



IEEE Guide for Operation and Maintenance of Turbine Generators

IEEE Power Engineering Society

Sponsored by the
Electric Machinery Committee

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IEEE Guide for Operation and Maintenance of Turbine Generators

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**Electric Machinery Committee
of the
IEEE Power Engineering Society**

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Abstract: This guide covers general recommendations for the operation, loading, and maintenance of turbine-driven synchronous generators that have cylindrical rotors.

Keywords: cylindrical rotors, operation and maintenance of turbine generators, reactive capability, rotor windings, stator windings, turbine-driven synchronous generators

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Introduction

This introduction is not part of IEEE Std 67-2005, IEEE Guide for Operation and Maintenance of Turbine Generators.

This introduction provides some background on the rationale for updating this guide.

The scope of the guide remains the same as the existing guide. It is updated to include the latest industry information that is relevant to the existing standard IEEE Std 67-1990.

Original Scope: This guide covers general recommendations for the operation, loading, and maintenance of turbine-driven synchronous generators of the types specified in the guide, that is, 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. Therefore, it is 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 and methods and give warning where hazards might be encountered. The user should keep in mind that this guide is written to cover the turbine generator. This guide is not intended to apply in any manner to the prime mover.

This guide is for the use of the users (power utilities) and manufacturers of turbine generators. The reason for the revision is that it has been ten years since it was previously revised and it needs updating due to the changes in the operating regimes of utilities today. The guide now includes such things as two-shifting operation information and considers the advances in machine designs.

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IEEE Guide for Operation and Maintenance of Turbine Generators

1. Overview

1.1 Scope

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

The generators covered by this guide are to have rated outputs of 10 MVA and above. Cylindrical-rotor, two-pole and four-pole generators below this rating are generally covered by NEMA MG 1.¹ 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. Therefore, it is 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 and methods and give warning where hazards might be encountered. The user should keep in mind that this guide is written to cover the turbine generator. This guide is not intended to apply in any manner to the prime mover.

1.2 Cautions

It must be recognized that component loads more severe than those permitted by the nameplate should not be applied without a thorough study of the possible consequences that might arise from the specific operating conditions. It is recommended that in all such cases the specific conditions be discussed with the manufacturer of the unit. Many IEEE and ANSI standards are referenced in this guide. The standards referenced will be those in effect when this revision is approved. Users are cautioned to carefully review the history of older machines with respect to IEEE and ANSI standards in effect at the time the particular generator was manufactured. Older machines may not operate satisfactorily to the requirements of modern standards with regard to temperature rise, overload capability, abnormal operating conditions, etc. A requirement for the proper and successful operation and maintenance of turbine generators is knowledge of their construction, operation, and system dynamic characteristics. Information of this type is contained in

¹ For information on references, see Clause 2.

this guide and more detailed and specific information is to be found in the manufacturer's instruction book and related technical data. Much of this information quite properly concerns the normal "round-the-clock" steady-state operating conditions. Advances in generator design and application over the past several decades have, however, made attention to unusual or transient conditions more important. Rapid and accurate comprehension and interpretation of changes in the machine or its operation characteristics is, therefore, also essential to efficient operation and maintenance.

1.3 Manufacturer and user responsibilities

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 the manufacturer and to indicate a 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 without checking the generator capability curves and other specified parameters.

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

Operator training is the responsibility of the user. The complex operating characteristics of a synchronous generator, its excitation system, and auxiliaries are not easily understood without proper instruction. Today's larger direct-cooled units have little or no operating capability without the cooling equipment. Stability considerations of the transmission and distribution systems make it essential to understand the basic relationships among a generator's terminal voltage, line current, active power, reactive power, rotor voltage, rotor current, frequency, speed, etc. This guide can be used as a reference document for an effective operator training program.

2. Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

These publications were used as references in preparing this guide and are useful in the interpretation of its meaning. They also include useful bibliographies.

IEEE Std 1TM, IEEE Recommended Practice: General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation.^{2,3}

IEEE Std 43TM, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery.

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

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³ IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

IEEE Std 62.2™, IEEE Guide for Diagnostic Field Testing of Electric Power Apparatus—Electrical Machinery.

IEEE Std 95™, IEEE Recommended Practice for Insulation Testing of AC Electric Machinery 2300 V and Above with High Direct Voltage.

IEEE Std 99™, IEEE Recommended Practice for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electric Equipment.

IEEE Std 115™, IEEE Guide: Test Procedures for Synchronous Machines, Part I—Acceptance and Performance Testing, Part II—Test Procedures and Parameter Determination for Dynamic Analysis.

IEEE Std 286™, IEEE Recommended Practice for Measurement of Power Factor TIP-UP of Electric Machinery Stator Coil Insulation.

IEEE Std 522™, IEEE Guide for Testing Turn Insulation of Form-Wound Stator Coils for Alternating-Current Electric Machines.

IEEE Std 1434™, IEEE Guide to Measurement of Partial Discharges in Rotating Machinery.

IEEE Std C37.102™, IEEE Guide for AC Generator Protection.

IEEE Std C50.13™, IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz, Synchronous Generators Rated 10 MVA and above.

NEMA MG 1-2003, Motors and Generators.⁴

3. Definitions

The latest revisions of *The Authoritative Dictionary of IEEE Standards Terms* [B1]⁵ and IEEE Std C50.13 should be consulted for terms applicable to this guide.

4. Classification of generators

4.1 Generator types

Turbine generators are classified by one of the stator types and one of the rotor types as follows.

- a) Stator types are defined by the method of stator winding cooling, either directly or indirectly.
- b) Rotor types are defined by the method of rotor winding cooling, either directly or indirectly.

NOTE—For turbine generators, the stator windings are typically called “armature windings,” and the rotor windings are typically called “field windings.” The terms are, therefore, used interchangeably.⁶

⁴ NEMA publications are available from Global Engineering Documents, 15 Inverness Way East, Englewood, CO 80112, USA (<http://global.ihs.com/>).

⁵ The numbers in brackets correspond to those of the bibliography in Annex A.

⁶ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

4.1.1 Directly cooled windings

Directly cooled stator or rotor windings are those in which the winding coolant (air, hydrogen, or liquid) flows in direct contact with the conductors so that the heat generated within the principal portion of the windings reaches the cooling medium without being transmitted through the groundwall insulation.

4.1.2 Indirectly cooled windings

Indirectly cooled stator or rotor windings are those in which the heat generated in conductors of the windings must flow through groundwall insulation before reaching the cooling medium (air or hydrogen).

For indirectly cooled stator windings, the stator core also acts as a heat sink for the stator winding. The heat generated by the conductor bars is removed by both the cooling gas flowing over it (particularly in the end-winding overhang) and by conduction to the large mass of the stator core (in the slot portion). The stator core is in turn cooled by the cooling gas medium.

4.2 Cooling methods

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 as a coolant flows through insulated ducts, which are part of the stator winding structure inside the groundwall insulation. The heat generated within the strands flows through the thin layers of strand insulation and duct insulation to the cooling hydrogen in the ducts.

4.2.1.2 Deionized water

Deionized water coolant flows through hollow conductor strands or through special coolant tubes. The heat generated within the conductors flows in two directions as follows.

- a) Directly into the cooling water flowing through hollow conductor strands
- b) Through thin layers of strand insulation from the solid strands and through the hollow conductor strand insulation or the insulation of the special coolant tubes carrying the water coolant

4.2.1.3 Insulating oil

Insulating oil coolant flows through hollow conductors in the same manner as it does for the deionized water types. Oil is not generally used in modern machines, but may be found in older machines still in operation.

4.2.2 Indirectly cooled stators

Indirectly cooled stators are classified according to the type of coolant used to remove heat from the stator windings. The coolant (air or hydrogen) flows through ventilating ducts in the stator-core iron.

4.2.3 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.

4.2.3.1 End-supplied axial/radial flow coolant

Coolant (air or hydrogen) is supplied to each end of the rotor and flows into conductor passages near the ends of the rotor body and/or into rotor subslots that carry coolant to conductor inlet passages at intervals along the rotor body length. The coolant is radially discharged into the generator air gap along the rotor body or at the center of the rotor.

4.2.3.2 Gap-supplied zone flow coolant

Coolant (air or hydrogen) 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 coolant is discharged through short outlet sections between the inlet sections along the length of the rotor body. The end portions of the windings are supplied with coolant from each end.

4.2.3.3 Deionized water coolant

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

4.2.4 Indirectly cooled rotors

Indirectly cooled rotors are classified according to the type of coolant used to remove heat from the rotor windings. The coolant (air or hydrogen) passes the rotor surface or flows through gas passages in the rotor body.

4.3 Coolant circulation methods

The cooling medium is circulated through passages in the generator by one of the following methods:

- a) Self-ventilated generators have cooling air or hydrogen circulated by means of an internal shaft-mounted fan(s) along with the self-pumping action of the rotor.
- b) Separately ventilated generators have cooling air or hydrogen circulated by an independent blower external to the machine.
- c) Liquid-cooled generators have the coolant circulated either by means integral to the machine or by circulating equipment external to the machine.

4.4 Other common terms

Based on the historical development of generator designs and cooling methods, a number of designations have been created as outlined in 4.2.1 through 4.2.4 to describe turbine-generator types. These descriptive designations make a distinction regarding the type of coolant used rather than giving a complete description as outlined in the preceding paragraphs.

4.4.1 Air-cooled generators

For totally enclosed water-to-air-cooled (TEWAC) generators, the enclosure should be so arranged as to prevent the free exchange of air between the inside and outside of the case but not sufficiently enclosed to be termed airtight. The enclosure should be arranged so that dust should not enter in sufficient quantity to interfere with satisfactory operation of the machine. These enclosures may provide filtered makeup air in a low-pressure zone of the enclosure to compensate for air leaking out from zones that are somewhat over atmospheric pressure.

For open ventilated (OV) air-cooled generators, the housing should be enclosed so as to prevent the free exchange of air anywhere but at the inlet and outlet openings, but not sufficiently enclosed to be termed airtight. The enclosure should be arranged so that dust should not enter in sufficient quantity through the enclosure, not including inlet and outlet openings, to interfere with satisfactory operation of the machine. Arrangements should be made between the user and manufacturer to arrange for adequate filtration of the ventilation airflow, either supplied with the generator housing or separately to meet the manufacturer's air-quality requirements.

In general, particular attention should be given to air-cooled generators with regard to airborne contaminants and discussed with the manufacturer to ensure appropriate mitigating measures are included in procurement requirements.

Air-cooled generators are designed to use air for cooling and they are classified as follows according to the type of enclosure:

- a) Open generators are self-ventilated machines, open to the surrounding air, having no restrictions to ventilation other than that necessitated by mechanical construction and any silencing and filtering equipment.
- b) Enclosed generators are either self-ventilated or separately ventilated with openings for the admission and discharge of the ventilating air; the machine is otherwise totally enclosed. These openings are arranged so that inlet and outlet ducts or pipes may be connected to them.
- c) Totally enclosed generators prevent the exchange of air between the inside and the outside of the enclosure, but not sufficiently enclosed to be termed airtight. Heat created by the generator losses is removed from the cooling air by internal or external heat exchangers.

4.4.2 Hydrogen-cooled generators

Hydrogen-cooled generators, using pressurized hydrogen, are totally enclosed machines having a gastight enclosure and hydrogen shaft seals to prevent the exchange of air and hydrogen. Heat created by the generator losses is removed from the hydrogen by heat exchangers integral to the generator housing.

4.4.3 Liquid-cooled generators

Liquid-cooled generators are designed to use deionized water or oil as coolant for the generator windings. Heat created by the winding losses is removed from the liquid coolant by heat exchangers external to the generator. Additional coolant circuits are required to remove heat from other sources, principally the core. Traditionally, hydrogen has been used for this purpose although some large liquid-cooled generators exist in which air is used for this purpose. However, designs also exist in which water (or oil) is the sole cooling medium for the entire generator; in this case, a common cooling system has been used to handle all cooling circuits.

5. Basis of rating

5.1 General considerations

The specification of a turbine-generator set requires the following two basic criteria:

- a) The proper matching of the mechanical characteristics of the prime mover and the generator
- b) Matching the output capability of the prime mover to the generator over the appropriate ambient temperature range

5.2 Temperature limits

IEEE Std 1 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 and will be expanded upon throughout this guide:

- a) Deterioration of the insulation is a function of time and temperature.
- b) The insulation is subjected to considerable mechanical stresses caused by vibration and expansion and contraction of the windings and surrounding parts with changes in load and temperature.
- c) 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 that ensure 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 or as derived from the temperature limits of the component materials given in IEEE Std 1.

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 (see IEEE Std C50.13).

5.3 Temperature rise

IEEE Std C50.13 specifies the observable rise that 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.

In some instances, greater output can be permitted with cold coolant temperatures lower than design level, permitting high temperature rises without exceeding established total temperature limitations. An example of this is the generally lower air and water temperatures that occur in the winter, which may offer some additional capacity in electrical equipment (see 6.1.2).

5.4 Methods of temperature measurement

5.4.1 Coolant temperatures

The number and location of coolant temperature sensors vary considerably depending on the type of cooling system employed. The cooling system's instruction book 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, cold coolant temperature detectors are frequently employed for the control of heat-exchanger raw secondary cooling water flow.

The cold coolant temperature should not exceed the maximum value specified on the generator nameplate; the maximum value is given in IEEE Std C50.13.

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 side of the bottom coil and the lower side of the top coil, as shown in Figure 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 only at one point. The resistance detector commonly known as RTD (resistance temperature detector) is a sensor that has a precise temperature-resistance coefficient, with an electrical resistance normally specified at a particular reference temperature. The dimensions of the RTD are usually the same as the filler strip used in the stator slot between the upper and lower stator conductors. The RTD leads are carefully routed from the device to a terminal block on the outer frame of the generator. For hydrogen-cooled generators, this terminal block must be gastight at appropriate design hydrogen pressures. Resistance of the detector may be as given in IEEE Std C50.13 or as otherwise specified by the purchaser. Generally at least 12 detectors are built into the machine, evenly distributed around the stator-core circumference. Each detector is installed, and the leads are brought out in such a manner that the detector itself is effectively protected from contact with cooling air or gas.

5.4.2.2 Directly cooled stator windings

In addition to embedded detectors as described above, the following temperature monitoring is generally applied.

The difference in temperature between stator winding strands and the coolant is a function of load. Because the cooling medium is in contact with, or flowing in an integral part of the conductor strands, temperature measurement of the warm, discharge coolant is considered a more accurate indication of the stator conductor temperature than embedded temperature detector measurements.

Either resistance- or thermocouple-type temperature detectors are 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.

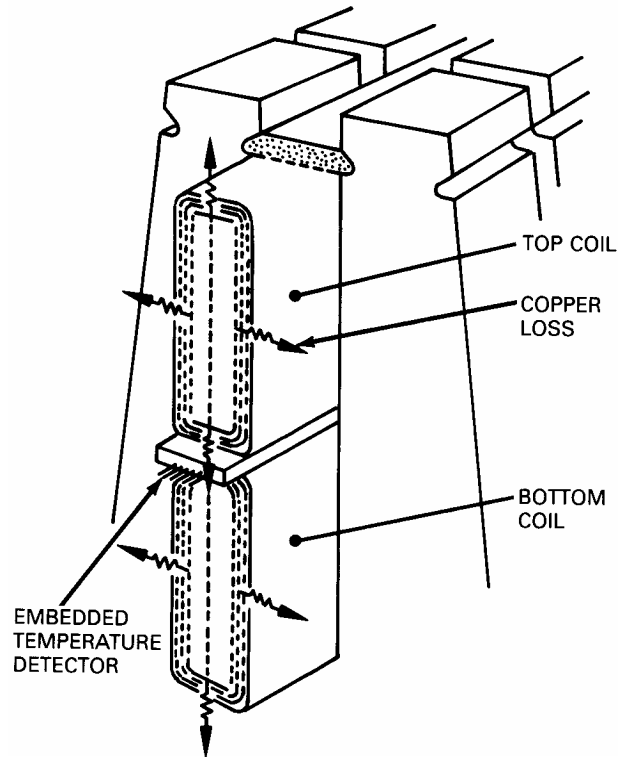


Figure 1—Heat flow and typical temperature detector location

5.4.3 Rotor windings

No simple method has been devised for measuring rotor hot-spot temperatures. Standard practice is to measure the average temperature of the winding by resistance using simultaneous voltage and current readings at the collector rings, and interpret these values in conjunction with the known cold resistance to find the operating temperatures. If the rotor voltage is measured at the brushes, there may be an error of 2 V to 4 V caused by brush voltage drop. To compensate for this effect, pilot brushes that carry no rotor current are sometimes used for measuring the rotor voltage. However, some users have experienced difficulty with pilot brushes caused by 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 as follows:

- a) To provide a bias voltage equal to the brush voltage drop
- b) To 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 collector rings, no simple method for measuring rotor winding temperature is currently available. However, telemetry methods are now available for measurement of voltage and current, remotely.

With regard to the hot-spot measurement, this can generally be derived from the average temperature measurement of the rotor winding. The manufacturer generally has data on the rotor design, which indicates the hottest location in the rotor winding and the maximum temperature at known conditions. The

difference in temperature rise of this hot spot provides a multiplier factor, which can be used to determine the hot-spot temperature when the average temperature of the rotor winding is known.

5.5 Limitations in the methods of measuring temperatures

5.5.1 Stator winding temperatures by embedded detectors

The detector element is located between the surfaces of the top and bottom coils and is separated from the copper of these coils by the coil insulation, as indicated in Figure 1. The difference between the temperature of the hot spot and the detector element is a function of the dimensions 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 at all loads.

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 for air-cooled generators. Tests conducted 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, but is largely a function of the heat flow from the copper to the cooler parts surrounding the coil, as indicated in Figure 1.

In directly cooled stator windings, the coolant enters the stator bar at one end. Flowing from one end to the other, the coolant becomes hotter as it removes heat from the copper.

The relationship of the copper temperature to the temperature measured by the embedded detector varies down the entire length of the stator bar. Therefore, the location of the embedded detector with respect to coolant flow must be considered.

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 also measured by means of resistance or thermocouple detectors.

It should also be recognized that the temperature difference between this discharge coolant temperature and the hot spot varies widely for different machine designs.

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 current in the conductors. If the liquid coolant flow in an individual coil is blocked (e.g., by copper corrosion), the temperature of the corresponding thermocouple on that coil may actually drop or assume the average temperature of the water manifold.

5.5.3 Rotor winding temperatures

The rotor winding temperature determined by calculated 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. To determine the hot spot temperature, the hot spot multiplier must be known.

For a given rotor design, the difference between the hot spot temperature and the average temperature may increase with the rotor length.

To compensate for this factor, IEEE Std C50.13 differentiates according to cooling principle. A lower temperature rise will also limit the differential expansion between conductor and steel in the larger rotors.

6. Loading

6.1 Limitations on loading

6.1.1 Nameplate rating

Each generator is provided with a nameplate that states the operating conditions for which the generator has been designed and constructed.

When the generator is operated within these nameplate conditions of electrical output, cooling medium temperatures, pressures, and flows, the machine will not exceed the temperature rises agreed upon at the time of purchase. In addition to the temperature limits required by standards, the manufacturer has design limits for critical quantities, i.e., flux densities, mechanical stress, mechanical and electromagnetic forces, and dielectric stress. These limits are based on design analysis and experience to ensure appropriate generator reliability. Loading of the generator within the nameplate capability will keep the machine within these design limits, and result in optimum reliability.

The generator should not be loaded beyond the nameplate capability without fully considering the potential loss of machine life or malfunction resulting from exceeding the design temperatures, or any of the other critical design limits.

6.1.2 Effect of loading on temperatures

A misunderstood effect of loading the generator beyond the nameplate rating is the increase in hot-spot temperature. Generally, the ratio of the hot-spot temperature to the observed temperature remains fairly constant for a given cold cooling temperature. However, if the cold coolant temperature is reduced in an attempt to obtain more output without exceeding the normal observed temperature, the hot-spot temperature may exceed the desirable temperature. This is illustrated in Figure 2. With 46 °C inlet coolant and 1.0 per-unit load, the observed temperature is 110 °C (point A), and the hot-spot temperature is 130 °C (point B). If the inlet coolant temperature is reduced to 30 °C and the load is increased to return to an observed temperature of 110 °C (point C), the hot-spot temperature in this example becomes 134 °C (point D). If the hot-spot temperature of 130 °C is not to be exceeded, then the observed temperature must be reduced to 106 °C (point F) by a suitable load change. It must be stressed that this figure is only an example, and the manufacturer should be consulted for the specifics of any given machine. Thus, to avoid exceeding the hot-spot temperature at increased loads by reducing cold coolant temperature, the observed temperature limits should be reduced below normal values.

A similar situation exists for hydrogen-cooled generators whose load capability increases with increasing hydrogen pressure. The limiting observable temperature must be reduced as the load capability is increased in order to maintain hot-spot temperature limits.

For most insulating materials, the loss of life because of elevated temperatures can be roughly estimated using the Arrhenius rule, which states that the rate of aging doubles for every 10 °C increase in temperature. This simple rule of reaction kinetics applies to both the asphalt and modern epoxy mica systems operating across a range of temperatures that include not only normal operating temperatures but also the epoxy curing temperatures.

Thermal aging is not the only effect of increased temperatures on insulating materials. The mechanical properties of many nonmetallic materials are very temperature dependent, and mechanical failure may result from extended exposure to temperatures above the design values. Thermal expansion effects can lead to gradual deterioration of components, which would normally be unaffected by load changes. If the distortion temperature is reached, a prompt failure can occur.

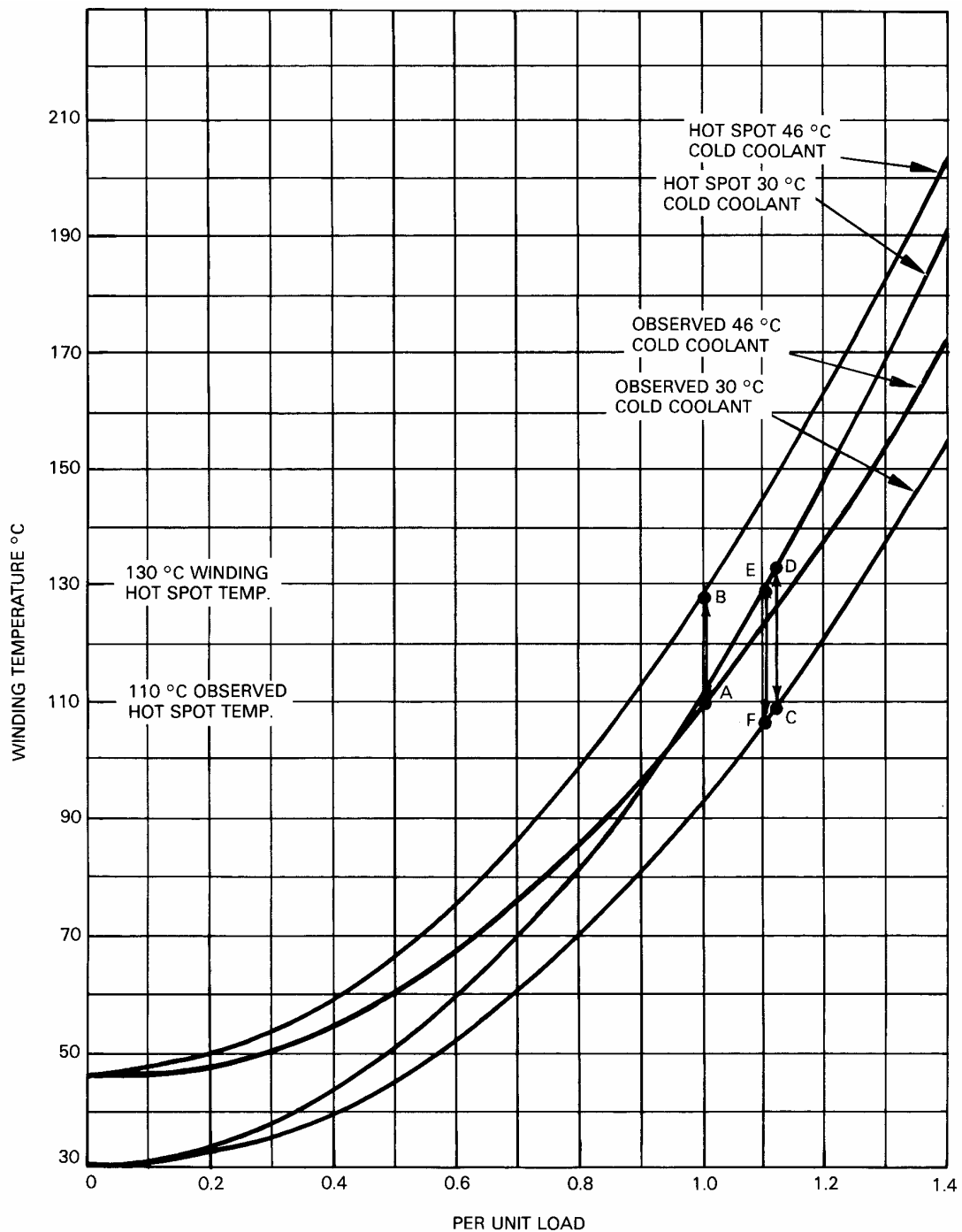


Figure 2—Typical effect of reduced coolant inlet temperature on hot-spot temperature

6.1.3 Other effects of loading beyond nameplate rating

While temperature effects are the most important aspect of operation beyond nameplate rating, they are not the only concern. Stator conductor forces, stresses in the walls of hollow cooling ducts, coolant temperature, and the vibration of current-carrying parts will all be increased. Heating of the stator core ends, and other stray magnetic effects will be greater, and can add to the adverse effects of elevated winding temperatures.

Operating life is also affected by thermal cycling of the generator. Thermal cycling refers to variations in load on the generator and the start-stop duty it may be required to undergo. Modern operating regimes often require the generator to change load numerous times in a single day and at fast rates. In addition, there is considerable requirement now to two-shift units. This is a term used to describe operating the generator during high-demand periods (i.e., daytime) and shutting down during low-demand periods (i.e., nighttime). The effect of this subjects the generator components to many thermal cycles, causing the materials in the generator to expand and contract to a far greater degree than they would under base-load operation. The main concern is the difference in coefficients of thermal expansion between the various components and the accelerated aging that is likely to occur from this type of operation. This type of duty is difficult to quantify in terms of the additional loss of life to the machine components, but it is known that the effect is significant and should be considered in the operation and maintenance planning for the generator.

6.2 Loading within rating

The maximum life expectancy for a generator is obtained by operating methods that produce low operating temperatures with the fewest temperature variations. It is, therefore, desirable to have equipment to control the cooling-system temperatures.

For OV air-cooled generators, there is sometimes no means provided for the control of the air temperature through the unit. For enclosed generators, whether air-cooled or hydrogen-cooled, control of the cooling system is available through the control of the secondary cooling water flow to coolers, and for liquid-cooled generators, by control of liquid-coolant temperatures for the windings. Conveniently located temperature-indicating or -recording instruments will provide valuable information during the operation of the machine.

6.3 Active and reactive power relationship

6.3.1 No-load characteristics

Operation of the machine with no load connected to its terminals is described by two characteristic curves shown in Figure 3: the no-load saturation curve and the short-circuit characteristic curve. The no-load saturation curve shows the relationship between terminal voltage and rotor current with the machine terminals open circuited and with the machine operating at rated speed. The per-unit base for the terminal voltage is the rated voltage of the generator. The rotor current required to reach rated terminal voltage measured on the saturation curve (point A) is known as the no-load rotor current and is the per-unit base for that current (1 pu rotor current). The “air-gap line” shown in Figure 3 is the straight-line extrapolation from the origin. The no-load saturation curve deviates from the straight line because of magnetic saturation of the iron in the generator.

The short-circuit characteristic curve relates the stator current to the rotor current with the machine terminals short circuited, and with the machine operating at rated speed. The rotor current at rated stator current (point B) is known as the short-circuit rotor current. The ratio of the no-load rotor current to the short-circuit rotor current is the short-circuit ratio (SCR) of the machine (approximately 0.47 in the

example of Figure 3). The SCR is an index of the inherent steady-state stability of the machine. In general, as the SCR increases, the machine becomes more stable.

Also shown in Figure 3 is the zero power-factor characteristic. This curve relates terminal voltage to rotor current with the machine delivering rated stator current into a purely reactive load, at rated speed. This curve is used to derive the Potier reactance, which can be used to estimate load excitation. This curve, for estimating purposes, is basically parallel to the no-load saturation curve but offset by the short-circuit rotor current. Point C shown in Figure 3 is the "rated load" point (i.e., the point of operation at rated terminal voltage, rated power factor, and rated stator current).

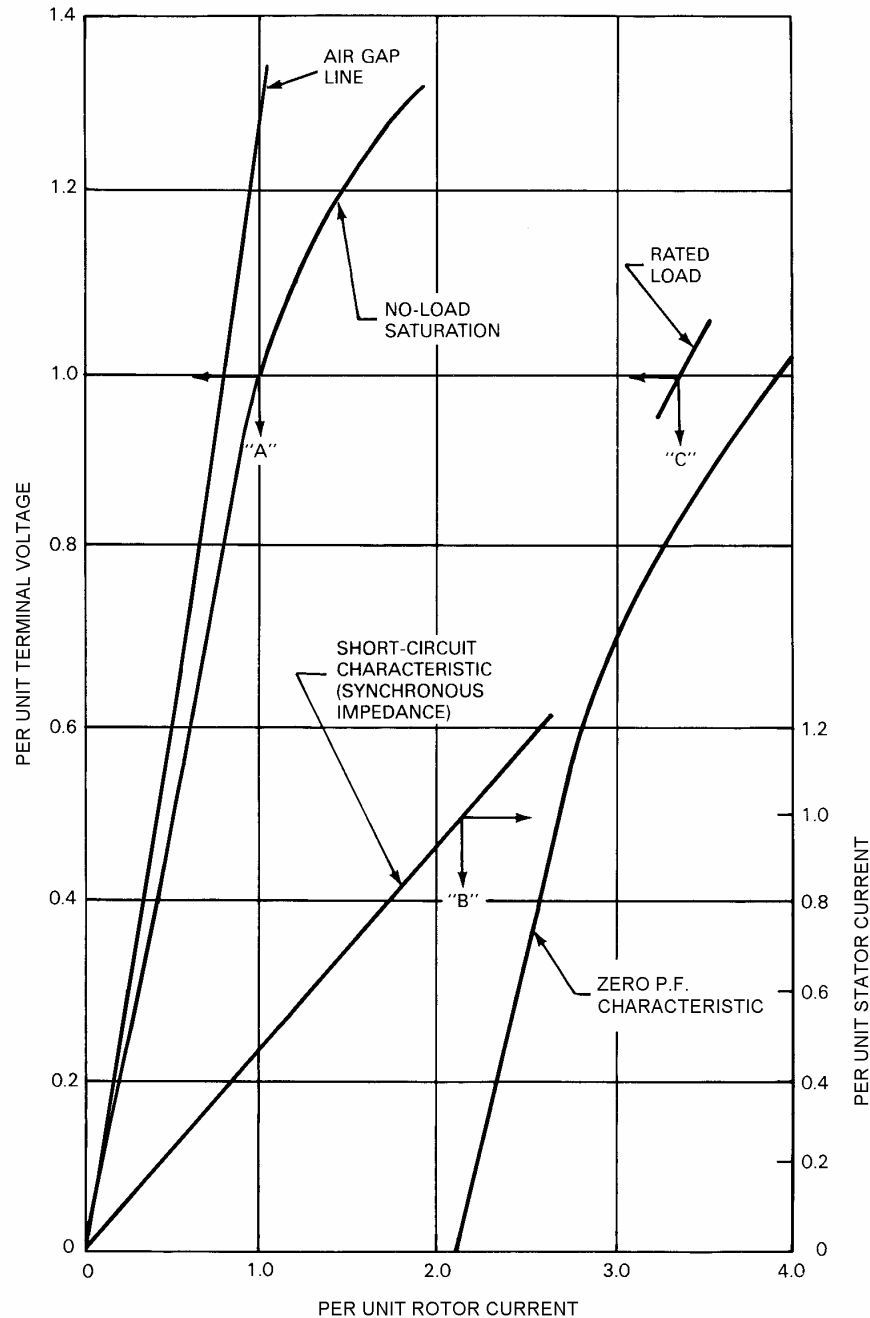


Figure 3—Typical saturation curve