the field winding within the coils of the stator winding. Direct current (dc) must also be applied to the field winding to create a strong magnetic field that will alternately convey north and south magnetic poles past the coils of the stator winding. This will create alternating current (ac) voltages in the stator winding.

The primary purpose of an excitation system for a synchronous generator is to supply the dc energy to produce the magnetic field in the field winding. Manipulating the output of the excitation system can change the stator terminal voltage and/or reactive power output of a synchronous machine.

## 2.1 Basics

An excitation system consists of two significant elements, the power output device (main exciter) and the controller section, which includes the voltage regulator, excitation limiters, and other control functions. These elements operate together to provide and control the dc field current required by a synchronous generator to meet a specified range of power system operating conditions. The excitation control system refers to the characteristics of the synchronous generator under control and the interconnected power system, as shown in Figure 1. Figure 2 is a simplified drawing of a synchronous machine showing how the excitation system is connected to the field winding of a synchronous machine to create an electromagnet. Carbon brushes and brass or steel collector rings connect the excitation system to the field winding.

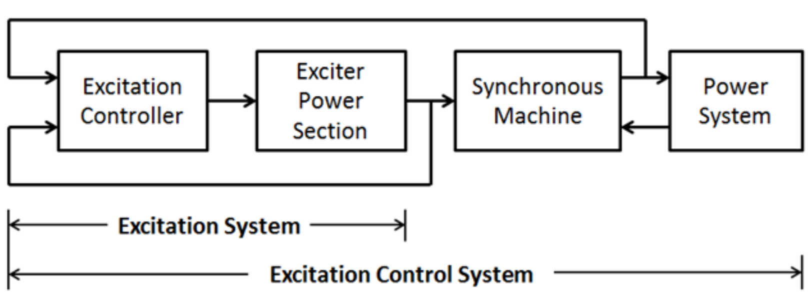


**Figure 1.—Excitation Control System Block Diagram.**

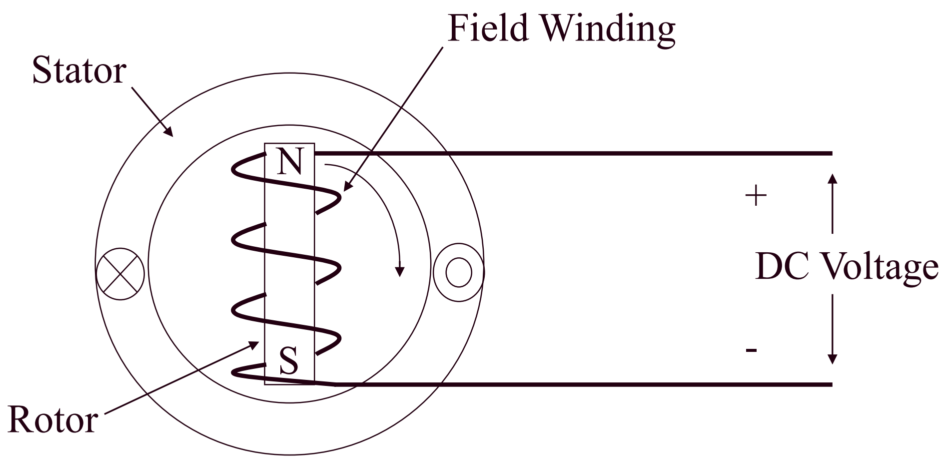


Figure 2.—Simplified Synchronous Machine.

## 2.2 Operation

Operating in automatic voltage regulator (AVR) mode is the most common way to control the excitation systems. AVR mode is a feedback control system consisting of electrical, analog electronic, or digital electronic circuits that manipulate the field current to match the synchronous machine terminal voltage to a setpoint. In this manner, the synchronous machine terminal voltage is maintained at the setpoint regardless of the load on the machine and the conditions in the external power system. Extreme power system conditions will overwhelm the AVR and affect terminal voltage. Power system regulating authorities such as North American Electric Reliability Corporation (NERC) and Western Electricity Coordinating Council (WECC) have policies that require NERC-qualifying generating units to operate in AVR mode.

The voltage regulator control switch (90CS) typically controls the voltage regulator setpoint (90) from 90 to 110 percent nominal machine voltage. The operation of limiters such as the Over-excitation (OEL) or the Under-excitation (UEL) limiters restrict the operating range to prevent damage to the synchronous machine.

A backup method for controlling field current (70), known as a field current regulator (FCR or manual excitation), that does not involve the control of machine terminal voltage is part of most excitation systems. A 70 device may utilize a simple power rheostat or a feedback control system that matches field current to a setpoint. The exciter field control switch (70CS) changes the field's current set point from 20 to 110 percent.

## 2.3 Types of Excitation Systems

Several types of excitation systems are typically categorized by the power output stage employed. Rotating commutator-type dc main exciters, static exciters with silicon-controlled rectifier (SCR), or thyristor solid-state power amplifiers, and brushless ac exciters with rotating diodes, are three types of excitation systems commonly used for hydroelectric generators. Electromechanical, magnetic amplifier, analog, or digital are further categorizations for excitation systems. Hydroelectric generators employ all these controller types.

### 2.3.1 Rotating DC Main Exciter Systems

Regardless of the type of control used for the main exciter field, there are several common problems associated with rotating main exciters. These include commutator surface irregularities, commutator brush problems, neutral plane adjustments, and low efficiency.

Commutator surface irregularities can be caused by accidental damage or because of improper refurbishment. The solution, in most instances, is to stone the commutator to restore a smooth surface. Brush problems have many causes and can be challenging to diagnose. The neutral plane adjustment refers to the position of the brushes with respect to the field poles and may be disturbed during a refurbishment of the generator. Measuring exciter field current values and output voltage and comparing these to the original exciter saturation curve provides a method of establishing proper neutral plane adjustment. Excessive ripple on the output voltage or arcing at the commutator may indicate this problem. More information on commutators can be found in Appendix A.

The maximum efficiency for this type of exciter is usually below 90 percent.

### 2.3.2 Non-Continuously Acting Systems

Systems installed before 1940 typically employed rotating dc main exciters, rotating pilot exciters, and controllers composed of electromechanical components. These systems were often referred to as non-continuously acting systems because control was performed by inserting or removing a block of resistance.

Figure 3 shows a simplified example of this system. The AVR controls terminal voltage by changing the resistance of the field rheostat. A sliding or rotating wiper assembly connected to resistance elements makes up the field rheostat. Changing the field rheostat changes the exciter field current, which, in turn, changes the exciter output voltage. Changing the exciter output voltage then changes the synchronous machine field current, resulting in a change in machine terminal voltage.

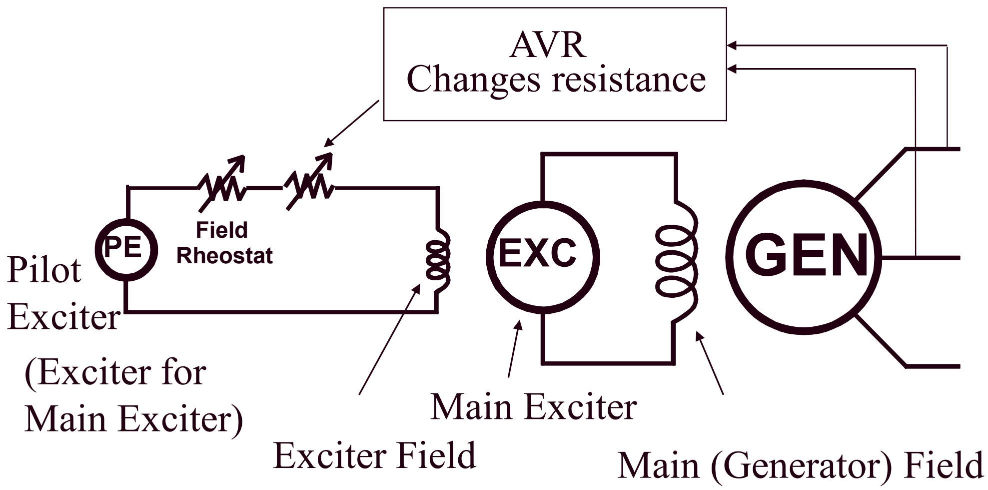


Figure 3.—Non-Continuously Acting Rotating DC Exciter System.

### 2.3.3 Magnetic Amplifier Systems

Replacing the pilot exciter with a magnetic amplifier and its control circuitry creates a magnetic amplifier-type excitation system. The system still has the rotating main exciter and the field rheostat. The AVR controls terminal voltage in this system by rapidly changing the amplidyne (or magnetic amplifier) output voltage. Changing the amplidyne output will shift the exciter field current, resulting in a shift in the output voltage. Changes in field current cause changes in the main machine field current and machine terminal voltage. See Figure 4 for a simplified example of this system. An induction motor, powered by station service, drives a permanent magnet generator at about 400 Hz. This setup provides power to the Amplidyne's power and control circuits (usually small magnetic amplifiers).

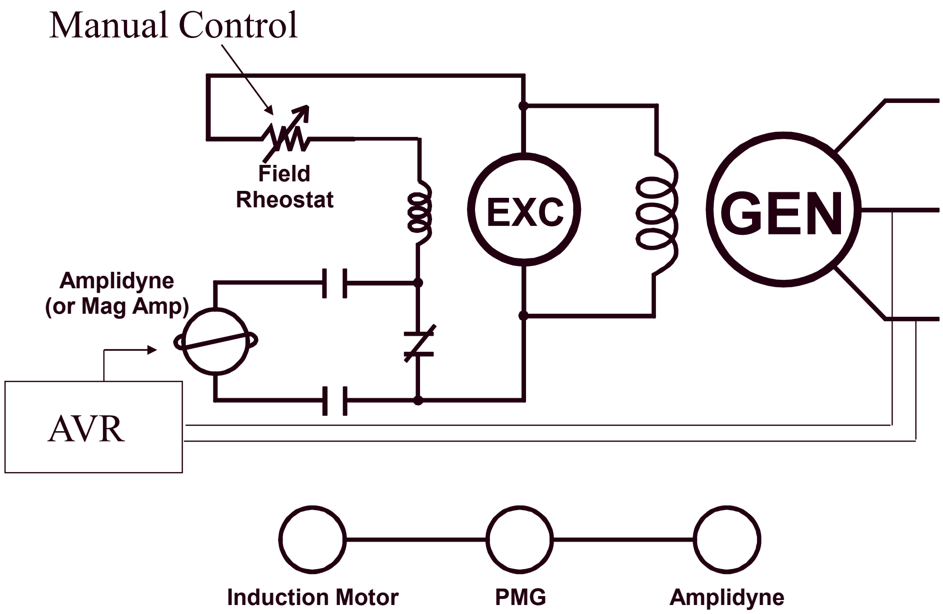


Figure 4.—Typical Magnetic Amplifier Excitation System.

### 2.3.4 Static SCR Pilot Exciter Systems

Upgrading the systems described in the previous two sections with an SCR bridge and dc main rotating exciter creates a Static Pilot Exciter system. Figure 5 shows a simplified example of this type of excitation system. The AVR controls terminal voltage by rapidly changing the SCR bridge output voltage in this system. Changing the SCR output voltage will change the rotating exciter field current, the rotating exciter output voltage, the main machine field current, and ultimately the machine terminal voltage. The power source for the SCR-bridge can be from station service or the generator terminals. The preferred power source is the generator terminal supply, making the excitation system independent from station service. Field flashing from station batteries or another reliable source must be available to start this type of excitation system as unit residual voltage may not be large enough to initiate the firing of the SCR bridge.

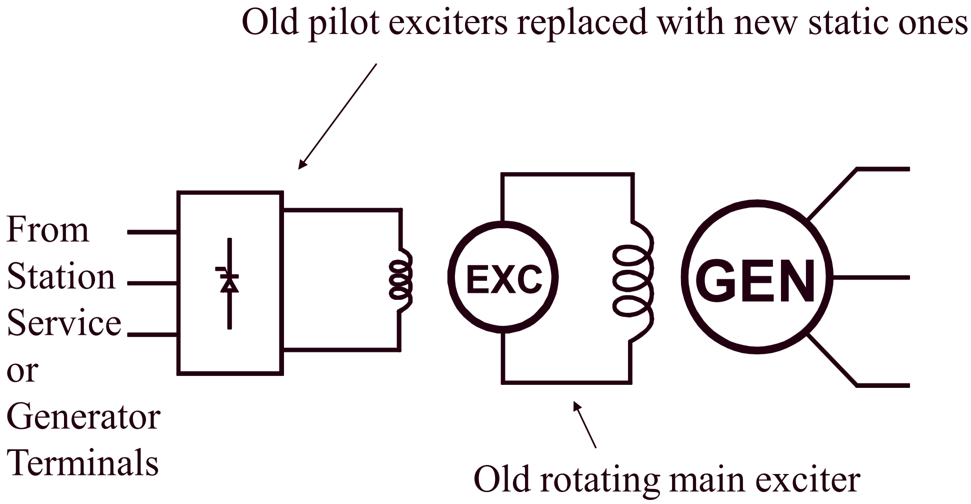


**Figure 5.—Static SCR Pilot Exciter.**

## 2.3.5 Static Exciter Systems

There is no rotating exciter in a fully static excitation system. Instead, a large SCR bridge or multiple parallel SCR bridge supplies the entire field current requirements of the main machine. In this system, the AVR controls the machine terminal voltage by changing the SCR bridge output voltage, directly changing the field current. Figure 6 shows a simplified example of this type of system. A transformer that powers this type of excitation system is known as a bus-fed system. A static exciter's efficiency is usually greater than 92 percent (assuming 96 percent in the SCR bridge and 96 percent in the excitation transformer for harmonic losses).

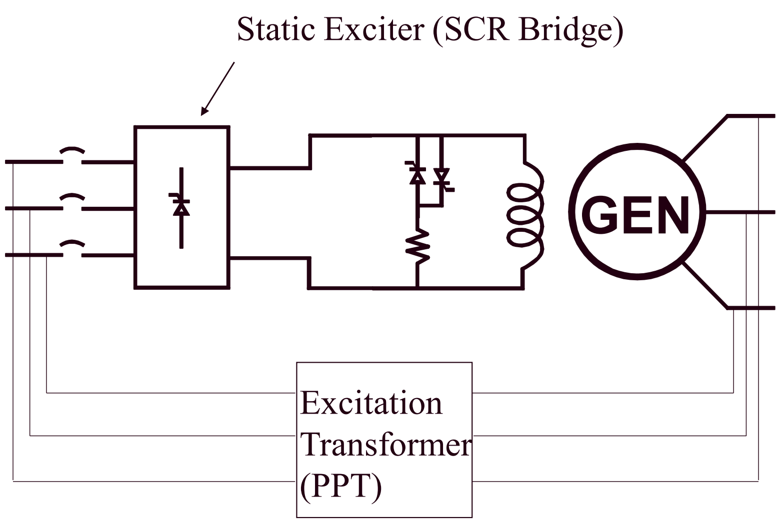


**Figure 6.—Fully Static Excitation System ("bus fed").**

### 2.3.6 Brushless Exciter Systems

The main exciter for these systems is an alternator with stationary field poles and a 3-phase armature winding on the rotor. A rotating 6-pulse diode bridge rectifies the armature voltage. The bridge and field windings are directly connected. Figure 7 shows a simplified example of a brushless excitation system. In this system, the AVR controls terminal voltage by changing the SCR bridge output voltage, which changes the alternator field current, change in field current results in changes in alternator output voltage, the machine field current, and ultimately the machine terminal voltage. Systems like this have no main field voltage feedback into the AVR controller, so some control functions (such as the OEL) must assume characteristics of the alternator.

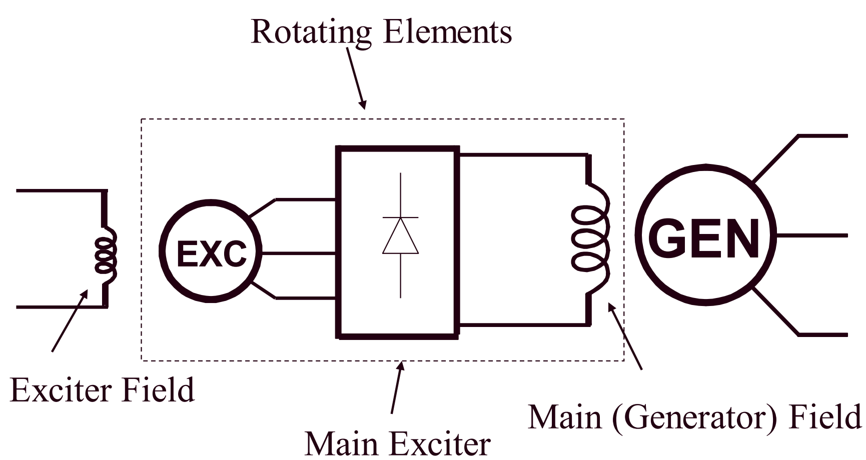


**Figure 7.—Brushless Excitation System.**

### 2.3.7 Analog Electronic Excitation Controllers

Analog electronic excitation system controllers implement all the excitation control functions (AVR, manual regulator, and limiters) in analog electronic circuits. Systems of this type were developed in the 1970s and were the prevalent controller type for decades. Typical first-generation controllers of this type had each function built on a separate module. The modules were then installed in a "card rack" with interconnected backplane wiring and a common power supply. A motor-operated potentiometer supplied the voltage regulator setpoint for these early implementations. Later generations of analog excitation controllers tended to be built on a single large, printed circuit board and had a digital reference adjuster for the voltage reference.

### 2.3.8 Digital Excitation System Controllers

A digital excitation system controller can be a computer-type device (based on single board computers) or a PLC (programmable logic controller)-type device. Computer-type controllers typically have more capability and flexibility than excitation controllers but less native I/O (input-output). Thus, computer-type excitation controllers will have sophisticated algorithms (such as differential equations for a PSS – Power System Stabilizer) built in but may require additional I/O modules connected by communication links. PLC-type excitation controllers typically are mounted in a shared rack with I/O modules but may need an external PSS.

Digital excitation system controllers perform all the functions analog electronic excitation systems do, but they perform the tasks much differently. Digital excitation systems sample all the machine voltages and currents and implement the terminal voltage and frequency, line current, field current, and real and reactive power transducers as code operating in the computer. Analog electronic excitation systems implement each of these transducers as separate electronic modules.

Digital electronic excitation controllers have self-diagnostic and extensive built-in test capabilities. It is easy to adapt this exciter type to various power system conditions by changing the control functions or applying different algorithms. At critical facilities, digital systems will include a backup controller and the second set of terminal voltage inputs rather than a manual regulator in case of failure of the primary controller.

### 2.3.9 Redundant Elements in Excitation Systems

Most excitation systems have some redundant (or backup) elements. Typical redundant components include SCR bridges, firing circuits, and excitation controllers (in digital systems). The corresponding sections of this document describe the redundant elements' operation in more detail.

A system with a redundant controller (AVR, manual regulator, limiters, transducers, and other components) will have the first controller called channel 1, A, or main and the second controller called channel 2, B, or redundant. These systems share two or more SCR bridges. These SCR bridges share the field current load. If one SCR bridge fails, the others will take over the field current load.

Potential transformers (PT) and current transformers (CT) are the sensing elements for the primary and redundant controller voltage regulators. In some applications, each controller has dedicated sets of sensing elements. Both controllers usually share a field current shunt. There is a control switch to select the channel in operation. For regular operation, the primary channel will be in control. When the main channel fails, the redundant channel will take over. When the redundant channel fails, the unit will trip.

## 2.4 Control Features

### 2.4.1 Automatic Voltage Regulator

The primary function of an Automatic Voltage Regulator (AVR) is to control the terminal voltage of the main unit (synchronous generator or motor). An AVR in its simplest form is shown in Figure 8. Terminal voltage is measured and compared to the voltage regulator setpoint (reference adjust). The "error" or difference between these two signals will determine whether the exciter output needs to be raised or lowered by the AVR. Changes in the exciter output voltage will cause the field current and subsequently the main unit terminal voltage to change until the error is zero. The voltage regulator setpoint can be controlled by the plant operator to meet unit and power system requirements.

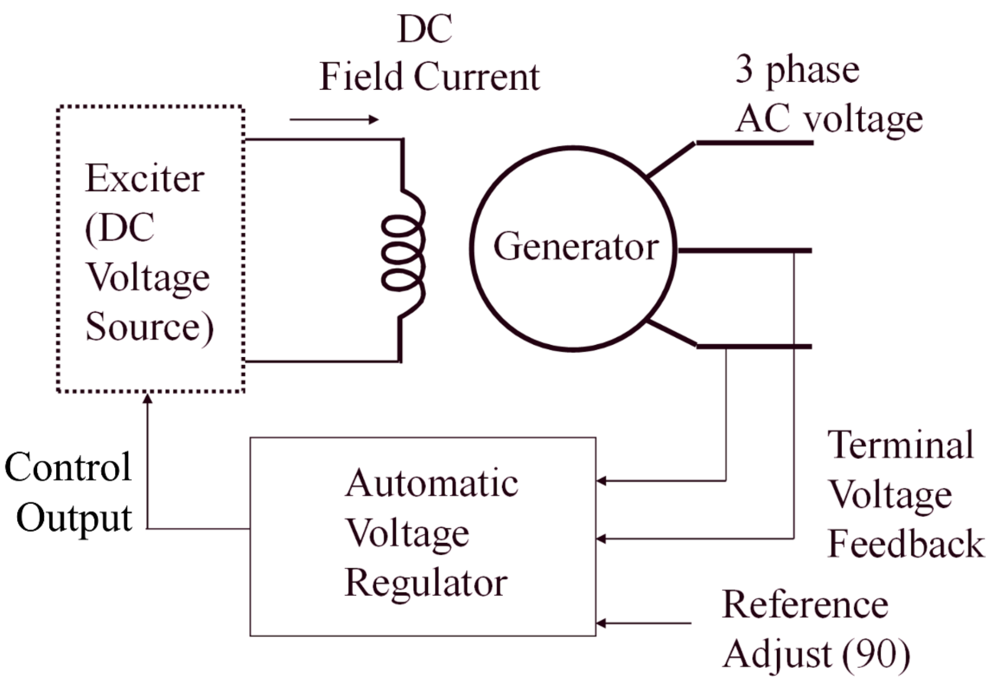


**Figure 8.—Automatic Voltage Regulator.**

Excitation control uses several different controller structures. The simplest excitation controller structure, the Proportional Gain Controller, is shown in Figure 9. This controller amplifies the error signal and uses the enlarged signal as the field voltage. A proportional controller can only be used in static excitation systems because there is no compensation for additional circuit elements (time constants). Proportional Plus Integral (shown in Figure 10) and Transient Gain Reduction Controllers (shown in Figure 11) are like Proportional Gain Controllers and can be used only on static excitation systems.

Excitation systems with rotating dc main exciters or brushless exciters require more complex controllers with compensation for additional time constants. These exciter power elements typically use Proportional, Integral, Derivative (PID) controllers (shown in Figure 12), Transient Gain Augmentation Controllers (shown in Figure 13), or Rate Feedback Controllers (shown in Figure 14). Exotic digital control algorithms such as model-based control, pole placement control, or state feedback control are possible with digital excitation systems but not required for the relatively simple task performed by an AVR.

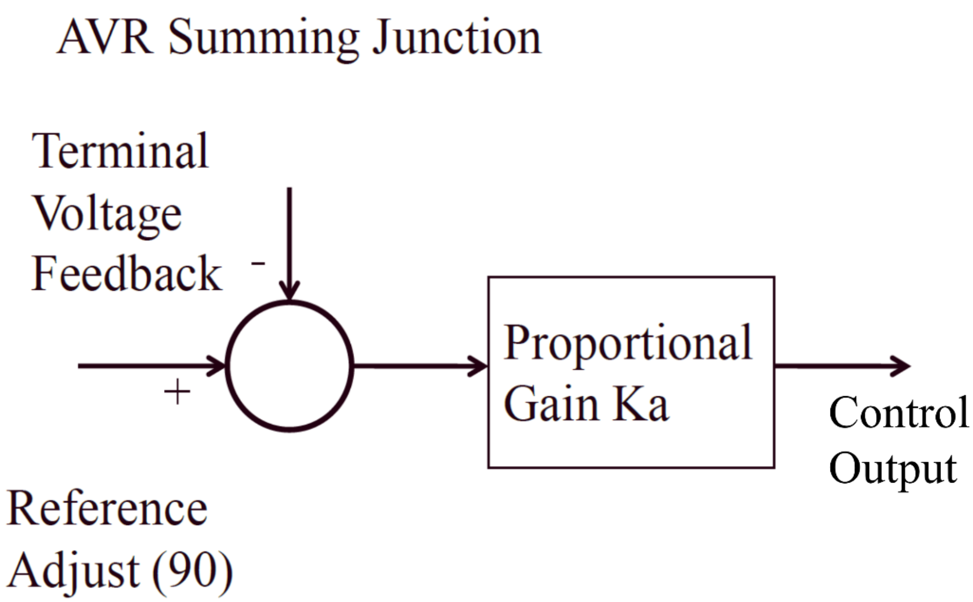


Figure 9.—Proportional Gain Controller.

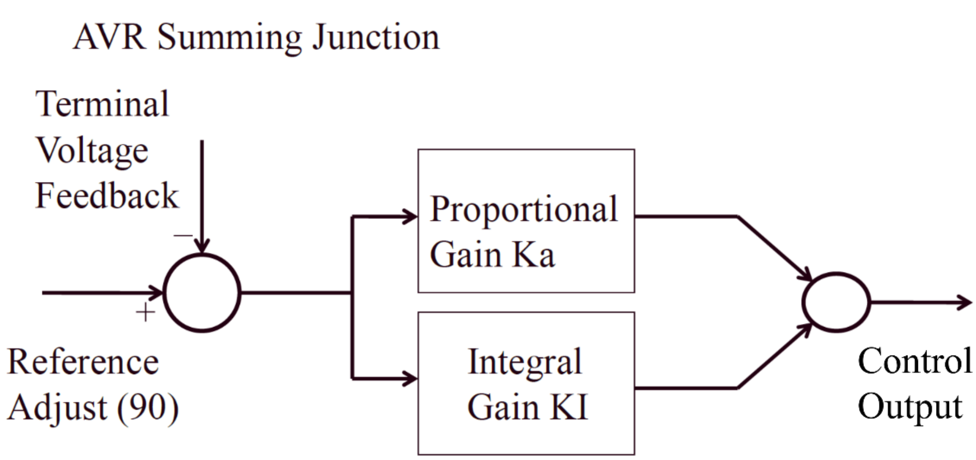


Figure 10.—Proportional Plus Integral Control.

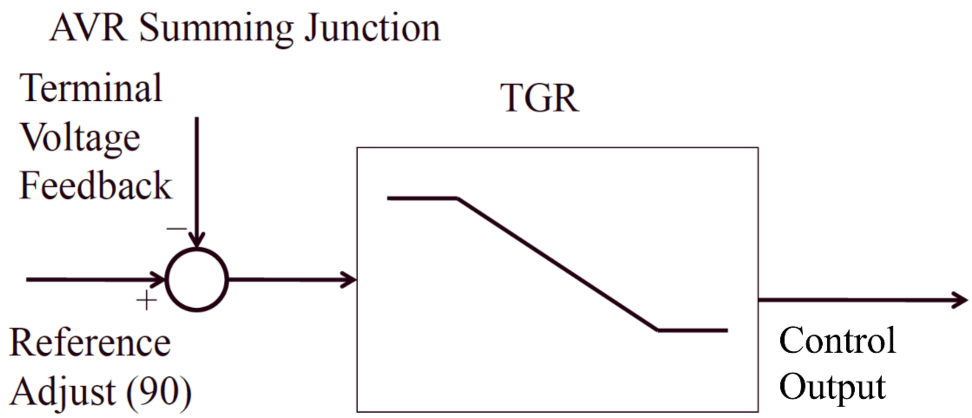


Figure 11.—Transient Gain Reduction Controller.

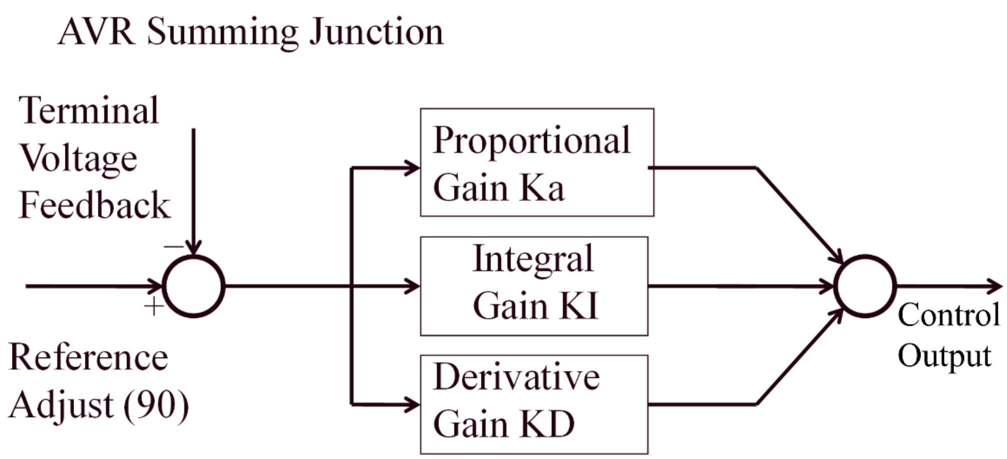


Figure 12.—PID (Proportional, Integral and Derivative) Control.

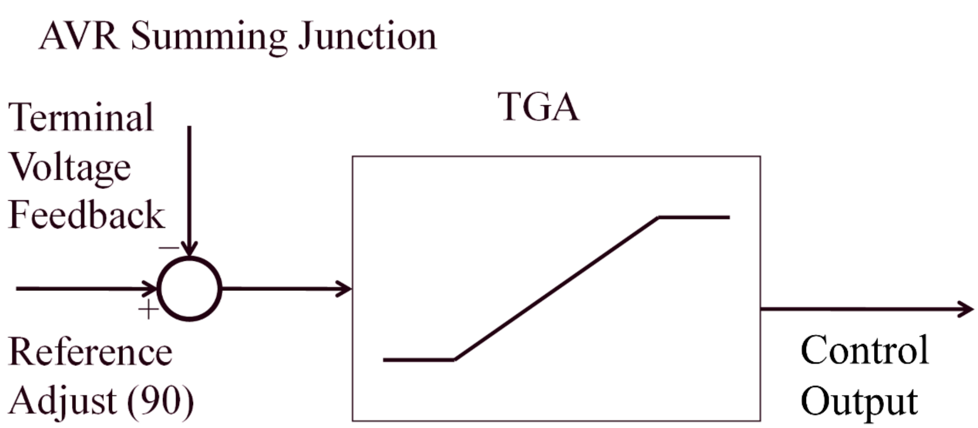


Figure 13.—Transient Gain Augmentation Controller.

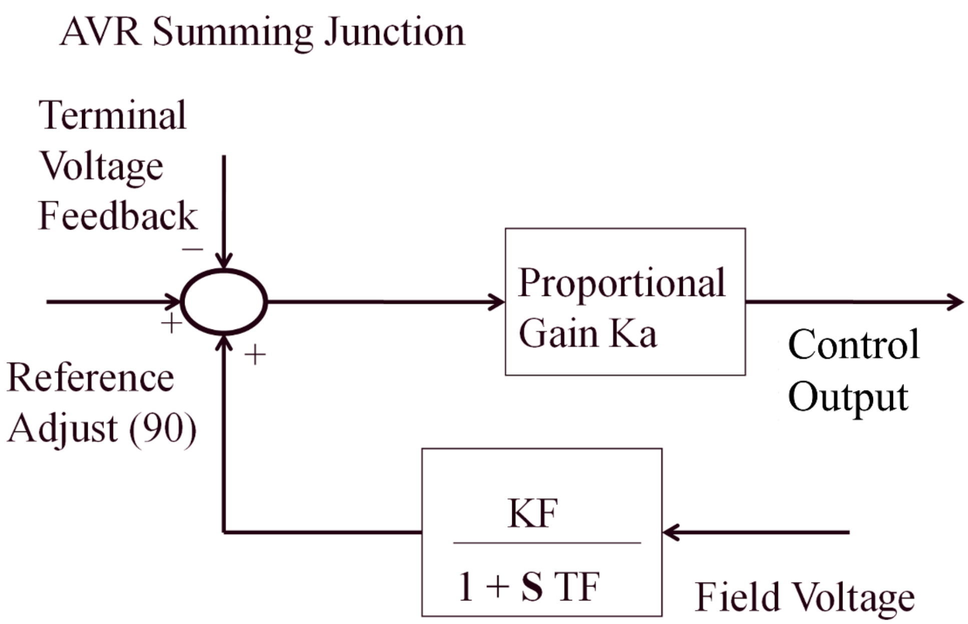


**Figure 14.—Rate Feedback Controller.**

### 2.4.2 Manual Regulator

The primary function of a manual regulator is to control the main machine field current (or field voltage in some cases). For some systems with rotating dc main exciters, the manual regulator may control the exciter field current or voltage rather than the main machine field. Systems with non-continuously acting AVRs or magnetic amplifier-type AVRs will use the field rheostat as manual control. However, systems employing static amplifiers (SCR bridges) do not have field rheostats. The use of a manual regulator controller that manipulates the SCR firing circuits is a requirement.

Some first-generation static exciters used an open-loop firing angle positioner, but most static exciters have a feedback controller that performs closed-loop control, as shown in Figure 15. The field quantity under control is measured and compared to the field current (or voltage) setpoint (reference adjust). The "error" or difference between these two signals will determine whether the exciter output needs to be raised or lowered by the manual regulator controller. Manual regulators typically use Proportional Gain, Proportional Plus Integral, or Transient Gain Reduction Controllers.

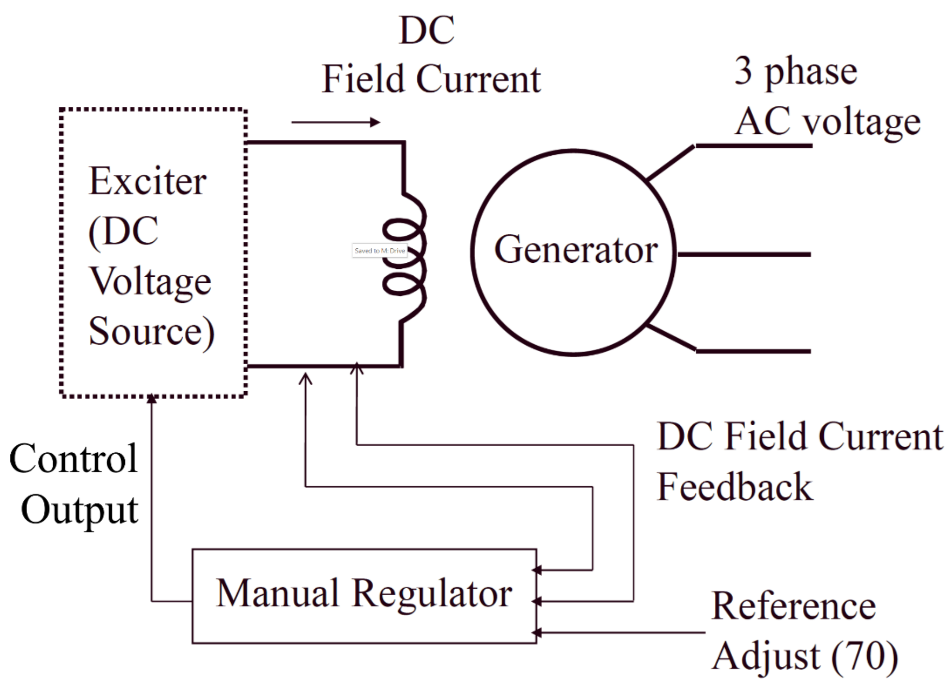


Figure 15.—Manual Regulator.

### 2.4.3 Reactive Current, Cross-Current, and Line-Drop Compensation

Units connected to the same step-up transformer use reactive current compensation and cross-current compensation. Using line drop compensation gives better control of power system voltage on the high side of the transformer. These compensators all work by measuring generator line current and adding a percentage of current (or a percentage of the reactive component of current) to the terminal voltage to create a new compensated feedback voltage, Vc. Cross-current compensators minimize the influence of adjacent generators but require line current measurement from any other generators(s) connected to the same step-up transformer. All these compensators must add the compensating current with the correct polarity to accomplish their tasks, as shown in Figure 16.

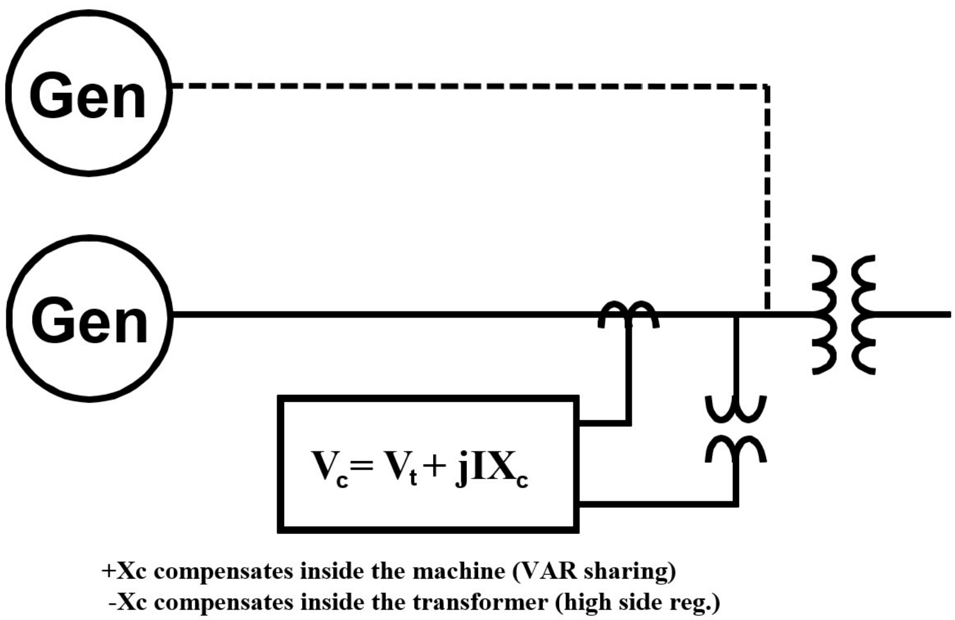


Figure 16.—Reactive Current and Line Drop Compensation.

### 2.4.4 Excitation Limiters

Excitation control systems have many limiters to prevent the excitation system from delivering too much or too little field current for the machine and power system conditions. Proper adjustment of excitation limiters will prevent a machine from being tripped by protective relaying and allow the generator to support the power system. A typical excitation system may include these limiters: volts per hertz limiter (V/Hz or HXL), terminal overvoltage limiter (OVL), off-line field current limiter, over-excitation limiter (OEL), under-excitation limiter (UEL), and stator current limiter (SCL). Limiters are usually active only when the AVR operates, not when the manual regulator is in control.

Limiters can be a summed-in type, the sum of the limiter output and the AVR error signal, or a take-over type, in which auctioning gate applies the limiter output to take control of the excitation system from the AVR. Figure 17 shows a block diagram of a summed-in type limiter. This limiter type is often referred to as a “soft” limiter because the AVR control loop is still active and will tend to oppose limiter action. The limiting level will depend on both the gain of the AVR control loop and the gain of the limiter signal path. This limiter will allow excitation to deviate beyond the limiter setpoint as the setpoint is driven farther into the limiting condition.

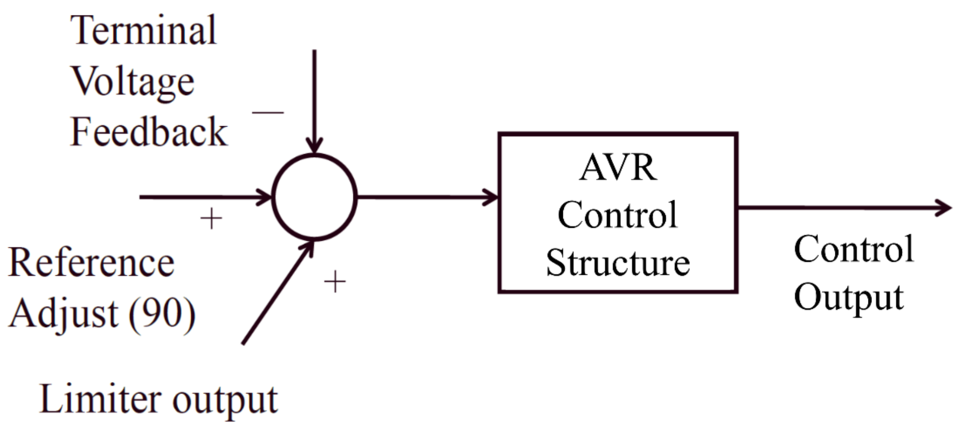


**Figure 17.—Summed-in Type Limiter.**

Figure 18 is a block diagram of a take-over type limiter. This limiter type is often referred to as a “hard” limiter because the limiter has its control loop that takes over control from the AVR. The limiting level for this limiter type is more accurate than that of a summed-in type limiter; however, ensuring stable operation requires adjustments to the limiter control parameters.

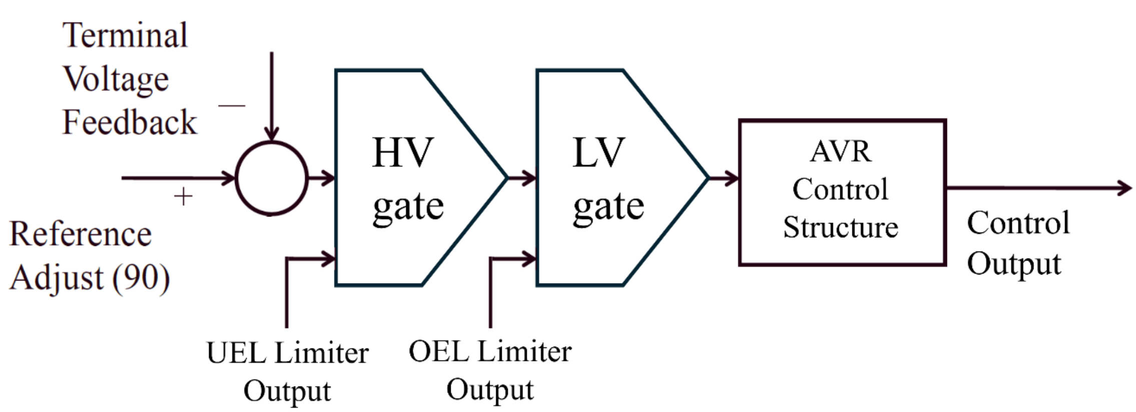


**Figure 18.—Take-Over Type Limiter.**

#### *2.4.4.1 Volts per Hertz Limiter (V/Hz or HXL)*

A V/Hz limiter is needed to protect the iron core of a generator and any connected transformers from excessive flux. If a magnetic circuit element operates at low frequency and nominal voltage, the body can overheat due to extreme flux because the voltage is a product of flux and frequency. A V/Hz limiter reduces the unit terminal voltage whenever its frequency is reduced below nominal by measuring the terminal voltage and frequency of the unit, calculating the V/Hz ratio, and applying a control signal to minimize excitation; this will limit the core losses in the generator and any connected transformers. V/Hz limiters are typically set at about 110-111 percent of rated V/Hz For hydroelectric generators.

#### *2.4.4.2 Terminal Overvoltage Limiter (OVL)*

A terminal voltage limiter restricts the terminal voltage of a unit to a pre-determined level. Some excitation systems route the output of this limiter directly into the firing circuits of an SCR bridge to provide a phase back signal until the terminal voltage drops below the limiting level. Once the voltage falls below the limit level and the phase back signal is released, the terminal voltage may rise and cause the excitation system to cycle between phase back and regular operation. This approach does limit terminal voltage but in a very oscillatory manner. OVL, a setting of 111-122 percent of V/Hz, becomes active when the V/Hz limiter fails.

Other excitation systems implement an OVL as a summed-in or takeover type function. These types have smoother control action and can be adjusted to the same value or just below the V/Hz limiter (about 109-110 percent) to become active before the V/Hz at normal operating speed.

#### *2.4.4.3 Off-line Field Current Limiter*

An off-line field current limiter restricts the field current of the unit as a method of limiting the terminal voltage. The AVR controller does not process this limiter and is operational anytime the unit is off-line. This limiter is typically adjusted to limit the terminal voltage to 111 percent of the rated terminal voltage with the unit at rated speed. Some off-line field current limiters may be implemented as firing angle limiters, which restrict the firing angle of the SCR bridge. Directly limiting the firing angle is not the preferred method because this also restricts the field forcing ceiling and may skew performance test results if not disabled during testing.

#### *2.4.4.4 Over-Excitation Limiter (OEL)*

An OEL (Over-Excitation Limiter) protects the generator field winding from overheating. It typically has two parts, an instantaneous and an inverse-time element. The instantaneous limiter sets the maximum amount of field current that the excitation system can deliver. A typical setting for this element is 140-160 percent of rated load field current.

The inverse-time limiter restricts the field current based on an inverse-time characteristic like the curve described in ANSI/IEEE C50.13-1989. The higher the field current, the shorter the time delay of this limiter. After the delay, this limiter typically reduces the field current to 105 percent of the rated load field current. Figure 19 shows a typical characteristic curve for the online field current limiter.

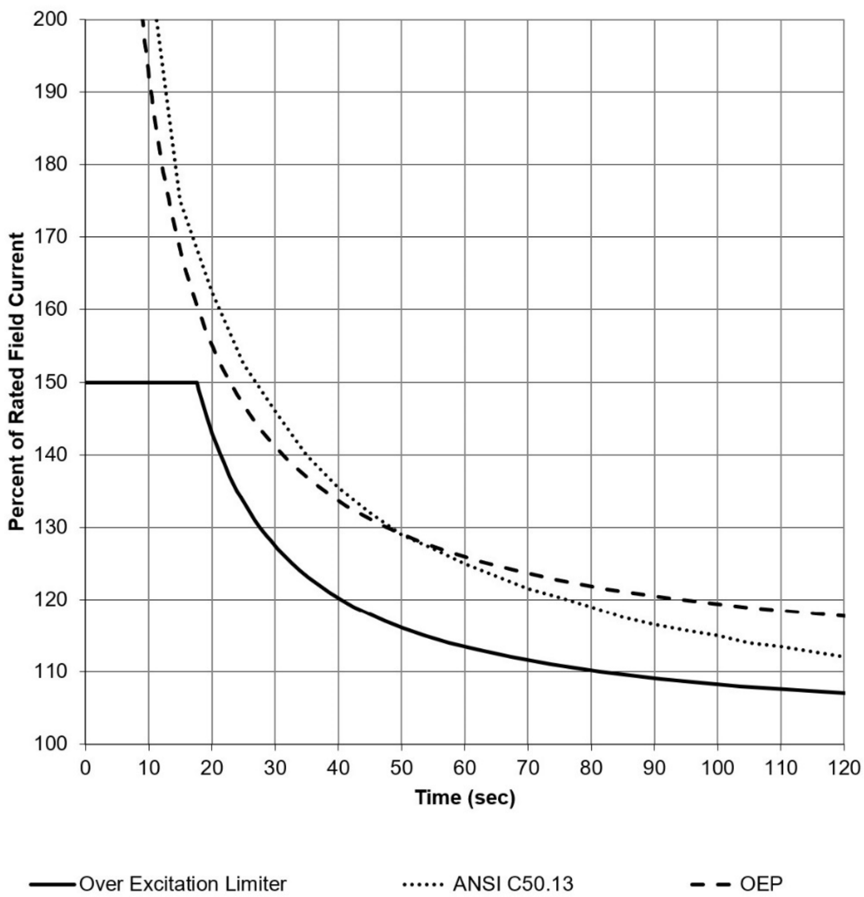


**Figure 19.—Over-Excitation Limiter.**

### *2.4.4.5 Under-Excitation Limiter (UEL)*

A UEL (Under-Excitation limiter) protects a generator against pole-slipping, stator overheating from the excessive under-excited operation, and overheating in the end iron region (this third condition applies only to cylindrical rotor units – not hydro salient pole machines). The UEL restricts the amount of reactive power the generator absorbs by increasing the excitation when the operations enter the limiting region. The limiter reactive power setpoint depends on the true power loading of the unit, as shown in Figure 20. At higher real power loads, the reactive limit value is smaller. A single sloped line can describe the limiting region for a UEL, a straight line combined with a sloped line, or a curved (or segmented) line, depending on the equipment supplier and the vintage of the equipment. The curve may also adjust based on operating terminal voltage.

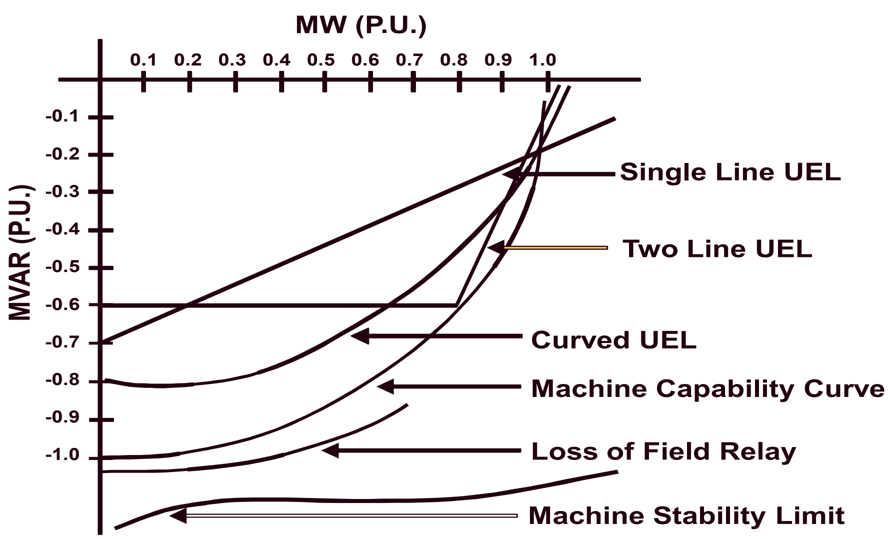


Figure 20.—Under-Excitation Limiter.

### *2.4.4.6 Stator Current Limiter (SCL)*

The stator current limiter can protect the stator winding from overheating when near full load operation of a unit. It cannot limit current in the stator winding from active power (watts) but can limit current in the stator from reactive power (VARs). It accomplishes limiting by monitoring stator current and applying a control signal to the AVR to boost or reduce excitation, bringing the VARs closer to zero. If at no VARs, the SCL will maintain near-zero VARs if the stator current becomes higher than the limiter setting. Setting the SCL to 105-110 percent of rated load stator current is typical. Most hydro units do not have this limiter active but may in the future.

### 2.4.5 Excitation System Protection

Protective relays are generally in place to trip the generator if the limiters do not work satisfactorily. These include field ground (64F), V/Hz (24), loss-of-sensing, bridge failure, over-excitation, loss of field (40), and overvoltage (59). Coordination must exist between these relays and their respective limiters (OVL, V/Hz, UEL, or OEL).

The field bus circuit is electrically floating from ground. A field ground relay or element (64F) can be used to detect the first field bus connection to ground and can be implemented using various techniques, typically using a voltage injection method. Field ground protection is often applied using definite time alarm and trip settings that can be set based on various parameters, such as if the facility is manned 24/7, operated remotely, and based on preferred facility operating practices. The alarm setpoint typically indicates a need for immediate shutdown and the trip setpoint would typically trigger a generator lockout condition.

The V/Hz (24) relay also typically includes an alarm and trip protective elements, which should be coordinated with the V/Hz limiters in the excitation system equipment. The V/Hz alarm typically involves a definite time pickup, and the V/Hz trip often includes a definite time pickup combined with an inverse-time protective characteristic. Coordination requirements for V/Hz protection can be found in NERC standard PRC-019 and protection requirements, such as “No Trip Zones”, can be found in NERC standard PRC-024. Additional protective guidance can be found IEEE protection guides, such as C37.102 and C37.106.

The loss-of-sensing feature, which is usually located within excitation equipment, detects the loss of terminal voltage condition. The loss-of-sensing feature will trip the unit if terminal voltage drops below a pre-determined value (typically 75 percent of rated voltage). If there is a redundant system, it will first transfer PTs and controllers, then transfer to manual FCR control, and finally trip if still active.

Usually, an excitation system will have two or three SCR bridges in an N+1 configuration. The N+1 configuration provides rated current capability with an “N” number of bridges and has one spare bridge available for redundancy. All SCR bridges share the load of field current. If one bridge fails, the other(s) will take over the burden of the field current. When all bridges fail, then the unit will trip. Detection of bridge fans not providing airflow can be alarmed before tripping the generator.

There are different types of over-excitation relay protection, which include definite time, instantaneous, and inverse-time protective characteristics. The pickup level setting is typically set at 120-130 percent of the rated field current with a time delay of 70-90 seconds to coordinate with the OEL curve to comply with NERC standard PRC-019 requirements. The typical instantaneous and inverse-time relay protection characteristic is similar to the OEL curve. This protection can be located in standalone protective relays or within excitation equipment.

The loss-of-field (40) relay typically includes two zones of protection provided by mho circles in the resistive (R) and reactance (X) plane, usually set with a negative offset characteristic to trip the generator and coordinated with the UEL. Testing has indicated that negative offset characteristics typically provide better coordination with the UEL than positive offset characteristics. These mho circle characteristics are set based on simulated loss of excitation machine responses and will operate when the operating trajectory in the RX plane stays within the mho circle for a specified amount of time. Coordination requirements for loss-of-field protection can be found in NERC standard PRC-019.

The overvoltage (59) relay typically includes two levels of protection, an instantaneous pickup and a definite time pickup. Protection could also include an inverse time protective characteristic, usually from older solid state or electromechanical relays. The pickup levels are based on historical setpoints and are typically maintained to be consistent across Reclamation generators. This protection should be coordinated with overvoltage limiters in the excitation equipment to comply with NERC standard PRC-019 requirements and with measured load rejections to avoid nuisance trips. The type of excitation system, rotating or static, will influence the overvoltage protection settings.

### 2.4.6 Power System Stabilizer

A Power System Stabilizer (PSS) helps to dampen power system mode oscillations and enhance the damping of the unit oscillation (local mode oscillation). The PSS measures frequency, power, or a combination of both. Most hydro units use a combination of both. The AVR uses the PSS solution as an input. The PSS is only active when the AVR is active. In manual regulator, the PSS is inactive. The PSS monitors the oscillation in the frequency and power signals. It then provides appropriate changes in voltage to the AVR to dampen power oscillations. Figure 21 shows a PSS added to an AVR, while Figure 22 shows a simple dual-input PSS block diagram.

Since panel meters may not show the oscillations, indicator lights or annunciation show PSS status. The PSS is active only when the PSS switch is in the on position, the unit is online, above a minimum real power value (usually 10 percent of the unit load rating), and within a typical terminal voltage range of 90-110 percent of rated. The PSS uses a multi-stage lead/lag phase compensator to accommodate the AVR phase lag.

The PSS output connection should be at a junction that is after the under-excitation limiter summed-in or take-over. This set-up will help to stabilize the under-excitation limiter action.

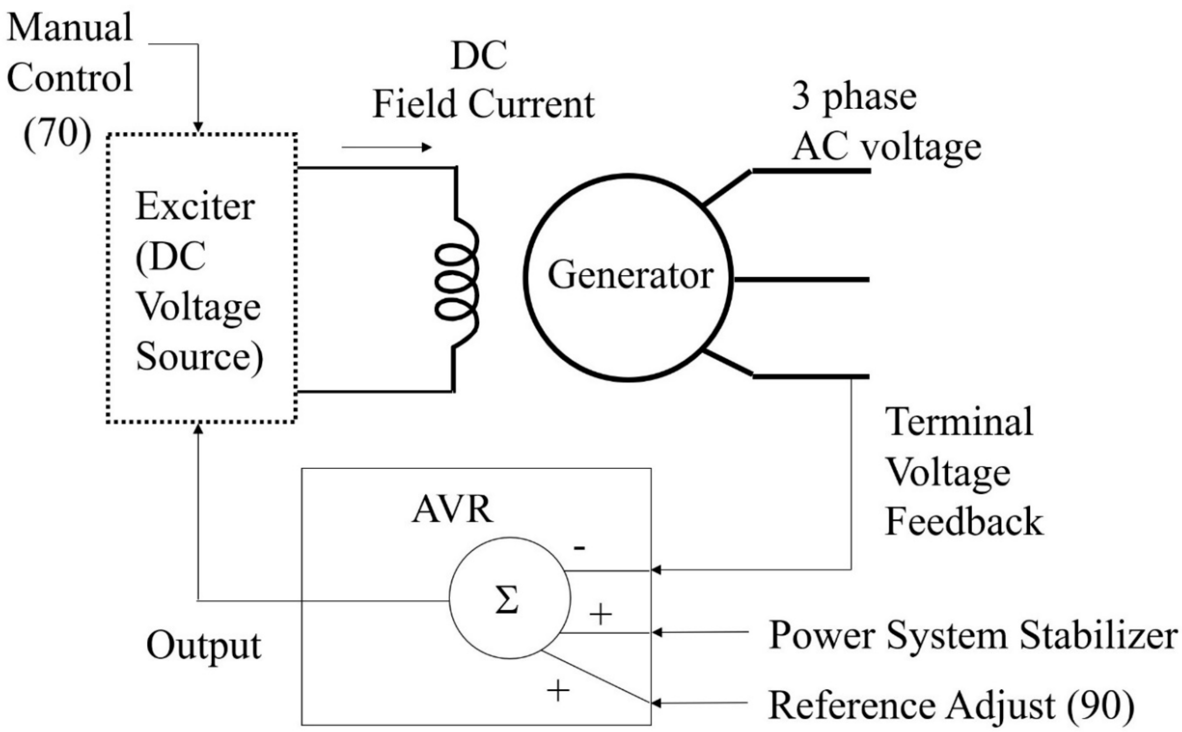


**Figure 21.—Power System Stabilizer (PSS) Added to the AVR.**

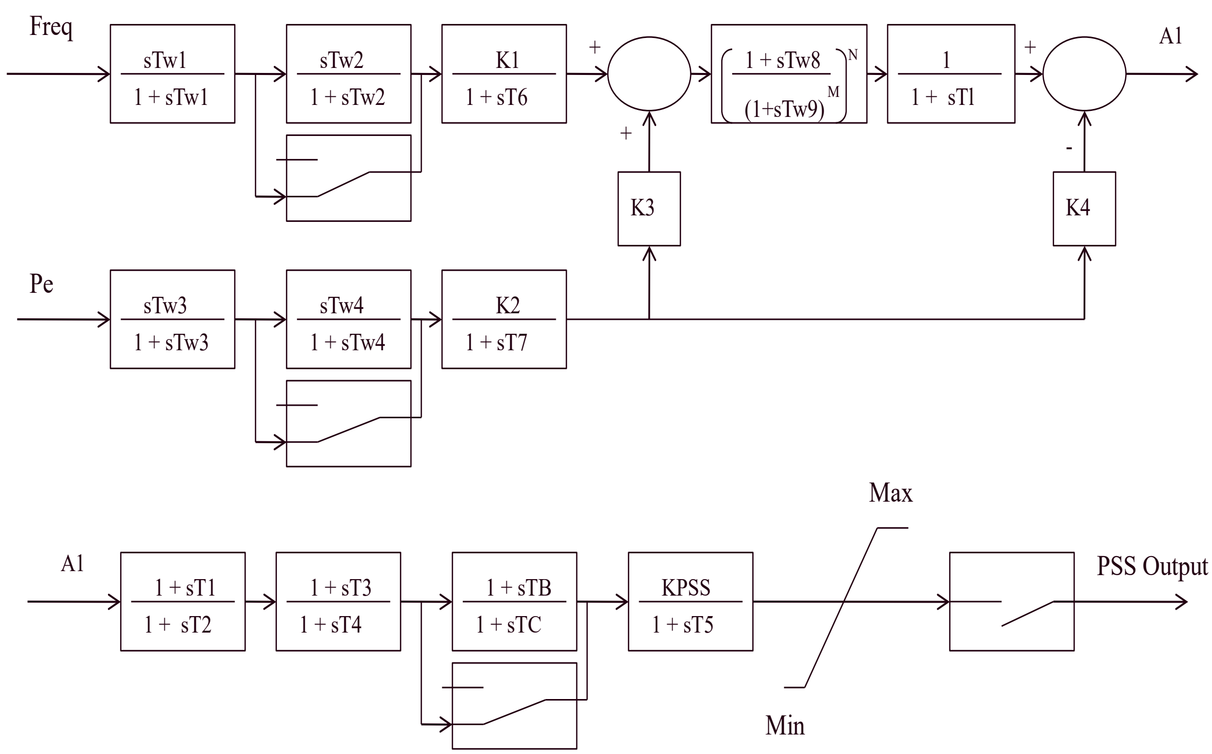


**Figure 22.—PSS Block Diagram.**

### 2.4.7 Field Temperature Monitoring

The resistance of copper rises with a temperature rise, as shown in Figure 23. Some excitation systems can calculate the field winding temperature based on field voltage and current measurements. These calculations must consider the voltage drop across collector ring brushes. Filtering may also be required to reduce noise in the output.

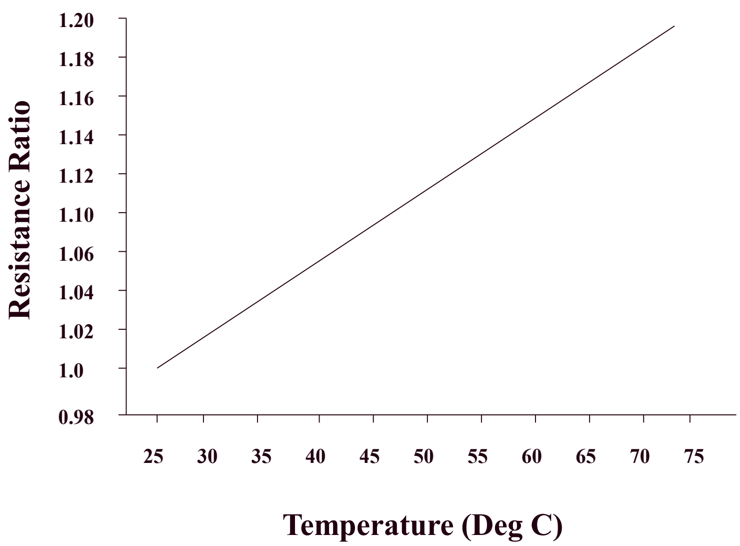


Figure 23.—Field Temperature Monitoring.

### 2.4.8 Power Source

A plant station service or a power potential transformer (PPT) can supply power to the excitation system. Unit terminals deliver power to the PPT. These power sources provide three-phase power to the SCR bridges of the excitation system.

### 2.4.9 SCR-Bridge & Field Discharge Circuit

The SCR-bridge converts a three-phase ac source into a dc source. The SCR-bridge has an input from a PPT or station service and outputs to the unit rotor field or rotating exciter field. Field Current can be isolated from the SCR-bridge using either an ac breaker on the incoming bridge power, a dc breaker on the output of the bridge, or both. The gate firing signals from either the manual regulator or the AVR control the SCR-bridge output magnitude. Figure 24 shows a simple SCR-bridge circuit.

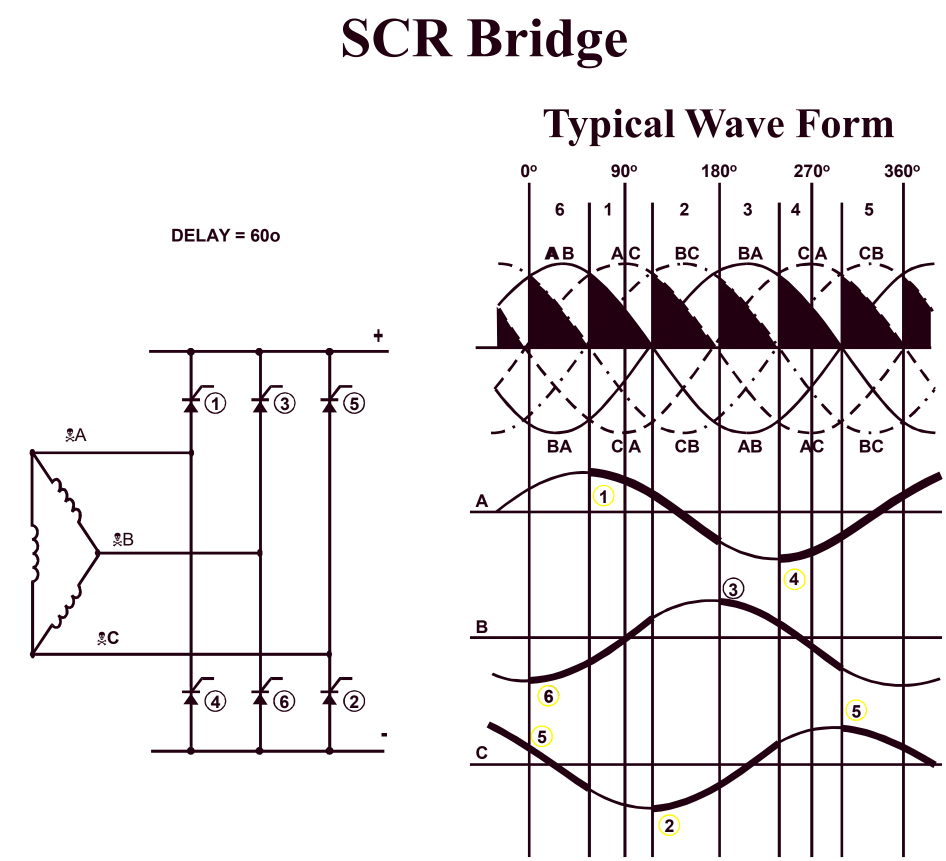


Figure 24.—SCR Bridge.

A field discharge circuit discharges the field current in the unit rotor winding or the rotating exciter field winding. Two types of field discharge circuits use an ac or dc breaker.

### 2.4.10 Field Discharge Circuit with AC Breaker

The field discharge resistor is connected in parallel with the field winding through a crowbar SCR circuit for the systems that utilize an ac breaker between the three-phase power source and the SCR bridge. This crowbar will connect a discharge resistor to the field winding during an excitation shutdown or a pole slip. During regular operation, the crowbar will disconnect the field discharge resistor. See Figure 25 for a simple crowbar circuit connection.

There should be a crowbar operation detection circuit. The crowbar circuit cannot handle continuous operation. The detection circuit should have a time delay of 20-30 seconds and then trip the unit if the current flows through the circuit beyond this time. The crowbar detection circuit is necessary to prevent a fire if the crowbar mis-operates during regular operation.

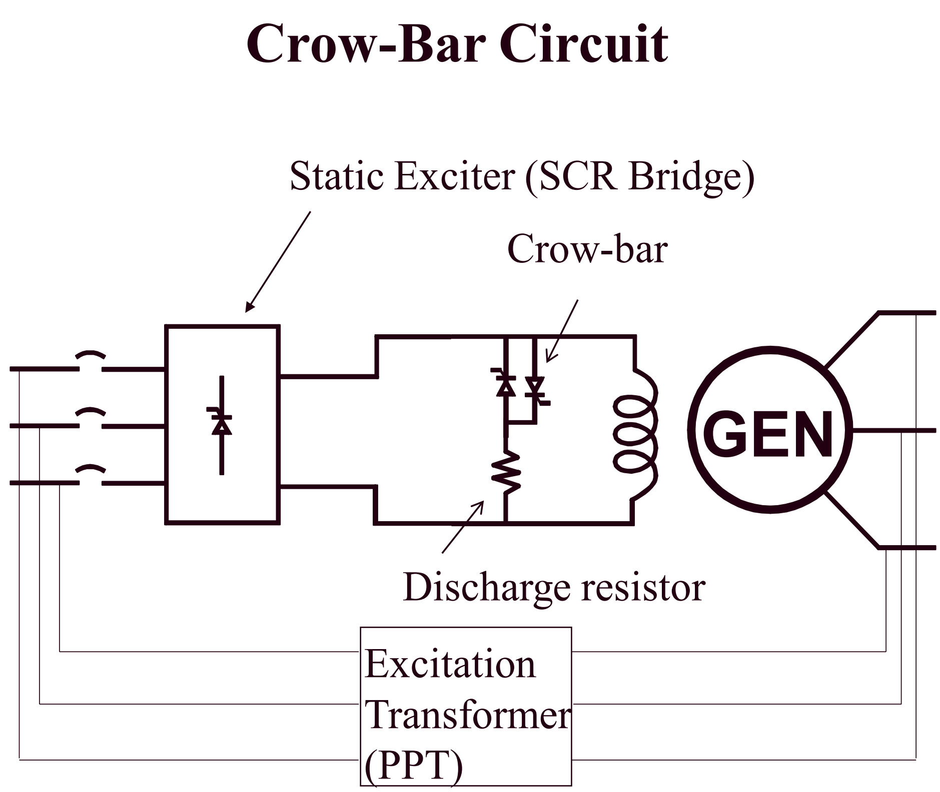


Figure 25.—Crow-Bar Circuit.

### 2.4.11 Field Discharge Circuit with DC Breaker

A dc breaker will be between the SCR bridges and the field winding. The breaker will also have an extra set of contacts that closes in a discharge resistor. The breaker contacts will open the connection of the dc field bus between the SCR bridges and the field winding and close the discharge resistor connection (parallel) with the field winding during shutdown operation. The excitation on command will close the dc field bus between the SCR bridges and the field winding and open the connection of the discharge resistor. Figure 26 shows a simple circuit of a dc breaker with a field discharge resistor. The open/close mechanism of these contacts should be make-before-break. Make-before-break means the discharge resistor contacts make up before breaking the connection with the dc bus.

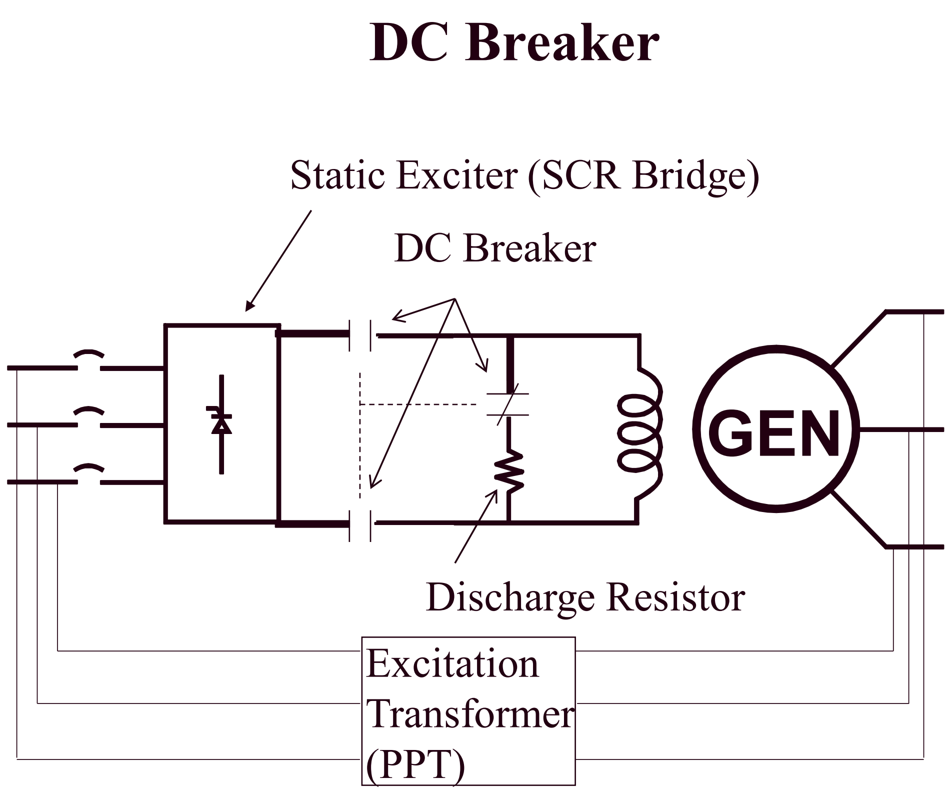


Figure 26.—DC Breaker.

### 2.4.12 Field Flashing

Field flashing is used to start up bus-fed static exciters and static pilot exciters. Polarity reversal in a rotating dc exciter can be done by Field flashing. The flashing level determination should occur during commissioning. Inadequate flashing may lead to subsequent incomplete starts, while over flashing may drop plant battery circuit below specification. Figure 27 shows a typical field flash circuit.

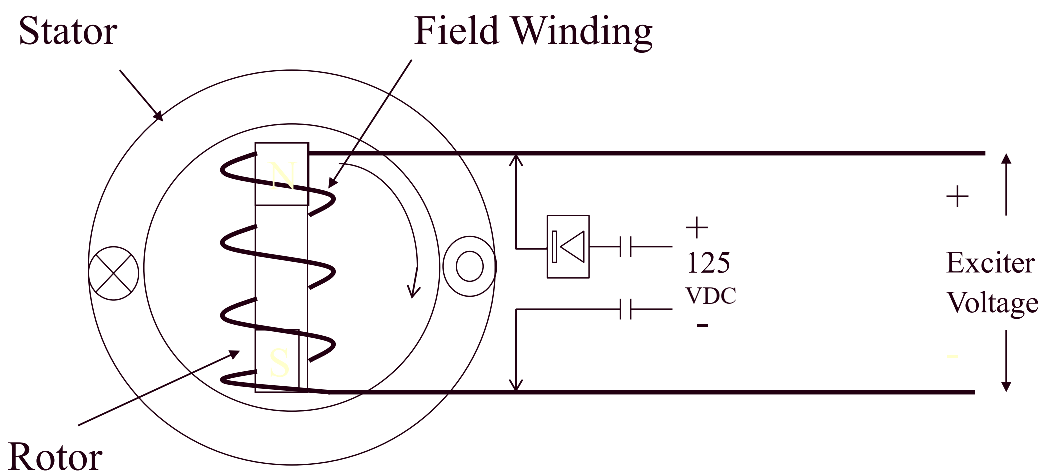


Figure 27.—Field Flash Circuit.

### 2.4.13 Start/Stop Control

The excitation start/stop control process depends on the mode the unit is operating. There are three modes of operation for a unit: local manual (LM), local auto (LA), and supervisory (S).

The speed switch closure enables the start control process in all three modes. The speed switch closes once the unit speed is above a pre-determined value, usually between 95-98 percent of the rated unit speed. If the unit speed drops below this value, with some hysteresis, the excitation turns off only while the generator breaker is open.

The excitation breaker must be closed in local manual mode before turning on the exciter. Then the excitation starting and stopping are controlled by the excitation on/off control switch. With the exciter breaker closed and the excitation switch on, the excitation will turn on when the speed switch closes.

The local auto mode automatically enables the excitation breaker and the excitation start/stop control, and the excitation will turn on with the speed switch closure.

In supervisory mode, the excitation start/stop control process is the same as in the local auto mode.

There is an inter-lock circuit to prevent the excitation turn-off once the unit is synchronized (online).

Excitation systems with a PPT require a field flashing circuit. The PPT has no power when the unit is down. The field flash process connects the station service battery to the Field winding for about 5-15 seconds. After the time delay expires, the battery is disconnected. While flashing the Field, the terminal voltage should build to about 25 percent of the rated terminal voltage. With 25 percent of the unit rated voltage, the PPT should provide enough power to the SCR bridges for the start-up process. The SCR bridges should be able to continue to build voltage with the appropriate firing signal.

Important: Disconnecting the Field flashing source too early can cause damage to the Field flashing contactor over time. It is essential to leave the Field flashing contactor closed until the field voltage has exceeded the Field flashing voltage to prevent arcing across the Field flashing contactor when opening the contactor.

The excitation will start once the SCR-bridges receive the appropriate firing signal for a system that uses the station service to provide power to the SCR bridges. Overvoltage of the generator will occur if field flashing is used in this configuration.

### 2.4.14 Operation Control

In AVR mode, with the unit off-line, the AVR will control the unit terminal voltage by changing the generator field current. Excitation raise/lower (90P) reference switch controls this process.

A rated terminal voltage of 90 percent is the lower limit on most machines. When reached, a green light illuminates to indicate that it is at the lower limit. 109-110 percent of rated terminal voltage is the upper limit. A red light comes on to show that the upper limit is active.

In AVR mode, with the unit online, the same AVR control process will change the unit terminal voltage and VARs. Raising the excitation will result in VARs flowing out of the generator (positive VARs). AVR reference, overvoltage limiter, volts/Hz limiter, and the OEL control the Upper VAR limit. Lowering the excitation will result in VARs flowing into the unit (negative VARs). AVR reference and UEL regulate the Lower Var limit.

In manual regulator mode, the manual regulator controls the generator field current with the unit off-line. The excitation raise/lower switch (70P) controls the field current setpoint. Eighty percent rated terminal voltage at rated speed is the lower limit in some systems, as indicated by the green light near 70P. A rated load field current of 105 percent is usually the upper limit, as indicated by a red light near the 70P.

With the unit off-line, exercise caution when raising the field current. The terminal voltage can exceed acceptable levels with as low as 55 percent of the rated load field current range (unless equipped with an off-line field current limiter). Regular unit operation in manual regulator mode is not allowed, except for testing.

In manual regulator mode, with the unit online, the same manual regulator control process will change the generator field current and unit VARs. Raising the excitation will result in VARs flowing out of the unit. Manual regulator reference is the only thing limiting the maximum VARs. A red light illuminates when at the upper limit. The over-excitation limiter is not active in this mode. Again, the manual regulator reference is the only thing limiting the minimum Vars. A green light illuminates when at the lower limit. The under-excitation limiter is not active in this mode.

Exercise caution when operating the field current in manual field current regulator mode. Even though the generator is online, the terminal voltage can exceed acceptable levels and easily exceed generator stator and field winding ratings. Normal operation of the unit in manual regulator mode is not allowed as most limiters are not active. The manual regulator should only be used for testing.

### 2.4.15 Operation Requirements

Current PSS tuning requirements follow the NERC/WECC standard VAR-001, VAR-002, VAR-501-WECC. Further requirements exist in the VAR NERC/WECC standards incorporated into the Reclamation Power Reliability Compliance Bulletins.

Reclamation NERC-qualifying facilities are required to report the loss of an AVR, PSS, or any other reactive power resources to the applicable Transmission Operator and document the notification to ensure compliance with NERC/WECC standards. Compliance with NERC/WECC standards includes switching the AVR into the manual mode or turning the PSS off. **{Notification must be completed within 30 minutes anytime a unit is available and online.}** After notifying the Transmission Operator, you must log the communication, date, and time in the control center logbook. Refer to FIST 1-2, Conduct of Power Operations for station log and reporting requirements.

Take the same steps as listed in the previous paragraph during testing or maintenance when changing the status of the AVR, PSS, or any other reactive power resources. Complete the reporting requirements both before and after testing or maintenance. For example, if the mode of operation will be changed several times during a shift for maintenance or test, only the initial switch operation and final switch operation need to be logged and reported.

The AVR and PSS are required to be in-service. If the AVR or PSS is out of service, place a special condition tag on the equipment, refer to FIST 1-1, Hazardous Energy Control Program for additional guidance. The unit should be taken out of service when there is a problem with the AVR or PSS.

# 3.0 Maintenance Program

## 3.1 General

Maintenance discussed assumes the following component boundaries associated with excitation equipment:

- Voltage regulator
- Rectifier banks
- DC generator and commutator
- Brush rigging
- Generator rotor field winding collection rings
- Generator shaft grounding mechanism
- Exciter coupling

The following components were evaluated and referenced to ensure the excitation system is properly maintained. Maintenance procedures are contained in separate FIST documents:

- Field breaker
- Generator field winding
- Protective Relays
- Transformers (power, current & potential)

## 3.2 Component Maintenance

### 3.2.1 Control and Power Components

#### *3.2.1.1 Operational Inspections*

Inspect the generator excitation control and power system cabinets.

1) Observe all indicating devices on the cabinet exterior.
2) Observe any visual and audible anomalies.
3) Report any anomalies found to the appropriate contact.

**[Check to ensure that the automatic voltage regulator and power system stabilizer are in the proper mode of operation.]** The AVR/PSS should be in automatic control per system design requirements.

1) If the AVR/PSS is equipped with manual control switch, a physical verification of operational mode shall be performed.
2) If the AVR/PSS is equipped with automatic control and the operator receives an alarm notification when the equipment is not functioning properly, a physical verification is not required.
3) If the AVR/PSS is found in a status other than automatic, ensure NERC/WECC reporting requirements are followed as described in section 2.4.15.

**[Infrared scan and thermal analysis.]** An infrared scan and thermal analysis of the unit excitation equipment is an effective way to assess equipment condition during operations. Due to the large variety of equipment designs, safety features, operating conditions, and facility configurations, equipment specific procedures should be developed to ensure personnel safety, consistent task performance and prevent a false sense of equipment conditions. See FIST 4-13, Thermal Analysis for additional information. The following is basic procedure to perform an infrared scan and thermal analysis.

**WARNING: Electrical shock and arc flash hazards exist when performing an infrared scan. Use Reclamation electrical safety procedures to keep personnel safe.**

**CAUTION: Failure to develop, implement equipment specific procedures, and use personnel trained and certified to analyze thermal images could result in a false sense of equipment condition.**

1) Determine thermal camera emissivity capabilities and minimum spot distanced based on camera resolution.
2) Verify the thermal camera temperature range supports maximum equipment operating temperatures. An emissivity setting of 0.95 is recommended.
3) Ensure personnel performing thermal analysis have received a minimum of Level I Thermal Analysis training.
4) Ensure thermal imaging equipment is calibrated according to manufacture recommendations.
5) Ensure thermal images are taken from the same location.
6) Perform thermal measurements while the equipment is at or near full load and stabilized.

7) Perform image analysis.
    i) Measure and record equipment temperatures for analysis and trending.
    ii) Analyze results. Refer to previous recorded images for trend analysis.
8) If abnormal conditions are found, schedule corrective maintenance to investigate and correct the condition.
9) If desired to extend maintenance outage intervals, the data captured from this task should be used to support justifications.

#### *3.2.1.2 Maintenance Inspections*

**[Inspect and clean exciter cabinets]** by performing the following.

1) General
    a) Inspect cabinet internals for dust, dirt, and conductive debris.
    b) Clean components by first using brush/and or an electrostatic free vacuum.
    c) Use clean, dry, low-pressure air not exceeding 30 psig for the final cleaning.

---

**Note:** The lists in 2)b) and 3) below may not be all inclusive and should be evaluated based on equipment designs. Incorporating inspections and components into a checklist can improve inspections and documentation. See appendix C for an example.

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2) Component specific inspections:
    a) Measure, record values, and document component inspection details to track equipment conditions.
    b) Inspect cabinet components identified in section 3) for:
        i) Signs of overheating such as bulges, burns, arc strikes.
        ii) Loose or missing fasteners.
        iii) Loose or damaged conductors, wires, and/or connections.
        iv) Nicked, cut, or damaged insulation and/or insulators.
        v) Condensation and corrosion.
        vi) Proper operation (e.g., motion, contact area or pressure, continuity, resistance).
    c) If any issues are found during inspection, schedule corrective maintenance to repair.
3) Component list:
    a) Cabinet enclosure panels, frame, hinges, mounts, and fasteners
    b) Contactors, contactor points, and arc chutes (Main and Auxiliary)

c) Relays
d) Fuses
e) Wires, Cables, Buswork, Ribbons, Fiber Optic Cables, and associated connectors
f) Grounds
g) Resistors
h) Rheostats
i) Switches
j) Push Buttons
k) Capacitors
l) Dampening Elements
m) Lights
n) Heat sinks
o) Printed Circuit Boards
p) SCR
q) Thyristors
r) Diodes
s) Rectifiers
t) Surge Suppressors
u) Human Machine Interface (HMI)
v) Heating and cooling equipment (see section 3.2.2)
w) Transducers and Meters

**[Check and calibrate exciter panel transducers and meters.]**

1) Ensure all equipment is accounted for and included in equipment job plans.
2) Inspect and calibrate in accordance with manufactures' guidance.
3) If manufacture guidance is not available, work with a technical expert to determine correct testing procedures.

**[Verify alarm and trip circuits.]**

1) Ensure all equipment is accounted for and included in equipment job plans.
2) Perform a functional test of the alarm and trip circuits, including wiring, and connections, from beginning to end to ensure integrity of the total circuit.

3) Ensure the operator receives the alarm or trip notification.
4) Document functional testing.

### 3.2.2 Heating and Cooling Components

#### *3.2.2.1 Filters*

**[Inspect excitation equipment air filters; clean or replace as necessary.]**

1) Inspect cabinet air filters for signs of visible dirt, debris, and clogging. Indications of a clogged filter are when there is an audible change in pressure when the filter is removed or shining a flashlight through the filter and observing very little light penetration.
2) If indications of a clogged filter are found.
   a) Replace disposable filter(s).
   b) Clean re-usable filter(s).
   c) Once re-usable filters are clean, inspect filter mesh for holes or signs of wear.
   d) If any holes or wear allow particles greater than original mesh size to pass through, replace filter.
3) Inspect the cabinet sealing face for dirt and debris.
4) If dirt and debris are found, clean.
5) Adjust filter inspection frequency based on environmental conditions.

#### *3.2.2.2 Heaters*

**[Check to ensure that the cabinet heaters are working properly.]**

1) Visually observe the enclosure and components for signs of moisture.
2) If moisture is present, verify the cabinet heater circuit is working by observing heat radiating from the heating element or by using thermal imaging equipment.
   a) When the ambient temperature is above the thermostat setpoint:
      i) Override the setpoint.
      ii) Verify the heater circuit works.
      iii) Return the thermostat to the setpoint after testing.
   b) If the heating circuit is not working correctly, schedule corrective maintenance to troubleshoot and repair.
   c) If heater circuit is working, adjust the thermostat setpoint to prevent condensation formation.
3) Visually observe the heaters for evidence of overheating by observing the heaters and surrounding components for signs of burning, charring, or bulging.

4) If there is evidence of overheating, schedule corrective maintenance to troubleshoot and repair.

#### *3.2.2.3 Fans*

For consistency, within this section, the word "fan" will cover both fans and blowers. While the two pieces of equipment operate slightly differently, the required maintenance is similar when used with this equipment.

**[Check the fan and motor for excessive vibration and noise. If excessive check for damaged or worn bearings.]**

1) Unmonitored
    a) During operation, check the fan and motor assembly for excessive vibration and noise.
    b) When observed, continue to monitor and schedule an inspection at the earliest convenience.
2) Monitored
    a) A fan and motor do not require a routine check for excessive vibration if monitoring equipment is installed. A monitoring system should be capable of sensing, trending, and alerting an operator of abnormal rotating machine vibration or an increase in current due to excessive friction, mass from dirt buildup on the fan blades, and loose or damaged components.
    b) If system data or a component presents a trend toward failure or otherwise indicates attention is needed, schedule corrective maintenance to correct the identified condition. Dependent on the type of monitoring equipment installed, the inspect and maintain fan assembly tasks below should be evaluated for applicability during routine maintenance.

**[Inspect and maintain fan assembly]** by performing the following:

1) Small Electronic Fans
    a) Small electronic fans require no maintenance and usually have a limited life.
        i) Track equipment run hours.
        ii) When the fan approaches the manufacture recommended life expectancy, replace the fan.
2) Large Industrial Fans
    a) Inspect the fan blades for dirt build up.
    b) Clean visible dirt.
    c) Inspect the fan for cracked, damaged, or missing blades.
    d) Inspect the fan mounting for loose or missing fasteners.
    e) Replace any missing fasteners.
    f) Tighten any loose fasteners to design torque specifications.
    g) If the fan is mounted with vibration dampening components (e.g. rubber, polyurethane), inspect for signs of cracking or deterioration.
    h) If cracking or deterioration is observed replace the components.
    i) Inspect the fan to drive motor components are in good condition and no components are loose, damaged, or missing (if applicable).
    j) Lubricate fan bearings (if applicable).
    k) When an abnormal noise or vibration exists perform basic fan maintenance.
    l) If basic fan maintenance did not identify or correct the problem, perform the following:
        i) Inspect bearings for wear or grinding noise.
        ii) If bearing wear or grinding noise is found, replace bearings.
        iii) If the abnormal vibration persists, inspect for a bent or improperly aligned shaft.
        iv) If an improper shaft alignment was found, correct the shaft alignment if adjustable.
        v) If a bent shaft is found, replace the shaft.
3) Fan Motors
    a) Measure and record insulation resistance of the motor.
    b) Measure and record motor current at each phase.
    c) Inspect Motor Frame Ground for proper installation.
    d) Lubricate motor bearings (if applicable).

4) Fan Shutter
   a) Verify proper operation of the shutter and the control circuit.
   b) Inspect for damaged or missing shutters, loose fasteners, and loose operating linkages.
   c) Lubricate shutter pivot points (if applicable).
5) Check the fan motor controller and control wiring for signs of heating, loose terminations, and contactor wear.
   a) Inspect insulating members, fuse contact points, and fuses for cleanliness, damage, and signs of overheating.
   b) Inspect main/auxiliary contactors and insulating members for cleanliness, damage, signs of overheating, contact arcing, and clean contacts.
   c) Check all wiring connections are tight.
   d) Inspect all wiring for insulation nicks, cuts, or signs of overheating damage.
6) Verify that the fan failure annunciation is functional.
   a) Simulate a fan failure and verify the following:
      i) Expected audible alarms are heard.
      ii) All applicable indicating lights are lit.

### 3.2.3 Commutator, Collector Rings, Brushes, and Brush Rigging

For consistency, within this section, the word "collector ring" will cover both commutators and collector (slip) rings. While the two pieces of equipment are slightly different in design, the required maintenance is similar. Additional information on this equipment can be found in Appendix A - .

#### *3.2.3.1 Operational Inspection*

**[Check commutator or collector ring and brush operation.]** Observe the following while the equipment is online:

1) Unmonitored
   a) Listen to the sound of the brushes against the collector rings.
      i) Quiet operation indicates properly seated brushes in with low friction between the contact surfaces.
      ii) An intermittent brush noise (e.g. squeaking) may be associated with the equipment runout pattern.
      iii) Brush squealing or chatter could indicate high friction film forming between the contact surfaces or current density differences between brushes.

b) Verify all brushes follow machine runout and are moving freely.

c) Inspect for:

i) Abnormal brush wear or carbon dust.

ii) Appearance of contact surface patina.

iii) Visible sparking.

d) If there are any indications of high film friction, abnormal brush wear or carbon dust, consult Appendix A - about equipment performance and maintenance, then determine and take corrective action.

2) Monitored

A continuously, fully monitored system does not require routine maintenance or calibration checks. If system data or a component presents a trend toward failure or otherwise indicates attention is needed, schedule corrective maintenance to correct the identified condition.

Infrared scan and thermal analysis of the commutator/collecting ring surface, brushes, and brush rigging.

The following information outlines the basic requirements to perform infrared thermal imaging on the equipment. This will allow the facility to survey and trend brushes during equipment operation. This can be used as the justification to extend maintenance outage intervals.

---

**CAUTION: Failure to develop, implement equipment specific procedures, and use personnel trained and certified to analyze thermal images could result in a false sense of equipment condition.**

---

a) Perform the unmonitored checks at the frequency defined in FIST 4-1B, Maintenance Scheduling for Electrical Equipment.

b) Determine that the backs of the brushes will be accessible to measure with your equipment. The back of all brushes may not be fully accessible, but a representative majority of brushes must be accessible to allow for equipment condition analysis.

c) If the back of the brushes (representative majority) are not accessible, this procedure cannot be used.

d) Tailor Table 1 temperatures to be equipment specific.

i) Work with the manufacturer, asset manager, and a technical expert to determine brush performance capabilities, assets operating conditions, and asset manager risk.

e) Determine thermal camera emissivity capabilities and minimum spot distance based on camera resolution.

f) Verify the thermal camera temperature range supports maximum equipment operating temperatures. An emissivity setting of 0.95 is recommended.

g) Ensure personnel performing thermal analysis have received a minimum of Level I Thermal Analysis training.

h) Ensure thermal imaging equipment is calibrated according to manufacture recommendations.

i) Perform thermal measurements:

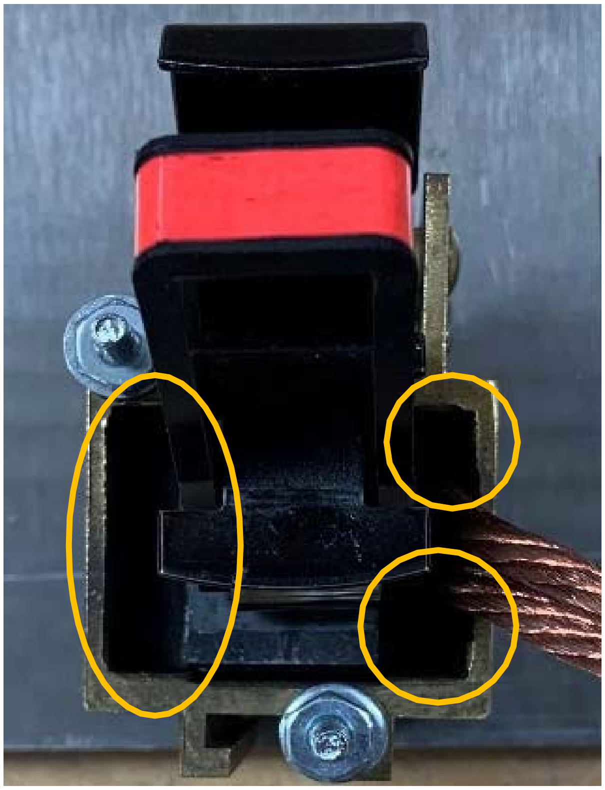
    i) Operate the camera and verify all settings are correctly set.

    ii) Access the back of the brushes for the upper polarity collector ring.

    iii) Ensure the camera is within the appropriate minimum distance (as identified above) of the brush to be measured.

    iv) Ensure the image is in focus.

    v) Take an image of the back of the brush such that the cavities formed by the back of the brush recess in the brush holder are in focus. See photograph 1.



**Photograph 1.—Brush and holder back view.**

vi) Adjust the camera to access the back of the brushes for the lower polarity collector ring.

vii) Repeat steps ii) through v) for the brush at this polarity. The measured temperature may be significantly different based on polarity.

viii) Ensure each brush polarity and image is tracked.

ix) Repeat steps ii) through vi) for the remaining brushes.

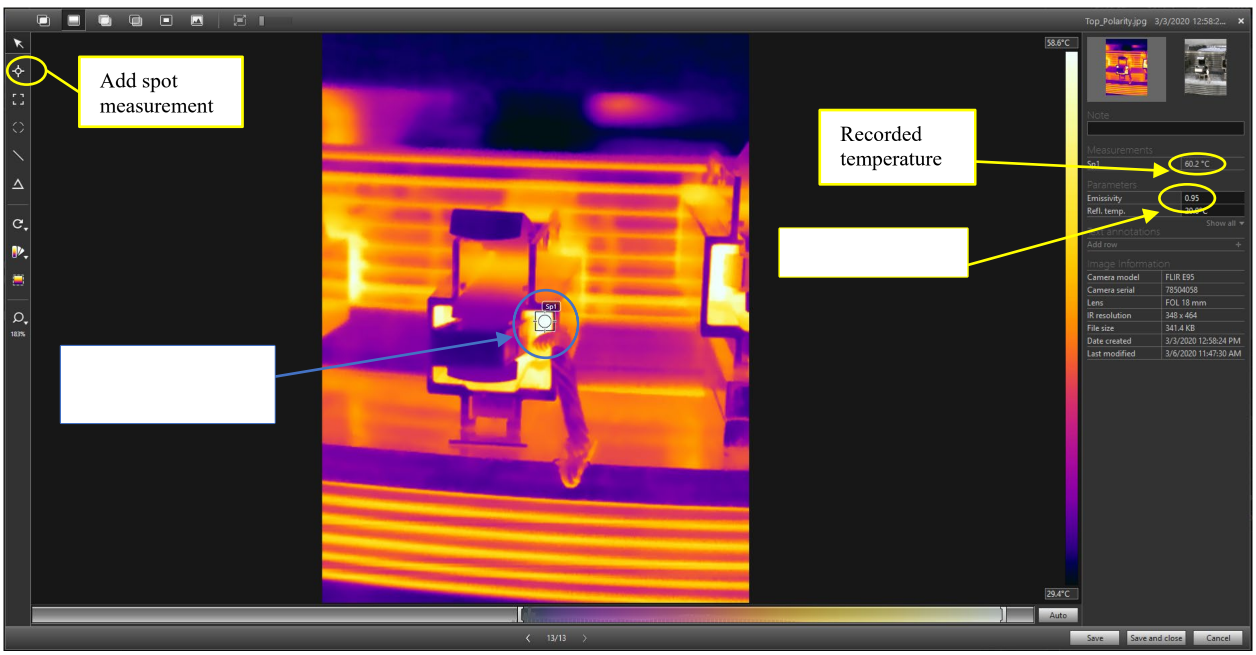
j) Image Analysis

i) Transfer image files to a device with thermal image analysis software.

ii) Select the image to be analyzed.

iii) If there is not already a spot measurement tool somewhere on the image, select the spot tool.

iv) Add a spot measurement to one of the brush cavities in the image.




**Photograph 2.—Brush and holder thermal image in an analysis software system.**

v) Document recorded brush temperature for analysis and trending.

vi) Repeat for the remaining brushes of the same polarity.

vii) Repeat for the brushes of the opposite polarity.

viii) Compare brush temperatures to table 1 and determine if corrective action is required.

Table 1.—Brush condition analysis and action

| Temperature[1] | Condition | Prescribed Action |
|---|---|---|
| < 40 °C (< 104 °F) | Cold | Brushes are running below operating temperature, continue to periodically monitor with infrared, and investigate any increase in brush dusting. Take pictures of positive and negative ring patina for trending. If low temperatures are due to low exciter load, consider changing operating regime. |
| 40 – 80 °C (104 – 176 °F) | Normal | Brushes are operating in their optimal range, indicating good contact surface film and exciter load. Continue infrared monitoring as normal to monitor for any changes in condition. Consider also taking pictures of positive and negative ring patina for trending. |
| 80 – 100 °C (176 – 212 °F) | Warm | The brushes are running above their operating temperature; routine maintenance may be necessary. Schedule an outage at the earliest convenience to perform further inspection as outlined in maintenance inspection section. |
| > 100 °C (> 212 °F) | Hot | If bulk temperatures or any one brush meets this condition, the brush(es) are running extremely hot. Take the unit offline, immediate inspection and possible corrective actions are recommended as outlined in the maintenance inspection section. |

Table Notes:

[1]Example temperatures only. End users must determine the equipment specific temperatures.

### *3.2.3.2 Maintenance Inspection*

**[Inspect, maintain, and document the condition of the commutator/collector ring surface, brushes, and brush rigging.]**

1) Check commutator or collector ring wear, note color, polish, or recondition to assure proper operation.
   a) Remove brushes from the contact surface.
   b) Visually inspect the contact surface for:
      i) Consistent color (brown to black)
      ii) Consistent surface finish
      iii) Uneven carbon build-up
      iv) Grooves and/or slots are full of carbon
      v) Chamfer deterioration (if applicable)
      vi) Evidence of electrolysis, transfer of metal, or erosion
      vii) Oil
   c) Clean the contact surface and grooves with a vacuum, soft brush, or soft cloth.
   d) If there is evidence of oil, lightly clean with a dielectric solvent.

e) When the carbon build up is inconsistent, rough, and/or heavy, and cannot be corrected during normal operation; schedule corrective action to reverse field polarity.

f) If the base metal becomes damaged, grooved, or surface finish roughness average is no longer per design tolerances, schedule corrective maintenance to recondition the surfaces to maximum brush life. See appendix A for additional guidance.

g) After any maintenance that affects the collector ring film, gradually ramp up the exciter to re-establish an optimal film.

2) Inspect brushes for freedom of movement.

a) Ensure brushes slide properly within brush-holder.

b) Ensure brushes with pivot points are free to pivot and do not bind to cause uneven wear.

c) Replace brushes that rattle or stick in place.

3) Examine brushes, check for proper contact, and burnish as needed:

a) Examine brushes for chips, cracks, wear grooves which prevent or limit free movement, and oil contamination.

b) Check wires for poor connections at the carbon interface and wire connector.

c) Inspect the wire for overheating, wear, and abrasion.

d) Replace if any of these issues are found.

e) Observe brush wear pattern.

f) Inspect brush contact surfaces carefully for pick-up of fine metal particles.

g) Inspect mating surface of brush and collector ring to ensure full contact.

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**CAUTION: Do not use an Emery type abrasive to burnish brushes. Emery type abrasive is conductive and jagged. Particles could imbed into the brush and cause rapid collector ring wear.**

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h) If the brush has fine metal pick up or is not in full contact burnish as needed.

i) Use a manufacturer suggested grit. If the information is unknown, use an 80 to 100 grit silicon garnet particle-based crocus or sandpaper.

ii) Apply full brush tension while passing the paper in the direction of prime mover rotation.

i) After burnishing, ensure brush length exceeds the minimum required length determined in step 4)c).

j) Replace the brush if the minimum brush length is not met.

4) Measure and record brush length to inspect for wear.
   a) Measure at the lowest point of the concaved surface to minimum wear point as specified by the manufacturer.
   b) Compare measured length to a new brush.
   c) Replace brushes based on historical wear data or if unknown if less than half the original length.
   d) If brushes are replaced perform step 3)h) to ensure proper contact.
   e) If brushes are replaced, document replacement.
   f) Record final as left brush length.
   g) If desired, trend brush wear rate to determine replacement interval.
5) Inspect brush rigging for loose bolts, connections, and defective springs.
   a) Clean all brush holders, supports, and insulators of all oil, dirt, grease, and carbon build up.
   b) Visually inspect brush holders for overheating, burs, cracks, or broken springs.
   c) If overheating, burs, crack, or broken springs are found, replace brush holder.
   d) Verify the brush holder is at the correct angle with respect to the collector ring surface as specified by the equipment manufacturer.
   e) If the brush holder is not at the correct angle, return the holder to the specified angle.
   f) Inspect brush holders for loose fasteners.
   g) If loose fasteners are found, tighten to design torque specification.
   h) Inspect the insulators for chips, cracks, or deterioration.
      i) Repaint any bare spots with insulating paint.
      ii) Replace cracked insulators.
   i) Inspect insulators for loose or missing fasteners.
      i) Replace any missing fasteners.
      ii) If any loose fasteners are found, tighten to design torque specification.
   j) Inspect brush rigging supports structure components are free of cracks or deterioration.
6) Measure and record brush guide spring tension.
   a) Use a calibrated dynamometer (scale) that is scaled to provide accurate measurement to the required pressure tolerances.
      i) If calibration services are not available, check calibration using known weight values.

b) Determine required spring pressures by original equipment manufacture or brush supplier recommendations.
c) Measure and record brush tension.
d) Verify pressure is within design tolerance.
e) Replace tension device if out of tolerance.

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**Note:** The following procedure assumes the equipment has the design capabilities to reverse field polarity. Reversing field polarity can prevent larger maintenance tasks such as removal and re-establishment of the film or resurfacing of the collector rings.

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Brush rigging: reverse field polarity if cathode (negative) brush wear from lack of film or anode (positive) brush wear and sparking for excess film is an issue.

1) Mark positive and negative conductors if not marked.
2) Loosen and remove conductor fasteners; capture to prevent loss into the generator rotor area.
3) Inspect conductor connector for oxidation, excessive heat discoloration, cracking, and metal fatigue damage.
4) If excessive heat discoloration, cracking, or metal fatigue is found, schedule corrective maintenance to replace the lugs.
5) If oxidation is found, clean the contact surfaces.
6) Swap conductor positions.
7) Reinstall and tighten fasteners to design torque specifications.

**[Inspect shaft suppression ground brush and associated circuitry.]**

1) Inspect the shaft suppression ground brush(es). See above for guidance.
2) Inspect shaft suppression capacitors for leaks.
3) If a capacitor has a leak, schedule corrective maintenance to replace it.
4) Inspect shaft suppression resistor for broken element or excessive burn marks.
5) If the resistor has a broken element or excessive burn marks, schedule corrective maintenance to repair.
6) Inspect shaft suppression assembly wiring and connectors for damage and deterioration.
7) Verify that the ground wire on the shaft suppressor has a good connection to ground.
8) If there is a poor connection to ground, schedule corrective maintenance to repair.

### 3.2.4 Generator Exciter Rotor, Stator, and Housing

The following section provides general guidance on maintaining rotating excitation components. Due to various equipment designs and potential equipment modifications the tasks below should be tailored to the specific equipment.

**[Clean and inspect the condition of the rotating exciter housing, stator, and rotor.]**

1) Clean dust, dirt, and debris from the rotating exciter housing.
    a) Utilize vacuums and soft brushes to ensure all accessible areas of exciter rotor, stator, and housing are free of carbon dust.
    b) If oil is present, use an Electron Dielectric Solvent to remove any buildup.
    c) Inspect air filters (if equipped). See section 3.2.2.1.
    d) Visually check for corrosion and condensation.
    e) If corrosion or condensation is found, schedule corrective maintenance to investigate and correct cause.
2) Inspect the condition of the rotating exciter stator.
    a) Check the exciter stator winding clamp connections for evidence of movement and fasteners are not loose, missing, or damaged.
        i) If paint or position markings are used, visually verify no marking misalignment
        ii) If fastener locking devices are used verify the device is not broken or loose.
    b) If any exciter stator winding clamp issues are found, schedule corrective maintenance to repair.
    c) Visually inspect the winding for loose taping, end turn lashing, mechanical damage, or damaged insulation.
    d) If insulation damage is found, schedule corrective maintenance to clean, repair, and recoat with an insulating compound that meets equipment design specifications.
    e) Visually inspect the stator conductors for the following:
        i) Signs of overheating such as bulges, burns, arcs strikes.
        ii) Loose or missing fasteners.
        iii) Loose or damaged wire and/or connections.
        iv) Nicked, cut, or damaged insulation and insulators.
    f) If any stator conductor issues are found, schedule correct maintenance to repair.

3) Inspect the condition of the rotating exciter rotor.
   a) Check exciter to generator shaft bolted connections for evidence of movement and fasteners are not loose, missing, or damaged.
      i) If paint or position markings are used, visually verify no marking misalignment
      ii) If fastener locking devices are used verify the device is not broken or loose.
   b) Check the exciter rotor winding clamping connections for evidence of movement and fasteners are not loose, missing, or damaged.
      i) If paint or position markings are used, visually verify no marking misalignment
      ii) If fastener locking devices are used verify the device is not broken or loose.
   c) Visually inspect the coil and winding for loose taping, mechanical damage, or damaged insulation.
   d) If insulation damage is found, schedule corrective maintenance to clean, repair, and recoat with an insulating compound that meets equipment design specifications.
   e) Perform maintenance on the commutator as specified in section 3.2.3.2.
   f) Spot check commutator groove depth with the following considerations:
      i) Measure and record groove depth.
      ii) Take measurements at four evenly spaced circumferential areas.
      iii) Take measurements at three axial readings at each circumferential area.
   g) Verify the commutator groove depth meets design tolerance specifications.
   h) If groove depth is out of tolerance and exciter performance is degraded, schedule corrective maintenance to restore performance.

### 3.2.5 Excitation Breaker

**[Perform excitation breaker maintenance.]** Breakers associated with the excitation system should be inspected, maintained, and tested in accordance with FIST 3-16, Maintenance of Power Circuit Breakers. Ensure breaker maintenance matches the correct equipment.

### 3.2.6 Excitation Transformer

**[Perform excitation transformer maintenance.]** Transformers associated with the excitation system should be inspected, maintained, and tested in accordance with FIST 3-30, Transformer Maintenance. Ensure transformer maintenance matches the correct equipment.

### 3.2.7 Excitation Protective Relays

**[Perform the exciter protective relays functional testing.]** Protective relays associated with the excitation system should be inspected, maintained, and tested in accordance with FIST 3-8, Operation, Maintenance, and Field Test Procedures for Protective Relays and Associated Circuits. Ensure protective relay maintenance matches the correct equipment.

## 3.3 Testing and Adjustment

### 3.3.1 Commissioning

Commissioning of the excitation system is critical to safe hydroelectric unit and Bulk Electrical System operation. Procedures for commissioning are found in FIST 4-7, Commissioning Guide for Hydroelectric Facilities.

### 3.3.2 Model Validation Testing

**{Perform Model Verification testing. Align the automatic voltage regulator (AVR) and power system stabilizer (PSS) equipment if abnormal behavior is observed or if model verification indicates that adjustments are necessary.}**

Model validation testing is required to collect the data from units to create a computer model that simulates the same responses as the actual units. Once the test data matches, the computer model will have the control and machine parameters to submit to WECC. These tests are typically done by the TSC with specialized test equipment. Below is the basic overview of the actions performed.

Typical tests that are needed for modeling:

1) Excitation control system AVR off-line step response.
2) Excitation control system AVR off-line frequency response (terminal voltage/reference test signal).
3) Generator off-line frequency response (terminal voltage/field voltage).
4) Rotating exciter frequency response (field voltage/exciter field voltage).
5) Governor off-line speed step response.
6) Unit speed vs. speed-adjust graph (only needed for unit with mechanical governor).
7) Unit V-curve.
8) Excitation control system AVR on-line step response with PSS off.
9) Excitation control system AVR on-line impulse response with PSS off.

10) Excitation control system AVR on-line frequency response (terminal voltage/reference input voltage) with PSS off.
11) Excitation control system AVR on-line step response with PSS on.
12) Excitation control system AVR on-line impulse response with PSS on.
13) Excitation control system AVR on-line frequency response (terminal voltage/reference input voltage) with PSS on.
14) Governor on-line speed step response.
15) Unit loading vs. speed-adjust graph.
16) Frequency response of the PSS leads/lags compensation.
17) **{Drive VARs to reach a limit in the leading and lagging states to verify Reactive Power capability.}**
    a) Test limiters at no load and full load.
    b) If the limiter fails to operate during testing, the operator should take action to restore excitation and generator to the operating limits.
    c) If the limiter failed to operate and cannot be corrected during testing, schedule corrective maintenance to investigate the cause and restore limiter operation.
18) Verify seamless transfer by swapping from auto to manual operation.
    a) Verify transfer from auto to manual by operating the manual control switch.
    b) For programable control systems, manually override the HMI or control logic to force a transfer from automatic to manual mode.

The TSC may require further testing and scheduling as requirements from NERC/WECC change.

### 3.3.3 Excitation Control System Realignment

Perform a realignment of the excitation control system while collecting WECC data. Tuning and adjustments may be necessary to verify proper and stable operation of the AVR, limiters, and PSS prior to final data collection. Confirm proper coordination between limiter settings and their corresponding protective relay settings. Check the AVR's range of control. Non-NERC qualifying analog systems will require more frequent realignment than their digital counterparts due to the component drift inherent in analog circuitry. Component drift occurs because of equipment vibrations and electrical component degradation over time.

### 3.3.4 Excitation Redundant Component Test

Redundant controls are evaluated and adjusted during the model validation testing, but an actual test of the equipment's ability to failover to the redundant components is not tested.

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**CAUTION: Hazard may exist with this procedure and should be properly identified.**

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**[Transfer to Redundant Controller and verify proper operations.]** Consult the component technical manual and electrical engineering for proper procedures and include these procedures in the maintenance job plan.

# 4.0 Troubleshooting

Troubleshooting the excitation system can be a challenging task and may require specialized equipment. Here is a basic guide:

1) The first step in excitation system troubleshooting is to determine the symptoms of the problem by asking the following:
   a) Are there oscillations?
   b) Did the AVR transfer to the manual or backup device?
   c) Did excitation increase or decrease?
   d) Did the unit trip?
   e) Are limiters active?
   f) Was the excitation system and components properly restored after maintenance?
2) The second step is to investigate:
   a) Bridge problems - examine the output waveform if the problem is in the power stage.
      i) Check the following:
         A) Airflow switches.
         B) Temperature switches or transducers.
         C) Blown fuse indicators.
   b) Operates manually, but not automatically - the problem is probably in the control circuits. The malfunction indicates issues with AVR electronics or interfacing control relays.
   c) Several areas to check are power supplies, firing circuits, setpoint potentiometers, feedback signals (and transducers), and supplementary input signals (from limiters and advanced controllers).
   d) Suspicious signals indicate that the board has failed.
      i) When replacing a board, the new board should have the same adjustments as the original board. Sometimes the exact settings do not produce the same performance,
      ii) Perform an excitation system realignment after any replacement operation.
   e) Relay setting overlap – protective relay settings may be incorrect or not coordinated with additional unit relay settings.

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# 5.0 Revision History

| Revision | Date | Change Summary | Reclamation Manual |
|---|---|---|---|
| 1.0 | 01/21/2026 | Major revision. Updated formatting. Provides an updated basic understanding of excitation systems. Incorporates maintenance tasks from all of Reclamations existing maintenance jobs plans. Language and terminology were aligned to support various types of equipment and improve a base template of maintenance tasks for consistency of asset maintenance across the fleet. Maintenance tasks and frequencies were evaluated to support Reclamations' Maintenance Improvement Initiative and provide flexibility for maintenance outages. | (FIST 032) Supersedes (FIST 000) |

# Appendix A - Commutator and Collector Ring Performance

Commutator and collector ring problems on hydroelectric generators are often misunderstood. This section provides basic elements to help maintenance personnel understand and better maintain commutator and collector rings. Information discussed here is only a small portion of the information available. If additional information is needed or maintenance staff encounter troubles which cannot be readily corrected, contact TSC Groups 86-68440 or 86-68450.

Good performance of both commutators and collector rings is mainly dependent upon the formation of the correct thickness of surface film, which is tough, glossy, and has low friction. Moisture absorbed from the surrounding air is an important component of the film. If the ambient air is abnormally dry the film dries, causes friction, and the rate-of-wear increases.

Heat increases the formation of oxides, which are also essential to a good low friction film. The most prevalent problem with exciters has resulted from insufficient heat because of insufficient load which has not allowed adequate film formation. Because the exciters are generously rated, the average load is only about half the nameplate rating. The manufacturer customarily equips the exciter with a good grade of electrographic brush according to the nameplate rating. These brushes may have good characteristics and excellent performance at nameplate rating or at medium to heavy load but perform poorly on light load..

**Commutator**

The following information is an approximate guide; the brush manufacturer's specific recommendations should be used.

Recognizing the design and use conditions above, it is not surprising that better performance can usually be obtained by removing half the brushes from the commutator surface. This increases the current density and temperature which aids film formation. Most electrographic brushes are recommended for current densities of 0.093 to 0.109 $A/mm^2$ (60 to 70 $A/in^2$) but will usually form a film satisfactorily for densities down to 0.062 $A/mm^2$ (40 $A/in^2$).

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**CAUTION: Do not interfere with proper brush stagger while operating a commutator with some of the brushes lifted. An equal number of positive and negative brushes must cover the same path on the commutator.**

---

It is usually easiest to avoid disturbing this stagger pattern by removing brushes toward one end of the commutator and concentrating current on the other portion. Wear can be distributed by periodically alternating portions of the commutator being used.

### Collector Rings

Unlike commutator performance, collector ring performance can seldom be improved by removing brushes. The most common trouble is excess film formation on one ring. Film is formed principally under the positive brush. The negative ring frequently shows the most wear, which is typically explained as lack of film or as transfer of metal in the direction of current flow.

Less film is required on rings, but excess film results eventually in punctured film, uneven distribution of current, sparking, roughness and rapid brush wear. While commutator brush film can be effectively managed by equalizing the brushes, similar benefits can often be achieved on collector rings by periodically reversing polarity. If the ring polarities can be changed as often as from one to three months the film can usually be maintained on both rings.

Longer intervals may serve only to distribute the roughness which develops. This type of frequent maintenance is sometimes impractical, and other types of film control can be used such as daily or weekly burnishing with canvas wiper tool, frequent use of light flexible abrasives, or occasional stoning.

It is important that collector rings be given frequent attention because, after film puncture and roughness develop, conditions are apt to become worse at an increasingly rapid rate resulting in proportionate brush wear and bridging of insulation by brush or metal which finally causes flashover. Other collector ring troubles are quite varied and must be treated as special problems.

### Humidity

The influence of humidity on brush wear is hard to identify because of the delay in appearance of its symptoms. Once a good film has formed, it will last from one to three months of inadequate humidity with no adverse results. However, if this persists, increased brush friction could wear through the film, especially if film formation is reduced by light load operation. Current density concentrates at the first bare brush areas, sparking starts, roughness develops, and once started, destruction may occur quickly.

Humidity that is extremely high or low can create brush film and wear problems. Extremely high can create excessive film and extremely low could create increased friction through lack of film. If you suspect this to be the cause of the brush wear work with the TSC or the brush manufacture to determine the corrective action.

### Canvas Wiper

To maintain a proper film, application of canvas to the rotating collector ring can be performed. This process is used to remove pollutants and excessive buildup from the film without removing the film itself. Many utilities find that routine application of canvas to the collector ring increases film and brush life. The following information serves as guidelines to make and use a canvas wiper tool for this routine film maintenance.

Build tooling (see Figure 28):

1) Obtain materials.
   a) Hardwood, rough dimensions larger than below.
   b) Hard woven canvas, clean.
   c) Rivets, sized to support final wood and cloth dimension.
   d) Linen tape, wider than rivet heads.
2) Cut hardwood to the following dimensions:
   a) Thickness: 1/4 to 3/8 inches.
   b) Width: Wider than the collecting ring face height.
   c) Length: Long enough to safely and efficiently apply the canvas wiper to the collector ring as shown in Figure 29.
3) Determine canvas dimensions based on final hardwood dimensions.
   a) Width: Wider than hardwood width
   b) Length: Allow enough for wrapping around the end of the hardwood and securing with a rivet as shown in Figure 28.
4) Cut 10 to 20 pieces of cloth.
5) Layer the 10 to 20 pieces of canvas on the end of a pliable hardwood strip as shown in Figure 28.
6) Secure the canvas in place with rivets.
7) Verify rivets are counter sunk below the canvas to prevent scoring damage to the collector ring face should personnel lose control of the wiper tool.
8) Wrap linen tape around the width of the canvas to cover the rivet heads.

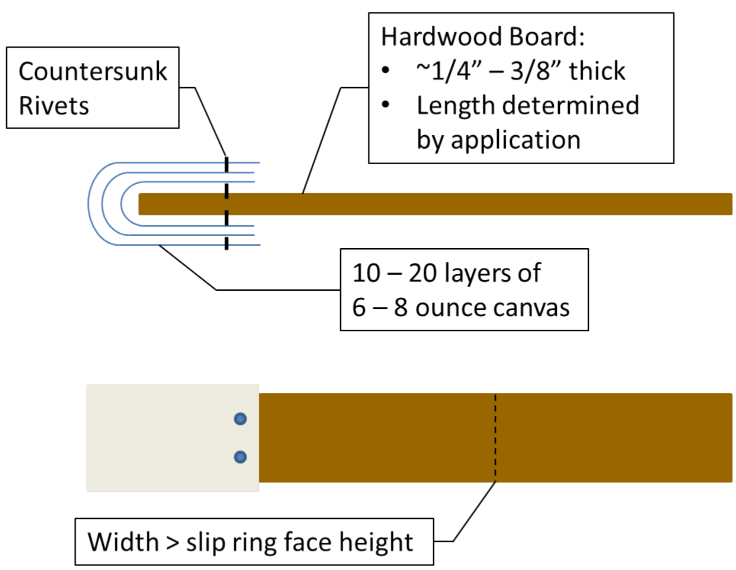



**Figure 28.—Canvas wiper.**

Use (see Figure 29):

1) The canvas wiper should be used with all the following considerations.
   a) Apply against the direction of rotation.
   b) Apply by hand with uniform pressure.
   c) Brace the leeward side of the wiper tool against a component of the brush rigging (i.e., use the brush rigging as a tool rest) for stability and safety.
   d) Maintain several layers of canvas at all times to pad the application layer and allow it to conform to the surface it is wiping.
   e) When the outer layer of canvas becomes worn or dirty, cut and remove the layer to reveal clean, unused canvas.

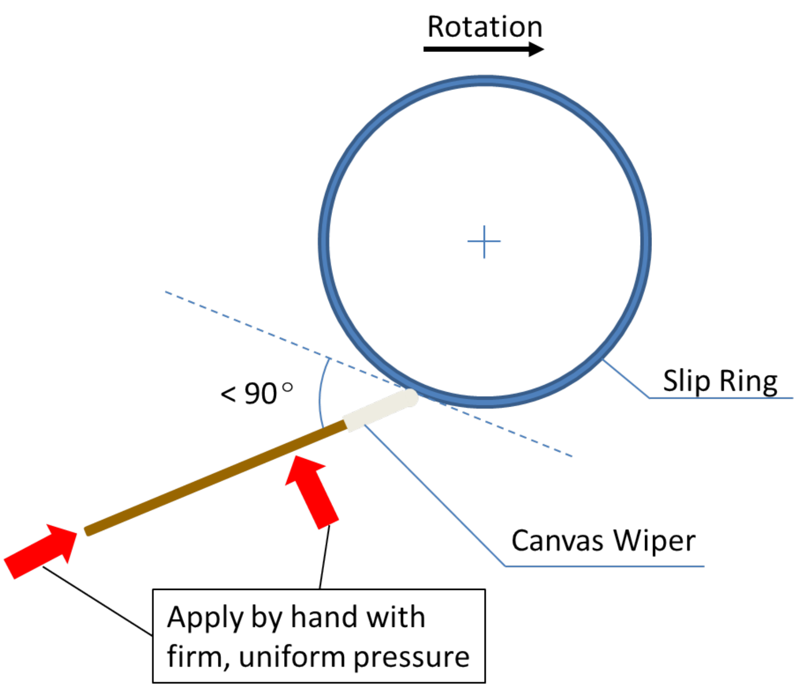



Figure 29.—Canvas wiper use.

**Stoning and Resurfacing**

If infrared monitoring is not used or routinely performed, changing conditions can often be missed. When an issue arises with enough severity as to accelerate to a critical condition before detection, resurfacing of the collector ring(s) associated with the condition may be necessary. In such a case, stoning of the collector ring should be treated as a last resort after all inspections and routine maintenance has been carried out to ensure normal operation in other aspects of the brush gear.

When stoning is necessary, hand stoning is never recommended for resurfacing. Hand stoning cannot effectively eliminate irregularities in the collector ring and increases safety risks to personnel. Moreover, hand stoning can often exacerbate flat spots on the surface of the collector ring. Stoning is therefore only recommended from properly affixed rigging that allows for precise, controlled, and constant stone contact pressure and radius from the axis of rotation. This section serves as general guidance to accomplish in-place resurfacing of the collector ring.

Incorporate a vacuum attachment at the trailing edge of the stoning contact surface to capture freed debris as it exits the abrading location.

All brushes should be pulled away from the collector ring to be stoned, as loose abrasive material can travel with the collector ring on its surface and become lodged in the brush contact surface and/or abrade the brush face, causing further issues when the machine is brought back online. Stoning must occur at specific rotational speeds for the stone in use as specified by the stone's manufacturer.

To calculate unit speed in revolutions per minute (RPM) for a known collector ring radius, use the following equation:

$$RPM=(60\ v_t)/2\pi r$$

Where r is collector ring radius in meters (m), $v_t$ is the recommended stoning speed in meters per second (m/s), and RPM is the recommended unit speed in revolutions per minute (RPM). Note that $v_t$ must always be in distance per second units and the units of r must match the distance units of $v_t$. For example, if the stone manufacturer reports the recommended stoning speed as 750 feet per minute, then this speed must first be converted into feet per second by dividing by 60 seconds (which gives 12.5 feet per second) before putting the speed in the above equation for $v_t$. In this example, the radius r must also be in units of feet.

If the recommended stoning speed (in RPM) deviates significantly from rated unit speed, personnel will need manual control over the governor to set unit speed at or near the recommended stoning speed for a given collector ring radius. If the recommended stoning speed cannot be reliably reached on the unit in question, then the stone manufacturer should be consulted to determine if the achievable speed is acceptable or if there is a stone that could be used at rated speed.

To determine the speed of the collector ring at the stoning surface (i.e. $v_t$) from a given RPM, solve the above equation for $v_t$ to get: $v_t=(RPM*2\pi r)/60$

If removing large amounts of surface material is required, start with a coarser stone and finish with the least coarse stone. Always finish with the stone manufacturer's recommended finishing stone to allow for proper surface roughness for the particular brush and collector ring material combination to ensure efficient brush seating and long-term film maintenance. For example, for a specific brush and collector ring combination, finishing with an "M" (medium grain) grade of stone to ensure a roughness of 1.3 – 2.0 micro-meters roughness average, which means the surface deviation from the mean surface level averages 1.3 – 2.0 micro-meters.

The stone and its mounting jig should follow the guidelines outlined in Figure 30.

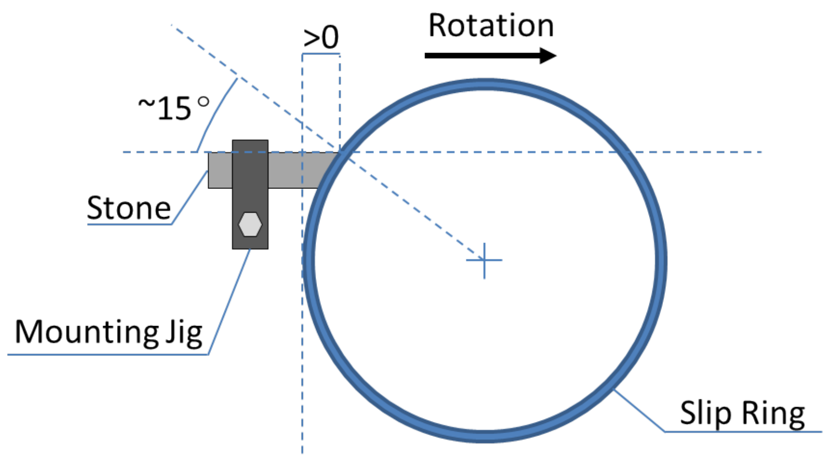



**Figure 30.—Stone and mounting jig setup.**

Proper mounting of the stone in accordance with Figure 30will prevent gouging the collector ring surface—should the stone fracture while grinding, its fragments will fall away rather than jam.

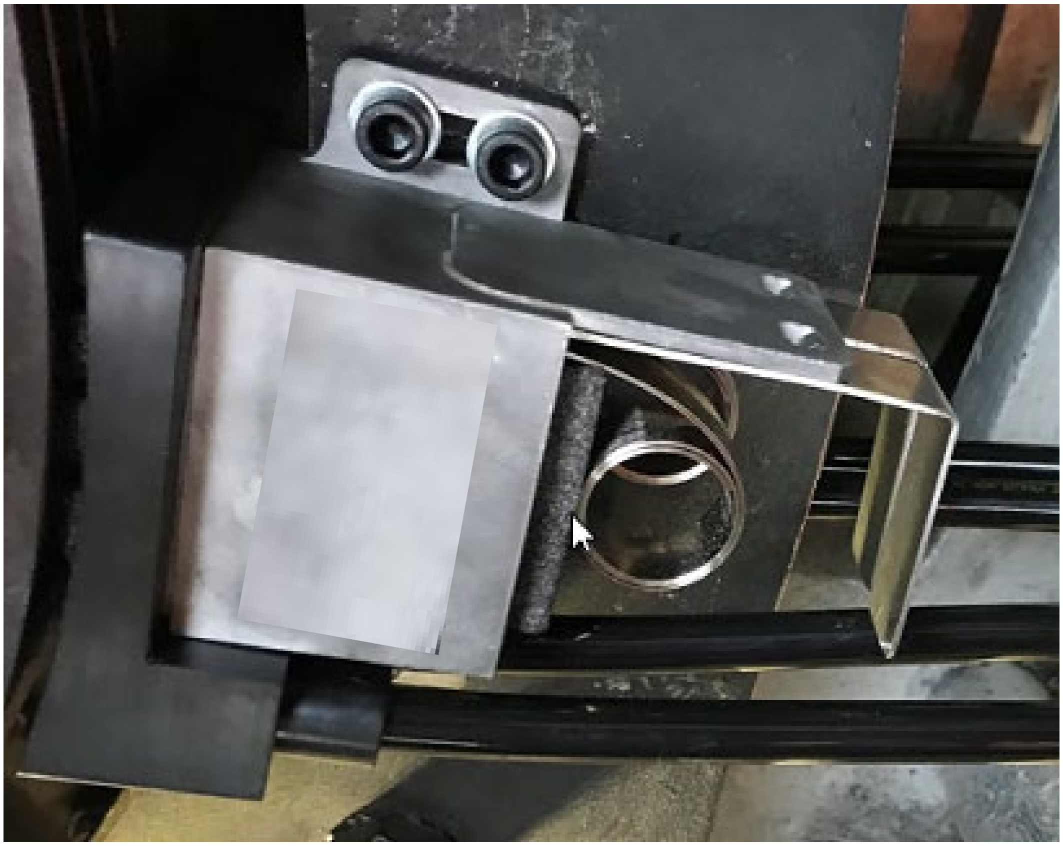
Note that there may be tradeoffs with the provided guidelines in Figure 30. For example, a stoning jig may not incorporate the 15-degree offset to more easily provide a uniform stoning surface and pressure. Such tradeoffs should be investigated and any decision to incorporate or ignore these guidelines provided during design and construction of a stoning jig should be weighed against all perceivable risks (e.g. the need for uniform stoning surface and pressure versus the risk of a stone breaking and gouging the surface).

Maintain sufficient stone in-feed pressure to ensure good grinding. Never attempt to speed up the grinding process by increasing the stone's contact pressure. Too much pressure could set up vibration in the stone or cause the stone to fracture, which could cause irreparable damage to the collector ring surface.

If the collector ring's face is wider than the stone face, axial travel will be necessary in the stone mounting jig. In such a case, axial travel parallel to the rotation axis must be ensured such that stone contact pressure does not vary as a function of axial travel.

Large diameter collector rings are typically designed and installed with a small amount of intentional runout. This intentional runout can be as much as 0.040 inches and serves to move each brush radially within its holder once per revolution. This radial brush action prevents the brushes and their spring mechanisms from sticking in place. For this reason, large diameter collector rings should not be stoned from a radially fixed location, as doing so would remove this intentional runout.

To prevent removal of radial runout in the collector ring, any stoning jig design should be axially and circumferentially fixed, while allowing for small radial movement in the stone as it follows the collector ring's intentional runout while applying relatively constant stoning pressure. An example of these stoning jigs is shown in the photo below. This jig has a spring to help maintain the correct pressure and integral vacuum tubes to help collect grinding debris.



**Photograph 3.—Collector ring spring fed stoning jig and integral vacuum assembly.**

# Appendix B - Characterizing the Damping of Time-Domain Waveforms

This section is a reference to aid those well versed in control systems.

It is easy to characterize the damping of time-domain waveforms if one assumes that a second order system produced the response. The following methods make this assumption. If multiple roots are present in the existing system, errors will result. The size of the errors depends on the influence of the other sources. Many times, these errors are negligible, but sometimes they are not. As in many engineering problems, exercise judgment when evaluating the results.

**How to Use the Damping Curves**

1. Find the magnitude of the change from the previous zero crossing for any two peaks.
2. Determine the ratio of these magnitudes (smaller value over larger).
3. Use the damping curves (Figure 31 and Figure 32) to find the value of ξ, the intersection of the ratio with the number of cycles between chosen peaks.
4. Measure the cycle duration (period) using peak-to-peak or zero crossing-to-zero crossings.
5. Calculate the resonant frequency ωr, the natural frequency ωn, and the attenuation σ.

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

Plot σ and ωr on the s-plane.

**How to Find the Values Without Using Curves**

Find the magnitude of the change from the previous zero crossing for any two peaks.
Determine the ratio of these magnitudes (more significant value over more minor).
Find the natural logarithm of the ratio.
To find σ, divide this value by the time elapsed between the chosen peaks.
Measure the duration of the cycle (period) using peak-to-peak or zero crossing-to-zero crossings.
Calculate the resonant frequency ωr, the natural frequency ωn, and the damping ratio ξ.

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

Plot σ and $\omega_r$ on the s-plane.

## Symbols

$\xi$ = damping ratio
$\omega_n$ = natural frequency
$\omega_r$ = resonant frequency, frequency of oscillation; imaginary part of complex pole
$\sigma$ = attenuation, time constant of decay; real part of complex pole
s = LaPlace operator

## Characteristic Equation

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

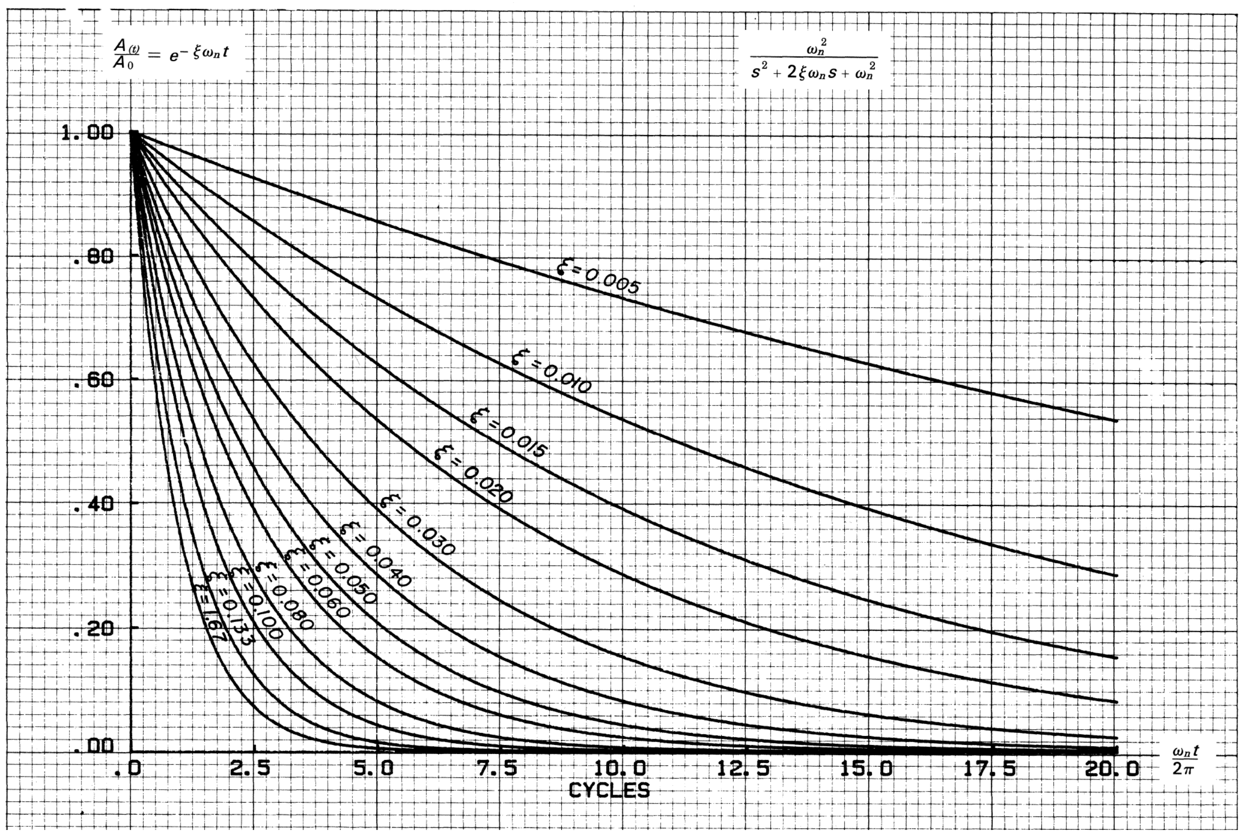



Figure 31.—Decrement of oscillation as a function of damping factor.

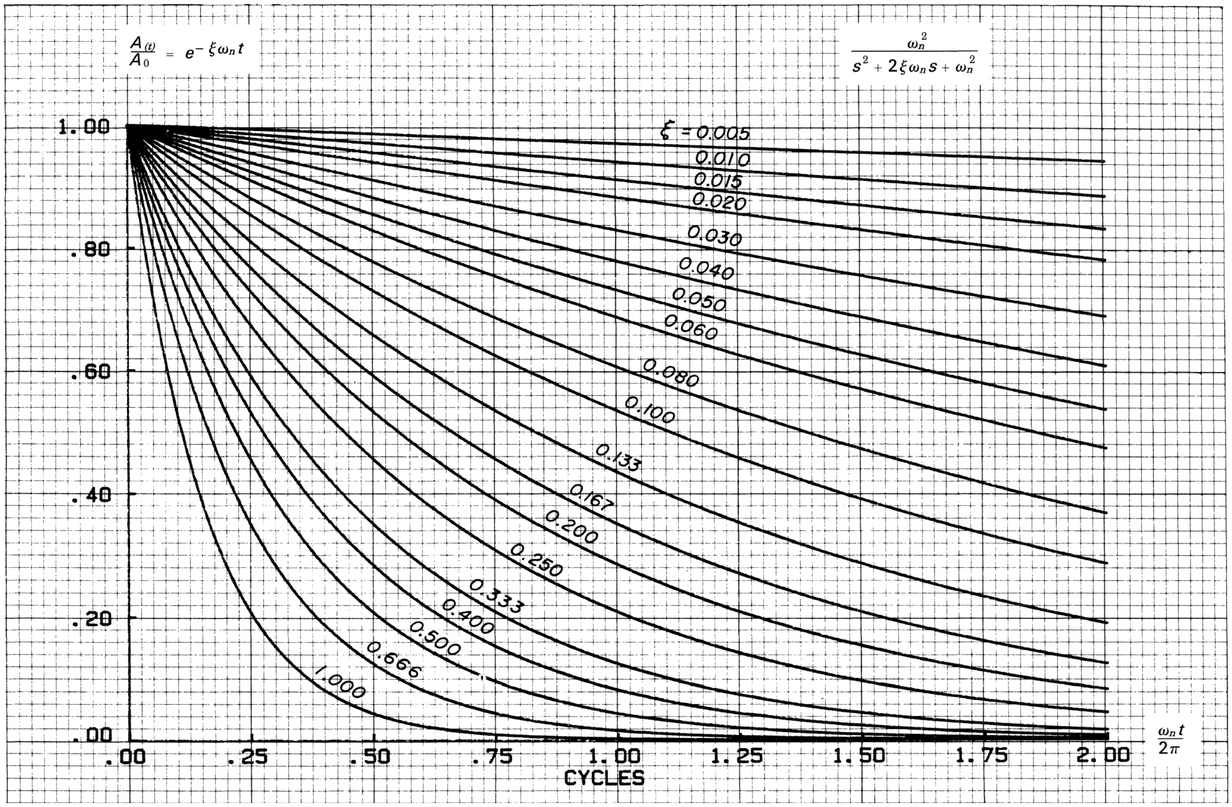



Figure 32.—Decrement of oscillation as a function of damping factor.

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# Appendix C - Excitation Controller Inspection Form Example

| Component | Inspection (place a check mark in each box after inspection) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Signs of overheating such as bulges, burns, arcs strikes | Loose or missing fasteners | Loose or damaged wire and/or connections | Nicked, cut, or damaged insulation and/or insulators | Condensation and/or corrosion | Proper operation | Measured values and notes |
| Cabinet enclosure: | - | - | - | - | - | - | |
| panels | | | | | | | |
| frame | | | | | | | |
| mounts | | | | | | | |
| fasteners | | | | | | | |
| Heater | | | | | | | |
| Cooling Fan | | | | | | | |
| Contactor XX: | - | - | - | - | - | - | |
| Main | | | | | | | |
| Aux | | | | | | | |
| Points | | | | | | | |
| Relay XX | | | | | | | |
| Fuses | | | | | | | |
| Wires | | | | | | | |
| Cables | | | | | | | |
| Ribbons | | | | | | | |
| Fiber Optic Cables | | | | | | | |
| Grounds | | | | | | | |
| Resistors | | | | | | | |
| Rheostats | | | | | | | |

| | Inspection (place a check mark in each box after inspection) | | | | | | |
|---|---|---|---|---|---|---|---|
| **Component** | Signs of overheating such as bulges, burns, arcs strikes | Loose or missing fasteners | Loose or damaged wire and/or connections | Nicked, cut, or damaged insulation and/or insulators | Condensation and/or corrosion | Proper operation | Measured values and notes |
| Switches | | | | | | | |
| Push Buttons | | | | | | | |
| Capacitors | | | | | | | |
| Dampening Elements | | | | | | | |
| Lights | | | | | | | |
| Heat sinks | | | | | | | |
| Printed Circuit Boards | | | | | | | |
| SCR | | | | | | | |
| Thyristors | | | | | | | |
| Diodes | | | | | | | |
| Rectifiers | | | | | | | |
| Surge Suppressors | | | | | | | |
| HMI | | | | | | | |
| Transducer XX | | | | | | | |
| Meters XX | | | | | | | |