7

Electrical Testing

Section Outline Page

7.1 TESTING INSULATION SYSTEMS OF ROTATING MACHINERY

Prepared by EASA Technical Services Committee

Predicting the exact time that insulation systems of motors and generators will fail is not possible. However, the condition of the insulation in these machines can be determined by several industry-proven tests (which include the insulation resistance, the polarization index and the DC leakage tests). These tests, their procedures and the criteria for evaluation are described here. When performed periodically, these tests are helpful for identifying gradual deterioration of the insulation with the ultimate goal of providing maintenance personnel with advanced warning as to when and what maintenance and/or repairs should be done.

CAUTION: Before proceeding with any of these tests, make sure the frame is grounded at all times. The windings also must be discharged against the frame after every test.

PRECAUTIONS

There are a few precautions to watch for whenever any electrical tests are performed. First, when using an unstable power supply, be sure to insert a constant-voltage transformer between the test set and the power source. This will prevent any voltage variations on the line from affecting the test results; or being passed on to the equipment under test and possibly damaging it. Therefore, prior to measuring the insulation resistance, windings must be completely discharged. Measure the discharge current at the beginning of the test to assure that the winding is completely discharged.

Next, make certain that the test-potential source is firmly connected to the winding so that no arcing will occur at the test leads. This includes the ground. All leads of the winding or portion of the winding under test should be connected together. Any part of the winding or accessories not under test should be connected together and grounded to the frame. For polyphase machines, it is best to test each phase separately (while grounding the phases not under test).

Before any testing is conducted, the winding insulation must be discharged. It is not safe to begin testing before the discharge current is almost zero and there is no discernible return voltage (less than approximately 20 V) after the ground is removed (in general, the winding should not be left ungrounded).

After completion of the test, discharge the winding through a suitable resistor (sized to limit the instantaneous current) for at least four times as long as the voltage application duration. This time interval is based on the R (resistive), L (inductive), C (geometric capacitive), and absorptive characteristics of the circuit during charging (time of the application of the voltage) and discharging (elapsed time since the removal of the voltage source and subsequent grounding of the winding under test). It is important to remember that the testing is not complete until the winding is discharged and there is no discernible voltage. It is recommended that subsequent testing not be conducted until the winding is fully discharged. The discharge current manifests itself in two components:

- A capacitive discharge current component, which decays nearly instantaneously, depending upon the discharge resistance.
- The absorption discharge current, which will decay from a high initial value to nearly zero with the same characteristics as the initial charging current but with the opposite polarity. This decay may take more than 30 minutes, depending on the insulation type and size of the test specimen.

INSULATION RESISTANCE TEST

Winding insulation resistance (IR) is measured using an insulation resistance tester that subjects the insulation under test to a DC voltage. The test is performed by connecting one lead from the test instrument to ground and the other lead to the conductor that is insulated from ground. Usually the positive meter lead is connected to ground. The insulation resistance is shown on the meter and is read after the voltage is applied for a period of one minute. For maximum effectiveness, conduct this test at regular intervals and record the results for comparison with future readings. This is known as "trending."

It is preferable to begin the test with the windings at room temperature:

- Measure and record the temperature of the windings.
- Measure and record the ambient humidity and temperature.
- Measure the insulation resistance between the windings and the frame of the machine.

GUIDELINES FOR DIRECT VOLTAGES TO BE APPLIED DURING INSULATION RESISTANCE TEST

Winding rated voltage (V)[a]	Insulation resistance test direct voltage (V)
<1000	500
1000–2500	500–1000
2501–5000	1000–2500
5001–12 000	2500–5000
>12 000	5000–10 000

[a] Rated line-to-line voltage for three-phase AC machines, line-to-ground voltage for single-phase machines, and rated direct voltage for DC machines or field windings.

Temperature correction

According to IEEE 43:

> Regardless of the cleanliness of the winding surface, if the winding temperature is at or below the dew point of the ambient air, a film of moisture may form on the insulation surface, which can lower the insulation resistance or polarization index. The effect is more pronounced if the surface is also contaminated, or if cracks in the insulation are present.

IEEE 43 also indicates that the insulation resistance can vary inversely, on an exponential basis, with the winding temperature. Further, in metals the free electrons at higher temperatures increase thermal agitation and thus increase resistivity; whereas, in insulators the higher thermal agitation frees electrons and decreases resistivity. The result is that the expected results of insulation resistance will decrease at higher temperatures. Since the recommended values are all at 40°C, different recommended values are necessary when the test specimen is at a different temperature.

When machines are tested that have been out-of-service, and when the winding temperature is below the dew point, they may have values considered too low, and may need to be dried out to meet expected levels. The history of the machine should help to determine the potential risk for returning "a failed" winding to service; however, further high-voltage testing is not recommended in such cases.

Note that the effects of moisture contamination on a healthy winding should not preclude obtaining acceptable readings. Table 7-1 shows the temperature-corrected minimum insulation resistances defined by IEEE 43.

TABLE 7-1: RECOMMENDED MINIMUM INSULATION RESISTANCE VALUES AT 40°C (ALL VALUES IN MΩ)

Minimum insulation resistance	Test specimen
IR_{1min} = kV + 1	For most windings made before about 1970, all field windings, and others not described below.
IR_{1min} = 100	For most AC windings built after about 1970 (form-wound coils).
IR_{1min} = 5	For most machines with random-wound stator coils and form-wound coils rated below 1 kV and DC armatures.

Notes:

1 IR_{1min} is the recommended insulation resistance, in megohms, at 40°C of the entire machine winding (all phases).

2 kV is the rated line-to-line voltage for three-phase AC machines, line-to-ground voltage for single-phase machines, and rated direct voltage for DC machines or field windings.

3 It may not be possible to obtain the above minimum IR_{1min} values for stator windings having extremely large end arm surface areas, or for DC armature windings with commutators. For such windings trending of historical IR_{1min} values can be used to help evaluate the condition of their insulation.

4 The values [in the above table] may not be applicable, in some cases, specifically when the complete winding overhang is treated with stress control material.

5 The values in the above table do not apply to "green" windings before global vacuum impregnation treatment.

Reference: IEEE Stds. 43, Table 3.

To avoid the effects of temperature in trend analysis, conduct subsequent tests when the winding is near the same temperature as the previous test. However, if the winding temperature cannot be controlled from one test to another, all insulation test values should be compared to acceptance values corrected to a common base temperature of 40°C. Though this corrected value is an approximation, it permits a more meaningful comparison of insulation resistance values obtained at different temperatures. (Tables 7-2 and 7-3 are derived from IEEE 43, 6.3.3.)

Trend analysis is often ambiguous, since moisture contamination normally lowers the insulation resistance and/or polarization index readings. As long as the insulation resistance remains fairly level, the insulation system is in good condition. High humidity can cause resistance values to drop, so lower resistance readings on one test do not always mean the insulation is beginning to deteriorate. (For this reason it is a good idea to record humidity readings for each test.)

NOTE: Table 7-2 and Table 7-3 are approximations and could lead to significant errors if used to evaluate insulation resistance at temperatures outside the range of 20-60°C (shown in grey). These values might also lead to errors with windings affected by moisture and dust.

TABLE 7-2: RECOMMENDED MINIMUM INSULATION RESISTANCE FOR "THERMOSETTING" INSULATION STATOR WINDING SYSTEMS BUILT AFTER ABOUT 1970

(ALL VALUES IN MΩ)

T (°C)	AC winding (form-wound)	Random-wound	Form-wound < 1 kV DC armatures	Field windings (kV+1) / value
10	143	7	7	(kV+1) / 0.7
20	125	6	6	(kV+1) / 0.8
30	111	6	6	(kV+1) / 0.9
40	100	5	5	(kV+1) / 1.0
50	67	3	3	(kV+1) / 1.5
60	43	2	2	(kV+1) / 2.3
70	30	2	2	(kV+1) / 3.3
80	22	1	1	(kV+1) / 4.6

TABLE 7-3: RECOMMENDED MINIMUM INSULATION RESISTANCE FOR "THERMOPLASTIC" INSULATION STATOR WINDING SYSTEMS BUILT BEFORE ABOUT 1970

(ALL VALUES IN MΩ)

T (°C)	All windings
10	(kV+1) / 0.125
20	(kV+1) / 0.25
30	(kV+1) / 0.5
40	(kV+1) / 1
50	(kV+1) / 2
60	(kV+1) / 4
70	(kV+1) / 8
80	(kV+1) / 16

Divide the value in Column 2 by (kV + 1), where kV is the rated line-to-line voltage for three-phase AC machines, line-to-ground voltage for single-phase machines, and rated direct voltage for DC machines or field windings`

If insulation resistance drops for two or three successive tests (maintaining the same test interval), the winding should be cleaned, dried and tested again. If the insulation resistance does not increase, the machine should be rewound.

It is difficult to predict the effect of moisture condensation on the surface if testing below the dew point, so an attempt to trend these values would introduce an unacceptable error. In such cases, previous tests of the machine under similar conditions should be the predominant factor in determining suitability for return to service.

POLARIZATION INDEX TEST

The polarization index (PI) test is another test for determining the suitability of a winding for service. An extension of the IR test, this index is calculated from measurements of the winding insulation resistance. The PI test may not apply to small random-wound machines because the absorption current (IA) becomes negligible in a matter of seconds.

To conduct the PI test, apply the test voltage to the winding for 10 minutes. Record the insulation resistance after one minute and again after 10 minutes. To determine the PI, divide the 10-minute reading by the one-minute reading.

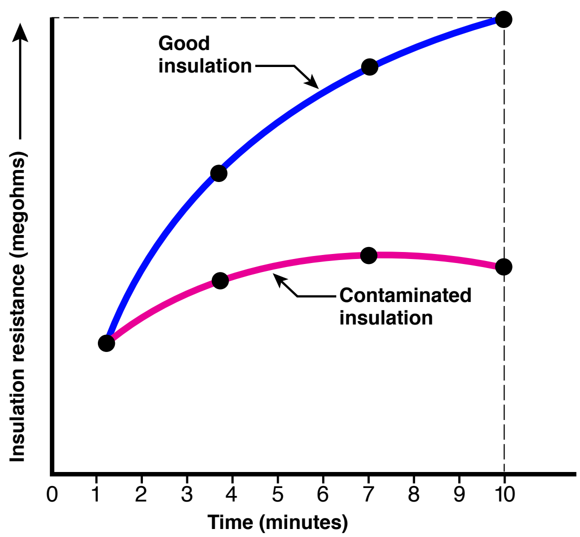
$$\mathrm{PI} = \frac{IR_{10\mathrm{min}}}{IR_{1\mathrm{min}}}$$

Correction for temperature is not necessary since both readings are taken at the same temperature.

The PI may also be calculated from readings of a microammeter (μA) using an external direct current supply. It is not necessary to convert this reading into resistance. Calculate the PI by the following formula:

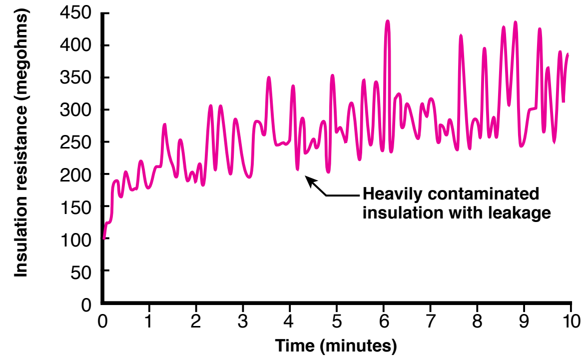
$$\mathrm{PI} = \frac{\mu A_{1\mathrm{min}}}{\mu A_{10\mathrm{min}}}$$

FIGURE 7-1



Plots of PI tests showing good insulation with a 10-minute value of about 3.0 times the one-minute value and contaminated insulation with a 10-minute value of about 1.4 times the one-minute value. Good insulation should have a PI of at least 2.0; anything less is considered unacceptable.

FIGURE 7-2



Plot of PI test of heavily contaminated insulation with leakage. Since the 10-minute value is about 1.4 - 1.6 times the one-minute value, the insulation is unacceptable.

The recommended minimum PI value for windings rated Class B (130°C) and higher is 2.0, and 1.5 for Class A (105°C) windings. Machines having windings with a lower index are usually unsuitable for service (see Figure 7-1 and Figure 7-2).

In modern insulation systems, a PI value of 1.0 is not uncommon. If the one-minute insulation resistance is above 5000 megohms, the calculated PI may not be meaningful. In such cases, the PI may be disregarded as a measure of winding condition.

The PI test is also helpful for identifying gradual deterioration of the insulation. Record test results and compare them with earlier readings from the same machine.

HIGH-POTENTIAL TEST

High-potential (overvoltage) tests are performed to detect weakness in the insulation structure that might lead to service failure. Visual inspection and insulation resistance tests with acceptable results should be performed before the high-potential test. Either AC or DC high-potential equipment may be used for the test. Because it is less destructive, DC overvoltage tests are recommended.

When performing a high-potential test, the AC or DC voltage should be applied between each electrical circuit and the frame. All other windings or circuits not under test should be connected to the frame.

The level of overvoltage that should be applied to motor and generator windings depends on the type of machine and its rated voltage. To avoid stressing the insulation excessively, repeated application of the high-potential test voltage is not recommended. For reconditioned windings, high-potential test should be performed at 60 percent of the test voltage for a new winding. For windings that have not been cleaned and dried, the AC test voltage should not exceed 125 to 150 percent of rated voltage; the DC test voltage should not exceed 215 to 255 percent of rated voltage. For additional information, refer to “High-Potential Tests Using AC” and “High-Potential Tests Using DC” in this section, and *ANSI/EASA AR100: Recommended Practice for the Repair of Rotating Electrical Apparatus*.

a. High-potential test (AC)

The AC test is usually performed at 50 Hz or 60 Hz, but on large equipment it can be performed at very low frequency (VLF), 0.1 Hz. One advantage of the very low frequency test is that the physical size of the test unit is greatly reduced. The size of the VLF test equipment is also small, hence the preference for performing this test as a VLF test in the service center or field. The winding is tested at the target voltage one time only (see Section 7.2). To avoid stressing the insulation excessively, repeated application of the high-potential test voltage is not recommended.

The test voltage should also be raised and lowered slowly. Rapid changes in voltage produce surges that could damage the windings. Raising and lowering the test voltage slowly also eliminates arcing at the leads, which is another source of surges.

Generally, the voltage should be raised at a rate that will allow the instruments to be read, but not so slowly as to prolong the test. The initial rate of rise of the test voltage should be such that the test set will not shutdown on over current. These conditions can usually be satisfied if the test voltage is raised to 75% of the target value relatively quickly, and then raised incrementally by 2% of the final value per second. After the target value has been reached and maintained for the prescribed time, the voltage can be reduced to zero by adjusting the test set controls. The test object should then be grounded through a suitable resistor to avoid large disruptive discharges. (Reference: IEEE Std. 4.)

When testing with AC, be sure the test transformer has the proper kVA rating. Breakdowns can occur during testing if the transformer is too small. The insulation being tested acts as a capacitor and is in series with the resistance and reactance of the transformer winding. If the transformer is too small, resonance is approached, which causes the voltage across the capacitor (insulation) to become considerably larger than the applied voltage.

Finally, when testing with DC, the apparatus becomes a charged capacitor. After testing, the windings must be grounded until complete discharge has taken place. Depending on the test voltage and winding capacitance, it may take some time (possibly hours) to fully discharge the windings. It is recommended that the leads be connected directly to ground for at least twice as long as the duration of the high-potential test.

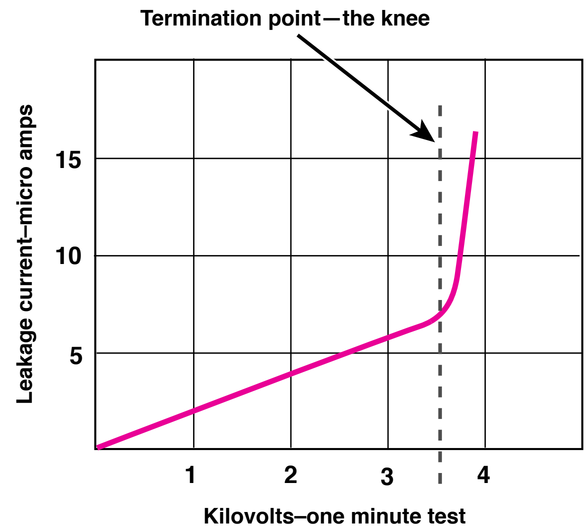
b. High-potential test (DC leakage)

Another test for determining the condition of an insulation system is the DC high-potential (DC leakage) test. A DC voltage is applied between the line lead and ground. If DC test equipment is chosen, be aware that the stress distribution differs from the AC test. DC testing must be for duration of one minute after test voltage is reached (see Section 7.3).

When voltage is first applied, absorption current as well as leakage current will flow, and the current readings will be quite high. The absorption current will decrease quite rapidly, and in a short time the meter will display only leakage current (a steady value).

It may be possible to provide notice of impending failure before it occurs by slowly raising the voltage in either a "ramp" or "step" format. For a ramp test, the voltage increases are constant and controlled by the test configuration, such as 100V/minute. For a step test, the voltage is increased in equal increments, normally 3% of the target voltage. Measure the time required for the current to level off on the initial step. Use the same time interval for the subsequent steps. At the end of each interval, read and record the leakage current and then increase the voltage to the next step.

FIGURE 7-3



(**NOTE:** Advance warning–the "knee" of impending failure–does not usually occur if the failure is within the slot section of the winding.)

Plot of a DC leakage test.

Plot the current in microamps against the applied kilovolts. As long as the plot is a straight line, the test can be continued. When the current rises sharply and the "knee" occurs, the test should be stopped. The voltage at the knee of the curve should be twice rated voltage plus 1000 or higher. Figure 7-3 shows a plot of this test.

At the completion of the test, the test object should be grounded through a suitable resistor to avoid large disruptive discharges. (Reference: IEEE Std. 95.) Depending on the test voltage and winding capacitance, it may take some time (possibly hours) to fully discharge the windings. It is recommended that the leads be connected directly to ground for at least twice as long as the duration of the high-potential test.

DIELECTRIC TEST

The capacitance test, dissipation factor test or power factor test can be used to determine the losses in insulating materials.

a. Capacitance test

As an insulation system ages, some of the organic resin is replaced with a void that fills with air and thus changes the dielectric constant of the insulation system. In older, pre-1970 machines the change in the dielectric constant was often significant enough that it was possible to detect the effects of aging by measuring the total *capacitance* of a winding. Though still possible on severely deteriorated newer windings, the change in capacitance is usually so subtle that it is difficult to observe until the winding is nearing failure. Therefore, on new windings, the capacitance test is less effective in a condition-based maintenance program. It does, however, have some merit for determining the extent of moisture contamination and delamination on the older windings.

- Delamination ➪ capacitance decreases (>1% change)
- Moisture contamination ➪ capacitance increases (>5% change)

The capacitance can be measured at a low voltage and is best done with a bridge that will eliminate the effect of the stray capacitance of the test supply.

A variation on the capacitance test is the *capacitance tip-up test*, which is performed on complete windings, or preferably individual winding phases, and measures the void content in the groundwall insulation of the stator form-wound coils. The basis for this test is that a relatively high voltage (e.g., phase-to-ground voltage) will ionize the gas in any voids that may be present in the groundwall, producing sufficiently high conductivity to short out the voids and cause partial discharge (PD). This produces an increase in capacitance between low and high line-to-ground voltage.

Normally this test is performed on each phase of a winding with an accurate capacitance bridge. The capacitance C_{lv} is measured at 0.2E, where E is the rated phase-to-phase voltage. C_{hv} also is measured at line-to-ground voltage, which is about 0.58E. The capacitance tip-up is:

$\Delta C = (C_{hv} - C_{lv})/C_{lv}$

The higher ΔC is, the more voids there are in the winding groundwall (see Table 7-4).

TABLE 7-4: CAPACITANCE TIP-UP TEST GUIDELINES FOR WELL-BONDED GROUNDWALL INSULATION

Insulation type	Typical capacitance change (ΔC)
Modern epoxy mica	< 1%*
Older asphaltic mica	< 2% or 3%

* Greg Stone, et al, *Electrical Insulation for Rotating Machines*, 12.6.3; Wiley & Sons, Inc., 2004.

Note that if the coils have semi-conducting and grading voltage stress control layers, these will influence the results of this test. At the higher voltage, the grading layers of silicon carbide material conduct, which increases the effective surface area and thus the capacitance of the sections of winding being tested. This may give a false indication of high void content. If the results are trended against time, however, an increase in ΔC may give a true indication of increased void content in the groundwall insulation.

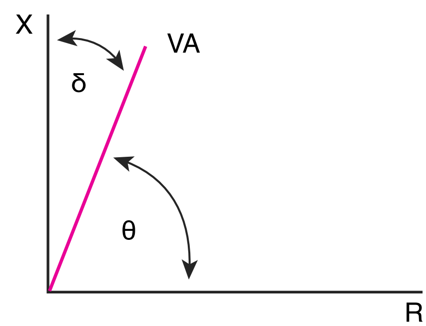
b. Dissipation factor test

This test is usually performed on form-wound windings rated above 6.0 kV. Losses can generally be used to indicate the condition of an insulation system and can be used over time to monitor insulation deterioration. The test is often performed in the factory on individual coils or bars (Reference: IEEE Std. 286).

The test is performed by energizing the winding with an AC power supply for the line-to-ground voltage and measuring the dissipation factor or power factor with a Schering bridge. The higher the power factor, the higher the losses. Test results can be affected by dirt, moisture and stress-grading materials. For tests performed in the factory, the owner usually specifies maximum acceptable test values for the coils being tested.

Like the capacitance test, the dissipation factor test also looks for any changes in the insulation system of the winding. This test, however, is done at high voltage steps that increase from zero to normal line-to-ground voltage. Its purpose is to observe the increase in real power loss due to the presence of voids in a delaminated insulation (Δ tan δ, Figure 7-4). As the applied test voltage increases, so will the partial discharge activity in the voids; thus the real power loss (mW) also will increase.

FIGURE 7-4



Dissipation factor test.

The absolute value of the dissipation factor (DF) is also useful in determining the extent of curing in a new insulation system.

DF= tan δ = mW / mVar = IR / IC

- Delamination ➪ Δ tan δ increases
- Moisture contamination ➪ tan δ increases

Typically the DF for epoxy mica windings is about 0.5%; for asphaltic mica windings it is 3 to 5%. Trending the results against time makes the best use of this test. As with the Δ capacitance test, voltage-stress coatings can produce ambiguous results at high voltage.

c. Power factor test

Similar to the dissipation factor (tan δ) the *power factor test* looks for any changes in the insulation system of the winding (Figure 7-4). The test is normally done at a specific applied voltage that makes it possible for comparing the results to other machines. This is a valuable test for determining the extent of curing in new coils or winding. Because the presence of the voltage stress control in a complete winding greatly affects the results, tests on complete windings can be ambiguous. (Reference: IEEE Std. 286.)

$PF = \cos\theta = mW / mVA = I_L / I_{total}$

Where: I_L = inductive current; and I_{total} = total current

- Delamination ➪ Δ cos θ increases

- Moisture contamination ➩ cos θ increases

  $PF_{polyethylene} = \leq 0.01\%$
  $PF_{epoxy} = \leq 0.5\%$
  $PF_{asphalt} = \leq 3 - 5\%$

The tip-up test ($\Delta \cos \theta$) is done at two voltages: one below the inception of partial discharge activity (25% line-to-ground); and one at line-to-ground voltage. As with the $\Delta \tan \delta$ test, the difference in the power factors at these two voltages can be attributed to the energy loss due to partial discharges. Therefore, this value trended over time may be helpful in determining the development of partial discharge activity in a winding.

As with the capacitance tip-up test, however, the results of this test are influenced by the presence of voltage-stress coatings on the coils, since at high line-to-ground voltage currents flow through it to produce additional power losses. Because this test method measures total energy, it is only sensitive to how widespread the PD is and not how close the winding is to failure (worst spot).

Tip-up = DF/PF_{high} - DF/PF_{low}

(Typical results: ≤ 0.5% for epoxy)

- High at 100% line-to-ground rated voltage (above PDIV)
- Low at 25% line-to-ground rated voltage (below PDIV)

Measure the increase in energy required to produce PD and therefore the quality of the bond.

This test is widely used as a quality check by manufacturers of resin rich and individual VPI coils. In this type of testing the grading layer on high voltage coils is "guarded out" by applying aluminum foil over it.

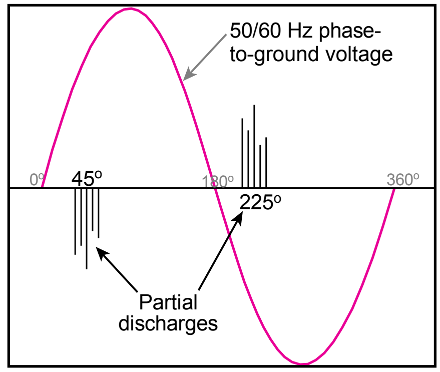
PARTIAL DISCHARGE TEST

The loss of mechanical bonding, coil/bar movement, deterioration of surface coatings, and contamination allows voids to form within the layers of tape or on the surface of solid insulation systems. When the applied 50/60 Hz increases sinusoidally, the apparent electric stress across the void increases until it exceeds 3 kV/mm or the equivalent breakdown voltage in the void.

Overvoltage is the state at which the voltage across a void exceeds the breakdown voltage required for the void size and gas. The larger the overvoltage achieved, the more intense are the space charge effects in the void. Although a void may be in an overvoltage state, breakdown will not occur until a free electron appears within the gap (due to cosmic or natural radiation) and starts an avalanche of electrons flowing across the gap and produces a very fast rise-time (a few nanoseconds) current pulse (Figure 7-5) called a partial discharge (PD). (Reference: IEEE Std. 1434.)

When a trend line is established for PD tests taken over a period from either online or offline results, it will be obvious that most show an up-and-down variation between successive tests. As an insulation system ages, however, there will be a discernible overall upward movement of PD with time. Aging is a very slow process and sudden increases are not expected in the PD test results. Though the condition of the stator winding can be assessed, time to failure cannot be predicted. The actual failure is normally the result of an unusual source of insulation stress such as lightning, out-of-phase synchronization, or severe overheating.

FIGURE 7-5

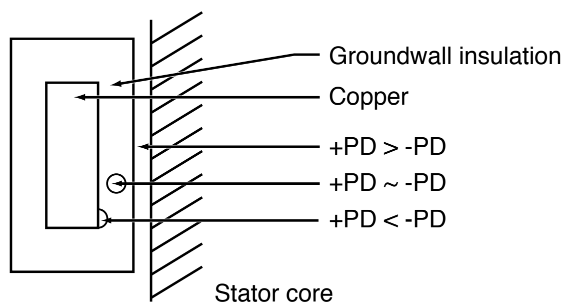


Partial discharge (PD) polarity.

These voids are distributed throughout the insulation and may discharge regardless of the "direction" of electrical stress across them. Because of this, such voids do not exhibit any real PD polarity predominance, and the PD clusters near 45° and 225°. Therefore, a fairly equal distribution of positive and negative discharges at the classic positions indicates general internal delamination or aging (Figure 7-5).

Modeling the actual characteristics of a pulse is difficult since the void dimensions, void gas and pressure, inductance, capacitance, and geometry (among other issues) can affect the magnitude and frequency of a pulse. However, there are some basic pulse characteristics that can be predicted based on the void location as shown in Figure 7-6.

FIGURE 7-6



Voids in the bulk of the insulation.

SURGE COMPARISON TEST

The surge test can be used to identify shorted turns in AC or DC coils. A series of pulses is injected into a coil, and the pulse rise time and repetition rate produce a resonant response in the coil. If the resonant-damped sine wave response is stable as the test voltage is increased, the coil does not have any shorts. Comparison of surge voltage waveforms for all coils of the same type can be effective, but in some cases this may not detect shorted turns if the impulse dissipates too quickly. (Ref. IEEE Std. 522.)

The surge tester simultaneously impulse tests two identical portions of the winding for comparison (coil-to-coil, group-to-group or phase-to-phase). If the portions being compared are not shorted, the superimposed waveforms should appear as one. Shorted turns normally result in a separation of the waveforms that becomes progressively worse as viewed from left-to-right. Neither the repetitive surge oscilloscope (RSO) nor the surge test may detect faults that only have low resistance when subjected to centrifugal forces during rotor operation.

a. Form-wound stator surge tests

The surge withstand capability of the winding should be verified at one or more of the following steps of the rewind: (a) individual coils before installation in slots (coil manufacturer tests are acceptable); (b) individual coils after installation but prior to connection, with wedging and bracing in place; (c) individual coils after series connections before connections between phase groups; (d) individual groups after connecting into phase groups but before connecting phase groups to one another; and/or (e) phases on the completely wound and fully-cured stator. Testing is recommended at steps (a) if not done by the coil manufacturer, (b) and (e) for quality assurance purposes.

Test levels are reduced for uncured coils and should be agreed upon in advance by the coil manufacturer, service center, and if required, the customer. The test values in Table 7-5 are adapted from IEEE Std. 522 and IEC Std. 60034-15. IEEE Std. 522 refers to 3.5 per unit (p.u.) as a standard withstand voltage and 2.0 p.u. as a reduced voltage test used for windings that are not likely to see high-magnitude, fast-fronted surges (where 1 p.u. = peak volts to ground of stator winding).

A single waveform surge pattern indicates that no faults or anomalies were detected. A multiple waveform surge pattern indicates a fault or anomaly requiring further analysis.

Note: Surge test results can be influenced by multiple factors, such as the presence of the rotor when testing a stator. Analysis of surge test results is subjective, even when using quantitative tools to compare waveforms.

TABLE 7-5: FORM COIL NEW WINDING SURGE TEST VOLTAGES

Rated voltage (V)	IEEE 522[1,4,5] 2.0 p.u. (kV)	IEEE 522[2,4,5] 3.5 p.u. (kV)	IEC 60034-15[3,4] $U'_p = 0.65\ U_p$	2E+1kV[6]
400	–	–	–	1.8
460	–	–	–	1.9
575	–	–	–	2.2
690	–	–	–	2.4
2300	3.8	6.6	9.2	–
3300	5.4	9.4	11.8	–
4000	6.5	11.4	13.7	–
6600	10.8	18.9	20.4	–
11000	18.0	31.4	31.9	–
13800	22.5	39.4	39.1	–

1. 2.0 p.u. = 2 • VL - L$\sqrt{2}$/3 kV, 0.2 μs front rise
2. 3.5 p.u. = 3.5 • VL - L$\sqrt{2}$/3 kV, 0.1 μs front rise
3. 1.0 Up = 4 • VL - L + 5kV, 0.2 ±0.1 μs front rise
4. Coils not fully processed (e.g., uncured resin-rich or dry (green) VPI) should be tested at a reduced voltage, generally 40-80% of the calculated value.
5. Maintenance tests of reconditioned windings may be performed at 75% of the calculated value.
   Caution: If the insulation design is unknown, use 75% of the 2.0 p.u. column values.
6. For machines rated below 2300 V, use values given under "Other Winding Surge Tests."

(Reference: ANSI/EASA Std. AR100, Table 4-3.)

b. Other windings surge tests

The winding surge test is most often applied to other windings, including random wound stators, at twice rated voltage plus 1000 volts with a 0.2±0.1 microsecond front rise.

A single waveform surge pattern indicates that no faults or anomalies were detected. A multiple waveform surge pattern indicates a fault or anomaly requiring further analysis.

Note: Surge test results can be influenced by multiple factors, such as the presence of the rotor when testing a stator. Analysis of surge test results is subjective, even when using quantitative tools to compare waveforms

c. Surge testing and error area ratio (EAR)

Most service centers perform some form of surge comparison testing, though terminology and methodology may vary. In simple terms, two winding responses or waveforms from a fast rise-time surge are compared, and if there is an excessive difference, the unit under test may have a defect. The waveform that is produced by the pulse is unique to the unit under test (e.g., a stator winding). The waveform will be a function of the resistance, capacitance and inductance of the test circuit, and quite a few variables can affect those characteristics.

One drawback with surge comparison testing is its subjectivity. That is, it is not always easy for technicians to reach the same conclusion when comparing two waveforms. To alleviate this problem, several test equipment manufacturers utilize analytical methods to evaluate the surge comparison test results. The goal is to remove as much subjectivity as possible so the technician can quickly decide what to do with the unit under test. The most popular analytical method now in use (in various forms) is the Error Area Ratio (EAR).

EAR capabilities are not necessary to perform surge comparison testing satisfactorily but it is useful technology that can assist operators in making an informed decision.

What is the EAR?

One way to explain EAR is to explore the concept graphically, as J. Lebesch once did [1]. Figure 7-7 (Page 7-10) illustrates a typical surge comparison test with a reference waveform (1) that begins at point A and has a fast rise time (steep slope) and

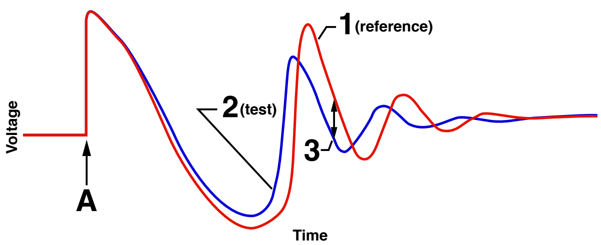
[1] J. Lebesch, "Method and Apparatus for Automatically Calculating the Integrity of an Electrical Coil," USA Patent 5,111,149, 5 May 1992.

a test waveform (2). It is common practice is to plot voltage on the vertical axis and time on the horizontal axis.

If these two waveforms were of test circuits with the same resistance, inductance and capacitance, they would be identical and look like one waveform if superimposed. But these waveforms are not identical, because they have different time dependencies (frequencies) and different voltage levels (amplitudes).

Early automated testing systems tried to determine the condition of a winding by calculating the difference in voltage between the two waveforms at various points in time (see point 3 in Figure 7-7). Most experts now think the EAR method is better.

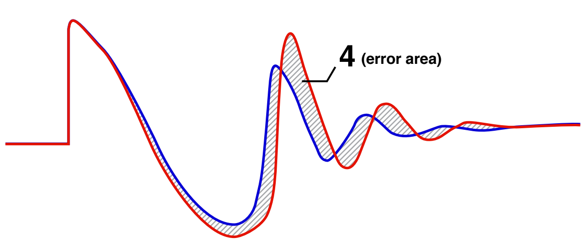
FIGURE 7-7



Early automated testing systems calculated the voltage difference between waveforms at some points in time (3 above).

If the two waveforms in Figure 7-7 should be identical, any difference between them can be considered error. Thus the shaded area between the waveforms in Figure 7-8 is called the Error Area (4). Obviously, the Error Area will become larger as differences between waveforms increase.

FIGURE 7-8

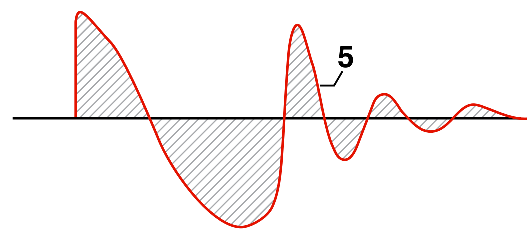


The difference between waveforms is the error area.

To develop a common set of acceptance criteria for windings of different size, shape, configuration,and so forth., it is important to normalize the result to something simple for comparison such as a percentage. Common practice is to compare the Error Area with the reference area (see Figure 7-9). For example, if the area in Figure 7-8 is 3 volt-seconds and the reference area in Figure 7-9 is 30 volt-seconds, the EAR would be 3/30 = 0.1 per unit or 10%.

The two most common applications of EAR are the pulse-to-pulse EAR and the line-to-line EAR. These are different tests and should be treated as such. A third use, not addressed here in detail, would be to compare an individual coil with

FIGURE 7-9



The reference area (point 5 above).

a reference master coil waveform stored in the memory of the test set.

Pulse-to-Pulse (P-P EAR)

When performing a surge test, it is not uncommon to find a short or fault that is only detected above a certain voltage. That is, as the test voltage is slowly increased, the waveform suddenly changes, usually shifting to the left (higher frequency), possibly with a noticeable change in amplitude.

The P-P EAR test looks for such changes by applying a voltage pulse to a winding (phase A, for example) and then pulsing the same winding with a slightly higher voltage. This normally produces a predictable difference between the two waveforms that the computer program recognizes. If the difference is significantly larger than expected, the calculated P-P EAR will increase, alerting the operator to a potential defect.

Because the P-P EAR test is only testing one winding or coil at different voltages, there are no concerns about differences in winding configuration or the magnetic circuit path, which allows testing of assembled machines.

Line-to-Line (L-L EAR)

Like the conventional surge comparison test, the L-L EAR compares two different windings or coils that should be the same. For example, with a three-phase stator, a L-L EAR would be calculated for A-B, B-C and A-C. It is not unusual for L-L EAR values to exceed P-P EAR values for a given unit under test. There are a several factors that cause this, including these examples:

- Winding configuration
  - Various concentric winding patterns
  - Lap winding over the span (lazy-lapping)
  - Testing one path only of a part-winding-start connection
- Core iron condition
  - Shorted laminations
  - Ground out pockets from failures
  - Geometric dissymmetry–e.g., varying back iron dimension
  - Rotor position, if installed; stator-rotor mutual coupling is a function of position

Since the L-L EAR compares two windings, it is valuable for finding differences between them–e.g., reversed coils, missing or extra turns, and connection issues. However, any of these conditions can yield false negatives. Winding resistance, small rotor testing and phase balance testing can provide useful information in these cases.

EAR acceptance criteria

Even though EAR testing provides an analytical method for determing acceptability, some subjectivity remains. The same pass/fail criteria for L-L EAR and P-P EAR will not necessarily be appropriate for every unit under test, and not all manufacturers of EAR-capable testers provide pass/fail criteria. The EAR values depend on the unit under test as well as the test equipment and data calculation method. Consult the test equipment manufacturer about reasonable starting points for establishing acceptance criteria. Typically, P-P EAR values for three-phase stators (with or without rotor installed) are below 10%. Acceptable L-L EAR values for three-phase stators (without rotor installed) are usually below 15%.

d. Synchronous rotor windings

The surge test may detect shorted turns, ground faults and high-resistance connections in salient pole and round rotor windings. For salient pole windings, turn short detection is best performed by testing individual poles and comparing the waveforms. For complete salient pole and round rotor windings, the test is performed from each end and the resultant waveforms are compared. For wound rotor windings, individual phases are tested; any change in waveform shape as the test voltage is increased indicates a defect.

The surge test involves injecting fast rise time pulses with a peak voltage magnitude of around 1000V into each end of the winding, and overlaying the resulting waveforms to check for similarity. If there are differences in the waveform frequencies, an experienced operator can determine the type of fault present.

WINDING RESISTANCE TEST

The winding resistance test compares phases or circuits to ensure they are balanced with respect to resistance. This is important if the winding configuration has been changed during rewind.

> **CAUTION:** Perform a 500V IR test between the rotor winding and shaft before conducting the surge test. Do not perform the surge test unless the IR value is at least 1.0 megohm.

According to CSA C392, phase resistances should be balanced within 1% for form windings and within 2% for random windings for the winding's copper resistance between phase leads or the circuit resistance of each phase. The values obtained can be used to determine winding losses for efficiency calculations.

The test is performed with milliohm meter and a device for measuring the winding temperature. For better results, measure the resistance with a digital low resistance ohmmeter (DLRO) or similar Wheatstone bridge instrument that circulates several tens or hundreds of amps through the windings.

Higher resistance in one phase indicates open coils or a poor connection or joints. Low resistance may be indicative of shorted turns. Any changes in trend should be investigated, but comparisons should only be made if the measurements were made at or corrected to the same temperature.

Note that the current should not approach the normal operating current of the winding because this will heat the winding and affect the resistance measurement; and if heating is severe, it could damage the insulation system.

SHORTED TURN TESTS

a) Turn-to-turn test

The turn-to-turn test is only useful for identifying shorts between turns on large edge-wound DC coils such as interpoles or edge-wound synchronous poles. It is performed by exciting the coils with AC or DC and then measuring the voltage between adjacent turns.

The equipment required for this test includes an accurate voltmeter (or millivolt meter), a current meter and an AC or DC source. The energizing source must be capable of providing enough current to produce a measurable voltage between turns, so an AC source is preferred.

To perform the test, measure the voltage between each turn and compare it to the others. As with the AC voltage drop test, the tolerance between turns is ±10% of the average voltage per turn. Note that the voltage between shorted turns will be between zero and half the average voltage measured between turns.

b. Impedance test

The term impedance test has two distinct meanings in electrical testing of electric motors. The first, and most common usage, refers to comparative testing of DC shunt fields or synchronous fields. The second is testing of salient-pole synchronous rotors, in which the connections between coils are not easily accessible.

When testing DC shunt fields or synchronous field coils, perform the test as follows: Apply an AC voltage (often 120 volts from a convenient outlet) to each individual field coil and record the current. As with any AC test, the tolerance is ±10% of the average. Because the impedance test is sensitive to even small differences in surrounding iron, position individual coils in exactly the same place for this test. Avoid placement on a metal table, a concrete floor (rebar), or near metal structures.

When testing DC shunt fields in the frame, take note of weldments such as lifting ears or feet, as well as openings in the frame (e.g., lead openings), as these can cause discrepancies in the test.

This test is more effective than comparing resistance since a shorted turn creates a much greater change in impedance than resistance.

c. Voltage drop test

This test is used to compare whole coils (as in a large synchronous or DC machine). AC voltage (usually 120V) is applied across the complete winding, and the voltage across each coil is measured. Since the impedance of a pole-mounted coil reduces much more than its resistance when a short is present, the AC voltage drop will be significantly less if there are shorted turns. Voltage drops that are >10% below the average value likely indicate shorted turns.

Because the coil impedance is also affected by differences in the nearby iron, an AC voltage drop test can be adversely influenced by weldments on the frame (lifting ears or feet) or openings (e.g., lead openings) near one or more coils. If the AC voltage drop results are within ±10% of the average, the coils are deemed to be good. If one or more coils falls outside this tolerance, the recommendation is to follow with a DC voltage drop test. Because the DC voltage drop test simply follows Ohm's Law, shorted turns are more difficult to reveal. For that reason, the tolerance for a DC voltage drop test is reduced to ±5% from the average (see Table 7-6).

TABLE 7-6: TURN-TO-TURN TEST TOLERANCE

Source	Tolerance
AC	± 10% of calculated average voltage drop
DC	± 5% of calculated average voltage drop

Cautions

- When applying an AC voltage drop test to a machine with compound fields (i.e., a shunt field and series field on the same pole), never apply AC voltage to the shunt field, as it may induce dangerously high voltages into the series fields. Rather, while the AC voltage is applied to the shunt field leads, also measure and record the voltage induced in the series fields. As with the shunt fields, the voltage drop tolerance for the series fields is ±10% of the average.
- When there are significant differences in the iron distribution around the coils, the results of an AC drop test may be misleading. In those cases, a DC drop test is useful to determine whether the AC results are due to shorted turns or influence of the iron.
- Using higher frequencies (120-400 Hz) can be very beneficial because it greatly reduces the current requirements.

Note: The same test cannot be used with a DC voltage drop; only AC voltage can be transformed.

RECURRENT SURGE OSCILLOGRAPHY (RSO TEST)

This test requires a special instrument called a reflectometer. The test instrument simultaneously injects low voltage (<100V peak), fast rising, high frequency voltage pulses into each end of the motor's field winding, and the resulting waveforms are compared on a dual-beam(trace) oscilloscope. This test can be used with the rotor turning, if it has slip rings. Features on one trace that are not identified on the other can identify the presence of:

- Shorted turns with a resistance <10 ohms
- Ground faults with a resistance <500 ohms
- High-resistance connections

The approximate location of a fault relative to the ends of the winding can also be determined from this test.

CURRENT SIGNATURE ANALYSIS (CSA)

> **CAUTION**: Although all of these methods are useful, any of them may result in a false positive. Therefore it is important to use more than one method before reaching any conclusions about an open rotor.

Motors with high-inertia loads are more apt to develop winding problems because of long accelerating time with high starting currents. Multiple frequent starts or severe duty motor applications also can lead to broken rotor bars. This is especially true if they have fabricated aluminum alloy rotor windings (cages) that have poor mechanical properties at high temperatures. Analysis of stator current with special Fast Fourier Transform (FFT) analysis technique can yield side band harmonic information to show the presence of cracked or broken rotor bars in fabricated squirrel-cage windings and air pockets in die-cast aluminum windings. Comparisons should be made to benchmark tests to establish the presence or absence of defects.

Rotor problems that can be detected by CSA are:

- Broken rotor bars
- Short-circuit rings
- Joints between the rotor bars and short-circuit rings

Aside from rotor faults, CSA can sometimes detect:

- Air gap eccentricity
- Missing magnetic wedges can lead to increased unbalanced magnetic pull (UMP)
- Bearing problems
- Shaft misalignment

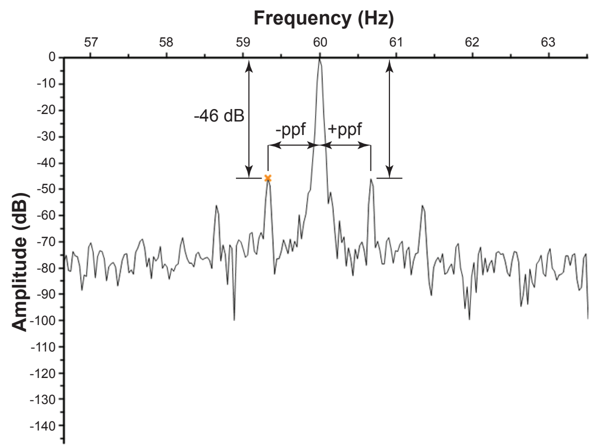
a. Broken rotor bars

The rotor currents in a cage winding produce an effective three-phase magnetic field, which has the same number of poles as the stator field but is rotating at slip frequency with respect to the rotating rotor. If rotor current asymmetry occurs, there will be a resultant backward (i.e., slower) rotating field at slip frequency with respect to the forward rotating rotor. Asymmetry results if there are one or more breaks in the rotor cage winding, preventing current from flowing through one or more bars. With respect to the stationary stator winding, this backward rotating field at slip frequency (f_{sb}) with respect to the rotor (as well as the resulting torque oscillation) induces currents in the stator winding at: $f_{sb} = f_1(1 \pm 2s)$.

In general, the difference between the current magnitude at line frequency (F_L) and the sidebands (F_{sb}) [± 2 × slip frequency removed from F_L] should be greater than 45dB for a rotor cage winding in good condition. A difference of less than this is often the sign of one or more broken rotor bars, a shorting ring, or joints between them. The smaller the dB difference between F_L and F_{sb}, the higher the probability for more than one broken rotor bar. This difference can be trended to detect broken bars in a squirrel-cage rotor winding.

CSA detects these sidebands by measuring the stator current on one phase with a current transformer. A high-resolution spectrum analyzer is used to detect sidebands about 1 Hz above and below power frequency. The "trick" is to measure slip speed accurately, even if the load is oscillating.

FIGURE 7-10



$f_s = (1 \pm ppf)$

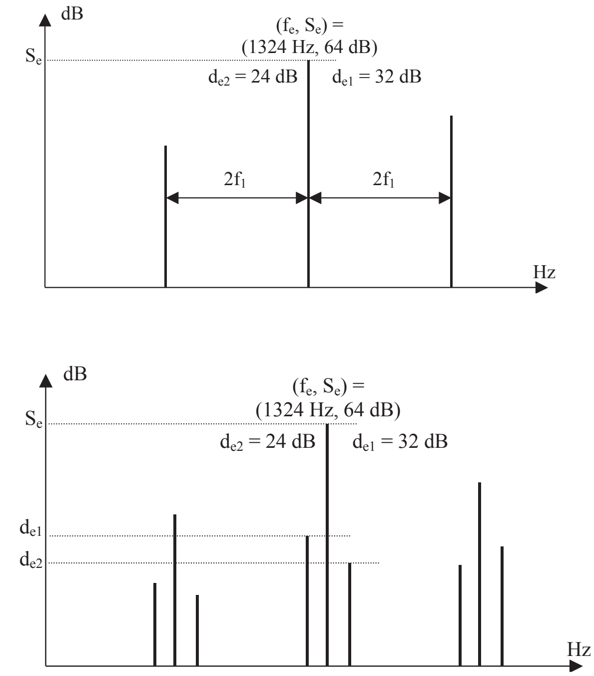
$n \cong \dfrac{2R}{p + 10\left(\frac{N}{20}\right)}$

R: No. of rotor slots
p: No. of pole pairs
N: Avg. f_{sb} magn. [dB]
n: Broken bar estimate

ppf: Pole pass frequency

Composite spectrum of broken rotor bar on condensate pump.

FIGURE 7-11



- Find the rotor slot-passing components spaced 2_{f1} apart.
- Pick the rotor slot-passing component with the highest magnitude.
- Find the rotational speed-frequency components($\pm f_r$) around these rotor slot-passing components.
- Based on the difference between S_e and the average of d_{e1} and d_{e2}:

AGE $\propto d_{avg} = [S_e - 0.5(d_{e1}+d_{e2})] = 64 - 0.5 \times 56 = 36$ dB

The smaller the d_{avg} is, the greater is the air gap eccentricity.

Calculation of specific frequencies of the current components indicative of air gap eccentricity.

If the identified sideband is due to broken bars an estimate of the number of breaks can be obtained if the number of rotor slots is known (see Figure 7-10).

Gearboxes with slow output speeds can give rise to fundamental current components, or harmonics thereof, in the frequency range in which broken bar components may be found. Thus, to avoid false indications of broken rotor bars, it is essential that gearbox wear be considered when investigating for broken rotor bars if current components from f_r, due to shafts rotating with N_r rpm are:

$f_m = f_r \pm mf_r$

(where $f_r = N_r/60$ and m = 1,2,3 etc., or a constant depending on the gear-box ratio)

b. Air gap eccentricity

Air gap eccentricity (AGE) can be caused by:

- Improper setting of stator-to-rotor air gaps during motor assembly
- Bearing housings that are not concentric with the stator bore
- Wear in sleeve and tilting pad guide bearings
- Shaft stiffness not high enough to prevent UMP
- Bent rotor shaft

Static eccentricity is when the minimum air gap is stationary relative to the stator; dynamic eccentricity occurs when the minimum air gap rotates with the rotor. Because static eccentricity leads to shaft bending from UMP, it is virtually impossible to have static eccentricity without some dynamic eccentricity. The specific frequencies of the current components indicative of air gap eccentricity (f_{ec}) may be calculated by:

$$f_{ec} = f_1 [R(1-s)/p \pm n_{ws}] \pm f_1 [(1-s)/p]$$

Where:

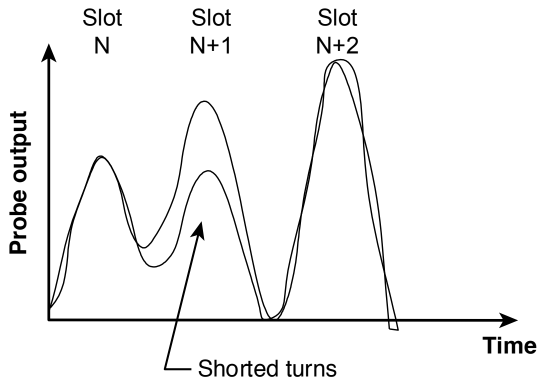
f_1 = Supply frequency
R = Number of rotor slots
s = Slip
p = Pole-pairs
n_{ws} = 1, 3, 5, 7, etc.

This formula equates to a series of slot-passing frequency components that are twice the power supply frequency apart and have sidebands that are ± rotational speed frequency (f_r) removed (see Figure 7-11).

AIR GAP FLUX MONITORING

Rotor flux monitoring involves measuring the magnetic flux in the generator air gap to determine if field winding shorts have occurred in the rotor poles. The radial magnetic flux is detected by means of a flat coil (or probe) consisting

FIGURE 7-12



Air-gap flux monitoring can identify coils with shorted turns.

of several dozen turns that is glued to stator teeth. As each rotor pole sweeps by the flux probe, it induces a voltage in the coil that is proportional to the flux from the passing pole.

Flux monitoring relies on measurement of the magnetic flux density produced by each coil in the rotor (Figure 7-12). By analyzing the waveforms and comparing them pole-to-pole, it is possible to identify slots with shorted turns. Any turn-to-turn short in a pole reduces the effective ampere-turns of that pole and thus the signal from the flux probe associated with that pole. Usually, coils with peak-to-peak difference larger than 3% compared to the same coil on another pole are considered to have shorted turns.

The voltage is measured by electronic instruments such as a digital oscilloscope or analog-digital (A/D) converter. In a salient pole machine, the radial magnetic flux profile across each rotor pole depends on the MW and MVAr loading of the machine. There are portable and continuous devices for online detection of shorted rotor turns on both salient pole rotors and round rotors.

GROWLER TEST

DC armatures and induction motor rotors can be tested using a growler. The growler consists of a partial magnetic circuit around which a coil is installed to induce flux into the magnetic components. The armature or AC rotor when placed against the growler completes the magnetic circuit. The flux through the armature or rotor induces current in the armature coils or rotor bars.

Open coils or open bars can be detected by placing a thin piece of carbon steel (e.g., a hacksaw blade) against each coil or bar. If the steel vibrates or buzzes (growls) with an armature, the coil below it is shorted (or the armature winding is equalized); if it vibrates with a rotor, the circuit through that bar is complete. If no vibration occurs with an armature, the coil is not shorted; with a rotor, no vibration indicates an open circuit in the bar below.

Other detection methods used with a growler include a magnetic film or iron filings. In some cases an infrared temperature detector can also be used. Growlers come in many sizes, and handheld ones can also be used to identify shorted turns in stator winding coils.

A simple growler consists of a U-shaped laminated core with a single-phase winding around it that is supplied from an AC source. Each rotor bar is scanned by moving the growler transversely along the core from one end to the other, or by rotating the rotor in a growler. If a bar break exists, no current is induced in that bar and the metal plate vibrates.

Another version of this device consists of a V-shaped magnetic core with an ammeter and resistor in series with the excitation coil. The rotor is placed in the "V" and slowly rotated. With this configuration, a significantly lower current indicates broken bars. (**Note:** This test will not detect cracked rotor bars, nor will it detect bar or shorting ring breaks that close when the rotor is cold or do not open until subjected to centrifugal running forces.)

HIGH-FREQUENCY BAR-TO-BAR TEST

The high-frequency bar-to-bar test compares two sections of the armature winding by simultaneously applying a continuous low voltage at high frequency to each section and comparing the impedances. If the impedances match, the indicator will read "0" or "null."

If the impedance of one section of a winding differs from that of another, the needle will swing left or right, indicating inequality. Unequal readings indicate a short or open in the winding. An armature that is completely shorted (e.g., thermally degraded) may result in equal but erroneous readings with the high-frequency bar-to-bar tester.

The high-frequency tester can be used to perform a bar- to-bar test even with the armature in the field frame (i.e., machine assembled). If the armature tests satisfactorily with the high-frequency tester, the armature is not shorted. However, a failed high-frequency test of the armature in an assembled machine is inconclusive. Magnetic coupling to the fields or anomalies in the field frame can cause false indications of inequality in the armature windings.

WOUND STATOR ASSEMBLY TEST

Also termed a ball test or hysteresis (dummy) rotor test, this test ensures that the phase voltages and currents in a three-phase stator and wound rotor winding are balanced by checking:

- Current balance and magnitude
- Connection joint integrity
- Polarity of groups

To perform the test, apply about 1/6 to 1/4 of the rated voltage to the open stator and measure the current with an ammeter. (**Caution:** Test duration must be short enough that the windings are not overheated.) To detect and discern winding unbalance with this test, it is important to confirm that the power source [voltage] is balanced within 1% percent. Typically the current should be balanced within 5 %.

DC WINDING POLARITY TESTS

The field winding in synchronous machines and shunt, series and interpole windings in DC machines should be checked for the correct polarity. Conduct the polarity test by applying clean DC power to the relevant leads as follows:

- **Shunt fields.** If the shunt field leads are only marked F1 and F2, apply DC to those leads. Use a compass, Detect-a-Pole, or similar device to confirm that the polarity of the fields alternate north-south-north-south, and so forth. If the shunt fields have more than two leads, for dual-voltage operation, connect the leads as per the manufacturer's/customer's markings to perform this test.

- **Synchronous rotating fields.** Conduct the DC polarity test in the same manner as for shunt fields.
- **Series fields.** Perform the test as with the shunt field leads, verifying alternating polarities.
- **Interpoles.** Besides the steps described thus far, connect the brushholder leads being careful to preserve the direction of current flow. Interpoles are often connected in multiple parallel circuits.
- **Compound-wound machines.** These have both shunt and series fields. Make sure the relative polarity of the fields is the same by performing the tests described in Methods 1 and 2.

Method 1

- To verify series versus shunt field polarity, connect a low-voltage analog DC meter (less than 3-volt scale) to the series field leads, with the meter positive lead connected to the motor S1 lead.
- Using a 12-24 volt DC supply, flash the shunt field by briefly applying the positive voltage to the motor F1 lead.
- If the voltmeter deflection is upscale (positive), the field leads are cumulative compound, which is almost always the correct relationship. If the voltmeter deflects downscale (negative), the field leads are differentially compounded and probably incorrect.

Method 2

- When operating as shunt wound (A1+ to F1+ and A2- to F2-), the motor should rotate counterclockwise (when facing the commutator end).
- Connect the fields in series configuration. If the field polarity is correct, the rotation should again be counterclockwise (when facing the commutator end).

  (**Warning:** Do not apply rated voltage for this step. Closely monitor motor speed to ensure the armature does not go into overspeed.)
- ***If the direction of rotation is incorrect for either the shunt or series test, those are the leads that are incorrectly marked.***

While most DC motor applications are cumulative, meaning the shunt and series on any pole are connected for the same polarity, and some generators are connected differentially (meaning opposing polarity), the lead markings for both are the same. In other words, the differential connection is only externally different than the cumulative connection.

SINGLE-PHASE ROTATION TEST

With the three-phase motor disconnected from the power supply, connect an instrumented, single-phase AC power source. Now apply 10-25% of the rated line-to-line voltage across two motor terminals to induce 50-100% of motor full-load current. Slowly turn the rotor by hand while monitoring the current drawn by the stator winding with an ammeter. Current fluctuations exceeding 3% indicate broken rotor bars and/or short-circuit rings.

(**Caution:** Test duration must be short enough that the windings are not overheated.)

This test may not detect bar or shorting ring breaks that close when the rotor is cold or do not open until subjected to centrifugal running forces.

7.2 HIGH-POTENTIAL TESTS USING AC

CAUTION: Follow all applicable safety procedures associated with high-potential testing, before, during and after the test.

INSULATION CONDITION TESTS

1. Perform visual inspection and insulation resistance tests before conducting the high-potential test shown below. The table at right shows the recommended minimum insulation resistances as defined by IEEE 43. (See the section "Insulation Resistance Test" on Page 7-3 for more information.) Be sure to completely discharge the winding after the test before beginning the high voltage test.
2. *The tables shown below are for testing new windings, one time only*, by applying *AC voltage*, 50-60 Hz, continuously for one minute between the winding and frame or core structure. Subsequent tests (such as acceptance tests) should beat 85% of these values, and thereafter should not be more than 2/3 of table values. To avoid excessive stressing of the insulation, repeated application of the high-potential test voltage is not recommended.
3. AC high-potential tests for windings which have not been cleaned and dried should not exceed 125 to 150% of rated voltage.
4. AC high-potential tests for *reconditioned windings* should be performed at 60% of the new winding test value.
5. Testing of electrical apparatus by the use of DC high potential test equipment is recommended. Multiply the AC test potential shown in the tables below by 1.7 to obtain the equivalent DC test potential, or see the chart for *High-Potential Tests Using DC* on Page 7-18.
6. All test results should be recorded and retained. Trends in results are often better indicators of condition than the absolute values.
7. See *ANSI/EASA AR100: Recommended Practice for the Repair of Rotating Electrical Apparatus* for additional information.

RECOMMENDED MINIMUM INSULATION RESISTANCE VALUES AT 40°C (ALL VALUES IN MΩ)

Minimum insulation resistance	Test specimen
IR_{1min} = kV + 1	For most windings made before about 1970, all field windings, and others not described below.
IR_{1min} = 100	For most AC windings built after about 1970 (form-wound coils).
IR_{1min} = 5	For most machines with random-wound stator coils and form-wound coils rated below 1 kV and DC armatures.

Notes:

1 IR_{1min} is the recommended insulation resistance, in megohms, at 40°C of the entire machine winding (all phases).

2 kV is the rated line-to-line voltage for three-phase ac machines, line-to-ground voltage for single-phase machines, and rated direct voltage for dc machines or field windings.

3 It may not be possible to obtain the above minimum IR_{1min} values for stator windings having extremely large end arm surface areas, or for dc armature windings with commutators. For such windings trending of historical IR_{1min} values can be used to help evaluate the condition of their insulation.

4 The values [in the above table] may not be applicable, in some cases, specifically when the complete winding overhang is treated with stress control material.

5 The values in the above table do not apply to "green" windings before global vacuum impregnation treatment.

Reference: IEEE Stds. 43, Table 3.

HIGH-POTENTIAL TEST OF NEW WINDINGS USING AC

DESCRIPTION OF MACHINE — EFFECTIVE AC HIGH-POTENTIAL TEST VOLTAGE

DC MOTORS AND GENERATORS	FIELD WINDING	ARMATURE WINDING
With armature or field windings rated 35 volts or less	500 volts	
Motors rated 0.5 hp (0.37 kW) and less, generators rated less than 250 watts, and for operation on circuits: a) 240 volts or less	1000 volts	
b) Above 240 volts	1000 volts + 2 times the rated voltage of the machine	
Motors rated greater than 0.5 hp (0.37 kW) and generators rated 250 watts and larger	1000 volts + 2 times the rated voltage of the machine	

UNIVERSAL MOTORS RATED 250 VOLTS OR LESS	FIELD WINDING	ARMATURE WINDING
Rated 0.5 hp (0.37 kW) and less, except motors marked for portable tools	1000 volts	
Rated greater than 0.5 hp (0.37 kW), and all motors marked for portable tools	1000 volts + 2 times the rated voltage of the motor	

References: NEMA Stds. MG 1, 12.3, 15.48, 20.17, 21.22.4, 21.22.5, 23.20 and 24.49.

HIGH-POTENTIAL TEST OF NEW WINDINGS USING AC–CONTINUED

DESCRIPTION OF MACHINE **EFFECTIVE AC HIGH-POTENTIAL TEST VOLTAGE**

<table>
<tr><th>AC INDUCTION MACHINES AND NONEXCITED SYNCHRONOUS MACHINES</th><th>STATOR WINDING</th><th>ROTOR WINDING</th></tr>
<tr><td>Motors rated 0.5 hp (0.37 kW) and less, generators rated 373 watts (or equivalent) and less, and for operation on circuits:
a) 250 volts or less</td><td>1000 volts</td><td rowspan="3">1000 volts + 2 times the secondary voltage</td></tr>
<tr><td>b) Above 250 volts</td><td rowspan="3">1000 volts + 2 times the rated voltage of the machine</td></tr>
<tr><td>Motors rated greater than 0.5 hp (0.37 kW), generators rated greater than 373 watts (or equivalent), and for:
a) Non-reversing duty</td></tr>
<tr><td>b) Reversing duty</td><td>1000 volts + 4 times the secondary voltage</td></tr>
</table>

<table>
<tr><th>AC SYNCHRONOUS MACHINES WITH SLIP RINGS</th><th>STATOR WINDING</th><th>FIELD WINDING</th></tr>
<tr><td rowspan="2">MOTORS</td><td rowspan="2">1000 volts + 2 times the rated voltage of the motor</td><td>Starting Method 1*
10 times the rated excitation voltage but not less than 2500 volts nor more than 5000 volts</td></tr>
<tr><td>Starting Method 2*
2 times the IR drop across the resistor but not less than 2500 volts</td></tr>
<tr><td>GENERATORS
a) With stator (armature) or field windings rated 35 volts or less</td><td colspan="2">500 volts</td></tr>
<tr><td>b) With output less than 250 watts and rated voltage 250 volts or less</td><td colspan="2">1000 volts</td></tr>
<tr><td>c) With rated excitation voltage 500 volts DC or less</td><td rowspan="2">1000 volts + 2 times the rated voltage of the generator</td><td>10 times the rated excitation voltage but not less than 1500 volts</td></tr>
<tr><td>d) With rated excitation voltage above 500 volts DC</td><td>4000 volts + 2 times the rated excitation voltage</td></tr>
</table>

<table>
<tr><th>AC BRUSHLESS SYNCHRONOUS MACHINES AND EXCITERS</th><th>MAIN STATOR WINDING</th><th>MAIN FIELD WINDING AND EXCITER ARMATURE</th></tr>
<tr><td>Armature (stator) or field windings rated 35 volts or less</td><td colspan="2">500 volts</td></tr>
<tr><td>With rated output less than 250 watts and 250 volts or less</td><td colspan="2">1000 volts</td></tr>
<tr><td>With rated main excitation voltage 350 volts DC or less</td><td rowspan="2">1000 volts + 2 times the rated voltage of the machine</td><td>10 times the rated excitation voltage but not less than 1500 volts**</td></tr>
<tr><td>With rated main excitation voltage greater than 350 volts DC</td><td>2800 volts + 2 times the rated excitation voltage**</td></tr>
<tr><td>BRUSHLESS EXCITERS</td><td>EXCITER STATOR (FIELDS)</td><td rowspan="4">Alternatively, the brushless exciter rotor (armature) shall be permitted to be tested at 1000 volts plus 2 times the rated nonrectified alternating current voltage but in no case less than 1500 volts.**</td></tr>
<tr><td>a) With exciter field excitation voltage not greater than 350 volts DC</td><td>10 times the rated excitation voltage but not less than 1500 volts</td></tr>
<tr><td>b) With exciter field excitation voltage greater than 350 volts DC</td><td>2800 volts + 2 times the rated excitation voltage</td></tr>
<tr><td>c) With AC-excited stators (fields)</td><td>1000 volts + 2 times the AC-rated voltage of the stator</td></tr>
</table>

* Starting Method 1: For a motor to be started with its field short-circuited or closed through an exciting armature.

Starting Method 2: For a motor to be started with a resistor in series with the field winding. The IR drop is taken as the product of the resistance and the current that would circulate in the field winding if short-circuited on itself at the specified starting voltage. (Reference: NEMA Stds. MG 1, 21.22.3).

** The brushless circuit components (diodes, thyristors, etc.) should be short-circuited (not grounded) during the test.

References: NEMA Stds. MG 1, 12.3, 15.48, 20.17, 21.22.4, 21.22.5, 23.20 and 24.49.

7.3 HIGH-POTENTIAL TESTS USING DC

CAUTION: Follow all applicable safety procedures associated with high-potential testing, before, during and after the test.

INSULATION CONDITION TESTS

1. Perform visual inspection and insulation resistance tests before conducting the high-potential test shown below. The table at right shows the recommended minimum insulation resistances as defined by IEEE 43. See the "Insulation Resistance Test" section on Page 7-3 for more information. Be sure to completely discharge the winding after the test before beginning the high voltage test.
2. *The tables shown below are for testing new windings, one-time only*, by applying *DC voltage*, continuously for one minute between the winding and frame or core structure. Subsequent tests (such as acceptance tests) should be at 85%of these values, and thereafter should not be more than 2/3 of table values. To avoid excessive stressing of the insulation, repeated application of the high-potential test voltage is not recommended.
3. DC high-potential tests for *windings which have not been cleaned and dried* should not exceed 215 to 255% of rated voltage.
4. DC high-potential tests for reconditioned windings should be performed at 60% of the new winding test value.
5. Testing of electrical apparatus by the use of DC high potential test equipment is recommended. Multiply the DC test potential shown in the tables below by 0.59 to obtain the equivalent AC test potential, or see the chart for *High-Potential Tests Using AC* on Page 7-16. The DC potential should be increased gradually to the desired test voltage to limit the charging current. DC testing must be for a duration of one (1) minute after test voltage is reached. *Caution: After a DC high-potential test, the winding must be grounded to the frame until the charge has decayed to zero*.
6. All tests results should be recorded and retained. Trends in results are often better indicators of condition than the absolute values.
7. See *ANSI/EASA AR100: Recommended Practice for the Repair of Rotating Electrical Apparatus* for additional information.

RECOMMENDED MINIMUM INSULATION RESISTANCE VALUES AT 40°C (ALL VALUES IN MΩ)

Minimum insulation resistance	Test specimen
IR_{1min} = kV + 1	For most windings made before about 1970, all field windings, and others not described below.
IR_{1min} = 100	For most AC windings built after about 1970 (form-wound coils).
IR_{1min} = 5	For most machines with random-wound stator coils and form-wound coils rated below 1 kV and DC armatures.

Notes:
1 IR_{1min} is the recommended insulation resistance, in megohms, at 40°C of the entire machine winding (all phases).
2 kV is the rated line-to-line voltage for three-phase AC machines, line-to-ground voltage for single-phase machines, and rated direct voltage for dc machines or field windings.
3 It may not be possible to obtain the above minimum IR_{1min} values for stator windings having extremely large end arm surface areas, or for dc armature windings with commutators. For such windings trending of historical IR_{1min} values can be used to help evaluate the condition of their insulation.
4 The values [in the above table] may not be applicable, in some cases, specifically when the complete winding overhang is treated with stress control material.
5 The values in the above table do not apply to "green" windings before global vacuum impregnation treatment.
Reference: IEEE Stds. 43, Table 3.

HIGH-POTENTIAL TEST OF NEW WINDINGS USING DC

<table>
<tr><th>DESCRIPTION OF MACHINE</th><th colspan="2">DC HIGH-POTENTIAL TEST VOLTAGE</th></tr>
<tr><th>DC MOTORS AND GENERATORS</th><th>FIELD WINDING</th><th>ARMATURE WINDING</th></tr>
<tr><td>With armature or field windings rated 35 volts or less</td><td colspan="2">850 volts</td></tr>
<tr><td>Motors rated 0.5 hp (0.37 kW) and less, generators rated less than 250 watts, and for operation on circuits:
a) 240 volts or less</td><td colspan="2">1700 volts</td></tr>
<tr><td>b) Above 240 volts</td><td colspan="2" rowspan="2">1700 volts + 3.4 times the rated voltage of the motor</td></tr>
<tr><td>Motors rated greater than 0.5 hp (0.37 kW) and generators rated 250 watts and larger</td></tr>
</table>

<table>
<tr><th>UNIVERSAL MOTORS RATED 250 VOLTS OR LESS</th><th>FIELD WINDING</th><th>ARMATURE WINDING</th></tr>
<tr><td>Rated 0.5 hp (0.37 kW) and less, except motors marked for portable tools</td><td colspan="2">1700 volts</td></tr>
<tr><td>Rated greater than 0.5 hp (0.37 kW), and all motors marked for portable tools</td><td colspan="2">1700 volts + 3.4 times the rated voltage of the motor</td></tr>
</table>

Caution: After completion of a DC high-potential test, the winding must be grounded to the frame (or core) until the charge has decayed to zero. (References: IEEE Stds. 4 and 95; and NEMA Stds. MG 1, 3.1.)

HIGH-POTENTIAL TEST OF NEW WINDINGS USING DC–CONTINUED

DESCRIPTION OF MACHINE **DC HIGH-POTENTIAL TEST VOLTAGE**

<table>
<tr><th>AC INDUCTION MACHINES AND NONEXCITED SYNCHRONOUS MACHINES</th><th>STATOR WINDING</th><th>ROTOR WINDING</th></tr>
<tr><td>Motors rated 0.5 hp (0.37 kW) and less, generators rated 373 watts (or equivalent) and less, and for operation on circuits:
a) 250 volts or less</td><td>1700 volts</td><td rowspan="3">1700 volts + 3.4 times the secondary voltage</td></tr>
<tr><td>b) Above 250 volts</td><td rowspan="3">1700 volts + 3.4 times the rated voltage of the motor</td></tr>
<tr><td>Motors rated greater than 0.5 hp (0.37 kW), generators rated greater than 373 watts (or equivalent), and for:
a) Non-reversing duty</td></tr>
<tr><td>b) Reversing duty</td><td>1700 volts + 6.8 times the secondary voltage</td></tr>
</table>

<table>
<tr><th>AC SYNCHRONOUS MACHINES WITH SLIP RINGS</th><th>STATOR WINDING</th><th>FIELD WINDING</th></tr>
<tr><td rowspan="2">MOTORS</td><td rowspan="2">1700 volts + 3.4 times the rated voltage of the motor</td><td>Starting Method 1*
17 times the rated excitation voltage but not less than 4250 volts nor more than 8500 volts</td></tr>
<tr><td>Starting Method 2*
3.4 times the IR drop across the resistor but not less than 4250 volts</td></tr>
<tr><td>GENERATORS
a) With stator (armature) or field windings rated 35 volts or less</td><td colspan="2">850 volts</td></tr>
<tr><td>b) With output less than 250 watts and rated voltage 250 volts or less</td><td colspan="2">1700 volts</td></tr>
<tr><td>c) With rated excitation voltage 500 volts DC or less</td><td rowspan="2">1700 volts + 3.4 times the rated voltage of the generator</td><td>17 times the rated excitation voltage but not less than 2550 volts</td></tr>
<tr><td>d) With rated excitation voltage above 500 volts DC</td><td>6800 volts + 3.4 times the rated excitation voltage</td></tr>
</table>

<table>
<tr><th>AC BRUSHLESS SYNCHRONOUS MACHINES AND EXCITERS</th><th>MAIN STATOR WINDING</th><th>MAIN FIELD WINDING AND EXCITER ARMATURE</th></tr>
<tr><td>Armature (stator) or field windings rated 35 volts or less</td><td colspan="2">850 volts</td></tr>
<tr><td>With rated output less than 250 watts and 250 volts or less</td><td colspan="2">1700 volts</td></tr>
<tr><td>With rated main excitation voltage 350 volts DC or less</td><td rowspan="2">1700 volts + 3.4 times the rated voltage of the machine</td><td>17 times the rated excitation voltage but not less than 2550 volts**</td></tr>
<tr><td>With rated main excitation voltage greater than 350 volts DC</td><td>4750 volts + 3.4 times the rated excitation voltage**</td></tr>
<tr><td>BRUSHLESS EXCITERS</td><td>EXCITER STATOR (FIELDS)</td><td rowspan="4">Alternatively, the brushless exciter rotor (armature) shall be permitted to be tested at 1700 volts plus 3.4 times the rated nonrectified alternating current voltage but in no case less than 2550 volts.**</td></tr>
<tr><td>a) With exciter field excitation voltage not greater than 350 volts DC</td><td>17 times the rated excitation voltage but not less than 2550 volts</td></tr>
<tr><td>b) With exciter field excitation voltage greater than 350 volts DC</td><td>4750 volts + 3.4 times the rated excitation voltage</td></tr>
<tr><td>c) With AC-excited stators (fields)</td><td>1700 volts + 3.4 times the AC-rated voltage of the stator</td></tr>
</table>

***** Starting Method 1: For a motor to be started with its field short-circuited or closed through an exciting armature.

Starting Method 2: For a motor to be started with a resistor in series with the field winding. The IR drop is taken as the product of the resistance and the current that would circulate in the field winding if short-circuited on itself at the specified starting voltage. (Reference: NEMA Stds. MG 1, 21.22.3).

****** The brushless circuit components (diodes, thyristors, etc.) should be short-circuited (not grounded) during the test.

References: NEMA Stds. MG 1, 12.3, 15.48, 20.17, 21.22.4, 21.22.5, 23.20 and 24.49.

Caution: After completion of a DC high-potential test, the winding must be grounded to the frame (or core) until the charge has decayed to zero. (References: IEEE Stds. 4 and 95; and NEMA Stds. MG 1, 3.1.)

7.4 CORE TESTING

There are three possible tests that can be used to assess the condition of the insulation on electrical steel laminations. One of these, the Franklin test, is used on the laminations prior to assembly; and the other two, the loop test and the stator core low energy test, are used on assembled equipment.

FRANKLIN TEST

The Franklin test is used in the factory prior to assembly to check the integrity of the insulation material applied to the lamination sheets. Several electrodes are attached to the lamination to be tested and a voltage applied to each. The current (if any) through each electrode is measured. The results are analyzed statistically to assess the overall integrity of the insulation material.

STATOR CORE LOOP TEST

The stator core test, often referred to as the loop test, has proven effective in detecting shorted laminations in stator core iron. The test gets its name from the loops of cable wound through the stator bore and around the outside of the frame.

The test involves establishing a specific magnetizing level for the core by energizing the loop turns with single-phase power. The circulating currents induced in the laminations will simulate the core loss and heat up the stator iron. The condition of the core can then be determined from the core temperature and power input.

No correlation is implied between the core loss watts value determined by the loop test described here and the core loss watts value determined by tests described in IEEE 112.[1]

The loop test can be used for single- and three-phase machines of any rated frequency, regardless of winding condition. Under certain conditions, it also can be applied to armature, wound rotor and squirrel cage rotor cores.

Using EASA's Stator Core Test Form

EASA's Stator Core Test Form (Page 7-21) provides a step-by-step procedure for calculating the number of turns and cable size required for a loop test. The form also has provision for recording the meter and temperature readings obtained during the test. Core sketches that show the location of measured dimensions and a wiring diagram of instrument connections are also included.

The following is an explanation of the calculations in the sequence they appear on the test form. (**Note:** More detailed explanations of some calculations are given in the "Annex" on Page 7-25.)

The first step is to measure and record four stator core dimensions (in inches or millimeters):

L = Length less air ducts

D_1 = Inside diameter

S = Slot depth

B = Back-iron depth

(Back-iron depth is the distance from the bottom of the slot to the OD of the laminations; if this distance varies, use the smallest dimension.)

Measure the dimensions as indicated on the core sketch using an accurate scale.

The section for calculating data is divided into two parts: one for dimensions in inches; the other for millimeters.

Calculate the mean diameter of the core back-iron (D) using the three radial dimensions just measured.

$$D = D_1 + (2 \times S) + B \text{ (inches or millimeters)}$$

The number of loop turns required to establish the desired magnetizing level is given by:

$$\text{Loop turns} = \frac{279 \times V_s}{f \times x\ L \times B} \quad \text{(dimensions in inches)}$$

$$\text{Loop turns} = \frac{180000\ x\ V_s}{f \times L \times B} \quad \text{(dimensions in mm)}$$

Where:

V_s = Supply voltage

f = Test frequency in Hz

If the result of the loop turn calculation is not a whole number, it must be rounded off. But rounding off the calculated number of turns will change the core's magnetic strength. If other test voltages are available, repeat the loop turn calculation for these voltage values, and choose the test voltage value that yields a number for loop turns that is nearest a whole number. Use this voltage as the test voltage, and record the test voltage and frequency under "Power Supply for Testing" on the test form.

The current required for the loop test is calculated in order to select the cable size and to make sure the power supply has sufficient amperage rating.

$$\text{Estimated amperes} = \frac{28 \times D}{\text{Loop turns}} \quad \text{(dimensions in inches)}$$

$$\text{Estimated amperes} = \frac{1.1 \times D}{\text{Loop turns}} \quad \text{(dimensions in mm)}$$

Select an insulated lead wire or cable whose ampacity exceeds the calculated ampere value. For selection of cables in AWG and metric sizes, use the "Lead Wire Selection" chart on the test form. If the calculated amperes fall between table values, use the next higher value.

The weight of the core back-iron is calculated to determine the watts loss per pound (or kilogram):

$$\text{Core weight} = 0.82 \times D \times L \times B \quad \text{(in pounds) (dimensions in inches)}$$

$$\text{Core weight} = \frac{D \times L \times B}{43821} \quad \text{(in kilograms) (dimensions in mm)}$$

These formulas calculate the weight of the core back-iron only and do not include teeth.

The induced voltage value that indicates the core flux level is the desired 85 kilo-lines per square inch (1.32 Tesla) is calculated as follows:

$V_i = 0.003585\ f \times L \times B$ (dimensions in inches)

$V_i = 0.000005557\ f \times L \times B$ (dimensions in millimeters)

Where: V_i is the calculated induced voltage.

STATOR CORE TEST FORM

kW					
Hp	RPM	Manufacturer		Frame	Type
Phase	Hz	Volts	Amps	Model	Serial No.

CORE DIMENSIONS	Length less air ducts	Inside diameter	Slot depth	Back iron depth
☐ Inch ☐ mm	L =	D_1 =	S =	B =

POWER SUPPLY FOR TESTING
V_S = Volts f = Hz

Use this section when core dimensions are in INCHES.

Mean Dia. (D)	D_1 + (2 x S) + B = + (2 x) + =	in	Mean Dia. (D)
Loop turns	$\frac{279 \times V_S}{f \times L \times B} = \frac{279 \times}{\times \quad \times} =$		Loop turns
Estimated amperes	$\frac{28 \times D}{\text{Loop turns}} = \frac{28 \times}{} =$		Estimated amperes
Calculated induced voltage (V_i)	0.003585 f x L x B (indicates desired core flux of 85 kilolines/sq²) =		Calculated induced voltage (V_i)
Core weight*	0.82 x D x L x B = 0.82 x x x =	lb	Core weight*

*Note: Weight calculation is based on back iron only and does not include teeth.

Use this section when core dimensions are in MILLIMETERS.

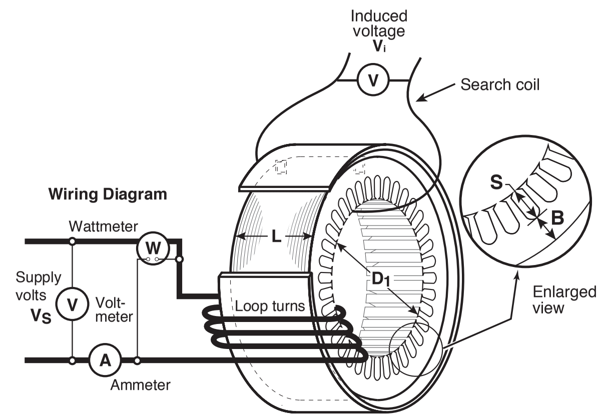
Mean Dia. (D)	D_1 + (2 x S) + B = + (2 x) + =	mm	Mean Dia. (D)
Loop turns	$\frac{180000 \times V_S}{f \times L \times B} = \frac{180000 \times}{\times \quad \times} =$		Loop turns
Estimated amperes	$\frac{1.1 \times D}{\text{Loop turns}} = \frac{1.1 \times}{} =$		Estimated amperes
Calculated induced voltage (V_i)	0.000005557 f x L x B (indicates desired core flux of 1.32 Tesla) =		Calculated induced voltage (V_i)
Core weight*	$\frac{D \times L \times B}{43821} = \frac{\times \quad \times}{43821} =$	kg	Core weight*

*Note: Weight calculation is based on back iron only and does not include teeth.

LEAD WIRE SELECTION																	
	Size AWG	18	16	14	12	10	8	6	4	3	2	1	1/0	2/0	3/0	4/0	LEAD SIZE
	Amperes†	**18**	**22**	**25**	**30**	**40**	**50**	**70**	**90**	**105**	**120**	**140**	**155**	**185**	**210**	**235**	
	Metric size mm²	1.0	1.5	2.5	4.0	6.0	10	16	25	25	35	50	50	70	95	120	

†Note: If estimated amperes fall between table's values, use next higher value for selection of lead wire or cable.

Remarks



CORE TEMPERATURES ☐ °F ☐ °C					TEST DATA	(Use only meters that read true RMS value.) METER READINGS			
Ambient	At start	At end	Rise	Time elapsed (minutes)		Volts	Amps	Induced Volts	Watts
					Before stripping				W_1
					After stripping				W_2

CORE ASSESSMENT $\frac{W_2}{W_1} = \frac{\quad}{\quad} =$

Disposition of core: ☐ Use ☐ Repair ☐ Scrap	
Watts/lb**	Watts/kg**
Watts/lb**	Watts/kg**

** Note: Watts loss per pound (per kilogram) calculations are based on back iron only and do not include teeth.

Job No.	Customer	Date	Tested by	Verified by	Ref. EASA *Technical Manual, Section 7*

The induced voltage is measured at the lead ends of a single turn loop “search coil” that is usually placed diametrically opposite the loop test coil turns. Since the induced voltage coil has no current flow, the smallest practical lead wire size can be used for the search coil.

Winding the loop coil for the stator core test

Compactly wind the loop coil through the stator bore and around the frame using the calculated cable size and the number of turns. To facilitate temperature measurements, locate the coil as far as possible from any suspected core damage. Even distribution of the loop turns will also make it easier to access the core when checking for temperature variations.

Procedures for stator core loop test

For the core test, select a single-phase power supply with a higher ampere rating than the estimated amperes calculated earlier. If possible, use a power supply with both variable voltage and the same frequency as the motor rating. Testing at rated frequency will ensure more reliable detection of suspected core damage. For non-standard frequencies, see the discussion in “Rotor or Armature Core Loop Test” on Page 7-23.

INSTRUMENTS REQUIRED FOR THE STATOR LOOP TEST

- Ammeter*
- Voltmeter*
- Wattmeter*
- Thermometers
- Pyrometer
- Infrared thermal scanner or other device for measuring temperature

* For accurate measurements, use only meters that read true RMS value and are calibrated at least annually against standards traceable to the National Institute of Standards and Technology (NIST) or equivalent standards laboratories.[2]

Connect the meters to the loop coil leads as shown on the test form wiring diagram. The meters should be connected as close to the loop coil as possible to reduce the influence of the cable’s watts loss on the meter reading. This is necessary because the wattmeter measures the core loss in the back-iron as well as the copper loss in the loop coil. Using a larger cable minimizes the watts loss from the cable.

Apply single-phase power to the test coil, preferably using the same frequency as the rating of the motor. Use the same supply voltage as was used in calculating the loop turns. Maintain this voltage for the duration of the test.

Start the test with the loop cable and core iron at ambient temperature. Record meter readings at the beginning of the test. Measure induced volts, amps, and watts and record the data in the “Test Data” section on the test form.

If the measured current deviates from calculated amperes, *do not adjust the supply voltage or the turns to make the amperage values conform*. Deviation from calculated current is to be expected because of variation in the magnetization characteristics of the stator laminations, or damage to the core iron.

Should the measured current be higher than the cable’s ampacity, replace the cable with one large enough to carry the current.

If the actual induced voltage varies from the calculated induced voltage by more than 5%, the supply voltage and current will need to be adjusted. If the induced voltage is low, either increase the supply voltage to increase the current, or remove turns from the loop to increase current. If the induced voltage is high, either reduce the supply voltage to reduce the current, or add turns to the loop to reduce current.

Calculate the watts loss per pound (or kilogram) of core weight and enter on the test form:

$$\text{Watts loss per lb (or kg)} = \frac{\text{Measured watts}}{\text{Calculated core weight}}$$

Keep in mind that this calculation represents the losses in the core back-iron, with error dependent upon the losses in the test cable. (**Note:** The larger the cable, the greater the portion of calculated watts losses that can be attributed to the core.)

Measurement of stator core temperatures

The stator core will begin to heat up when the loop coil is energized. If the laminations are not damaged, the surface temperatures will stay uniform and typically increase 5°C to 10°C (10°F to 20°F) in about 30 minutes.[3] The rate of rise, however, will vary with the size of motor. The test duration needs to be longer for larger and 2 pole cores.

Localized core damage–detected as hot spots that heat up several times faster than undamaged areas–will be evident from measurement of core temperatures during the test. Hot spots near the bore surface may be detected within minutes of testing. Hot spots in the back-iron, particularly for large 2-pole cores, may take more than 20 minutes of testing to be evident at the bore surface.

Frequent measurement of core temperature during testing is necessary to assure early detection of hot spots. Terminate the test as soon as hot spots are detected to prevent further damage to the core, and then mark the damaged areas. Repairs should be made and the core retested.

Record core temperatures at the start and at the end of the test, along with ambient temperature and time elapsed for the test. Calculate and record the temperature rise of the core iron (temperature at the end of the test minus temperature at the start of the test).

Assessment of stator core iron

Evaluate the test data to determine whether the interlaminar insulation is good or must be repaired. The core iron may be used if the test indicates:

- Minimal core temperature rise (less than 15°C/27°F).
- Localized core heating is not prevalent.
- Watts loss per pound (or kilogram) of core weight compares favorably with published data or measurements taken on similar cores.

  (**Note:** Losses for good core iron will vary from 1-5 watts per pound (2-11 watts per kilogram), depending on lamination material grade, gage and processing.)

Repair or replace the core if any of the following conditions are present:

- The temperature of the core is high or rises rapidly.
- Localized (hot spot) heating is prevalent.
- The watts loss per pound (or kilogram) data is high or compares unfavorably with reference data.

  (**Note:** Watts loss per pound/kilogram as calculated for the loop test represents the loss in the core back-iron only.)

Core testing stators that are to be rewound

Stators that are to be rewound must be burned out and stripped properly to avoid damaging the laminations.[4] Such stators should be core tested both before and after stripping to ensure that the core losses (and resulting lower motor efficiency) have not increased during the burnout process.

Both "before" and "after" tests must be performed under the same conditions to get reliable test results.

The first test is made before burnout and stripping of the core by winding a loop coil around the stator as described earlier. The test is then performed exactly as described earlier. Record the core temperatures and meter readings including wattmeter reading (W_1,) and the calculated watts loss per pound (or kilogram) of core weight on the line "Before stripping" on the test form.

The second test is made after the core has been stripped and is ready for rewinding. Wind the loop coil around the core and frame in the identical manner as in the first test. Use the same number of turns and, if possible, use the same cable. Should the original cable not be available, use one of the same length, size, and resistance.

Perform the second test using the same voltage and frequency and at approximately the same ambient temperature as the first test. Record the temperature and meter readings including wattmeter reading (W_2) and calculated watts loss per pound (or kilogram) of core weight on the line "After stripping" on the test form.

Determine the condition of the stator by comparing the two wattmeter readings, W_1 and W_2. If the ratio W_2:W_1 is not greater than 1.2, the core can be considered suitable for rewinding, provided it also qualifies as explained earlier in the section "Assessment of core iron."

If the ratio W_2:W_1 is greater than 1.2, the core should be repaired or replaced.

Guidelines for obtaining reliable stator core test results

- Use only instruments that read true RMS value, are calibrated and are suitable for the test frequency. Connect all meters as close to the loop coil as possible.
- Perform the test at the same voltage as was used for calculating the number of loop turns, and preferably at the same frequency as the motor rating.
- Start the test with the loop cable and core iron at ambient temperature. Record meter readings at the beginning of the test.
- If the measured current deviates from the calculated amperes, do not adjust the voltage or the turns to make the amperage values conform.
- When the core test is repeated on a stator, make sure both tests are performed under the same conditions. Use the same test voltage, frequency, and number of loop turns. Reuse the same loop cable.

Safety rules for stator core testing

- Do not touch the loop coil or stator core while the coil is energized.
- Do not use shielded cable for the loop coil as voltage will also be induced into the cable shield.
- Do not leave any metallic objects in the stator bore during testing.

ROTOR OR ARMATURE CORE LOOP TEST

The loop test can also be applied to rotating cores, with some conditions (see the EASA Rotor/Armature Core Test Form on Page 7-24). The stator core test, which has a long history of development and success, is based on testing of 60 Hz and 50 Hz cores. But the eddy-current losses that the test attempts to quantify are frequency-dependent and vary as the square of the applied frequency.

$$P_e = 7.47 \times 10^{-14} (B^2 f^2 t^2)/(\rho \delta) \qquad \text{(Formula 1)}$$

Where:

P_e = Watts/lb

B = Flux density

ρ = Electrical resistivity (ohms/cm)

f = Frequency (operating)

δ = Density of core material (g/cm^3)

t = Lamination thickness (cm)

> **NOTE**
>
> Operating frequency is defined differently for stators, armatures and rotors.
>
> **Stators:** Line frequency
>
> **Armatures:** Poles x rpm / 120
>
> **Rotors:** [1 - (rpm / Synchronous rpm)] × Line frequency

When attempting to core test a rotor or armature, the *operating frequency* of the core must be taken into account. For example, a Design B squirrel cage rotor has an effective operating frequency that is less than 1 Hz. The losses, as determined by a core loss test applied using a 60 Hz power supply, are many times as great as the actual losses when the rotor is in normal service. That is, the losses in service will be only a small fraction of those experienced during the 60 Hz loop test.

To adjust for this, the core test should target 12-15 kilolines of flux per square inch (1.8 - 2.3 kilolines of flux/cm^2).

The *operating frequency of a rotor is determined by*:

[1 - (rpm / Synchronous rpm)] × Line frequency

Core loss testing of a squirrel cage rotor, for the reasons explained above, is of limited value.

On the other hand, an armature may have an operating frequency higher than the 60 Hz test. The *operating frequency of an armature is determined by the formula*:

Poles × rpm / 120

DC machines are often used over a speed range, so the calculation should use the customer's actual operating speed (if known) or the base speed listed on the nameplate. Although no standard specifically addresses this aspect of core losses, it is reasonable to extrapolate the losses based on the 60 Hz test, adjusting for the operating frequency.

To understand the effect of frequency on core loss, see Figure 7-13 (Page 7-25). Further complicating this issue, the relationship between electrical resistivity (of steel) and

ROTOR / ARMATURE CORE TEST FORM

kW					
Hp	RPM	Manufacturer		Frame	Type
Phase	Hz	Volts	Amps	Model	Serial No.

CORE DIMENSIONS ☐ Inch ☐ mm	Length less air ducts L =	Outside diameter D_O =	Slot depth S =	Back iron depth B =

POWER SUPPLY FOR TESTING
V_S = Volts f = Hz

Unless the search lead can be passed through the core, fully encompassing the back iron, only a hot spot test can be performed.

Use this section when core dimensions are in INCHES.

Mean Dia. (D)	$D = D_O - (2S + B)$ = - (2 x +) =	in	Mean Dia. (D)
Loop turns	$\frac{279 \times V_S}{f \times L \times B} = \frac{279 \times}{\quad \times \quad \times} =$		Loop turns
Estimated amperes	$\frac{28 \times D}{\text{Loop turns}} = \frac{28 \times}{} =$		Estimated amperes
Calculated induced voltage (V_i)	0.003585 f x L x B (indicates desired core flux of 85 kilolines/sq²) =		Calculated induced voltage (V_i)
Core weight*	0.82 x D x L x B = 0.82 x x x =	lb	Core weight*

*Note: Weight calculation is based on back iron only and does not include teeth.

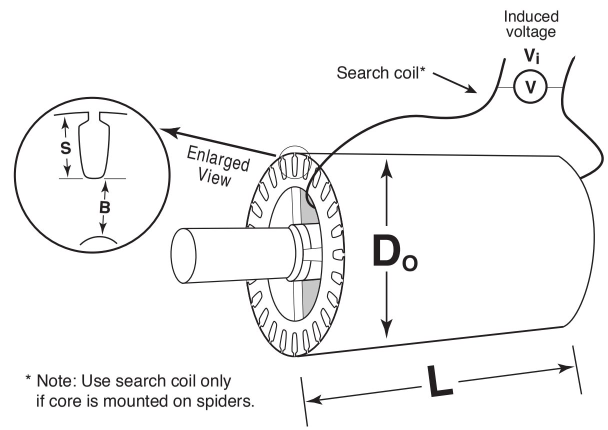
Use this section when core dimensions are in MILLIMETERS.

Mean Dia. (D)	$D = D_O - (2S + B)$ = - (2 x +) =	mm	Mean Dia. (D)
Loop turns	$\frac{180000 \times V_S}{f \times L \times B} = \frac{180000 \times}{\quad \times \quad \times} =$		Loop turns
Estimated amperes	$\frac{1.10 \times D}{\text{Loop turns}} = \frac{1.10 \times}{} =$		Estimated amperes
Calculated induced voltage (V_i)	0.000005557 f x L x B (indicates desired core flux of 1.32 Tesla) =		Calculated induced voltage (V_i)
Core weight*	$\frac{D \times L \times B}{43821} = \frac{\quad \times \quad \times}{43821} =$	kg	Core weight*

*Note: Weight calculation is based on back iron only and does not include teeth.

LEAD WIRE SELECTION	Size AWG	18	16	14	12	10	8	6	4	3	2	1	1/0	2/0	3/0	4/0	LEAD SIZE	
	Amperes†	**18**	**22**	**25**	**30**	**40**	**50**	**70**	**90**	**105**	**120**	**140**	**155**	**185**	**210**	**235**		
	Metric size mm²	1.0	1.5	2.5	4.0	6.0	10	16	25	25	35	50	50	70	95	120		

†Note: If estimated amperes fall between table's values, use next higher value for selection of lead wire or cable.



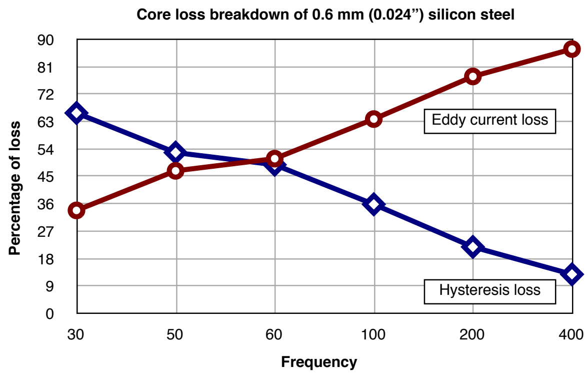
* Note: Use search coil only if core is mounted on spiders.

CORE TEMPERATURES ☐ °F ☐ °C					TEST DATA	(Use only meters that read true RMS value.) METER READINGS				CORE ASSESSMENT $\frac{W_2}{W_1}$ = ――― =	
Ambient	At start	At end	Rise	Time elapsed (minutes)		Volts	Amps	Induced Volts	Watts	Disposition of core: ☐ Use ☐ Repair ☐ Scrap	
					Before stripping				W_1	Watts/lb**	Watts/kg**
					After stripping				W_2	Watts/lb**	Watts/kg**

** Note: Watts loss per pound (per kilogram) calculations are based on back iron only and do not include teeth.

Job No.	Customer	Date	Tested by	Verified by	Ref. EASA *Technical Manual, Section 7*

FIGURE 7-13



The “(B^2 f^2 t^2)” portion of Formula 1 (Page 7-23) and these curves demonstrate why manufacturers use thinner laminations for designs operating at higher frequencies.

operating frequency: eddy-current loss does not increase in proportion to the increasing frequency.

To factor in the effect of frequency on core testing, consider the relative watts loss per pound or kilogram for the same core at various frequencies. Table 7-7 uses 6 watts/lb (13 watt/kg) as an arbitrary base. Since eddy-current losses are proportional to the square of the frequency, it is logical to apply the square root of 6 watts loss/lb ($\sqrt{6} = 2.45$) value at 60 Hz and change that in proportion to other operating frequencies.

At 60 Hz, core losses are evenly divided between eddy-current and hysteresis losses. At 120 Hz, the losses are about 30% hysteresis and 70% eddy-current. And at 240 Hz, the losses are approximately 80% eddy-current and only 20% hysteresis.

TABLE 7-7: ADJUSTMENT FACTORS FOR DIFFERENT OPERATING FREQUENCY, CORE LOSS

Imperial units						
Losses (watts/lb)	**Hz**					
	25	**50**	**60**	**120**	**240**	**400**
Eddy current	1	4.2	6	24	96	267
Hysteresis	2.4	3.4	6	14	27	40
Total	**3.4**	**7.6**	**12**	**38**	**123**	**307**
Metric units						
Losses (watts/kg)	**Hz**					
	25	**50**	**60**	**120**	**240**	**400**
Eddy current	2.3	9	13	52	207	576
Hysteresis	5.3	7.4	13	30	58	86
Total	**7.6**	**16.4**	**26**	**82**	**265**	**662**

For example, to determine the equivalent losses for 120 Hz, double the 6 watts/lb (13 watts/kg) value, and square it. If a 60 Hz core loss test of a 120 Hz core indicates losses of 6 watts/lb (13 watts/kg), the *expected* eddy-current losses operating at 120 Hz would be 24 watts/lb (51.8 watts/kg). See the formulas below. Reasonable limits for frequencies other than 60 Hz should be determined by collecting actual data.

Expected loss is estimated by:

$$\text{Watts/lb} = [(f/60)\sqrt{6}]^2$$

or

$$\text{Watts/kg} = [(f/60)\sqrt{13}]^2$$

Where: f = Frequency, applied

When preparing to core test an armature or rotor core, the loop turns must fully encompass the back-iron. If the laminations are mounted directly to the shaft, and shaft clamps

ANNEX FOR CORE LOOP TESTS

This annex explains how the formulas for loop turns, estimated amperes and core weight are derived. It also explains the basis for the magnetic circuit calculations used in this test procedure.

Loop turns

The formula for calculating volts per turn of an AC coil per IEEE Std 56 [5] is:

$$\text{VPT} = 4.44 \times f \times Ø \times 10^{-8} \qquad \text{(Formula 1)}$$

Where:

VPT = volts per turn

f = frequency in Hertz

Ø = number of flux lines

VPT is equal to supply voltage, V_S, divided by number of loop turns. Substituting V_s/Turns for VPT, Formula 1 becomes:

$$V_s/\text{Turn} = 4.44 \times f \times Ø \times 10^{-8} \qquad \text{(Formula 2)}$$

Since flux is equal to the product of back-iron flux density times back-iron area, and back-iron area is L x B, then the formula for volts per turn becomes:

$$V_s/\text{Turn} = 4.44 \times f \times B_c \times L \times B \times 0.95 \times 10^{-8} \qquad \text{(Formula 3)}$$

Where:

B_c = back-iron flux density in lines per square inch

0.95 = assumed core stacking factor

Substituting this value for B_c, Formula 3 becomes:

$$V_s/\text{Turn} = 0.003585 \times f \times L \times B = \frac{f \times L \times B}{279} \qquad \text{(Formula 4)}$$

Thus, when core dimensions are taken in inches,

$$\text{Loop turns} = \frac{279 \times V_s}{f \times L \times B} \qquad \text{(Formula 5)}$$

Continues on Page 7-26.

are required, that is suitable for applying the required flux. However, connecting the sensing leads of a core loss tester directly to the shaft clamps results in error. In that case, the sensing leads would only measure the voltage drop across the shaft, not the induced voltage.

REFERENCES

[1] IEEE Std. 112: *Standard Test Procedure for Polyphase Induction Motors and Generators*.

[2] ANSI/EASA Std. AR100: *Recommended Practice for the Repair of Electrical Apparatus*; ISO/IEC 17025: *General requirements for the competence of testing and calibration laboratories*; and ISO 10012: *Measurement Management Systems–Requirements for Measurement Processes and Measuring Equipment*.

[3] Richard L. Nailen, "What Core Loss Testers Can Do," Electrical Apparatus, February 1986, 45.

[4] EASA Tech Note 16: "Guidelines for Maintaining Motor Efficiency During Rebuilding." (St. Louis: EASA, Inc., Revised 2007). [Now part of the EASA *Technical Manual,* Section 2, 2020. See pp. 2-98 to 2-100.]

[5] IEEE Std. 56: *Guide for Insulation Maintenance of Electric Machines*.

[6] Chuck Yung, "Core Loss Testing: A Good Procedure Gone Astray?" IEEE PCIC, 2009.

Note: This article was first published as *EASA Tech Note 17* (October 1992). It was reviewed and updated in October 2020.

ANNEX FOR CORE LOOP TESTS–CONTINUED

Since one inch equals 25.4 mm, the magnetic flux density of 85,000 lines per inch^2 equals 131.75 lines per mm^2. Substituting this value for B_c, Formula 3 becomes:

$$V_s/\text{Turn} = 555.72 \times f \times L \times B \times 10^{-8} = \frac{f \times L \times B}{180000} \quad \text{(Formula 6)}$$

Thus, when the core dimensions are taken in millimeters,

$$\text{Loop turns} = \frac{180000 \times V_s}{f \times L \times B} \quad \text{(Formula 7)}$$

The induced voltage value that indicates the core flux level is the desired 85 kilolines per square inch (1.32 Tesla) is calculated:

Vi = 0.003585 f × L × B [dimensions in inches]

Vi = 0.000005557 f × L × B [dimensions in millimeters]

Where Vi is the calculated induced voltage.

The induced voltage is measured at the lead ends of a single turn loop "search coil" that is usually placed diametrically opposite the loop test coil turns. Since the induced voltage coil has no current flow, the smallest practical lead wire size can be used.

Estimated amperes

Since the ampere-turns needed for driving the flux through the back-iron are equal to the length of the flux path times the magnetizing force H, and the length of the flux path is 3.14 x D, then the formula for ampere-turns becomes:

$$\text{Ampere-turns} = 3.14 \times D \times H \quad \text{(Formula 8)}$$

The value of the magnetizing force required to produce 85,000 lines per inch^2 is equal to 9 ampere-turns per inch (per IEEE Std 56).

When core dimensions are taken in inches and 9 ampere-turns per inch is substituted for H, Formula 8 becomes:

$$\text{Ampere-turns} = 28 \times D \quad \text{(Formula 9)}$$

From this, and since the ampere-turns are equal to the estimated amperes times number of loop turns,

$$\text{Estimated amperes} = \frac{28 \times D}{\text{Loop turns}} \quad \text{(Formula 10)}$$

When the core dimensions are measured in millimeters, the constant, 28, in Formula 10 is divided by the inch-to-millimeter conversion factor 25.4, so that:

$$\text{Estimated amperes} = \frac{1.1 \times D}{\text{Loop turns}} \quad \text{(Formula 11)}$$

Core weight

The back-iron weight is equal to volume times density:

$$\text{Weight} = 3.14 \times D \times L \times B \times 0.95 \times\times \text{ Density} \quad \text{(Formula 12)}$$

Assumed core stacking factor is 0.95.

Inch dimensions. Density of steel is assumed to be 0.276 lbs/in^3 or 7.65 grams/cm^3.

Thus, when core dimensions are taken in inches and 0.276 lbs/in^3 is substituted for the density of steel, Formula 12 becomes:

$$\text{Back-iron weight} = 0.82 \times D \times L \times B \text{ (lbs)} \quad \text{(Formula 13)}$$

Millimeter dimensions. When core dimensions are taken in millimeters, use 7.65 grams/cm^3 for the density of steel.

Substituting 7.65 grams/cm^3 for the density of steel and considering that 1 kilogram equals 1000 grams, and 1 cm^3 equals 1000 mm^3, Formula 12 becomes:

$$\text{Back-iron weight} = 22.82 \times D \times L \times B \times 10^{-6} = \frac{D \times L \times B}{43821} \text{ (kg)} \quad \text{(Formula 14)}$$

STATOR CORE LOW ENERGY TEST

Electromagnetic core imperfection detector (EL CID) test

The principle underlying the EL CID method is that measurable currents will flow through failed or severely deteriorated interlaminar insulation when a flux of only a few percent of the rated value is induced in the core.

Excitation

An excitation loop consisting of a few turns of small, low-voltage cable is used to induce a weak magnetic field (2-10% of nominal flux) in the core of the machine under test (Figure 7-14). The resultant eddy currents due to the interlaminar insulation defects are detected using a **Chattock or Rogowski type pickup coil** (also known as Maxwell's worm) that is constructed from a defined number of turns per length of fine wire wound on a flexible, non-magnetic core (see Figure 7-15).

One advantage of the EL CID test over traditional high-power tests is that the cable used for the low-voltage excitation loop is typically only 0.08-0.16" (2-4 mm) in diameter.

Test procedures

Where possible, calculate the single-turn voltage (volts-per-turn) for the excitation loop using stator winding design information as indicated in the Annex for the Stator Core Low-Energy Test (Page 7-29). Consequently, the parameters of the exciting coil (number of turns and cross-section) must be calculated based upon the size of the core. A separate single-turn reference coil is installed, in the same manner as with the excitation loop turns, to measure the actual induced flux.

Before starting the test, inspect the stator and remove any conductive material that would short the laminations together.

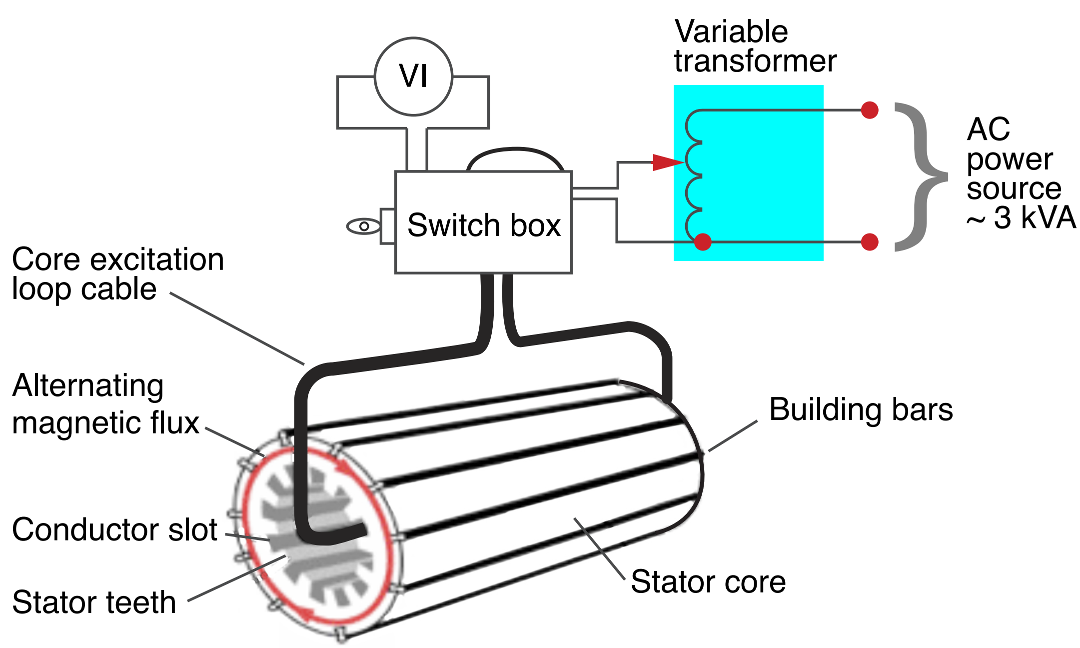
Pull the excitation loop through the central axis of the bore (but not in contact with it) and then around the outside of the stator frame. Next, adjust the Chattock-Rogowski **pickup** coil so that it rides smoothly and freely on the outside edges of two adjacent teeth without wobbling or binding (Figure 7-15). Good practice also includes numbering the core teeth to provide an easy means of referencing any faults located.

Once the above requirements have been met, place the Chattock-Rogowski pickup coil over a slot and scan its entire length while observing and recording current readings. Repeat

FIGURE 7-15

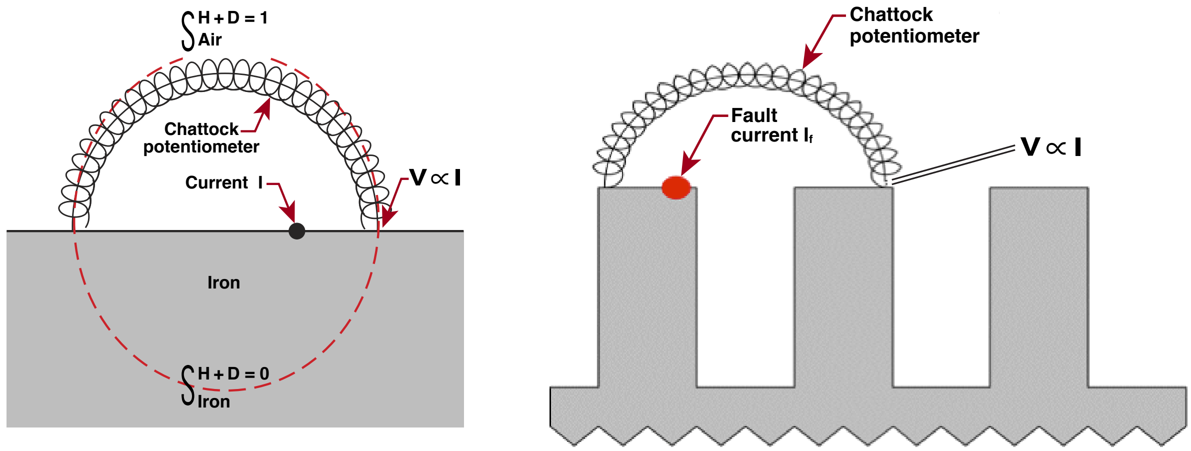
Adjust the Chattock-Rogowski pickup coils to ride smoothly and freely on the outside edges of two adjacent core teeth without binding or wobbling.

FIGURE 7-14



An low-voltage excitation loop is used to induce a weak magnetic field (2-10% of nominal flux) in the core for the ELCID test.

FIGURE 7-16



Chattock-Rogowski pickup coil being used to find interlaminar insulation defects during an ELCID test.

this procedure with each slot until the entire core or a selected portion of it has been tested.

When the Chattock-Rogowski pickup coil is placed across two core teeth, the voltage induced by the fault current is approximately proportional to the eddy current flowing in the area encompassed by the pick-up coil, the two teeth it spans, and the core behind them. The eddy currents due to faults result in fluxes that are phase shifted with respect to a reference flux (Figure 7-16).

The signals from the pickup and reference coils are fed to a processor that performs an angle comparison (Figure 7-17) to determine the axial eddy current (quadrature current) output detected by the pickup coil (in milliamperes).

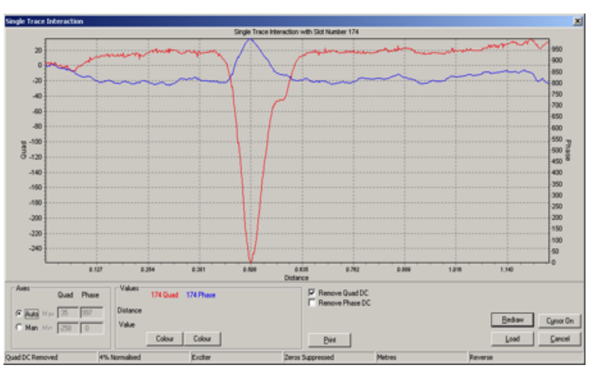
Interpretation

The EL CID test has high sensitivity, so it can detect small magnetic disturbances that may not affect the reliability of the stator. This can make it difficult to interpret the results and determine the appropriate level that warrants further investigation and/or repair. In general, responses that exceed 100 mA should be regarded as significant faults that should be investigated further. The expected temperature rise is **5-10°C (10-20°F)** for each 100 mA of fault (quadrature) current measured.

Apart from absolute magnitude, some indication of the location of the fault may be obtained by examining the polarity and number of slots affected. For a fault within the span of the pickup coil, the quadrature signal must go in the **opposite** direction of the polarity of the in-phase signal.

Note that no reading will be obtained at a fault location if the electrical circuit is not completed elsewhere (e.g., no electrical contact between laminations and building bars). For the same reason, such a fault will not create a hot spot in normal operation.

FIGURE 7-17



An angle comparison of the signals detected by the Chattock-Rogowski pickup and reference coils during the ELCID test provide a measure of the axial eddy current (in milliamperes).

ANNEX FOR STATOR CORE LOW ENERGY TEST

EXCITATION CURRENT CALCULATION FOR STATOR CORE LOW ENERGY TEST

Voltage rating (kV)	$V_{p\text{-}p}$
No. of slots	S
No. of windings (bars or coils) / Slot	W (normally = 2 but not always!)
No. of parallel circuits / Phase	C
No. of series turns / Coil	T (always = 1 for a bar)
No. turns / Phase	$Tp = \frac{S \times W \times T}{(3 \times C \times 2)}$

To apply the correct level of excitation, it is necessary to know the rated rms voltage along a single length of the core for the winding (V_r).

$$V_r = \frac{V_{p\text{-}p}}{2 \times K \times 1.73 \times T_p} \text{ and } V_t = 0.04 \times V_r \text{ for 4\% excitation}$$

Where: $V_{p\text{-}p}$ = rated phase-to-phase voltage
T_p = number of turns in series per phase (computed earlier)
K = combined spread and short pitch factor. A value of 0.92 is used for all generators.
The 2 in the denominator allows for the fact that the core voltage is generated down each side or half of the turn.

Example 1

Consider a 23 kV, three-phase, 660 MW generator with 42 slots, two bars/slot and two parallels.

$$T_p = \frac{42 \times 2 \times 1}{(3 \times 2 \times 2)} = 7 \text{ series turns per phase}$$

Since $V_{p\text{-}p}$ = 23 kV

$$V_r = \frac{23000}{2 \times 0.92 \times 1.73 \times 7} = 1032$$

Thus the standard V_t for excitation is 1032 V × 0.04 = 41.2 V. The simplified formula is:

$$V_t\,(V) = \frac{12.56 \times V_{p\text{-}p}\,(kV)}{T_p} = \frac{12.56 \times 23}{7} = 41.27 \text{ V}$$

Calculations based on core size–and for other machines where the winding is not known:

Assuming a mean flux of ~0.9 Tesla rms, and

Where:

f = Frequency

l = Core length in metres

d= Depth of core (distance from slot base to core OD) in meters

$V_t \approx 0.226$ f l d (metric)

If l and d are measured in inches:

$V_t \approx 0.000146$ f l d (inches)

Example 2

Calculate the single-turn voltage for the following motor:

f = 60 Hz

l = 40 in (1.016 m)

d = 4 in (0.1016 m)

$V_t \approx 0.226 \times 60 \times 1 \times 0.1$ V = 1.399 V (metric)

If l and d are measured in inches:

$V_t \approx 0.000146 \times 60 \times 40 \times 4$ V = 1.4 V (inches)

When installing the excitation system, if the excitation cable is taken around the core more than once (e.g., on motors and hydro generators), remember to divide the measured voltage by the number of cable turns around the core.

After calculating the single-turn voltage (V_t), divide it by the core length in meters and express the value as volts per meter.

- For medium to large 2-pole turbine generators, it should be 4-6 V/m.
- For typical hydro generators, it should be 1-3 V/m.
- For small to medium motors, it should be 0.7-2 V/m.

These values are NOT absolute, but if the answer lies outside of these ranges, double-check the calculations before accepting the result.

Calculating the excitation power requirement

For a winding with N_W turns, the excitation current in an individual turn (I_{Wt}) is given by:

I_{Wt} = Ampere-turns / N_W

The total excitation winding voltage (V_w) is:

$V_W \approx V_t \times N_W$

The approximate total apparent excitation power requirement is simply:

VA $\approx V_W \times I_{wt} \approx V_t \times$ Ampere-turns

To achieve 4% of rated voltage requires on the order of 2-15 ampere-turns per meter mean circumference of core.

- The 660 MW generator in Example 1 has an outer core diameter of 3 m and a diameter at the base of the slots of 2.2 m, giving a mean diameter of 2.6 m. The mean circumference is 8.16 m and the ampere-turn requirement will thus be in the range of 16-120 ampere-turns.
- For the 660 MW generator being considered: V_t = 41.2 V and I_W < 80 ampere-turns.
- In this example, requiring V_t = 41.2 V, a six-turn winding powered from a 240 V supply would give almost the recommended 4% value.
  - The I_{Wt} current would be < 80 A-turns/6 turns = 13.3 amps.
  - The total excitation winding voltage will be:
  - $V_W = 41.2 \times 6 = 247.2$ V
  - The total power requirement will be 13.3 amps × 247.2 V = 3.288 kVA
- A 120 V mains supply would require a three-turn winding but the current would be increased to a maximum of 27 amps.

7.5 TESTING OF SQUIRREL CAGE ROTORS

Prepared by the Technical Services Committee

INTRODUCTION

The procedures outlined in this article cover the basic methods and equipment needed for testing squirrel cage rotors. They are organized in two sections: those performed with the rotor removed from the motor, and those performed with the motor fully assembled.

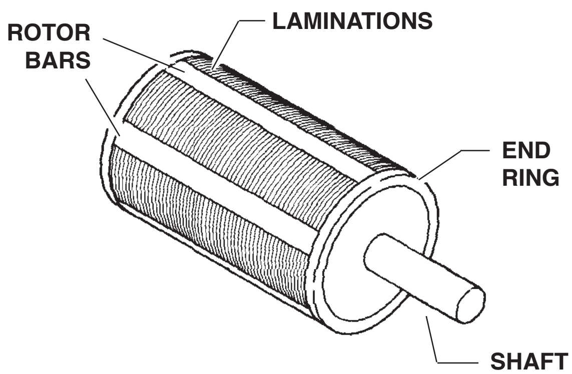
SQUIRREL CAGE ROTOR CONSTRUCTION

Virtually all squirrel cage rotors have copper or aluminum bars and the end rings (see Figure 7-18). Copper (or copper alloy) rotors are usually of fabricated design–i.e., bars and end rings are brazed or welded together when the rotor is assembled. Relatively few copper rotors have cast bars.

By contrast, aluminum rotors are usually die-cast–i.e., bars and end rings are formed in one machine operation. Exceptions include some larger machines (typically above NEMA frame) with fabricated aluminum bars (usually extruded) that are welded to the end rings.

The procedures presented here can be used to detect defects in copper and aluminum squirrel cage rotors of either fabricated or die-cast construction.

FIGURE 7-18



Squirrel cage rotor.

ROTOR INSPECTION AND TESTING–DISASSEMBLED MOTOR

Preparation

Equipment and materials that can be used to test for rotor faults with the motor apart include:

- A growler of the proper size
- Fine iron filings and a sheet of paper
- Ordinary hacksaw blade
- Magnetic imaging material
- Core-loss tester
- Infrared thermometer/camera
- Low-resistance ohmmeter with a micro-ohm scale

After the rotor has been removed from the stator, it should be thoroughly cleaned and carefully inspected.

Inspection

Inspect the rotor carefully, looking for cracked end rings and end rings that have separated from the laminations (indicating broken bars). Current through cracked or broken areas will be reduced due to increased resistance, so be sure to note their locations on the data sheet.

Check for signs that the rotor has become hot enough to melt the alloy that forms the squirrel cage–e.g., particles of melted metal that have run or been slung from the rotor slots. With cast-aluminum rotors, evidence of melted metal may mean that the size of the rotor bars has been reduced, thus reducing their current-carrying capacity. Note all discrepancies on the data card.

Next, closely inspect each rotor bar for signs of localized heating. If the rotor has previously been painted, these will often appear as blackened spots where arcing current has “broken through” the painted finish. These burn marks indicate that there is either a high resistance joint or a break in the rotor cage.

A broken bar sometimes will cause current to arc to adjacent bars and burn through a section of laminations. In severe cases, arcing current may burn through the top of the slot, possibly causing the rotor bar to rub the stator core.

Electrical tests

With the motor disassembled, the following electrical tests can be used to detect broken bars in fabricated rotors or voids in die-cast rotor cages. Follow appropriate electrical safety procedures during these tests. Use a meter, not your hands, to search for hot spots.

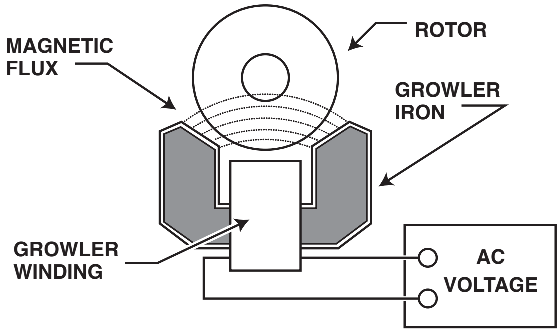
Growler test

A very basic test to find rotor defects can be performed with a growler of the proper size (see Figure 7-19 on Page 7-31). Note that the growler should span at least one-third of the rotor surface and one-third of its length. If it is too large, flux lines will pass above the rotor. If it is too small, too few lines of flux will pass through the rotor. In either case, test results will be erroneous.

Iron filings method–To perform this test, place the rotor on the growler and lay a piece of paper over the area of the rotor that the growler spans. (Note: The paper will keep iron filings from sticking to the rotor during and after the growler test. Putting the filings in a resealable plastic bag will serve the same purpose.)

Now energize the growler and sprinkle iron filings on the paper. As you move the paper from one bar to the next, the filings will align with the magnetic field induced in each good bar by the growler. The filings will not align where there is an open in a rotor bar.

FIGURE 7-19



The growler.

Mark any defective bars for repair or further testing and record their location on the data sheet.

Hacksaw blade method–The growler test can also be performed with an ordinary hacksaw blade instead of paper and iron filings. To do so, energize the growler and place the blade across the bar to be tested. If the blade vibrates, the bar is good. If not, the bar is open.

Magnetic imaging method–Magnetic imaging material can also be used in place of iron filings or a hacksaw blade. Available from some winding material suppliers, this material displays an image of the rotor bars when the power supply is energized. Although the image remains after the power is turned off, the material can be reused since a new image is produced each time power is applied.

Whether you use magnetic imaging material, iron filings or a hacksaw blade, the procedure is the same. Mark the starting point and turn the rotor as necessary to test each bar. Depending upon the size of the rotor and the strength of the growler's magnetic field, it may be necessary to turn off the growler in order to turn the rotor.

Hand-held growler–A hand-held growler can also be used to test for defects in rotors. To do so, place the growler on the rotor so that it spans the bar being tested. Energize the growler and test each bar as described above, using a piece of paper and iron filings, a hacksaw blade, or magnetic imaging material.

Defects due to thermal expansion–Thermal expansion sometimes causes rotor bars to open at operating temperature and close as the rotor cools down. Left undetected, such defects can weaken the motor under load conditions, thereby degrading performance. Consequently, rotors that pass the initial growler test should be warmed to operating temperature and tested again. To warm the rotor, leave it on the energized growler or place it in a baking oven.

High current AC power tests

There are two ways to use high current AC power to detect rotor defects: the iron filings method and the hot spot method. Some core-loss testers have sufficient high current capacity to perform these tests.

Iron filings method–Connect a high current AC power supply to each end of the rotor shaft and apply enough current to induce a magnetic field in the rotor. Lay a piece of paper on top of a rotor bar and sprinkle on iron filings, as described for the growler test. The filings will align with the rotor bar unless there is an open in the bar. Turn the rotor and repeat the procedure until the entire surface of the rotor has been tested.

Note that a hacksaw blade or magnetic imaging material can be used in place of paper and iron filings for this test. Follow the same procedures as for the growler test.

Hot spot method–To locate hot spots on a rotor, connect a lead from a high current AC machine to each end of the rotor shaft and apply power. The rotor should heat up slowly and evenly if it has no open bars or end rings. A weakened bar may result in a hot spot. An open bar will show up as a cool or cold spot. An infrared thermometer or an infrared camera may be used to identify localized temperature variations. (Note: Some infrared devices may be affected by or yield erroneous results if they are placed in a magnetic field.)

Low-resistance ohmmeter test

A low-resistance ohmmeter that uses a four-point measuring technique is useful for checking the continuity of the material in the slots and for detecting cracks in fabricated rotor bars or "blow holes" in the cast material. To perform this test, measure the micro-ohm resistance across each bar, making certain that you are testing both ends of the same bar.

To assure reliable results, take all measurements at equal distances on each bar. Wrapping a strip of masking tape around the circumference of the rotor at each end will form guides for these measurements. The masking tape can also be used to mark defective bars.

To check for a blow hole or crack in an end ring, check the resistance from bar to bar on each end ring. To detect faults that may be related to thermal expansion, repeat the test with the rotor at operating temperature. Heat the rotor as described above.

ROTOR TESTING–ASSEMBLED MOTOR

Preparation

Equipment that can be used to test for rotor faults with the motor assembled includes:

- Variable-voltage power supply
- Clamp-on ammeters
- Voltmeters
- Vibration analyzer

Special devices

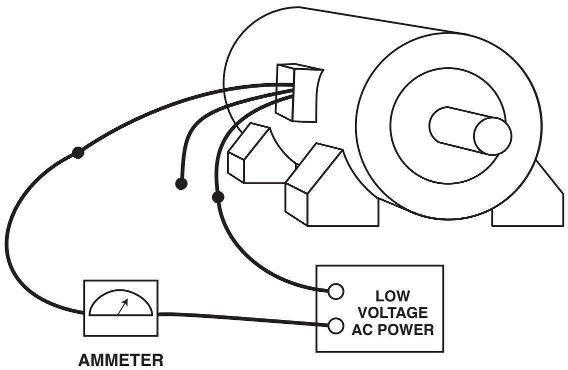
- Fast Fourier Transform/spectrum analyzer
- Current transformer
- Stray flux pickup coil

Static method

Single-phase rotor test–This consists of applying one-fourth of rated AC voltage to two phases of an induction motor while slowly rotating the rotor by hand. A clamp-on ammeter is used to measure any fluctuations in current (see Figure 7-20 on Page 7-32).

A fluctuation in current of more than 3 percent (3 percent maximum for a used rotor and 1 percent maximum for a new rotor) usually indicates a broken bar and will occur each time

FIGURE 7-20



Single-phase rotor test.

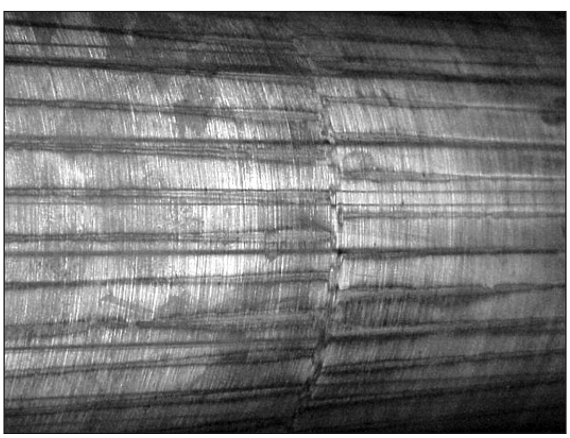
the open bar passes under an energized pole. Fluctuations of less than 1 percent indicate a good rotor.

Equipment required includes an adequate power supply and a clamp-on ammeter. Data consists of visual observation of current fluctuation.

This test is one of the simplest, least expensive and most reliable methods of identifying the integrity of the rotor bars. In addition, this test can often be performed at the job site.

Note: With a double-cage rotor, a defect in one cage may be masked by the other cage. Instead of using a skew, a few manufacturers use an offset which looks like two complete rotor cages joined in the middle (see Figure 7-21). The static single-phase ammeter test may not detect an open in one end of the rotor.

FIGURE 7-21



This rotor has a unique construction in which the bars are straight but offset in the middle of the rotor. This is equivalent to a one-half rotor slot skew.

Dynamic methods

The following techniques can detect faults in a rotor cage while the motor is operating under load.

Vibration analyzer method

A vibration analyzer can identify the vibration frequencies of an operating motor and help determine whether a problem is due to electrical or mechanical causes. The vibration frequency caused by electrical problems, such as an open rotor cage, is generally 2 times line frequency–e.g., 7200 cycles per minute for a 60 hertz supply. Other problems that cause vibrations at 2 times line frequency are: out-of-round rotor; misaligned rotor and stator (unequal air gap); elliptical stator core; and open or shorted stator winding.

To determine if the problem is electrical or mechanical, turn off the motor. If the vibrations stop at the instant the motor is de-energized, the cause is probably electrical. A motor with an open rotor bar commonly will draw higher currents at rated load and run a little slower than its rated rpm. It may also make the pointer on an analog ammeter appear to oscillate at pole pass frequency. This method requires at least half load to detect open rotor bars. Vibrations caused by electrical problems generally increase as the load is increased.

Specialized methods

The following two methods for detecting broken rotor bars and other rotor defects in a motor that is running require special equipment and analytical training.

Stray flux pickup coil–A special circular coil for measuring stray flux can be attached to the exterior of a motor to monitor conditions that alter the electrical characteristics of the motor. The coil is usually mounted concentric with the shaft on the outboard end bracket. The voltage or current from the coil is displayed and analyzed on a spectrum analyzer.

Motor current monitoring system–A motor current monitoring system that detects rotor currents induced into the stator windings works in much the same way as the flux monitor. A current transformer on the motor line provides a current signal that is displayed and analyzed by a spectrum analyzer.

Results from the stray flux pickup coil and the motor current monitor system are analyzed and interpreted in the same manner. The fault frequency components occur as upper and lower sidebands of specific harmonics of the rotor speed. Detecting broken bars consists of measuring changes in the amplitude of one or more of these sidebands and comparing them to the line frequency component.

Note: This article was published as *EASA Tech Note 23* (July 1996). It was reviewed and updated as necessary in October 2020.

7.6 DYNAMOMETER TESTING ELECTRIC MOTORS

By Charles Koffler
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San Leandro, CA

Most of the electrical energy consumed by a motor is delivered at the output shaft as mechanical power. The energy that does not emerge at the output shaft appears as heat or friction and windage losses. This energy loss is said to be consumed by the motor to overcome its internal losses.

In view of the continually rising costs of electric energy, motor users and electric utilities have become extremely interested in the magnitude of these losses. Their interest has been so great in fact that motor testing facilities have become a desirable addition to any active motor service shop.

Before explaining the equipment and procedures that can be used in accurately measuring energy losses and motor efficiency, a few definitions are in order. Motor energy loss, when expressed in terms of motor efficiency, is the ratio of output power to input power. This can be expressed as a percentage, or described by the following equation:

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}} \times 100\%$$

The best way to measure input power is with a wattmeter. Input power can also be calculated using a voltmeter, an ammeter and a power factor meter.

Output power, on the other hand, is more difficult to measure. The motor must be driving a known load if the efficiency is to be determined. In addition, the wide variety of possible motor/load combinations demand that the test loading be variable, so that efficiency can be measured over the entire load range. This requires some type of dynamometer.

Various kinds of dynamometers are available, and for each different type there are several designs. The conventional cradled dynamometer enjoys wide use and is available from many sources, including used equipment dealers. It will be the basis for this discussion.

The basic function of a dynamometer is to measure output power. Power is the product of torque multiplied by speed:

$$\text{Power} = \text{Torque} \times \text{rpm}$$

To make this relationship meaningful, however, the units must be defined.

If:

a. Power is to be in hp or kW;
b. Torque is to be in lb·ft or N·m; and
c. Speed is to be in rpm;

Then:

d. $$\text{hp} = \frac{\text{Torque (lb·ft)} \times \text{rpm}}{5250} \qquad \text{kW} = \frac{\text{Torque (N·m)} \times \text{rpm}}{9550}$$

To determine output power directly, a dynamometer must load a motor while measuring load torque and load speed.

When a device absorbs power, it also absorbs heat. Since this is true of an absorption dynamometer, provisions must be made to cool the unit–or at least the parts that absorb heat.

The absorption dynamometer is a brake cradled in trunnion bearings. Although both elements of this brake can rotate, the motion of one is restricted to just a few degrees by a torque arm connected to a scale or other weighting device. As indicated above, some provision must be made to cool the brake assembly.

Internal bearings support the input (rotatable) member of the braking unit, and the whole unit is mounted in trunnion bearings atop pedestals. The brake assembly must be balanced and capable of moving freely. Its movement must not be restricted by cables or hoses. Only the torque arm should prevent rotation.

Braking action can be achieved in any one of several ways: from friction (low power); from electric generator action; from eddy current drag; or from water wheel drag. The electric and eddy current types are the most accurate and are preferred for motor testing.

Pulse pickups (for speed) and load cells (for torque) provide measurements that can be presented on digital indicators. Besides being convenient to use, digital indicators also increase speed and accuracy when taking data.

A dynamometer is a basic measuring tool. The results obtained cannot be questioned except by data taken from another dynamometer. Because of this, it is impractical to speak in terms of dynamometer accuracy. The machine and its associated instrumentation, however, should be kept in excellent condition and calibrated frequently. Hopefully, accuracy of 1 percent of maximum rating can be achieved on the best units. Tests made below 20 percent of maximum rating give data of doubtful value.

In testing electric motors with a dynamometer, it is customary to take current and voltage readings of input power, as well as wattmeter readings. These readings make it possible to calculate kVA and power factor in addition to efficiency. The electrical metering system usually requires the use of current and potential transformers. Whether or not these are used, the data sheet should be arranged so that the actual meter readings can be entered.

Appropriate multipliers can be applied when calculations are performed. Figure 7-22 (Page 7-34) shows a data sheet with amps multiplied by 6, volts multiplied by 4, and watts multiplied by 0.24.

TEST PROCEDURES

Before a motor is tested, it should be put on the dynamometer and operated at rated load long enough for the temperature to stabilize. Even then, as data is taken at different loadings, it will be necessary to wait until all meters and indicators have settled down before recording the readings.

FIGURE 7-22

XYZ ELECTRIC MOTOR SERVICE
1331 Baur Blvd. • St. Louis, MO 63132

NEMA Eff: 93.0 Guar. 92

HP 20 S.F. 1.15 MFGR ABC Electric Motor Corp. JOB # 184532 DATE 1/3/16
SPEED 1770 RPM MODEL # 12345 CUST. DLG MFG Co
F.L.A. 47.4/23.7 AMP TYPE Energy Save OWNER XYZ
VOLTS 230/460/3/60 S/N 98765 METER: 06 AM X 6
ENCL. TEFC FRAME 256T TEMP 40°C INS B 07 VM X 4
NEMA DES. B CODE HISTORY New 08 WM X 0.24 (KW)

SHEET: 05 133-1

MOTOR TEST DATA

	01	02		03 LINE CURRENT					04 LINE VOLTAGE					05							
		TORQ	MECH	METER READING				AVG	METER READING				AVG	LOAD WATTS				ELECT			TEST METER CART
	RPM	LB-FT	HP	A	B	C	AVG	AMP	A-B	B-C	C-A	AVG	VOLTS	MTR	KW	KVA	P.F. %	HP	EFF %	% LOAD	CURRENT TAP 30 AMP
1	1765	75	25.5	4.58	5.10	4.72	4.80	28.8	118.0	120.0	118.0	118.7	474.8	84.5	20.3	23.7	85.6	27.2	93.9	128	
2	1773	60	20.6	3.62	4.09	3.81	3.84	23.0	118.7	120.5	118.5	119.2	476.8	67.5	16.2	19.0	85.1	21.7	94.8	103	
3	1780	45	15.6	2.78	3.23	2.90	2.97	17.8	119.0	120.5	118.0	119.2	476.8	50.1	12.0	14.7	81.7	16.1	96.7	78	
4	1787	30	10.5	2.01	2.48	2.18	2.22	13.3	119.0	120.5	119.0	119.5	478.0	34.3	8.23	11.0	74.6	11.0	95.5	53	
5	1794	15	5.45	1.42	1.80	1.59	1.60	9.60	118.7	120.5	118.5	119.2	476.8	18.1	4.34	7.93	54.8	5.82	93.6	27	
6	1799	0.8	0.60	1.10	1.33	1.33	1.25	7.5	119.0	121.0	119.0	119.7	478.8	3.0	0.72	6.22	11.6	0.97	62.1	3	
7	1794	15	5.45	1.43	1.76	1.66	1.62	9.72	119.0	121.0	119.0	119.7	478.8	17.9	4.30	8.06	53.3	5.76	94.6	27	
8	1788	30	10.5	2.04	2.42	2.23	2.23	13.4	119.7	121.0	119.0	119.7	478.8	34.3	8.23	11.1	74.2	11.0	95.5	53	
9	1781	45	15.6	2.78	3.21	2.99	12.99	7.9	119.0	121.0	119.0	119.7	478.8	50.3	12.1	14.9	81.1	16.2	96.3	78	
10	1774	60	20.6	3.63	4.1	3.82	3.85	23.1	118.7	120.0	118.0	118.9	475.6	67.5	16.2	19.0	85.1	21.7	94.8	103	
11	1766	75	25.5	4.54	5.01	4.75	4.77	28.6	118.0	119.5	118.0	118.5	474.0	84.8	20.4	23.5	86.6	27.3	93.6	128	
12																					
13																					
14																					
15																					
16																					
17	1799	0.8		3.3	3.9	3.85	3.68	7.36	119	120.3	118.5			9.8	.784	09 DYNO K = 0.95 lb-ft					Motor - Dyno
18														4.2	336	AM x 2 VM x 4 WM x 0 .08					Motor Only

Typical dynamometer motor test data.

During the warm-up period, instrumentation should be checked for proper scale ranges. Line voltage and current balance should be observed. If frequency is doubtful, it too should be verified. Motor nameplate data should be entered on the data sheet if this was not done previously.

Data should be taken at a variety of load points, including points well into the overload range. One possible procedure would be to start at 150 percent of full load, reducing the torque in 25 percent decrements until the dynamometer minimum load is reached. As a check, the readings could then be repeated by taking data at 25 percent increments until 150 percent of full load has been attained.

When the above procedure has been completed, the dynamometer should be reduced to absolutely minimum load, so that nothing but dynamometer windage and bearing friction are affecting the motor's loading. Record data under these conditions. Dynamometer torque and kW input are especially important.

When this information has been recorded, separate the coupling between the motor and the dynamometer and operate the motor alone. Take data on the electrical input, especially kW input. These last two observations will allow you to calculate the Dynamometer Correction Factor (torque which the motor supplied, but which did not register on the dynamometer indicator). This is the windage and friction of the dynamometer rotor.

A list of equipment needed and the formulas used to make the necessary calculations are provided at the conclusion of this article.

The test outlined above generally follows the procedures of IEEE 112 Method B. Although it is not as thorough as the IEEE test, it should yield valid results if performed carefully on good equipment. Curves of efficiency, power factor, horsepower, amperes and rpm can be plotted against torque or percent of load. Figure 7-23 (Page 7-35) shows the efficiency and power factor plotted against percent of load for the data shown in Figure 7-22.

TESTING WITHOUT A DYNAMOMETER

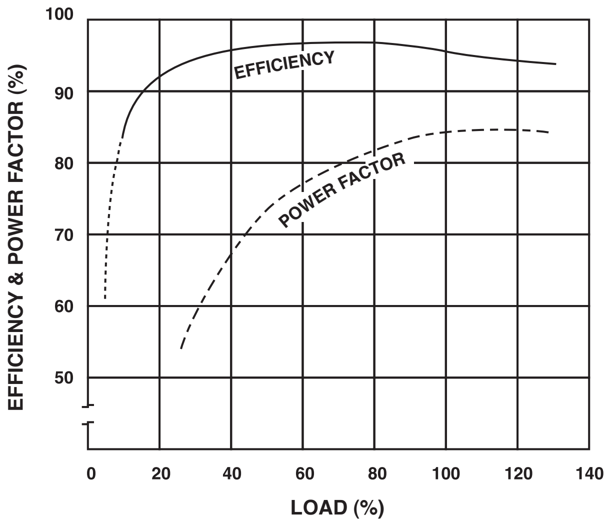
Another approach to motor testing is within the capabilities of some facilities. Attacking the problem from the opposite point of view, this method allows you to determine the efficiency of the motor when it is driving its own particular load. The reasoning behind this approach is as follows:

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}} \times 100\%$$

But:

Power output = Power input - Power lost

FIGURE 7-23



Efficiency and power factor plotted against percent of load for the data shown in Figure 1.

Therefore, *efficiency can be calculated*:

$$\text{Efficiency} = \frac{\text{Power input - Losses}}{\text{Power input}} \times 100\%$$

Since this method does not require measurement of output power, a dynamometer is not required. It is necessary, however, to determine the losses quite accurately, and this is an involved procedure. Those interested should refer to IEEE 112 Method E.

DYNAMOMETER TEST FORMULAS

1. Dynamometer correction $= \dfrac{7.04\,(A - B)}{N} - C$

   Correction in lb·ft

   A = Motor and dynamometer watts

   B = Motor only watts

   N = Motor and dynamometer speed (rpm)

   C = Motor and dynamometer scale reading (lb·ft)

   Add correction to all torque readings.

2. Mechanical hp $= \dfrac{\text{Torque (lb·ft) x Speed (rpm)}}{5250}$

3. kVA = Line volts x Line amps x 1.732/1000 (for 3 phase)

   kVA = Line volts x Line amps/1000 (for 1 phase)

4. Power factor $= \dfrac{kW}{kVA} \times 100\%$

5. Electrical hp $= \dfrac{kW}{0.746}$

6. Efficiency $= \dfrac{\text{Mechanical hp}}{\text{Electrical hp}} \times 100\%$

   $= \dfrac{\text{Watts output}}{\text{Watts input}} \times 100\%$

7. % Load $= \dfrac{\text{Mechanical hp}}{\text{Rated motor hp}} \times 100\%$

EQUIPMENT LIST

1. Absorption dynamometer
   - With balance weights.
   - With scale checking arm and weights.
   - With weighing system (preferably calibrated load cell type with digital readout).
   - With speed measuring system (preferably pulse-counting type with digital readout).
2. Wattmeter, three-phase (or 2 single-phase meters), 0.5% accuracy*, 60 Hz AC.
   - Current coils: 0 - 5 amperes
   - Voltage coils: 120 volts
3. Ammeter, 0 - 5 amperes, 60 Hz, 0.5% accuracy*
4. Voltmeter, 0 - 150 volts, 60 Hz, 0.5% accuracy*
5. Current transformer (2 required)
   - Secondary rating: 5A, 60 Hz
   - Primary rating: should have multiple taps to cover range of motor currents expected.
   - Must be high quality instrument transformers (ordinary doughnut types are not suitable for use with wattmeter or for power factor calculations).
6. Potential transformers (2 required)
   - Secondary rating: 120V, 60 Hz
   - Primary rating: should have multiple taps to cover range of line voltages expected.
   - Should be high quality instrument.

   (Note: All instruments should be calibrated on a regular schedule.)

* Digital instrumentation with much greater accuracy is available. These instruments analyze wave shapes to determine power, etc.

Note: This article was first published as *EASA Tech Note 5* (October 1984). It was reviewed and updated as necessary in October 2020.

7.7 HOW TO SET UP A SLIP-RING MOTOR FOR USE AS A VARIABLE-VOLTAGE REGULATOR

By James J. Anderson (deceased)
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One of the most important pieces of equipment today in an aggressive service center is a means of variable voltage for AC testing. The source should be three phase and have a sizeable amperage rating.

For a service center handling motors in the range of 10 hp and below, the rating should be no less than 20 amperes. From here on in the size of the unit would be according to the size of equipment handled by the service center. The voltage ratings must be 600 volts minimum. (The need for this will be brought out later.)

There are three good means for obtaining a variable AC source. One is variac ganged together for the proper voltage and current requirement. After a 20 amp rating and in voltages above 120 these get very costly unless they can be found on the used market. Even so, they are hard to find above 120 volts.

Another means for an easily adjustable source is a motor-generator set using a regular three-phase alternator, but wound for 600-800 volts. In using a unit like this, the capacity of the motor and generator will run a motor idle equal to about four times the generator's capacity. The voltage adjustment to the alternator field can be done with a rectifier/variac combination. A motor or a transformer can be brought up on test smoothly and easily with this unit.

Another simple means is the use of a slip-ring motor connected and used as an induction voltage regulator. This is one of the best and least expensive ways of getting a variable-voltage source with a large capacity. Slip-ring motors of all capacities are quite plentiful on the used market. A four-pole machine is the best, and only 90 degrees mechanical rotation is used.

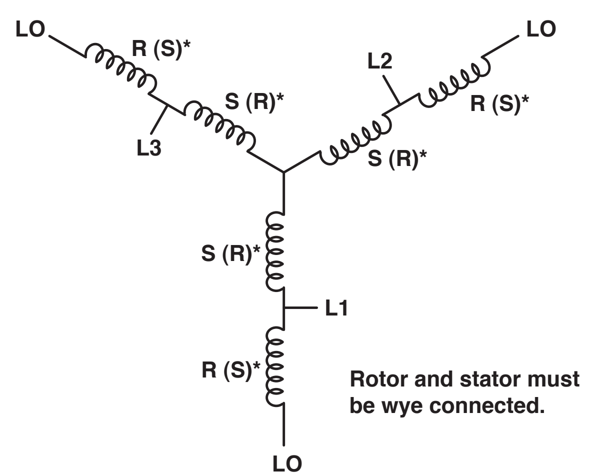
The electrical connection used is shown in Figure 7-24. It is merely a three-phase autotransformer. For best results, the stator-rotor turns ratio should be 1:1. This will give a zero voltage condition in the opposing position, and twice the applied voltage in the additive position.

At this point, refer to Figure 7-25. Position A shows the stator and rotor voltage in phase opposition. Position B shows the rotor moved 45 degrees and the voltage add to produce 41 percent more voltage on the load terminals than the applied voltage. Position C shows the rotor moved 90 degrees to where the stator-rotor voltages add to twice the applied voltage. If the turns ratio is not 1:1, a voltage condition of unequal proportions would exist.

As an example, suppose we had a slip-ring motor with a 220-volt stator and a rotor of 330 volts. If we were to use the stator as the exciting winding and the rotor as the load winding (R), we would find that, when the rotor is in Position A, the line or L_o voltage is 330 minus 220, or 110 volts. This is produced from the rotor. Between Positions A and C we would get various L_o voltages equal to the vector sum (angle of rotation) of 220 and 330 volts. When we reach Position C, we would have L_o voltage equal to the sum of 330 and 220, or 550 volts.

In making a turns ratio of 1:1 with a good slip-ring motor, coils can be cut out of the rotor or the stator to meet the conditions. Even turns can be cut out of coils to get as close to a 1:1 ratio as possible. Either the stator or rotor can be used for the exciting winding. Whichever winding is used for the R or load winding, the phases have to have the six leads brought out for the connection, as shown in Figure 7-24. The leads have to

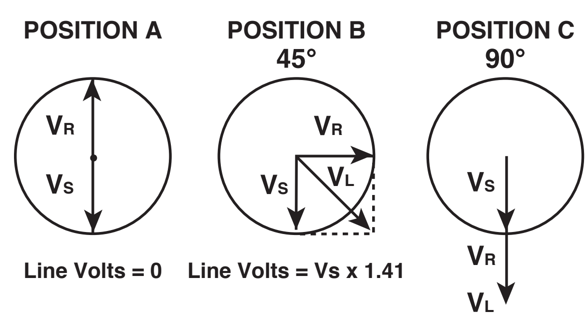
FIGURE 7-24



Autotransformer extended wye.

* Either stator or rotor can be opened. It is often easier to lift the stator connection than the rotor connection.

FIGURE 7-25



Turns: ratio 1:1

Line volts = $V_S + V_R$

4-pole = 90° rotation

be phased out with respect to the exciting winding, but this is just a matter of swapping leads of the R winding until all L_o voltages are equal, and of turning the rotor to reach a zero and maximum condition.

A smooth means of turning the rotor for the various voltages can be had by coupling a gear box directly onto the motor shaft. We have found that using a ratio of 720:1 gives a smooth, slow voltage rise. If the maximum voltage output is 900 volts, then for every degree of rotation there are 10 volts. Consequently, the rotor cannot be turned too fast. The motor has an opposing torque to the gear box, so use a strong one, and no flexible coupling between motor shaft and gear box. The input to the gear box can be driven by a brake motor or handwheel, whichever you prefer. On a 500 hp (375 kW) unit we used a 3 hp (2.25 kW) gearbox of 360:1 ratio and belted that to a variable DC motor with a 2:1 ratio. We used only a 1/2 hp (3/8 kW) motor.

If forced-air cooling is employed, the unit can be used to its full rated amperage capacity. If no cooling is used, it should be derated about 50 percent for continuous duty. For intermittent or 10 minute duty, it could be used to rated capacity or even higher: 200 percent duty is no problem for short time tests.

Note: This article is reprinted from the July 1968 issue of *Electrical Apparatus Service* (now *Electrical Apparatus*).

7.8 TESTING OF SERVO MOTORS

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Note: Specific identification of test equipment in this article is not an endorsement of the products. The intent is to illustrate the scope and potential cost of the equipment needed to perform brushless servo motor repair.

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Generally speaking, the tools and instruments needed to repair and test brushless servo motors fall into one of two groups.

Group 1–those usually found in an electric motor service center.

Group 2–those that may not usually be found in an electric motor service center.

GROUP 1 INSTRUMENTS

The following instruments are normally found in an electric motor service center.

A multimeter, as the name implies, is a multiple-function instrument that is used to measure voltage, current, and resistance. A good quality multimeter is a basic requirement in servo motor testing. It may be either analog or digital but should of dependable quality. The multimeter in Figure 7-26 is an Extech Multimaster 560.

FIGURE 7-26

Multimeter for measuring voltage, current and resistance.

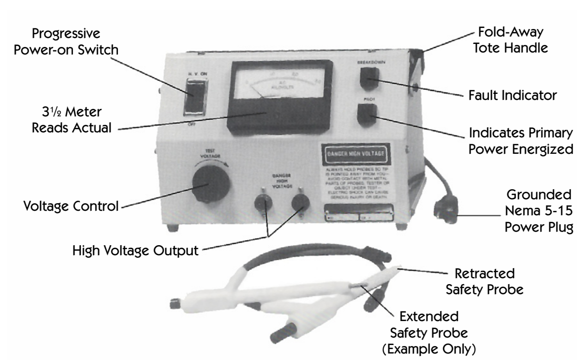
A **megohmmeter** is used to test the quality of the insulation of brushless servo motors in the same way as for testing the insulation systems of other motors. With servo motors, though, it is important not to contact the electronic circuits during the tests. Preferably the instrument should have selectable test voltages, although the test level is typically 500 volts. The unit in Figure 7-27 is an Amprobe AMB-4D with selectable output voltages of 250, 500, and 1000 volts.

The **high-potential tester** or "hipot" is another instrument that most motor repair technicians are already familiar with. It is used in the same way for high-potential testing of servo motor windings as it is for testing standard induction motors. Features of the tester should include the ability to connect to the circuit being tested and then increase the test voltage to the desired test level. It also should test up to twice rated voltage + 1000 VAC, or 3.4 x rated volts + 1700 VDC. Figure 7-28 shows a Slaughter model 306-3.0 AC test unit.

FIGURE 7-27

Megohmmeter for measuring ground insulation resistance.

FIGURE 7-28



High-potential tester for verifying ground insulation strength..

A **surge tester** tests the windings of servo motors in the same manner that it tests windings of standard induction motors. Before surge testing servo motors, ***always remove the permanent magnet rotor from the stator***. Then ground and isolate all circuits not being tested.

Surge testing may detect insulation that has been weakened by contaminants common in machining applications that employ servo motors (e.g., cutting oils, dirt and filings).

FIGURE 7-29

Surge tester to check for winding

It may also identify loose windings that have been damaged by wire vibration. A Baker ST-112E surge tester is shown in Figure 7-29.

A resistance bridge is used for testing the resistance of windings and other low-resistance circuits. Many servo motor manufacturers specify the winding resistance of their units, so this test can indicate if the winding has been changed (e.g., turns, wire size, connection). Resistance measurement of the winding also will detect unbalance that could be due to open or shorted windings. For consistent readings, the temperature of the windings at the time of the test is important. The winding resistance will vary with changes in temperature. A Yokogawa Model 2769 double bridge is pictured in Figure 7-30.

FIGURE 7-30

Low-resistance bridge to measure winding resistance.

GROUP 2 INSTRUMENTS

The following instruments are *not* normally present in an electric motor service center.

Oscilloscopes are used to observe waveforms and timing differences of these waveforms. A good quality oscilloscope with storage and printout capability is one of the most frequently used tools in the testing of servo motors. It should have a minimum of two channels. An oscilloscope with two isolated channels is very useful for testing circuits that do not have a common reference point. The unit pictured in Figure 7-31 is a Fluke 196 digital scopemeter.

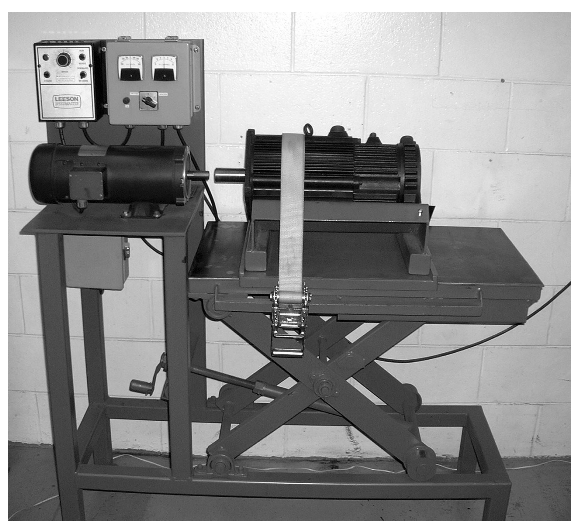
FIGURE 7-31

Oscilloscope for observing waveforms.

A **variable-speed test stand** (Figure 7-32) is necessary for working on brushless servo motors. By back-driving the servo motor at a desired speed, it is possible to verify the commutation alignment, the voltage level of the counter voltage, and the waveform. When driven, the permanent magnet rotors that are used in these motors will turn the motors into AC alternators. The counter-generated voltage will be equivalent to the applied voltage when the motor is running.

The test stand must be mechanically adjustable, in order to align the shaft of the drive motor with the shaft of the servo

FIGURE 7-32



Test stand to back-drive a servo motor.

FIGURE 7-33

Variable regulated voltage supply to power auxiliary devices.

motor. The speed of the drive motor also must be adjustable, and there must be an accurate method of reading the rpm.

Variable regulated voltage supplies are used to power the auxiliary devices during testing, and for such other applications as releasing magnetic brakes. A variable supply is also needed for lockup of the rotor. The unit pictured in Figure 7-33 is a Spence Tek Model 6306A. It has a triple output supply for 5.0 volts and two variable outputs for 0 - 30 volts at 6 amps each.

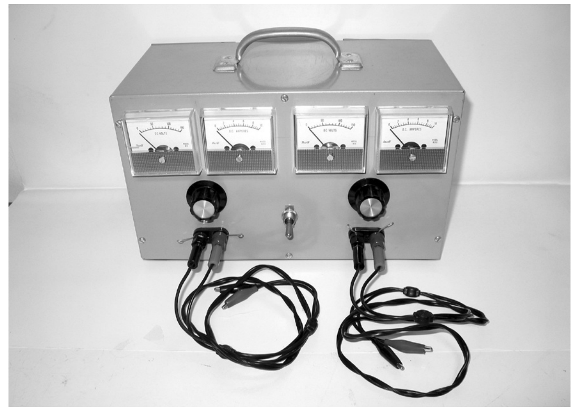
Signal generators are used for testing auxiliary devices like resolvers. To test resolvers, you need the ability to generate a variable-frequency sine wave. A frequency range of 1,000 - 20,000 Hz with an adjustable output voltage of 2 - 10 volts is ideal. The unit pictured in Figure 7-34 is a CSI/Speco Model SS-1.

A shop-built **dual unregulated variable voltage DC power supply** is shown in Figure 7-35. This supply was built

FIGURE 7-34

Variable voltage and frequency sine wave signal generator for resolver testing.

FIGURE 7-35



Unregulated variable voltage DC supply for powering permanent magnet DC motors.

FIGURE 7-36

Pulse count tester for encoder/resolver testing.

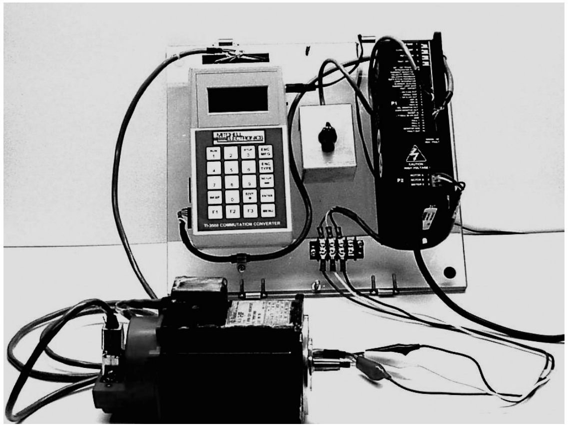
from two 0 - 90 volt DC power supplies that were designed to supply power for permanent magnet DC motors with a 90-volt armature circuit. This makes available a dual DC voltage of 0 - 90 volts at 10 amps.

Encoder/resolver test equipment is used for counting pulses on encoder outputs and for testing the pulse width and the relationships of pulses to each other. Pulse commutation signals are tested and set. Testing of serial encoders requires special decoding equipment to read the signals.

The angular position of a resolver may be determined at 90-degree increments with an oscilloscope. (See “Brushless Servo Motors: How Are They Different?” in Section 2 of this manual.) However, resolver-to-digital interface equipment will allow the angular position to be determined for all positions of the resolver. Figure 7-36 shows a Mitchell Electronics TI- 5000R test unit.

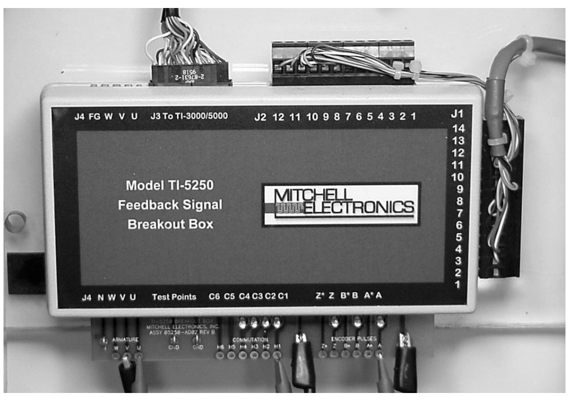
Servo motor drive amplifiers are used for test running motors after repairs have been made. The ability to test run a motor up to operating speed is useful for checking its dynamic operation, including bearings, vibration, noise, rubs, and overall

FIGURE 7-37



Servo drive amplifier for test running motors.

FIGURE 7-38



Signal breakout box for checking feedback and counter-generated voltages.

operating condition. Test units like the Mitchell Electronics TI-3000R (Figure 7-37) convert commutation signals to match a standard amplifier, making it possible to test run many kinds of servo motors.

Signal breakout boxes are used to check various feedback and counter-generated voltages. They provide quick, easy and safe availability to the voltages and feedback signals for oscilloscope test probes. The unit pictured in Figure 7-38 is the Mitchell Electronics TI-5250.

Flux meters are very helpful for measuring and comparing the flux densities of the permanent magnets used in servo motors. Although air-gap flux density is hard to measure due to limited access, it is only needed for motor design and redesign. Rules of thumb are sufficient for other cases. If the magnetic material is ferrite (sometimes called ceramic), the air-gap flux density typically will be 3 - 4 kilogauss. For rare earth magnets, it usually will be 8 - 10 kilogauss. Measurement of torque, BEMF voltage, and waveform will give better information about the magnets. However, the ability to measure the flux balance between poles when a motor is disassembled can sometimes be helpful. The flux meter shown in Figure 7-39 is an F.W. Bell Model 5080 Gauss/Teslameter.

FIGURE 7-39

Flux meter to measure and compare magnetic flux levels.

FIGURE 7-40

Tools like this tachometer and torque wrench that are typically found in service centers can also be used for servo repairs.

The above list of tools and instruments is not all-inclusive. Nor does it cover all of the equipment and facilities that may be needed for servo motor repair. For example, the work area must have electrical power and a compressed air supply. As Figure 7-40 shows, some standard service center tools can also be used for servo motor repair and testing. Other equipment, such as vibration analysis instruments for testing vibration and bearings, may be shared throughout the service center.

Although a dynamometer may be of some value for heat-cycle testing or redesign, it is not required for repairing servo motors. The fact that brushless servo motors develop full torque at stall allows measurement of the stall torque with a torque wrench at zero speed. This test will indicate if the motor falls within the designed torque.

Equipment for re-magnetizing permanent magnets is not a requirement for repairing brushless servo motors, all of which use ferrite, neodymium-iron-boron (Nd-Fe-B), or samarium-cobalt (SmCo) magnets. Unlike the Alnico magnets used in tachometer generators and disc motors, these magnets are not affected by disassembly and removal of the rotor and very rarely require re-magnetization.

Separation of servo motor repair operations from standard motor repair areas is highly recommended. It also is essential to dedicate the required tools, instruments, equipment, and personnel to the task in order to build a successful servo motor repair offering.

Note: This article was first published in *EASA Currents*, March 2006. It was reviewed and updated as necessary in October 2020.

7.9 REFERENCED STANDARDS

The following standards are referenced in this section of the *EASA Technical Manual*.

ANSI/EASA Std. AR100-2020: *Recommended Practice for the Repair of Electrical Apparatus.* EASA, Inc. St. Louis, MO, 2020.

CSA-C392-20: *Testing of Three-Phase Squirrel Cage Induction Motors During Refurbishment*. Canadian Standards Association. Toronto, ON, 2020.

IEEE Std. 4-2013: *Standard for High-Voltage Testing Techniques*. Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2013.

IEEE Std. 43-2013: *Recommended Practice for Testing Insulation Resistance of Electric Machinery*. Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2013.

IEEE Std. 56-2016: *Guide for Insulation Maintenance of Electric Machines*. New York: Institute of Electrical and Electronics Engineers, Inc., 2016.

IEEE Std. 95-2002: *Recommended Practice for Insulation Testing of AC Electric Machinery (2300 V and Above) With High Direct Voltage*. Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2002.

IEEE Std. 112-2017: *Standard Test Procedure for Polyphase Induction Motors and Generators*. Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2017.

IEEE Std. 286-2000: *Recommended Practice for Measurement of Power Factor Tip-Up of Electric Machinery Stator Coil Insulation*. Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2002.

IEEE Std. 522-2004: *Guide for Testing Turn Insulation of Form-Wound Stator Coils for Alternating-Current Electric Machines*. Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2004.

IEEE Std. 1434-2014: *Guide for the Measurement of Partial Discharges in AC Electric Machinery*. Institute of Electrical and Electronics Engineers, Inc. New York, NY, 2014.

ISO Std. 10012-2003: *Measurement management systems–Requirements for measurement processes and measuring equipment*. International Organization for Standardization. Geneva, Switzerland, 2003.

ISO/IEC Std. 17025-2017: *General requirements for the competence of testing and calibration laboratories*. International Organization for Standardization. Geneva, Switzerland, 2017.

NEMA Stds. MG 1-2016 (Rev. 2018): *Motors and Generators*. National Electrical Manufacturers Association. Rosslyn, VA, 2018.

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