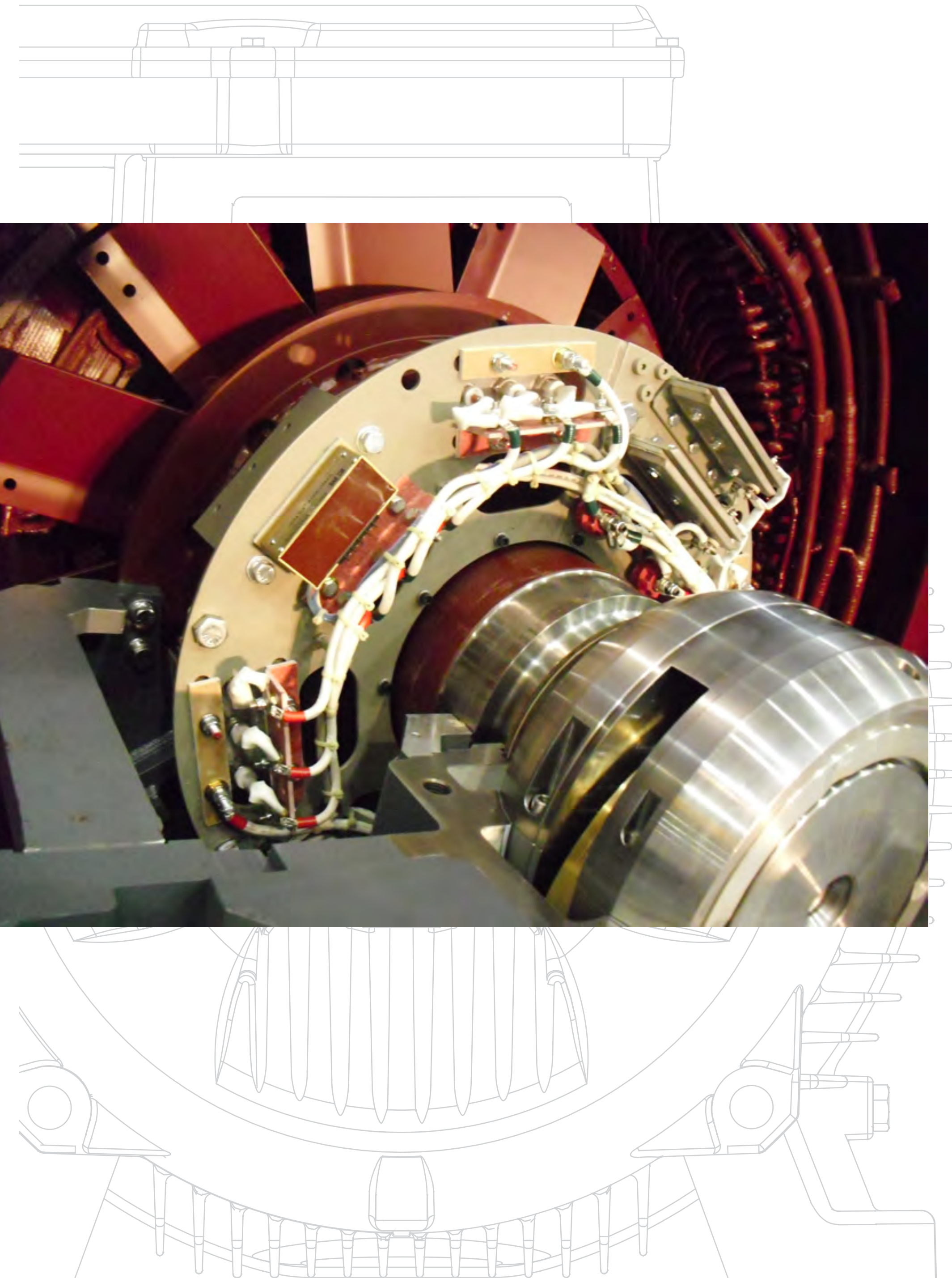
Motors | Automation | Energy | Transmission & Distribution | Coatings

Synchronous Motor Handbook

Electric Machinery Company



E-M WEG Group

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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.

Lloyd's Register
LRQA

CERTIFICATE OF APPROVAL

This is to certify that the Quality Management System of:

Electric Machinery Company, Inc.
800 Central Avenue NE
Minneapolis, Minnesota 55413, USA

has been approved by Lloyd's Register Quality Assurance to the following Quality Management System Standards:

ISO 9001:2008

The Quality Management System is applicable to:

Design, Manufacture, Technical Support and Service of Electric Motors, Electric Generators, and Magnetic Couplers.

Approval Certificate No: UQA 0102338

Original Approval: February 12, 1993
Current Certificate: January 1, 2015
Certificate Expiry: December 31, 2017

Issued by: Lloyd's Register Quality Assurance, Inc

ANAB

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

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

Product Range

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

**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.

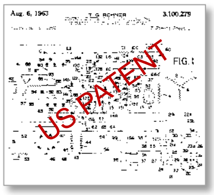
Nuclear Safety Related Equipment:

- 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

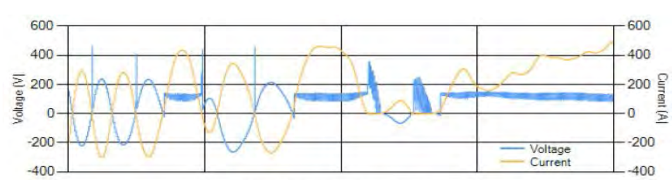
- Built upon the reliable Sync-Rite™ technology developed by EM
- Data logging and wireless data transmission added in an integrated design
- Designed specifically to interface directly with users and plant monitoring systems
- Monitoring features increase reliability and reduce downtime

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

Sync-Rite Plus™



Typical Synchronization Waveforms

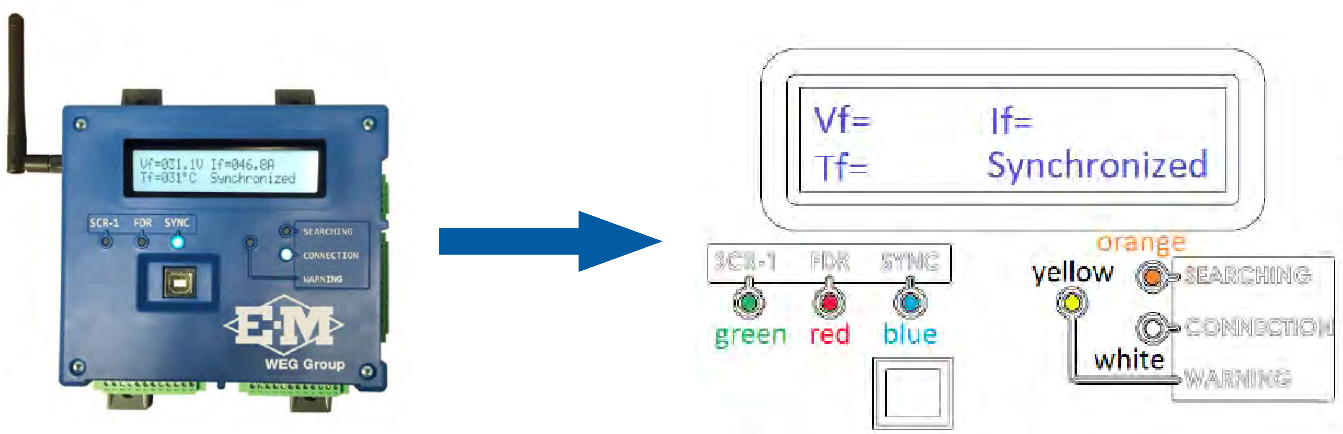
Sync-Rite Plus™ System

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™

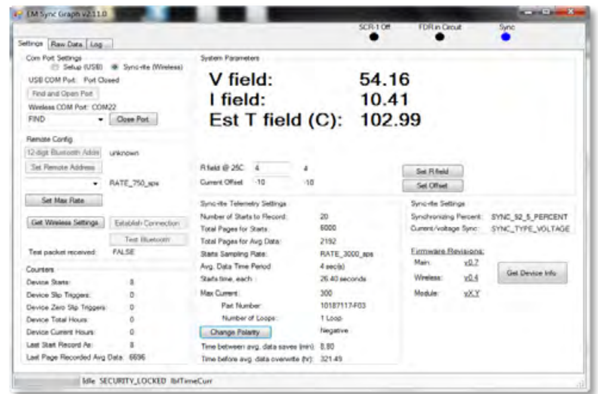
- Convenient and continuous display of field current, voltage, and temperature
- Displays easy to understand operating mode messages along with warning messages
- Real-time indicators that replicate the LEDs on the Sync-Rite Plus™
- Customizable warning indicator, which can be configured by the user
- 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™

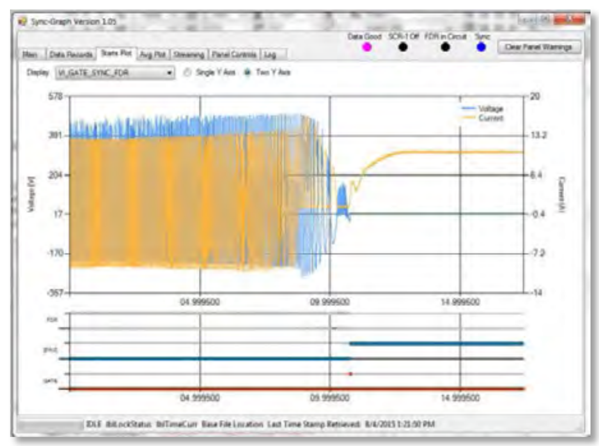
- Sync-Graph makes it easy to visualize starting and average records via graphs
  - Track changes in load conditions
  - View conditions that may be preventing synchronization
  - View changes in field voltage and current over time
  - Track changes in the estimated field temperature
- The streaming 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

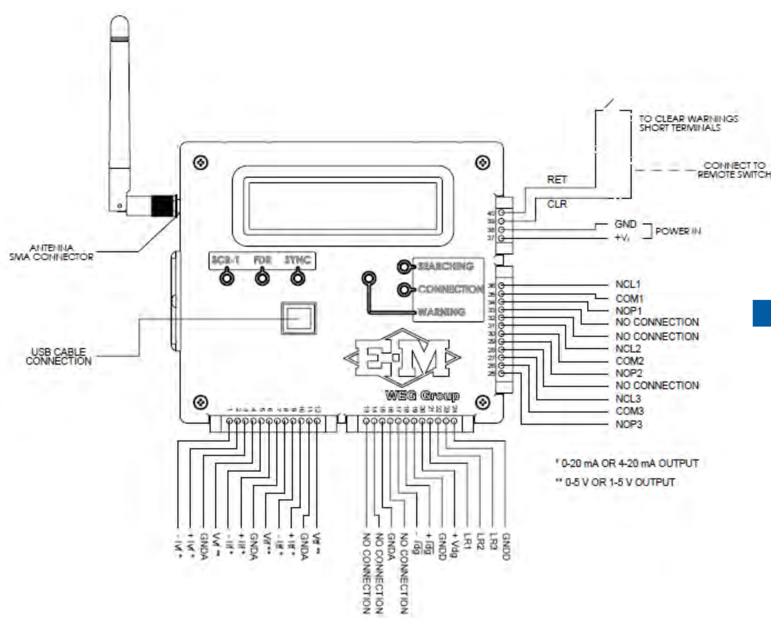


System Integration

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



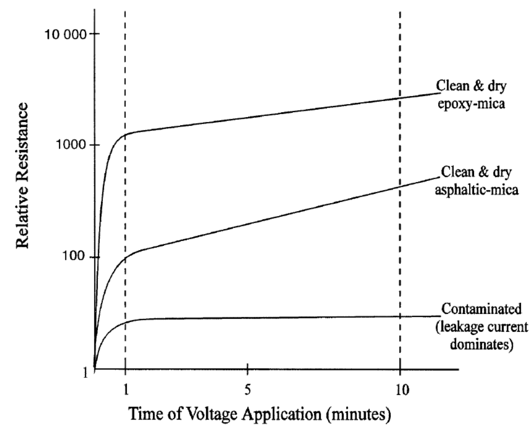


Recommended Electrical Testing

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.



Polarity Index Interpretation [2]

Typical Electrical Testing Results

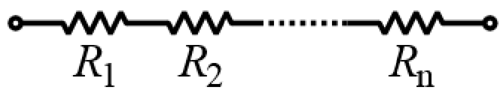
Component	Typical DC Test Voltage	Acceptable Insulation Resistance Results	Typical Resistance of Circuit
Main Stator	2 x Line Voltage + 1 (kV)	>200MΩ (Desirable)	Less than 1Ω per phase
		>2MΩ (Minimum)	
Main Rotor	500V	>200MΩ (Desirable)	Between 1Ω and 5Ω
		>2MΩ (Minimum)	
Exciter Rotor	500V	>200MΩ (Desirable)	Less than 1Ω per phase
		>2MΩ (Minimum)	
Exciter Stator	500V	>200MΩ (Desirable)	Between 1Ω and 5Ω
		>2MΩ (Minimum)	

IEEE DCS 2015-04. INSTALLATION AND MAINTENANCE OF SYNCHRONOUS MOTORS, Sean Orchuk, Matt Florczykowski. IEEE PPIC Conference 2015.
[1] IEEE Standard 43, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery, American National Standards Institute, NY Reaffirmed 2006: IEEE
[2] National Electrical Manufacturers Association, NEMA MG1-2009, Section 3, Part 21 – Large Machines – Synchronous Motors, VA: NEMA

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.



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 VTest, the expected voltage drop across any pole would be given by the formula:

$$V_{Pole} = \frac{V_{Test}}{n_{Poles}}$$

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:

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

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

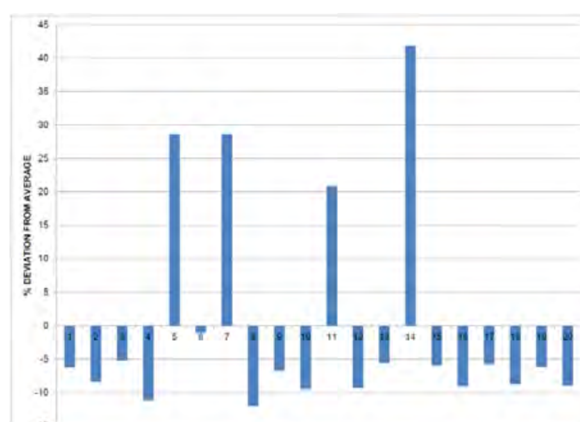
$$\%_{Deviation} = \frac{V_{Pole} - V_{Average}}{V_{Average}} \times 100$$

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

$$V_{Pole} = \frac{120 \text{ Volts}}{\left(\frac{24 \text{ Poles}}{3}\right)} \text{ x 15 Volts / Pole}$$



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.

Critical Fastener Marking

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

Typical Material Properties

Component	Material	Yield Stress (psi)	Ultimate Stress (psi)
Grade 5 Bolt	SAE J429 Grade 5	92,000	120,000
Grade 8 Bolt	SAE J429 Grade 8	130,000	150,000
Silicon Bronze Bolt	UNS65500 H06	60,000	108,000
Welded Frame or Soleplate	ASTM A36	36,000	60,000
Cast Motor Frame	ASTM A48 No 30B	N/A	30,000

IEEE DCS 2015-04. INSTALLATION AND MAINTENANCE OF SYNCHRONOUS MOTORS, Sean Orchuk, Matt Florczykowski. IEEE PPIC Conference 2015.
[1] IEEE Standard 43, IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery, American National Standards Institute, NY Reaffirmed 2006: IEEE
[2] National Electrical Manufacturers Association, NEMA MG1-2009, Section 3, Part 21 – Large Machines – Synchronous Motors, VA: NEMA

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

Nominal Dia. (in.)	threads per inch	Tensile Stress Area (sq. in.)	307A ASTM A307 Grade A Clamp Load (Lbs.)	ASTM A307 Grade A Tightening Torque K = 0.15	K = 0.17	K = 0.20	SAE J429 Grade 5 Clamp Load (Lbs.)	SAE J429 Grade 5 Tightening Torque K = 0.15	K = 0.17	K = 0.20	SAE J429 Grade 8 Clamp Load (Lbs.)	SAE J429 Grade 8 Tightening Torque K = 0.15	K = 0.17	K = 0.20
Unified Coarse Thread Series														
1/4	20	0.0318	859	32 in-lbs	37 in-lbs	43 in-lbs	2029	76 in-lbs	86 in-lbs	101 in-lbs	2864	107 in-lbs	122 in-lbs	143 in-lbs
5/16	18	0.0524	1416	66	75	88	3342	157	178	209	4719	221	251	295
3/8	16	0.0775	2092	10 ft-lbs	11 ft-lbs	13 ft-lbs	4940	23 ft-lbs	26 ft-lbs	31 ft-lbs	6974	33 ft-lbs	37 ft-lbs	44 ft-lbs
7/16	14	0.1063	2870	16	18	21	6777	37	42	49	9568	52	59	70
1/2	13	0.1419	3831	24	27	32	9046	57	64	75	12771	80	90	106
9/16	12	0.1819	4912	35	39	46	11599	82	92	109	16375	115	130	154
5/8	11	0.2260	6102	48	54	64	14408	113	128	150	20340	159	180	212
3/4	10	0.3345	9030	85	96	113	21322	200	227	267	30101	282	320	376
7/8	9	0.4617	12467	136	155	182	29436	322	365	429	41556	455	515	606
1	8	0.6057	16355	204	232	273	38616	483	547	644	54517	681	772	909
1 1/4	7	0.9691	26166	409	463	545	53786	840	952	1121	87220	1363	1545	1817
1 1/2	6	1.4053	37942	711	806	949	77991	1462	1657	1950	126473	2371	2688	3162
Fine Thread Series														
1/4	28	0.0364	982	37 in-lbs	42 in-lbs	49 in-lbs	2319	87 in-lbs	99 in-lbs	116 in-lbs	3274	123 in-lbs	139 in-lbs	164 in-lbs
5/16	24	0.0581	1568	73	83	98	3702	174	197	231	5226	245	278	327
3/8	24	0.0878	2371	11 ft-lbs	13 ft-lbs	15 ft-lbs	5599	26 ft-lbs	30 ft-lbs	35 ft-lbs	7905	37 ft-lbs	42 ft-lbs	49 ft-lbs
7/16	20	0.1187	3205	18	20	23	7568	41	47	55	10684	58	66	78
1/2	20	0.1600	4319	27	31	36	10197	64	72	85	14396	90	102	120
9/16	18	0.2030	5480	39	44	51	12940	91	103	121	18268	128	146	171
5/8	18	0.2560	6911	54	61	72	16317	127	144	170	23036	180	204	240
3/4	16	0.3730	10070	94	107	126	23776	223	253	297	33566	315	357	420
7/8	14	0.5095	13756	150	171	201	32479	355	403	474	45853	502	568	669
1	14	0.6799	18357	229	260	306	43343	542	614	722	61190	765	867	1020
1 1/4	12	1.0729	28970	453	513	604	59548	930	1055	1241	96565	1509	1710	2012
1 1/2	12	1.5810	42688	800	907	1067	87747	1645	1865	2194	142292	2668	3024	3557

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.

Torque values calculated from formula T=KDF, where

- K = 0.15 for "lubricated" conditions
- K = 0.17 for zinc plated and dry conditions; we have also found various forms of customer applied thread lockers to have a similar K value
- K = 0.20 for plain and dry conditions
- D = Nominal Diameter
- F = Clamp Load

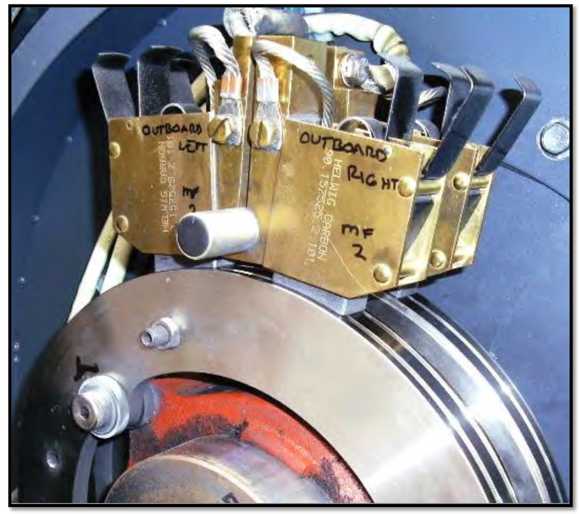
Caution: All material included in this chart is advisory only, and its use by anyone is voluntary. In developing this information, Fastenal has made a determined effort to present its contents accurately. Extreme caution should be used when using a formula for torque/tension relationships. Torque is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

Toque-Tension Relationship for A307!, Grade 5, 8 & 9 Bolts - Fastenal Engineering & Design Support - F.E.D.S. Rev 3-6-09

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

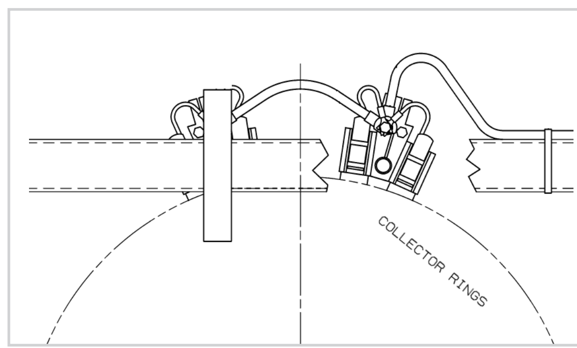
Collector Rings

- 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

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



Assembly of the Brush Holder

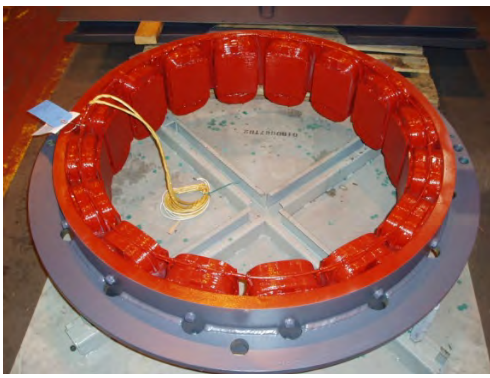
Collector Ring - Maintenance

- 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

Contaminated collector ring treated with insulating varnish in the field

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

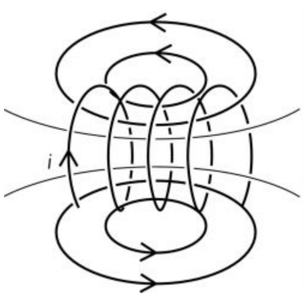


Exciter Stator (DC Input)

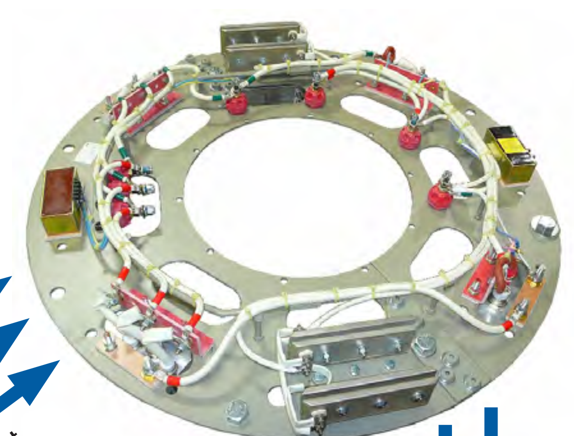
+

-

Exciter Power Supply
(Variable DC Output)



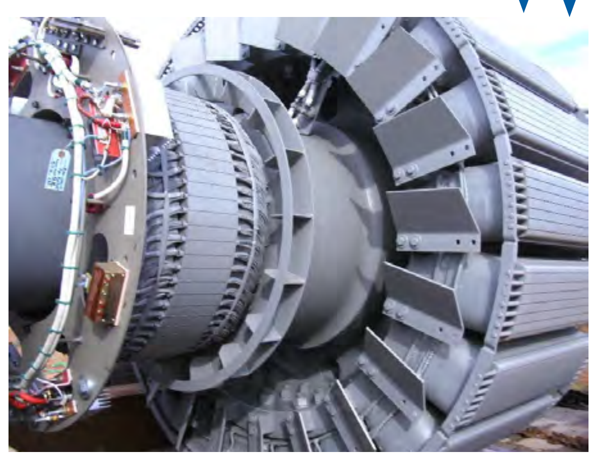
Exciter stator induces current in
the exciter rotor



Diode Wheel
(AC Input - DC Output)

3-phase AC output

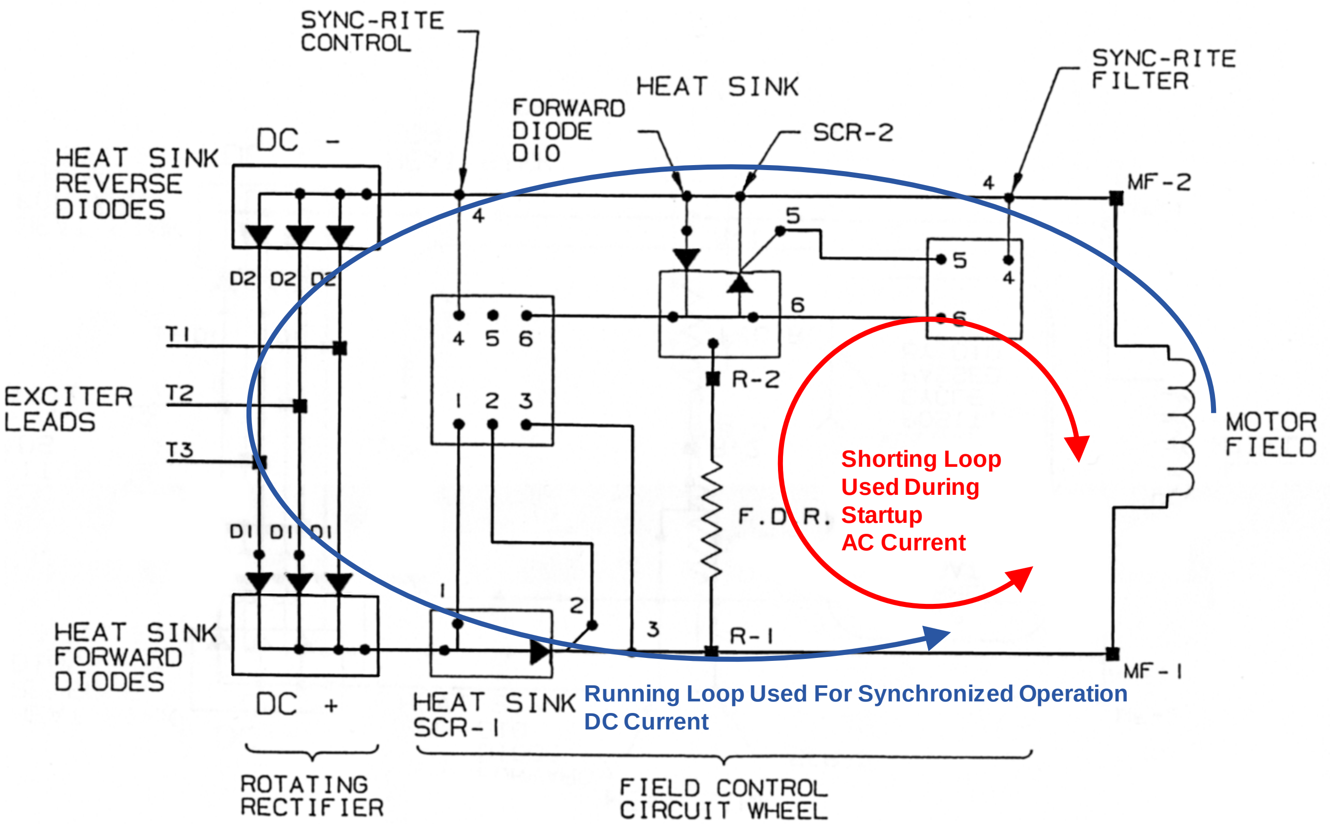
Exciter Rotor (AC Output)



Main Rotor (DC Input)

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



Brushless Diode Wheel Schematic

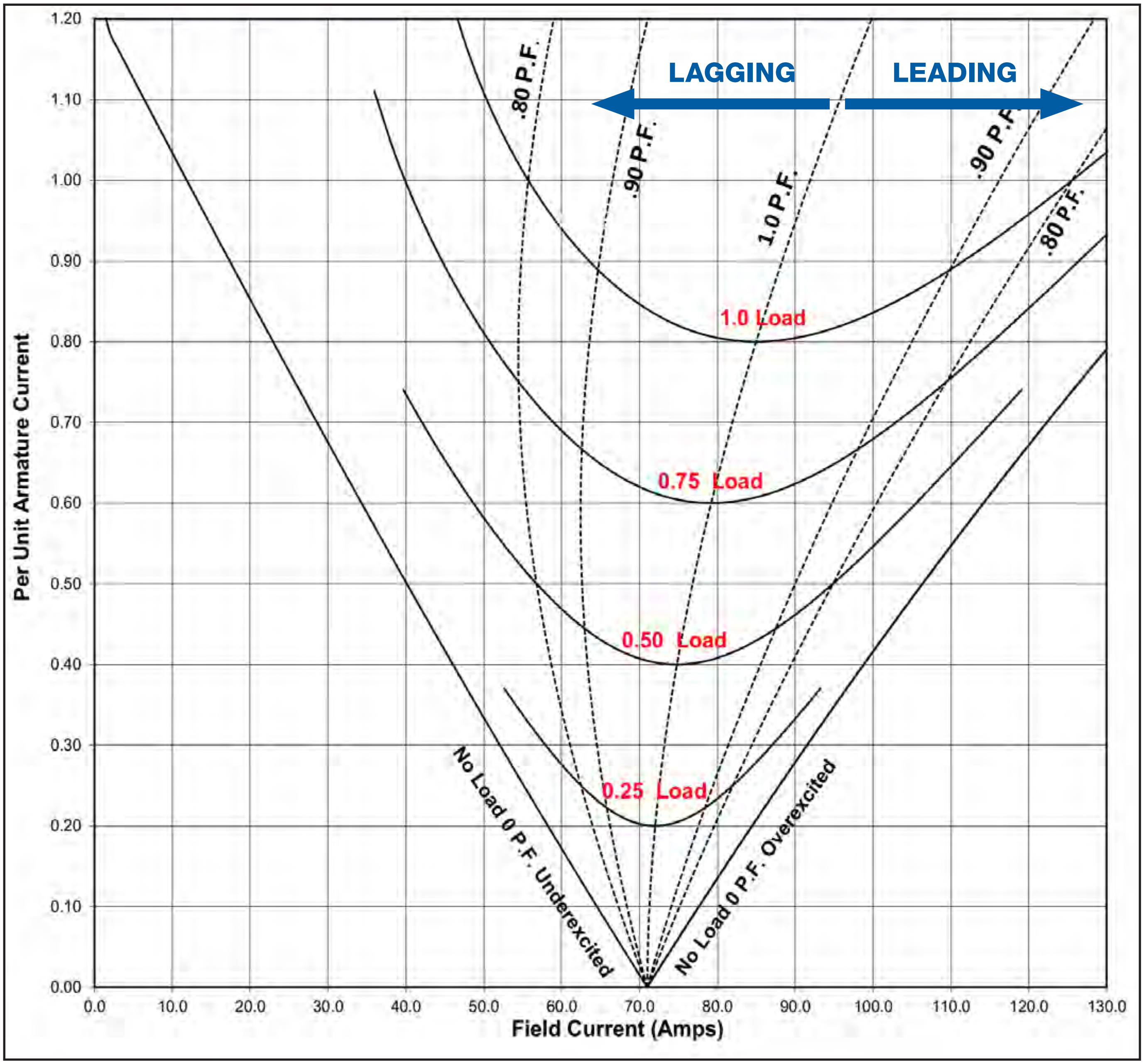
Note:
Red LED on Sync-Rite Plus™ = resistors in circuit
Green LED Flashing on Sync Rite Plus™ = SCR-1 attempting to fire
Blue LED on Sync Rite Plus™ = synchronized

Resistors in Circuit and SCR-1 Attempting to Fire

Motor 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

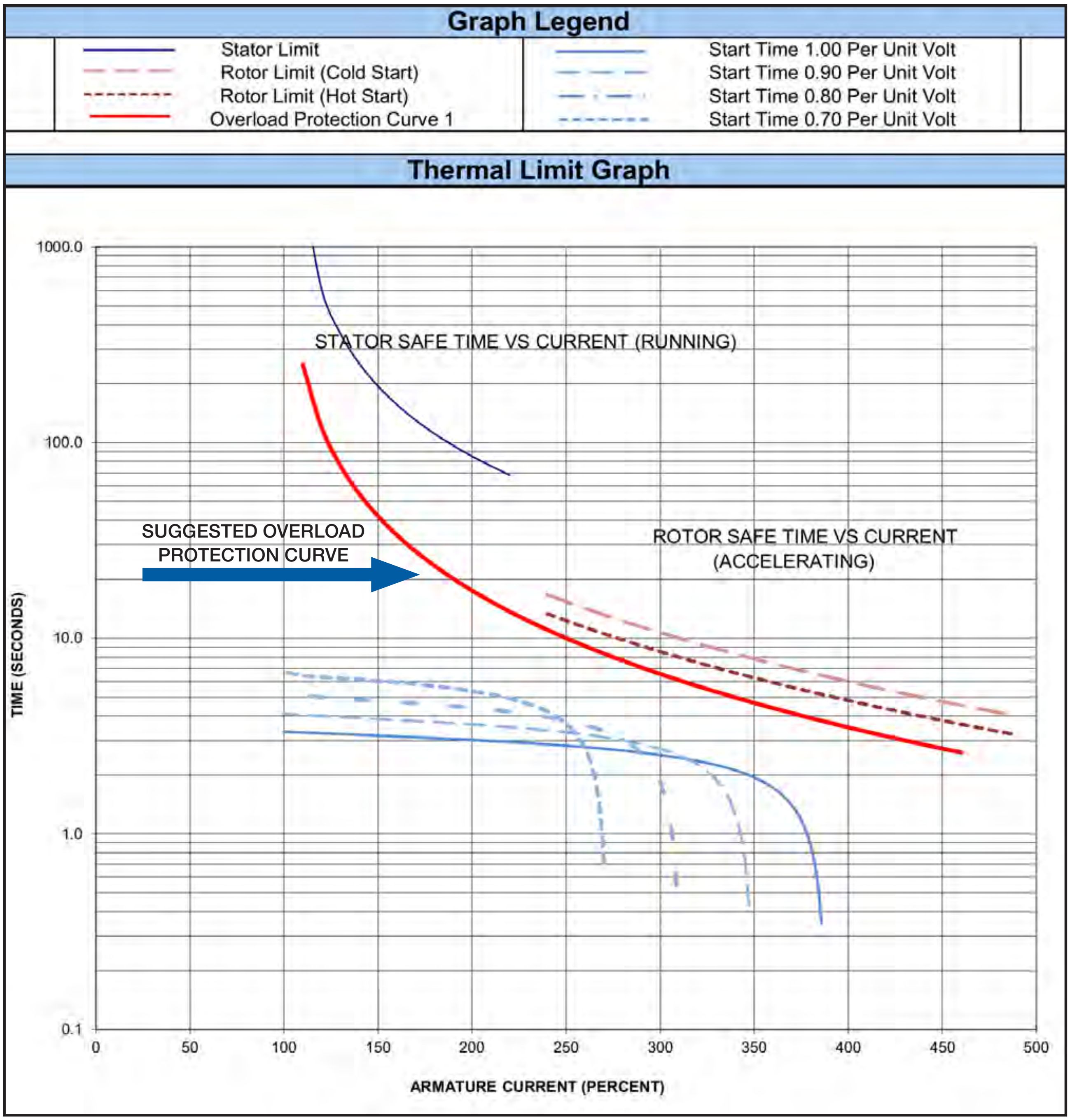


Typical Statically-Excited (Collector Ring) Synchronous Motor

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



Typical Thermal Limit Curve for a Synchronous Motor

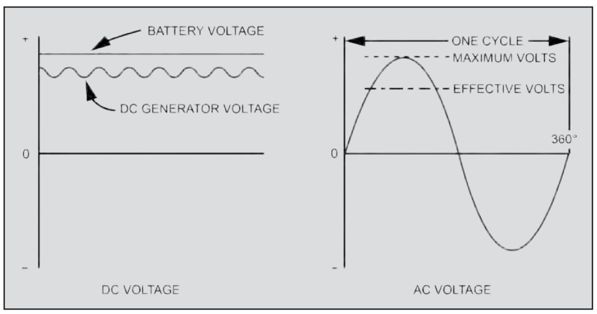
Definitions and Formulas

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.



Direct Current and Alternating Current

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

$$\text{Synchronous speed} = \frac{60 \times \text{Hz}}{\text{number of pairs of poles}}$$

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:

RMS (Root Mean Square) volts = 0.707 x 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.

Definitions and Formulas

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:

Ohms XL (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 (X_C): 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:

$$\text{Ohms Xe (Capacitive Reactance)} = \frac{1}{2 \pi f C}$$

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:

$$Z(\text{OHMS}) = \sqrt{R2+(X_L\text{-}X_C)^2}$$

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 θ of lag (or lead), will be:

$$\text{Tan } \theta = \frac{X_L - X_c}{R}$$

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 (Watts) = E x 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 de circuit) we find that:

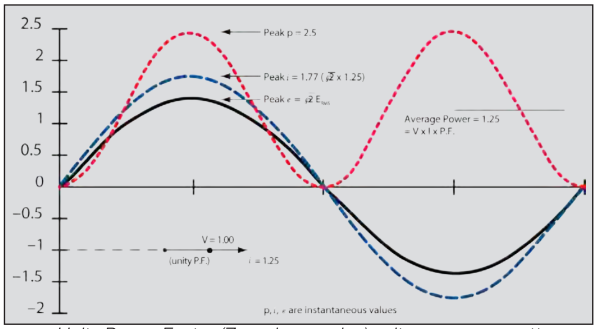
W = E x I x P F = POWER
and that
VA (voltamperes) =
E x I = APPARENT POWER

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 θ of lag (or lead) of the current with respect to the voltage.

Definitions and Formulas

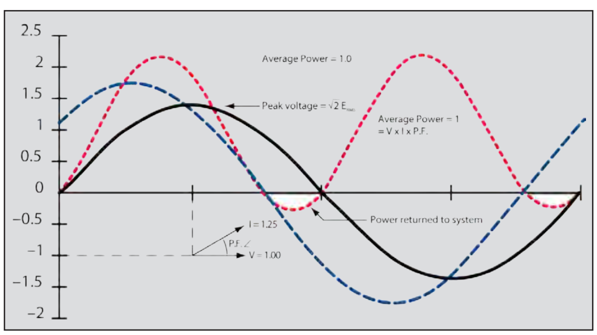
Graphical Representation of Power Factor

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.



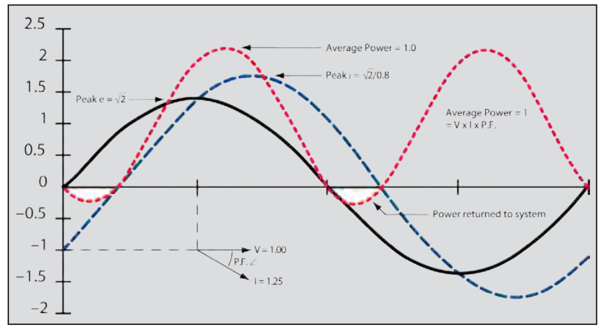
Unity Power Factor (Zero degrees lag) volts, amperes, watt

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.



0.866 Lagging Power Factor (30 degrees lag) volts, amperes, watts

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:

$$I_R \div I, \text{ or cosine } \theta$$

The quadrature compont I_X equals I sine θ.

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

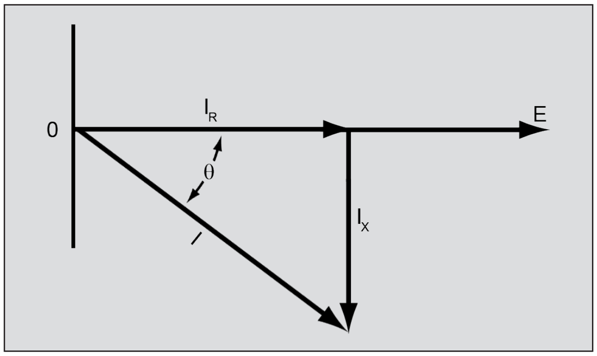
$$\frac{I_x}{I_R} = \text{Tangent } \theta$$

This relationship is useful in power factor correction calculations.

Definitions and Formulas

Power (w), (Kw), (MW): Electrical power is measured in watts or multiples tqereof; 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 6f 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.



Vector representation of Power Current Component (I_R) and Magnetizing Current Component (I_X) of Total Current (I)

Kilovolt Amperes

KILOVOLT AMPERES: Alternating current ratings are expressed in kVA or, in large quantities, in megavolt amperes as shown in Power Formula for Various AC Power Services Table.

Reactive kVA, (RkVA), (kvar)

Reactive KVA, (RKVA), (KVAR): The product of volts and quadrature component of current on three phase service is:

$$RkVA = \frac{1.73\ EI_X}{1000}$$

$$\frac{RkVA}{kVA} = \text{Sine } \theta \qquad \frac{RkVA}{kW} = \text{Tangent } \theta$$

where θ 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)

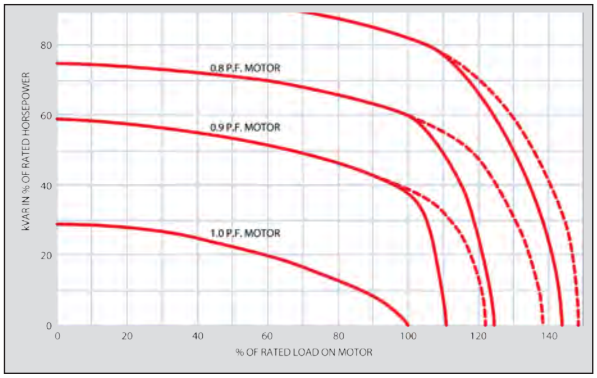
Torque (T): Torque is the turning of a motor, expressed in pound-feet, and is equivalent to the tangential pull at a radius of one foot. The various important torques for induction and synchronous motors will be covered in their respective sections.

Power Formula for Various AC Power Services

Power Service	Watts	Kilowatts	Megawatts	kVA	MVA
dc	W = EI	$KW = \frac{EI}{1000}$	$MW = \frac{EI}{1\ 000\ 000}$		
Single Phase ac	W = EI x PF	$KW = \frac{EI \times PF}{1000}$	$MW = \frac{EI \times PF}{1\ 000\ 000}$	$kVA = \frac{EI}{1000}$	$MVA = \frac{EI}{1\ 000\ 000}$
Two Phase ac	W = 2EI x PF	$KW = \frac{2EI \times PF}{1000}$	$MW = \frac{2EI \times PF}{1\ 000\ 000}$	$kVA = \frac{2EI}{1000}$	$MVA = \frac{2EI}{1\ 000\ 000}$
Three Phase ac	W = 1.73EI x PF	$KW = \frac{1.73EI \times PF}{1000}$	$MW = \frac{1.73EI \times PF}{1\ 000\ 000}$	$kVA = \frac{1.73EI}{1000}$	$MVA = \frac{1.73EI}{1\ 000\ 000}$

Definitions and Formulas

Reactive Capability of Synchronous Motors



Reactive Capability of Synchronous Motors

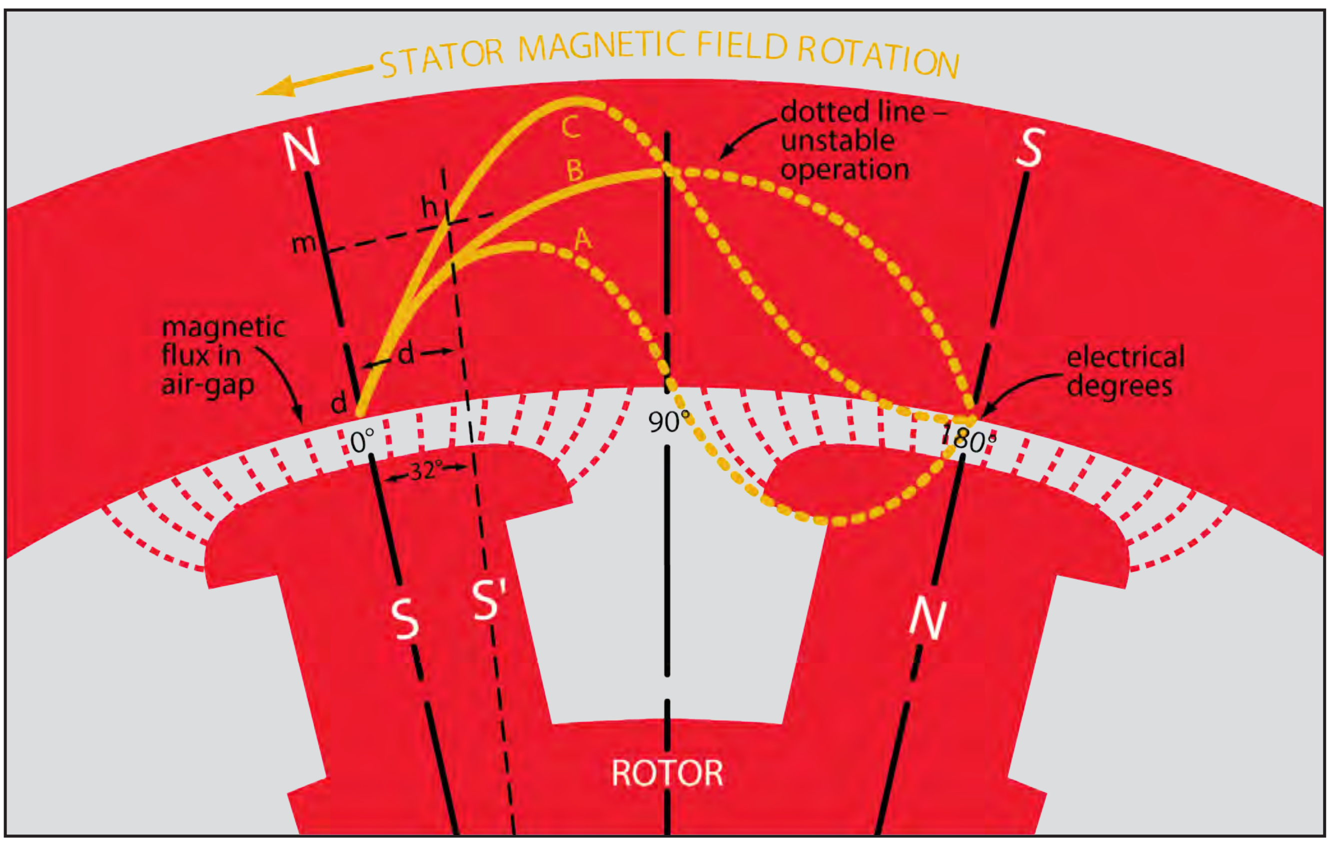
Refer to the reactive capability figure above. From these curves it is possible to dertermine the approximate leading kva in percent of rated horsepower for various conditions of load and for motors designed for various power factor values at full load.

For instance, a 250 hp, 0.8 power factor motor operating at 100% load will deliver approximately 60% of its horsepower rating, or 250 x 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

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



Power Factor Angle Within Synchronous Motors

Notes

QUICK REFERENCE
MOTOR HORSEPOWER:
STATOR CURRENT:
VOLTAGE:
SERIAL NUMBER:
EXCITATION CURRENT:
EXCITATION VOLTAGE:

Notes

QUICK REFERENCE
MOTOR HORSEPOWER:
STATOR CURRENT:
VOLTAGE:
SERIAL NUMBER:
EXCITATION CURRENT:
EXCITATION VOLTAGE:

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