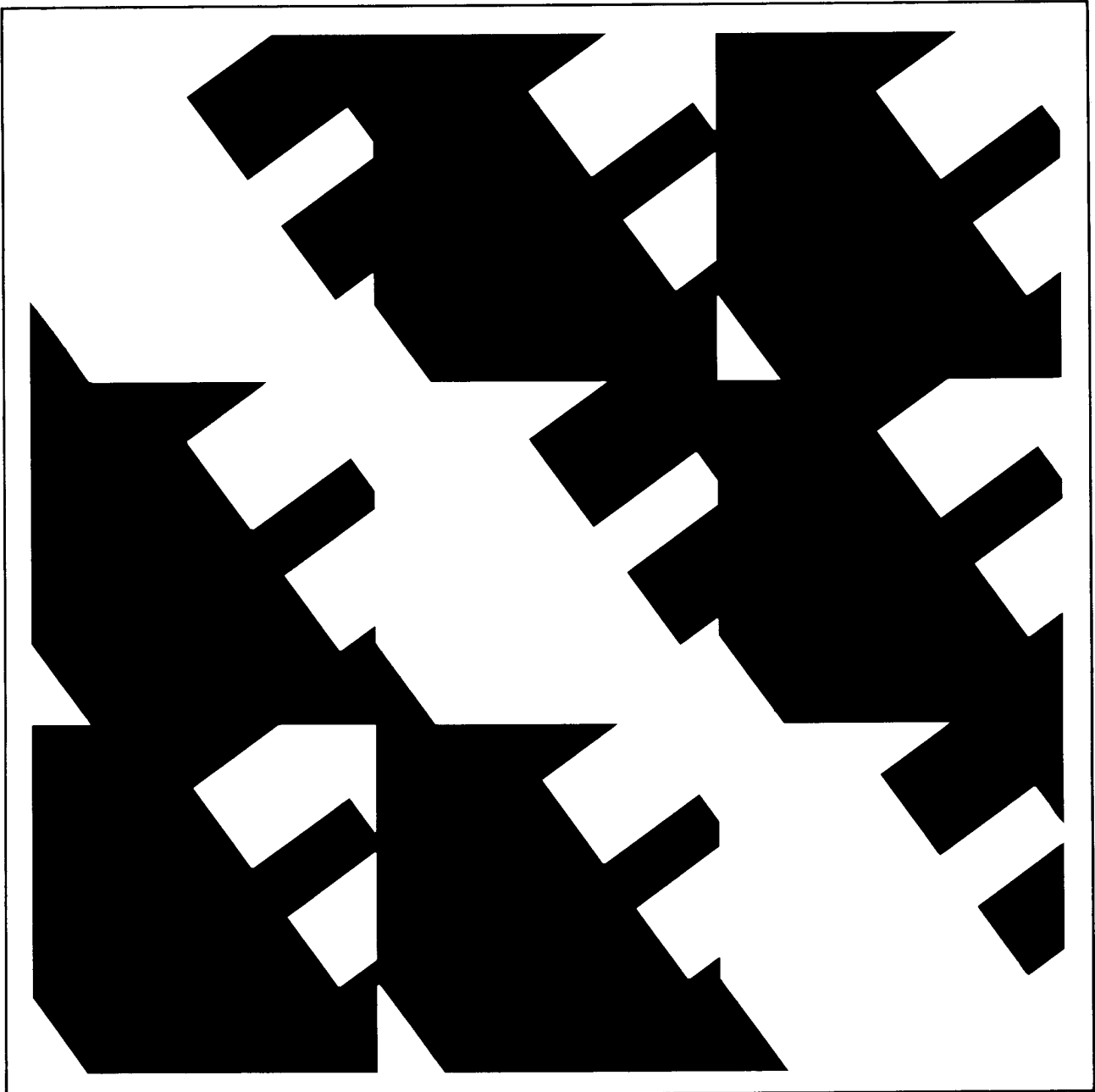


IEEE Guide for Operation and Maintenance of Hydro-Generators

ANSI/IEEE Std 492-1974



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Hydro-Generators**

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of the
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Foreword

(This foreword is not part of IEEE Std 492-1974, Guide for Operation and Maintenance of Hydro-Generators.)

This document 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 a user with information to guide him in understanding the limits of his equipment and methods he may employ to reduce down-time 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, 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 or peaking needs. To this end, the guide contains some sections devoted to pumped-storage applications. It is considered desirable that the document 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. These should be addressed to:

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Contents

SECTION	PAGE
1. Scope	5
2. Caution	5
3. Manufacturer's and User's Responsibility	5
4. Types of Units	5
5. Bases of Rating	6
5.1 General Considerations	6
5.2 Temperature Limits	6
5.3 Mechanical Stress Limits	7
5.4 Temperature Rise	7
5.5 Methods of Temperature Measurement	8
5.6 Limitations in the Methods of Measuring Temperatures	9
6. Loading	10
6.1 Relation of Load and Temperature Rise—Stator and Field	10
6.2 Loading Within Rating	10
6.3 Loading—Power and Reactive Power Relationship	10
6.4 Loading Outside of Nameplate Rating	13
6.5 General Considerations	15
7. Operation	15
7.1 General	15
7.2 Starting and Loading	19
7.3 Braking and Stopping	21
7.4 Load Rejection and Runaway	22
7.5 Automatic Supervision and Protection	22
7.6 Unusual or Dangerous Operating Conditions	22
7.7 Cooling Systems	25
7.8 Fire-Protection Systems	26
7.9 Vibration Detection and Correction	26
7.10 Operation of Generator/Motors	26
8. Maintenance	27
8.1 General Considerations	27
8.2 Frequency of Inspections	27
8.3 Inspection and Maintenance Procedures	28
8.4 Cleaning	34
8.5 Testing	34
8.6 Extensive Downtime—Care of Machine	34
8.7 Safety Precautions	35
9. Miscellaneous	35
9.1 Verification of Protective Relaying	35
10. Standard References	35
11. Bibliography	36

SECTION	PAGE
FIGURES	
Fig 1 Heat Flow and Typical Temperature Detector Location	11
Fig 2 Typical Temperature Rise versus Stator and Field Current Squared	13
Fig 3 Typical Hydro-Generator Saturation Curves	14
Fig 4 Typical Hydro-Generator Vee Curves	15
Fig 5 Typical Hydro-Generator Capability Curves	16
Fig 6 Typical Steady-State Power Angle Curve	19

IEEE Guide for Operation and Maintenance of Hydro-Generators

1. Scope

1.1 This guide covers general recommendations for the operation, loading, and maintenance of hydro-generators and generator/motors (pump/turbines), having salient pole rotors and conventional cooling systems (as distinct from conductor-cooling systems). It does not apply to generators having cylindrical rotors. In this guide, the term hydro-generator is used to describe a generator driven by a hydraulic turbine or water wheel.

1.2 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.

1.3 Equipment manufacturers have taken different approaches to the solution of design problems, and it is not practical to discuss all the variations of machine design. However, many of the operational and maintenance problems are common to all the designs, and recommendations can be given concerning solutions to these problems. The most that the guide can accomplish is to provide guideposts, which, on one hand, disclose accepted and tried values or methods and, on the other hand, give warnings where hazards might be encountered. The guide is not intended to apply in any way to the prime mover.

2. Caution

2.1 It must be recognized that loads more severe than those permitted by the nameplate should not be applied without 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, if possible, the situation be discussed with the manufacturer of the machine.

3. Manufacturer's and User's Responsibility

3.1 Some discussions in the guide involve operation under conditions not covered by nameplate or specifications conditions. While the insulation is capable of safe operation up to the temperature limits set by the standards, effects of the operating condition on other parts of the machine must be studied and evaluated.

3.2 When a generator is operated within its nameplate rating, the user normally may expect maximum reliability and life. On occasions, consideration must be given to operation beyond the nameplate rating. In that case, all the various factors involved must be carefully considered in determining the user's risks.

3.3 While a nameplate does not signify more than specified characteristics, it should be recognized that manufacturers must have some guide in designing a generator which will indicate probable conditions under which the generator will operate. With this in mind, the manufacturer's desire to stay within nameplate rating should be appreciated.

4. Types of Units

4.1 This guide applies primarily to vertical hydro-generators, although horizontal generators are also discussed in less detail. Nearly all the material concerning hydro-generators will apply also to generator/motors such as those used for pumped-storage systems, and

one section relates various starting methods used for generator/motors. The guide applies to both open and totally enclosed machines. Machines having air-to-water heat exchangers are described in this guide as water-air-cooled machines.

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

- (1) Suspended—thrust bearing located above the rotor, and machine has two guide bearings
- (2) Umbrella—thrust bearing located below the rotor, and one guide bearing is located in close proximity to the thrust bearing
- (3) Modified umbrella—thrust bearing below the rotor. Machine has two guide bearings, one above and one below the rotor

5. Bases of Rating

5.1 General Considerations.

5.1.1 Hydro-generators are generally rated on a continuous duty basis with the output rating expressed in kilovolt-amperes available at the terminals at a specified speed, frequency, voltage, and power factor. For rated output, the service conditions specified for the design of the machine must be observed. One of the usual service conditions is the requirement that the temperature of the cooling air will not exceed 40°C and not be less than 10°C (see ANSI C50.10-1965, General Requirements for Synchronous Machines, Section 3). For general definitions refer to ANSI C50.10-1965 and for generator definitions to ANSI C50.12-1965, Requirements for Salient Pole Synchronous Generators and Condensers.

Special generator capabilities and service conditions might have been specified at the time of manufacture. This information is usually listed in the generator instruction book or can be obtained from the manufacturer.

5.1.2 It is generally recognized that the actual output capability of a hydraulic turbine or the load conditions might not match the nameplate rating of the generator exactly. When other than rated load and service conditions exist, the limitations of temperature rise,

mechanical stress, etc, must be considered as discussed in the following sections.

5.2 Temperature Limits.

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

The stator and rotor winding insulation system classes are defined in ANSI C50.10-1965, Section 6, and the corresponding temperature rises are listed in ANSI C50.12-1965, Section 5, and further discussed in Section 5.4 of this guide.

IEEE Std 1-1969, General Principles for Temperature Limits in the Rating of Electric Equipment, discusses the general principles upon which the insulation system temperature limits are based. The test procedures used to develop the limits are described in IEEE Std 99-1970, Guide for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electric Equipment.

5.2.2 For normal life expectancy, generator loading should be so controlled that the hotspot temperatures of the machine windings do not exceed the limiting temperatures of the insulation systems.

In most cases the hotspot temperatures cannot be measured directly and therefore realistic additions must be made to the maximum observable temperatures in order to estimate the hotspot temperature and maximum allowable generator loading. The generator manufacturer should be consulted to establish relationship between the observable temperature and the hotspot temperature, particularly if special loadings, beyond the nameplate rating, are contemplated.

5.2.3 The thermal aging of insulation systems and generator parts is a function of the hotspot temperature and the duration of that temperature. In addition, the changes of load and temperature and the rate of change make the windings, bearings, and the surrounding parts subject to additional differential mechanical stresses. Thus generators with variable load cycles usually show signs of more rapid aging than the baseload units.

5.3 Mechanical Stress Limits

5.3.1 Coupling, Shaft, Rotor Spider. These parts are usually designed for maximum specified turbine horsepower and downthrust. They should also be coordinated in design and mechanical load carrying capability with the turbine shaft. (Coupling design reference ANSI B49.1-1967 (R1971), Integrally Forged Flange Type Shaft Couplings for Hydroelectric Units.)

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

If during operation persistent vibrations at some fixed frequency should occur due to hydraulic forces, the resonant frequencies of rotating parts and associated members (fans, baffles, brackets) should be investigated because usually no allowance has been made for this condition in the initial design.

The first critical speed of the generator rotating system (the shaft, rotor, exciter, etc) is usually designed to be above the specified maximum turbine overspeed and thus outside any operating speed.

5.3.2 Rotor Rim. Rotor rims are designed for maximum specified turbine overspeed which might be as high as twice the rated speed. Thus, at the rated load and speed, the rim stress and expansion are usually quite moderate. However, as 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. If, in addition to overspeed, additional acceleration forces are present due to sudden speed increase and possible hydraulic upthrust, some slight movement or misalignment of the rim stack and the fasteners between the rim and the spider might occur. Usually the design margins are such that the occasional partial overspeeds are of no consequence. However, if additional forces are combined with overspeeds and these occur often, periodic inspections of rim and associated parts are recommended.

5.3.3 Bearings and Bearing Brackets. The majority of hydro-generators are vertical, and

are usually equipped with a segmental shoe-type thrust bearing and with one or two guide bearings. Horizontal 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 certain specified length of time without excessive overheating. Usually there is also 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 also dependent on supply of clean cooling water in specified quantities and at temperatures not exceeding the temperature specified for design of bearings.

Thrust bearing brackets are usually 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 and possible resonance.

5.3.4 Stator Frames. Stator frames and soleplates are usually designed for maximum short-circuit torque capability and the stresses at rated load are thus quite low. However, should a three-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 as the stresses on the stator and its winding become high in comparison with rated load.

5.4 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). ANSI C50.12-1965, Section 5, specifies the limiting observable temperature rises which will not be exceeded when the generator is operating at nameplate rating. This should not be construed as specifying allowable operating temperature rises without regard to rated load. Thus, if the observable temperature rise of a generator is below the standard

value at rated load, this does not mean that the generator load can be increased above the rated load until the limiting temperature rise stated in the standard is reached (see Section 6.1.2).

For overloading, refer to Sections 6.4.2 and 7.1.3.

5.5 Methods of Temperature Measurement. The commonly used methods for determining the temperatures are described below.

5.5.1 Stator Winding. For conventionally (air) cooled machines, the embedded resistance-type detectors (RTD's) between the upper and lower coil sides (Fig 1) are recommended and most commonly used. The description, size, and location of RTD's is given in ANSI C50.10-1965, Section 5. While RTD's 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.

Instrumentation to read and record the detector output is discussed in Section 5.6.1.

5.5.2 Stator Core. For stator cores the thermometer method of measurement is specified in ANSI C50.12-1965, Section 5, Table 1. This method is defined in ANSI C50.10-1965, Section 5.1.1 and in IEEE Std 115-1965, Test Procedure for Synchronous Machines, Section 5.15.05.

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 or an RTD has been embedded permanently in the tooth or yoke portion of the core by building it into the core during stacking operations in the factory. In this case a continuous monitoring of the core temperature is feasible. However, it is generally considered more important to measure and record the stator coil temperature rather than the stator core temperature.

5.5.3 Rotor Windings.

5.5.3.1 Field Windings. The resistance method (as defined in ANSI C50.10-1965, Section 5.1.2 and IEEE Std 115-1965, Sections 5.15.15 and 2.10) is used for acceptance testing and operational monitoring of rotor field winding temperature. It should be recognized that this method measures the average tem-

perature 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 the field accurately without including the voltage drop of the brushes supplying the field current. For acceptance testing, this is usually accomplished with insulated brushes which 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, the other practical methods of brush drop compensation are:

(1) Provide a bias voltage equal to the brush drop

(2) Calibrate the temperature indicating device for a value of a resistance equal to the sum of the expected full-load temperature resistance of the field winding 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.

5.5.3.2 Amortisseur Windings. The amortisseur windings in the pole faces are generally designed to withstand thermally a single-phase short circuit with equivalent I_2^2t equal to or less than 40 (see ANSI C50.12-1965, Section 6). If temperature measurement of the amortisseur bars and connection rings is necessary for some special operating condition(s), this can be adequately accomplished with special tests by using a series of temperature-sensitive paints painted on the amortisseur. 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 manufacturer with regard to the duty cycle and mechanical stresses involved and could be in the order to 300° C. Thus the temperature-sensitive paints could be chosen with approximately 25° C intervals and still have adequate accuracy for the purpose.

5.5.4 Collector Rings. The thermometer method after shutdown (see IEEE 115-1965, Section 5.35) is used to determine the collector ring temperature. If this is done at various field current loadings then a curve of collector

ring temperature rise 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.

5.5.5 Ambient Temperatures. In accordance with ANSI C50.12-1965, Section 5.1, the temperature of the cooling (ambient) air for open ventilated machines is the temperature of the air entering the ventilating openings of the machine.

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

Alcohol or mercury thermometers or thermocouples are generally used for acceptance testing. For operational monitoring, thermocouples, RTD's, 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 the indications is used as the base for temperature rise calculations and the indicator reading closest to the mean value should be used for operational monitoring (See IEEE Std 115-1965, Section 5.25 and IEEE Std 119-1974, Recommended Practice for Temperature Measurement as Applied to Electrical Apparatus, Section 7).

5.6 Limitations in the Methods of Measuring Temperatures. It should be recognized that there are limitations in the methods of measuring temperatures. These are discussed below.

5.6.1 Instrumentation. For safe operation of large generators, the reliability and accuracy of temperature indicating and recording devices is of paramount importance.

Whereas the instruments themselves might be calibrated and accurate, the problems usually arise from the long distance, bad connections, and stray fields between sensing element (thermometer bulb, RTD, or thermocouple) and the indicating or recording panel instrument.

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

Most of the common problems and sources of error are discussed in IEEE Std 119-1973 and in IEEE Std 115-1965, Sections 5.15, 5.20, 5.25, and 5.30.

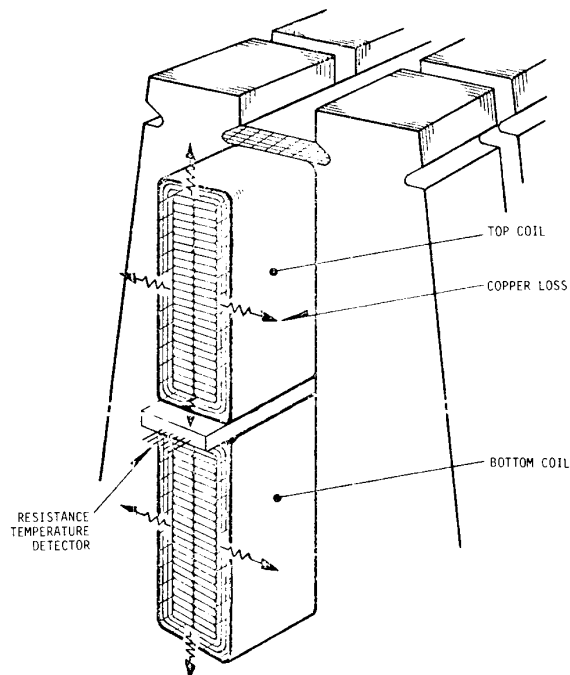
5.6.2 Stator Winding Temperatures by Embedded Detector. The detector is separated from the copper by the insulating wall of the coil (Fig 1) and therefore will always indicate somewhat lower temperatures than the hot-spot of the copper.

The difference between the hotspot 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 to assure that the actual hotspot temperature does not exceed the limiting temperature of the stator insulation class. If then, as the result, the observable temperature rise of the detector appears to be low, with respect to the guaranteed value, it does not necessarily mean that a margin for overloading exists.

5.6.3 Stator Core Temperature. The limitations in measuring the maximum stator core

Fig 1
Heat Flow and Typical
Temperature Detector Location



temperatures with an embedded detector lie in the fact that it is very difficult to make provision for mounting of the detector and knowing in advance which part of the core is going to have the maximum temperature. Also the stator coil temperature is usually more critical from the operating point of view than the core. However, if the unit is operating above rated voltage or at low power factor (either overexcited or underexcited), it can be very useful to observe the increase in stator core temperature to avoid excessive increases.

5.6.4 Field Winding Temperature. The field winding temperature measured by resistance gives an indication of the average temperature throughout the winding. Thus, it does not indicate the magnitude of the hotspot temperature with respect to the average temperature. If overloadings are considered, the hotspot temperature is the critical one, and proper allowance has to be made for the difference between the average and the estimated hotspot temperature.

6. Loading

6.1 Relation of Load and Temperature Rise—Stator and Field. The hydro-generator nameplate states the output rating and rated operating conditions for which the generator has been designed.

6.1.1 When operating within nameplate condition of electric output and cooling medium, many machines will not reach the guaranteed temperature rises which are stated on the nameplate. The reason for such a situation lies in the fact that the observable temperature rise alone does not constitute the only basis for the design of a generator. Other factors which influence design include: hotspot temperature (as discussed in Sections 5.6.2, 5.6.3, and 5.6.4), strength of metals and insulating materials, magnitudes of forces due to thermal expansion and vibration, margins for safety, reliability, and design prediction accuracy. Thus, in a balanced design, the temperature rise of stator and field winding at rated load might be several degrees below the guaranteed value in order to assure reasonable life expectancy and trouble-free operation.

6.1.2 If heat runs have been performed on a

generator at several load points of stator and field current at rated voltage, then the observed temperature rises could be plotted as a function of stator and field current squared. The resultant curves are usually close to a straight line as shown in Fig 2 and provide a convenient operating guide to estimate the temperature rises and total temperatures for various load and coolant conditions.

6.2 Loading Within Rating. Optimum loadings from the standpoint of maximum life expectancy for the generator are those that result in minimum temperature variations at the lowest practicable temperature level.

6.2.1 For varying load conditions this is possible only for totally enclosed water-air-cooled machines where flow of cooling water can be adjusted to regulate the cold air temperature to suit loading conditions and reduce winding temperature variations. This may have to be adjusted seasonally, because usually it is not feasible during periods of high cooling-water temperature to increase the cooling waterflow enough to maintain constant winding temperature at maximum loads.

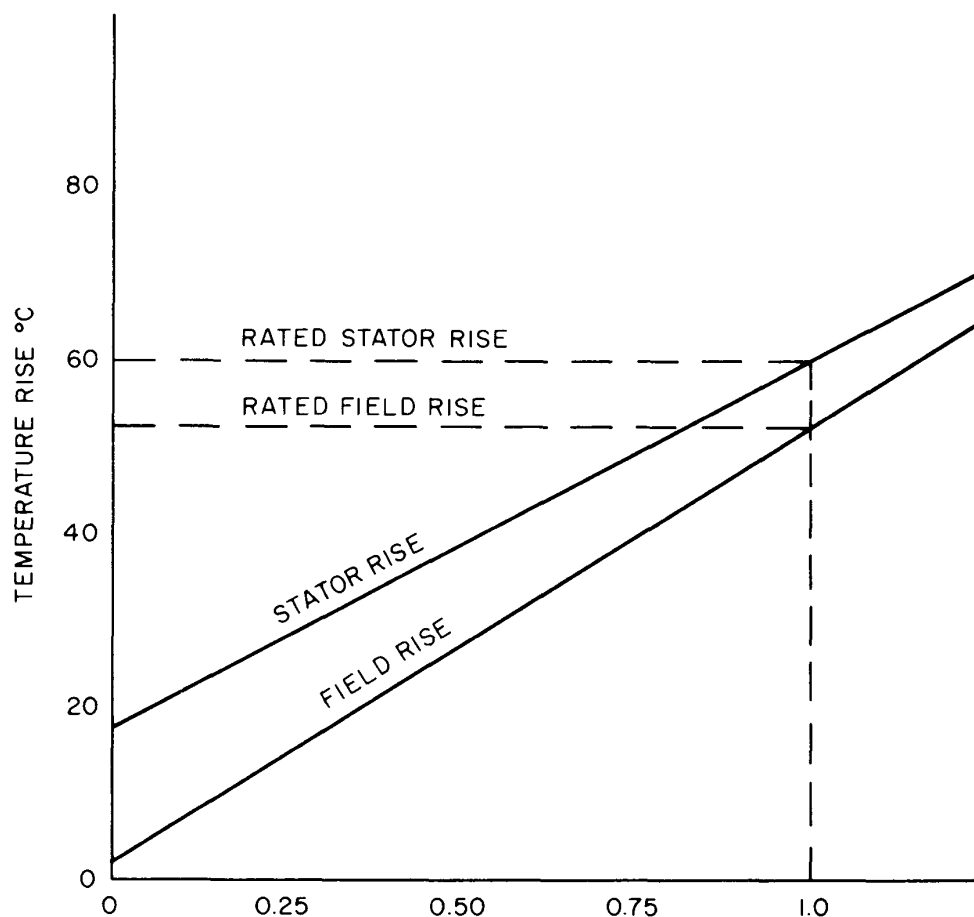
6.2.2 Open machines usually do not have means of controlling the inlet air temperature; however, for machines which have control dampers and means of recirculation of air, the above discussion applies.

6.2.3 Generator characteristic curves are useful to determine the relationship between the field current and the required load setting and to avoid overloading beyond the rating of the machine. Typical curves are shown in Figs 3, 4, and 5.

The saturation curves (Fig 3) give the relationship of terminal voltage, stator current, and field current. Load characteristic (Vee) curves (Fig 4) indicate the apparent power in kilovolt-amperes and field current relationship for various power factors at rated voltage.

A capability curve (Fig 5) indicates generator capability in terms of power in kilowatts and reactive power in kilovars with the indicated limitations for various regions.

6.3 Loading—Power 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 by that machine.



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

Fig 2 Typical Temperature Rise versus Stator and Field Current Squared

Increasing the excitation will tend to make a generator supply more overexcited reactive power and decreasing the excitation will cause it to supply less reactive power or absorb it.

6.3.1 Typical load characteristic curves related to power factor are shown on Fig 4. As can be seen from these curves, when a generator is operated at lower than rated power factor (overexcited), the generator output is limited by field heating and maximum allowable field current.

In the underexcited region the excitation system might be limiting in terms of its capability of supplying zero or negative excitation. The ultimate stability limit for underexcited operation can be established by the generator manufacturer with consideration given to the excitation system capability. Stability limits are discussed in Section 7.1.2.2.

6.3.2 The relationships between power in kilowatts and reactive power in kilovars as discussed above are also apparent from the ca-