Synchronous Motor
Characteristics

Synchronous Motors are three-phase AC motors which run at synchronous speed, without slip.

(In an induction motor the rotor must have some "slip". The rotor speed must be less than, or lag behind, that of the rotating stator flux in order for current to be induced into the rotor. If an induction motor rotor were to achieve synchronous speed, no lines of force would cut through the rotor, so no current would be induced in the rotor and no torque would be developed.)

Synchronous motors have the following characteristics:

- A three-phase stator similar to that of an induction motor. Medium voltage stators are often used.
- A wound rotor (rotating field) which has the same number of poles as the stator, and is supplied by an external source of direct current (DC). Both brush-type and brushless exciters are used to supply the DC field current to the rotor. The rotor current establishes a north/south magnetic pole relationship in the rotor poles enabling the rotor to "lock-in-step" with the rotating stator flux.
- Starts as an induction motor. The synchronous motor rotor also has a squirrel-cage winding, known as an Amortisseur winding, which produces torque for motor starting.
- Synchronous motors will run at synchronous speed in accordance with the formula:

$$\textbf{Synchronous RPM} = \frac{\textbf{120 x Frequency}}{\textbf{Number of Poles}}$$

Example: the speed of a 24 -Pole Synchronous Motor operating at 60 Hz would be:

120 x 60 / 24 = 7200 / 24 = 300 RPM

Synchronous Motor Operation

- The squirrel-cage Amortisseur winding in the rotor produces *Starting Torque* and *Accelerating Torque* to bring the synchronous motor up to speed.
- When the motor speed reaches approximately 97% of nameplate RPM, the DC field current is applied to the rotor producing *Pull-in Torque* and the rotor will pull-in-step and "synchronize" with the rotating flux field in the stator. The motor will run at synchronous speed and produce *Synchronous Torque*.
- After synchronization, the *Pull-out Torque* cannot be exceeded or the motor will pull out-of-step. Occasionally, if the overload is momentary, the motor will "slip-a-pole" and resynchronize. Pull-out protection must be provided otherwise the motor will run as an induction motor drawing high current with the possibility of severe motor damage.

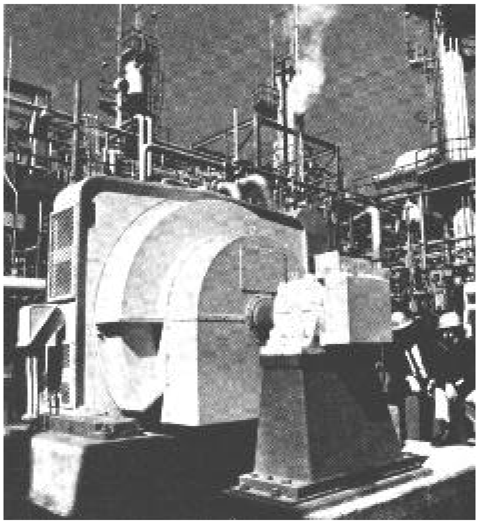
Advantages of Synchronous Motors

The initial cost of a synchronous motor is more than that of a conventional AC induction motor due to the expense of the wound rotor and synchronizing circuitry. These initial costs are often off-set by:

- Precise speed regulation makes the synchronous motor an ideal choice for certain industrial processes and as a prime mover for generators.
- Synchronous motors have speed / torque characteristics which are ideally suited for direct drive of large horsepower, low-rpm loads such as reciprocating compressors.
- Synchronous motors operate at an improved power factor, thereby improving overall system power factor and eliminating or reducing utility power factor penalties. An improved power factor also reduces the system voltage drop and the voltage drop at the motor terminals.

Synchronous Motor
Construction

2000 Horsepower Synchronous Motor
In Refinery Service



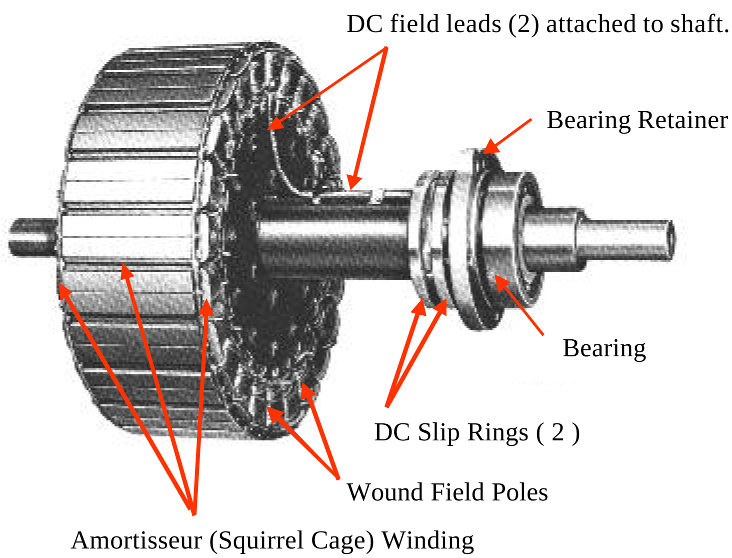
Electric Machinery Photo

Characteristics and Features

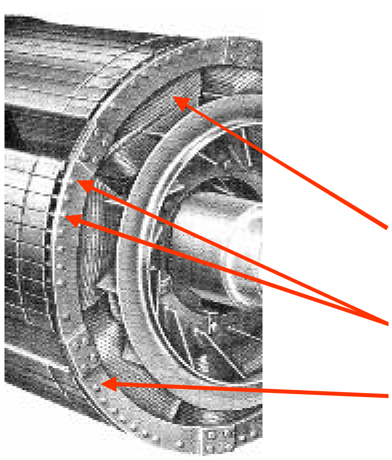
- The rotation of a synchronous motor is established by the phase sequence of the three-phase AC applied to the motor stator. As with a three-phase induction motor, synchronous motor rotation is changed by reversing any two stator leads. Rotor polarity has no effect on rotation.
- Synchronous motors are often direct-coupled to the load and may share a common shaft and bearings with the load.
- Large synchronous motors are usually started across-the-line. Occasionally, reduced voltage starting methods, such as autotransformer or part-winding starting, may be employed.

Synchronous Motor Rotors

- The Salient-Pole unit shown at the right is a brush-type rotor that uses slip rings for application of the DC field current.
- Low voltage DC is used for the rotating field. 120 VDC and 250 VDC are typical.
- Slip ring polarity is not critical and should be periodically reversed to equalize the wear on the slip rings. The negative polarity ring will sustain more wear than the positive ring due to electrolysis.
- Slip rings are usually made of steel for extended life.



Electric Machinery Photo



Electric Machinery Photo

Detail of Amortisseur Winding

Synchronous motors start as an induction motor utilizing the Amortisseur winding which is a squirrel-cage-type winding with short-circuited rotor bars.

Wound Field Pole - Energized by separate source of DC for synchronous operation.

Squirrel-Cage Rotor Bars

Shorting Ring - One on each end of rotor.

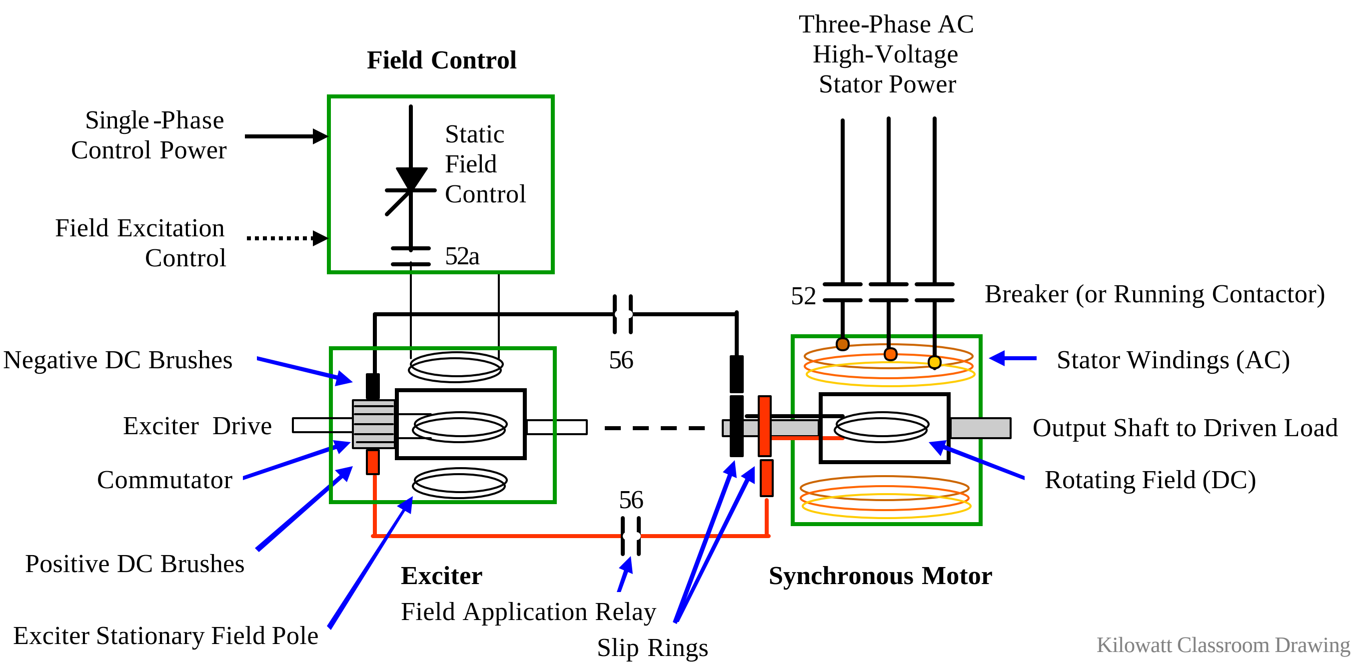
Synchronous Motor
Brush-Type Excitation Systems

Excitation Methods

Two methods are commonly utilized for the application of the direct current (DC) field current to the rotor of a synchronous motor.

- Brush-type systems apply the output of a separate DC generator (exciter) to the slip rings of the rotor.
- Brushless excitation systems utilize an integral exciter and rotating rectifier assembly that eliminates the need for brushes and slip rings.

Brush-Type Excitation System



System Analysis

In this excitation method the DC field current for the synchronous motor is provided by a separate DC generator known as an exciter. The exciter is a shunt-or compound-wound DC machine that is driven either by the synchronous motor itself (dashed line) or by a separate drive motor. Excavators, for example, often have an "exciter line" consisting of a number of exciters which are driven by an single AC induction motor.

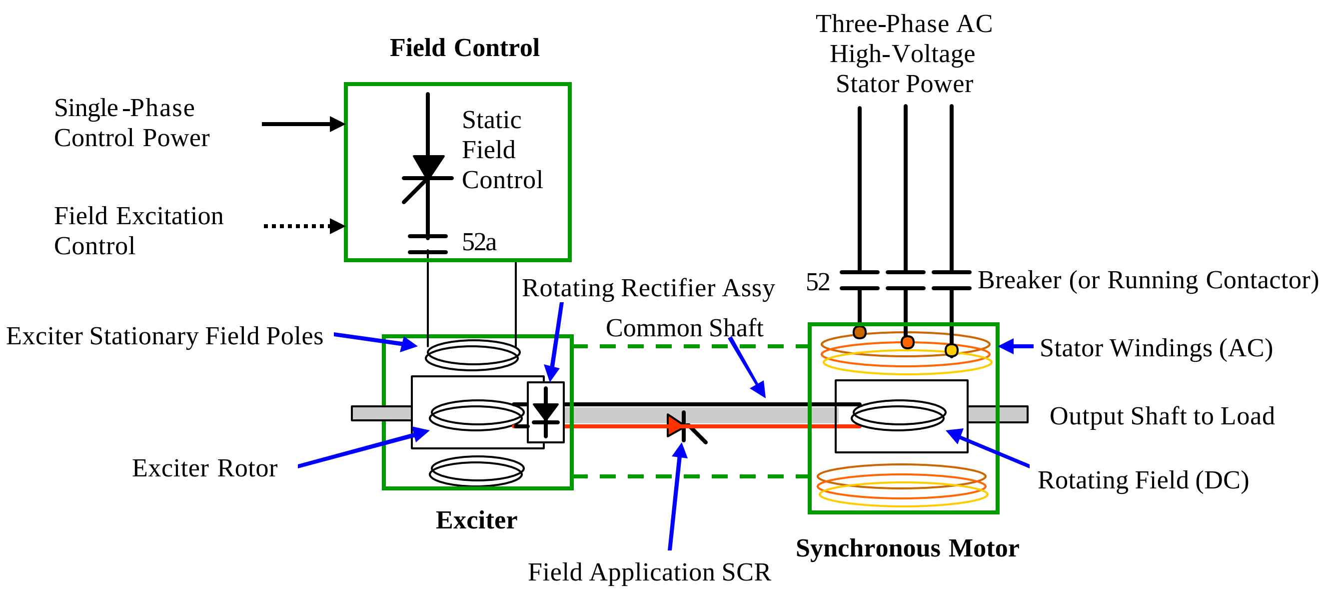
The shunt field of the exciter is separately excited by the solid state control. Some excitation controls provide for manual adjustment of the field strength. Other systems automatically regulate the synchronous motor field in a closed-loop configuration designed to maintain adequate field strength for varying loads or to maintain a constant power factor. The exciter shunt field is energized when the 52a auxiliary contact in the main breaker closes..

In the above illustrated system, the exciter shunt-field strength controls the DC output of the exciter which is picked off by the commutator brushes, bused to the motor slip-ring brushes, and applied via the slip rings to the main rotating field of the synchronous motor.

The synchronous motor starts as a induction motor. When the rotor achieves near-synchronous speed, the motor field current is applied by the closure of the Field Application Relay (Standard Device Designation #56).

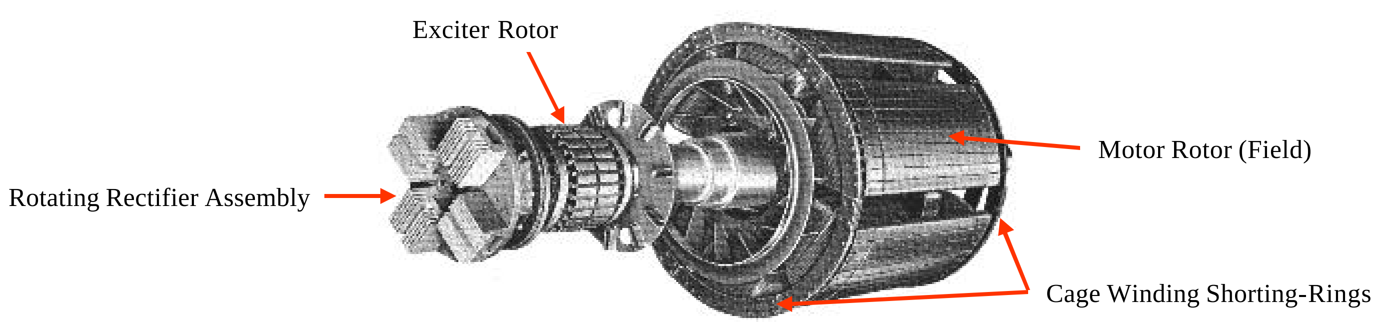
Synchronous Motor
Brushless Exciters

Brushless Excitation System



Kilowatt Classroom Drawing

Brushless Machine Rotor



Electric Machinery Photo

System Analysis

This excitation method eliminates the need for brushes, both on the exciter and the motor.

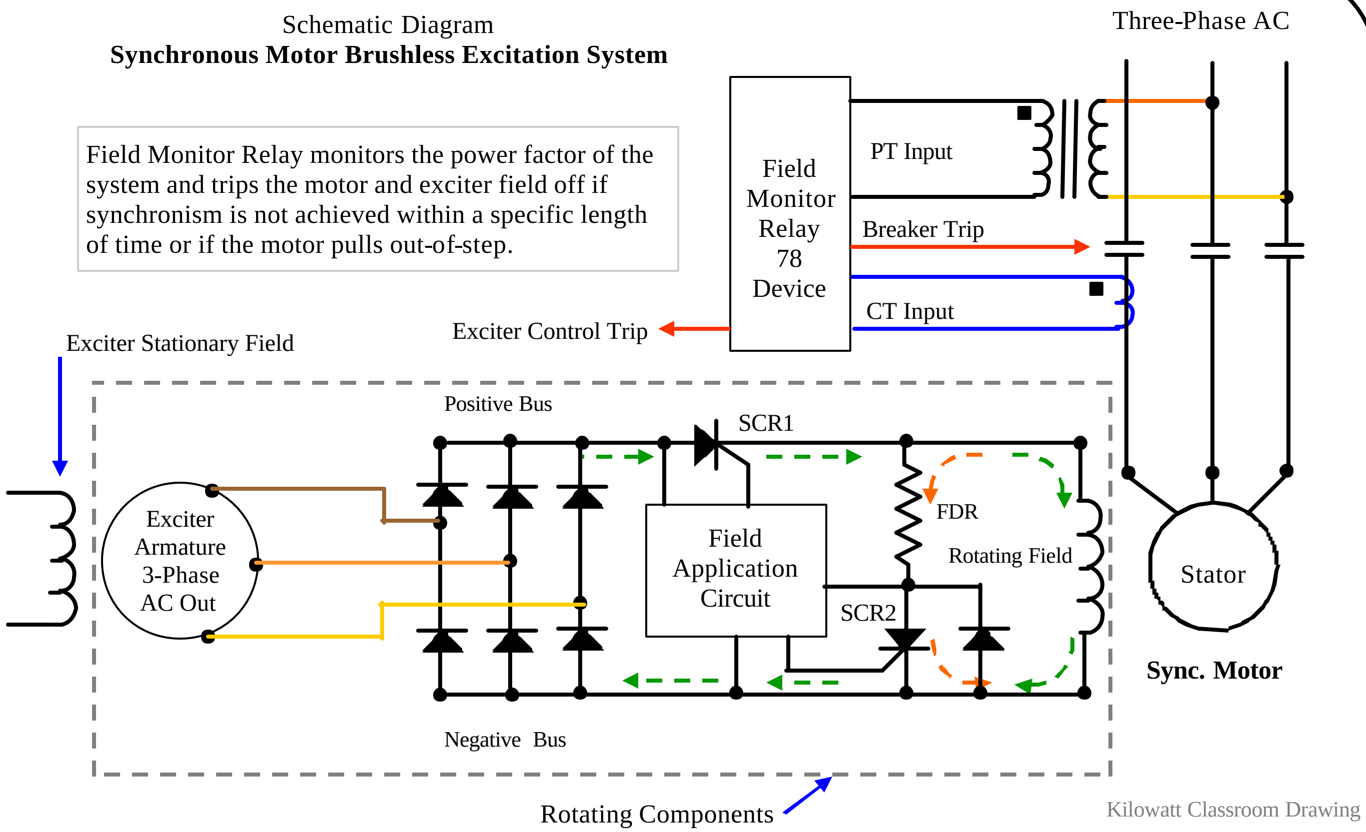
When the motor is started the machine breaker (Std Device #52) closes and applies three-phase AC to the motor stator windings. The motor starts as an induction motor using the Amortisseur winding in the rotor.

The Machine Breaker 52a auxiliary contact also closes and applies the DC output of the solid-state Field Control to the exciter stationary winding. A three-phase alternating current is induced in the exciter rotor windings and this induced voltage is rectified by the rotating rectifier assembly. When the rotor achieves near synchronous speed the Field Application SCR is fired by the Synchronizing Control Package and the rectified DC is applied to the synchronous motor rotating field. See schematic on the next page for additional details.

Synchronous Motor
Synchronizing Principle

Schematic Diagram
Synchronous Motor Brushless Excitation System

Field Monitor Relay monitors the power factor of the system and trips the motor and exciter field off if synchronism is not achieved within a specific length of time or if the motor pulls out-of-step.



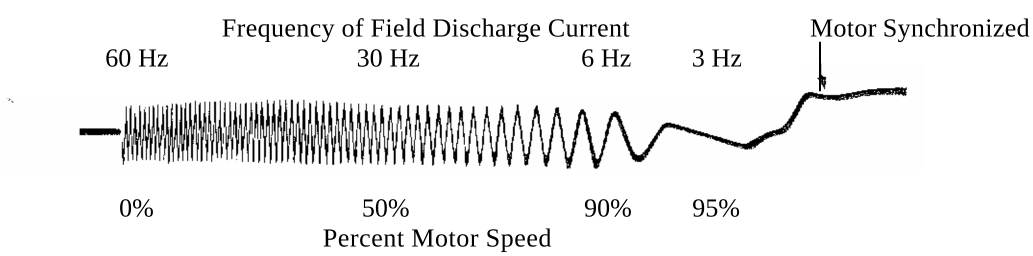
Field Application System

The Field Application Circuit in a synchronous motor excitation system must perform three functions:

- Provide a discharge path for the current which is induced into the wound rotor during start and open this circuit when excitation is applied. During start the motor is operating as an induction motor with the torque being produced by the squirrel cage winding. The wound rotor is also being cut by the rotating stator flux and has a voltage induced in it. During this phase of the start-up SCR2 in the above diagram is gated "on" by the Field Application Circuit and provides a discharge path for the induced rotor current through the Field Discharge Resistor (FDR) as shown by the dashed red arrows. The frequency of this induced rotor current "tells" the application circuit the speed at which the rotor is running. See oscilloscope waveform below.

- When the rotor speed reaches about 97% of synchronous and the rotor polarity is correct to achieve synchronism, SCR2 will turn "off " and SCR1is gated "on" allowing the rectified DC current from the rotating three-phase bridge rectifier to flow through the rotating field, as shown by the green dashed arrows, producing the necessary *Synchronizing Torque* for the rotor to pull-in step with the rotating stator flux.

- The Field Application Circuit must remove excitation immediately if the motor pulls out-of-step.

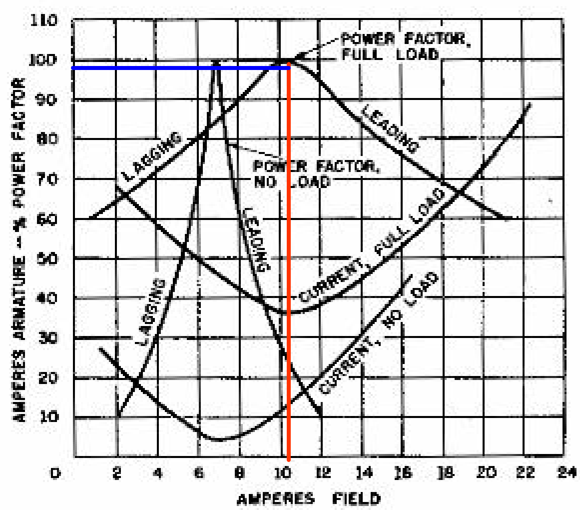


Waveform of Induced Field Current During Start

Synchronous Motor Power Factor

An important advantage of a synchronous motor is that the motor power factor can be controlled by adjusting the excitation of the rotating DC field. Unlike AC induction motors which always run at a lagging power factor, synchronous motors can run at unity or even at a leading power factor. This will improve the over-all electrical system power factor and voltage drop and also improve the voltage drop at the terminals of the motor. (See The Electrician's Notebook article *Principles of Voltage Regulation* for a description of how improving the system power factor also improves the system voltage drop.)

Typical "V" Curves



Interpreting "V" Curves

The synchronous motor "V Curves" shown above illustrate the effect of excitation (field amps) on the armature (stator) amps and on system power factor. There are separate "V" Curves for No-Load and Full-Load and sometimes the motor manufacturer publishes curves for 25%, 50%, and 75% load. Note that the Armature Amperage and Power Factor "V" Curves are actually inverted "V's".

Assume it is desired to determine the field excitation which will produce unity power factor operation at full motor load. Project across from the unity power factor (100%) operating point on the Y-Axis to the peak of the inverted Power Factor "V" Curve (blue line). From this intersection, project down (red line) from the full-load unity power factor (100%) operating point to determine the required field current on the X-Axis. In this example the required DC field current is shown to be just over 10 amps. Note at unity power factor operation the armature (stator) full-load amps is at the minimum value.

Increasing the field amps above the value required for unity power factor operation will cause the machine to run with a *leading* power factor, while field weakening caused the motor power factor to become *lagging*. When the motor runs *either* leading or lagging, the armature (stator) amps increases above the unity power factor value.