

IEEE Guide for Operation and Maintenance of Turbine Generators

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Abstract: IEEE Std 67-1990, *IEEE Guide for Operation and Maintenance of Turbine Generators*, 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, turbine-driven synchronous generators, reactive capability, rotor windings, stator windings

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Foreword

(This Foreword is not a part of IEEE Std 67-1990, IEEE Guide for Operation and Maintenance of Turbine Generators.)

Originally published in July, 1957, as a trial-use document, this guide 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 then IEEE Rotating Machinery Committee to begin work on an extensive revision of IEEE Std 67-1963 .

In the 1972 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 emphasized the undesirability of operation of a generator by means of stator-winding temperature indications. The bibliography was updated and grouped by subject to facilitate its use. In 1980, the guide was reaffirmed.

In January, 1986, a Standards Project Authorization (PAR) was issued to revise the guide. The present guide has retained the original format; however, several editorial changes have been made. These changes serve to:

- 1) Revise this guide to more closely reflect the state of the art of machines in service in the 1980's
- 2) Update this guide with respect to operation and maintenance experience gained since 1972 and thus provide acceptable performance criteria
- 3) Expand upon certain areas and issues in order to make them clearer and more meaningful
- 4) Update the bibliography

A rather significant addition to this guide is the appendix, "Problem Diagnosis." We thought about this appendix for quite some time before we put it into its final form. Remember, this is a guide, an educational tool to assist in the early diagnosis of generator-related problems. This appendix is not an attempt to list every possible cause of a given situation; we have tried to list the most probable or most likely cause of a given event. We hope that this appendix will be useful to all utilities and users. This appendix does not contain any mandatory requirements.

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IEEE Guide for Operation and Maintenance of Turbine Generators

1. Introduction

1.1 Scope

This guide covers general recommendations for the operation, loading, and maintenance of turbine-driven synchronous generators of the types specified in Section 4, 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.

1.2 References

The following IEEE, ANSI, and NEMA publications were used as references in preparing this guide and are useful in the interpretation of its meaning. These standards include useful bibliographies.

[1] ANSI C50.10-1965, General Requirements for Synchronous Machines.¹

[2] ANSI C50.13-1989, Requirements for Cylindrical Rotor Synchronous Generators.

[3] ANSI C50.14-1977 (Reaff. 1989), Requirements for Combustion Gas Turbine Driven Cylindrical Rotor Synchronous Generators.

[4] ANSI C50.15-1989, Requirements for Hydrogen-Cooled Combustion Gas-Turbine-Driven Cylindrical-Rotor Synchronous Generators.

¹ANSI publications are available from the Sales Department of the American National Standards Institute, 1430 Broadway, New York, NY 10018.

- [5] IEEE C37.102-1987, IEEE Guide for AC Generator Protection (ANSI).²
- [6] IEEE Std 1-1986, IEEE Standard General Principles for Temperature Limits in the Rating of Electric Equipment and for the Evaluation of Electrical Insulation (ANSI).
- [7] IEEE Std 4-1978, IEEE Standard Techniques for High Voltage Testing (ANSI).
- [8] IEEE Std 43-1974 (Reaff. 1984), IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery (ANSI).
- [9] IEEE Std 56-1977 (Reaff. 1982), IEEE Guide for Insulation Maintenance for Large AC Rotating Machinery (10 000 kVA and Larger) (ANSI).
- [10] IEEE Std 95-1977 (Reaff. 1982), IEEE Recommended Practice for Insulation Testing of Large AC Rotating Machinery with High Direct Voltage (ANSI).
- [11] IEEE Std 99-1980, IEEE Recommended Practice for the Preparation of Test Procedures for the Thermal Evaluation of Insulation Systems for Electric Equipment (ANSI).
- [12] IEEE Std 115-1983, IEEE Test Procedures for Synchronous Machines (ANSI).
- [13] IEEE Std 115A-1987, IEEE Standard Procedures for Obtaining Synchronous Machine Parameters by Standstill Frequency Response Testing.
- [14] IEEE Std 119-1974, IEEE Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus.
- [15] IEEE Std 268-1982, IEEE Standard for Metric Practice (ANSI).
- [16] IEEE Std 286-1975 (Reaff. 1981), IEEE Recommended Practice for Measurement of Power-Factor Tip-Up of Rotating Machinery Stator Coil Insulation (ANSI).
- [17] IEEE Std 421.1-1986, IEEE Definitions for Excitation Systems for Synchronous Machines (ANSI).
- [18] IEEE Std 421B-1979, IEEE Standard for High-Potential Test Requirements for Excitation Systems for Synchronous Machines (ANSI).
- [19] NEMA MG1-1978 (Reaff. 1981), Motors and Generators.

1.3 Definitions

coolant (cooling medium): A fluid, usually air, hydrogen, or water, used to remove heat from a machine or from certain of its components.

temperature rise of a machine component: The difference between the temperature of the part under consideration and the ambient temperature.

²IEEE publications are available from the Institute of Electrical and Electronics Engineers, IEEE Service Center, 445 Hoes Lane, Piscataway, NJ 08855-1331.

2. Cautions

It must be recognized that 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 requisite for the proper and successful operation and maintenance of turbine generators is knowledge of their construction and operating characteristics. Information of this type is contained in 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.

3. Manufacturer's and User's Responsibility

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 carefully be 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, field voltage, field current, frequency, speed, etc. This guide can be used as a reference document for an effective operator training program.

4. Classification of Generators

4.1 Generator Types

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

- 1) Stator types are defined by the method of stator-winding cooling, either directly or indirectly.
- 2) 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.

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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 flowing through the ground wall insulation.

4.1.2 Indirectly Cooled Windings

Indirectly cooled stator or rotor windings are those in which the heat generated within the principal portion of the windings must flow through ground wall insulation before reaching the cooling medium (air or hydrogen).

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 coolant flows through insulated ducts, which are part of the stator winding structure inside of the ground wall 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.

- 1) Directly into the cooling water flowing through hollow conductor strands.
- 2) 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.

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 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 field winding and flows axially through hollow field conductors or tubing nested in the field 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:

- 1) 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.
- 2) Separately ventilated generators have cooling air or hydrogen circulated by an independent blower external to the machine.
- 3) 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 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

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

- 1) 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.
- 2) Enclosed generators are 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 generators prevent exchange of air between the inside and the outside of the enclosure, but not sufficiently enclosed to be called 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 gas-tight 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 (see 4.2.1 and 4.2.3). 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. However, designs 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 coordination of the mechanical requirements of the turbine and the electrical requirements of the generator. For the steam turbine, one of the principal load limitations is the maximum torque that the turbine can deliver under various conditions of steam pressure, steam temperature, and condenser vacuum. For the generator, the rating is governed by considerations related to the useful life of the insulation system and other machine parts; these are affected by temperature, differential expansion, and long-term vibration.

5.2 Temperature Limits

IEEE Std 1-1986 [6]³ 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:

- 1) Deterioration of the insulation is a function of the time during which it is subjected to high temperature, as well as the absolute value 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 that assure normal insulation life expectancy, it is important that hot spot temperatures of the machine not exceed the limiting temperatures of the insulation system as established by test procedures developed in accordance with IEEE Std 99-1980 [11] or as derived from the temperature limits of the component materials given in IEEE Std 1-1986 [6].

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 ANSI C50.14-1977 [3].

³The numbers in brackets correspond to the references listed in 1.2 of this guide.

5.3 Temperature Rise

ANSI C50.13-1989 [2] 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 water flow.

The cold coolant temperature should not exceed the maximum value specified on the generator nameplate.

Maximum values as specified in ANSI C50.13-1989 [2] 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 two-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 detector commonly known as RTD (resistance temperature detector) is a sensor that has a precise temperature-resistance coefficient, normally specified as an electrical resistance 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 gas tight at appropriate design hydrogen pressures. Length and resistance of the detector may be as specified in ANSI C50.10-1965 [1] or as otherwise specified by the purchaser. Usually 12 detectors are built into the machine, evenly distributed around the stator core circumference. Each detector is installed and the leads brought out in such a manner that the detector itself is effectively protected from contact with cooling air or gas.

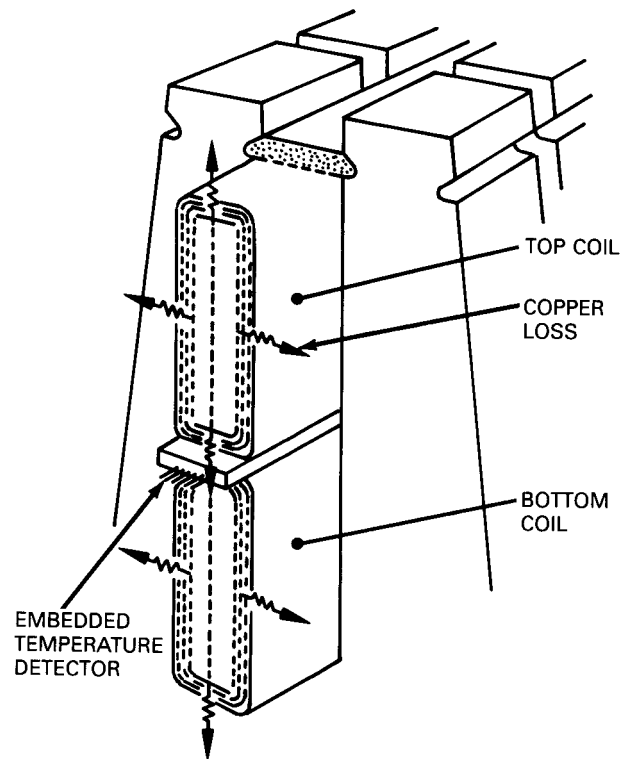


Figure 1—Heat Flow and Typical Temperature Detector Location

5.4.2.2 Directly Cooled Stator Windings

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.

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 interpreting 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 to 4 volts due to brush voltage drop. To compensate for this effect, pilot brushes that carry no field current are sometimes used for measuring the field voltage. However, some users have experienced difficulty with pilot brushes due to 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 fullload rotor current.

For excitation systems that do not employ collector rings, no simple method for measuring rotor-winding temperature is currently available.

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 Fig 1. The difference between the temperature of the hot spot and 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 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 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 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.

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 current in the conductors. A caution, if the liquid coolant flow in an individual coil is blocked (e.g., by copper corrosion), 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.

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, ANSI C50.13-1989 [2] calls for a lower temperature rise for the larger machines. The 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 to 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 set 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 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. 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 Fig 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 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.

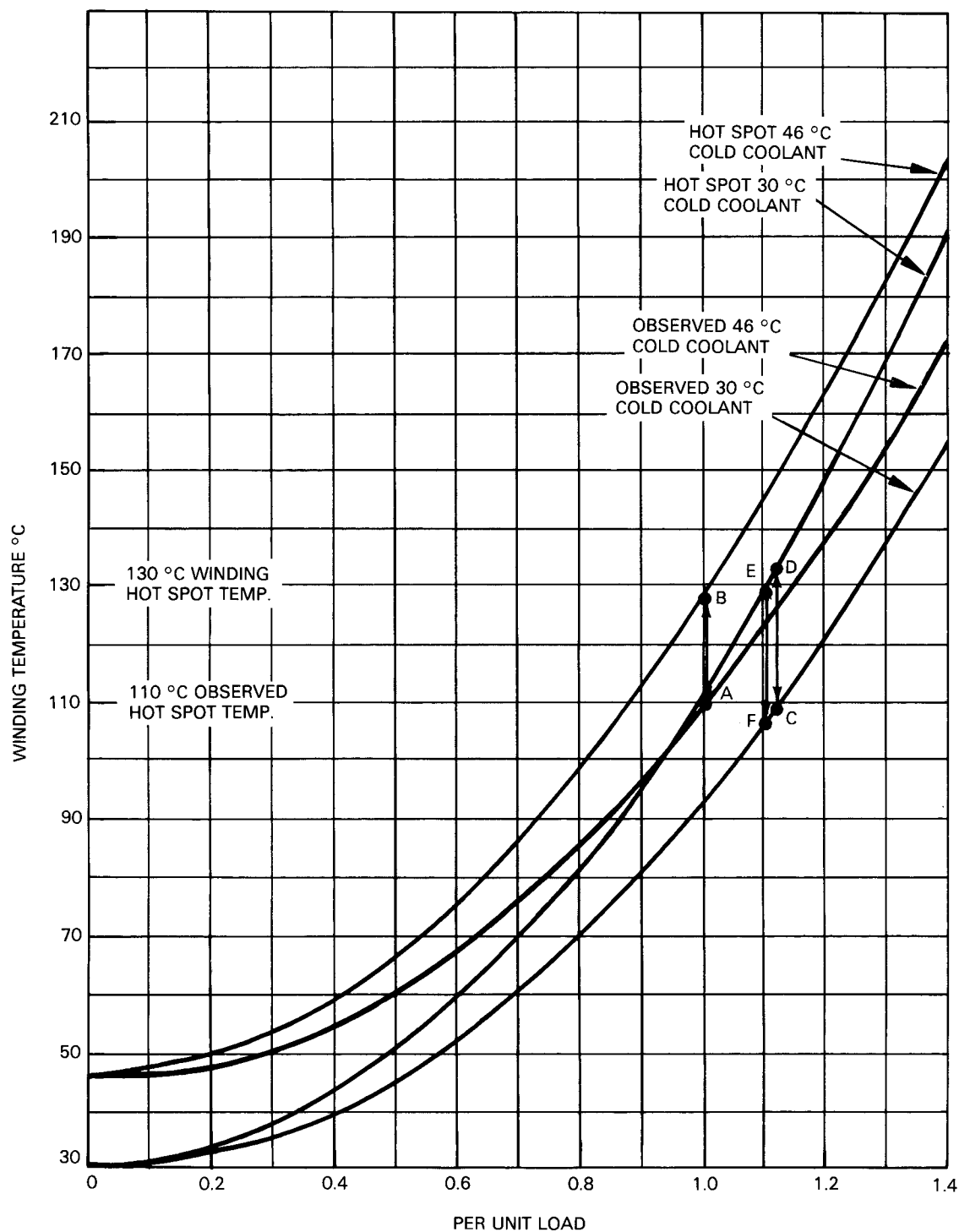


Figure 2—Typical Effect of Reduced Coolant Inlet Temperature on Hot Spot Temperature

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 due to 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 non-metallic 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, prompt failure can occur.

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, 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.

6.1.4 Operating Life

A base loaded generator can typically be expected to provide a useful life of 30 to 40 years when properly maintained and operated within the limits set by the manufacturer and the nameplate. Sufficient design margin is provided to ensure that temperature rises, forces and stresses are within the capabilities of the materials used in the machine. Before loading the machine beyond the nameplate rating, all the factors relating to overloading should be considered, and a full awareness of their implications developed. The machine can be operated beyond the nameplate rating, but the design margins will be encroached on, and some loss of normal life will be accumulated. The amount of life lost is difficult to quantify, and will depend greatly upon the specific machine design. The greater the overload, the more life will be removed from the generator, and as a general trend, the more highly rated the machine, the less margin there is to accept overload without loss of normal life. If abnormal operation is contemplated, the manufacturer should be consulted.

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 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 raw 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 in 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 the terminal is described by two characteristic curves; the no-load saturation curve and the short-circuit characteristic curve. The saturation curve (Fig 3) shows the relationship between terminal voltage and field current with the machine terminals open circuited, and with the machine operating at rated speed (point A). The straight line part of the characteristic is known as the “air-gap line” and the deviation from this line at higher voltages is due to magnetic saturation of the iron. The field current at rated terminal voltage is known as the no-load field current often

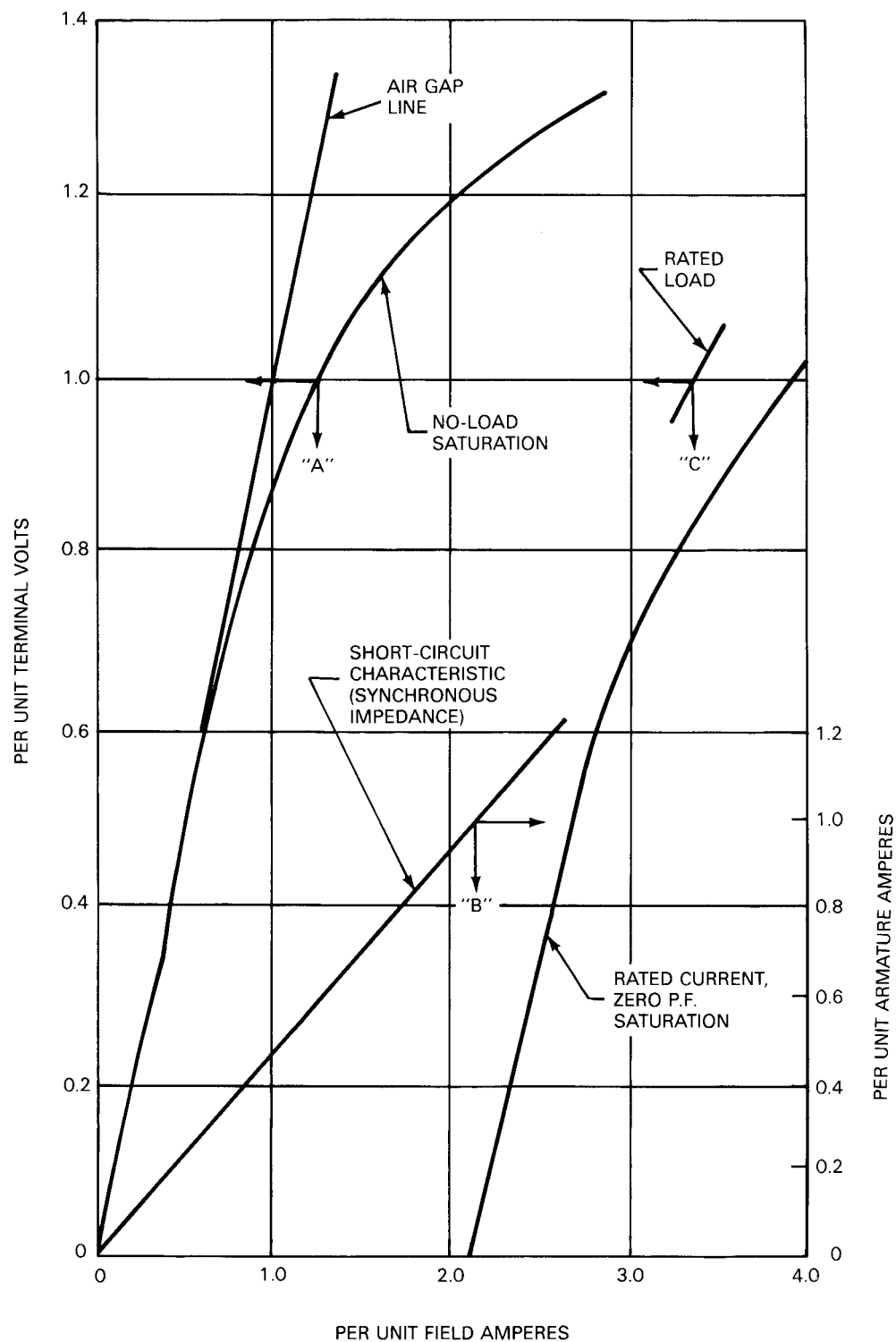


Figure 3—Typical Saturation Curve

called 1 pu field current. The short-circuit characteristic curve relates the stator current to the field current with the machine terminals short circuited, and the machine operating at rated speed. The field current at rated stator current (point B) is known as the short-circuit field current.

The ratio of the no-load field current to the short-circuit field current is the short-circuit ratio (SCR) of the machine, and is an index of the inherent steady-state stability of the machine. In general, the higher the SCR, the more stable the machine.

Also shown on Fig 3 is the zero power factor characteristic. This curve relates terminal voltage to field 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 shortcircuit field current. Point 'C' on Fig 3 is the "rated load" point; i.e., the point of operation at rated stator current and stator voltage at rated power factor.

6.3.2 Load Characteristics

If a machine is operating with an isolated load, then the power factor of the machine is determined by the load. However, in the more usual case of several machines supplying a load, the power factor of each machine can be different. The real power (kW) supplied by each machine is determined by the prime mover. The reactive power (kvar) supplied by each machine is determined by the excitation level.

Figure 4 shows the typical relationship between field current, kVA, and power factor at rated voltage and frequency. Curves of constant kW are also shown. Superimposed on these curves are the thermal operating limits imposed by the machine design. The maximum current that the field is designed to carry defines the upper limit on loading in the overexcited (lagging power factor) region, the right side of the figure. This is a vertical line at constant field current, extending from the zero power factor overexcited line to the rated power factor overexcited line. Since the field current carrying capability of a typical hydrogen-cooled machine is dependent on gas pressure, a number of such lines are shown, each corresponding to a different hydrogen gas pressure.

Similarly, the stator winding is designed to carry a maximum current corresponding to the rating of the machine.

The limit imposed by stator winding heating is a horizontal line in the upper part of Fig 4. Because of current-dependent effects in nonliquid-cooled components, this limit depends on gas pressure in both directly cooled and indirectly cooled generators.

In the underexcited (leading power factor) region, the left region of Fig 4, the load carrying capability is limited by stator core end heating. This is indicated by the sloping lines on the upper-left part of the figure.

The location of these limits depends on the design of the machine, and the type of cooling used, thus the shape of the curves and the location of the limits will vary from machine to machine. These curves, and the limits shown on them, represent the regions within which the machine may be safely loaded, without exceeding guaranteed temperature rises.

The curves in Fig 4 may be transformed into curves relating real and reactive power, as shown in Fig 5. In these curves, the field current limit, the stator winding current limit and the stator core end heating limit become boundaries, and lines of constant power factor become straight lines intersecting at the origin of the figure. There is a separate boundary for each gas pressure. Please note that the terms "lagging," "overexcited," and "Vars out" are used interchangeably as are the terms "leading," "underexcited," and "Vars in," which are used to indicate the quadrant of the reactive capability curve in which the machine is operating.

These curves represent the capability of the main generator at rated voltage and frequency. Other limits are imposed by associated equipment, such as the turbine, by system voltages, and, in some cases, by the system stability limits. A typical steady-state stability limit is shown in Fig 5.

The curves can be obtained from the instruction book or from the manufacturer, and must be used for all decisions pertaining to the capability of the generator.

6.3.3 Method of Estimating the Reactive Capability Curve

To construct the reactive capability curve accurately, a fairly complex calculation procedure is required to establish the constant field current line in the overexcited region and the end heating limits in the underexcited region. For this reason, it is necessary to use the manufacturer's curves for leading in these regions.

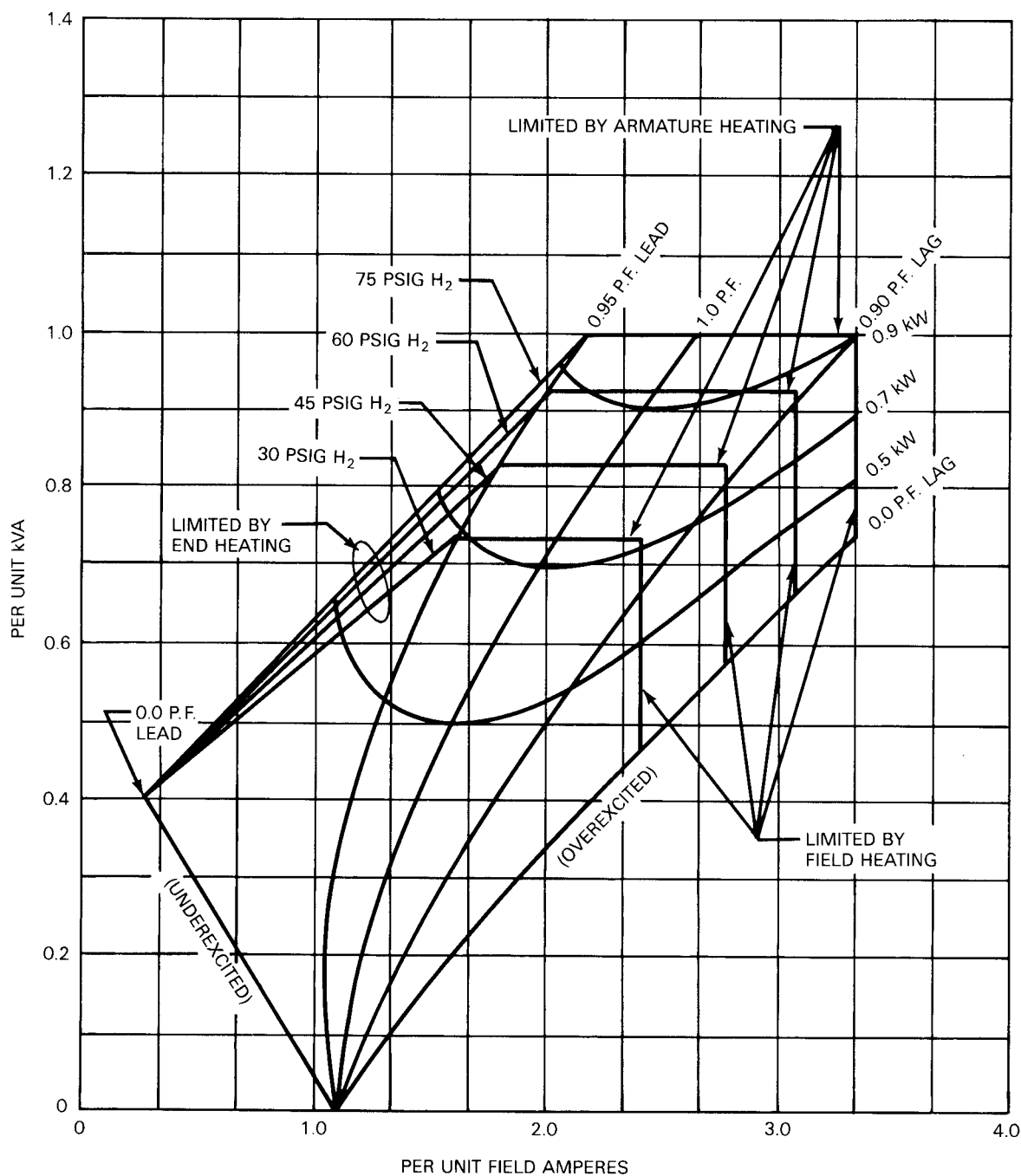


Figure 4—Typical Load Characteristic (Vee) Curve