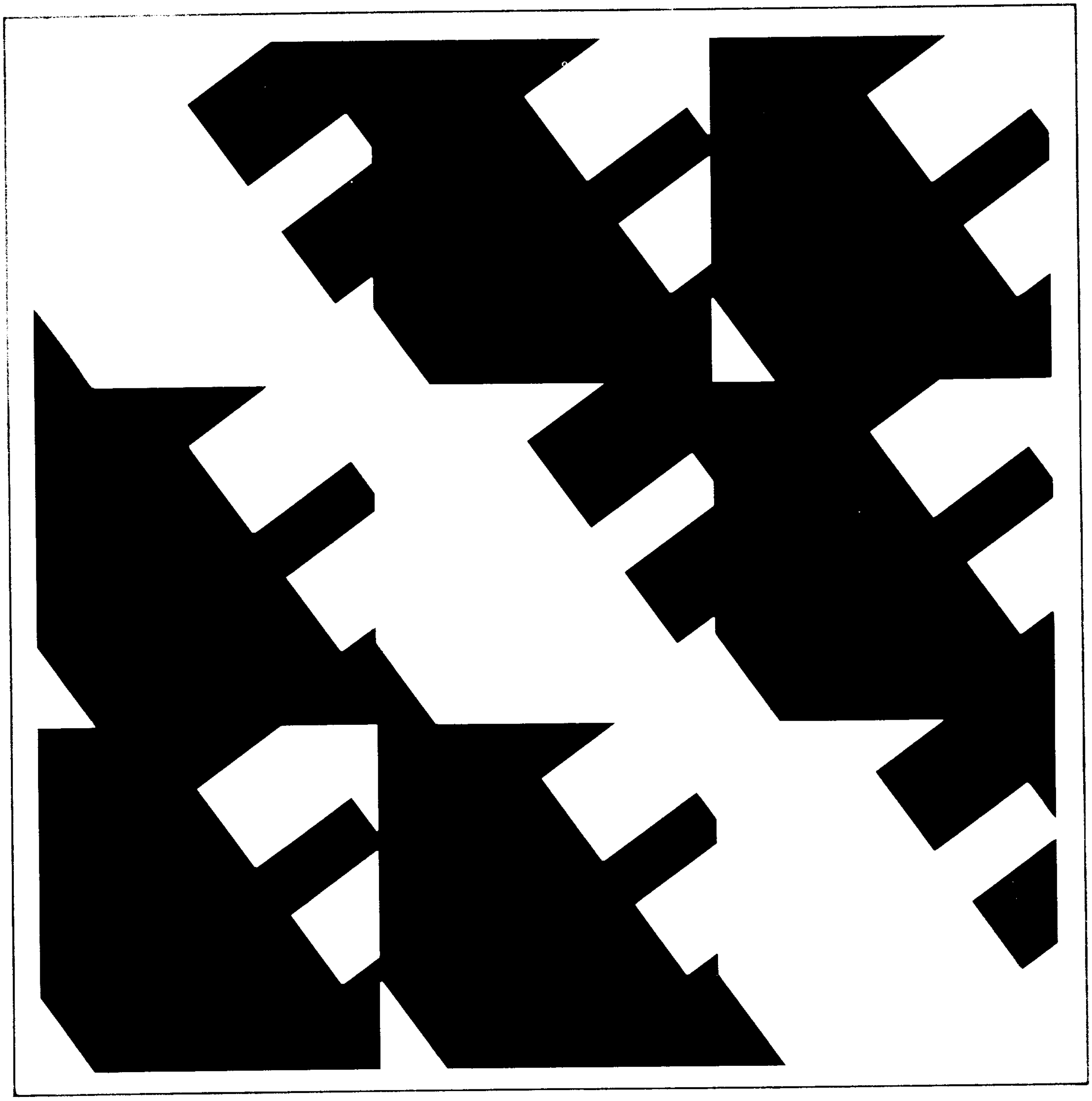
AMERICAN NATIONAL STANDARD
(Reaffirmed 1981)

ANSI/IEEE Std 67-1972
(Reaffirmed 1980)
(Revision of IEEE
Std 67-1963)

IEEE Guide for Operation and Maintenance of Turbine Generators

ANSI/IEEE Std 67-1972



Published by The Institute of Electrical and Electronics Engineers, Inc 345 East 47th Street, New York, NY 10017, USA
June 21, 1972
SH40675

ANSI/IEEE
Std 67-1972
(IEEE Reaffirmed 1980)
(ANSI Reaffirmed 1981)
(Revision of IEEE
Std 67-1963)

An American National Standard

IEEE Guide for Operation and Maintenance of Turbine Generators

Sponsor

Rotating Machinery Committee
of the
IEEE Power Engineering Society

Approved September 16, 1971
Reaffirmed September 18, 1980

IEEE Standards Board

Approved November 10, 1972
Reaffirmed December 22, 1981

American National Standards Institute

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

Approved September 16, 1971

IEEE Standards Committee

B. B. Barrow, *Chairman*

J. Forster, *Vice Chairman*

S. I. Sherr, *Secretary*

S. J. Angello
E. C. Barnes
F. K. Becker
W. H. Cook
W. H. Devenish
C. J. Essel
R. F. Estoppey
J. A. Goetz
A. D. Hasley
G. E. Hertig
A. R. Hileman
H. Lance
D. T. Michael
J. B. Owens
R. H. Rose, II
S. V. Soanes
L. Van Rooij
R. V. Wachter
B. O. Weinschel
C. E. White
W. T. Wintringham

Foreword

(This foreword is not a part of the IEEE Guide for Operation and Maintenance of Turbine Generators)

Originally published in July 1957 as a trial-use document, the Guide for Operation and Maintenance of Turbine Generators was updated and issued as a full-status IEEE Guide in 1963. In March 1969 a working group was appointed within the Synchronous Machinery Subcommittee of the IEEE Rotating Machinery Committee to begin work on an extensive revision of the 1963 edition.

In the course of this revision, the guide was enlarged to include directly cooled machines and to stress the importance of generator operation using the generator capability curve and other related operating curves. It also emphasizes the undesirability of operation of a generator by means of stator winding temperature indications. The bibliography section has been updated and has been grouped by subject to facilitate its use.

The IEEE will maintain this guide current with the state of the technology. Comments are invited on this guide, as well as suggestions for additional material that should be included. These should be addressed to:

Secretary
IEEE Standards Committee
The Institute of Electrical and Electronics Engineers, Inc.
345 East 47 Street
New York, N. Y. 10017

Members of the working group that prepared the present revision were:

W. J. Foley, Jr., *Chairman*

M. Balanson
J. M. Brown
C. H. Fleming

J. A. Massingill
W. J. Sheets
R. A. Towne

IEEE Standards documents are developed within the Technical Committees of the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE which have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least once every five years for revision or reaffirmation. When a document is more than five years old, and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason IEEE and the members of its technical committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
345 East 47th Street
New York, NY 10017
USA

Contents

SECTION PAGE

SECTION PAGE

FIGURES

An American National Standard

IEEE Guide for Operation and Maintenance of Turbine Generators

1. Scope

This guide covers general recommendations for the operation, loading, and maintenance of turbine-driven synchronous generators of the types specified in Section 4 below, having cylindrical rotors. It does not apply to generators having salient-pole rotors.

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

Because of the rapid development in generator design and because of the ingenuity of individual generator designers, many variations are incorporated in existing machines. It is therefore not possible in this guide to assign specific values or fixed methods. The most that this guide can accomplish is to offer accepted and tried values or methods and give warning where hazards might be encountered. The user should keep in mind that this guide is written in terms of the turbine generator, and that certain considerations herein have been included because of their importance in directing attention to other related matters. This guide is not intended to apply in any manner to the prime mover.

NOTE: It is often practice in industry to refer to various types of power in terms of the units in which these types of power are normally measured. To avoid the possibility of confusion, units of measure are shown in parentheses when the terms reactive power (kvar), apparent power (kVA), and active power (kW) are used.

2. Caution

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. It is recommended that in all such cases the specific condition be discussed with the manufacturer of the unit.

3. Manufacturer's and User's Responsibility

3.1 Some suggestions made 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 and/or purchaser's specifications. 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.

3.2 When a generator is operated within its capability, the user may expect maximum reliability and life. On occasions, consideration must be given to operation beyond the range of the capability curves. In those cases, all of the various factors involved must carefully be considered in determing the user's risks.

4. Methods of Cooling

This guide applies to turbine generators of the following types, distinguished according to methods of cooling:

4.1 Indirectly-Cooled Types. Indirectly-cooled generators are those in which the heat generated within the principal portion of the windings must flow through major ground insulation before reaching the cooling medium. Cooling air or hydrogen is circulated through passages in the generator by one of two methods:

(1) *Self-Ventilated Generator.* A self-ventilated generator has cooling air or hydrogen circulated by means integral with the machine.

(2) *Separately-Ventilated Generator.* A separately-ventilated generator has cooling air or hydrogen circulated by an independent fan or blower external to the machine.

4.1.1 ***Air-Cooled Generators.*** Air-cooled generators are designed to use air for cooling and they are classified according to the method of enclosure.

(1) *Open Generator.* An open generator is a self-ventilated machine, open to the surrounding air, having no restriction to ventilation other than that necessitated by mechanical construction and any silencing and filtering equipment.

(2) *Enclosed Generator.* An enclosed generator is either self-ventilated or separately ventilated with openings for the admission and discharge of the ventilating air, the machine being otherwise totally enclosed. These openings are so arranged that inlet and outlet ducts or pipes may be connected to them.

(3) *Totally-Enclosed Generator.* A totally-enclosed generator is so enclosed as to prevent exchange of air between the inside and the outside of the case, but not sufficiently enclosed to be termed airtight. Heat created by the generator losses is removed from the cooling air by heat exchangers.

4.1.2 ***Hydrogen-Cooled Generator.*** A hydrogen-cooled generator is designed to use hydrogen for cooling instead of air. It is a totally enclosed machine having a strong gastight enclosure. Heat created by the generator losses is removed from the hydrogen by heat exchangers.

4.2 Directly-Cooled Types. Directly-cooled generators are those in which the coolant or coolants (hydrogen or liquid) for the windings flows in close contact with the conductors so that the heat generated within the principal portion of the windings reaches the cooling medium without flowing through the major ground insulation. Coolants may be circulated either by means integral with the machine or by circulating equipment external to the machine.

4.2.1 ***Directly-Cooled Stators.*** Directly-cooled stators are classified according to the type of coolant used to remove heat from the stator windings.

4.2.1.1 *Hydrogen.* Hydrogen coolant flows within insulated ducts which are part of the stator winding structure inside of the major ground insulation. The heat generated within the conductors flows through the thin layers of conductor insulation and duct insulation to the cooling hydrogen in the ducts.

4.2.1.2 *Deionized Water.* Deionized water coolant flows within hollow conductor strands. The heat generated within the conductors flows in either of two ways:

(1) Directly into the cooling water flowing within hollow conductor strands

(2) Through thin layers of strand insulation to the hollow strands carrying the water coolant if some solid strands are nested within the stator winding structure

4.2.1.3 *Insulating Oil.* Insulating oil coolant flows in the same manner as for the deionized water types in 4.2.1.2 above.

4.2.2 ***Directly-Cooled Rotors.*** Directly-cooled rotors are classified according to the types of coolant used to remove heat from the rotor windings and the flow pattern of the coolant within the slot portion of the windings.

4.2.2.1 *Hydrogen Coolant With End Supply.* Hydrogen is supplied to each end of the rotor and flows into conductor passages near the ends of the rotor body and/or into subslots which carry coolant to supply conductor inlet passages at intervals along the rotor body length. The hydrogen coolant is discharged into the generator air gap.

4.2.2.2 *Hydrogen Coolant With Gap Supply.* Hydrogen coolant is fed into conductor passages from the gap by short inlet sections along the length of the rotor body either by self-pumping or by pressurized gap zones maintained by gap baffles. The hydrogen coolant is discharged through short outlet sections between the inlet sections along the length of the rotor body. The end positions of the winding are supplied with hydrogen coolant from each end.

4.2.2.3 *Water Coolant.* Deionized water coolant is fed axially through piping inside the rotor shaft to radial connections that enter an inlet water box. The water coolant then flows axially through hollow field conductors or tubing nested in the field windings to the opposite end of the rotor. The water coolant may then exit at that end or return to the inlet end of the rotor. The water coolant exits by way of radial connections to outlet piping inside the rotor shaft.

5. Bases of Rating

5.1 General Considerations. The bases upon which turbine generators are rated for normal operation are distinctly different from the consideration with regard to the turbine driving unit. In the case of the steam turbine, for instance, one of the principal load limitations is the maximum torque that the steam turbine can deliver under certain conditions of steam pressure, temperature, and vacuum. In the case of the generator to which it is connected, there is in most cases no torque limitation to the generator loading. However, the generator rating is limited by considerations related to the useful life of the insulation and other machine parts; principally, these considerations are the effects of temperature, differential expansion, and vibration.

5.2 Temperature Limits. IEEE Std 1-1969, General Principles for Temperature Limits in the Rating of Electric Equipment, discusses the general principles upon which temperature limits are based. In considering limits for the temperature of machine parts, the following points must be remembered:

(1) Deterioration of the insulation is a function of the time during which it is subjected to high temperature, as well as magnitude of the temperature

(2) The insulation is subjected to considerable mechanical stresses due to expansion and contraction of the windings and surrounding parts with changes in load and temperature

(3) In most cases, the maximum insulation temperature cannot be measured directly, and correction must be made to the measured temperatures to approximate the hot-spot temperature.

Generally, in considering turbine-generator loadings to insure normal insulation life expectancy, it is important that hot-spot temperatures of the machine do not exceed the limiting temperatures of the insulation system as established by test procedures developed in accordance with IEEE Std 99-1970, Guide for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electric Equipment, or as derived from the temperature limits of the component materials given in IEEE Std 1-1969.

Some generators, such as those driven by gas turbines, are operated for short-time duty periods at higher than normal temperature in such a way as to make the average rate of thermal deterioration over the total elapsed time consistent with the designed life expectancy.

5.3 Temperature Rise. Temperature rise of a machine component is defined as the difference between the temperature of that component and the cold coolant temperature. ANSI C50.13-1965 specifies the observable rises which the manufacturer guarantees will not be exceeded when the generator is operated at nameplate rating. It must not be construed as specifying allowable operating temperature rises.

On some applications, such as air-cooled 2-pole open-ventilated generators, greater output is achieved with lower cold coolant temperatures, permitting higher temperature rise without exceeding established total temperature limitations.

5.4 Methods of Temperature Measurement.

5.4.1 ***Coolant Temperatures.*** Coolant is defined as the medium used to remove heat from the active parts of the machine. The number and location of coolant temperature sensors vary considerably depending on the type of cooling system employed. The instruction book of the manufacturer should be consulted in each individual case.

The cold coolant temperature is measured by resistance or thermocouple detectors located either in thermometer wells in the side of the generator or inside the generator in the cold coolant streams.

In addition, coolant temperature detectors are frequently employed for the control of heat exchanger raw water flow. See Section 6.5.1 for definition of "raw water."

The cold coolant temperature should not exceed the maximum value specified on the generator nameplate. Maximum values as specified in ANSI C50.13-1965 range from 40° C to 50° C, depending on the type of cooling employed and on the manufacturer's practice. On some applications, such as air-cooled 2-pole open-ventilated generators, the cold coolant temperature may be outside this range.

5.4.2 ***Stator Windings.*** The method of measuring stator winding temperatures depends on the type of cooling employed.

5.4.2.1 *Indirectly-Cooled Stator Windings.* Winding temperature is measured by means of embedded detectors of the resistance or thermocouple type placed between the upper and lower coil sides, as shown in Fig. 1. Resistance detectors are used in most indirectly-cooled machines and are preferred since they indicate the mean temperature of the coils over a length of several core packs rather than at only one point. The resistance detectors consist of a coil of standard copper wire or of some suitable alloy material. This coil is wound on a suitable form to make it thin in the direction of the depth of the slot, and make its width some fraction of the total width of the slot. Leads are brought out from the end of the resistance detector coil to the end of the slot between stator coils, or to the side of the coil through one of the ventilating ducts, and hence to terminals suitable for connection to the temperature indicator leads.

Length and resistance of the resistance detector may be as specified in ANSI C50.10-1965 (resistance is 10 ohms at 25°C) or as otherwise specified by the purchaser. At least six detectors are built into the machine, suitably distributed around the circumference, located between the coil sides, and in positions along the length of the slots normally having the highest temperature. The detector is located, wherever possible, in the center of the slot with respect to the slot width and in intimate contact with the insulation of the upper coil side. Each detector is installed and the leads brought out in such a manner that the detector is effectively protected from contact with cooling air or gas.

While resistance detectors are most commonly used at present, and preferred for the reasons noted above, thermocouple-type detectors are sometimes utilized.

5.4.2.2 *Directly-Cooled Stator Windings.* 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 resistance or thermocouple-type temperature detectors are commonly employed for directly-cooled windings. In the case of gas-cooled windings, the coolant temperature detectors are mounted at the end of an insulating duct at the warm coolant discharge. In the case of liquid-cooled windings, the coolant temperature detectors are mounted at the ground potential end of insulating hoses at the warm coolant discharge.

5.4.3 ***Rotor Windings.*** No simple method has been devised for measuring rotor hot-spot temperatures; the practice is therefore to measure the average temperature of the winding by resistance using simultaneous voltage and current readings at the collector rings, and interpreting these values in conjunction with the known cold-resistance value into the operating temperatures. If the rotor voltage is measured at the brushes, there may be a total error of 2 to 4V due to brush voltage drop. To compensate for this effect, pilot brushes that carry no field current are sometimes used for measuring the potential of the rings. However, some users have experienced difficulty with pilot brushes due to a rapid film buildup that causes inaccuracy of the temperature measurement and in some cases interferes with the operation of the other brushes.

More practical methods of compensation are to:

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

(2) Calibrate the temperature-indicating or recording device for a value of resistance equal to the sum of the expected full-load temperature resistance of the rotor winding plus the equivalent resistance of the brush voltage drop at full-load rotor current.

For excitation systems that do not employ stationary rotor current-carrying components, no simple method for measuring rotor winding temperatures is currently available.

5.5 Limitations in the Methods of Measuring Temperature.

5.5.1 ***Stator Winding Temperatures by Embedded Detectors.*** The detector element is located between the surfaces of the upper and lower coil sides and is separated from the copper of these coils by the insulating wall of the coil, as indicated in Fig. 1. The difference between the temperature of the hot spot and

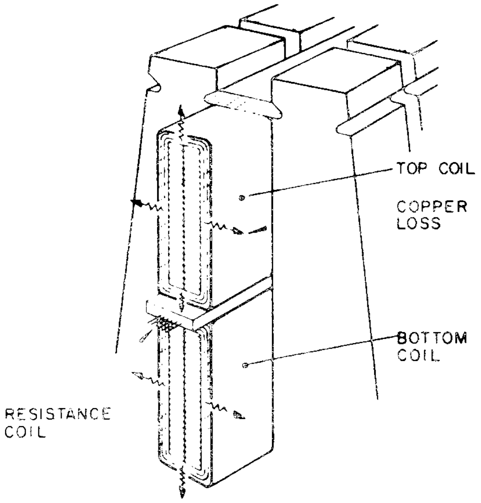


Fig. 1
Heat Flow and Typical Temperature Detector Location

the detector element is a function of the proportions of the slot, the thickness of the insulating wall of the coils, the amount of heat to be conducted through the insulation, etc. It is impossible to generalize correctly as to what the difference between the detector and the hot spot temperature will be for all machines.

In the case of indirectly-cooled units, the embedded detector will always indicate temperatures somewhat lower than the temperature of the insulated copper of the windings. The difference between the hottest spot of the copper in the stator coil and the resistance detector of a hydrogen-cooled generator may be considerably higher than the 10°C allowance originally established for air-cooled generators. Tests made on large hydrogen-cooled turbine generators would indicate that the difference between the copper temperature and the detector temperature is practically unaffected by a change in gas pressure in a hydrogen-cooled generator, but is largely a function of the heat flow from the copper to the cooler parts surrounding the coil as indicated in Fig. 1.

In the case of directly-cooled units, the coolant enters one end of the stator coil at a low temperature and discharges from the other end at a higher temperature, 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 axial location in the slot and the relative temperature of the core at that point.

5.5.2 *Stator Winding Temperature by Discharge Coolant Temperature.* In the case of directly-cooled stator windings, the temperature of the discharge coolant is measured by means of resistance or thermocouple detectors. The temperature difference between this discharge coolant temperature and the hot spot varies widely for different machines. This difference depends on the coolant gas or liquid, winding construction, and design practice, and may be specified for a given design as a function of load.

5.5.3 *Rotor Winding Temperatures.* The rotor temperature measured by resistance gives an indication of the average temperature throughout the winding. As such, it does not indicate the magnitude of the hot-spot temperature with respect to the average temperature. The hot-spot temperature will be somewhat higher with respect to the average temperature in longer rotors than in shorter rotors of the same general design, except for long rotors with multiple parallel gas-flow circuits. To compensate for this factor, ANSI C50.13-1965 calls for a lower temperature rise for the larger machines. The lower temperature rise will also counteract the increased differential expansion between conductor and steel in the larger rotors.

6. Loading

6.1 Relation of Load and Temperature Rise-Stator and Rotor. As a primary guide to the loading of a generator, each generator is provided with a nameplate that states the operating conditions for which the generator has been designed and constructed. When operating within nameplate conditions of electric output and standard cooling-medium temperature, pressure, and flow, many machines will not reach the temperature rises that are given as maximal limits in ANSI C50.13-1965, but will be found to operate at considerably lower observable temperature rises. The reason for such a situation lies in the basic fact that temperature rise alone does not constitute a sufficient basis for the design of a generator. The design also depends on other information, such as strength of metals and insulating materials, magnitudes of frictional forces resulting from expansion and contraction of machine elements because of temperature change, accuracy of the means available for the determination of the magnitudes of pertinent physical phenomena, and other data accumulated as the result of experience.

For hydrogen-cooled generators whose load capability increases with increasing hydrogen pressure, the limiting observable stator temperature rise by temperature detector must decrease as the load capability increases, in order to maintain hot-spot temperature limits. In this case, too, considerable variation between individual machines will be found in practice.

It is therefore necessary to use discretion in loading machines on the basis of observed stator temperature resistance-detector readings, as these readings may appear to indicate considerable temperature margin which may not exist. Also, in determining the temperature at which the rotor is to be operated in any particular case, it is important to consider the hot-spot temperature.

To assure reasonable life expectancy, trouble-free operation, and minimum maintenance, generator designers allow certain margins of safety in their designs. The realization of the designers' intentions depends to a large degree upon methods of operation. When the generator is operated within the nameplate rating, the temperature rises of rotor and stator windings are moderate, while differential expansion and vibration are also limited. Such conservative operation results in adequate service life and reduced probability of generator outage caused by insulation failure, provided the windings are not subjected to excessive mechanical or electrical stresses caused by short circuits or voltage surges.

In summary, any loading in excess of that permissible by the nameplate must be approached with full awareness of all of the factors that are affected by such loading, and not only by consideration of limiting temperature rise, as given by these standards. While turbine generators can, of course, be loaded above their nameplate current rating without incurring immediate failure, such overloading nonetheless encroaches on the design margins that exist when the generator is operated at nameplate rating, and inevitably shortens insulation life. This reduction in life cannot be evaluated precisely, but is significant, especially with serious overloading. The effects on insulation life are cumulative and depend upon the time of exposure to each temperature level. While operating engineers may choose to overload the units on their own responsibility, recognizing the disadvantages of such operation, it is recommended that the generator be operated within the limits of its capability curve.

6.2 Loading Within Rating. Optimum operating methods from the standpoint of maximum life expectancy for a generator are those that result in a minimum temperature change at the lowest practicable temperature level. It is therefore desirable to have equipment to control the cooling system temperatures.

For open, air-cooled generators there is sometimes no means provided for the control of the air temperature through the unit. If there are means provided, the succeeding discussion applies.

For closed cooling system generators, whether air-cooled or hydrogen-cooled, control of the cooling system is available through the control of the raw water flow to coolers, and for liquid-cooled generators, by control of liquid coolant temperatures for the windings. See Section 6.5.1 for definition of "raw-water."

Although the considerations here presented apply particularly to a hydrogen-cooled generator, a considerable portion of the fundamentals developed are applicable to operation of air-cooled generators having closed cooling systems.

Conveniently located temperature indicating or recording instruments for obtaining the temperatures of the stator windings and of the rotor windings will provide valuable information in the operation of the machine.

6.3 Loading - Active and Reactive Power (kW and kvar) Relationship. When one generator alone supplies an isolated load, the power factor and the reactive power (kvar) are determined by the load. In a system whose

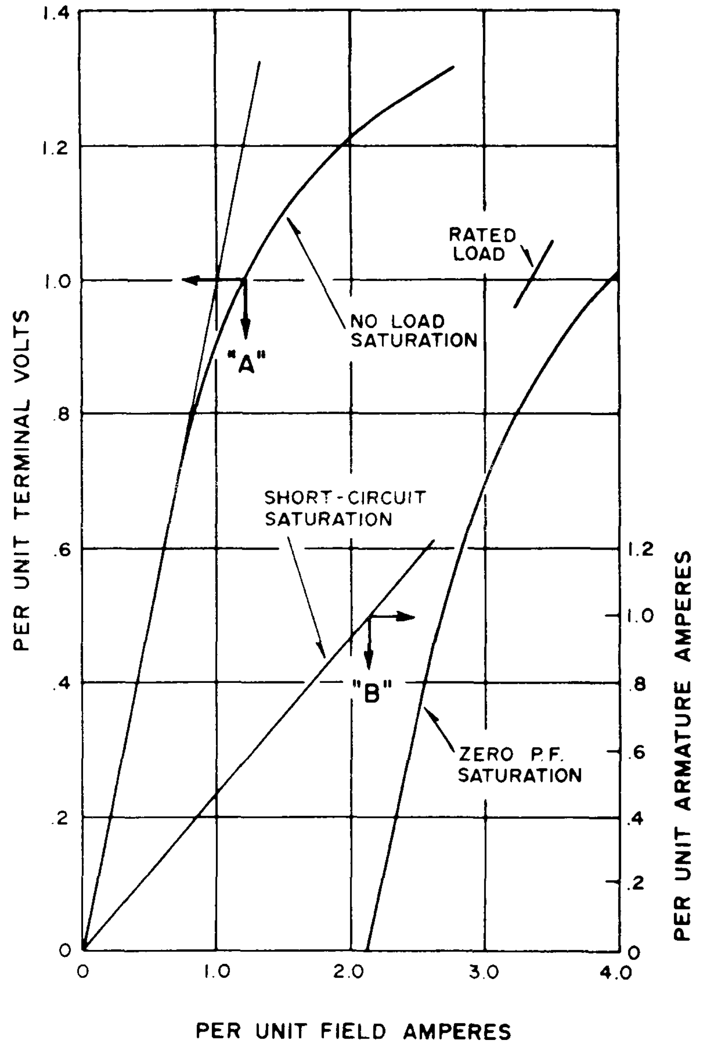


Fig. 2
Typical Saturation Curves

load is supplied by a number of generators in parallel, the division of the reactive power (kvar) load between the generators is determined by the relative excitation of each machine. In such a system, the principal effect of a change in excitation on one generator will be to vary the amount of reactive current supplied by that machine, and the voltage will tend to be held constant by the other generators connected to the system since they will collectively balance the reactive power (kvar) so shifted. Increasing the excitation will tend to make a generator supply more lagging reactive power (kvar) and decreasing the excitation will cause it to supply less lagging reactive power (kvar) or to supply leading reactive power (kvar).

A typical no-load saturation and short-circuit saturation curve as shown on Fig. 2 is often helpful and may be obtained from the manufacturer. Typical load characteristic ("vee") curves for one type of generator are shown in Fig. 3. Similar curves apply to other types of generators. These curves show the variation in excitation requirements for various loads at various power factors and at rated voltage. It may be noted that in the range generally between rated lagging power factor

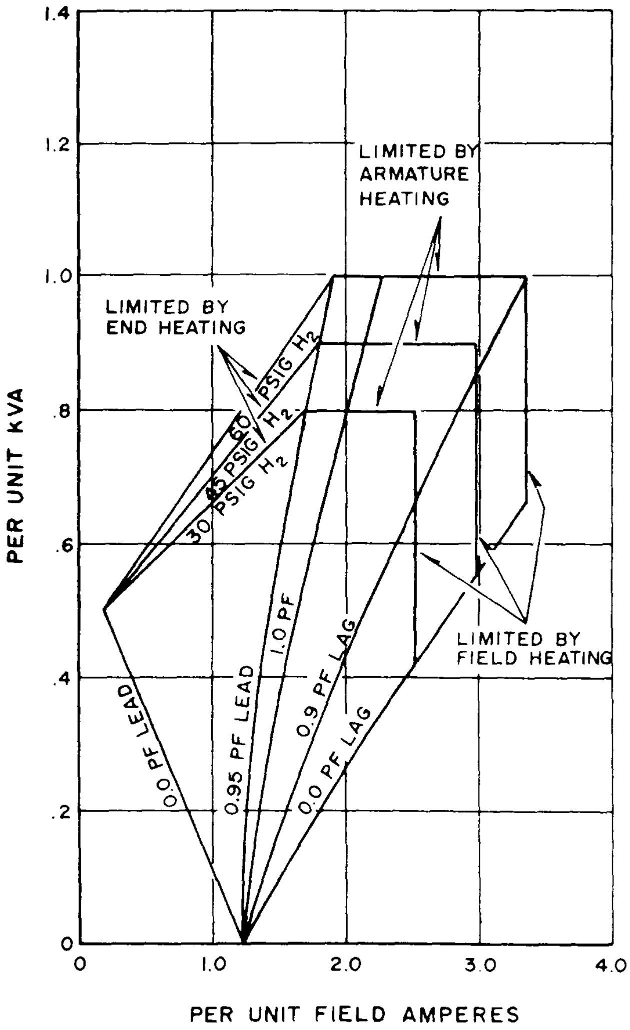


Fig. 3
Typical Load Characteristic Curves

60 psig = 515 MN/m^2
45 psig = 412 MN/m^2
30 psig = 308 MN/m^2

to unity or slightly leading power factor, the generator output is limited by armature heating (maximum rated armature current corresponding to hydrogen pressure rating). In the overexcited region between rated power factor and zero power factor lagging, the generator output is limited by field heating (maximum rated field current corresponding to hydrogen pressure rating). Localized heating of the stator core end structure limits the generator output in the underexcited region. Limits imposed by this end heating are dependent upon the design of a particular generator. Some generators may carry full nameplate kVA (apparent power) load well into the underexcited region, while other generators may not be safely operated at full apparent power (kVA) at power factors between 0.9 lagging and 1.0, nor in the underexcited region.

A reactive capability curve similar to that

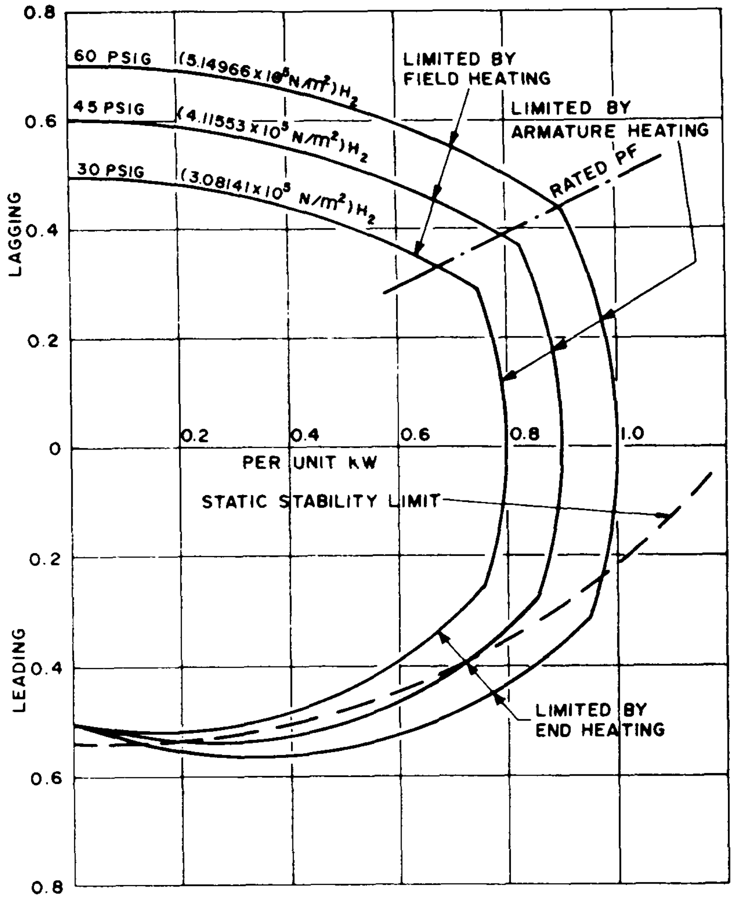


Fig. 4
Typical Reactive Capability Curve

shown on Fig. 4 may be used as a guide for controlling active and reactive power (kW and kvar) at rated voltage and frequency so as to obtain optimum insulation life and safe loading of the machine. Field heating, armature heating, and localized end heating of the stator core limit the machine capability in the regions indicated in the typical reactive capability curve, Fig. 4.

The static stability limit curve is conveniently plotted on the reactive capability curve. This is shown as a dashed line in Fig. 4. It is important to note that this curve is a function of machine and external system reactances and is not a function of machine component heating.

The permissible loading of each generator is determined by its specific design. It is therefore recommended that when these curves are to be used to establish operating limits, the applicable curve for each generator in question should be obtained from the instruction book or the manufacturer.

The following method, illustrated by Fig. 5, may also be used for constructing an approximate reactive capability curve in the over-excited region, similar to that shown on Fig. 4.

(1) With the 0-kW, 0-kvar point as the center, draw an arc between a point at rated kilowatts, rated power factor and the abscissa of the kilowatt scale.

(2) Draw an arc between the rated kilowatt, rated power factor point and the kilovar ordinate scale using as a center a point on the leading kilovar ordinate equal to the generator short-circuit ratio (SCR) times the rated kVA (apparent power).

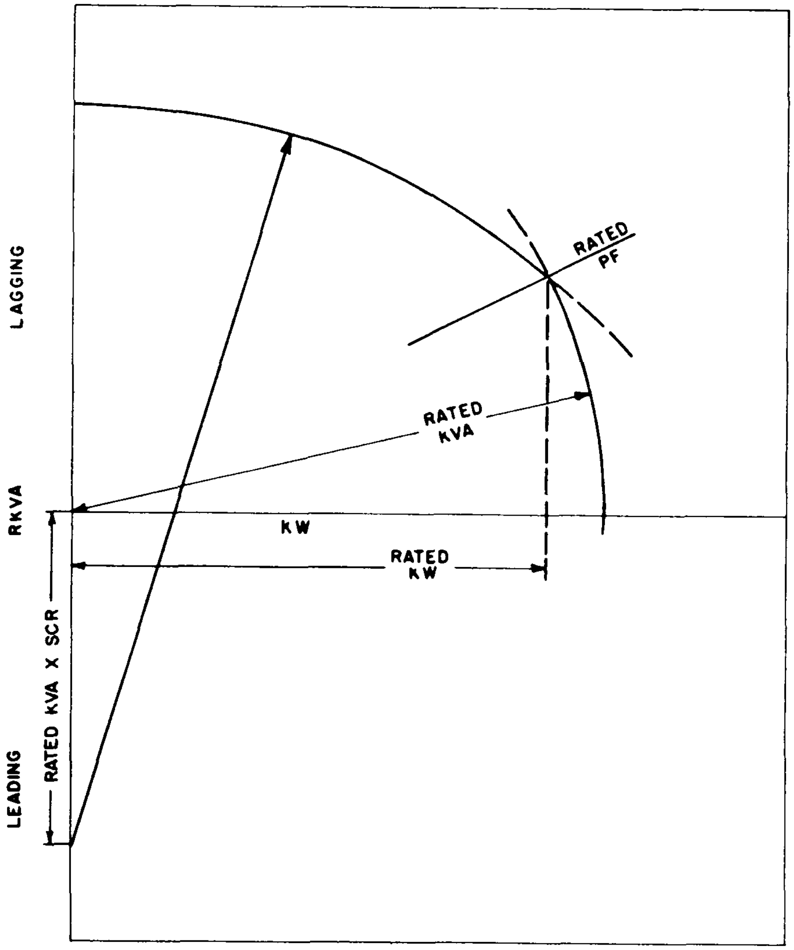


Fig. 5
Construction of Approximate Reactive Capability Curve

NOTE: The short circuit ratio (SCR) is specified with the rating of the machine. It may also be obtained by reference to the generator saturation curve, since short-circuit ratio is the ratio of the field current for rated open-circuit armature voltage and rated frequency (A on Fig. 2) to the field current for rated armature current on sustained symmetrical short-circuit at rated frequency (B on Fig. 2): SCR = A/B.

This approximate method does not recognize any factors in the design of the generator which may limit allowable stator core end heating in the underexcited region. It should therefore be used with caution when operating in the vicinity of unity power factor. Neither does it recognize generator saturation effects in the overexcited region and may, therefore, be considerably optimistic.

During times of moderate and heavy system loads, it will usually be possible to control and distribute the active and reactive power (kW and kvar) loading among several generators in such a manner as to obtain the desired loading from the individual generators within their capability. Special operating conditions may be encountered, however, when it may not be possible to stay within the capability of the machine. In these instances, it is essential that all pertinent capability data should be available to the operator for quick reference. See Section 6.4

During light load or off-peak periods, or to satisfy certain other operating requirements, it may be found necessary to operate the generators near unity power factor. Generators whose rated power factor is some lagging value should not, as a general rule, be operated at near unity or leading power factor unless precise data are available to establish safe limits as an operating guide for each individual generator. These data are provided by the generator capability curves (Fig. 4). They should be used to establish limiting related values of kilowatts, kilovars, and power factors, which should not be exceeded. The establishment of these values must also consider generator stability, which is a function of both the generator and the system, and values should be chosen so that system disturbances of usual magnitude will not cause the generator to lose synchronism. Minimum excitation limiter equipment prevents operation in the area of instability when the voltage regulator is in service.

6.4 Loading Outside of Nameplate Rating. It may be necessary to operate a generator under the following conditions:

(1) At rated frequency, but at other than rated voltage. Refer to Section 6.4.1 and ANSI C50.13-1965.

(2) At rated voltage/frequency ratio, but at other than rated frequency. Refer to Section 6.4.2. ANSI C50.13-1965 does not provide for this condition.

(3) Above rated kVA (apparent power) but at rated voltage and frequency. Refer to Sections 6.1 and 6.4.3. ANSI C50.13-1965 does not provide for this condition.

(4) Both voltage/frequency ratio and frequency at other than rated value. Refer to Sections 6.4.1 and 6.4.2. ANSI C50.13-1965 does not provide for these conditions.

(5) During short-time abnormal conditions. ANSI C50.13-1965 specifies generator capabilities with regard to the following characteristics:

(a) Armature winding short-time thermal requirements

(b) Field winding short-time thermal requirements

(c) Rotor short-time thermal requirements for unbalanced faults

(d) Mechanical requirements for short circuit

(6) Continuous unbalanced load. In general, the manufacturer should be consulted for the derating required for unbalanced loads. For the maximum value of negative phase sequence current that may be carried without derating the generator, see Section 7.8 and ANSI C50.13-1965.

6.4.1 ***Operation at Other Than Rated Voltage.*** Practically all generators are designed for safe operation at rated kVA (apparent power), power factor, and frequency with a voltage variation of 5 percent above or below rated. However, a significant increase in the voltage/frequency ratio results in oversaturation of the magnetic core. Of particular concern is the stray flux induced in nonlaminated frame components which are not designed for this and can be severely overheated. Since the normal temperature-monitoring devices do not provide data from such components, damage can take place before the operator is aware of it. If, under unusual circumstances, it is required to operate at a voltage more than 5 percent above or below rated, the manufacturer should be consulted for limiting outputs under these conditions.

6.4.2 ***Operation at Other Than Rated Frequency.*** A reduction in generator frequency at constant voltage/frequency ratio requires the generator to be derated. The amount of derating depends on the type of cooling employed as well as the reduction in speed. The manufacturer should be consulted for the capability of individual generators at reduced frequency. Deviations from rated voltage/frequency ratio will require additional reduction in capability as specified by the manufacturer.

6.4.3 ***Operation at Other Than Rated kVA (Apparent Power).*** Open-ventilated air-cooled generators for gas turbine peaking service sometimes have peaking capabilities above the nameplate rating to match the gas turbine peaking capabilities for short-time duty periods. The temperature rise limits are set either by the standards or the manufacturer in such a way as to make the predicted average rate of thermal deterioration over the elapsed time consistent with the desired life expectancy of the complete power unit and in accordance with economic requirements.

6.5 General Considerations.

6.5.1 ***At Low Ambient Gas Temperature.*** Allowance must be made for increased difference between hot-spot and detector temperatures when exceeding nameplate current. Maintaining a low ambient temperature results in lower total temperature of the windings at all loads, less distortion of the metal parts, and less drying out of the gaskets. In the case of generators cooled with air supplied from out-of-doors, it sometimes is not readily practicable to control the temperature of the cold coolant, which means that at low ambient temperature it may be necessary to throttle the cooling air flow to avoid condensation on the generator surfaces exposed to warm room air.

In the case of totally enclosed generators it may be found advantageous to regulate the raw water flow to the heat exchanger in such a manner as to result in cold coolant temperatures lower than the nameplate value.

In this guide, the term "raw water" will be used to designate the water used to remove heat from the heat exchangers, even though this water might be condensate, well, river, lake, or sea water.

With either manual or automatic regulation, the control points should be chosen in accordance with the manufacturer's recommendations. It should be borne in mind that too low a cold coolant temperature may be detrimental to some insulation systems, and may produce undesirable effects on the mechanical balance of the unit.

In view of the lower losses at low generator loads, the generator hot-spot temperature variation will be reduced by varying the ambient temperature inversely with the load. This method of operation would effect some saving in cooling-water flow at low loads. This is not to be interpreted as a recommendation to operate the generator at constant hot-spot temperature.

In order to maintain all parts of open-ventilated air-cooled generators at a safe temperature, it may be found advantageous to furnish heaters in the generator during periods of shutdown and also to temporarily recirculate the air during startup at initial loading. As the generator is loaded and heated by its losses, the heaters should be removed from service and air recirculation should be discontinued.

6.5.2 *At Low Raw Water Temperature.* Where the raw water supply temperature is below the rated raw water temperature of the coolers, care must be taken to prevent formation of condensation, which will occur if the dew point of the cooling air or gas is higher than the temperature of the coolant. To avoid condensation, a recirculating system to raise the temperature of the raw water may be provided. Dehumidifying-type dryers are available that can be connected into the generator cooling circuit and are suitable for drying air or gas under any pressure at which the cooling system operates. In these dryers, a dessicant absorbs the moisture which then is driven off outside the cooling system. Some users provide for continuous supervision of dew point through the installation of dew-point recorders provided with maximum alarm contacts. Care should be exercised when using very low temperature coolant that a sudden drop in load will not cause the cooling air or gas to reach dew point temperature, which will result in condensed moisture being deposited.

6.5.3 *At High Raw Water Temperature.* Generators must be derated generally for high raw water temperatures. The manufacturer should be consulted regarding the capabilities of individual machines. Refer to Section 7.4.2.

6.5.4 *Concerning Life Expectancy.* Because of the complexity of the process that determines the rate of deterioration of the components of a rotating machine, it is often impossible to coordinate methods of operation with respect to temperature or loading with the normal life expectancy of the machine. For operation at rated loads and at the maximum hot-spot temperatures that these rated loads produce in specified ambient conditions, economically satisfactory life can be realized. The degree of reduction in life to be expected through excessive loadings of a machine is generally indeterminate for rotating machines. Therefore, no quantitative correlation between degrees of overloading and degrees of loss of life is considered possible.

7. Operation

7.1 Requirements for Operation. Operation of a turbine generator requires consideration of several factors.

7.1.1 *Stator Winding Temperature.* Operation of the generator by means of stator winding temperature indications is undesirable, as stated in Section 6. Stator winding temperature indications are useful, however, in providing a continuous record of the temperature history of the unit. Any trend away from past temperature performance is an indication of a change in machine condition and should be investigated.

Instruments used at the switchboard for measuring the temperature of the stator winding by resistance detector operate on the basis of change in resistance of the detector element; they may be made to record the temperatures of a large number of detectors on a continuous recording meter, or to indicate the temperatures on a common meter with a selector switch to connect the individual coils. It is common practice to provide multipoint recorders with adjustable alarm contacts.

7.1.2 *Rotor Winding Temperature.* Operation at power factors less than the rated value in the overexcited region is limited by rotor winding temperature (see Figs. 3 and 4). In this region the full rated kVA (apparent power) of the generator cannot be realized due to this limitation. Any operating method must recognize this limitation. The record of rotor temperature can also be useful in detecting collector ring brush problems. Indications of erratic changes of the temperature can be caused by brush arcing and incipient collector ring flashover.

7.1.3 *Stator Core Temperature.* Operation in the underexcited region is limited by additional heating in the extreme ends of the stator core where temperatures are not detected by the usual stator winding temperature detectors. Due consideration must be given to this effect.

7.1.4 *Stator Differential Expansion.* The capability of the stator winding is limited not only by total temperature and winding vibration, but also by the effects of differential expansion between the stator coils and the stator core. Differential expansion is a function of the total temperatures of the winding and the core. This factor is more critical in long machines than short ones. During load changes the copper temperature changes more rapidly than the core temperature, thus accentuating this differential expansion problem. These factors require that the maximum load on the machine be limited so as to reduce differential expansion and that changes in load be made so as to minimize variations in differential expansion. Frequent variations in differential expansion may result in damage to the stator coil insulation. Modern insulation systems provide more protection against such effects than earlier systems provided.

7.1.5 *Shaft Alignment.* The generator and turbine shafts are usually connected by means of a bolted flanged coupling. During operation, these shafts must be maintained in alignment. Misalignment may cause vibration, increased shaft stresses and a redistribution of the bearing loading, all of which, if excessive, will result in increased mechanical vibration and may lead to mechanical failure.

The variation in elevation of the generator shaft is a function of the temperature of its supporting members. Where bracket and bearings are integral, the temperature of the bracket and the frame which supports it varies directly with the cold coolant temperature. Consequently, the generator shaft elevation varies with the cold coolant temperature. The generator should be operated so as to minimize the possibility of misalignment between the generator and turbine shafts during load changes.

7.1.6 *Frame Distortion.* Extreme changes in the cold coolant temperature may cause dimensional changes of the frame ends, with consequent working of the mechanical joints and gaskets. In the case of hydrogen-cooled machines, this may result in increased hydrogen leakage and maintenance. The performance of the gaskets is also adversely affected by high temperatures. Consequently, the manufacturer's recommendations of cold coolant temperature limits should be followed.

7.1.7 *Condensation on Water Pipes and Frame.* Operation of the coolers with water which is colder than the dew point of the room air will cause objectionable condensation on the external water pipes and frame.

7.2 Capability Curves. Typical generator operating curves are shown in Figs. 3 and 4. Similar curves applicable to the particular generator should be used to guide its operation.

7.2.1 *Stator Winding Temperature.* Since the stator winding temperature detectors may not give a true indication of the hot-spot temperatures, the machine should be loaded within the limits shown on the capability and other operating curves provided by the manufacturer. The capability curve (Fig. 4) shows the limits of operation as governed by stator winding temperature in the overexcited (lagging power factor) and underexcited (leading power factor) regions. It establishes limits for the apparent power (kVA) output, thus limiting heating in the stator winding. Temperature readings should be taken and recorded by the user; since their primary purpose is to indicate incorrect operation or changes in the generator, they are recommended for supplementary information.

7.2.2 *Rotor Winding Temperature.* The capability curve should be used to guide operation in the overexcited (lagging power factor) range below rated power factor to assist in keeping the machine within its limits of rotor heating.

7.2.3 *Stator Core End Temperature.* In the underexcited (leading power factor) region, the capability curve also indicates limits of loading as established by heating of the stator core end structure.

Operation in the underexcited region may lead to a stability problem which is a function of system characteristics and may further limit the permissible loading in this region. See Section 6.3.

7.2.4 *Use of Capability Curve.* The operation of the generator according to capability curves may be accomplished by the use of instruments to measure active and reactive power (kW and kvar), terminal voltage, line current, and when available, field current. Generators are usually operated between rated power factor and unity power factor. In this range, the generator can be controlled by the terminal voltage and line current since the stator winding heating limits the load. Unless specified otherwise, alternating-current generators may be operated within ±5 percent of rated terminal voltage, and safe temperatures will be realized if operation is maintained within the limits expressed by the reactive capability curve.

7.3 Operating Recommendations. It is recommended that the generator be operated in accordance with the generator capability curve and other related operating curves with rated raw water flow in the coolers, except that for partial loads the raw water flow be regulated to maintain the desired internal temperature as recommended by the manufacturer.

Excepting such factors as those involving various hydrogen gas pressures, air-cooled machines are operated in the same fashion as generators employing other coolants.

7.4 Miscellaneous Considerations. Some of the miscellaneous considerations in the operation of a turbine generator are as follows.

7.4.1 *Hydrogen Pressure.* In the case of hydrogen-cooled machines, it is common practice to maintain the hydrogen pressure constant at a value corresponding to the maximum scheduled apparent power (kVA), neglecting momentary load variations. It is uneconomical to reduce this pressure for short-duration reductions in load.

7.4.2 *Use of Hydrogen Pressure Regulation Curve.* A typical hydrogen pressure regulation curve is shown in Fig. 6 for a gas-cooled generator normally rated at 60 psig (515 MN/m^2). It shows the relation between maximum load, maximum permissible cold gas temperature, water temperature and hydrogen pressure for safe operation of a specific machine. The rated quantity and the rated temperature of water required by the generator gas coolers are such as to absorb full-load generator losses corresponding to its basic rating and maintain the cold gas temperature at the corresponding proper value. It will be noted that as the hydrogen pressure changes along a given cooler water temperature ordinate, the permissible load also changes. Operation with the cold gas temperature within the range indicated will not cause variation in generator frame temperature sufficient to change the bearing elevation to an extent that will produce undesirable misalignment of the generator and turbine shafts.

7.4.3 *Hydrogen Purity.* Although the upper limit of an explosive hydrogen-air mixture is 75 percent hydrogen, the purity of the hydrogen gas contained in a hydrogen-cooled generator should be maintained in accordance with

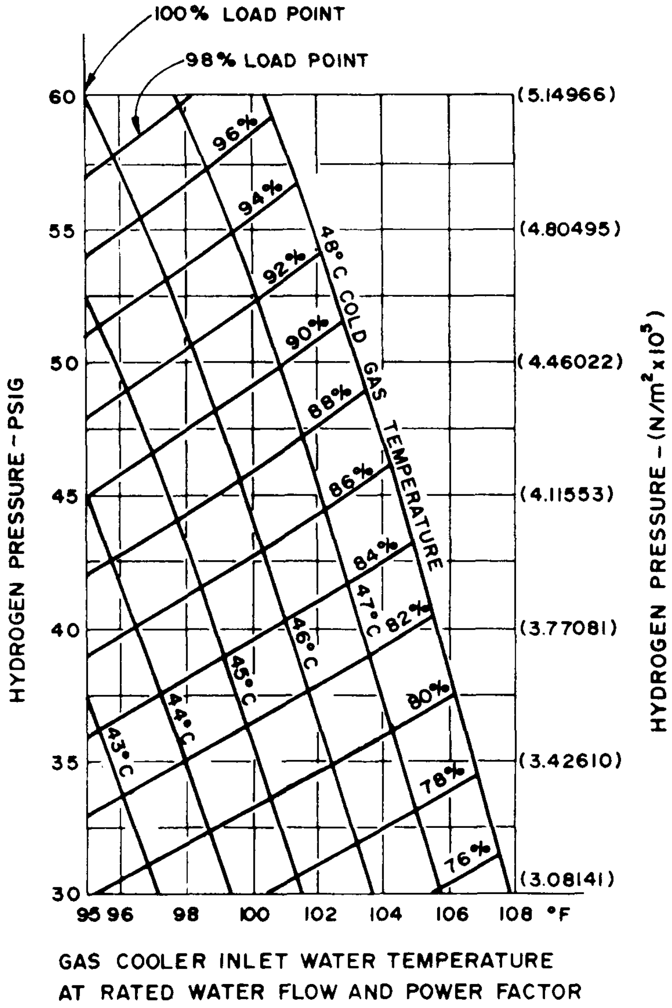


Fig. 6
Typical Hydrogen Pressure Regulation Curve for Gas-Cooled Generators

the manufacturer's instructions for the most effective use of the hydrogen as the cooling agent. Experience indicates that purity will range from a value of approximately 95 percent up to approximately 99 percent according to length of time in service. However, when necessary, an operating range between 90 and 96 percent is allowable and is considered safe. While the machine is filled with hydrogen but shut down, whether at standstill or slow roll, the desired purity must also be maintained to prevent an explosive mixture.

In order to prevent an explosive hydrogen-air mixture inside the generator during the act of filling the machine with hydrogen or removing the hydrogen from it, an inert gas such as carbon dioxide (CO_2) must be used to thoroughly purge the air or hydrogen inside the machine casing.

7.4.4 *Operation of Hydrogen-Cooled Generators in Air or CO_2.* As a general rule a hydrogen-cooled generator should not be operated in air or CO_2 without first having obtained the manufacturer's limitations, since there is a possibility of failure of some generator components due to the higher density of these gases.

7.4.5 ***Initial Filling of Coolers.*** When initially filling the coolers, the flow of raw water should be controlled so that the entire cooler will be vented and filled with water at a rate such that the design pressure will not be exceeded due to water hammer.

With multisection coolers which are in series for gas flow and in parallel for water flow, care must be exercised to equalize the water flow through the sections. This may be done by the use of flow meters or pressure gages on the water flow to the sections. It cannot be done by equalizing the water or gas temperatures.

7.4.6 ***Normal Cooler Operation.*** The flow of water to the coolers should be controlled so that the entire cooler will be filled with water by continuous venting and so that design pressure will not be exceeded.

7.4.7 ***Control of Raw Water During Load Changes.*** There is no inherent lower limit in the active power (kW) loading of a generator itself, although the prime mover and associated equipment may impose such a limit. When operating at loads varying from a low value up to rated full load, the desired degree of cooling system control depends on the time duration and extent of the load swings. Where load swings are more or less unpredictable and irregular, some form of automatic regulation of the raw water is advantageous. Any method of controlling the raw water flow should avoid reaching the dew point of the cooling air or gas.

When the raw water to the cooler is above the rated temperature, the water flow may not be increased without the possibility of incurring damage to the cooler tubes by erosion.

7.4.8 ***Control of Raw Water Prior to Shutdown.*** When load is being reduced on a unit, prior to shutdown, the raw water flow should be controlled so as to maintain desired internal temperatures as recommended by the manufacturer.

7.4.9 ***Stator Coil Water Conductivity.*** In water-cooled generators, the water is circulated through each bar, through hollow conductors or tubes, to remove the heat generated in the stator winding. In order to minimize leakage current, it is important that the water have a low conductivity.

7.5 Starting, Quick Starting and Rate of Load Changes. This section does not give complete instructions on starting turbine generators but discusses some important aspects of the problem.

When starting a turbine generator, by either the long-time slow-warmup or the quick-start method, the rate of speed increase from zero speed to full speed is a matter of concern only in respect to the prime mover and is immaterial in respect to the generator or exciter, unless the manufacturer has specified special limitations.

Starting and load changing procedures depend on the method of cooling (refer to Section 4) and the type of excitation system. In addition, special procedures are required for generators driven by cross-compound turbines. The manufacturer's recommended procedures should be followed.

In the process of starting a machine, the following precautions should be carefully observed.

(1) For the first start of a new machine or after any work has been done on any connections that involve synchronizing, it is essential to verify the agreement of phase rotation and of phase correspondence of the generator with the system and other connected generators.

(2) Standards do not require design of a machine able to withstand currents and mechanical forces due to incorrect phasing or incorrect synchronizing. In general, the synchronizing accuracy should be such that at the moment of closing of the synchronizing breaker contacts, the phase angle between the generator and the bus is as close to zero as possible. In order to facilitate this procedure, the speed of the unit should be matched to the system speed such that the synchroscope is revolving clockwise at a speed not greater than one revolution every 15 s. Consideration should be given of the breaker closing time in establishing the initiation of synchronization. The voltage of the incoming generator should be matched to the system immediately prior to synchronizing. The use of automatic synchronizing is recommended to avoid errors.

(3) Cross-compound units whose generator stator windings are permanently tied together must not be permitted to operate with excitation applied when the generators are out of synchronism with each other, or with one or both generators at rest. For special synchronizing procedures see Section 7.10.

Except for the precautions in regard to synchronizing, phase relations, and preheating (see Section 7.11), the starting procedure of turbine generators is primarily determined by the requirement of the prime mover, and such procedures are generally the result of the manufacturer's recommendations and user's experiences.

When a single generator supplies an isolated load, the rate of load change on the machine depends solely upon the rate at which the external loads are switched on or off, provided that the turbine governor operation is such as to hold rated speed. In this type of system the power factor of the generator and the active and reactive power (kW and kvar) loading are determined by the load demands.

In a system supplied by a number of turbine generators operating in parallel, the division of active power (kW) on any generator depends on the mechanical torque applied to each generator by its turbine and is controlled by action of the turbine governor. The division of active power (kW) is practically independent of excitation; however, the division of reactive power (kvar) among generators is a function of excitation. The relationships and limitations of the active and reactive power (kW and kvar) loading of generators are covered in Section 6.

The ability of any generator to follow a load change is determined solely by the sensitivity and speed of response of the turbine governor. The governor may be equipped with an electric speed changer and arranged for manual control or for automatic frequency control.

7.6 Shutdowns. As with the considerations for starting, the stopping or shutdown procedures for turbine generators are determined by the requirements of the prime mover. Frequent starting and stopping (cycling) is extremely rigorous duty for a generator and should be considered as a factor in the life expectancy of the windings and rotating mechanical parts.

For normal operation, the procedure is determined by the manufacturer's recommendations and user's experience.

Under emergency shutdown, different procedures are used depending upon conditions. In case of emergency, the unit may be reduced in speed rapidly by applying or increasing the field current, provided the differential or ground relays did not trip the machine or indicate any faults. A simple guide to allowable excitation would be a constant voltage/frequency ratio basis. A maximum field current of 110 percent of the no-load normal voltage value is usually recommended, although in some cases higher values may be authorized by the manufacturer. Excessive field current at no load causes magnetic flux saturation in the armature core and forces flux into the stator frame resulting in eddy current heating in the stator frame structure. It may also adversely affect external equipment such as power transformers, potential transformers, etc.

When shutting down a generator with the field excited, all remaining excitation should be removed at about 1/3 to 1/4 of rated speed to prevent excessive field winding temperature due to lack of adequate ventilation at low speed.

7.7 Automatic Supervision and Protection. In order to reduce operating manpower, obtain more adequate supervision and protection, and prevent or minimize possible damage to the generator, devices are provided to give alarm and/or to initiate shutdown of a unit when certain limits are reached. Although the extent to which it may be desired to provide such facilities may depend somewhat upon such factors as the age, type, rating, and importance of the machine, suitable devices are available to meet these protective problems.

7.7.1 *For Stator Winding.* Protective devices for the stator winding which will initiate removal of the generator from the system, deenergize its excitation, and sometimes trip the turbine stop valves, are generally provided to function for the following faults:

(1) Balanced and unbalanced faults beyond the generator breaker

(2) Balanced and unbalanced faults ex-

ternal to the generator up to and including the generator breaker. For limitations under short-time unbalanced fault conditions, refer to the paragraph on "Short Circuit Requirements" in ANSI C50.13-1965

(3) Insulation failure of the generator winding and other internal faults

7.7.2 *For Rotor Winding.* Protective devices for the rotor windings which may be used to initiate the removal of the generator from the system or for alarm purposes only are generally provided to function for the following faults:

(1) Short circuits in rotor winding
(2) Open circuits in rotor winding
(3) Grounds on the field circuit

7.7.3 *For Other Conditions.* These and other protective devices often are provided to alarm and/or trip the generator for the following conditions:

(1) Excessive current in stator or rotor
(2) Unbalanced current operation
(3) Out-of-step operation
(4) Loss-of-excitation
(5) Excessive temperatures
(6) Excessive vibration
(7) Failure of bearing insulation
(8) Fire
(9) Reduced flow of coolant
(10) Excessive voltage/frequency ratio
(11) Operation beyond the underexcitation limit
(12) High conductivity of coolant
(13) Stator winding ground current
(14) Excessive bearing temperatures
(15) Field ground detection

7.8 Unbalanced Current Operation. Operation of a generator under a condition of unbalanced-phase armature currents, produces eddy currents on the surface of the rotor and in the rotor wedges. These eddy currents are at a frequency that is twice the rated frequency of the generator (120 Hz for a 60-Hz machine) and their magnitudes depend not only on the unbalance between the various phase currents, but also on the actual amounts of these currents. These eddy currents must flow along the wedges and tooth surfaces, from wedges to the teeth, across the wedges at the ends of the rotor body or into the retaining ring and in the amortisseur winding, if provided. Localized heating is produced at the wedge joints and retaining ring fits, in addition to heating of the rotor surface. Excessively unbalanced phase currents may cause localized overheating of the wedges or retaining rings due to these eddy currents.

Fig. 7 shows curves which may be used to calculate negative phase sequence current when the magnitudes of the three unbalanced phase currents are known, and Fig. 8 shows a typical set of curves for an indirectly-cooled generator which can be used as a rough guide to indicate quickly whether any given unbalance in armature currents is permissible. A helpful rule-of-thumb for calculating current components with these low values of unbalance is that the positive phase sequence current is approximately the average of the three phase currents, and the negative phase sequence current is approximately the maximum deviation of any of the phase currents from the average. For directly-cooled generators, the maximum permissible negative sequence current is in the order of 0.08 to 0.09 of the per-unit rated phase current (for the gas pressure being used for operation) for generators up to approximately 1000 MVA. These limits necessarily ignore many important factors of design and operating conditions, such as increases in torque pulsations, losses, effects of zero phase sequence currents and effects of harmonic currents. Users should consult the manufacturer for more accurate recommendations in specific cases. Capability during unbalanced, steady-state, and fault condtions is specified in ANSI C50.13-1965.

7.9 Out-of-Synchronism Operation (Field Maintained). Operation of a generator out-of-synchronism with part or full-field excitation maintained places the most severe type of duty on the unit. Such operation produces heavy surge currents in the armature windings of a magnitude that may exceed those associated with the machine short-circuit requirements (ANSI C50.13-1965) and cause serious damage to the winding. Such operation also produces torque reversals that create, in many parts of the unit, high mechanical stresses of magnitudes that may be several times those produced by rated torque. High induced voltages and currents in the field circuit may cause flashover of the collector rings and of the commutator of an associated exciter.

For these reasons, although it may be diffi-

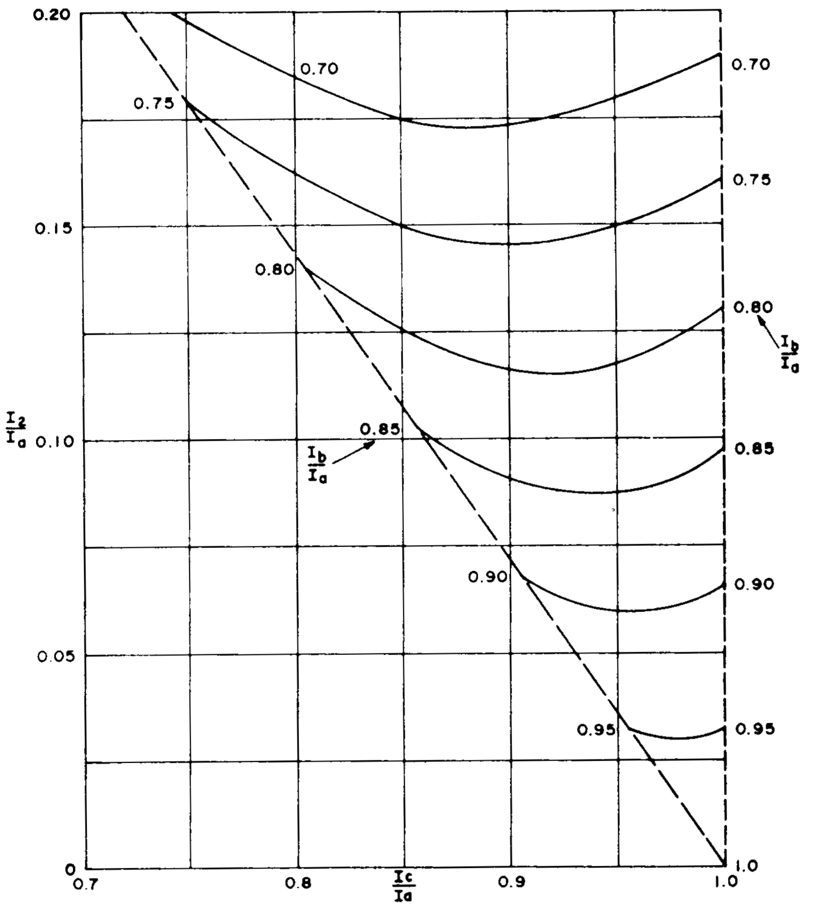


Fig. 7
Negative Phase Sequence Current Calculation Curves
(for case of no zero phase current)

I_a = Largest of three phase currents
I_b = Smallest of three phase currents
I_c = Third phase current, of intermediate value
All currents in per unit or in amperes

cult to identify the out-of-synchronism condition, it must be identified promptly and the condition remedied. Possible corrective action includes removal of the unit from the system.

7.10 Loss of Field Excitation. Complete loss of excitation on an operating generator can result in dangerous overheating of its rotor within a very short time unless the machine is disconnected from the system. Large generators having cylindrical rotors without amortisseur windings are particularly vulnerable in this respect. The degree to which this heating will occur depends on the initial load on the generator, the manner in which the field current is lost, and the manner in which the generator is connected to the system. When excitation is lost, the generator tends to overspeed and operates as an induction generator. This overspeed normally results in a reduction in load due to the characteristics of the turbine governor, as well as an increase in armature current associated with low voltage at the generator terminals, and is accompanied by high rotor currents. These rotor currents will flow both through the rotor winding

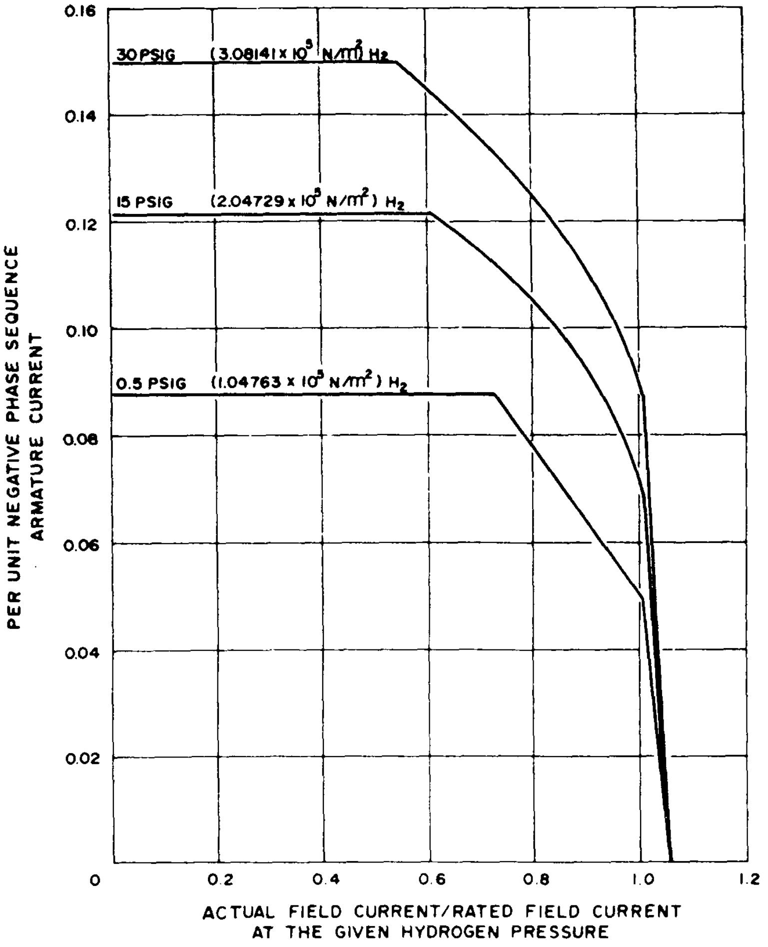


Fig. 8

Typical Allowable Negative Phase Sequence Stator Currents for an Indirectly Cooled Generator

(provided the field circuit is not open) and through the rotor body, completing the circuit at the end of the rotor body. The rotor body currents will cause high and possibly dangerous temperatures in a very short time, particularly where the currents flow across the wedges and retaining rings at the ends of the rotor body. Since the loss of field condition also corresponds to operation with very low excitation, overheating of the end portions of the stator core may result.

Some users provide a loss-of-field relay to trip the generator breaker removing the unit from the system and in some cases also to trip the turbine stop valves, while others provide alarm indication only. Time can often be saved on single-shaft generators by avoiding tripping of the stop valves and following precautionary checks to restore excitation and resynchronize to the system. Cross-compound sets with directly interconnected stator circuits can be resynchronized with the system only if the elements of the set are in synchronism with each other. If the elements of the set are out of synchronism, normal starting procedure must be used to return the set to the line.

Recent developments in the industry have established that it may be possible to resynchronize particular cross-compound generators, after an accidental trip, without returning the two generators to turning gear speed. This procedure should be established only after very careful consideration with the manufacturer.

Where neither loss-of-field tripping nor alarm indication is provided, the operator must recognize the condition and manually perform the functions described for the relay above. If the loss-of-field condition has persisted for some considerable or unknown length of time, the rotor should be inspected at the earliest opportunity.

If excitation is lost, the usual procedure should be to return the machine to the system using the normal synchronizing procedure. If excitation is lost by circumstances such as accidental tripping of the field breaker, tripping the generator breaker may sometimes be avoided by immediately re-establishing the excitation.

7.11 Field Preheating. This is not a requirement on modern generators because the improvement of conductor materials has reduced the likelihood of damage from normal thermal cycling. On older units, preheating of some large generator fields may be used to minimize rotor winding deformation which is caused by the interaction of centrifugal force, expansion, and contraction due to temperature changes. For example, when a machine is started up normally without preheating, it is brought up to speed with the rotor body and field winding at essentially the same temperature. As the speed is raised toward full speed, the centrifugal force clamps the field winding to the rotor body indirectly through the wedges. Then when excitation current is applied before the machine is synchronized and later when the field current is increased as the machine loading is increased, the winding conductors try to expand axially but cannot do so because they are clamped in position by centrifugal force and friction. This results in compressive stress which may be beyond the ability of the metal to withstand for many cycles. When the machine is shut down and the centrifugal forces are released, the winding may become permanently shortened. This may result in end-turn distortion after a number of thermal cycles. Since the wear and tear on the insulation as well as the distortion of the windings is a function of the numbers of starts and stops, pre-heating becomes more desirable as the frequency of the number of shutdowns increases.

In any particular case the user should consult the manufacturer concerning the need for field preheating. Caution is required for units with direct-connected transformers because of the possibility of damage to the transformers from the increased exciting current with low-frequency operation.

It may be desirable in some cases to prewarm the rotor forging when starting up or overspeeding the unit in order to reduce its susceptibility to brittle failure. When this is required it should be carried out in accordance with the manufacturer's recommendations.

7.12 Operation With Field Circuit Grounded. Usually the rotor winding and all of its excitation supply circuit is operated as a completely ungrounded system. On such a system, the existence of a single ground at any point in the system will not interfere with the normal operation of the generator. Its presence can be detected by a suitable ground relay and alarm. Upon indication of this initial ground it is advisable to shut down the machine and correct the trouble promptly.

If the initial ground should occur at some point in the generator rotor winding, a second ground in the excitation circuit may prove serious. When a double ground exists, part of the field winding will be shorted out through the shaft forging. This condition will cause a magnetic and/or thermal unbalance that may result in serious vibration of amplitude sufficient to wreck the machine if allowed to exist too long. The use of vibration detection and protection equipment would assure instant knowledge of such a condition and take the machine off the line more quickly than the time it would take an alert operator to become informed and take corrective action.

Loss-of-field relay protection cannot be depended upon to trip the generator in case part of the rotor winding is short-circuited by a double ground because:

(1) Its operation is based upon the principle of reactive power (kvar)

(2) It is not sensitive to either magnetic or thermal unbalance in the rotor nor the resultant vibration

(3) The change in reactive power (kvar)

caused by the partially shorted field may not be sufficient to actuate a loss-of-field relay

7.13 Field Forcing by Voltage Regulator. Continuous-acting fast response voltage regulators used with exciters having high ceiling voltages are employed by many users to improve system stability and reliability. At times of prolonged system low voltage, this automatic equipment can impose a severe overload upon both the field and armature. For a particular unit, the manufacturer should be consulted to determine the maximum time the overload condition can be permitted. Automatic means should be provided to relieve the overload at the end of this time and return the machine to its maximum permissible continuous load.

7.14 Loss of Coolant Flow. In the event that stator winding cooling water flow is lost in a directly-cooled machine, the generator output must be reduced to the manufacturer's recommended capability without coolant flow. This load reduction must be accomplished in a limited amount of time. When loss of flow is also accompanied by high conductivity of the water, the reduced load may be carried only for a limited time, in line with the manufacturer's recommendations. Under these circumstances, if flow cannot be re-established within acceptable conductivity limits (thereby permitting the resumption of normal loading), the unit must be taken off the line and excitation removed. The coolant can then be thoroughly removed in accordance with manufacturer's instructions and the no-flow capability restored.

7.15 Operation Under Extreme Emergency Condtions. Under extreme emergency conditions, a power system may experience large disturbances in voltage, current, power flow, and frequency, even to the point that some generators may not remain synchronized with the system. It may be necessary for the operator to decide quickly whether and when to trip a given generator from the system. By keeping the generator connected to the system the operator would support the power system and possibly prevent its collapse if it remained synchronized with the system, but would accept unusual risk of damage to the equipment. It is not possible to anticipate all of the contingencies that extreme system emergencies can produce, nor is it possible to discount the hazards of interaction of two or more simultaneous stress conditions.

Due to the complex relationships and the many factors involved, it is recommended that guidelines concerning action to be taken during such conditions be prepared by the user for each generating unit. The guidelines should constitute a portion of an overall system plan to alleviate system conditions sufficiently to preclude the necessity of operating the generators under extreme emergency conditions for any but very short time periods; and even then, there can be an unusual risk of incurring equipment damage. These plans should be the result of careful evaluation of the effects of operating at extreme conditions based not only on consultations with equipment suppliers but also, where possible, on results of composite nondamaging tests of the actual unit and its associated auxiliaries to determine specific limiting conditions for the unit as a whole. Such testing may be difficult because, for example, conventional temperature instrumentation may not follow fast transients and may not be located at the areas which would become limiting under abnormal conditions. Also, many points that may incur critical stresses have no instrumentation to indicate their level.

If the user elects to load the generator beyond its rated capability at his own discretion and risk, he should evolve operating restrictions on definable parameters of plausible emergency conditions, such as:

(1) Duration
(2) Stator voltage and phase unbalance
(3) Frequency
(4) Voltage/frequency ratio
(5) Stator current
(6) Field voltage
(7) Field current
(8) Voltage regulator output
(9) Exciter output
(10) Observable temperatures and rates of rise
(11) Stability limits
(12) Vibration limits

The user must also give consideration to the characteristics of the main and auxiliary transformers and power plant auxiliaries including instrumentation, particularly as affected by low frequency and voltage, in arriving at "minimum-risk" emergency operating procedures. In addition, turbine vibration and blade resonance conditions may be encountered at reduced speed.

During system emergency conditions, the automatic regulation equipment (including voltage/frequency protection) should always be in service in order that the benefits of automatic response be realized when operating critieria are rapidly changing.

8. Maintenance

8.1 General Considerations. Parts of a turbine-generator such as collector brushes are subject to wear and require frequent adjustment and replacement. Other parts such as coolers and the ventilating system may accumulate dirt or foreign material and require occasional cleaning. Winding insulation deteriorates with age and requires careful inspection and maintenance to obtain reliable service. All parts are exposed to continual vibration, stress, and temperature changes, and may in time become loose or possibly fracture. As a consequence, it is important to observe the operation of the unit and to investigate any unusual changes in the performance, sound, temperature, vibration, or appearance. In addition, a regular schedule of inspection, testing, and preventive maintenance should be adopted so that minor troubles may be eliminated before they develop into major ones.

The expense of inspecting and maintaining machines which appear to be in good condition, rather than operating the machine until failure occurs in service, can be justified on the basis of increased reliability and lower overall cost. Furthermore, there is a distinct advantage in maintaining machines at periods when outages can be planned so as not to interfere with peak loads on the system.

Many parts of the machine may be given routine checks while the machine is operating. The more complete inspections and maintenance will require shutdown and some disassembly. In general, it is recommended that a complete inspection be made after the first year of operation. Thereafter, it may be possible to operate for several years between general inspection periods. The time between inspection periods should be determined by the manufacturer's recommendations and the user's experience. Consideration should be given to the number of hours of operation, number of starts, number of severe short circuits on the system or other high-current transients, outages for turbine repairs, conditions found in previous inspections, and other factors.

8.2 Collector Rings and Brushes. In order to insure that the collector rings and brushes are in good operating condition and thereby to avoid trouble, the following maintenance schedule is recommended.

8.2.1 *Daily Inspections.* Since trouble from defective brushes can develop suddenly, it is recommended that a visual inspection of the brushes be made during each daily work shift. If sparking of the brushes or excessive brush dust or vibration is detected, the brushes should be serviced as explained under the weekly inspection.

8.2.2 *Weekly Inspections.* Once a week the brushes should be given a complete inspection as follows. If the following operations are carried out while the machine is in service, the necessary safety precautions should be observed.

(1) Excessive dust should be removed from the collector-ring insulation and brush rigging. This may be accomplished with compressed air. If dust is allowed to accumulate, it will likely cause breakdown in the insulation. It may also cause sticking of the brushes in the holders unless removed regularly.

(2) Take each brush by the shunt and move it up and down in the holder. This serves two purposes: to shake the dust out of the holder and to check the brush freedom in the holder.

(3) Replace any worn brushes when necessary.

(4) Adjust the pressure of all brushes to the value recommended by the manufacturer. It is important that this pressure be maintained and that the pressure be effective in keeping the brush in firm contact with the collector.

(5) Check to be sure that all brushes and brush holders are correctly aligned in accordance with the manufacturer's instructions. No brush should overhang the edge of the collector ring under any operating condition.

(6) Check the smoothness of collector ring operation as indicated by brush vibration. If the brush is riding rough or the collector ring seems eccentric, the collector rings should be examined carefully at the earliest opportunity to determine if reconditioning is necessary.

8.2.3 *Shutdown Inspection.* Whenever a complete brush replacement is made or at the time of major shutdown, the brush and collector ring assembly should be given a complete servicing. Brush operation and ring wear are benefited by occasional reversal of collector ring polarity. In addition to the routine carried out of each weekly inspection, the following work should be done.

(1) The collector insulation should be cleaned thoroughly. If there is evidence of oil, the collector assembly should be wiped clean with a cloth slightly dampened with a cleaning fluid recommended by the manufacturer and thoroughly dried. Excessive wetting with fluid may wash impurities into inaccessible crevices. The use of chlorinated cleaning fluid should be avoided because of adverse effect on brushes. The insulation resistance of the collector insulation and rotor winding should be measured with an insulation resistance tester. If the insulation resistance is unsatisfactory, based either on previous readings or on values stated in IEEE Std 43-1961, the collector leads should be inspected for sources of low insulation resistance and, if necessary, segregated or dried out in accordance with usual procedure.

(2) The collector rings should be checked to see that they are cylindrical and running true within the limits set by the manufacturer. Rough collector rings will cause momentary separation between the brush and ring, with burning of the ring resulting. Vibration of the collector ring or brush rigging will also cause this trouble. In general, blackening and cutting of the collector rings is an indication of poor brush service. Rings in this condition will have to be ground in order to restore them to a true and smooth condition.

(3) The inside of the brush holder boxes should be cleaned before installing new brushes and the brushes wiped off where they are not replaced. Brushes of different grades should not be mixed. The grade should not be changed without consultation with the manufacturer.

(4) Replace any worn or damaged parts and check all items given under weekly inspection.

8.3 Air Filters. Dirty air filters will reduce the amount of cooling air circulated, resulting in possible overheating of parts. They will also allow the entrance of dirt and grit which may damage the machine and choke the ventilating ducts. Air filters should be inspected periodically and cleaned or replaced when necessary.

8.4 Gas or Air Coolers. The effectiveness of coolers will be reduced due to accumulation of sludge or other matter in the cooler tubes. If water conditions are such as to cause the accumulation of foreign material in the cooler, periodic cleaning should be carried out. Dirt in the cooler or deterioration of the cooler performance is indicated by an increase in temperature difference between the average water temperature and the average gas temperature for the same load condition.

The effectiveness of the coolers will also be reduced if the outer heat transfer surface of the tubes becomes dirty due to oil, dust or other causes.

The cooler tubes should be examined for traces of moisture, and the drains checked for water which may indicate leaks. Whenever the machine is shut down during freezing weather, all water should be drained from the cooler tubes if the coolers are exposed to the low temperature.

Cooler tubes of air-cooled generators may be cleaned when required with the unit in operation. The manufacturer should be consulted as to the limiting values of output to be observed during the tube cleaning process.

In the case of hydrogen-cooled machines, cleaning of the tubes when hydrogen is in the casing is extremely hazardous and is not recommended. If the operator chooses to accept the hazard potential associated with this operation, the manufacturer should be consulted as to the limiting values of hydrogen pressure and output to be observed during the tube cleaning process.

8.5 Hydrogen Leak Detection. In general, hydrogen leaks are indicated by excessive hydrogen consumption. If the amount of hydrogen required per day to maintain a given gas pressure is much in excess of normal or the manufacturer's guarantee, there may be some abnormal leakage and the matter should be investigated and corrected. The presence of leakage can be detected by observing the ability of the system to hold gas under pressure. To obtain satisfactory results it is necessary to correct the observed pressure drop for changes in temperature and barometric pressure. Formulas for calculating gas leakage when these corrections are made are as follow:

$$L = 238\left[\frac{V}{H}\;\frac{P_1 + B_1}{273 + T_1} - \frac{P_2 + B_2}{273 + T_2}\right]$$

where

L = leakage for average gas pressure, cubic feet per day
P_1 = initial gas pressure, inches of mercury
P_2 = final gas pressure, inches of mercury
B_1 = initial barometric pressure, inches of mercury
B_2 = final barometric pressure, inches of mercury
T_1 = initial temperature, °C
T_2 = final temperature, °C
V = gas content of generator, cubic feet
H = duration of test, hours

$$L = 0.07028\,\frac{V}{H}\left[\frac{P_1 + B_1}{T_1} - \frac{P_2 + B_2}{T_2}\right]$$

where

L = leakage for average gas pressure, cubic meter per day
P_1 = initial gas pressure, newtons per square meter
P_2 = final gas pressure, newtons per square meter
B_1 = initial barometric pressure, newtons per square meter
B_2 = final barometric pressure, newtons per square meter
T_1 = initial temperature, kelvins
T_2 = final temperature, kelvins
V = gas content of generator, cubic meters
H = duration of test, hours

If the leakage tests are made with air, the results should be multiplied by 3.75 to obtain the equivalent leakage of hydrogen of 98 percent purity. This is in accordance with the law of gas leakage, being inversely proportional to the square root of the molecular weight if the pressure is constant.

If the leakage rate is not within specified limits, a systematic search for leaks should be made either with soap or other liquid solutions or by means of leak detectors for Freon 12. The use of odorants such as ether is not recommended.

Liquid soap solutions provide a relatively quick and simple method of leak detection and evaluation. They are not suitable for inaccessible parts or for very small leaks. Solutions of industrial or domestic liquid soap with the addition of glycerine as a thickening agent are satisfactory. Liquid soap will form bubbles when applied over a small leak and will form craters where the gas blows through when applied over a large leak. The hydrogen piping can be isolated from the generator and tested independently.

Hydrogen leaks around the generator, and concentrations of hydrogen gas at any point in the lubrication system or the structure surrounding the generator, may be detected by means of a combustible gas meter[1] or by use of an ultrasonic probe. Devices employing heated grid plates are not to be used with hydrogen in the machine.

The location of leaks may also be determined by injecting Freon 12 gas into the generator at the rate of 1 lb per 500 cubic feet (1 kg per 30 cubic meter) of machine volume. Freon is inert, nontoxic, and readily available in bottles containing 10 lb (4.5 kg) or 22 lb (10 kg) of gas. Very small quantities of Freon at leakage points can be detected with the aid of suitable halide detectors. Halide detectors are, in the words of the manufacturer, "just a little safer than a candle flame." *They must not be used with hydrogen in the generator.*

8.6 Complete Inspection. For a complete inspection, the end shields should be removed and, in the case of large generators, the rotor should be removed from the stator. Great care should be exercised in removing the rotor to avoid damage to the armature punchings, stator windings, bearings, machined surfaces of the stator, collectors, rotor fans, bearing journals, or retaining rings on the rotor. If fan

---

[1] One source of such a meter is the Mine Safety Appliance Company.

blades are removed, they should be carefully identified for replacement. Identification marks should be made by nondamaging means. Prick punches, chisel marks, number stamps, and similar surface-damaging devices should generally be avoided. Particular attention should be given to the following parts.

8.6.1 *Armature Windings.* The ends of the armature winding should be inspected for deposits of oil and evidences of corona discharge. Corona is indicated by white spots on, or disintegration of, the insulation varnish at high dielectric stress points. If cleaning is necessary, the procedure given under 8.7 should be followed. After cleaning, the winding connections and insulation should be carefully inspected. All bracing and cording should be inspected for looseness. Stresses set up by short circuits, vibration, or thermal expansion may cause damage and consequent movement of these parts. If there is any sign of movement, tape separations, cracking, insulation swelling, compound migration, mechanical damage from loose metal pieces, loose slot wedges, corona damage, or other trouble, suitable repairs should be made. Gas passages should be checked and any obstructions removed. Refer to IEEE Std 56-1958, Guide for Insulation Maintenance for Large A-C Rotating Machinery.

In liquid conductor cooled machines all connections, hoses, and piping should be inspected and tested to insure that there are no cooling system leaks.

8.6.2 *Armature Core and Frame.* The armature core finger plates and structural parts should be inspected particularly for evidence of hot spots as shown by discoloration, looseness, or damaged punchings. Powdered red oxide of iron may be an indication of fretting between iron or steel parts, fretting between stator wedges and core laminations, or core looseness. The bore of the stator should be thoroughly inspected to make sure that no foreign metallic objects are present. If the core is in need of painting, all surfaces should be cleaned as recommended in the section on cleaning, and the punchings sprayed with oil-resistant varnish. The inside of the frame should be checked for evidence of oil which would indicate oil leakage from the shaft seals past the oil deflectors or from bearing housing joints.

8.6.3 *Rotor.* The rotor should be examined for movement or distortion of field coils and end winding blocking, dirt in ventilating ducts, loose wedges, local hot spots on the rotor surfaces, and evidence of overheating or burning at the contact surfaces between the wedges, retaining ring, and rotor body. If evidence of local heating is found, the manufacturer should be consulted as to the need for internal inspection to determine if repairs are necessary. The collector rings and field leads should be cleaned and inspected for evidence of local heating. If necessary, the outside surfaces of the rotor body and retaining rings should be cleaned and a coat of varnish should be applied to prevent rusting. Only a thin uniform coat should be applied since the rate of heat transfer from the rotor surface may be appreciably reduced by a too-heavy buildup of total thickness of varnish and uneven thickness may lead to nonuniform temperature and hence vibration.

8.6.4 *Terminal Bushings.* Stator lead bushings should be inspected for evidence of cracks, looseness of parts, or oil leakage, and should be thoroughly cleaned.

8.6.5 *Fans.* Fan blades should be inspected for cracks. Suspected blades should be tested by some means such as the fluorescent or red dye, or magnetic particle methods, taking care that the windings are fully protected.

8.6.6 *Retaining Rings and End Discs.* Retaining rings and discs should be tested for cracks by some means such as the ultrasonic detection, fluorescent or red dye, or magnetic particle methods, taking care that the windings are fully protected.

8.6.7 *Hydrogen Seals.* A complete inspection of hydrogen seals should be made in connection with each major overhaul, at which time the seal should be dismantled completely and the seal oil grooves and holes cleaned and refinished if necessary. The wearing surfaces of the seal ring and shaft should be checked for alignment and wear, refinished if necessary, and the complete seal reassembled with extreme care in order to insure proper shaft-to-seal clearance in the final assembly.

8.6.8 *Seal Oil and Vacuum Pumps.* The hydrogen seal oil and vacuum pump and motors should be dismantled for a thorough inspection in connection with each major overhaul.

8.6.9 *Bearings.* The bearings should be inspected carefully and proper means used to assure a continuous bearing surface. The bearing assembly should be checked for tightness and true alignment. If particles of dirt are found embedded in the babbitt, the entire lubricating system should be flushed out and the oil cleaned.

8.6.10 *Gas Control.* The operation of all gas control equipment and the alarm system should be tested.

8.6.11 *Miscellaneous.* All accessible bolts of the unit should be checked for tightness. Damaged gaskets should be replaced.

8.7 Cleaning and Painting. Dust should be removed, preferably by a vacuum cleaner. If compressed air must be used, care should be exercised in the application of pressure so as not to damage the insulation. The usual safety precautions for handling compressed air should be observed. Since condensation often occurs in air lines, it should be ascertained that the air is free from moisture before being directed into the generator. All exposed surfaces may be wiped with clean cloths to remove any remaining oil or dirt. It may be necessary to use a cleaning solution recommended by the manufacturer in order to effectively remove the dirt.

Care should be exercised in using cleaning fluids because of their toxic effect and possible explosion hazard. Special attention should be given to ventilation, and it is suggested that any cleaning work be done by more than one workman so that if one is overcome the others can help him.

Any cleaning fluid is more or less a solvent for insulating compounds, hence the application of these fluids in large quantities should be avoided. They should not be allowed to remain in contact with the winding any longer than necessary to remove the oil and dirt. Excessive wetting should be avoided as it washes impurities into inaccessible crevices.

After the windings and core have been cleaned, they should be inspected carefully for any signs of deterioration. If required, one or two very thin coats of insulating varnish recommended by the manufacturer may be applied. Compatibility between new and existing varnishes should be checked. The unnecessary and frequent application of coats of varnish may result in more harm than benefit.

8.8 Moisture Protection. While the end covers are off the machine for inspection during shutdown, the coils should be protected from dirt and moisture and the temperature within the machine should be kept above the surrounding air. If for any reason the machine cannot be kept dry during this time, then the normal procedure recommended by the manufacturer should be followed to determine if dry-out is needed before the machine is returned to service.

8.9 Testing. For proper maintenance of the machine, it is necessary to combine tests of proven significance with visual inspection. The use of either visual inspection or any presently known test procedures alone is not sufficient for a proper understanding of the condition of the machine. Both visual inspection and proper test procedures must be utilized and coordinated in order to reach a sound conclusion.

In the maintenance of generators, the user is concerned principally with three problems:

(1) Providing the basis for an immediate decision as to the serviceability and any necessary corrective action

(2) Observing the long-time trends in behavior

(3) Anticipating and thereby avoiding possible service failures

Each of the following tests is directed toward detecting a particular type of trouble, or to follow long-time trends. All tests are not required at every inspection period. The method of making these tests and the interpretation of the test results are discussed in greater detail in IEEE Std 43-1961, Recommended Practice for Testing Insulation Resistance of Rotating Machinery, and IEEE Std 56-1958, Guide for Insulation Maintenance for Large A-C Rotating Machinery.

(1) Insulation resistance tests at low-voltage direct current are primarily to detect grounds and wet or dirty insulation. Tests at 500 to 5000 V are included.

(2) Insulation resistance tests at high-voltage direct current reveal characteristics which may not be disclosed by the low-voltage test.

(3) Dielectric absorption tests furnish information concerning the relative condition of the insulation with respect to moisture and other contaminants.

(4) Dielectric overvoltage tests establish at the time of test that the winding is capable of withstanding the applied voltage. Such tests may be destructive to a greater or lesser extent. Both alternating-current and direct-current tests have been widely used for maintenance overvoltage testing. To avoid the possibility of causing an extensive insulation fire, dielectric overvoltage tests should be made only under one of the following conditions:

- (a) In air with end bells removed so that the windings are readily accessible
- (b) In hydrogen atmosphere of safe purity with generator closed
- (c) In CO_2 atmosphere with generator closed

(5) Insulation power factor tests are used to detect moisture and voids in the insulation and indicate amount of ionization. See IEEE Std 286-1968.

(6) Slot discharge tests detect surface discharge which may be injurious.

(7) Surge comparison tests are used to test turn-to-turn insulation.

(8) Corona probe tests indicate and locate unusual ionization about the insulation structure.

(9) Winding resistance tests-direct-current detect loose connections and open-circuited windings.

(10) Rotor-winding impedance tests detect and assist in locating turn-to-turn faults.

(11) Interlaminar insulation tests detect and locate damaged areas in the stator core.

(12) Resistance of through-bolt insulation in stator core should be measured.

(13) Insulation resistance of rotor winding should be monitored during operation with a suitable ground detection and, while at rest, with a portable insulation resistance tester (megger).

In directly-cooled machines using water for coolant, the following restrictions in the application of tests (1) through (4) above are recommended.

(1) Tests (1), (2), and (3) should be conducted after all the water has been removed from the winding because the parallel paths to ground provided by the water in the hoses contribute enough conductivity to reduce the insulation resistance reading to a level below the normally accepted limits.

(2) Test (4) can be accomplished with water in the stator windings, provided the test set has sufficient capability to supply the additional leakage current through the water in the hoses. However, the water must be circulated to avoid overheating.

9. Miscellaneous

9.1 General. The operation and maintenance of modern high-speed turbine-driven generators require a thorough knowledge of their construction, as well as the ability to recognize the symptoms and understand the causes of impending damage and failure which may be due to or result in conditions which are chiefly of a mechanical nature. Topics which readily fall within this category may be classified as:

Eccentricity of rotor in stator
Axial position of rotor with respect to stator
Vibration
Shaft current and bearing insulation

9.2 Eccentricity of Rotor in Stator. The initial assembly of a turbine-generator unit involves careful alignment of the generator rotor with the turbine spindle, as well as accurate positioning of the stator with respect to the rotor. Eccentricity of the rotor is more serious on four-pole machines than on two-pole units, because the magnetic flux in the region of the small gap is in parallel with that in the region of the long gap rather than in series, and hence subject to more variation per revolution. Even in two-pole units, however, the flux density wave becomes higher near the pole center as it approaches the region of the small gap, and the magnetic pull is appreciably greater in this region. Besides the pulsating unbalanced magnetic forces, the changes in flux distribution cause induced currents in rotor winding, wedges, and surface, and circulating currents between parallel stator circuits with consequent increased losses and temperatures. Excessive inequality in the gap can also adversely affect the fringing fluxes at the core and region and may result in abnormal local temperatures in clamping plates or retaining rings. The maintenance of accurate centering is also important to be sure of maintaining uniform clearances at oil deflectors, fans, baffles, etc, where tolerances are often small.

Concentricity is initially established by careful measurement of the air gap in at least four positions at each end of the generator. The procedure and allowable tolerances will vary somewhat depending on the air gap length, the number of poles, whether the unit is air or hydrogen cooled, and whether the rotor is supported in pedestal or bracket-type bearings.

In some machines having bracket-type bearings, the adjustment of the air gap as well as the clearances at oil deflectors, baffles, seals, fan shrouds, etc, is accomplished at the factory prior to shipment. In other types, these adjustments may be made or rechecked during installation of the unit, and should preferably be done under the supervision of the manufacturer's erection engineer. In any case, the procedure and allowable tolerances recommended by the manufacturer should be followed, in the initial installation as well as in subsequent reassemblies.

Once properly centered, the rotor is not likely to shift suddenly except in case of accident. With separately supported pedestal bearings, settling or growth of the foundation or grouting over an extended period may disturb concentricity, as well as the alignment between rotor and turbine spindle. Abnormal wear of the babbitt will also tend to bring about these same results. Checking the gap for uniformity at regular inspection periods is therefore advisable, and can often be done quickly by tapered feelers, thickness gage, or pin gage. These measurements can be made either in the air gap or between rotor bearing fit and outer frame bore if the position of the latter is previously determined relative to stator inner frame bore. If measurements are made in the gap, care must be exercised to be sure the gage is in contact with a tooth rather than a slot wedge and far enough from the core end to avoid the tapered or stepped end laminations, if employed.

9.3 Axial Position of Rotor with Respect to Stator. The rotor should be reasonably well centered axially with respect to the stator under all operating conditions. Appreciable asymmetry not only produces an end thrust, but can seriously affect the end fringing flux and produce abnormal local heating of the fingerplates and retaining rings.

If the generator has bracket-type bearings supported from the end covers, the correct axial location of the rotor can usually be obtained by adjustment relative to the bearing center lines. These are permanently located in relation to the stator core and yoke by the machined end cover fits against the stator. In this type, the fan shrouds, seals, baffles, oil deflectors, etc may sometimes be adjusted at the factory before shipment to suit the bearing positions and in such cases should need no further checking. Adequate provision is usually made for axial movement of the coupling due to thermal changes in the turbine, and for any additional expansion of the rotor when the unit is loaded as well as for any necessary axial clearance for disengaging the coupling.

For machines with separate pedestal-type bearings, initial axial centering is often accomplished after the rotor has been lined up and coupled to the turbine by the adjustment of the stator position on the base plate. If this had not been done previously at the factory, or if for any reason the stator was not suitably dowelled or keyed to the base plate, axial centering must be done when the unit is installed.

Since the method of adjustment and permissible tolerances depend upon individual design details, the manufacturer's recommendations should be followed for each unit. Once the correct stator location has been established, subsequent checking of axial positioning is seldom necessary unless either the thrust bearing or the stator have been moved from their initial setting. The adjustment of fan shrouds, baffles, etc, however, may be necessary whenever they are disturbed, or after the rotor is removed and replaced.

When axial centering of the rotor must be rechecked, measurements should be made between stator core ends and some reference point on the rotor such as the outer end of the retaining rings if they are equally spaced from the rotor body. Measurements at several points around the periphery are recommended to allow for unevenness in the punchings.

9.4 Vibration. The vibration of a turbine-generator unit may originate from a number of widely different causes. The most common source of rotor vibration arises from slight physical dissymmetries in the rotor as built that result in nonuniform weight distribution around the geometric axis. To overcome roughness from this source, turbine-generator rotors are carefully balanced at the factory before shipment. Touchup balancing is often necessary after installation because of the influence of the foundations, and of the turbine spindle if solidly coupled. Other causes of rotor roughness have been traced to thermal or magnetic sources and to the inequality in rotor stiffness in the direct and quadrature axes, as well as to improper adjustment of bearing clearances, to oil whip, and other factors related to lubrication.

Measurement of rotor vibration is most commonly made near the bearings. Several types of instruments are in general use that accurately measure or record the amplitude of movement. Experience has shown that a single set of permissible bearing or journal vibration amplitudes cannot be established that would safely cover all types and ranges of ratings. Consequently, the manufacturer's recommendations should be followed in each case.

Core vibration in two-pole generators results from the magnetic pull in the air gap, the force being greater in the direct axis than in the quadrature axis. The rotating magnetic pull tends to deform the core elliptically, thus creating a double-frequency component of core vibration. Adequate rigid bracing to limit the magnitude of the core distortion on large two-pole machines has proven to be impractical from the standpoint of shipping clearances, stator weight, and appearance. In most large modern two-pole machines, core vibration is therefore usually isolated from the outer wrapper and foundation by means of some form of flexible support.

Occasionally, the core or some parts of the outer wrapper plate or lagging may resonate at, or near, twice rated frequency, and the acceptable vibration amplitude of these parts will in most cases depend upon their manner of support or the nuisance value in the form of unpleasant noise, provided the core vibration is known to be safe. Proportions of four-pole stators have been such that core vibration has seldom been troublesome.

The sudden appearance of new vibration or an increase in existing amplitude may be of greater significance to the operator than the steady continuous type of vibration. For this reason, a history of vibration amplitudes is desirable for all machines. One of the first signs of short-circuited rotor turns may be increased rotor vibration. Removal of excitation will often indicate whether the effect is electromagnetic, thermal, or both. Measurement of rotor resistance is seldom a reliable indication unless the exact temperature is also known. If the rotor has a temperature recorder, the chart should be examined for indications of a sudden drop in rotor resistance at the time vibration appeared. The rotor impedance with 110 V, rated frequency applied to the rings is sometimes useful for detecting rotor turn short circuits, provided an initial reading with no shorted turns is available for comparison. Most rotors will not take more than 5 to 10 A at 110 V, and hence can be tested from the lighting circuit if the rotor winding is not grounded. Comparison of the no-load saturation curve with the original curve also is a good check for short-circuited rotor winding turns.

Unlike short-circuited turns in the stator, short-circuited rotor turns may not necessarily require reinsulation. Rotors have been known to operate for years with a few short circuits between successive turns in one or more coils. Experience has shown that short-circuited rotor turns are not usually progressive in nature and are more apt to reduce the temperatures in their respective coils than increase them. Of course, they do require a higher excitation current, and hence the average rotor temperature is increased even though a voltage-drop type of temperature indicator may show the reverse.

If short-circuited turns cause a thermal unbalance, the vibration will vary with temperature and hence will lag any increase in excitation by the length of time required for heating to occur. If variation from the cold to the hot condition is not too great, weight adjustments can sometimes be made to keep the amplitude entirely within a satisfactory range for all temperatures. Otherwise, either thermal balancing or reinsulation of the shorted turns is necessary.

Location of the slots containing short-circuited turns or coils may be possible in solid rotors without retaining ring removal, by measuring the leakage flux across the top of the slot wedge with an alternating voltage applied to the collector rings, and comparing the readings for the various slots. With non-magnetic wedges, a single shorted turn out of 20 or 30 turns will reduce by nearly 50 percent the alternating voltage induced in an exploring coil held above the slot wedge. Slots with magnetic wedges should be compared with each other, as their leakage flux is quite low. An oscilloscope is often useful to measure the low exploring coil voltage if a 110-V ac supply is used across the collector rings. Other means are also used, such as an ac potentiometer or a vectormeter. In some cases, a detector coil may be built into the stator, in the main stator body, embedded in a stator slot wedge or placed in the gap.

Increased rotor vibration could also indicate displacement of rotor coil blocking or physical damage to the shaft or fans as well as tight or distorted bearings. A fiber baffle rubbing the shaft at one point has been known to cause severe shaft vibration. Such cases are unaffected by removal of excitation and, after tripping, often continue during retardation.

Sudden appearance of stator vibration or noise might indicate abnormally high terminal voltage, unbalanced load, or a loosening of the core to a point where some of the laminations have ceased to act as a rigid ring. It could also mean loosening of some parts, whether internal or external, that have become resonant at the frequency of the applied force or are being rattled about by the ventilating gas. In double-winding machines, a characteristic noise can be clearly noticed when load is suddenly removed from one of the windings.

The appearance of vibration has also been traced to such external factors as the shifting of foundation due to settling or thermal changes, coupling misalignment or uneven wear, roughness transmitted from the turbine spindle, unequal expansion of the turbine and generator bearing supports, and even to other machines in the same power plant.

9.5 Shaft Currents and Bearing Insulation. The most common cause of induced shaft voltages is the inequality in reluctance of the parallel flux paths linking the rotor and the consequent pulsations in this component of flux. These induced voltages are generally higher in larger machines because more magnetic material is used. If both bearings complete an electric circuit with each other through the frame or base plate, substantial currents may flow through bearing oil films and may damage the shaft journals and the babbitt surface, as well as gears or other metallic parts in contact with rotor or turbine spindle. Under certain conditions, sludging of the lubricating oil may also occur.

By suitable combinations of partings, lamination segments, and number of poles, the voltages from this source can sometimes be minimized, but the choice of these design details is greatly restricted in turbine generators. Consequently, the outboard end of the rotor is usually insulated from ground, including the bearing, all piping connections, exciter coupling or bearings, hydrogen seal, etc.

Shaft currents can also result from a magnetized shaft, bearing pedestal, or end cover or from windings or end connections that produce axial flux in the rotor. The currents induced from these sources do not always flow from bearing to bearing, but can flow from shaft to babbitt at one end of the bearing and back again at the other end of the same bearing. The bearing insulation will not prevent this type of circulating current. Fortunately, this condition is not common, and the current from it are not usually very great. It can often be detected by characteristic scratches appearing at the extremities of the bearing journal, and its correction is usually possible by demagnetization of the affected parts. Cases of magnetized shafts, bearings, and end covers have been known to result from the dryout of stator windings using direct current, or from double ground faults in rotors.

Bearing currents have also been found to originate from electrostatic charges generated within the steam turbine. Pitting or abnormal wear of worm gears as well as objectionable radio and television interference have been traced to this source. The remedy in such cases is to apply a grounding brush anywhere on the shaft or spindle except at the outboard end of the generator, which must not be grounded. When a generator is driven from both ends, care must be exercised in the location of grounding brushes, so that generator shaft currents cannot circulate.

The use of grounding brushes at both ends of the unit to short circuit the shaft currents induced along the shaft has not been uniformly effective since the brushes themselves often have an appreciable contact potential drop. However, in some cases, damage to gears near the front end of the turbine has been reduced by the installation of a grounding brush near the gear.

Where instructions for testing the bearing and seal insulation are furnished by the manufacturer, these should be followed. The following checks may be made during assembly:

(1) After all piping and conduit connections to the machine have been completed, but before the shaft is placed in contact with the bearing, measure the resistance across each bearing insulation to ground with a 500-V insulation-resistance tester. Generally, a minimum of ½ megohm is accepted as satisfactory.

(2) To check the insulation of pipe joints while the unit is running, several dry cells or a storage battery may be connected from the pedestal (or insulated bearing bracket if bracket-type) to a point on the pipe 2 or 3 ft (600 or 900 mm) beyond the insulated flange. A direct-potential millivoltmeter connected across the 2- or 3-ft (600 or 900 mm) length of pipe between flange and battery connection will indicate whether any current is flowing through the insulated joint.

(3) If the bearing is mounted within the end cover, the insulation is sometimes located between the bearing pads and the bearing or between the bearing ring and end shield. In hydrogen-cooled machines, gland seal insulation may be located between the seal and either the vents, brackets, or end shields. No separate gland seal insulation or bearing insulation is necessary if the bracket itself is insulated. In some types, oil seals are also insulated, and in some cases both hydrogen seals or both ends of the rotor may be insulated rather than only one. The insulation of such enclosed parts should be checked individually as each part is assembled. The insulation of thrust-bearing-type seals may be rechecked by pressing the seal ring back away from the shaft flange before the top half of the bearing is assembled. The main bearings and circular-type seals may be rechecked by lifting the rotor a few mils and sliding a thin sheet of insulation under the journal. Care must be exercised to avoid damaging oil deflectors or other stationary parts by excessive lifting of the rotor.

With pedestal-type bearings or with bracket bearings where the outboard bracket is insulated from ground, there are various means to check the insulation of the outboard bearing while the unit is running.

(1) Perhaps the simplest consists of two successive measurements of voltage using an ac-dc millivoltmeter, the first from a sliding contact on the shaft to ground at the outboard end of rotor, and the second from the pedestal (or insulated bracket) to ground with a dead short from this sliding contact on the shaft to the pedestal (or insulated bracket). If the bearing insulation is satisfactory, both readings will be alike; if not, the second will be lower than the first.

(2) If the bearing is accessible, a portable-type volt-ohm-meter instrument containing a high-resistance voltmeter (calibrated in ohms) and flashlight batteries to provide a 4½- to 6-V supply, may be used with probe-tipped test leads to measure resistance across each bearing insulation to ground in parallel with the oil film. One side is placed on the bearing and the other on ground. Generally 1000 Ω is accepted as a minimum in this test. This test may be made periodically and a record of such periodic readings will be found useful.

(3) When the generator is running with excitation applied, solidly ground one end of a copper wire and touch the other end to the generator shaft. If a small spark occurs when the end of the wire is removed from the shaft, the shaft insulation is satisfactory. If no spark occurs, the shaft is probably grounded and the insulation should be checked. *This method should be used with caution on hydrogen-cooled machines because of explosion danger.*

In many instances, facilities are incorporated in the bearing insulation system design to permit direct testing of the insulation.

The most common causes of faulty bearing or seal insulation are metallic chips or slivers in bolt holes or across small internal clearances. Embedded thermocouples, graphite or paint on insulating material or pipe flanges, and low-resistance gasket material, as well as other forms of dirt, moisture, or foreign matter have also been found to cause trouble.

Shaft currents may also result from the use of some types of instruments, protective devices, or solid-state excitation systems, which may impose an alternating voltage on the field winding by means of capacitance linking. Such voltages may cause shaft-to-ground currents to flow. These currents can be avoided by proper use of wave traps, or other similar equipments. Even direct current relays can cause similar shaft current phenomena if the source contains a voltage ripple that produces effects similar to those of an alternating voltage. In such cases, suitable means must be found to eliminate the applied-voltage ripple.

10. Standards References

The following IEEE, NEMA, and American National Standards publications were used as references in preparing this guide and are useful in the interpretation of its meaning.[2]

ANSI C50.10-1965, General Requirements for Synchronous Machines

ANSI C50.13-1965, Requirements for Cylindrical Rotor Synchronous Generators

IEEE Std 1-1969, General Principles for Temperature Limits in the Rating of Electric Equipment

IEEE Std 4-1968, Techniques for Dielectric Tests (ANSI C68.1-1968)

IEEE Std 43-1961, Recommended Practice for Testing Insulation Resistance of Rotating Machinerv

IEEE Std 56-1958, Guide for Insulation Maintenance for Large Alternating-Current Rotating Machinery

IEEE Std 95-1962, Guide for Insulation Testing of Large A-C Rotating Machinery with High Direct Voltage

IEEE Std 99-1970, Guide for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electric Equipment

IEEE Std 115-1965, Test Procedure for Synchronous Machines

IEEE Std 119-1966, Master Test Procedure for Temperature Measurement of Electric Apparatus

IEEE Std 123-1953, Preferred Standards for Large 3600 rpm 3-Phase 60-Cycle Condensing Steam Turbine Generators (Larger Than 10,000-KW Rated Capacity) (withdrawn)

IEEE Std 124-1953, Standard Specification Data for Generators for Large 3600-rpm 3-Phase 60-Cycle Condensing Steam Turbine Generators (Larger Than 10,000-KW Rated Capacity) (withdrawn)

IEEE Std 270-1966, Definitions of General (Fundamental and Derived) Electrical and Electronics Terms

IEEE Std 286-1968, Proposed IEEE Recommended Practice for Measurement of Power-Factor Tip-Up of Rotating Machinery Stator Coil Insulation

IEEE Std 322-1971, Recommended Practice, Rules for the Use of Units of the International System of Units

NEMA MG1-1967, Motors and Generators

11. Bibliography

11.1 Operation.

11.1.1 *Temperature and Loading.*

NEWBURY and FECHHEIMER. Embedded Detectors in Large Generators. *(Westinghouse) Electric Journal*, Sept 1920.

SNELL, D. S. Loading of Hydrogen-Cooled Generators at Elevated Gas Pressures. *AIEE Transactions*, vol 69, pt. I, 1950, pp 186-204.

---

[2] Available from:
American National Standards Institute
1430 Broadway
New York, N. Y. 10018

Standards Department
Institute of Electrical and Electronics Engineers
345 East 47 Street, New York, N. Y. 10017

National Electrical Manufacturers Association
155 East 44th Street, New York, N. Y. 10017

ALGER, J. R. M., KILBOURNE, C. E., and SNELL, D. S. Turbine Generator Stator-Winding Temperatures at Various Hydrogen Pressures. *AIEE Transactions (Power Apparatus and Systems)*, vol 74, Apr 1955, pp 232-251.

JOHNSON, J. S., BOTTS, J. C. Physical Effects of Thermal Cycling on Stator Coil Insulation of Turbine Generators. *AIEE Transactions (Power Apparatus and Systems)*, vol 75, June 1956, pp 249-253.

STERRETT, C. C., and TOWNE, R. A., Operation of Hydrogen-Cooled Turbine-Generators. *AIEE Transactions (Power Apparatus and Systems)*, vol 74, June 1955, pp 433-439.

CARTER, J. H. and GORMAN, R. E. Operation of Large Steam Turbine Generators. *AIEE Transactions (Power Apparatus and Systems)*, vol 75, Apr 1956, pp 217-226.

TOWNE, R. A. Operation of Hydrogen Cooled Turbine Generators. *Westinghouse Engineer*, vol 18, July 1958, p 123.

LORY, M. R., and WAGNER, C. L. Transient Thermal Problems of Large Generators. *AIEE Transactions (Power Apparatus and Systems)*, vol 80, Feb 1962, pp 965-975.

JONES, N. H., TEMOSHOK, M., and WINCHESTER, R. L. Design of Conductor-Cooled Steam Turbine-Generators and Application to Modern Power Systems. *IEEE Transactions on Power Apparatus and Systems*, vol 84, Feb 1965, pp 131-146.

11.1.2 *Excitation and Stability.*

ANDERSON, H. C., SIMMONS, H. O., JR, and WOODROW, C. A. System Stability Limitations and Generator Loading. *AIEE Transactions*, vol 72, June 1953, pp 406-423.

ADAMS, C. G., and McCLURE, J. B. Underexcited Operation of Turbogenerators. *AIEE Transactions*, vol 72, June 1953, pp 406-423.

ESTCOURT, V. F., HOLLEY, C. H., JOHNSON, W. R., and LIGHT, P. H. Underexcited Operation of Large Turbine Generators on Pacific Gas and Electric Company's System. *AIEE Transactions (Power Apparatus and Systems)*, vol 72, Feb 1953, pp 16-22.

MICHELSON, E. L. and LISCHER, L. F. Generator Stability at Low Excitation. *AIEE Transactions*, vol 67, 1948, pp 1-9.

FARNHAM, S. B. and SWARTHOUT, R. W. Field Excitation in Relation to Machine and System Operation. *AIEE Transactions (Power Apparatus and Systems)*, vol 72, Dec 1953, pp 1215-1223.

KEKELA, J. and FIRESTONE, L. Underexcited Operations of Generators. *IEEE Transactions on Power Apparatus and Systems*, vol 83, Aug 1964, pp 811-817.

ROBERTS, W. J., and WEBB, R. L. Operation of Turbine Generators During Off-Peak High Power-Factor Periods — Practices of one Utility in a Metropolitan Area. *AIEE Transactions (Power Apparatus and Systems)*, vol 74, June 1955, pp 461-467.

11.1.3 *Operation Under Emergency Conditions*

BAUMAN, H. A., HAHN, G. R., and METCALF, C. N. The Effect of Frequency Reduction on Plant Capacity and on System Operations. *AIEE Transactions (Power Apparatus and Systems)*, vol 73, 1954, p 1632.

GANTHER, C. E. and MALLET, A. A. Operation of Generating Units During Serious System Disturbances. *IEEE Transactions on Power Apparatus and Systems* (Special Supplement), vol S-82, 1963, pp 679-683.

BOBO, P. O., SKOOGLUND, J. W., and WAGNER, C. L. Performance of Excitation Systems Under Abnormal Conditions. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-87, Feb 1968, pp 547-553.

AKERS, H. T., DICKINSON, J. D., and SKOOGLUND, J. W. Operation and Protection of Large Steam Turbine Generators Under Abnormal Conditions. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-87, Apr 1968, pp 1180-1188.

HILLERY, R. H., and HOLDUP, E. D. Load Rejection Testing of Large Thermal-Electric Generating Units. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-87, June 1968, pp 1440-1453.

LAY, R. K., LENFEST, E. H., TEMOSHOK, M., and WINCHESTER, R. L. Electrical Resynchronizing of a Large Cross-Compound Turbine-Generator Set:

Part I — Analytical Study. *IEEE Transactions on Power Apparatus and Systems*, vol 88, July 1969, pp 1137-1146.

LEVINE, D. L., LAY, R. K., and TEMOSHOK, M. Electrical Resynchronizing of a Large Cross-Compound Turbine-Generator Set: Part II — Field Tests. *IEEE Transactions on Power Apparatus and Systems*, vol 88, July 1969, pp 1146-1150.

JONES, N. H., TEMOSHOK, M., and WINCHESTER, R. L. Design of Conductor-Cooled Steam Turbine-Generators and Application to Modern Power Systems. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-84, Feb 1965, pp 131-146.

NOYES, E. G., and SKOOGLUND, J. W. Underfrequency Operation of Large Steam Turbine-Generator Units. *Westinghouse Engineer*, May 1967, pp 73-76.

PAULUS, C. F. Effects of Low Frequency and Voltage Upon Generator Capability. EEI paper, St. Louis, Mo., Feb 1964.

11.2 Operation and Maintenance

BARTON, S. C., and OLSON, W. H. M. Operation and Maintenance of Hydrogen Systems for Turbine Generators. *AIEE Transactions (Power Apparatus and Systems)*, vol 75, Apr 1956, pp 86-94.

SIDWAY, C. L., and CLEVENGER, C. M. Steam Turbine-Generator Operating and Maintenance Methods of the Southern California Edison Company. *AIEE Transactions (Power Apparatus and Systems)*, vol 74, Apr 1955, pp 60-65.

GALLAGHER, E. I. Turbine Generator Operation and Maintenance Practice of Philadelphia Electric Company. *AIEE Transactions (Power Apparatus and Systems)*, vol 74, Apr 1955, pp 48-49.

BRYANT, O. N., STERRETT, C. C., and SAUTER, D. M. Controls for Operation of Steam Turbine Generator Units. *AIEE Transactions*, vol 73, 1954, p 79.

JOHNSON, J. S. A Maintenance Inspection Program for Large Rotating Machines. *AIEE Transactions*, vol 70, 1951, pp 749-755.

11.3 Protection and Relaying

BARKLE, J. E., STERRETT, C. C., and FOUNTAIN, L. L. Detection of Grounds in Generator Field Windings. *AIEE Transactions (Power Apparatus and Systems)*, vol 74, June 1955, pp 467-472.

AIEE Committee Report. Relay Protection of A-C Generators. *AIEE Transactions (Power Apparatus and Systems)*, vol 70, 1951, pp 275-282.

IEEE Committee Report. Survey of Underfrequency Relay Tripping of Load Under Emergency Conditions. *IEEE Transactions on Power Apparatus and Systems*, vol PAS-87, May 1968, pp 1362-1366.

BAUMAN, H. A., DRISCOLL, J. M., ONDERDONK, P. T., and WEBB, R. L. Protection of Turbine Generators and Boilers by Automatic Tripping. *AIEE Transactions (Power Apparatus and Systems)*, vol 72, Dec 1953, pp 1248-1260.

WEBB, R. L., and MURRAY, C. S. Vibration Protection for Rotating Machinery. *AIEE Transactions*, vol 63, July 1944, pp 534-537.

BLACKBURN, J. L., and TREMAINE, R. L. Loss-of-Field Protection for Synchronous Machines. *AIEE Transactions (Power Apparatus and Systems), vol 73, Aug 1954, pp 765-777.*

11.4 Rotors

NOEST, J. G. Prevention of Rotor-Winding Deformation on Turbogenerators. *AIEE Transactions*, vol 63, July 1944, pp 514-519.

GILSON, W. J., Jr, and TAYLOR, H. D. Field Preheating for Large Turbine Generators. *AIEE Transactions (Power Apparatus and Systems)*, vol 73, Dec 1954, pp 1375-1383.

GILSON, W. J., Jr, and TEMOSHOK, M. Turbine-Generator Rotor Prewarming. *AIEE Transactions (Power Apparatus and Systems)*, vol 76, Aug 1957, pp 549-556.

KING, E. I. and BATCHELOR, J. W. Effects of Unbalanced Current on Turbine-Generators. *IEEE Transactions on Power Apparatus and Systems*, vol 84, Feb 1965, pp 121-125.

KUDLACIK, H. W., and WILLYOUNG, D. M. Local Rotor Winding Temperature Measurements for Large Turbine-Generator Fields. *AIEE Transactions on Power Apparatus and Systems*, vol 81, Feb 1963, pp 687-694.

KALBACH, J. F. Locating Shorted Turns in A-C Turbine Generator Field Coils. *Power*, vol 93, no 4, Apr 1949, pp 80-81.

HERMAN, P. K., MAHRT, R., and DOON, H. H. Detecting and Locating Interturn Short Circuits on Turbine-Generator Rotors. *IEEE Transactions on Power Apparatus and Systems*, vol 82, Oct 1963, pp 686-698.

RAMAN, K. S., GROSS, E. T. B. Rapid Demagnetization of Large Synchronous Machines. *IEEE Transactions on Power Apparatus and Systems* (Special Supplement), vol S-82, 1963, pp 642-663.

ROSENBERG, L. T. Eccentricity, Vibration, and Shaft Currents in Turbine Generators. *AIEE Transactions (Power Apparatus and Systems)*, vol 74, Apr 1955, pp 38-41.

GROBEL, L. P. Balancing Turbine Generator Rotors. *General Electric Review*, July 1953, p 22.

SWANN, S. A. Effect of Rotor Eccentricity on the Magnetic Field in the Air Gap of a Non-Salient Pole Machine. *Proceedings of the IEE*, vol 110, no 5, 1963, p 903.

LAFFOON, C. M., HAGG, A. C., JANTHEY, C. H., and HELLER, P. R. Modern Practice in Balancing Large Turbine-Generator Rotors. *AIEE Transactions*, vol 70, 1951, pp 593-598.

KING, W. F. Thermal Balancing of Large Rotors. *Allis-Chalmers Electrical Review*, third quarter, 1947, p 8.

KING, W. F. Balancing is Easy if You Know How. *Allis-Chalmers Electrical Review*, third quarter, 1946, p 25.

LAFFOON, C. M., and ROSE, B. A. Special Problems of Two-Pole Turbine Generators. *AIEE Transactions*, vol 59, Jan 1940, pp 30-34.

11.5 Stator Magnetic Vibration and Noise

PENNIMAN, A. L., Jr, and TAYLOR, H. D. Suppression of Magnetic Vibration and Noise of Two-Pole Turbine Generators. *AIEE Transactions*, vol 60, June 1941, pp 283-288.

ROSENZWEIG, S. Elementary Considerations of Vibration Control. *Isolation* (The Korfund Company, Inc. Long Island City, N. Y.) vol 5, no 1, Sept 1936, p 1.

ROSENZWEIG, S. Vibration Isolation by Means of Steel Springs. *Isolation*, vol 5, no 1, Sept 1936, p 10.

BAUDRY, R. A., HELLER, P. R., and CURTIS, L. P. Magnetic Vibrations in A-C Generator Stators. *AIEE Transactions Power Apparatus and Systems*, vol 73, June 1954, pp 508-516.

11.6 Bearings and Shaft Currents

TEN BROEKE, F. A. Bearing Corrosion in Turbo-Generators. *Corrosion* Dec 1948, p 590.

OLSEN, O. A. Shaft Currents in A-C Machinery. *Power Generation*, Nov 1949, p 102.

ALGER, P. L., and SAMSON, H. W. Shaft Currents in Electric Machines. *AIEE Transactions*, vol 43, Feb 1924, pp 235-245.

BUCHANAN, W. Current in Bearings of Electric Generators. *Electrician* (London), vol 75, May 28, 1915, pp 266-267.