

IEEE Guide for Operation and Maintenance of Hydro-Generators

Sponsor
**Rotating Machinery Committee
of the
IEEE Power Engineering Society**

Approved 28 January 1999
Reaffirmed 31 March 2011

IEEE-SA Standards Board

Approved 12 May 1999
Reaffirmed 16 April 2012

American National Standards Institute

Abstract: General recommendations for the operation, loading, and maintenance of synchronous hydro-generators and generator/motors are covered. This guide does not apply to synchronous machines having cylindrical rotors. In this guide, the term hydro-generator is used to describe a synchronous machine coupled to a hydraulic turbine or pump-turbine. This guide is not intended to apply in any way to the prime mover.

Keywords: generator, generator/motor, horizontal hydro-generator, hydro-generator, loading, maintenance, operation, pumped-storage system, synchronous hydro-generator, vertical hydro-generator

The Institute of Electrical and Electronics Engineers, Inc.
345 East 47th Street, New York, NY 10017-2394, USA

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Print: ISBN 0-7381-1535-5

PDF: ISBN 0-7381-1536-3

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Introduction

(This introduction is not part of IEEE Std 492-1999, IEEE Guide for Operation and Maintenance of Hydro-Generators.)

This guide was prepared to set forth operating experience and maintenance practices that have been used successfully over a period of years by several major operators of hydro-electrical equipment. Accompanying the operating and maintenance background has been the input of manufacturers of large electrical equipment, resulting in a combination of experience factors and design philosophy that will provide users with information to guide them in understanding the limits of the equipment and methods that may be employed to reduce downtime to a minimum.

The development of this guide was begun in early 1969, when it was felt that a document similar to IEEE Std 67-1972, IEEE Guide for Operation and Maintenance of Turbine Generators (ANSI C50.30-1972), should be available to operators of hydro-electric equipment. Such a document was considered to be of particular value to organizations normally involved only with turbine-generators, but who had entered the hydro-electric field to meet the increasing energy of peaking needs. To this end, the guide contains some sections devoted to pumped-storage applications. A substantial revision toward the current document was begun in 1987. It is considered desirable that this guide be updated and that the pumped-storage sections be expanded as future needs dictate. Comments are invited on this guide as well as suggestions for additional material that should be included.

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IEEE Guide for Operation and Maintenance of Hydro-Generators

1. Overview

1.1 Scope

1.1.1 Application

This guide covers general recommendations for the operation, loading, and maintenance of synchronous hydro-generators and generator/motors. It does not apply to synchronous machines having cylindrical rotors. In this guide, the term hydro-generator is used to describe a synchronous machine coupled to a hydraulic turbine or pump-turbine. This guide is not intended to apply in any way to the prime mover.

1.1.2 Manufacturer's instructions

This guide is not intended to supplant specific or general instructions contained in the manufacturer's instruction book or in any contractual agreement between the manufacturer and the purchaser of a given machine.

1.1.3 Limitations due to various designs

Equipment manufacturers have taken different approaches to the solution of design requirements; therefore, it is not practical to relate specifically in this guide to all the variations of machine design. However, many of the operational and maintenance procedures and problems are common to all the designs and, therefore, recommendations are given concerning solutions to these procedures and problems. The most that this document can accomplish is to provide guidelines, which, on one hand, disclose accepted and tried values or methods, and on the other hand, give warnings where hazards might be encountered.

1.1.4 Exciters

This guide does not cover in detail associated rotating or stationary excitation systems.

1.2 Caution

1.2.1 Load conditions beyond design rating

It should be recognized that conditions more severe than those specified by the nameplate, instruction book, or any contractual agreement between the manufacturer and the purchaser should not be applied to the machine. If there is a need to exceed the specified conditions, it should be done only after a thorough study of the various considerations pertinent to the specific condition and also the capabilities of the machine and associated equipment. It is recommended that the situation be discussed with the manufacturer of the machine.

1.2.2 Reference publications

Many IEEE and ANSI standards are referenced in this guide. The standards referenced in this revision are those in effect when this guide was approved. Users are cautioned to carefully review the history of older machines with respect to IEEE and ANSI standards in effect at the time the particular generator was manufactured. Older machines may not operate satisfactorily to the requirements of modern standards with regard to temperature rise, overload capability, abnormal operating conditions, etc.

2. References

The following standards were used as references in preparing this guide and apply to the machines described in it. When any of the IEEE standards referred to in this guide are superseded by an approved version, the revision shall apply.

ANSI C50.10-1990, Rotating Electrical Machinery—Synchronous Machines.¹

ANSI C50.12-1982 (Reaff 1989), Requirements for Salient Pole Synchronous Generators and Generator/Motors for Hydraulic Turbine Applications.

IEEE Std 1-1986 (Reaff 1992), IEEE Standard General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation.²

IEEE Std 43-1974 (Reaff 1991), IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery.

IEEE Std 56-1977 (Reaff 1991), IEEE Guide for Insulation Maintenance for Large Alternating-Current Rotating Machinery (10 000 kVA and Larger).

IEEE Std 95-1977 (Reaff 1991), IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage.

IEEE Std 99-1980 (Reaff 1992), IEEE Recommended Practice for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electric Equipment.

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.

¹ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://www.standards.ieee.org/>).

IEEE Std 113-1985 (Withdrawn), IEEE Guide: Test Procedures for Direct Current Machines.³

IEEE Std 115-1995, IEEE Guide: Test Procedures for Synchronous Machines.

IEEE Std 119-1974 (Withdrawn), IEEE Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus.⁴

IEEE Std 286-1975 (Withdrawn), IEEE Recommended Practice for Measurement of Power-Factor Tip-Up of Rotating Machinery Stator Coil Insulation.⁵

IEEE Std 421.1-1986 (Reaff 1996), IEEE Standard Definitions for Excitation Systems for Synchronous Machines.

IEEE Std 522-1992, IEEE Guide for Testing Turn-to-Turn Insulation on Form-Wound Stator Coils for Alternating-Current Rotating Electric Machines.

IEEE Std 1147-1991 (Reaff 1996), IEEE Guide for the Rehabilitation of Hydroelectric Power Plants.

3. Manufacturer's and user's responsibility

3.1 Intended use

A thorough interchange of design requirements should exist between the user and the manufacturer. The user should clearly specify, in addition to the usual nameplate data and machine characteristics, the planned operating modes of the generator in as much detail as possible. Based on industry standards and sound design and operating practice, this information will establish the nameplate rating, temperature limits, and capability curves. The manufacturer is responsible for understanding the requirements and producing a machine to perform as required.

3.2 Operating range

Some discussions in this guide involve operation under conditions not covered by nameplate or specification conditions. The purpose of a generator nameplate is to identify the machine with respect to manufacturer and to indicate basic rating as fixed by the purchaser's specification. The temperatures stated on the nameplate are in accordance with applicable industry standards or purchaser's specifications, or both. It should not be assumed that the generator is capable of safe operation up to these temperature levels. The range of safe operation is defined by the generator capability curves. It is important for users to understand and train operators to be familiar with generator capability curves and other characteristics so that safe operating conditions (conducive to long life of the equipment) are maintained.

³IEEE Std 113-1985, IEEE Std 119-1974, and IEEE Std 286-1975 have been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181 (global.ihs.com/).

⁴See Footnote 3.

⁵See Footnote 3.

4. Types of units

4.1 General

This guide applies primarily to vertical hydro-generators, but most of the recommended practices also apply to horizontal hydro-generators. Nearly all of the material concerning hydro-generators will apply also to generator/motors used in pumped-storage systems. A discussion of the operation of generator/motors and a review of the various methods used to start these machines can be found in 7.10.

4.2 Mechanical classifications

Vertical hydro-generators are classified mechanically by the position of the thrust bearing with respect to the rotor. The following categories are covered by this guide:

- a) *Suspended.* The thrust bearing is located above the rotor and there may be one or two guide bearings, one of which is always above the rotor.
- b) *Umbrella.* The thrust bearing is located below the rotor and one guide bearing is located in close proximity to the thrust bearing.
- c) *Modified umbrella.* The thrust bearing is located below the rotor and there are two guide bearings, one above and one below the rotor.

4.3 Cooling classifications

Hydro-generators are also classified by the cooling method used for the rotor and stator. The categories described in 4.3.1 and 4.3.2 are covered by this guide.

4.3.1 Indirectly-cooled types

Indirectly-cooled generators are those in which the heat generated within the windings must flow through the ground insulation before reaching the cooling medium. Cooling air is circulated through passages in the generators by either of the following methods:

- a) *Self-ventilated generator.* A self-ventilated generator has cooling air circulated by means integral within the machine.
- b) *Separately-ventilated generator.* A separately-ventilated generator has cooling air circulated by an independent fan or blower system external to the machine rotor and stator.

Most indirectly-cooled generators over 10 MVA and built since 1930 are totally enclosed. The enclosure allows the internal cooling air to be circulated in a closed loop through the generator and thence through air-to-water heat exchangers located within the enclosure where the heat created by the generator losses is removed from the air before it returns to the machine.

4.3.2 Directly-cooled types

Directly-cooled generators are those in which the coolant for the windings flows in close contact with the conductors so that the heat generated within the windings is transferred directly to the coolant without passing through the ground insulation. Directly-cooled generators are totally enclosed. Internal air will be circulated to cool the rotor winding (if it is not directly cooled) and perhaps the stator core in a manner similar to indirectly-cooled machines.

4.3.2.1 Directly-cooled stators

Directly-cooled stator coils (bars) normally have de-ionized water coolant flowing within hollow strands of the conductor. The heat generated within the conductor flows in either of the following two ways:

- a) Directly into the cooling water flowing within the hollow strands.
- b) Through thin layers of strand insulation to the hollow strands carrying the water coolant if some solid strands are interspersed between the hollow strands in the coil.

Other winding parts, such as connectors between the coils (bars), parallel rings, main leads, and neutral leads, may or may not be directly cooled by water.

4.3.2.2 Directly-cooled rotors

Directly-cooled rotors normally have de-ionized water coolant fed through manifold piping and down the rotor shaft to radial pipes that connect to coil inlet water boxes. The water coolant then flows axially through hollow field coil conductors or tubing nested in the field coils. The water coolant exits by way of connections to outlet piping at the rotor shaft. A water distributor with seals is necessary to transfer cooling water from the stationary piping to the rotating shaft.

5. Basis of rating

5.1 General considerations

5.1.1 Rating parameters

Hydro-generators are generally rated on a continuous-duty basis with the net output expressed in kilovolt-amperes (kVA) available at the terminals at a rated speed, frequency, voltage, and power factor. For rated output, the service conditions specified for the machine must be observed. The usual service conditions are specified in ANSI C50.10-1990,⁶ including the temperature of the cooling air which shall be between 10 °C and 40 °C. Special generator capabilities and service conditions may have been specified at the time of manufacture. This information is usually found in the instruction book or can be obtained from the manufacturer or the purchase specification.

The generalized standard for hydro-generators is ANSI C50.12-1982. The previous issue of this standard, ANSI C50.12-1965, allowed a dual rating based on a 60 °C temperature rise at the nominal rating and an above 60 °C rise at 115% of the nominal rating. The latest issue recognizes a single maximum rating only at specified temperature rises that are dependent on the voltage rating and class of insulation of the windings.

The generator nameplate or instruction book should always be consulted to ascertain the allowable temperature rise for which the generator in question has been designed. In any case where major rehabilitation is considered or where the basis of rating (including overspeeds and thrusts) may change, refer to IEEE Std 1147-1991.

5.1.2 Loading within capabilities

It is generally recognized that the actual load capability of a hydraulic turbine or the load conditions may not match the nameplate of the generator. When other than rated load and service conditions exist, operation

⁶Information on references can be found in Clause 2.

within the manufacturer's capability curve will maintain temperatures, mechanical stresses, and electrical parameters within design limits.

5.2 Mechanical stress limits

5.2.1 Coupling, shaft, rotor spider

These parts are usually designed for maximum specified generator kVA at unity power factor, or maximum specified turbine horsepower and hydraulic thrust. They should also be coordinated in design and mechanical load-carrying capability with the turbine shaft.

The design stress limits allow for adequate safety margins to take care of stress concentrations and dynamic loading during short circuits or temporary hydraulic disturbances. However, if loading above the design power output are possible, the gate limits on the turbine should be set so that excessive mechanical overloads are prevented.

If during operation unusual vibrations at some fixed frequency or load condition should develop, the cause and effect should be investigated. This is especially true where there are two or more large rotational inertias on a given shaft as switching or fault transients can overstress shaft system elements or excite torsional natural frequencies.

The first critical speed of the turbine-generator rotating system (the shafts, turbine runner, generator rotor, exciter rotor, and the associated bearings and supports) is usually designed to be above the maximum turbine overspeed or runaway speed (whichever is greater), and thus outside any operating speed.

5.2.2 Rotor rim

Rotor rims are designed to have a margin of safety at the maximum specified turbine overspeed. Thus, at rated load and speed, the rim stress and expansion are quite moderate. However, since the rim stress and expansion increase with the square of the speed, even partial overspeeds during load rejections can cause relatively large values of rim stress and expansion. The design margins are such that the occasional partial overspeeds are of no consequence. If in addition to overspeed, additional acceleration forces are present due to unbalanced magnetic pull or vibration, some movement or misalignment of the original rim stack with reference to the spider may occur with a resultant balance shift. Furthermore, if the rim mounting is inadequate to return the rim to center at normal speed, vibration levels may increase. Inspections of rim and associated parts and air gap are recommended especially after an increase of vibration or after a noncontrolled overspeed.

5.2.3 Rotor poles

Rotor poles and windings are designed to have a margin of safety at the maximum specified turbine overspeed. The stress levels at rated speed are then relatively low but increase quickly with speed. In general, poles and pole windings should be visually inspected after abnormally high rotational speed transients for any evidence of deformation. Electrical testing should be carried out in any case of doubt.

5.2.4 Bearings and bearing brackets

The majority of hydro-generators have vertical shafts and are usually equipped with a segmental, shoe-type thrust bearing and one or two guide bearings. Horizontal shaft units may be similarly equipped.

Thrust bearings are designed to carry maximum specified hydraulic thrust and the weight of rotating parts of the turbine and generator. They are also capable of operating at maximum specified overspeed for a specified length of time without damage. Usually there is a requirement that the oil quantities and bearing design must

be adequate to operate without cooling water for a limited time period. The successful operation of bearings is dependent on a supply of clean cooling water in specified quantities and at temperatures not exceeding the temperature specified for that bearing design.

Thrust bearing brackets are designed for the total steady-state hydraulic thrust and weight of rotating parts with the deflection limited to a certain value. Due to this deflection limitation, stresses in the bracket are usually low. If, however, high transient thrust conditions or vibration forces are present during operation, the bracket and its component parts should be investigated for load capability, elevation setting, deflection, and possible resonance.

5.2.5 Stator frames

Stator frames and soleplates are designed for maximum short-circuit capability, and the tangential stresses at rated load are thus quite low. However, should a three-phase, two-phase, or single-phase short circuit occur, or if the machine is synchronized more than 30° out-of-phase, the machine and its foundation should be inspected for possible damage. Loosening of the torque dowels or keys at the soleplates may allow the stator to shift horizontally and thus unbalance the air gap, resulting in increased unbalanced magnetic pull in the offset direction. It is necessary for large diameter stators to move radially on the soleplates with temperature changes to minimize stator core buckling, and foundation and structural stresses. The dowels or keys therefore should be in such condition as to allow this expansion but not allow circumferential or lateral motion.

5.3 Temperature rise

The observable temperature rise of a machine component is defined as the difference between the maximum observable temperature of the component and the average temperature of the cold coolant (air in indirectly-cooled machines or water in directly-cooled machines).

ANSI C50.12-1982, Clause 5 and Tables 1 and 2 specify the limiting observable temperature rises, which must not be exceeded when the generator is operating at or below nameplate rating. (Note that these temperature rises do not necessarily apply to machines designed prior to 1982.) These standards should not be construed as specifying allowable temperature rises without regard to machine rating. Thus, if the observable temperature rise of a generator is below the standard value at rated load, it does not mean that the generator load can be increased above the capability curve until the limiting temperature rise listed in the standard is reached. Refer to 7.7.4 for operational monitoring for directly-cooled machines.

5.4 Temperature limits

5.4.1 Insulation and temperature

The stator and field windings, stator core, stator and field leads, and generator bearings are subject to thermal aging or effects of differential expansion, or both. Therefore, the maximum temperature rise limits for most of these parts have been established.

The stator and field winding insulation system classes are defined in Clause 6 of ANSI C50.10-1990. IEEE Std 1-1986 discusses the general principles upon which the insulation system temperature limits are based.

5.4.2 Hot-spot temperature

For normal life expectancy, generator loading should be so controlled that the hot-spot temperatures of the machine windings do not exceed the limiting temperatures of the insulation systems. In most cases, the hot-spot temperatures cannot be measured directly and therefore realistic additions must be made to the maximum observable temperatures in order to estimate the hot-spot temperature. The generator manufacturer

should be consulted to establish the relationship between the observable temperature and the hot-spot temperature.

5.4.3 Thermal aging

The thermal aging of insulation systems and generator parts is a function of the hot-spot temperature and the duration of that temperature. See 7.1.3.1 for an expanded discussion of this subject.

5.5 Methods of temperature measurement

The commonly used methods for determining temperatures in each portion of the machine with some general limitations are described in 5.5.1 through 5.5.6.

5.5.1 Limitations in the methods of measuring temperatures

It should be recognized that there are limitations in the methods of measuring temperatures. Therefore, to minimize error and to ensure safe operation of large generators, the reliability and accuracy of temperature indicating, recording, and computing devices are of paramount importance.

Whereas the instruments themselves might be calibrated and accurate, problems may arise from the long distance, bad connections, and stray fields between the sensing element [thermometer bulb, resistance-type detector (RTD), or thermocouple] and the indicating or recording devices.

When acceptance tests are run on a new machine, there is usually a good opportunity to compare panel instrument readings with those from laboratory instruments used for testing. Any significant differences should be investigated and inaccuracies should be corrected.

Most of the common problems and sources of error are discussed in IEEE Std 119-1974 and in 6.4 through 6.9 of IEEE Std 115-1995.

5.5.2 Ambient temperatures

In accordance with 5.2 of ANSI C50.12-1982, the temperature of the ambient cooling air for open ventilated machines is the average temperature of the external air entering the ventilating openings of the machine.

For totally enclosed water-air-cooled machines, the temperature of the cooling air is the average temperature of the air leaving the coolers.

Alcohol or mercury thermometers, thermocouples, or RTDs are generally used to measure cooling air temperature for acceptance testing. For operational monitoring of air temperature, thermocouples, RTDs, or filled system thermometers are most commonly used.

In large machines with several ventilating openings or coolers, the ambient air temperature usually varies with the location. The mean value of these temperatures is used as the basis for temperature rise calculations and the indicator reading closest to the mean value should be used for operational monitoring. (See 6.6 of IEEE Std 115-1995, and Clause 7 of IEEE Std 119-1974.)

5.5.3 Stator winding

5.5.3.1 Indirectly-cooled stator windings

For conventional air-cooled machines, embedded RTDs between the upper and lower coil sides (Figure 1) are recommended and are most commonly used to measure stator winding temperature.

The description, size, and location of RTDs is given in Clause 5 of ANSI C50.10-1990. While RTDs are preferred, since they indicate the mean temperature of the coils over a length of several core packs, the use of thermocouple-type detectors is also recognized as an acceptable practice.

The accuracy of the temperature readings is limited by various factors. For indirectly-cooled machines the detector is separated from the copper by the insulating wall of the coil (Figure 1) and therefore will always indicate lower temperatures than the hot spot of the copper. The difference between the hot-spot temperature and the sensor temperature is a function of the insulation wall thickness, proportions of the slot, the amount of heat to be conducted through the insulation, and several other factors.

These factors have been taken into account in the design of the machine per ANSI C50.12-1982 to ensure that the actual hot-spot temperature does not exceed the limiting temperature of the stator insulation class. If the observable temperature rise of the detector is lower than the guaranteed value, it does not mean that a margin for overloading exists.

The use of radiation-type temperature sensing equipment can sometimes be used as a diagnostic tool for initial survey of the unit and for future maintenance for detecting hot individual coils, coil connections, and circuit rings.

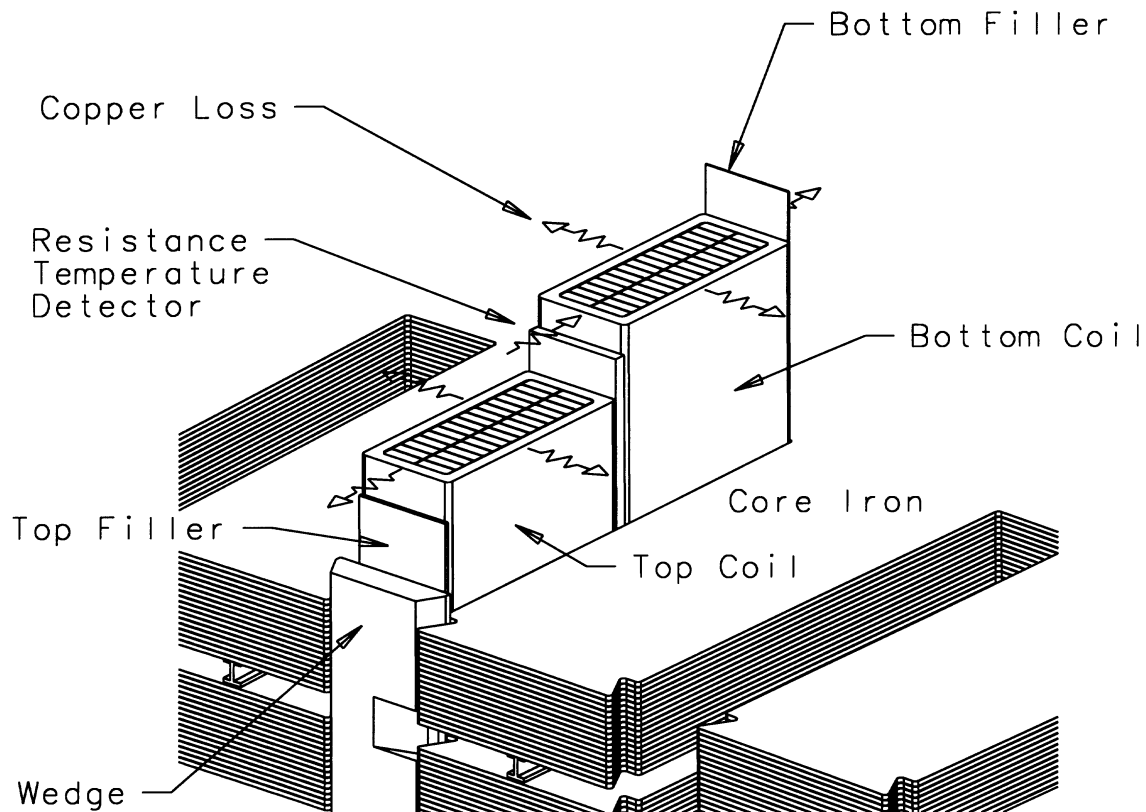


Figure 1—Heat flow and typical temperature detector location

5.5.3.2 Directly-cooled stator windings

In the case of directly-cooled units, the coolant enters one end of a stator coil at a low temperature, passes through one or more coils, and discharges at a higher temperature, thus causing the copper to have a similar temperature pattern. In this case, the embedded detectors may indicate either higher or lower than the

temperature of the insulated copper of the winding, depending upon their location within the winding and the relative temperature of the teeth and core at that point. Thus their value is to serve as a means of detecting unexpected temperature changes, which usually signal the beginning of trouble.

The difference in temperature between stator winding strands and the coolant is a consistent function of load, permitting the temperature of the warm discharge coolant to serve as a dependable means of determining the hot-spot temperature by use of appropriate curves or calculations. Measurement of the warm discharge coolant temperature is, therefore, generally employed in preference to the use of detectors embedded between coils in the slot. Either an RTD or a thermocouple-type temperature detector is commonly used. For liquid-cooled windings these coolant temperature detectors are mounted at the ground potential end of the insulating hoses at the warm coolant discharge.

The temperature difference between the discharge coolant and the hot spot varies widely for different machines. This difference depends on the coolant liquid, winding construction, and design practice, and may be specified for a given design as a function of load.

5.5.4 Stator core

For stator cores the thermometer or detector method of measurement is specified in ANSI C50.12-1982, Clause 5, Table 1. The thermometer is defined in 5.1.1 of ANSI C50.10-1990 and 6.4.2 of IEEE Std 115-1995. Stator core temperatures can also be monitored using noncontact thermal imaging devices.

Usually the stator core temperatures are measured during acceptance testing by applying an alcohol thermometer or a thermocouple at the back of the core. Sometimes a thermocouple (occasionally an RTD, which requires much more space) has been embedded permanently in the tooth or yoke portion of the core during stacking operations. In this case, continuous monitoring of the core temperature is feasible. An embedded thermocouple will generally indicate a higher temperature than a surface-mounted detector. It is difficult in advance to know where the core hot spot will occur but if the unit is operating above rated voltage or at low power factor (either overexcited or underexcited) it can be useful to observe the core temperature to avoid overheating of the coil insulation surface.

Measurement of the maximum stator core temperatures with an embedded detector may be limited since it is very difficult to make provisions for mounting of the detector and to know in advance which part of the core will have the maximum temperature. The stator coil temperature is usually more critical from the operating point of view than the core. Stator bore surface damage or slot iron damage may create local warm or hot conditions, but it is unlikely to be detected by local temperature instruments unless they have been specifically installed in damaged areas.

5.5.5 Rotor windings

5.5.5.1 Field windings

The resistance method (as defined in 5.1.2 of ANSI C50.10-1990 and 6.4.4 and 3.3 of IEEE Std 115-1995) is used for acceptance testing and operational monitoring of field winding temperature. It should be recognized that this method measures the average temperature of the field winding and not the hot-spot temperature.

In order to determine the field temperature accurately with the resistance method, it is important to measure the voltage drop across collector rings accurately without including the voltage drop of the brushes supplying the field current. For acceptance testing, this is usually accomplished with insulated brushes that do not carry any field current and do not have an established surface film with significant voltage drop.

For operational monitoring, the insulated brushes do not always work consistently due to rapid film buildup. In this case, elimination of the insulated brush plus practical methods of brush drop compensation are as follows:

- a) Provide a bias voltage equal to the brush drop (about 3 V).
- b) Calibrate the temperature indicating device for a value of field winding resistance plus the equivalent resistance of the brush voltage drop at full-load field current.

Both of these methods generally have adequate accuracy for day-to-day operation and may be calibrated to be accurate near full-load conditions.

Hot-spot temperatures are seldom important except on some wire-wound field coils on small machines or on some encapsulated coils where a special allowance can be made.

On water-cooled field windings the manufacturer's method of temperature determination and cooling must be followed.

5.5.5.2 Amortisseur windings

The amortisseur windings in the pole faces are generally designed to thermally withstand negative sequence current transients with an equivalent $I_2^2 t$ equal to or less than 40 (see Clause 6 of ANSI C50.12-1982) and a continuous I_2 of either 5% or 10%. If temperature measurement of the amortisseur bars and connection rings is necessary for some special operating condition, this might be adequately accomplished with special tests by using a series of temperature-sensitive paints. The range and interval of these paints should be chosen to correspond to the expected temperatures. The maximum design temperatures for amortisseur windings are established by the manufacturer with regard to the duty cycle and mechanical stresses involved and could be in the order of 300 °C. Thus the temperature-sensitive paints could be chosen with approximately 25 °C intervals and still have adequate accuracy for the purpose. Harmonic load currents will also affect amortisseur temperatures. Noncontact thermal imaging sensors can be used to monitor amortisseur temperatures.

5.5.6 Collector rings

The thermometer method after shutdown (see 6.8 of IEEE Std 115-1995) is used to determine the collector ring temperature. If this is done at various field current loadings then a curve of collector ring temperature versus field current can be established as an operating guide. Infrared or optical temperature measuring instruments, or temperature-sensitive paints may also be useful in determining collector ring temperatures. Total temperature should be maintained within the class of insulating materials used.

6. Loading

6.1 Relation of load and temperature rise—Stator and field

The hydro-generator nameplate and capability curves define the limits of operation for which the machine has been designed.

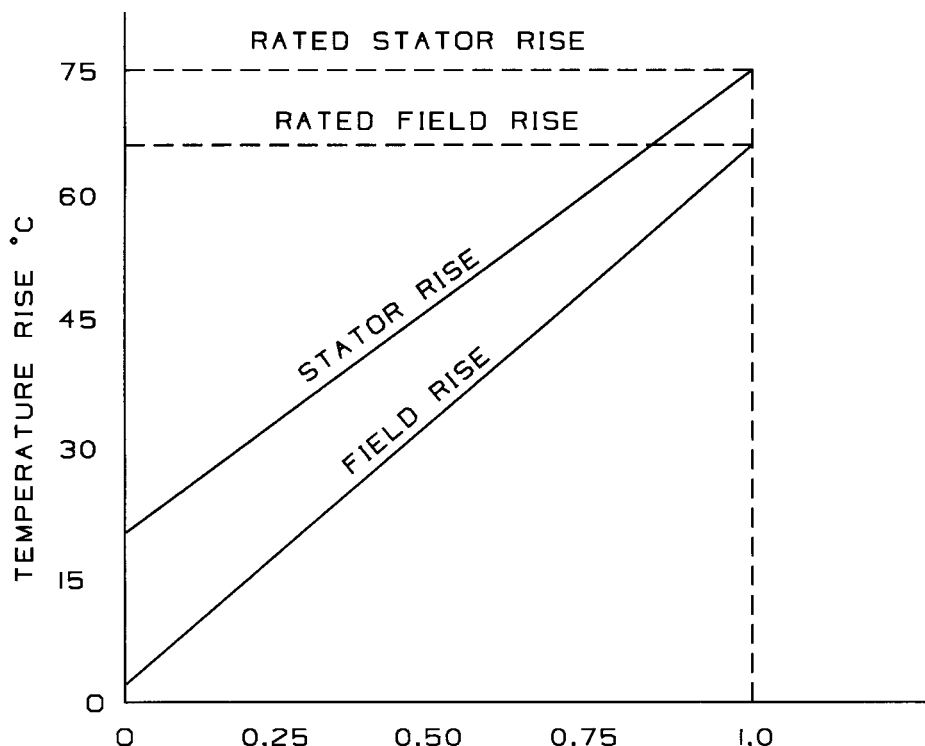
6.1.1 Lower than specified temperatures

When operating within the above-defined condition of electrical output and cooling medium, many machines will operate below the guaranteed temperature rises that are stated on the nameplate. The reason for this is that the observable temperature rise alone does not constitute the only basis for the design of a generator. Other factors that influence design include hot-spot temperature (as discussed in 5.4.2, 5.4.3,

5.5.3.1, 5.5.3.2, and 5.5.5.1), strength of metals and insulating materials, magnitudes of forces due to thermal expansion and vibration, margins for safety, reliability, load cycling, and design prediction accuracy. Thus in a balanced design, the temperature rise of stator and field winding at rated load might be below the guaranteed value in order to ensure reasonable life expectancy and trouble-free operation.

6.1.2 Temperature versus load

If heat runs have been performed on a generator at several load points (preferably three) of stator and field current at rated voltage, then the observed temperature rises can be plotted as functions of stator and field current. The rise is roughly a function of the current squared as shown in Figure 2, and provides a convenient operating guide to estimate the temperature rises and total temperatures for various load and coolant conditions. It may also serve as a guide for any change in machine condition. See IEEE Std 115-1995.



NOTE: Values along the abscissa correspond to $\left(\frac{\text{field current}}{\text{rated field current}} \right)^2$
or to $\left(\frac{\text{stator current}}{\text{rated stator current}} \right)^2$

Figure 2—Typical temperature rise vs. stator and field current squared

6.1.3 Temperature and variation

Ideal loadings from the standpoint of maximum life expectancy for the generator insulation system are those that result in minimum temperature variations of the winding or core at the lowest recommended temperature level.

6.1.4 Temperature control using cooling water

For varying load conditions on totally enclosed, indirectly-cooled machines, temperature control can be partially achieved by adjusting cooling water flow to regulate the cold air temperature. This should be adjusted seasonally to minimize average winding temperature. During operation, the cooler discharge air should not exceed 40 °C nor fall below 10 °C. Low flow adjustments should be made cautiously to avoid stopping flows in some tubes with resultant expansion problems for the tubes.

In the case of extremely low cooling water temperature, it may be necessary to throttle the water flow to avoid excessive condensation at the coolers. Excessive condensation will only occur if there is a water leak in the piping, foundation, or coolers, or if a small to moderate amount of fresh moist air is continuously admitted to the machine enclosure with the dew point above the cooling water temperature. Throttling the water will only help if the fresh air into the housing has a dew point below the water temperature in the coolers and there are no water leaks.

6.1.5 Temperature control using air flow

Open machines usually do not have means of controlling the inlet air temperature. For machines that have control dampers and means of recirculation of air, the discussion in 6.1.4 applies. It may be necessary to throttle the cooling air flow, if dampers are provided, to avoid extremely low inlet air temperatures or condensation.

6.1.6 Temperature control for directly-cooled machines

For machines having directly-cooled stator windings, the maximum outlet temperature of the coolant must be controlled so as to be kept below its boiling point at high loads and above the dew point of the cooling air at low loads and low coolant temperatures. Temperature controls should be adjusted to minimize thermal cycling of copper strands within the ground insulation of the winding.

6.2 Generator characteristic curves

Generator characteristic curves define the relationship between kVA output, field current, stator current, and terminal voltage. They are useful in determining the required load setting to avoid overloading beyond the rating of the machine. Typical curves are shown in Figures 3 through 5.

The saturation curve (Figure 3) gives the relationship of terminal voltage, stator current, and field current. Load characteristic (Vee) curves (Figure 4) indicate the ac line current as a function of field current for various power factors at rated voltage. The capability curve (Figure 5) indicates the envelope of maximum output limit on loading in terms of power in kilowatts and reactive power in kilovars at rated voltage with other limitations for various regions of operation.

6.3 Loading—Active and reactive power relationship

In a system with several generators in parallel, the principal effect of a change in excitation on one generator will be to vary the amount of reactive current supplied or absorbed by that machine. Increasing the excitation will make a generator supply more overexcited reactive power, and decreasing the excitation will cause it to supply less reactive power or absorb it.

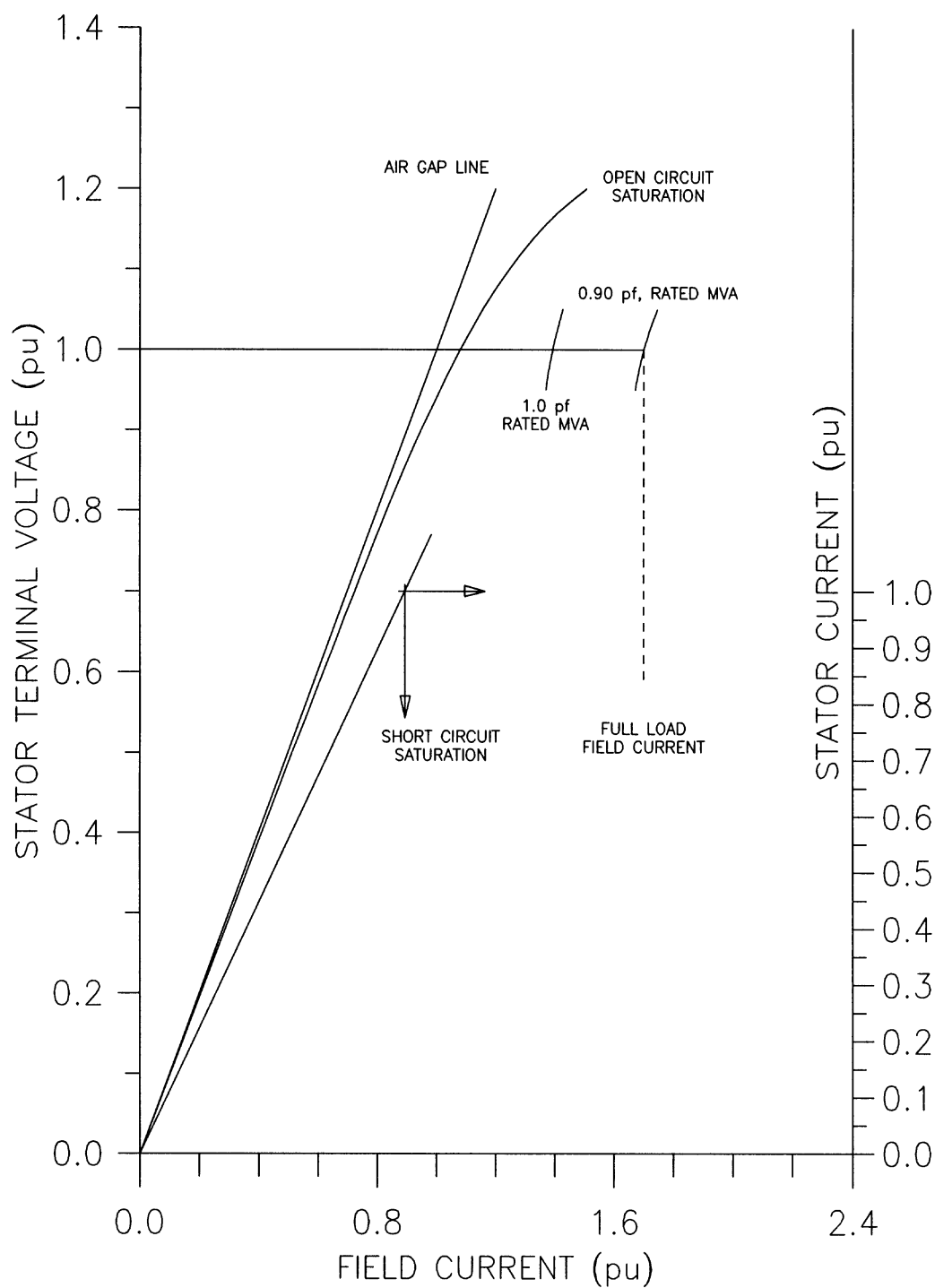


Figure 3—Typical hydro-generator saturation curves

6.3.1 Field current

Typical load characteristic curves related to power factor are shown in Figure 4. These are useful in analyzing the relationship between field current or stator current, kVA, and power factor. As can be seen from this figure, when a generator is operated at lower than rated power factor overexcited, the field current required is higher than that required for rated load, the field winding will operate at a higher temperature, and the current may exceed the capability of the excitation system.

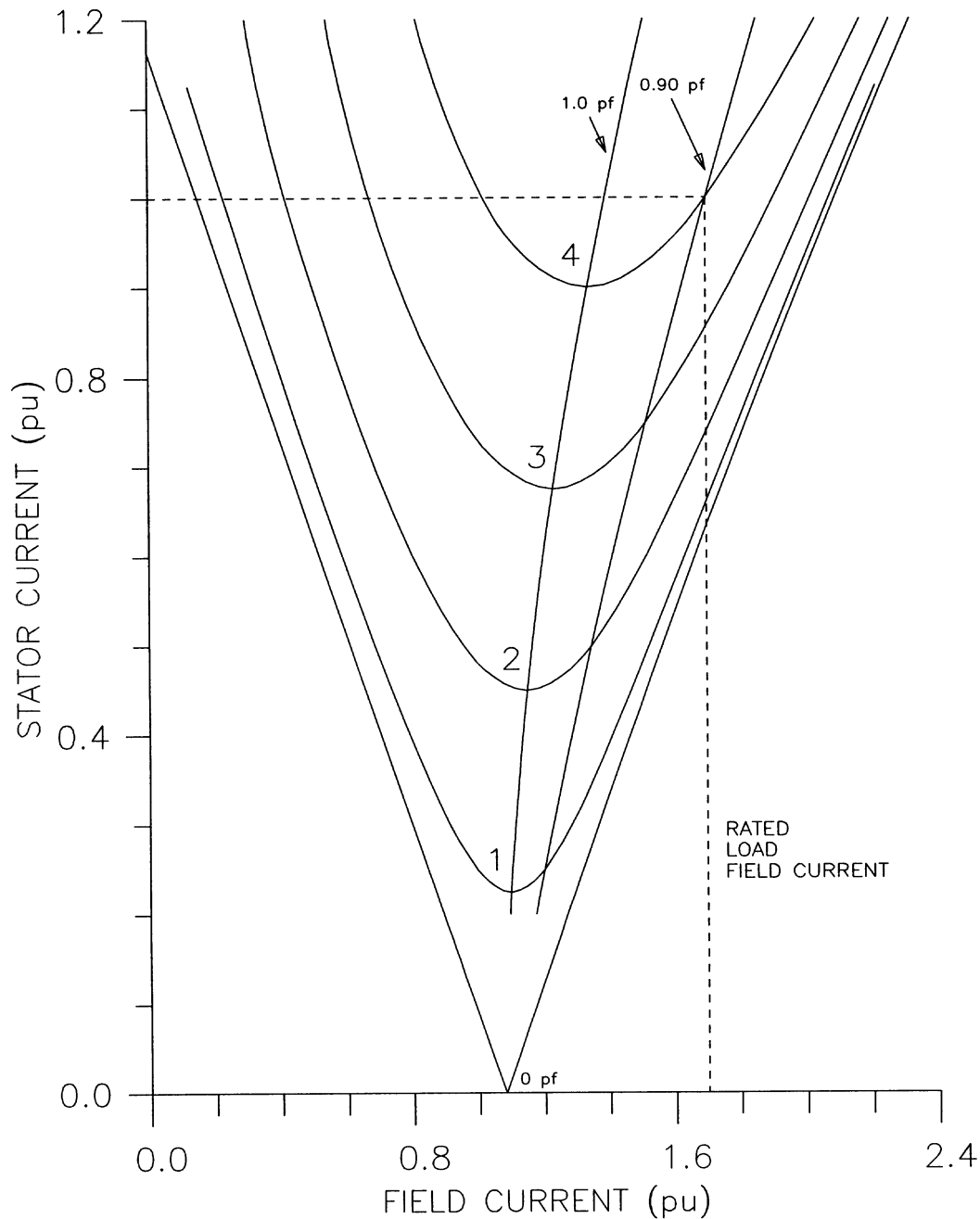


Figure 4—Typical hydro-generator vee curves