

# RECLAMATION

*Managing Water in the West*

Design Standards No. 12

## Plant Testing

Chapter 1: Synchronous Generator, Motor, and Generator/Motor  
Field Tests

Phase 4 Final



## **Mission Statements**

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

## **Design Standards Signature Sheet**

**Design Standards No. 12**

# **Plant Testing**

**DS-12(1): Phase 4 Final  
August 2018**

**Chapter 1: Synchronous Generator, Motor, and Generator/Motor  
Field Tests**

**Approved:**

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**Deputy Commissioner, Operations**

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**Date**



# Foreword

## Purpose

The Bureau of Reclamation (Reclamation) design standards present technical requirements and processes to enable design professionals to prepare design documents and reports necessary to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. Compliance with these design standards assists in the development and improvement of Reclamation facilities in a way that protects the public's health, safety, and welfare; recognizes needs of all stakeholders; and achieves lasting value and functionality necessary for Reclamation facilities. Responsible designers accomplish this goal through compliance with these design standards and all other applicable technical codes, as well as incorporation of the stakeholders' vision and values, that are then reflected in the constructed facilities.

## Application of Design Standards

Reclamation design activities, whether performed by Reclamation or by a non-Reclamation entity, must be performed in accordance with established Reclamation design criteria and standards, and approved national design standards, if applicable. Exceptions to this requirement shall be in accordance with provisions of *Reclamation Manual Policy*, Performing Design and Construction Activities, FAC P03.

In addition to these design standards, designers shall integrate sound engineering judgment, applicable national codes and design standards, site-specific technical considerations, and project-specific considerations to ensure suitable designs are produced that protect the public's investment and safety. Designers shall use the most current edition of national codes and design standards consistent with Reclamation design standards. Reclamation design standards may include exceptions to requirements of national codes and design standards.

## Proposed Revisions

Reclamation designers should inform the Technical Service Center (TSC), via Reclamation's Design Standards Website notification procedure, of any recommended updates or changes to Reclamation design standards to meet current and/or improved design practices.



**Chapter Signature Sheet  
Bureau of Reclamation  
Technical Service Center**

**Design Standards No. 12**

# **Plant Testing**

## **Chapter 1: Synchronous Generator, Motor, and Generator/Motor Field Tests**

**DS-12(1):<sup>1</sup> Phase 4 Final  
August 2018**

Chapter 1 – Synchronous Generator, Motor, and Generator/Motor Field Tests is a new chapter within Design Standards No. 12.

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<sup>1</sup> DS-12(1) refers to Design Standards No. 12, chapter 1.

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## Chapter 1

# Plant Testing

## 1.1 General Sections

### 1.1.1 Specific Standards Required

Tests shall be conducted in accordance with the applicable sections of the Institute of Electrical and Electronics Engineers (IEEE) Standard 115™, Guide for Test Procedures for Synchronous Machines, [1] and referenced standards therein. Throughout this design standard, reference is made to IEEE Standard 115™ as IEEE 115.

### 1.1.2 Deviations and Proposed Revisions

Plant test activities must be performed in accordance with established Reclamation testing criteria and technical standards and approved national test standards. Exceptions to this requirement will require approval by Reclamation's Electrical and Mechanical Engineering Division of the TSC or the regional contracting officer.

## 1.2 Scope of Chapter

This chapter specifies recommended tests for large (above 1 megavolt ampere [MVA]) synchronous generators, motors, and generator/motor installations for new machines or existing machines that have been modified or updated. These tests also may be performed on existing machines, where needed, to obtain engineering data for design/specifications. The test procedures described herein are for generators; test procedures for large motors and generator/motors are similar, except as indicated.

## 1.3 Conduct of Tests

These tests are conducted to obtain machine parameters to determine performance, compliance with specifications, and for engineering records. These tests are usually conducted by representatives of the contractor, under the direction of the contracting officer, and observed by representatives of the Electrical and Mechanical Engineering Division of the TSC. In some cases, representatives of the Electrical and Mechanical Engineering Division may assist in performing part or all of the tests. The tests are typical; additions, revisions, and omissions may be made as conditions or specifications require.

### **1.3.1 Test Documentation**

The contractor is required by the solicitation to submit a proposed test procedure for approval. It should include specific references to the appropriate paragraphs of IEEE 115. Often, the contractor's documentation of the tests is limited in detail and description. Reclamation's representatives should use the contractor's test procedure, the test procedure described in this design standard, and IEEE 115 in their participation and observation of the machine field tests.

At a minimum, the contractor should document test procedures for each test to show the required test configuration (electrical, mechanical, hydraulic) for the machine under test and any required temporary modifications to other plant equipment associated with the test (e.g., exciter, governor, station service electrical power, other plant generators). All issues of safety should be addressed in the procedure, such as electrical and mechanical hazards, operational constraints, access barriers, etc. Documentation for test results should be provided as required by the solicitation and should be descriptive enough to demonstrate how the data was obtained and to validate accuracy.

## **1.4 Recommended Tests**

The following tests are recommended on all generators, except where indicated below or by the solicitation; the tests recommended for one unit only are required on only one generator of a group of identical machines furnished under one set of specifications:

- A. Dielectric tests of the armature and field windings (section 1.5.1), all units
- B. Resistance of armature and field windings (section 1.5.2), all units
- C. Armature voltage balanced and residual component telephone influence factor determination (section 1.5.3), one unit only
- D. Armature voltage waveform deviation factor (section 1.5.4), one unit only
- E. Line-charging capacity (section 1.5.5), one unit only
- F. Determination of efficiency, one unit only, and moment of inertia ( $WR^2$ ) of rotating parts, one unit only, optional (section 1.5.6)
- G. Heat run tests (section 1.5.7), one unit only

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- H. Sudden short circuit tests of field and armature (including armature voltage recovery) to determine the following machine parameters (section 1.5.8), one unit only - optional:
- (1) Direct-axis rated voltage and rated current transient reactance  $X'd$
  - (2) Direct-axis rated voltage and rated current subtransient reactance  $X''d$
  - (3) Direct-axis rated voltage and rated current transient short circuit time constant  $\tau'_d$
  - (4) Direct-axis rated voltage and rated current subtransient short circuit time constant  $\tau''_d$
  - (5) Direct-axis transient open-circuit time constant  $\tau'_{do}$
- I. Tests to determine the following characteristic curves (section 1.5.9), one unit only:
- (1) Open-circuit saturation (section 1.5.9.1)
  - (2) Short circuit saturation (section 1.5.9.2)
  - (3) Rated current, zero power factor overexcited saturation (section 1.5.9.3)
  - (4) Main-field current with various load (V-curve) (section 1.5.9.4),
- J. Stator air housing ozone concentration (section 1.5.10), all units
- K. Stator air housing CO<sub>2</sub> discharge test (section 1.5.11), one unit only - optional
- L. Overspeed test (section 1.5.12), one unit only - optional
- M. Excitation system, including control and voltage regulating equipment (section 1.5.13), all units

## 1.5 Field Test Procedures

Generator tests shall be conducted in accordance with the applicable sections of IEEE 115 and as described herein. In the event of a discrepancy, the more stringent requirements of this standard shall apply.

## 1.5.1 Dielectric Tests

Dielectric tests for acceptance or periodic maintenance testing of armature and field windings for new, rewind, or existing generators are prescribed by the Electrical and Mechanical Engineering Division of the TSC in Facilities Instructions, Standards, and Techniques (FIST) Volume 3-1, Testing Solid Insulation of Electrical Machinery [2].

## 1.5.2 Resistance of Armature and Field Windings

Resistance measurements of armature and field windings should be made with a double bridge or other direct current (dc) means such as the ammeter-voltmeter method. The method of measurement must not significantly change the temperature of the winding and, therefore, should not pass more than 10-percent (%) rated current through the winding for a short period of time. If a dc power supply is used, as for the ammeter-voltmeter method, ensure that the current is steady because some power supplies can become unstable when connected to the low resistance and high inductance load of the field winding. Typical connections are shown in figure 1.5.2-1.

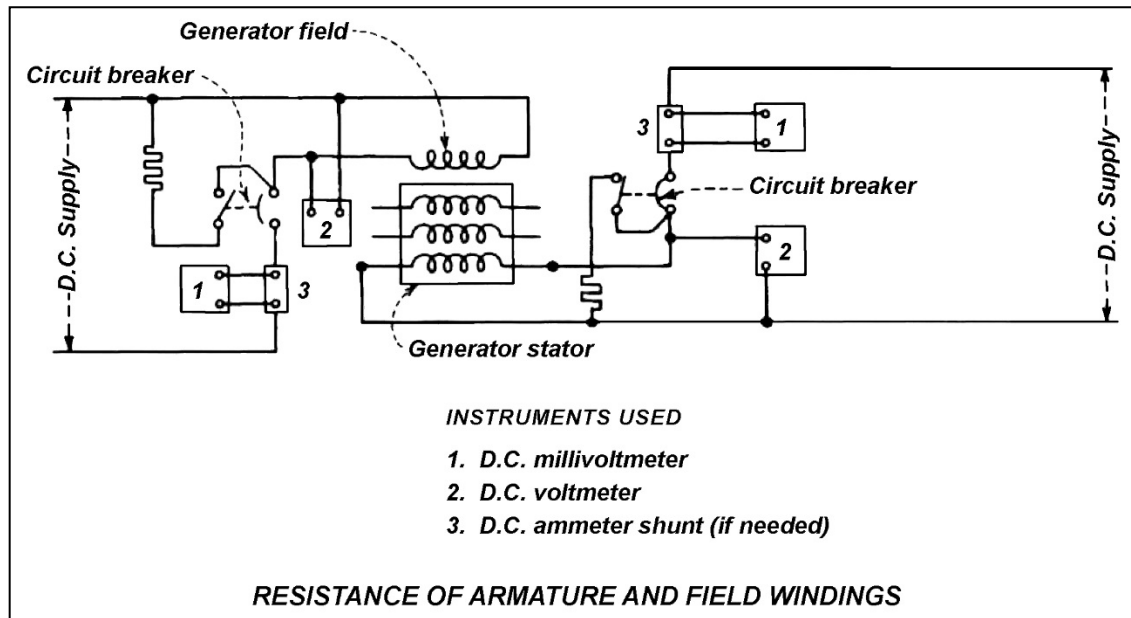


Figure 1.5.2-1. Resistance of armature and field windings tests.

Equipment for measuring the field winding should be connected directly to the collector rings (without brushes), and all brushes should be lifted from the rings. The three-phase armature winding should be disconnected completely from all external shunt devices (potential transformers, surge suppression equipment, etc.),



and the resistance measuring equipment should be connected directly to the manufacturer's defined armature winding terminals. Resistance for each phase of the armature winding, line-to-neutral, should be measured. Finally, the winding resistance usually is corrected to a specified temperature (section 1.6.1).

The generator should be shut down and allowed to cool to ambient temperature for approximately 18 hours prior to the test. Accurate readings of the temperature of the windings at the time of the test must be recorded. The average temperature of the field winding should be determined by not less than four thermometers (two each attached near the top and bottom of field poles in different locations around the rotor). The average temperature of the armature winding should be measured using not less than four existing embedded resistance temperature detectors (RTD). The four (or more) temperature readings for each winding are then averaged to single values.

The following item should be considered when performing this test:

- Small errors in field winding resistance measurement (or current and voltage to compute resistance) will cause a comparatively large error in calculating the winding temperature. Test instruments should read to four or greater significant-figure accuracy.

### 1.5.3 Armature Voltage Balanced and Residual Component Telephone Influence Factor

The telephone influence factor (TIF) (for generators only) is measured with a telephone influence meter consisting of an impedance network having the characteristics of the harmonic weighting factors coupled to a suitable indicating instrument. A harmonic analyzer with TIF weighting factor software also could be used for this test. The test generator excitation current should be taken from an essentially ripple-free dc source so as not to influence TIF readings. A rotating dc exciter is preferred to an alternating current (ac) rectifying type static exciter. Potential transformers used for these tests should be tested to demonstrate that they do not add significant harmonic content, which would influence TIF readings. TIF calculation procedure is given in section 1.6.2.

#### 1.5.3.1 Balanced TIF

To measure the balanced TIF, the meter or analyzer should be connected through a potential transformer line-to-line to one pair of armature terminals of the machine under test. The armature should be disconnected from any other equipment (power and potential transformers, surge suppression devices, etc.). The unit is operated at rated speed with excitation corresponding to no-load rated, open-circuit armature voltage. The test unit speed, true root mean square (rms) line-to-line voltage, and rms values of fundamental and harmonic components of

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line-to-line voltage should be recorded. A true rms reading digital voltmeter may be used for the former voltage measurement.

### 1.5.3.2 Residual Component TIF

The test generator armature should be connected in delta with one corner open with the unit operating at rated speed with excitation corresponding to no-load rated open-circuit voltage. The TIF meter or analyzer should be connected across the open corner of the delta so that it monitors the residual, or zero sequence component voltage ( $3 V_o$ ). TIF recordings are taken with the test unit operating at rated speed and armature voltage.

The residual component TIF may also be obtained by connecting the primaries of three potential transformers in wye to the terminals of the machine, and also connecting the secondaries of these potential transformers in delta with one corner open. The neutral of the potential transformers' primary circuit must be connected to the machine neutral. The TIF meter is then connected across the secondary delta open corner so that it monitors the residual, or zero sequence component voltage ( $3 V_o$ ). TIF recordings are taken with the test unit operating at rated speed and armature voltage.

The following item should be considered when performing the residual component test:

- If the test machine armature winding is connected in delta with one corner open, only a small percentage of rated line-to-line voltage will appear across the broken delta, necessitating the use of a low ratio potential transformer to connect to the TIF meter. Should a fault occur in the armature winding during the test, the broken delta voltage could approach rated phase (line-to-neutral) voltage. The test equipment configuration must safely isolate personnel from possible high voltage. For this safety concern alone, it may be advantageous to conduct the residual component test with the machine armature windings connected in wye and use the potential transformer secondary to form the delta.

### 1.5.4 Armature Voltage Waveform Deviation Factor

The test for waveform deviation factor of armature terminal voltage (generators only) should be made with a waveform recorder in conjunction with the open-circuit saturation test (section 1.5.9.1). This test is conducted with the unit operating at rated voltage and rated speed. The armature should be disconnected from any other equipment (power and potential transformers, surge suppression devices, etc.). Line-to-line voltage waveforms of each phase should be obtained at the terminals of the generator. For adequate data analysis, the waveform recorder should be capable of reproducing traces of half-cycle waveforms with a

minimum 4-centimeter (cm) amplitude and 5-cm distance between zero crossings. Typical connections are shown in figure 1.5.4-1.

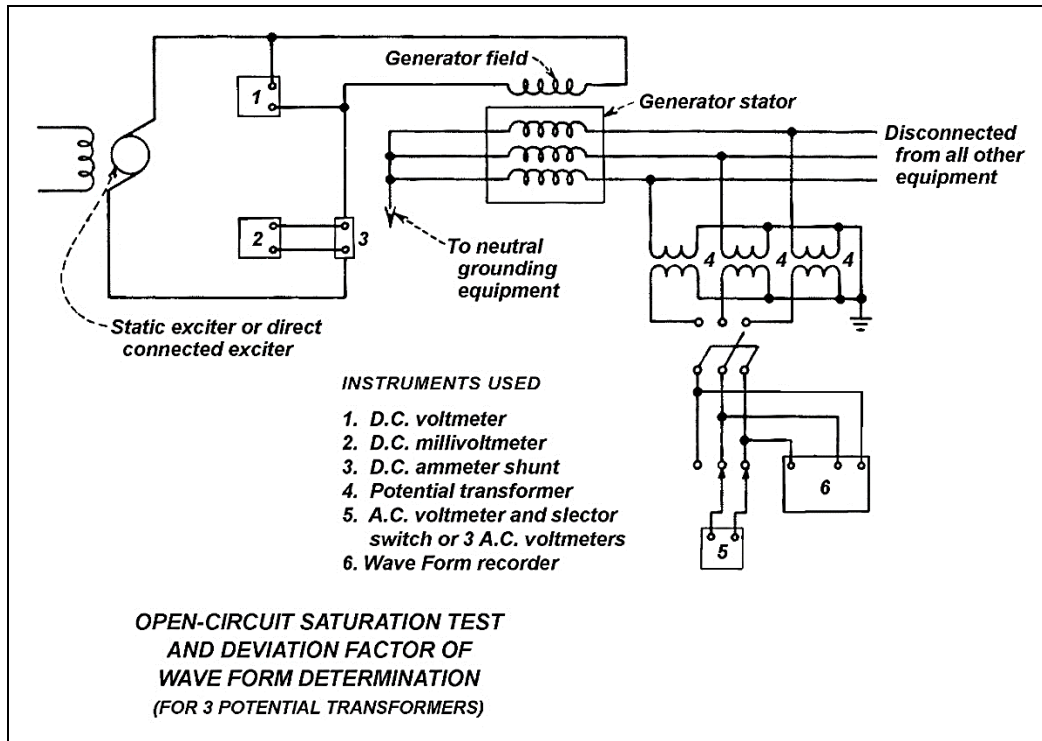


Figure 1.5.4-1. Generator field test wiring diagram. Open-circuit saturation test and deviation factor of waveform determination.

## 1.5.5 Line-Charging Capacity

The generator under test is driven at rated speed and rated armature voltage with the excitation of the test generator reduced to zero when connected to a load consisting of idle-running overexcited synchronous machines. The turbine of the test generator should furnish only enough power to supply all the losses of the test generator (no electrical power in or out of the test generator). The line-charging capacity is the reactive power into the test generator when operating synchronously under this condition at zero power factor. If additional reactive load is required, the generator may be connected to an unloaded transmission line or another generator at or near the plant that is producing reactive power, as shown in figure 1.5.5-1. Generator rotation speed, armature rms current and line-to-line voltage, and field current should be recorded at the test operating point. See section 1.6.4 for line-charging reactive power calculation.

If the test generator field current cannot be reduced to zero, or the armature current will exceed rated value with zero field current, a series of tests at

successively smaller values of excitation may be used to determine the test value. Readings may be taken at several values of armature current versus decreasing field current at rated armature voltage, from which a curve is plotted. The line-charging capacity may be obtained by extrapolating the curve to zero field current.

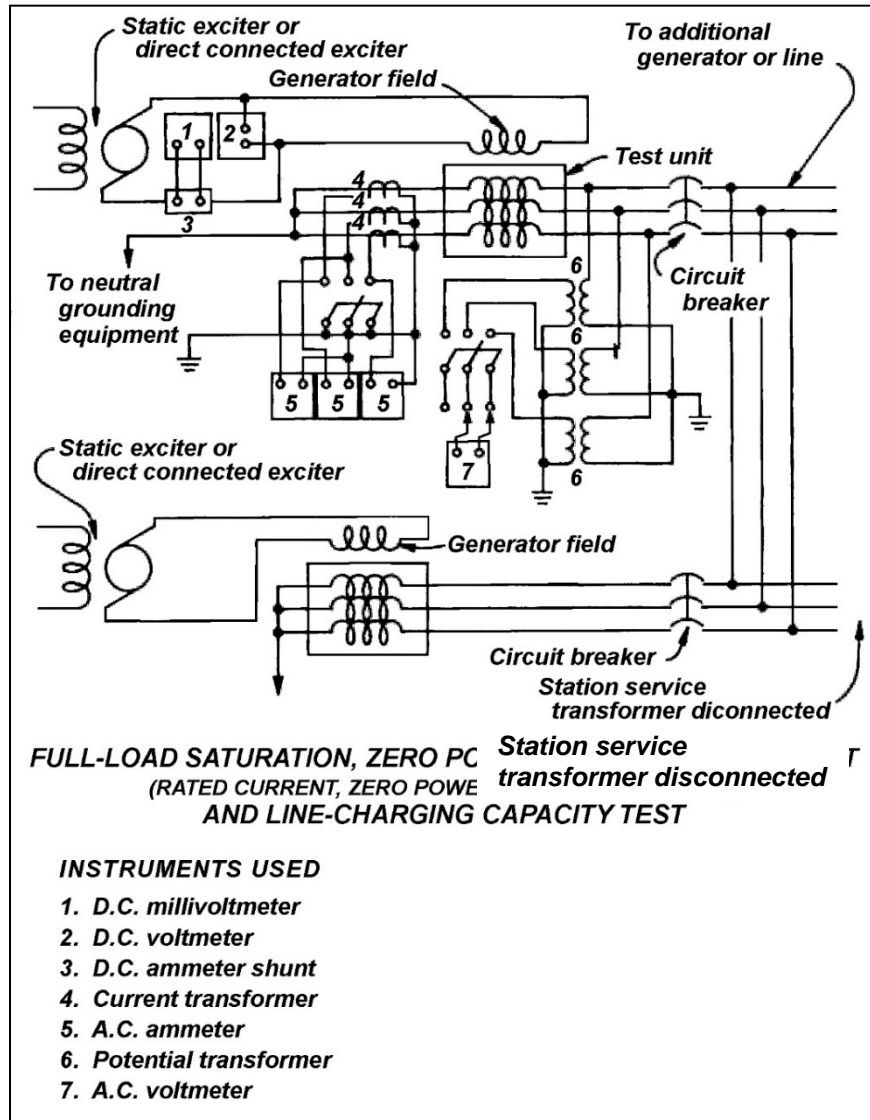


Figure 1.5.5-1. Full-load saturation, zero power factor lagging test and line-charging capacity test.

The following items should be considered when performing this test:

- The test generator will remain in synchronism operating at greatly reduced or zero field current due to rotor pole saliency (reluctance torque), provided that the power factor is maintained near zero.

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- Test generator loss-of-field protective relaying should be disabled.
- Exciter minimum excitation limiters may also need to be adjusted to allow for zero, or near zero, field current.
- It is important to keep the test generator at or near rated voltage (as much as possible) since there is no correction for voltage in the calculation procedure (see section 1.6.4).

For motors, an approximate line-charging capacity may be determined using a similar test procedure for generators with the motor operating online at zero power factor underexcited. The pump impeller must be unwatered or uncoupled from the motor.

### 1.5.6 Determination of Efficiency and $WR^2$ of Rotating Parts

For efficiency testing, machine losses are segregated as follows:

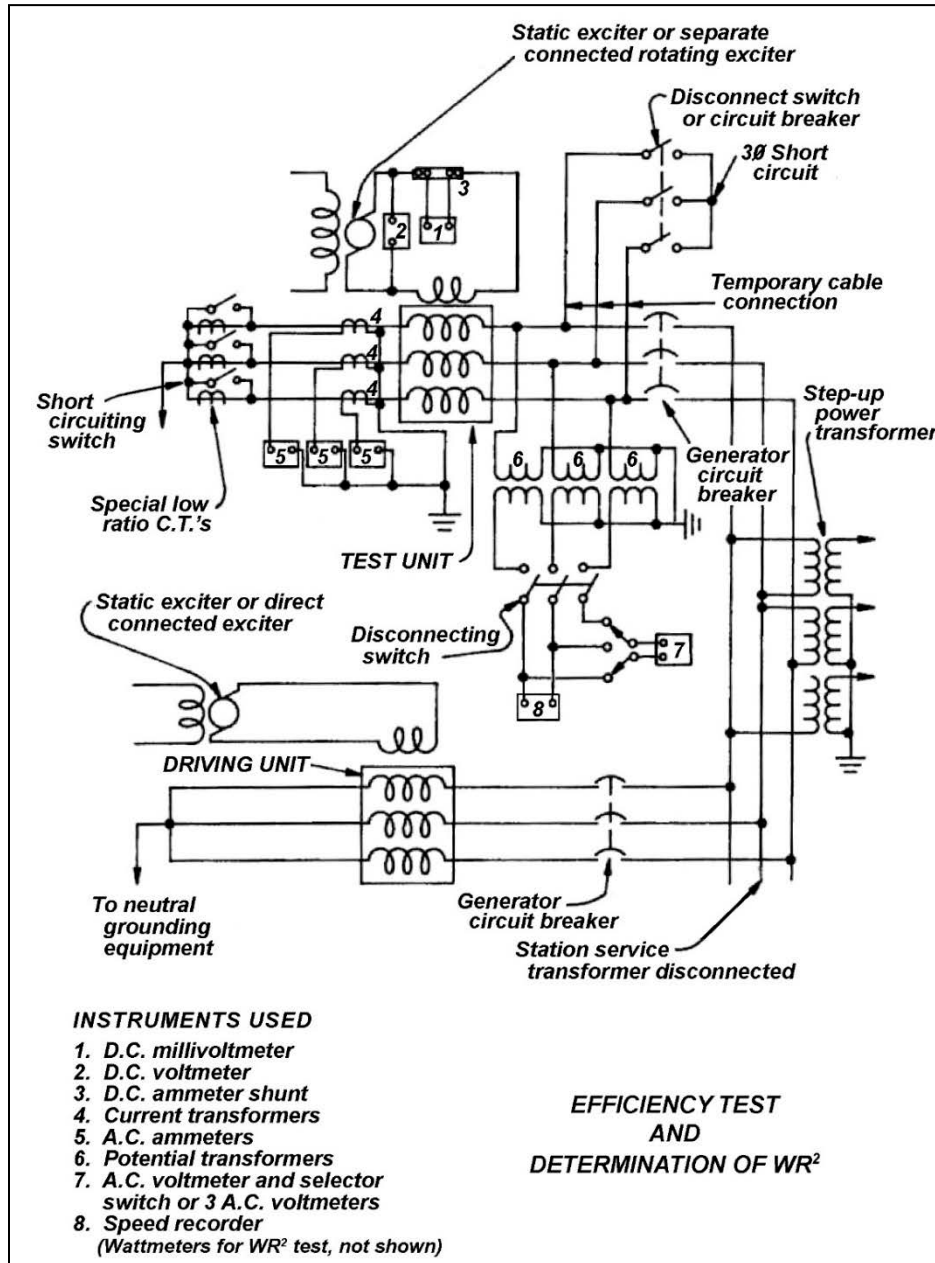
- Friction and windage loss (section 1.5.6.1)
- Core loss (section 1.5.6.2)
- Stray load loss (section 1.5.6.3)
- Field  $I^2R$  loss at specified temperature (section 1.5.6.4)
- Armature  $I^2R$  loss at specified temperature (section 1.5.6.4)
- Excitation system losses (section 1.5.6.5)

Generator and motor specifications typically specify maximum or warranted values for certain segregated losses (e.g., core or armature  $I^2R$ ) and, in some cases, for efficiency. Penalty schedules for these losses can occur in increments as low as 1 kilowatt (kW). Therefore, a high degree of accuracy is required for loss measurement that otherwise would not be necessary for determination of efficiency alone. Segregated losses in kilowatts should be measured to one decimal place accuracy (0.1 kW). Refer to section 1.6.5 for loss calculation procedure.

It is noted that the only quantities that must be determined by test for use in the formula for efficiency are the losses. The total losses are only a small percentage of the machine output (generator) or input (motor) when **operating at or very near its rating**, so that the small errors involved in determining the losses by test will result in extremely small errors in the efficiency result. This is, therefore, an inherently accurate method of determining machine efficiency from test results. Various test methods for determining the segregated losses are considered by IEEE 115 as being acceptable. Among these are the retardation method and separate-drive method. In the few instances where generators are tested in the

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factory, the separate-drive method may be used. However, the machines are most commonly tested after installation at the site. In this case, the retardation method is used, and this is the method described in the following paragraphs. Typical connections and instruments are shown in figure 1.5.6-1.



**Figure 1.5.6-1. Efficiency test and determination of  $WR^2$ .**

All segregated loss tests are performed with the generator (motor) uncoupled from its turbine (pump impeller) and the generator operated as a motor. Uncoupled

operation usually poses no mechanical problems (i.e., bearings); however, the generator manufacturer should be consulted.

### **1.5.6.1 Friction and Windage Loss Test**

The test unit must be started as a motor, either synchronous or induction. Details of the starting method and the connections to be used are decided upon by the generator contractor and the contracting officer prior to beginning the test program. When the induction motor method of starting is used, the driving unit is operated at reduced speed and voltage until the speeds of the two units are the same and they have been synchronized. To improve starting torque when using the induction start method, a resistance approximately equal to that of the main generator field is sometimes placed in series with the field winding of the test unit. A short-circuiting switch should be placed in parallel with this resistor so that the resistor may be shunted out after the test generator has started to rotate. The field winding never should be opened during induction starting, or damaging overvoltage will result. Synchronous starting requires that both the test (driven) machine and the driving unit have field current applied at standstill at approximately speed-no-load rated voltage values. This precludes the use of direct-connected rotating exciters or generator terminal connected static exciters. Elapsed time with field current applied without rotation should be minimized to avoid overheating the collector rings and brushes.

After the generator has been started by one of the above methods and before beginning the loss test, the test generator should be operated at no-load (zero volt-ampere reactive [var]) and rated speed for about 2 hours so that the bearing friction will approach a constant value and all bearings will have reached normal operating temperature. Two retardation runs should be made to determine whether constant loss conditions have been attained. This procedure should be followed any time that loss tests are resumed after an appreciable period of shutdown.

To measure the combined friction and windage losses, the speed of both units should be increased by the driving unit to approximately 120% rated speed. The alternating current (ac) tie circuit breaker should then be opened to disconnect the test unit armature from the driving unit. Immediately thereafter, the field current of the test unit should be reduced to zero, and a digital frequency transducer, speed-time recorder, or digital recorder placed in service. Speed of the test unit should be recorded until it has dropped to 80% or less of rated speed.

To meet the accuracy requirement for segregated loss measurement given in section 1.5.6, the speed recording equipment should be capable of determining rotation speed and its time derivative (slope) as the test unit coasts through the rated speed point to within  $\pm 0.1\%$ . Bearing temperatures should be recorded, and the open-circuit armature rms voltage should be recorded at the rated speed point. The following items should be considered when performing the friction and windage test:

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- During deceleration, an open-circuit armature voltage may develop without excitation due to residual magnetic flux in the rotor pole iron. Armature voltage also may be present if the dc output of a rotating exciter cannot be reduced to zero. This residual armature voltage adds a small component of core loss to the windage and friction measurement.
- Core loss is approximately proportional to the square of armature voltage if saturation is neglected (Boldea, equation 7.207) [3]. To keep core loss from becoming appreciable, the rotor should be demagnetized if the residual open-circuit armature voltage exceeds about 3% of rated voltage at rated speed. Demagnetizing the rotor in the short time available while the test generator decelerates from 120% to 100% speed is accomplished by reversing the polarity of the field circuit and raising the current from zero to the value necessary to drive the armature voltage to zero. Due to hysteresis, the value of reverse field current required typically exceeds 50% of the field current for rated open-circuit armature voltage at rated speed.
- Armature voltage is proportional to speed; therefore, the voltage will reach approximately 120% rated while obtaining the initial overspeed if normal field current is applied. The field current of both units may be reduced so that rated armature voltage is not exceeded on overspeed while maintaining little or no reactive power transfer.
- If armature winding voltage surge suppression devices are direct connected to the generator terminals, determine if this equipment should be disconnected to avoid damage from overvoltage.

### 1.5.6.2 Open-Circuit Core Loss Test

Core loss is determined using a test method that is similar to the friction and windage test, except that the unit is excited during the test. The loss measured by this test includes both the friction and windage loss plus open-circuit core loss. Core loss is determined by subtracting friction and windage loss from the loss measured by this test.

The combined friction and windage plus open-circuit core loss test should be conducted in a manner similar to the friction and windage loss test described in section 1.5.6.1. The test and driving units should be brought to 120% of rated speed to initiate a test. A minimum of two tests should be conducted with the field current of the test generator adjusted to give slightly above and below rated open-circuit armature voltage (not to exceed  $\pm 2\%$ ) at rated speed. Additional tests may be repeated at various values of field current to obtain sufficient points for plotting a core-loss curve (refer to IEEE 115). The values of field current shall be taken from the open-circuit saturation curve determined from section 1.5.9.1. Readings of field current and the three armature line-to-line rms voltages should be taken at least every 15 seconds and at the point of rated speed.



The following items should be considered when performing the open-circuit core loss test:

- Armature voltage is proportional to speed; therefore, the voltage will reach approximately 120% rated at the initiation of this test. Consult with the generator manufacturer before performing the test. If the overvoltage is objectionable, a lower initial overspeed should be determined. This consideration also applies to the unit step-up power transformer if it is connected during startup.
- If armature winding voltage surge suppression devices are direct connected to the generator terminals, determine if this equipment should be disconnected to avoid damage from overvoltage.
- Exciter overvoltage limiters and relaying as well as volts/hertz limiters and relaying should be reviewed for undesirable interaction during testing and temporary adjustments should be made as necessary or these functions may need to be disabled.
- The test generator should be excited from a separate source to maintain constant field current during deceleration. If a direct-connected rotating exciter must be used, it should be adjusted continuously for constant excitation, and its power input should be subtracted from the loss calculations.

If the only segregated test required is a core loss test, it may be possible to measure core loss without uncoupling the turbine (pump impeller). To obtain accurate results it is necessary to lower the water level below the bottom of the runner. Preferably, the water should be about 1 meter below the runner to minimize water turbulence impacting test results. IEEE 115 also references a caloric test method that can be used to measure core losses. The caloric method does not require uncoupling the turbine but additional effort to insure accurate test data is required to obtain satisfactory results.

### 1.5.6.3 Stray Load Loss Test

Stray load loss is determined using a test method that is similar to the friction and windage test, except that the armature is shorted and the unit excited during the test. The loss measured by this test includes the friction and windage loss, plus stray load loss, plus the armature  $I^2R$  loss. Stray load loss is determined by subtracting friction and windage losses and armature  $I^2R$  loss from the loss measured by this test.

The combined friction and windage plus short circuit load loss test should be conducted in a manner similar to the friction and windage loss test described in section 1.5.6.1, except that the armature must be connected to a three-phase short circuit. A minimum of two tests should be conducted with the field current of the

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test generator adjusted to give slightly above and below rated armature current at rated speed. Additional tests may be repeated at various values of field current to obtain sufficient points for plotting a load-loss curve (refer to IEEE 115). The values of field current shall be taken from the short circuit saturation curve determined from section 1.5.9.2. The test should proceed as follows:

- (1) The test and driving units should be brought to 120% of rated speed.
- (2) Open the ac tie circuit breaker to disconnect the test unit armature from the driving unit.
- (3) Reduce the field current of the test unit to zero. Close the armature short circuit switch. Place the speed-time recorder in service. Readjust the field current of the test unit to the predetermined value for desired short circuit armature current at rated speed.
- (4) Readings of field current and the three-phase armature rms currents should be taken at least every 15 seconds and at the point of rated speed. At least four of the armature embedded RTDs should be read at 1-minute intervals or less during these tests.

See the item in Section 1.5.9.2, “Short Circuit Saturation,” concerning armature residual circulating current and shorting switch rating. A circuit breaker may be required to conduct the stray load loss test.

### 1.5.6.4 Armature and Field Winding $I^2R$ Losses

Armature and field winding  $I^2R$  losses are not determined by specific tests but are calculated from measurements of resistance and current under specified conditions. Refer to section 1.6.5.4 for calculation procedures and rating definitions.

### 1.5.6.5 Excitation System Losses

Excitation system losses are a small component of the segregated losses and a smaller fraction of the generator rated kilowatt output. A typical rotating exciter is 85% efficient (static exciters are more efficient), which implies that excitation system losses will not exceed about 15% of the field winding  $I^2R$  loss. For large hydrogenerators, the field  $I^2R$  loss is approximately 0.2% of rated kilowatt output. Therefore, excitation system losses will not exceed about 0.03% rated kilowatt output and are insignificant in determining efficiency.

The inclusion of excitation system losses for calculation of generator efficiency should be determined by the solicitation or by agreement between the contractor and contracting officer. However, no guidelines are provided in this standard for measuring excitation system losses. Refer to IEEE C50.12<sup>TM</sup> [4] for a discussion of excitation system losses.

#### 1.5.6.6 $WR^2$ of Rotating Parts Test

Loss measurement by the electric power input test method can be performed to verify the friction, windage, and core-loss values determined by the above retardation tests. It also can be used to verify the accuracy of the calculated value of moment of inertia ( $WR^2$ ) of rotating parts. The calculated  $WR^2$  is a design value provided by the generator manufacturer. The tested value of  $WR^2$  is computed from the losses determined by this test and the rate of deceleration data measured during the friction, windage, and core-loss test described in section 1.5.6.2. The electric power input test typically is conducted only when the manufacturer's calculated  $WR^2$  is in question or if the measured losses and efficiency by retardation do not meet warranted values. It is, therefore, a test requiring a high degree of accuracy of measurements. See section 1.6.5.5 for the  $WR^2$  calculation procedure.

To conduct this test, the unit is uncoupled from its turbine, as done for the retardation tests. The test unit and driving unit should be brought to rated speed. The field current of the test unit should then be adjusted to give rated armature voltage, and the field current of the driving unit should be adjusted for minimum armature current (unity power factor). Three low-ratio instrument current transformers should be used for measuring armature current and power, having a primary current rating equal to approximately 5% rated current. During the starting and adjustment periods, these current transformer primaries should be short circuited.

Readings should be recorded for the test unit armature power (watts) input and three-phase rms voltages and currents, field current, and speed. Indicating wattmeters may be used for this test; however, if the readings are not stable enough to be accurate, three single-phase watt-hour standards should be used for reading the input. For highest accuracy, power readings from watt or watt-hour meters should be corrected for instrument transformer ratio and phase angle error of the connected burdens. The test should be repeated for armature voltage settings ranging from 110% rated voltage (including 100%) to the lowest value obtainable for stable readings (all at minimum armature current). Five complete readings should be taken at each voltage step to obtain good average readings. Typical connections and instruments are shown in figure 1.5.6-1.

The following item should be considered when performing this test:

- The purpose of obtaining test data at the lowest armature voltage possible is to eliminate open-circuit core loss in determining friction and windage loss. The ability of the test and driving units to remain in synchronism at rated speed determines the minimum armature voltage. Typically, synchronism cannot be sustained below 30% rated voltage.

## 1.5.7 Heat Run Tests

Heat run tests are conducted in two parts:

- (1) A trial heat run to determine placement of temperature sensors in the cold-air discharge path of the stator housing air coolers (assuming the machine is enclosed with a recirculating cooling system) to determine the ambient temperature of the cooling air
- (2) An actual heat run to determine the ambient temperature of the cooling air and temperature rise of all specified machine parts at a specified operating (load) condition

### 1.5.7.1 General Procedure

The unit under test should be driven by its turbine and connected to the system load at rated speed and rated armature voltage, current, and power factor with all coolers in service. If an automatic cooling water control system has been provided for the stator air housing coolers, the automatic controls should be disabled for all heat runs. Cooling waterflow to all other parts (bearings, etc.) should be normal. During the heat run the unit should be operated at a consistent loading. Determine by test if the voltage regulator should be in manual or automatic regulation mode to maintain consistent loading.

The armature load power factor of the test generator may be determined from readings of load watts and vars by the following equation:

$$pf = \frac{P_W}{\sqrt{P_W^2 + P_R^2}} \quad (1)$$

where:

- pf = armature load power factor, dimensionless
- $P_W$  = armature real load, kW
- $P_R$  = armature reactive load, kilovar (kvar)

### 1.5.7.2 Trial Heat Run

Not less than 20 temperature devices (thermocouples or resistance temperature detectors) should be installed in the cold air discharge from one (pilot) air cooler. The devices should be installed not more than 6 inches from the face of the pilot cooler and should be spaced at approximately equal intervals. Figure 1.5.7.2-1 shows an example installation of thermocouple type temperature sensors at the discharge side of an air cooler. The sensors should be wired to recording equipment located outside the air housing so that the housing can remain closed during operation.



**Figure 1.5.7.2-1. Trial heat run test (section 1.5.7.2). Photograph showing placement of 20 thermocouples at the cold air discharge face of an air cooler inside the stator air housing.**

With the test generator operating under the approximate rated load, and with the cooling water supply adjusted as it will be used during the actual heat run test, temperature readings of all temperature sensors on this pilot cooler should be observed and recorded, and the readings should be averaged to a single value. The average temperature so determined from the 20 sensors should then be used to locate at least four sensors (monitor sensors) in the pilot group that produce the same average temperature within  $\pm 1$  degrees Celsius ( $^{\circ}\text{C}$ ). Four (or more) monitor sensors are then installed at each air cooler in the same relative positions as determined from the pilot cooler.

The average of all monitor temperature sensors from all of the air coolers (at least four per cooler) will represent the ambient air temperature for the generator during the period of constant temperature operation of the actual heat run. This ambient temperature should be used to determine the temperature rise of the various machine parts (section 1.6.6.2).

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The following item should be considered when performing this test:

- Duration of trial heat run should be long enough to allow adequate stability of temperature readings to determine the location of the monitor sensors. It is not necessary to meet the temperatures stabilization criteria as discussed in section 1.5.7.3.

### 1.5.7.3 Actual Heat Run

The unit should be operated until all machine temperatures listed below have become constant within 2 °C for three consecutive half-hourly readings while the test generator is loaded as described in Section 1.5.7.1, “General Procedure.” The following electrical quantities and temperatures should be read every half hour until all temperatures have reached constant values. Accuracy of test instruments should be within the following percents of reading: temperature devices:  $\pm 0.5$  °C; armature electrical quantities:  $\pm 1\%$ ; and field electrical quantities: to four or more significant figures.

- (1) Air cooler temperature monitor sensors (minimum four per cooler) installed during the trial heat run (section 1.5.7.2).
- (2) Armature winding temperature in at least 12 places by RTD.
- (3) Stator core temperature in at least four places by thermocouple or RTD.
- (4) Upper guide, thrust, lower guide, and turbine bearings metal temperature by embedded detector.
- (5) Cooling water supply and discharge temperatures for air coolers and bearings by thermometers. (Measuring cooling waterflow is optional.)
- (6) Armature rms current and line-to-line voltage, and watts and vars load.
- (7) Field current and voltage (for calculation of resistance and temperature).

All the above electrical quantities and temperatures should be recorded for the last three consecutive half-hourly readings representing constant temperature operation. Calculation of machine temperatures is covered in section 1.6.6.

The following items should be considered when performing the heat run test:

- Measurements of field current and voltage should be done with the voltage regulator inactive (manual or dc regulate mode) and the power system stabilizer (PSS), if provided, shut off (in manual mode, the PSS is inactive). Otherwise, the current and voltage may drift during readings and degrade accuracy. Often, consistent field voltage cannot be read due to rapid

fluctuation when the power system stabilizer is active. Field current and voltage readings should be taken simultaneously to ensure accuracy of resistance calculation. The field voltage must be measured at the collector rings with an isolated pair of brushes to exclude brush voltage drop from the field current. Figure 1.5.7.3-1 shows a pair of handheld brushes on dry wooden rods for this purpose.



**Figure 1.5.7.3-1. Heat run test (section 1.5.7.3). Carbon brushes mounted to dry wooden sticks are held against the field collector rings for voltage measurement to determine field resistance.**

- Other plant generators, if available, should be used to adjust plant reactive loading as necessary to hold the armature voltage of the test generator within  $\pm 2\%$  rated when operating at rated load. Power system voltage conditions may change with time; therefore, the test generator armature voltage should be monitored during the heat run and corrected as necessary by readjusting the other plant generator(s).
- Reduced turbine head or flow restrictions may limit the test generator load to less than rated kilowatt output. In this case, three heat runs should be made at different loads, all at rated power factor. The temperature rise of the armature and field windings and stator core can then be determined by plotting their temperature rises versus kilovolt ampere squared (kVA)<sup>2</sup> on linear axes and extrapolating to rated (kVA)<sup>2</sup>. The highest load of the three heat runs should be as close to rated load as possible.

## 1.5.8 Sudden Short Circuit Tests

### 1.5.8.1 Three-Phase Sudden Short Circuit of Armature

The three-phase sudden short circuit test is performed to determine the following generator parameters: direct-axis transient reactance  $X'_d$ ; direct-axis subtransient reactance  $X''_d$ ; direct-axis transient short circuit time constant  $\tau'_d$ ; and direct-axis subtransient short circuit time constant  $\tau''_d$ . These parameters are used, among other things, to approximate the generator armature ac current component following the application of a three-phase sudden short circuit by the following classic equation:

$$I(t) = E \left[ \frac{1}{X_{ds}} + \left( \frac{1}{X'_d} - \frac{1}{X_{ds}} \right) e^{-\frac{t}{\tau'_d}} + \left( \frac{1}{X''_d} - \frac{1}{X'_d} \right) e^{-\frac{t}{\tau''_d}} \right] \quad (2)$$

where:

- $I(t)$  = armature ac rms short circuit current
- $E$  = armature rms voltage before short circuit
- $t$  = time from instant of short circuit, seconds

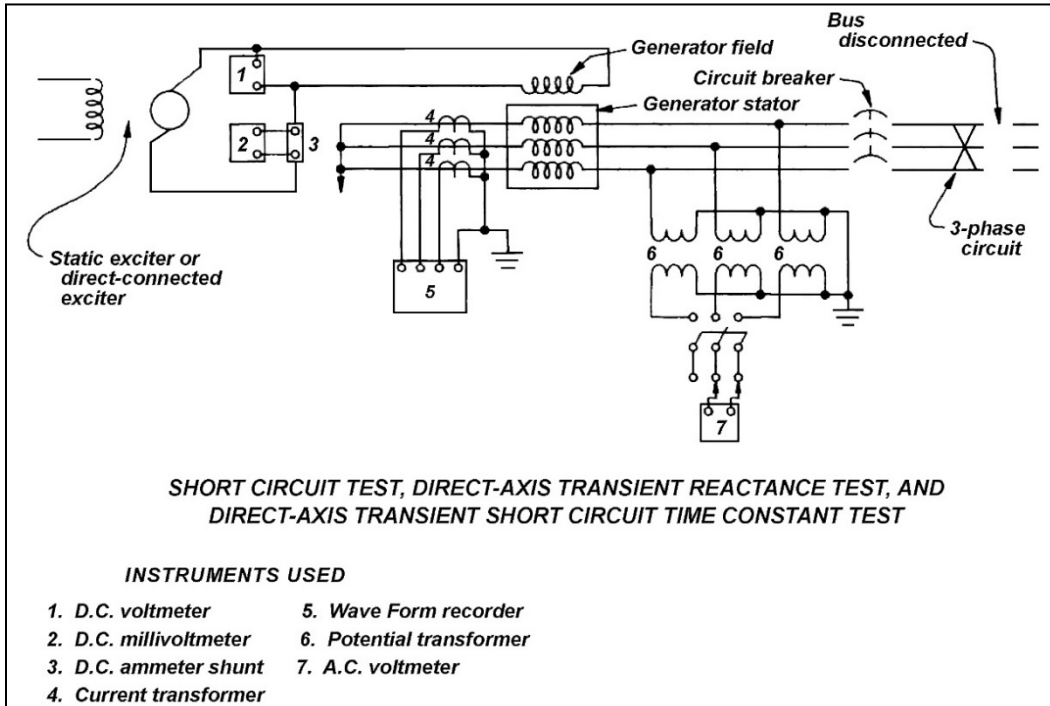
Equation (2) is for information only. Refer to the *IEEE Standard Dictionary - Glossary of Terms and Definitions* [5] for definitions of these parameters. See section 1.6.7 for parameter calculations.

To perform the three-phase short circuit test, the generator under test, while operating at no-load rated speed and rated armature voltage, is abruptly short circuited by means of the generator circuit breaker through a temporary three-phase short circuit connection. Readings of speed, armature line-to-line rms voltage, field current, and field voltage should be recorded immediately before and during the application of the short circuit. A digital recorder should be used to record waveforms of the three armature currents during the application of the short circuit. The armature currents should be recorded for a long enough period to ensure that they reach steady-state (approximately 5 seconds). If the first short circuit does not produce a completely offset current wave (or nearly so) on any phase, additional short circuits, not to exceed a total of three, should be placed on the test generator until the desired results are obtained. Typical connections are shown in figure 1.5.8.1-1.

Note that the parameter values obtained from the above test description are the **rated voltage** values. If **rated current** values are required, the short circuit test must be conducted with the generator armature voltage adjusted (lowered) so that the initial value of transient current is equal to rated armature current. This implies that the pre-short armature voltage must equal  $X'_d$ , both in per-unit. In this case, the manufacturer design value for  $X'_d$  can be used to estimate the required pre-short armature voltage. More than one (not to exceed three) short circuit test



may be necessary to adjust the pre-short armature voltage so that the initial transient current is equal to the rated armature current.



**Figure 1.5.8.1-1. Short circuit test, direct-axis transient and subtransient reactance test, and direct-axis transient and subtransient short circuit time constant test.**

The following items should be considered when performing the three-phase short circuit test:

- The resistance and inductance of the external field circuit must be negligible compared to the field winding self-resistance and inductance, and constant excitation source voltage must be maintained during the application of the three-phase armature short circuit. To accomplish this, the exciter voltage regulator should be out of service, and the rheostat setting (for rotating exciter) should remain unchanged throughout the test. Static main or pilot exciters should be operated at a fixed firing angle on the rectifier bridge, or otherwise in a manual (nonauto regulate) mode with an internal feedback control loop that regulates field voltage rather than field current (most static exciters regulate field current, not voltage). This test precludes the use of a static exciter that is direct connected to the test generator bus for a source of excitation power. For direct connected static exciters, the power feed would need to be moved to a separate source. The resistance and inductance of the external field circuit is typically negligible if the exciter is rated for normal field current.

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- Armature winding line-to-line voltage measurements (prior to short circuit) should be taken between each pair of winding terminals, and the three readings should be averaged to a single value.
- If instrument current transformers are used to measure armature current, check that the ratio accuracy will not be affected due to saturation from dc offset in the short circuit current waveforms. Current shunts or Hall effect devices may offer better performance.
- Depending on the configuration for shorting the generator armature winding, current may flow in portions of the existing generator bus containing current transformers used to create zones of relay protection (typically differential) for the generator and/or unit step-up transformer. These protective relay schemes should be reviewed for undesirable interaction with the test configuration and disabled, as necessary.
- The short circuit test causes severe mechanical stress on the machine. The generator manufacturer should be consulted before conducting this test.

### 1.5.8.2 Field Winding Sudden Short Circuit

The field winding sudden short circuit test is performed to determine the direct-axis transient open-circuit time constant  $\tau'_{do}$ .

To perform the field winding short circuit test, the generator under test should be driven by its turbine at no load, rated speed, and rated voltage with the armature leads open circuited. A resistor with resistance approximately equal to that of the generator main field should be placed in series with the test unit between the exciter and the short-circuiting circuit breaker or switch. The field is then suddenly short circuited, and one of the line-to-line armature voltage waveforms is recorded. Typical instruments and connections are shown in figure 1.5.8.2-1.

For static excitation systems, it may be possible to lower the resistance of the series resistor if the static exciter output can be switched off when the shorting breaker is closed. Consult the exciter manufacturer or the Electrical and Mechanical Engineering Division of the TSC for additional guidance.

The direct-axis transient open-circuit time constant  $\tau'_{do}$  also may be determined by the armature voltage recovery test method wherein the three-phase armature short circuit is suddenly removed. Refer to IEEE 115 for the test procedure. The armature voltage recovery test method may be preferred in cases where the following considerations apply.

- The external resistor in series with the field circuit will dissipate considerable heat and may need to be very large in physical size.

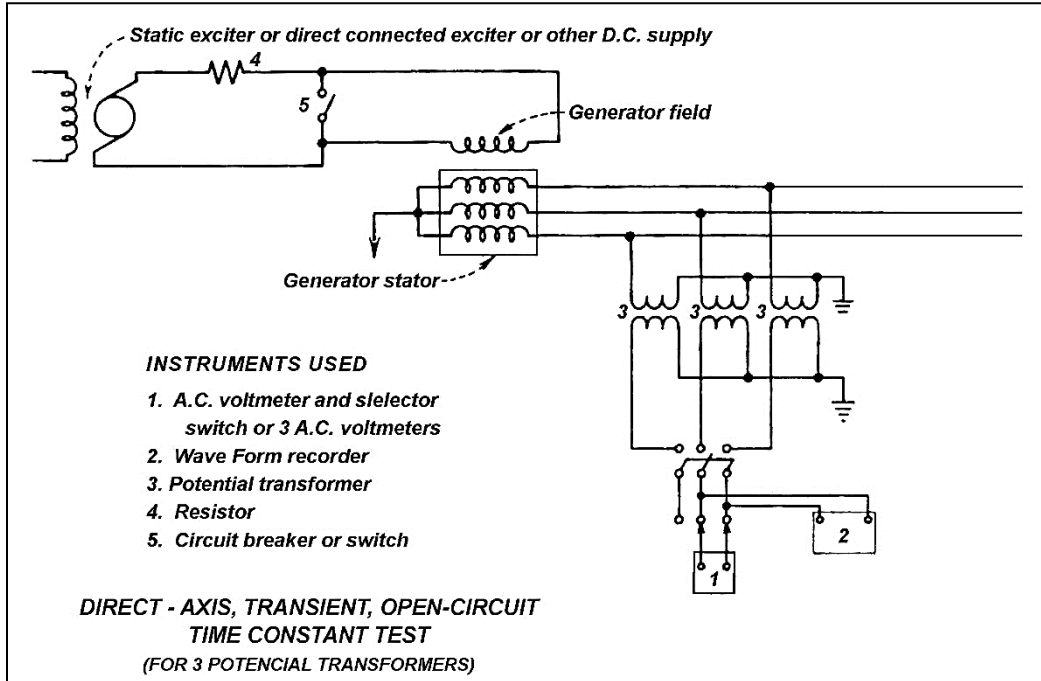


Figure 1.5.8.2-1. Short circuit test, direct-axis transient open-circuit time constant test.

- The maximum voltage output and short circuit capacity of the exciter may have conflicting restrictions on the value of external resistance that can be inserted in series with the field winding and still obtain field current for rated speed, no-load armature voltage.

## 1.5.9 Generator Characteristic Curves

The following data curves are obtained by test to determine the generator field current, armature current, and armature voltage operating characteristics and to determine machine parameters for direct-axis reactance  $X_d$ , Potier reactance  $X_p$ , and short circuit ratio (SCR). To achieve best accuracy of the curves, test instrument readings for armature voltage or current should be taken for each phase, and the three-phase average value should be computed. Test instruments should be accurate to within  $\pm 1\%$  of reading. The existing unit control board instruments should not be used for any test data, except the board wattmeter may be used to determine the zero power operating point for tests requiring zero power factor.

### 1.5.9.1 Open-Circuit Saturation

To perform the open-circuit saturation test, the generator under test should be driven by its turbine at rated speed with the armature open circuited (unit circuit breaker open). Instrument readings of field current, armature line-to-line rms

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voltage, and rotation speed should be recorded for various values of field current increased in successive steps starting from zero, or near zero, until a value of armature voltage of 120% (or as high as agreed by the generator manufacturer) is reached. Approximately 18 data point sets, including at rated armature voltage, should be taken in accordance with IEEE 115. Typical connections and test instrumentation are shown in figure 1.5.4-1. See section 1.6.8.1 for plotting data.

The following items should be considered when performing this test to obtain a smooth and accurate open-circuit saturation curve plot:

- Armature terminal voltage is proportional to rotation speed; therefore, speed should be held constant for the duration of the test. This is not always possible when running offline. Therefore, armature voltage readings should be corrected for speed deviation exceeding  $\pm 1\%$  of rated speed.
- Test data should be taken with progressively increasing field current to remove the effects of hysteresis in the test results. If field current is decreased at any time during the test, the field current should be lowered to zero (or minimum value possible) and then increased to the next test point.
- The generator excitation system is typically in manual regulating mode to control field current (not necessarily armature voltage). Static exciters deriving source power from the test generator terminals are not suitable for this test. For direct connected static exciters, the power feed would need to be moved to a separate source. For a rotating exciter, an adjustable regulated dc power supply works well for this test. Exciter overvoltage limiters and relaying, as well as the volts/hertz limiter and relay, should be reviewed for undesirable interaction, and temporary adjustments should be made as necessary, or these functions may need to be temporarily disabled.
- If armature winding voltage surge suppression devices are direct connected to the generator terminals, determine if this equipment should be disconnected to avoid damage from overvoltage.

### 1.5.9.2 Short Circuit Saturation

To perform the short circuit saturation test, the generator under test should be driven by its turbine at rated speed with the armature short circuited. Suitable shorting bars, three-phase shorting switch, or circuit breaker capable of carrying up to 125% rated armature current must be connected to the generator terminals. For example, an existing generator bus ground switch could be used if it has an adequate current rating, and the switch is configured so that when the three phases are shorted together the connection to ground can be removed.

Instrument readings of field current, armature rms current in each phase, and rotation speed should be recorded for approximately four values of field current starting at a value that produces a maximum armature test current of

approximately 125% (or as high as agreed by the generator manufacturer) and then decreasing in steps so that winding temperature remains as constant as possible during the tests in accordance with IEEE 115. One data point should occur at 100% rated armature current. Typical connections and test instrumentation are shown in figure 1.5.8.1-1. See section 1.6.8.2 for plotting data.

The following items should be considered when performing this test:

- Up to approximately 10% rated armature current can circulate in the three-phase short without field excitation at rated speed due to residual magnetism in the rotor pole iron. Therefore, if a shorting switch is used, it must be capable of making and interrupting this circulating current, or the generator rotation should be stopped before the switch is closed or opened.
- Depending on the configuration for shorting the generator armature winding, current may flow in portions of existing generator bus containing current transformers used to create zones of relay protection (typically differential) for the generator and/or unit step-up transformer. These protective relay schemes should be reviewed for undesirable interaction with the test configuration and disabled, as necessary.
- Generator rotation speed has minimal effect on armature short circuit current; however, rated speed should be maintained within  $\pm 5\%$ .
- Generator field current cannot be supplied by a static excitation system deriving source power from the test generator terminals. In this case, another source of excitation ac power or an external source of dc excitation current must be used.

### 1.5.9.3 Rated Current, Zero Power Factor Overexcited Saturation

This test ideally requires a second load generator connected in parallel (back to back) with the test generator. The two generators are brought to rated speed by their turbines, excited, and then synchronized in parallel. The turbine of the test generator should furnish only enough power to supply all the losses of the test generator (no electrical real power in or out of the test generator). The test generator field current is raised (overexcited), while the load generator field current is lowered until rated armature current is obtained at rated armature terminal voltage at the test generator. This is the condition for rated current at zero power factor.

Readings of the test generator field current, armature rms current and line-to-line voltage, and rotation speed should be recorded at the rated armature current and voltage, zero power factor condition. The test generator terminal voltage then should be gradually raised to approximately 5% above rated voltage, while the load generator field current is adjusted to maintain rated armature current at the

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test generator. A set of readings is taken at this point. A third set of readings is taken in similar fashion at approximately 5% below rated voltage. Typical connections and instruments are shown in figure 1.5.5-1. See section 1.6.8.3 for plotting data.

The following items should be considered when performing this test:

- If the operating conditions to obtain the test data cannot be achieved using a single load generator (inadequate capacity to absorb reactive power), an additional load generator may be required and/or the test generator may remain connected to the power system. In this case, only one data point set is usually taken at or near rated armature voltage.
- If a second direct connected load generator is not available, the test generator may remain connected to the power system via the step-up transformer, and additional load generator(s) at or near the plant can be used to absorb reactive power from the power system. With this arrangement, lowering the test generator bus voltage by adjusting the tap, if available, on the generator step-up transformer will increase the amount of reactive power the test generator can supply to the power system. In this case, only one data point set is usually taken at or near rated armature voltage.
- Operating the test generator overexcited while connected to the power system may cause excessive overvoltage, either at the plant bus or on the power system, especially if a local load generator is not used to absorb some of the reactive power out of the test generator. In this case, it may only be possible to achieve zero power factor operation of the test generator at or near rated armature voltage at less than rated armature current. This is acceptable and can be corrected in the calculation of Potier reactance  $X_p$ .
- The protective relay schemes and overexcitation limiters and protection should be reviewed for undesirable interaction with the test load points, and adjustments should be made as necessary.
- The test generator field current value required for this test may exceed nameplate field current rating. The test should be performed quickly so as not to exceed field winding temperature rise limits.

As an alternative to the test procedure outlined above, the data may be obtained with the test generator uncoupled from its turbine and operated as a motor. The test generator and a driving generator should be connected in parallel, synchronized at very low speed, or back-to-back started in synchronism, and then brought to rated speed. The field current of the test generator should be increased (overexcited) while, simultaneously, the field current for the driving generator is decreased sufficiently to obtain rated voltage and rated current on the armature of

the test generator. This is the condition for rated current at zero power factor. The remainder of the test should be performed as outlined above.

### 1.5.9.4 Field Current Versus Load (V-Curves) Test

The V-curve test is made only to obtain operating information. The results are not linked to the generator specification requirements. The test should be performed by operating the test generator at rated speed and armature voltage at 100%, 75%, 50%, and 25% real kilowatt load. At each kilowatt load, the power factor should be adjusted to 5 values; unity plus 2 values leading (underexcited) and 2 values lagging (overexcited) between unity and rated power factor (total 20 loading points) as shown in the example on figure 1.5.9.4-1. One additional load test should be performed at rated armature load and power factor at 105% rated armature voltage.

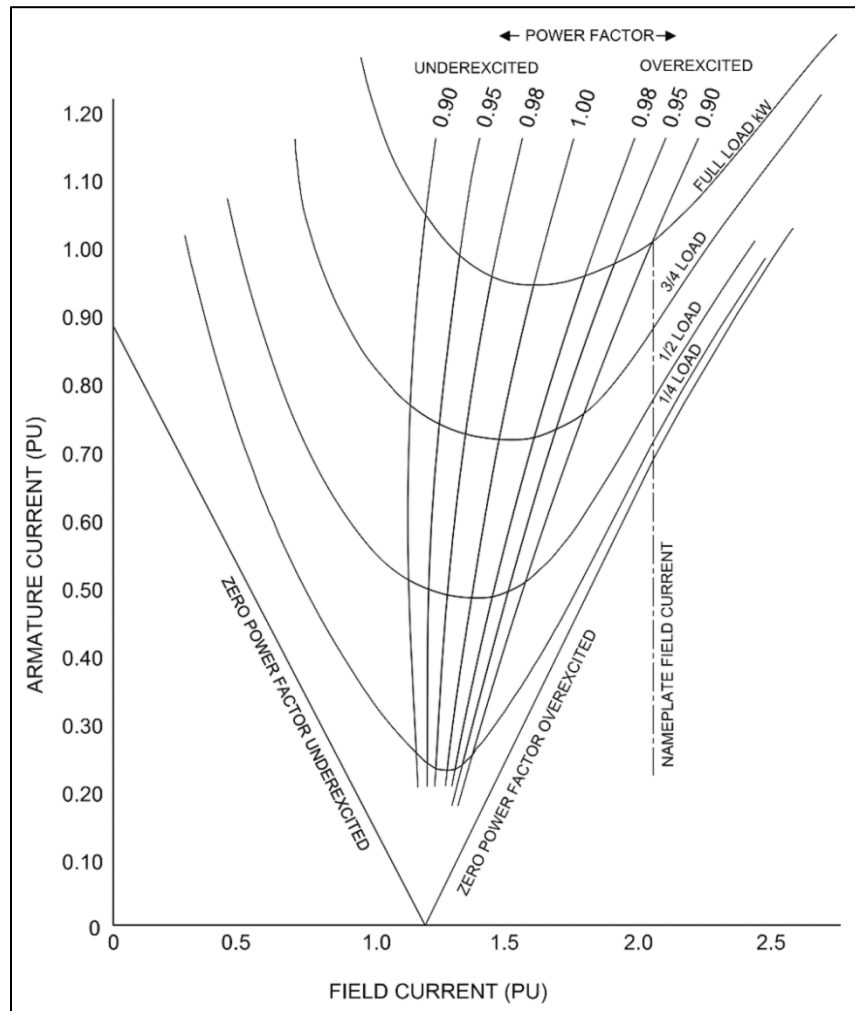


Figure 1.5.9.4-1. Field current versus armature load (V-curves) test (section 1.6.8.4). Typical hydrogenerator 0.9 power factor, 1.1 short circuit ratio. It is not necessary to obtain test load data at less than rated power factor as may be inferred in the figure.

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Readings of armature real and reactive load power, rms current, rms line-to-line voltage, and field current of the test generator are taken at each of the above load points.

The following items should be considered when performing the V-curve test:

- This test may require other plant running generators to adjust reactive loading as necessary to hold the armature voltage of the test generator within  $\pm 2\%$  of rated at each loading point.
- Data should be taken at each kilowatt loading level starting with the lowest excitation point (leading power factor) and then increasing excitation to each additional point until the highest desired excitation data point is achieved (lagging power factor). This reduces the effect of hysteresis on the data.
- It is preferred that the minimum excitation limit is one of the data points for each kilowatt loading level.
- Ensure that the generator has stabilized (kilowatts and kvars are no longer changing) prior to recording data.

### **1.5.10 Stator Air Housing Ozone Concentration**

If the machine is enclosed with a recirculating cooling system, tests should be conducted to determine the ozone concentration in parts per million inside the stator air housing. An ozone concentration meter equipped with an air sampling pump should be used with an air intake tube inserted approximately 1 foot into the air housing from an open bolt hole or other small opening at the top of the housing (deck plate). This test should be performed near the end of the heat run test, while the machine is running and with the air housing having been fully closed (normal operating condition) for the entire duration of the heat run.

### **1.5.11 Stator Air Housing CO<sub>2</sub> Discharge Test**

This test is made in accordance with FIST 5-12 [6] to demonstrate the ability of the generator to maintain an air housing carbon dioxide (CO<sub>2</sub>) gas concentration, check operation of the air housing pressure relief devices, and verify pressure equalization in the bearing oil pots as required by the generator specifications. This test should be conducted concurrently with a 100% load rejection test. Suggested connections and instruments are shown in figure 1.5.11-1.

The CO<sub>2</sub> analyzing equipment should be checked for zero point test with the external hose connections attached to the instrument, but with the opposite end of the hoses in atmospheric air. After the zero point test has been made, connect the



hoses to the generator and make sure that the open end fresh-air hose is far enough away from the generator so that escaping CO<sub>2</sub> will not enter the fresh-air hose intake.

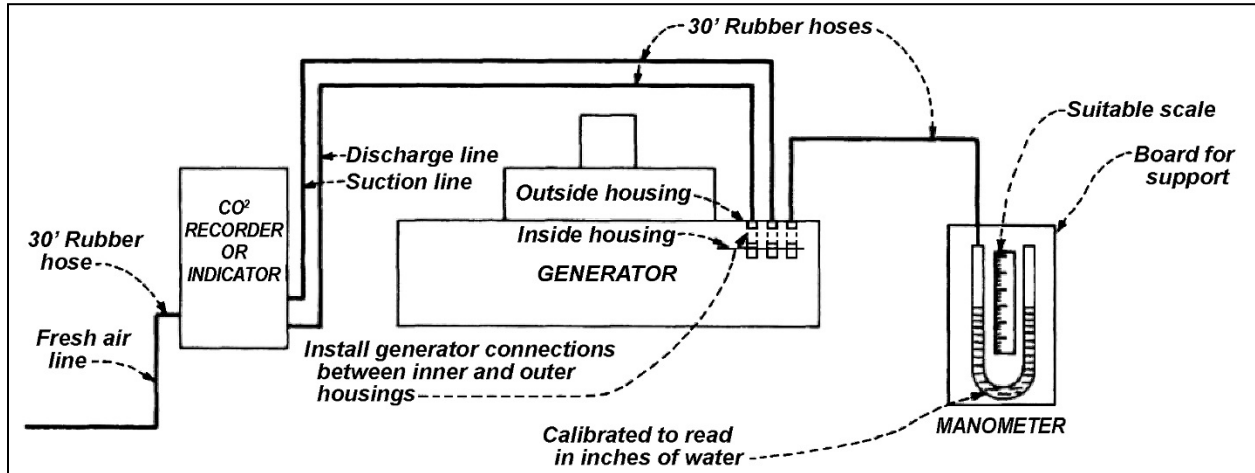


Figure 1.5.11-1. CO<sub>2</sub> discharge test.

As CO<sub>2</sub> is 1.5 times heavier than air, it tends to settle in lower levels of the plant. This can be life threatening due to oxygen displacement. Proper safety precautions must be followed during testing. See FIST 5-12 for additional information.

### 1.5.11.1 Test Procedure

- (1) Inspect the generator housing for tightness. Close all access openings and check floor drains within the generator housing for adequate seal. Check the generator pressure relief doors for free swing.
- (2) Take initial readings at all stations.
- (3) Obtain the static reading on the housing pressure manometer. This reading should be taken with both legs of the manometer open to atmospheric pressure. Then, take the initial reading of the manometer with one leg connected to the generator air housing and with the generator running. This will be called the initial reading. The water column height on the legs under this condition will no longer be the same as the static reading because of the increased pressure in the generator housing caused by the generator rotation. Immediately after the CO<sub>2</sub> has been discharged in step 4, both manometer legs should be read every 30 seconds until the end of the test. The manometer reading should be at its maximum value a few seconds after the discharge of the CO<sub>2</sub>. Record the magnitude and time of this maximum peak.

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- (4) With the test generator operating at full load and normal voltage, trip the generator differential lockout relay, releasing CO<sub>2</sub>. Take readings from the CO<sub>2</sub> analyzer at 5-second intervals until maximum concentration is reached, and take readings at 1-minute intervals from zero test time until the end of the test. The delayed CO<sub>2</sub> cylinders should be blocked so that they do not discharge.
- (5) Record the revolutions per minute (rpm) as indicated by the governor tachometer. Record the maximum unit overspeed and the time in seconds it occurred after zero test time. Record the temperature of the thrust and guide bearings before the CO<sub>2</sub> discharge and at the conclusion of the test.
- (6) Note the time of opening and closing of the generator housing pressure relief doors. Record unit speed at 15-second intervals until the unit comes to rest. Note time and revolutions per minute of all brake applications.

### 1.5.12 Overspeed Test

In order to demonstrate the ability of the generator to successfully withstand the mechanical stresses incident to the maximum runaway speed (not to exceed the maximum value of runaway speed guaranteed by the generator contractor), which can be attained by the combined unit at the hydrostatic head available at the time that the other tests are made, the unit under test should be operated offline (unit main circuit breaker open), unexcited, with the turbine gates wide open. Collector ring and commutator brushes may be lifted at the option of the contractor.

Starting with the generator operating at approximately rated speed, the turbine gates should be gradually opened to the wide-open position. As soon as the speed becomes constant or the maximum runaway speed guaranteed by the generator contractor is reached, the gates should be immediately closed. The rate the turbine gates are opened should be controlled so that the elapsed time, from starting at rated speed to turbine gate closure, does not exceed 5 minutes. The speed should be measured by a calibrated tachometer. Runaway speeds of turbines have the following approximate percentages of rated speed:

- Impulse (Pelton) turbines: 188%
- Francis turbines: 193%
- Propeller-type (Kaplan) turbines: 214%

The following data should be recorded:

- (1) Revolutions per minute by test tachometer
- (2) Revolutions per minute by governor and unit control board tachometers

- (3) Reservoir and tailwater elevations
- (4) Bearing temperatures before, during, and following the test
- (5) Vibration – upper, lower, and turbine guide bearings

Following the test, the generator rotor should be physically checked for any signs of fatigue or excessive component movement.

The following item should be considered when performing the runaway speed test:

- Severe overvoltage of the armature winding could occur during this test. To ensure this does not occur it is imperative that field current excitation is not applied. This can be accomplished by disabling the excitation system and opening the generator field breaker.

### **1.5.13 Excitation System**

Procedures for performing excitation system tests are not offered in IEEE 115; therefore, test details and procedures are prescribed by the Electrical and Mechanical Engineering Division of the TSC. Refer to the solicitation and/or technical report REC-ERC-91-2, *Excitation System Commissioning Procedures* [7], for guidelines for excitation system testing.

## **1.6 Determination of Generator Parameters**

The interpretation of all test data and calculation of all generator parameters should be in accordance with the applicable sections of IEEE 115 and as described herein.

### **1.6.1 Resistance of Armature and Field Windings**

The values of armature and field winding resistances determined from section 1.5.2 should be corrected to specified temperature in accordance with IEEE 115 using the following equation:

$$R_s = R_t \left( \frac{t_s + k}{t_t + k} \right) \quad (3)$$

where:

$R_s$  = winding resistance, corrected to specified temperature,  $t_s$ , ohms

$t_s$  = specified temperature, °C

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$R_t$  = test value of winding resistance, ohms

$t_t$  = average temperature of winding during test, °C

$k$  = characteristic constant for winding conductor material (234.5 for pure copper), °C

The specified temperature should be 95 °C or 115 °C for Class B or F winding insulation, respectively. In some cases, 75 °C may be used for existing machines having the older Class A insulation rating system.

### 1.6.2 Armature Voltage Balanced and Residual Component TIF Calculation

The balanced and residual component TIF should be determined from the TIF tests in section 1.5.3 and as outlined in IEEE 115, with the following equations:

$$TIF = \frac{\sqrt{\sum(T_n E_{nb})^2}}{E_{RMSb}} \quad \text{balanced} \quad (4)$$

$$TIF = \frac{\sqrt{\sum(T_n E_{nr})^2}}{3E_{RMSr}} \quad \text{residual component} \quad (5)$$

where:

$TIF$  = telephone influence factor accounting for the combined effects of the fundamental and harmonic components of armature voltage, dimensionless

$T_n$  = TIF weighting factor for the  $n^{\text{th}}$  harmonic (including first fundamental)

$E_{nb}$  = rms value of  $n^{\text{th}}$  harmonic component of armature line-to-line voltage (including first fundamental), V

$E_{nr}$  = rms value of  $n^{\text{th}}$  harmonic component of armature open corner of delta ( $3 V_0$ ) voltage (including first fundamental), V

$E_{RMSb}$  = true rms value of armature line-to-line voltage waveform, V

$E_{RMSr}$  = true rms value of armature one phase of delta or line-to-neutral voltage waveform, V

Values of TIF weighting factors  $T_n$  are given in IEEE standard C50.12™ [4].

### 1.6.3 Armature Voltage Waveform Deviation Factor Calculation

Waveform deviation factor is determined as outlined in IEEE 115 for each armature line-to-line voltage from the waveform deviation factor test described in section 1.5.4.

### 1.6.4 Line-Charging Capacity

The reactive power line-charging capacity of a generator (see test in section 1.5.5) at rated voltage, zero power factor underexcited is calculated by the following equation:

$$P_{LC} = \sqrt{3}V_{LL}I_L \quad (6)$$

where:

$P_{LC}$  = line-charging reactive power, Megavars (MVAR)

$V_{LL}$  = armature rms line-to-line voltage, kV

$I_L$  = armature rms current, kiloamps (kA)

Equation (6) gives an approximate value of line-charging capacity for motors because real power motor losses are included in armature current.

### 1.6.5 Efficiency, Segregated Losses, and $WR^2$ of Rotating Parts

The efficiency of the generator or motor should be computed from the following expressions:

$$\text{Generator efficiency (\%)} = 100 - \frac{\text{losses} \times 100}{(\text{electrical output} + \text{losses})} \quad (7)$$

$$\text{Motor efficiency (\%)} = 100 - \frac{\text{losses} \times 100}{\text{electrical input}} \quad (8)$$

The following segregated losses should be calculated to one decimal place accuracy (0.1 kW).

#### 1.6.5.1 Friction and Windage Loss

Combined friction and windage loss is calculated with the following equation:

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$$\text{loss in kilowatts} = k \cdot J \cdot n \cdot \frac{dn}{dt} \quad (9)$$

where:

$n$  = rotation speed, revolutions per minute (rpm)

$\frac{dn}{dt}$  = rate of deceleration (determined from slope of speed-time curve at  $n$ ), rotations per minute per second (rpm/s)

$J = WR^2$  = moment of inertia of test generator rotating parts (excluding turbine), pound times square foot (lb•ft<sup>2</sup>), or kilogram times square meter (kg•m<sup>2</sup>)

$k$  = conversion coefficient;  $0.4621 \times 10^{-6}$  for English System units or  $1.0966 \times 10^{-5}$  for the International System (SI) units

Friction and windage loss are calculated at rated speed from the speed-time curve obtained in section 1.5.6.1. Note that loss equation (9) can be calculated at any speed.

### 1.6.5.2 Open-Circuit Core Loss

Open-circuit core loss is calculated by subtracting the friction and windage loss determined in section 1.6.5.1 from the combined friction and windage plus core loss.

To determine the combined friction and windage plus core loss, calculate the loss at rated speed from the speed-time curves for the two retardation tests in section 1.5.6.2 using equation (9). These combined loss values are for armature voltages slightly above and below rated. The combined loss at rated armature voltage is determined by interpolation of the two values to rated voltage. Use an average of the three-phase armature voltage readings for the interpolation.

### 1.6.5.3 Stray Load Loss

Stray load loss is calculated by subtracting friction and windage loss (determined in section 1.6.5.1) and armature  $I^2R$  loss (section 1.6.5.4) from the combined friction and windage, plus short circuit load loss discussed in the following paragraph.

To determine the combined friction and windage plus short circuit load loss, calculate the loss at rated speed from the speed-time curves for the two short circuit retardation tests in section 1.5.6.3 using equation (9). These combined loss values are for armature currents slightly above and below rated. The combined loss at rated armature current is determined by interpolation of the two values to rated current. Use the average of the three-phase armature current readings for the interpolation. If the three-phase short is not applied directly to the defined

armature terminals of the test unit, the  $I^2R$  losses in the connecting bus should be determined and subtracted from the interpolated loss value.

Armature  $I^2R$  loss is calculated at rated current given in equation (10) of section 1.6.5.4. Armature winding resistance  $R_a$  for this calculation is corrected to the winding temperature of the stray load loss test, which is the average of the four embedded RTD readings from section 1.5.6.3.

#### 1.6.5.4 Armature and Field Winding $I^2R$ Losses

Armature and field winding segregated  $I^2R$  losses are stated at a specified (corrected) temperature of 95 °C or 115 °C for Class B or F winding insulation, respectively. In some cases, 75 °C may be used for existing machines having the older Class A insulation rating system.

##### 1.6.5.4.1 Armature $I^2R$ Loss Calculation

Armature  $I^2R$  copper loss is calculated at rated current with the following equation:

$$P_{ar} = \frac{I_{a1}^2 R_{a1} + I_{a2}^2 R_{a2} + I_{a3}^2 R_{a3}}{1000} \quad (10)$$

where:

$P_{ar}$  = armature three-phase winding  $I^2R$  power loss for armature current at given load, kW

$I_{a1,2,3}$  = armature rms current in each phase, amperes (A)

$R_{a1,2,3}$  = armature per phase (line-to-neutral) dc resistance at a given temperature, ohm

The per phase dc resistance of the armature at the specified temperature is determined from equation (3) using the measured winding resistances and temperature from the winding resistance test in section 1.5.2 as the base (test) values.

##### 1.6.5.4.2 Field Winding $I^2R$ Loss Calculation

Field winding  $I^2R$  copper loss is calculated at the field current required for operation at rated armature load voltage, kilovolt ampere (kVA), and power factor; at the specified winding temperature given above.

$$P_{fr} = \frac{I_f^2 R_f}{1000} \quad (11)$$

where:

$P_{fr}$  = field winding  $I^2R$  power loss, kW

$I_f$  = field current at rated armature load, A

$R_f$  = field winding average dc resistance at specified temperature, ohms

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Field winding resistance  $R_f$  is the corrected resistance value from section 1.6.1. Field current is taken from the heat run test (section 1.5.7.3) at rated kVA output. If rated output is not achieved, the field current for rated output must be predicted using one of the methods described in IEEE 115 (e.g., Potier reactance method or phasor diagram analysis).

### 1.6.5.5 $WR^2$ of Rotating Parts

The tested  $WR^2$  moment of inertia can be found from equation (9) by solving for  $J$  using the values of friction and windage plus open-circuit core loss determined from the rated voltage electric power input test (section 1.5.6.6) and the rate of speed deceleration ( $\frac{dn}{dt}$ ) from the combined friction and windage plus core loss retardation test (section 1.5.6.2) corrected to rated voltage (section 1.6.5.2). Total loss measured by the electric power input test contains friction, windage, open-circuit core, armature  $I^2R$ , and stray load losses. The stray load loss may be neglected at the low armature current used for the test (approximately 5% rated). By subtracting the armature  $I^2R$  loss (determined at test current  $I$  and for  $R$  at the winding test temperature) from the measured total loss value, the value for friction and windage plus open-circuit core loss is obtained for substitution into equation (9).

#### 1.6.5.5.1 *Optional Loss Data*

The data from the electric power input method can be used to determine friction and windage loss plus the core loss of the test unit. Friction and windage plus the core loss of the test unit at various armature voltages can be obtained by subtracting the calculated armature copper ( $I^2R$ ) loss from the power (kilowatts) input.

With the remaining loss in kilowatts as abscissas (X-axis) and armature volts squared as ordinates (Y-axis), a curve should be plotted from the test data. Extrapolating this curve to zero voltage will give the friction and windage loss of the unit under test. By subtracting the friction and windage loss from the power input (minus the armature copper [ $I^2R$ ] loss), the core loss of the test unit at various voltages can be plotted.

## 1.6.6 Heat Run Temperatures

### 1.6.6.1 Total Temperature

The total (ambient plus rise) temperature of the machine parts listed in section 1.5.7.3 during the period of constant temperature operation is determined from the average of the last three consecutive half-hour readings. The total temperature for the armature winding and stator core is determined using the hottest temperature sensor for each part, respectively. The total temperature of the field winding is calculated by the resistance method (see section 1.6.6.3).



### 1.6.6.2 Temperature Rise

The temperature rise of the armature and field windings and stator core during the period of constant temperature operation is calculated by subtracting the average of the last three consecutive half-hour readings for ambient cooling air temperature determined in accordance with section 1.5.7.3 from the total temperature of the winding or core (see section 1.6.6.1).

### 1.6.6.3 Field Winding Total Temperature by Resistance Method

Field winding temperature during the period of constant temperature operation is calculated in accordance with IEEE 115 and the following equation:

$$t_{ft} = t_{fb} + \left( \frac{R_{ft} - R_{fb}}{R_{fb}} \right) (t_{fb} + k) \quad (12)$$

where:

$t_{ft}$  = average total temperature of field winding when  $R_{ft}$  was measured, °C

$R_{ft}$  = resistance of field winding at test heat run temperature, ohms

$R_{fb}$  = reference resistance of field winding at base (cool ambient) temperature, ohms

$t_{fb}$  = average total temperature of field winding when  $R_{fb}$  was measured, °C

$k$  = characteristic constant for winding conductor material (234.5 for pure copper), °C

Values for the reference (base) field temperature and resistance are taken as described in section 1.5.2. Resistance of the field winding at constant heat run temperature is calculated from the measured values of field current and voltage taken as described in section 1.5.7.3 and:

$$R_{ft} = \frac{V_f}{I_f} \quad (13)$$

where:

$V_f$  = field voltage measured at collector rings (without brush voltage drop), V

$I_f$  = field current, A

All measured values of field resistance, current, and voltage, and calculated field resistance should be determined to four-significant-figure accuracy. This will ensure that the calculated total temperature  $t_{ft}$  and temperature rise of the field winding are accurate to within  $\pm 1^\circ\text{C}$ .

## 1.6.7 Determination of Parameters $X'_d, X''_d, \tau'_d, \tau''_d, \tau'_{do}$

### 1.6.7.1 Armature Three-Phase Sudden Short Circuit $X'_d, X''_d, \tau'_d, \tau''_d$

The procedure in IEEE 115 for the armature three-phase sudden short circuit test method should be used to determine values of direct-axis transient reactance  $X'_d$ , direct-axis subtransient reactance  $X''_d$ , direct-axis transient short circuit time constant  $\tau'_d$ , and direct-axis subtransient short circuit time constant  $\tau''_d$ . Current versus time curves (essentially straight lines on a semilog plot) for the transient and subtransient components of armature symmetrical current (disregarding dc offset current) should be drawn from each phase of the short circuit current test waveforms obtained as described in section 1.5.8.1. The initial values of transient and subtransient currents (at  $t = 0$ ) and time to  $e^{-1}$  of initial values can readily be determined as shown by the graphical examples in IEEE 115. An example calculation of  $X'_d$  and  $X''_d$ , based on the initial transient and subtransient currents, is also given in IEEE 115.

The direct-axis transient short circuit time constant  $\tau'_d$  determined by test usually is corrected to a specified field winding temperature with the following equation:

$$\tau'_d = \tau'_{dt} \left( \frac{k+t_{ft}}{k+t_s} \right) \quad (14)$$

where:

$\tau'_d$  = direct-axis transient short circuit time constant at specified temperature  $t_s$ , sec

$t_s$  = field winding specified temperature, °C

$\tau'_{dt}$  = direct-axis transient short circuit time constant at field winding test temperature, sec

$t_{ft}$  = average total temperature of field winding during test, °C

The average total temperature of the field winding during the short circuit test is determined in a similar manner as for the heat run test with equations (12) and (13). However, in this case, it is only necessary to measure field current and voltage once to determine field winding resistance immediately prior to applying the sudden short circuit. The specified field winding temperature should be 95 °C or 115 °C for Class B or F winding insulation, respectively. In some cases, 75 °C may be used for existing machines having the older Class A rating system.

### 1.6.7.2 Field Winding Sudden Short Circuit $\tau'_{do}$

The direct-axis transient open-circuit time constant  $\tau'_{do}$  is the time in seconds for the value of open-circuit armature voltage to decrease to  $e^{-1}$  of an initial value

corresponding to the extrapolation of the envelope of the symmetrical voltage wave to the instant of field short circuit (see test procedure in section 1.5.8.2), neglecting the high-decrement components during the first few cycles. The time constant should be corrected to specified field winding temperature in a similar manner as for  $\tau'_d$  with equation (14).

## 1.6.8 Generator Characteristic Curves

### 1.6.8.1 Open-Circuit Saturation

Data points for field current and armature rms voltage (see test described in section 1.5.9.1) should be plotted as shown in the example generator saturation curves of figure 1.6.8.2-1. Residual magnetic flux in the rotor pole iron may create a nonzero armature voltage with zero field current, causing the plotted data curve to not intersect the origin at zero field current and armature voltage. In this case, the curve may be extrapolated to zero from the straight-line portion of the curve in the vicinity of the origin. The air gap line should be drawn by extending the straight-line lower portion of the curve out to an armature voltage of approximately 125% rated.

### 1.6.8.2 Short Circuit Saturation

Data points for field current and armature rms current (see test described in section 1.5.9.2) should be plotted as shown in the example generator saturation curves of figure 1.6.8.2-1.

Residual magnetic flux in the rotor pole iron may create a nonzero armature current with zero field current, causing the plotted data curve to not intersect the origin at zero field and armature currents. In this case, the curve may be extrapolated to zero from the straight-line portion of the curve in the vicinity of the origin.

### 1.6.8.3 Rated Current, Zero Power Factor Overexcited Saturation

The three data points for field current and armature rms voltage (see test described in section 1.5.9.3) should be plotted as shown in the example generator saturation curves of figure 1.6.8.2-1. A fourth data point can be plotted on the field current axis (zero armature voltage) at the value of field current that produces rated armature current for the short circuit saturation test (section 1.5.9.2). The rated current, zero power saturation curve, can then be drawn through these four data points, which is essentially parallel to the open-circuit saturation curve.

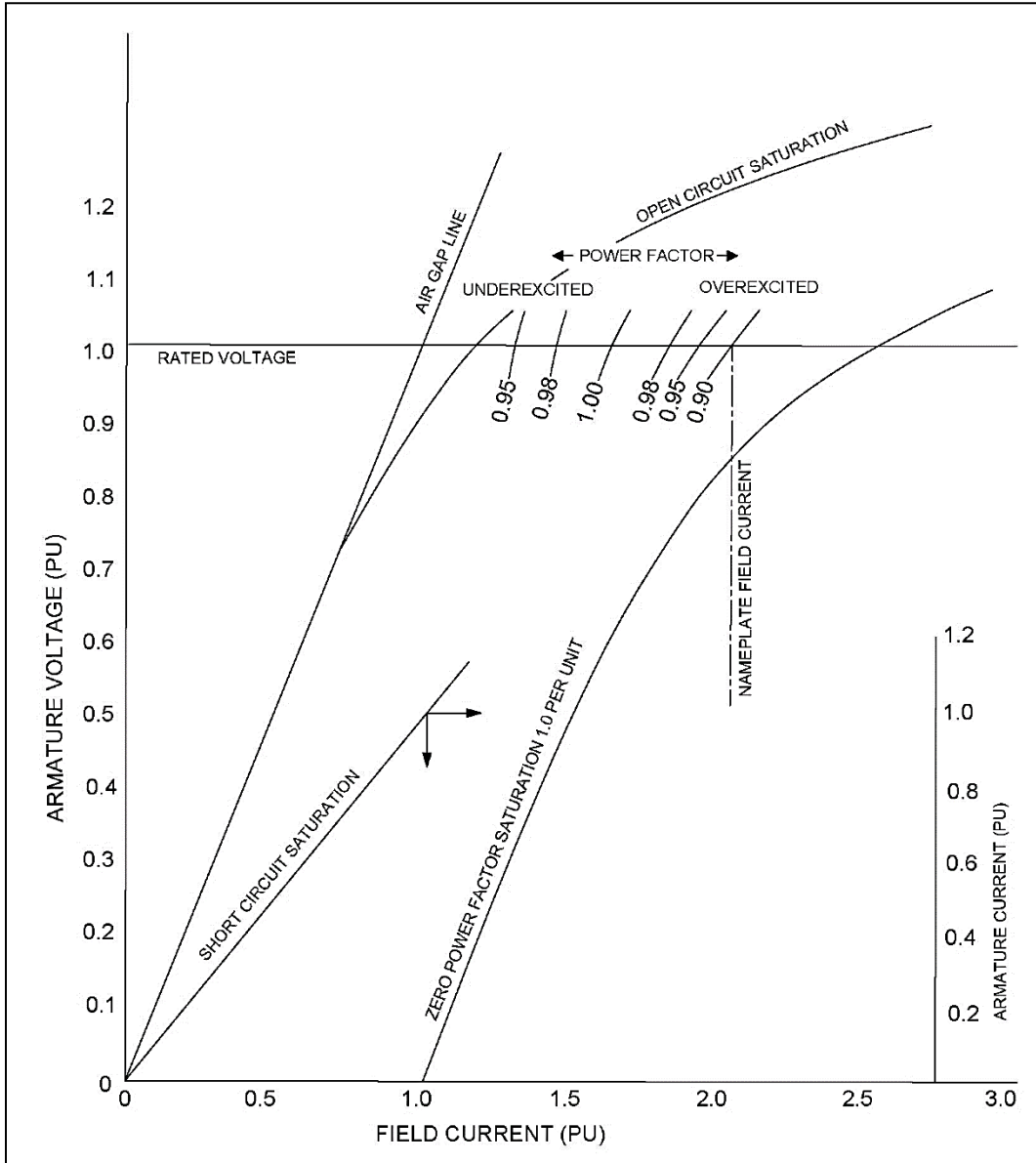


Figure 1.6.8.2-1. Saturation curves (section 1.6.8). Typical hydrogenerator 0.9 power factor, 1.1 short circuit ratio.

### 1.6.8.4 V-Curves

Armature current versus field current (in amps or per unit) is plotted as shown in figure 1.5.9.4-1 for the 20 data points obtained in the test described in section 1.5.9.4.

### 1.6.8.5 Determination of Parameters $X_d$ , $X_p$ , and SCR from Saturation Curves

#### 1.6.8.5.1 Unsaturated Direct-Axis Reactance $X_{du}$

The direct-axis unsaturated synchronous reactance  $X_{du}$  is calculated with the following equation:

$$X_{du} = \frac{I_{FSI}}{I_{FG}} \quad (15)$$

where:

$X_{du}$  = unsaturated direct-axis synchronous reactance, per unit

$I_{FSI}$  = field current at rated armature current on the short circuit saturation curve, A

$I_{FG}$  = field current at rated air-gap line armature voltage on the open-circuit saturation curve, V

Refer to figure 1.6.8.5.1-1 for an example graphical solution of  $X_{du}$ .

#### 1.6.8.5.2 Saturated Direct-Axis Reactance $X_{ds}$

Determination of the saturated direct-axis reactance  $X_{ds}$  from machine test data requires manipulation of equations from the IEEE 115 sections describing direct-axis synchronous reactance and load excitation (field current) prediction involving armature leakage (Potier) reactance. The following derived equation may be used to determine  $X_{ds}$  when the direct-axis unsaturated synchronous reactance  $X_{du}$  and Potier reactance  $X_p$  are known:

$$X_{ds} = \frac{X_{du} - X_p}{K_d} + X_p \quad (16)$$

where:

$X_{ds}$  = saturated direct-axis synchronous reactance

$X_{du}$  = unsaturated direct-axis synchronous reactance

$X_p$  = Potier reactance

$K_d$  = saturation factor, dimensionless, and units of reactance are in ohms or per unit

Refer to appendix A for example calculation of  $X_{ds}$ .

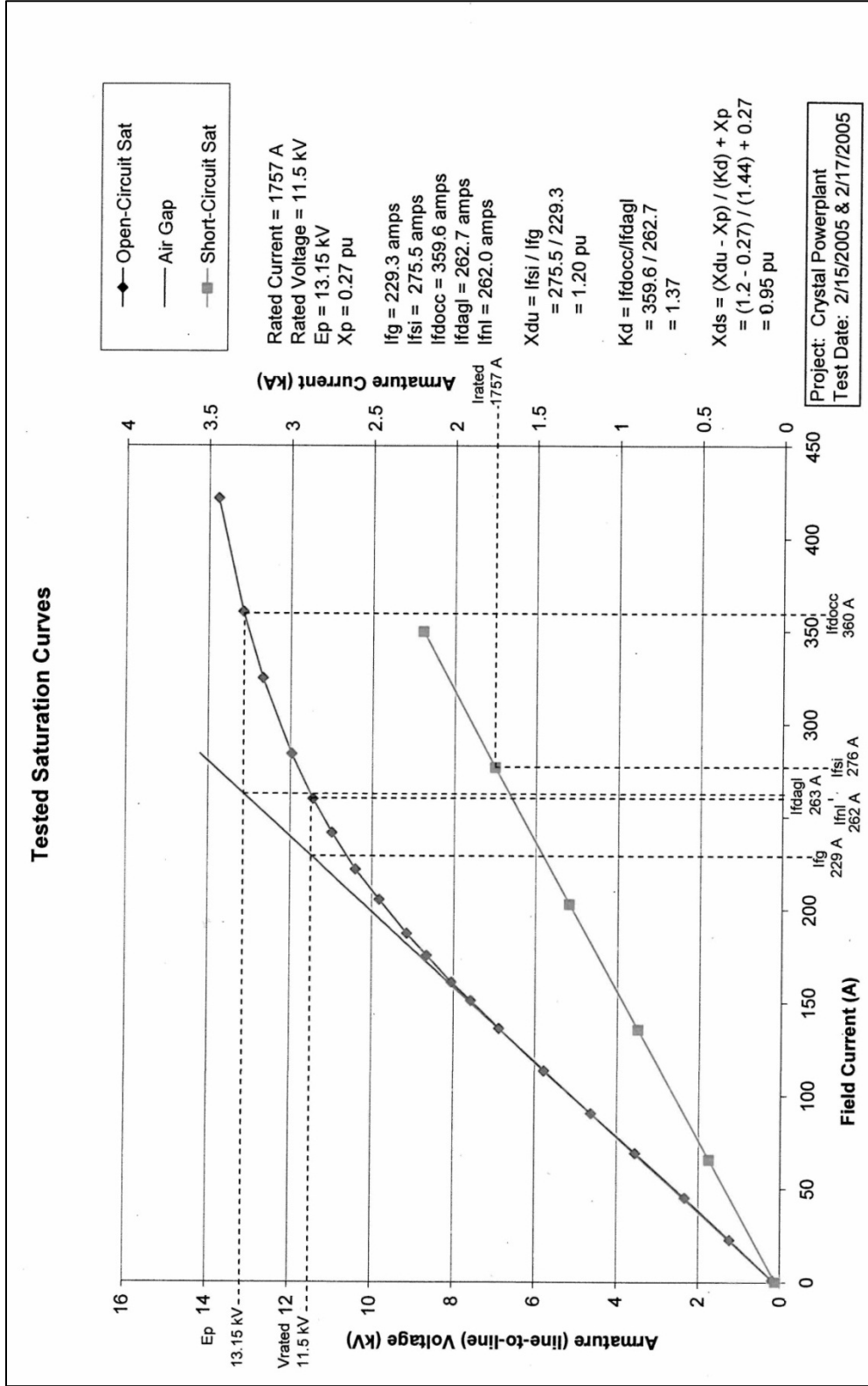


Figure 1.6.8.5.1-1. Example graphical determination of direct-axis reactance  $X_{du}$  (unsaturated) and  $X_{ds}$  (saturated) (section 1.6.8.5).

### 1.6.8.5.3 Potier Reactance $X_p$

Potier reactance  $X_p$  is determined by the zero power factor method with the open-circuit saturation (plotting test curves described in section 1.6.8.1) and rated current zero power factor overexcited saturation (plotting test curves described in section 1.6.8.3) test curves in accordance with IEEE 115. An example calculation procedure is shown in figure 1.6.8.5.3-1. Note that the final step to determine  $X_p$  divides the  $IX_p$  product by the armature test current  $I$ . This inherently compensates the value of  $X_p$  for an armature test current different from rated. Satisfactory results have been obtained with armature current down to 50% rated for the zero power factor overexcited saturation test although it is preferred that the test be performed at 100% rated armature current, if possible.

### 1.6.8.5.4 Short Circuit Ratio

Short circuit ratio is calculated with field current data from the open-circuit and short circuit saturations test curves (tests described in sections 1.6.8.1 and 1.6.8.2) and the following equation:

$$SCR = \frac{I_{FNL}}{I_{FSI}} \quad (17)$$

where:

$I_{FNL}$  = field current at rated armature voltage on the open-circuit saturation curve, A

$I_{FSI}$  = field current at rated armature current on the short circuit saturation curve, A

Refer to figure 1.6.8.5.1-1 for a graphical representation of these values.

## 1.6.9 Stator Air Housing CO<sub>2</sub> Discharge

The test results from the test described in section 1.5.11 should be shown on curves plotted as follows:

- (1) Time in minutes elapsed after initial discharge versus CO<sub>2</sub> concentration percent of volume.
- (2) Time in seconds after initial discharge versus CO<sub>2</sub> concentration percent of volume to include the period from initial discharge to maximum concentration.
- (3) Revolutions per minute versus time elapsed after initial discharge.
- (4) Air housing pressure (inches of water) versus time elapsed after initial discharge.

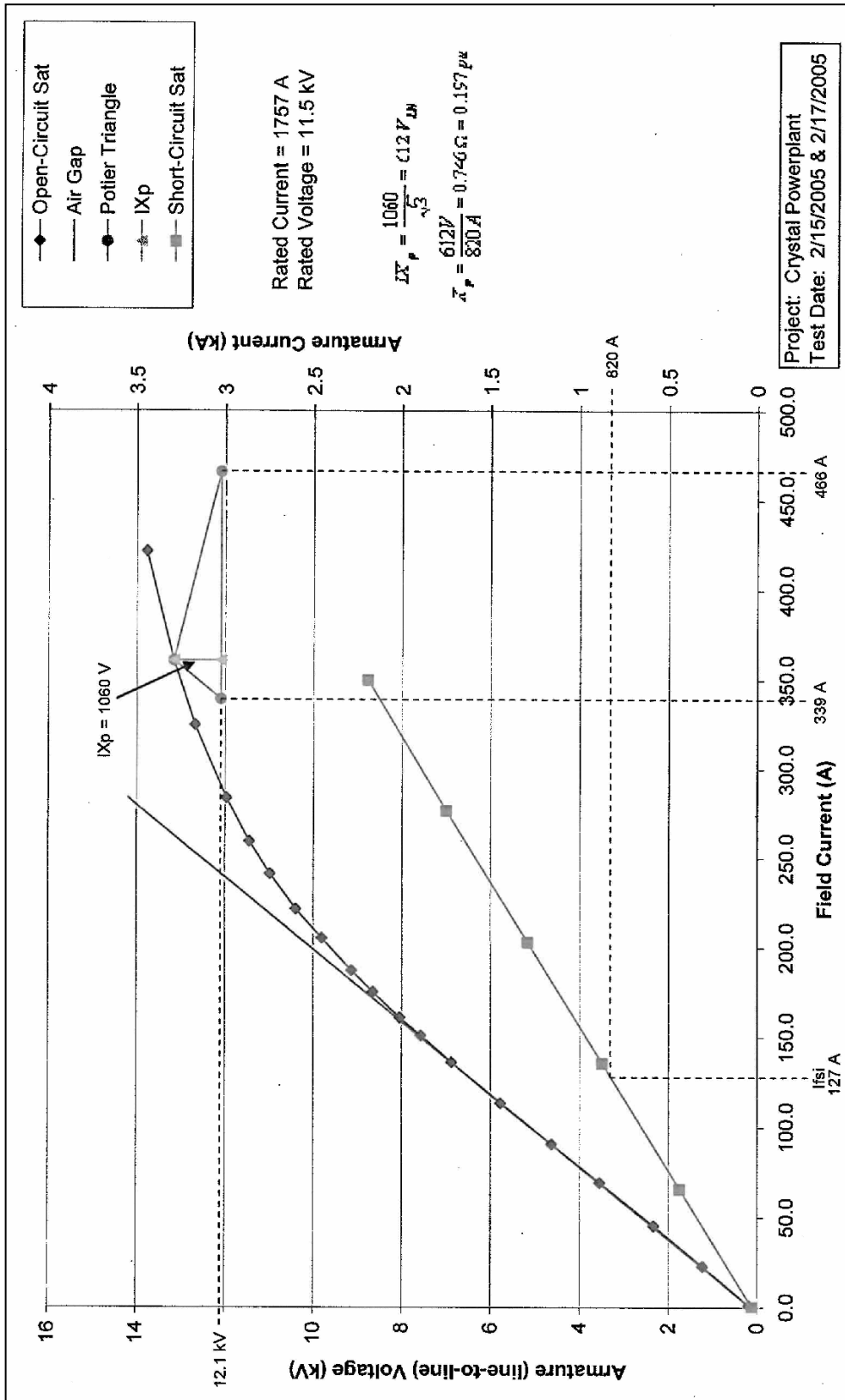


Figure 1.6.8.5.3-1. Example graphical determination of Potier reactance  $X_p$  from tested open-circuit and short circuit saturation curves (section 1.6.8.5.3). Data point (466A, 12.1 kilovolts) represents the rated voltage, zero power factor overexcited test. This zero power factor test was conducted at 820-ampere armature current, which is substantially less than rated. Calculation of  $X_p$  (equation (2) in this figure) compensates for the actual value of armature test current.



## 1.7 Test Instrumentation

All test instrumentation should be accurate to within  $\pm 2\%$  of reading, except where higher accuracy is stated in the field test procedures subparagraphs of section 1.5. The existing plant unit control board instruments and recorders should not be used for collecting test data, except where noted in this standard or only in specific applications agreed to by the contractor and contracting officer. These devices must be calibration certified as discussed below.

Calibration tests should be performed on each test instrument (meters, bridges, recorders, etc.) both before and after the generator tests are conducted. Certificates of calibration shall be provided to the Contracting Officer for all calibration tests of every test instrument. If any instrumentation is found out of calibration following completion of the generator tests, the associated test data shall be considered invalid.

## 1.8 References

- [1] The Institute of Electrical and Electronics Engineers, Inc., 2009. IEEE Standard 115<sup>TM</sup> – *IEEE Guide for Test Procedures for Synchronous Machines*.
- [2] Bureau of Reclamation, 2011. *Testing Solid Insulation of Electrical Machinery*. Facilities Instructions, Standards, and Techniques, Volume 3-1.
- [3] Boldea, Ion. 2006. *Synchronous Generators, The Electric Generators Handbook*. CRC Press.
- [4] The Institute of Electrical and Electronics Engineers, Inc., 2005. IEEE Standard C50.12<sup>TM</sup> – *IEEE Standard of Salient-Pole 50 Hz and 60 Hz Synchronous Generators and Generator/Motors for Hydraulic Turbine Applications Rated 5 MVA and Above*.
- [5] The Institute of Electrical and Electronics Engineers, Inc., 2009. *The IEEE Standard Dictionary – Glossary of Terms and Definitions*.
- [6] Bureau of Reclamation, May 2005. *CO<sub>2</sub> System Operation and Maintenance*, Facilities Instructions, Standards, and Techniques, Volume 5-12.
- [7] Bureau of Reclamation, September 1991. REC-ERC-91-2 – *Excitation System Commissioning Procedures*.



## **Appendix A**

Graphical Determination of Saturated Direct-Axis  
Reactance  $X_{ds}$



## Appendix A

# Graphical Determination of Saturated Direct-Axis Reactance $X_{ds}$

Refer to section 1.6.8.5.2 and figure 1.6.8.5.1-1. Saturation factor  $K_d$  is found by the following expression from IEEE 115:

$$K_d = \frac{I_{fdocc}}{I_{fdagl}} \quad (A1)$$

where:

$I_{fdocc}$  = field current on the open-circuit saturation curve corresponding to  $E_p$

$I_{fdagl}$  = field current on the air-gap line corresponding to  $E_p$

$E_p$  = Potier voltage

Potier voltage  $E_p$  at rated armature output (1 per unit voltage and current) is found by:

$$E_p = \sqrt{(\cos \phi)^2 + (\sin \phi + X_p)^2} \quad (A2)$$

where:

$X_p$  = Potier reactance, per unit (see section 1.6.8.5.3)

$\phi$  = rated power factor angle (positive for overexcited, negative for underexcited)

In the example of figure 1.6.8.5.1-1, the Potier reactance  $X_p = 0.27$  per unit, and the rated power factor is 0.9 lagging (overexcited), making  $\phi = 25.84^\circ$ . Therefore,  $E_p$  from equation (A2) is 1.14 per unit or 13.15 kV. Corresponding values of  $I_{fdocc}$  and  $I_{fdagl}$  from the open-circuit saturation curve and air-gap line are 360 A and 263 A, respectively. Plugging these values into equation (A1) gives  $K_d = 1.37$ . Finally, reactance  $X_{ds} = 0.95$  per unit is found from equation (16), using the value  $X_{du} = 1.2$  per unit given in figure 1.6.8.5.1-1.