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About Electric Machinery Company (EM)

For over 125 years, EM has earned its reputation for designing, manufacturing, and servicing large, custom-engineered electrical motors and generators in the U.S. and worldwide.

**Vision**
Be the global leader for products and services provided through Electric Machinery Company - WEG Group.

**Mission**
Achieve continuous and sustainable growth providing high value products and services to our customers while maintaining simplicity and adhering to our core values.

**Values**

**We Value People**
We encourage integrity, ethics and constant support to personal development.

**We Value Team Work**
We respectfully work together to achieve positive results corporately and personally.

**We Value Efficiency**
We strive to improve daily in all aspects of our personal and professional endeavors.

**We Value Flexibility**
We encourage, anticipate, and embrace change.

**We Value Innovation**
We pursue new technologies and ideas to create solutions.

**We Value Leadership**
We must lead to provide the best customer experience in our industry.

**Quality Policy**
Through the continuous development of our employees and systems, Electric Machinery is committed to providing our Customers superior value and authentic quality, meeting or exceeding their expectations.

---

[Certificate of Approval Image]
EM History

WEG EM has earned its reputation for designing, manufacturing, and servicing large, custom-engineered electrical motors and generators in the U.S. and worldwide by developing:

- First high-starting-torque synchronous motor
- First automatic starting system for synchronous motors
- First 2-pole induction motor design to operate below its first critical speed
- First solid-state brushless excitation system
- Pioneered the Duraguard™ insulation system in the early '70s

Today, EM’s Duraguard™ process, using epoxy resin tape and vacuum pressure impregnation (VPI), is recognized as the benchmark of the industry.

1891    EM founded as a service shop
1897    EM began manufacturing direct current motors & generators
1921    EM develops its first synchronous motor and following year its first induction motor
1944    Worthington Machinery Corporation purchased EM for manufacturing 2-pole generators
1967    EM builds new turbo generator factory in St. Cloud, MN
1977    Turbo generator factory in St. Cloud sold to Brown Boveri Corp.
1979    McGraw-Edison Company acquired Worthington Corp.
1983    EM aligned as part of the Turbodyne Division of McGraw Edison Company
1984    Turbodyne Division was acquired by Dresser Industries, Inc.
1987    Dresser Industries & Ingersoll-Rand merge compressor businesses forming Dresser-Rand Co.
1997    EM becomes a separate motor and generator division of Dresser-Rand
1999    Ideal Electric Holding Co. purchased EM from Dresser-Rand
2007    Ideal sells EM to Converteam Group
2011    Converteam Group was acquired by GE
2011    WEG Group purchases EM from GE, becoming WEG's first manufacturing facility in North America
WEG Overview

PLANTS AND BRANCHES

GLOBAL PRESENCE

Argentina
Chile
Colombia
Venezuela
Peru

Mexico
USA
Portugal
Italy
Spain

France
Austria
UK
Germany
Belgium

Netherlands
Sweden
UAE
Russia
India

China
Singapore
Japan
Australia
South Africa

(*) Jaraguá do Sul (SC); Guaramirim (SC); Blumenau (SC); Itajaí (SC);
Joaçaba (SC); São José (SC); Gravataí (RS); São Bernardo do Campo (SP);
Mauá (SP); Monte Alto (SP); Linhares (ES); Manaus (AM).

Factory
Comercial Branch

Brazil(*)
Argentina
USA
Germany
Spain
China

Colombia
Mexico
Austria
Portugal
India
South Africa
WEG Global Presence

WEG AROUND THE WORLD
NUMBER OF EMPLOYEES

Total:
29,194 Employees

Total Overseas
8,933 Employees

30% Overseas
Data from 12/31/2016

North America
3,041

South America
727

Brazil
20,261

Europe and Middle East
1,251

Africa
644

Australasia
3,270
EM Products

EM products provide customers a superior value in terms of quality, proven reliability, low maintenance performance and long life in critical services.

**Synchronous Motors**
- Brushless excitation
- High efficiency ratings
- Low inrush currents
- Plant power factor correction
- Constant speed with varying load
- Ease of alignment (larger air gap)

**Induction Motors**
- Simple & rugged design
- Low cost
- Higher starting torque capability
- Minimal maintenance

**Turbo Generators**
- Brushless excitation
- Low vibration levels
- Flexibility of application

**Excitation and Controls**
- Custom excitation systems developed to fit in existing machine footprint
- Digital systems maintain power factor, offer redundancy, and data-logging
- Combined excitation and protective systems integrated into one package
- Full factory acceptance testing at our rotating equipment lab in Minnesota

**Engineered Solutions and Training**
- Engineered rotor removal and inspection tools designed to reduce outage duration and minimize risk
- Increase starting torque or overall rating of synchronous motors
- Improve net efficiency and electrical stability with digital power factor control
- Protective relay settings reports to ensure your equipment is correctly protected
- Perform a spare parts inventory to ensure maximum overlap of spares and reduce overhead
- On-site synchronous motor training

EM products provide customers a superior value in terms of quality, proven reliability, low maintenance performance and long life in critical services.
## Product Range

<table>
<thead>
<tr>
<th></th>
<th>Induction Motor</th>
<th>ST20 Turbogenerator Line</th>
<th>Synchronous Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output Range:</strong></td>
<td>1,000 - 25,000 HP</td>
<td>6,000 - 200,000 kVA</td>
<td>400 - 150,000 HP</td>
</tr>
<tr>
<td><strong>Speed:</strong></td>
<td>200 - 3,600 RPM</td>
<td>3,000 - 3,600 RPM</td>
<td>150 - 3,600 RPM</td>
</tr>
<tr>
<td><strong>Frequency:</strong></td>
<td>50 Hz / 60 Hz</td>
<td>50 Hz / 60 Hz</td>
<td>50 Hz / 60 Hz</td>
</tr>
<tr>
<td><strong>Voltages:</strong></td>
<td>2,300 - 14,400 V</td>
<td>4,160 - 14,400 V</td>
<td>2,300 - 14,400 V</td>
</tr>
<tr>
<td><strong>Construction:</strong></td>
<td>Horizontal &amp; Vertical*</td>
<td>Horizontal</td>
<td>Horizontal &amp; Vertical</td>
</tr>
<tr>
<td><strong>Excitation:</strong></td>
<td>N/A</td>
<td>Brushless Excitation, Static with Collector Rings</td>
<td>Brushless Excitation, Static with Collector Rings</td>
</tr>
<tr>
<td><strong>Standards:</strong></td>
<td>NEMA, IEEE, IEC, API 541, ISO 9001</td>
<td>NEMA, ANSI, IEEE, IEC, API 546, ISO 9001</td>
<td>NEMA, IEEE, IEC, API 546, ISO 9001</td>
</tr>
<tr>
<td><strong>Enclosures:</strong></td>
<td>DP, DPG, WPI, WPII, PMDP™, TEWAC, TEAAC, TEFV</td>
<td>Room Air Cooled, TEWAC, TEAAC</td>
<td>DP, DPG, WPI, WPII, PMDP™, TEWAC, TEAAC, TEFV</td>
</tr>
<tr>
<td><strong>Applications:</strong></td>
<td>Pumps, Centrifugal Compressors, Extruders, Fans, Mixers</td>
<td>Steam and Gas Turbines</td>
<td>Steam and Gas Turbines</td>
</tr>
<tr>
<td><strong>Special Notes:</strong></td>
<td>True Stiff-Shaft 2 Pole Design, Options of Semi-Stiff or Flexible Shaft</td>
<td>Continuous or Peaking Duty</td>
<td>Industry Leading Synchronization System</td>
</tr>
</tbody>
</table>

*Vertical = Limited HP for 2 Poles

Special ratings not found above are available upon request as Electric Machinery can design and manufacture to your exact specifications.

### Nuclear Safety Related Equipment:
- Motors and generators built and tested for Class 1E safety related applications.
- Quality assurance program meeting requirements of ASME NQA-1

### After Sales Support and Service:
- Installation, commissioning and start-up
- Field Service engineers available 24/7
- Repair services and original parts available
Sync-Rite™ History

1963

1977

1988

1997

2015

EM Sync-Rite™ Controller
Industry-leading control module for synchronous machines
- Developed and patented by EM in the early '60s
- Technology quickly duplicated by all major synchronous motor and controls manufacturers

Microprocessor-based Sync-Rite™
Modern upgrade of industry standard
- Increased robustness
- Need for speed potentiometer eliminated

Sync-Rite™ Plus
Next-generation industry standard controls
- Built upon the reliable Sync-Rite™ technology developed by EM
- Data logging and wireless data transmission added in an integrated design
- Designed specifically to interface directly with users and plant monitoring systems
- Monitoring features increase reliability and reduce downtime

Sync-Rite Plus™ Controller
Industry leading synchronous motor starting control, now with the added benefits of data logging and wireless streaming technology.
- Reliably synchronizes any brushless synchronous motor
- Interchangeable with all legacy Sync-Rite™ models
- Monitors and records: field voltage, field current, FDR status (in or out of circuit), and firing of SCR-1
- Customizable control settings allow controller to be optimized for various motors and loads
- Slip sync speeds from 90% to 99.5%
- Zero slip sync times from 2 to 5.5 seconds
- Wireless transceiver for streaming data and downloading data records without shutting the machine down
- USB port allows data to be gathered when the machine is not running
- Starting records provide an invaluable tool for solving synchronization issues should they occur
- Average records track changes in the operating conditions of the machine to identify issues early, allowing users to take corrective actions before issues become serious
- Original Sync-Rite™ Control’s green and red indicators and a new blue indicator that gives positive Sync-Rite Plus™ Filter confirmation that the motor has been synchronized

Typical Synchronization Waveforms
Sync-Rite Plus™ System

Advanced monitoring allows integration of motor controls and plant systems. Integrated system includes the Sync-Rite Plus™ controller, Sync-Rite Plus™ Display Panel and Sync-Graph software.

Sync-Rite Plus™ Display Panel

A convenient device for monitoring and downloading data wirelessly from the Sync-Rite Plus™

- Convenient and continuous display of field current, voltage, and temperature
- Displays easy to understand operating mode messages along with warning messages
- Real-time indicators that replicate the LEDs on the Sync-Rite Plus™
- Customizable warning indicator, which can be configured by the user
- Proprietary algorithm for detecting open diodes, shorted diodes, or exciter phase-to-phase shorts
Sync-Graph Software
A powerful software tool for monitoring and downloading data from the Sync-Rite Plus™

- Sync-Graph makes it easy to visualize starting and average records via graphs
- Track changes in load conditions
- View conditions that may be preventing synchronization
- View changes in field voltage and current over time
- Track changes in the estimated field temperature
- The streaming and graphing capabilities of Sync-Graph can eliminate the need for additional data acquisition equipment
- Monitor a motor’s field voltage, current, and estimated temperature along with displaying the Sync-Rite Plus™ settings

System Integration
The Sync-Rite Plus™ Display Panel provides flexible output options for interfacing with user equipment and data acquisition systems.

- Three double throw relays that can be configured to energize based on warnings, synchronization, or wireless connection state
- Digital outputs (5V logic) that correspond to relays
- Three 0 to 5V or 1 to 5V (user selectable range) output voltages corresponding to the motor’s field voltage, field current, and estimated field temperature
- Three 0 to 20mA or 4 to 20mA (user selectable range) output currents corresponding to the motor’s field voltage, field current, and estimated field temperature
Recommended Electrical Testing

A complete set of electrical tests on a synchronous motor typically requires only 2-4 hours of downtime and provides an accurate benchmark of both the condition of the windings, and any deviation from previous results. Recording these tests quarterly or annually provides the end-user with an excellent baseline as to the condition of the motor. IEEE-43 details the insulation resistance tests and should be used as a guide for all insulation resistance testing of synchronous motors. IEEE-43 also provides a useful interpretation tool to the results of the Polarity Index test, and this is featured in the Polarity Index Interpretation figure. A contaminated winding will typically display an insulation resistance which fails to increase over the duration of the test, and this may be compared to previous results to plan for a stator cleaning or major overhaul.[1]

In addition to the insulation resistance tests, the continuity of each circuit of a synchronous motor should be tested and recorded to quantify any change from previous results, and a pole-drop test should be performed on motors whose windings have been in operation for longer than 20 years. The Typical Electrical Testing Results table features the four common components of a synchronous motor, and typical values associated with the electrical testing of each. There are instances where deviations from the list will occur, and the end-user must always consult with the OEM manual to ensure the results align with expected values. Deviations from the list below demand further investigation to prevent damage to windings.

AC insulation resistance testing of stator windings may provide additional insight into the strength of the insulation. The voltage of an AC insulation test must not exceed the nameplate voltage of the motor, and protective measures must be in place to prevent excessive voltage excursions. The use of surge testing also applies a substantial AC voltage onto stator coils and because of the transformer effect, may apply a destructive voltage to the rotor coils. It is therefore critical to short the rotor leads of a synchronous motor during any AC test on the stator to prevent rotor damage. These tests should only be carried out by highly-qualified electricians under the supervision of OEM or plant engineers.


Typical Electrical Testing Results

<table>
<thead>
<tr>
<th>Component</th>
<th>Typical DC Test Voltage</th>
<th>Acceptable Insulation Resistance Results</th>
<th>Typical Resistance of Circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Stator</td>
<td>2 x Line Voltage + 1 (kV)</td>
<td>&gt;200MΩ (Desirable) &gt;2MΩ (Minimum)</td>
<td>Less than 1Ω per phase</td>
</tr>
<tr>
<td>Main Rotor</td>
<td>500V</td>
<td>&gt;200MΩ (Desirable) &gt;2MΩ (Minimum)</td>
<td>Between 1Ω and 5Ω</td>
</tr>
<tr>
<td>Exciter Rotor</td>
<td>500V</td>
<td>&gt;200MΩ (Desirable) &gt;2MΩ (Minimum)</td>
<td>Less than 1Ω per phase</td>
</tr>
<tr>
<td>Exciter Stator</td>
<td>500V</td>
<td>&gt;200MΩ (Desirable) &gt;2MΩ (Minimum)</td>
<td>Between 1Ω and 5Ω</td>
</tr>
</tbody>
</table>
Condition Monitoring of Salient Rotor Poles

Static Testing - Pole Drop
Salient rotor poles are typically connected in a simple series circuit which may be represented as shown in the figure below. The resistance of each rotor pole is proportional to the resistance of the wire and the number of turns and is therefore approximately identical among poles at the time of manufacture.

\[ R_1 \cdot R_2 \cdots \cdot R_n \]

Constant voltage alternating current is used for the pole drop test as it tends to expose weak shorts between adjacent turns, and typically 120VAC single-phase power is connected as this voltage is readily-available and similar in magnitude to the nominal operating rotor voltage.

To complete a pole drop test, voltage is applied to the main rotor leads with all auxiliary devices such as collector rings, brushless exciters and field connections removed, and the voltage drop across each pole is measured directly. For a rotor with “n” poles and an applied voltage of \( V_{\text{Test}} \), the expected voltage drop across any pole would be given by the formula:

\[
V_{\text{Pole}} = \frac{V_{\text{Test}}}{n_{\text{Poles}}}
\]

For larger motors which may operate at high nominal rotor current, it is common to design the rotor with two or more parallel circuits. In this case, the voltage drop across a given pole is increased by an amount proportional to the number of circuits. The equation below provides the expected voltage drop for a rotor with “m” parallel circuits:

\[
V_{\text{Pole}} = \frac{V_{\text{Test}}}{\left( \frac{n_{\text{Poles}}}{m_{\text{Circuits}}} \right)}
\]

To calculate the deviation of each pole from the average, use the formula below:

\[
\% \text{Deviation} = \frac{V_{\text{Pole}} - V_{\text{Average}}}{V_{\text{Average}}} \times 100
\]

Deviation of more than 10% is a strong-indication that shorted poles are present, and the shorted poles will typically appear as a positive deviation when plotted. In the figure below, the 4 poles with positive deviations were all found to have significant shorts.

Example:
- 3 Parallel Circuit Winding
- 120 Volts AC Applied
- 24 Poles

\[
V_{\text{Pole}} = \frac{120 \text{ Volts}}{\left( \frac{24 \text{ Poles}}{3} \right)} \times 15 \text{ Volts / Pole}
\]

Pole Drop Results - % Deviation
Recommended Torque

“The torque values can only be achieved if nut (or tapped hole) has a proof load greater than or equal to the bolt’s minimum ultimate tensile strength.”

Once the final alignment step is complete, all critical fasteners must be tightened to the values recommended in the OEM installation manual. Critical fasteners include the main hold-down bolts, bearing hold-down and bracket bolts, and any fasteners on the rotor. These fasteners must be correctly preloaded during normal operation and will react the extreme loads applied during off-design events such as short-circuit or fault conditions. The use of lubricant on the threads of any fastener will have a significant impact on the torque required to achieve the desired preload in the fastener. The application of lubricant, whether oil or anti-seize compound must be confirmed with the OEM manual to ensure excessive torque is not applied.

A common mistake in motor installation is to apply SAE Grade 5 or 8 torque values based on the pattern marked on the bolt heads. Synchronous motor frames and soleplates are typically machined from ASTM A36 or similar commercial-grade steel. This steel has a yield strength of 36,000 PSI compared to 74,000 PSI and 120,000 PSI yield strength for SAE Grade 5 and 8 fasteners respectively. Applying SAE Grade 8 torque to a fastener which is threaded into ASTM A36 steel, especially when the fastener is lubricated is likely to damage the female threads and will not provide additional clamping force.

After applying the correct torque using a calibrated tool, the fasteners must marked as shown in Critical Fastener Marking figure. Marking fasteners with a line that extends from the head of the fastener to the mating surface allows any operator or technician to visually confirm the fastener has not vibrated loose, and provides an indication that the final torque has been applied.

Torque Rules

- Apply “Grade” Torque on Thru Bolts
- Apply ASTM A307 Torque Per Table For Tapped Holes In Plate Steel Or Motor Frames
- Apply ASTM A307 Torque To Lead Connections With Silicon-Bronze Fasteners

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Yield Stress (psi)</th>
<th>Ultimate Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 5 Bolt</td>
<td>SAE J429 Grade 5</td>
<td>92,000</td>
<td>120,000</td>
</tr>
<tr>
<td>Grade 8 Bolt</td>
<td>SAE J429 Grade 8</td>
<td>130,000</td>
<td>150,000</td>
</tr>
<tr>
<td>Silicon Bronze Bolt</td>
<td>UNS65500 H06</td>
<td>60,000</td>
<td>108,000</td>
</tr>
<tr>
<td>Welded Frame or Soleplate</td>
<td>ASTM A36</td>
<td>36,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Cast Motor Frame</td>
<td>ASTM A48 No 30B</td>
<td>N/A</td>
<td>30,000</td>
</tr>
</tbody>
</table>
Recommended Torque Table - Courtesy Fastenal

For large fasteners, a torque multiplier and calibrated torque wrench will give the most-accurate results.

Torque-Tension Relationship for A307A, Grade 5 and 8 Bolts

<table>
<thead>
<tr>
<th>Nominal Dia. (in.)</th>
<th>threads per inch</th>
<th>Tensile Stress Area (sq. in.)</th>
<th>ASTM A307 Grade A</th>
<th>SAE J429 Grade 5</th>
<th>SAE J429 Grade 8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tightening Torque (Lbs.)</td>
<td>Clamp Load (Lbs.)</td>
<td>Tightening Torque (Lbs.)</td>
<td>Clamp Load (Lbs.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K = 0.15</td>
<td>K = 0.17</td>
<td>K = 0.20</td>
<td>K = 0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2319</td>
<td>157</td>
<td>116</td>
<td>2864</td>
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<td>87</td>
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<td>209</td>
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<td>122</td>
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<tr>
<td>1/4</td>
<td>20</td>
<td>0.0318</td>
<td>859</td>
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<td>1441</td>
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<tr>
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<td>16</td>
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<td>416</td>
<td>546</td>
<td>949</td>
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<tr>
<td>3/8</td>
<td>16</td>
<td>0.0775</td>
<td>2092</td>
<td>3342</td>
<td>5024</td>
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<tr>
<td>7/16</td>
<td>14</td>
<td>0.1063</td>
<td>2807</td>
<td>4940</td>
<td>6974</td>
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<tr>
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<td>3831</td>
<td>9046</td>
<td>12771</td>
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<td>11</td>
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<td>6102</td>
<td>14408</td>
<td>20340</td>
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<tr>
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<td>0.3345</td>
<td>9030</td>
<td>21322</td>
<td>30101</td>
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<tr>
<td>7/8</td>
<td>9</td>
<td>0.4617</td>
<td>12467</td>
<td>29436</td>
<td>41556</td>
</tr>
<tr>
<td>7/16</td>
<td>8</td>
<td>0.6057</td>
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<tr>
<td>1</td>
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<td>26166</td>
<td>53786</td>
<td>87220</td>
</tr>
<tr>
<td>1 1/4</td>
<td>6</td>
<td>1.0533</td>
<td>37942</td>
<td>77991</td>
<td>126473</td>
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<td>1 1/2</td>
<td>5</td>
<td>1.4053</td>
<td>711</td>
<td>1462</td>
<td>2371</td>
</tr>
</tbody>
</table>

Clamp load calculated as 75% of the proof load when specified by the standard. ASTM A307 utilized 75% of 36,000 PSI. Torque values for 1/4 and 5/16-in series are in inch-pounds. All other torque values are in foot-pounds.

Dangerous values are in red. Clamp load calculated as 75% of the proof load when specified by the standard. ASTM A307 utilized 75% of 36,000 PSI. Torque values for 1/4 and 5/16-in series are in inch-pounds. All other torque values are in foot-pounds.

The torque values can only be achieved if nut (or tapped hole) has a proof load greater than or equal to the bolt’s minimum ultimate tensile strength.

Clamp load calculated as 75% of the proof load when specified by the standard. ASTM A307 utilized 75% of 36,000 PSI. Torque values for 1/4 and 5/16-in series are in inch-pounds. All other torque values are in foot-pounds.

For large fasteners, a torque multiplier and calibrated torque wrench will give the most-accurate results.

Caution: All material included in this chart is advisory only, and its use by anyone is voluntary. In developing this information, Fastenal has made a determined effort to present its contents accurately. Extreme caution should be used when using a formula for torque/tension relationships. Torque is only an indirect indication of tension. Under/over tightening of fasteners can result.
Collector Rings

All synchronous motors need a source of direct current for their field winding. One way to get the power to the field winding is through brushes and collector rings.

**Collector Ring - Tests**

**Brush Holder Gap**
- Must be 3/16 (0.1875-inches)

**Brush Wear**
- Must be >50% brush length remaining
- No chipping or chattering

**Collector Rings**
- Run-out < 0.002-inches for high-speed motors
- Run-out < 0.010-inches for low-speed motors
- Surface finish < 50 micro-inches

**Electrical Tests**
- Insulation resistance >2MΩ from ring to ground and ring to ring

<table>
<thead>
<tr>
<th>Test</th>
<th>Success Criteria</th>
<th>If Test Fails</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush Holder Gap</td>
<td>0.188 +/- 0.05 inches</td>
<td>Adjust Brush Holders or Mounting Stud</td>
</tr>
<tr>
<td>Brush Length</td>
<td>&gt; 50% Original</td>
<td>Replace Brushes</td>
</tr>
<tr>
<td>Brush Condition</td>
<td>No Chipping or Chattering</td>
<td>Replace Brush and Springs</td>
</tr>
<tr>
<td>Collector Ring Surface Finish</td>
<td>&lt; 50 µ-in</td>
<td>Hone or Grind Rings</td>
</tr>
<tr>
<td>Collector Ring Runout</td>
<td>&lt; 0.003-inches</td>
<td>Re-Align Rings on Shaft</td>
</tr>
<tr>
<td>Spark Gap</td>
<td>0.07 +/- 0.01 inches</td>
<td>Adjust or Replace Studs</td>
</tr>
<tr>
<td>Insulation Resistance</td>
<td>&gt; 2MΩ</td>
<td>Clean All Insulators and Varnish Assembly</td>
</tr>
</tbody>
</table>

**Collector Ring - Maintenance**
- Replace main field leads – as needed
- Replace springs – as needed
- Replace brushes – as needed
- Replace insulating washers and bushings – as needed
- Clean assembly with non-residue cleaner
- Varnish collector ring assembly
- Prepare brushes with sandpaper
Brushless Excitation

- Exciter (generator) takes DC power as input and rotation causes 3-phase AC current to flow in rotor
- Rotor passes current through diode bridge
- DC current is output from diode wheel to rotor
- Changing DC input to exciter changes the strength of the North/South poles in the rotor
Brushless Excitation

- The three forward and three reverse diodes "rectify" the 3-phase AC current induced in the exciter rotor
- The Sync-Rite Plus™ gates SCR-1 to apply voltage to the main field
- The Sync-Rite Plus™ Filter gates on SCR-2 during starting to protect the main field

Note:
Red LED on Sync-Rite Plus™ = resistors in circuit
Green LED Flashing on Sync Rite Plus™ = SCR-1 attempting to fire
Blue LED on Sync Rite Plus™ = synchronized
Vee Curve

- As one increases excitation, the stator current will change
- An increase in stator current due to an increase in excitation ensures the motor is leading
- If the stator current falls as one increases excitation, continue increasing until the current begins to increase
- The lowest stator current value at a given load will be the Unity or Power Factor = 1 point
Thermal Limit Curve

Electric Machinery offers protective relay reports to ensure the correct settings are applied.

- Ensure the overload protection is below the rotor and stator damage curves, but well-above the expected operating curves.

**Graph Legend**

- Stator Limit
- Rotor Limit (Cold Start)
- Rotor Limit (Hot Start)
- Overload Protection Curve 1

**Thermal Limit Graph**

Typical Thermal Limit Curve for a Synchronous Motor
Definitions and Formulas

Direct Current (dc)
Direct current (dc) and voltage are substantially uniform in value and do not reverse in direction. Voltage across a battery or thermocouple is true dc. The output of a commutator-type generator is slightly pulsating due to commutator ripple. Both uniform and pulsating direct current, or voltage, are shown in the figure below.

Alternating Current (ac)
Alternating current (ac) and voltage alternate regularly in value and direction as illustrated in below. One alternation is one-half cycle or 180 electrical degrees.

Frequency
Frequency is expressed in Hertz (Hz). One Hertz is one cycle per second, and each cycle is 360 electrical degrees. Although 25 and 50 Hz have been fairly common in power work, they are rapidly being supplanted by 60 Hz. 180 and 360 Hz are common for high frequency hand tools; motors on aircraft are commonly 400 Hz.

Synchronous Speed
Synchronous speed = \( \frac{60 \times \text{Hz}}{\text{number of pairs of poles}} \)

Thus for 4 poles (2 pairs) and 60 Hz:

\[
\text{Synchronous speed} = \frac{60 \times 60}{2} = 1800 \text{ rpm}
\]

Voltage (E)
Voltage (E): A volt is the unit of electrical pressure, or difference in potential; it is analogous to a pound-per-square-inch, hydraulically.

For dc, the maximum and effective voltage are the same. For ac (with a true sine wave) the following relationship exists:

\[
\text{RMS (Root Mean Square) volts} = 0.707 \times \text{Maximum volts}
\]

The RMS value is important because it is also the “effective” value as measured by a common ac voltmeter. It is proportional to the electrical force delivered to a circuit. Unless otherwise specified, voltage values are always effective values. In numerical equations expressing power where it is combined with current (I), the symbol E is used to express volts. In general terms in expressing capacity, when combined with amperes (A), the symbol V is used. Examples following will illustrate this.

Current (I)
Current (I): The ampere is the rate of flow of current; it is analogous to a gpm hydraulically. As measured by a common ac ammeter (and in common usage) current values are expressed in effective amperes.

Resistance (R)
Resistance (R): Resistance is the hindrance to steady flow of dc in a circuit. Resistance is expressed in ohms. The fundamental expression of Ohm’s Law is:

\[
I = \frac{E}{R}
\]

Where:
- I = Current in amperes
- E = Voltage in volts
- R = Resistance in ohms

Reactance (X)
Reactance (x): The principal hindrance to flow of ac is usually the reactance in a circuit. As explained below, reactance may be either inductive or capacitive and is expressed in ohms.

Inductance (L)
Inductance (L); Inductive Reactance (X_L): Any electromagnetic device has what is equivalent to magnetic inertia. This inertia creates a delay to the change of current flow, and is apparent on a change in voltage value.
In an ac circuit the instantaneous voltage value is always changing and the inductive reactance (magnetic inertia) causes the resultant current change to lag behind the voltage change. This characteristic is known as inductance, is expressed by the symbol L, and is measured in Henries.

When inductance is present in an ac circuit with sine wave voltage impressed at a fixed frequency, the result is an inductive reactance expressed as follows:

\[ \text{Ohms } XL \text{ (Inductive Reactance)} = 2\pi f L \]

If a circuit is 100% inductive (zero resistance), the current values will lag the corresponding voltage values by 90 electrical degrees.

**Capacitance (C)**

Capacitance Reactance (Xc): Capacitance (C); Capacitance Reactance (Xc): If voltage is applied to two conductors separated by an insulator, electrons will flow into the insulator and it will build up an electrical charge. If an alternating voltage is applied, electrons will flow into and out of the insulator as it charges and discharges with changes in value and direction of the applied voltage.

In such circuits the charge becomes a maximum but the current approaches zero as the voltage approaches a maximum. As the voltage, continuing its cycle, drops to zero the discharging current increases to a maximum. Thus the change in current precedes the corresponding change in voltage by 90 electrical degrees. This characteristic of being able to take an electrical charge is known as capacitance, and is expressed in Farads (F). Capacitive reactance (Xc) is expressed in ohms and for a sine wave at a fixed frequency is determined by the formula:

\[ \text{Ohms } Xc \text{ (Capacitive Reactance)} = \frac{1}{2\pi f C} \]

**Impedance (Z)**

Impedance (Z): No circuit will be 100% resistance, reactance, or capacitance, but will be some combination of these. Usually, one component will be of such magnitude compared to the other two that it will be the only one considered.

In a fixed frequency circuit, having sine wave characteristics, the total hindrance to current flow will be the impedance (Z) expressed as follows:

\[ Z(\text{OHMS}) = \sqrt{R^2 + (X_L - X_C)^2} \]

Where \(X_L\) exceeds \(X_C\), the current will lag behind the voltage. Where \(X_C\) exceeds \(X_L\), the current will lead the voltage. The tangent of the angle \(\theta\) of lag (or lead), will be:

\[ \tan \theta = \frac{X_L - X_C}{R} \]

In many ac power circuits the inductive reactance, \(X_L\), is so large compared to \(R\) or to \(X_C\) that for practical purposes it may be considered the total impedance.

**Power Factor (PF)**

Power Factor (PF): In dc circuits power is the product of volts and amperes, thus:

\[ W \text{ (Watts)} = E \times I \]

However, in ac power circuits some periods of time in each cycle may have voltage and current of opposing sign (positive or negative) and their product will be negative, denoting negative power. This must be subtracted from the positive power for each cycle to yield the net power. The correction factor applied to make this is then a factor by which we multiply apparent power to obtain actual power. This is known as POWER FACTOR. In a single phase ac circuit (closely analogous to a dc circuit) we find that:

\[ W = E \times I \times P F = \text{POWER} \]

and that

\[ VA \text{ (voltamperes)} = E \times I = \text{APPARENT POWER} \]

For each cycle the power is positive when \(E\) and \(I\) are both either positive or negative. The power is negative when one value is positive with the other negative. The resultant is a power flow of twice line frequency, into and out of the load with the actual power transmitted being the difference of the two. Mathematically, it can be demonstrated that the Power Factor of a circuit (expressed as a decimal) is equal to the cosine of the angle \(\theta\) of lag (or lead) of the current with respect to the voltage.
Definitions and Formulas

Graphical Representation of Power Factor
The Unity Power Factor figure illustrates values of E, I and W for a single phase circuit when current and voltage are in phase. (θ = 0 degrees and cosine θ = 1.0). The power, W, is represented by the shaded area.

Unity Power Factor (Zero degrees lag) volts, amperes, watt

The Zero Lagging Power Factor figure below represents a condition where the current lags the voltage by 90 degrees (θ = 90 degrees and cosine θ = 0.0). The product of E x I is alternately positive and negative in equal amounts. Except for losses no actual power is transmitted. The load device is magnetized by power flow during one-quarter cycle, and during the next quarter cycle (as the device demagnetizes) an equal amount of power flows back into the power source.

Zero Lagging Power Factor (90 degrees lag) volts, amperes, watts

The 0.866 Lagging Power Factor figure below represents a condition where the current lags the voltage by 30 degrees. The net power W equals the area of the positive component, dotted black, less the area of the negative component, dotted color. The power factor is the net area divided by the total area. Mathematically this is the cosine of the angle of lag (30 degrees) or 0.866.

In all three examples above the E and I values are unchanged so the apparent power is the same in all cases. The actual power changes with changes in the angle by which the current lags the voltage. In an alternating current circuit it may be convenient to consider voltage, current or impedance as being composed of two components in quadrature. If one element (such as the voltage) is represented by a vector, the current (whether leading or lagging) can be represented by two vectors, one in phase with the voltage and one in quadrature with it. This is shown in the Vector representation below where E is the voltage, I_R is the in-phase component of currents, and I_x is the quadrature component. The current lags the voltage by an angle θ of 30 degrees. The inphase or power component I_R is equal to I times the cosine of 30 degrees, or 0.8661. The wattless component I_x (sometimes called the magnetizing current) is equal to I times the sine of 30 degrees, or 0.5 I.

The quadrature component I_x is also called the reactive component. In the case of transformers and induction motors this component serves the important function of magnetizing the device during one quarter-cycle; the energy thus transmitted is returned to the power source during the next quarter-cycle. The power factor is always the ratio of the in-phase component of current to the total current and is equal to:

\[
\frac{I_R}{I} = \cos \theta
\]

The quadrature compont I_x equals I sine θ.

The ratio of quadrature component I_x to in-phase component I_R:

\[
\frac{I_x}{I_R} = \tan \theta
\]

This relationship is useful in power factor correction calculations.
Definitions and Formulas

Power (w), (Kw), (MW): Electrical power is measured in watts or multiples thereof; see the Power Formula for Various AC Power Services Table:

A kilowatt is the common measure of power and equals 1000 watts or 1.34 horsepower. A megawatt is used in expressing large quantities of power and is equal to 1,000,000 watts. A kilowatt-hour is the usual expression for energy consumption and is the equivalent of using one kilowatt average power for a period of one hour.

\[ \text{RkVA} = \frac{1.73 EI_x}{1000} \]

where \( \theta \) is the angle of lag (or lead) of the current with respect to the voltage. Both RkVA and kvar are used to express reactive kVA.

**Right Hand Rule**

Right Hand Rule: Magnetic lines of force encircle a wire carrying current. If the current be dc, or for instantaneous values of ac, and if the wire be gripped in the right hand with the thumb pointing in direction of flow of current, the fingers will indicate the direction of the lines of force.

**Squirrel Cage Winding**

Squirrel Cage Winding: A uniformly distributed winding of cage bars, connected by end rings, in the outer periphery of the squirrel cage rotor.

**Amortisseur Winding**

Amortisseur Winding: a non-uniform winding of bars and end-rings in pole faces of synchronous motors. For convenience the bars are frequently called cage bars, upper and lower cage, etc.

**Torque (T)**

Torque (T): Torque is the turning of a motor, expressed in pound-feet, and is equivalent to the tangential pull at a radius of one foot. The various important torques for induction and synchronous motors will be covered in their respective sections.

<table>
<thead>
<tr>
<th>Power Service</th>
<th>Watts</th>
<th>Kilowatts</th>
<th>Megawatts</th>
<th>kVA</th>
<th>MVA</th>
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</thead>
<tbody>
<tr>
<td>dc</td>
<td>( W = EI )</td>
<td>( KW = \frac{EI}{1000} )</td>
<td>( MW = \frac{EI}{1000 000} )</td>
<td>( kVA = \frac{EI}{1000} )</td>
<td>( MVA = \frac{EI}{1000 000} )</td>
</tr>
<tr>
<td>Single Phase ac</td>
<td>( W = EI \times PF )</td>
<td>( KW = \frac{EI 	imes PF}{1000} )</td>
<td>( MW = \frac{EI 	imes PF}{1000 000} )</td>
<td>( kVA = \frac{2EI}{1000} )</td>
<td>( MVA = \frac{2EI}{1000 000} )</td>
</tr>
<tr>
<td>Two Phase ac</td>
<td>( W = 2EI \times PF )</td>
<td>( KW = \frac{2EI 	imes PF}{1000} )</td>
<td>( MW = \frac{2EI 	imes PF}{1000 000} )</td>
<td>( kVA = \frac{2EI}{1000} )</td>
<td>( MVA = \frac{2EI}{1000 000} )</td>
</tr>
<tr>
<td>Three Phase ac</td>
<td>( W = 1.73EI \times PF )</td>
<td>( KW = \frac{1.73EI 	imes PF}{1000} )</td>
<td>( MW = \frac{1.73EI 	imes PF}{1000 000} )</td>
<td>( kVA = \frac{1.73EI}{1000} )</td>
<td>( MVA = \frac{1.73EI}{1000 000} )</td>
</tr>
</tbody>
</table>
Definitions and Formulas

Reactive Capability of Synchronous Motors

For instance, a 250 hp, 0.8 power factor motor operating at 100% load will deliver approximately 60% of its horsepower rating, or $250 \times 0.6 = 150$ leading Rkva to the system.

In each case the motor is considered operating at full rated excitation from zero to 100% load. Above 100% load the excitation is reduced so as to maintain full rated stator amperes. Obviously if the excitation is not reduced the motor will draw much more kva and deliver more leading reactive kva. However the rated stator amperes will be exceeded and the motor would overheat.

**Power Factor Angle Within Synchronous Motors**

Refer to the reactive capability figure above. From these curves it is possible to determine the approximate leading kva in percent of rated horsepower for various conditions of load and for motors designed for various power factor values at full load.

The Diagram shows conditions in a synchronous motor when operating in synchronism at no load. When the motor is loaded the rotor will drop back along the curve C, the curve of synchronous torque, sufficiently to develop the load torque. C is the resultant of magnetic reluctance torque, A, and the definite polarity torque, B. The maximum synchronous torque is reached at about 70 electrical degrees lag of the rotor.
# Notes

## QUICK REFERENCE

<table>
<thead>
<tr>
<th>MOTOR HORSEPOWER:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>STATOR CURRENT:</td>
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</tr>
<tr>
<td>SERIAL NUMBER:</td>
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<tr>
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<tr>
<td>EXCITATION VOLTAGE:</td>
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</table>
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MOTOR HORSEPOWER:

STATOR CURRENT:

VOLTAGE:

SERIAL NUMBER:

EXCITATION CURRENT:

EXCITATION VOLTAGE: