

Synchronous motor

A **synchronous electric motor** is an AC motor in which the rotation rate of the shaft is synchronized with the frequency of the AC supply current; the rotation period is exactly equal to an integral number of AC cycles. Synchronous motors contain electromagnets on the stator of the motor that create a magnetic field which rotates in time with the oscillations of the line current. The rotor turns in step with this field, at the same rate.

Another way of saying this is that the motor does not rely on "*slip*" under usual operating conditions, and as a result produces torque at synchronous speed. Synchronous motors can be contrasted with induction motors, which must slip in order to produce torque. The speed of the synchronous motor is determined by the number of magnetic poles and the line frequency.

Synchronous motors are available in sub-fractional **self-excited** sizes to high-horsepower **direct-current excited** industrial sizes. In the fractional horsepower range, most synchronous motors are used where precise constant speed is required. In high-horsepower industrial sizes, the synchronous motor provides two important functions. First, it is a highly efficient means of converting AC energy to work. Second, it can operate at leading or unity power factor and thereby provide power-factor correction.

Type

There are two major types of synchronous motors: 'non-excited' and 'direct-current excited', which have no self-starting capability to reach synchronism without extra excitation means, such as electronic control or induction.

With recent advances in independent brushless excitation control of the rotor winding set that eliminates reliance on slip for operation, the 'brushless wound-rotor doubly fed electric machine' is the third type of synchronous motor with all the theoretical qualities of the synchronous motor and the wound-rotor doubly fed motor combined, such as power factor correction, highest power density, highest potential torque density, low cost electronic controller, highest efficiency, etc.

Non-excited motors

In non-excited motors, the rotor is made of solid steel. At synchronous speed it rotates in step with the rotating magnetic field of the stator, so it has an almost-constant magnetic field through it. The external stator field magnetizes the rotor, inducing the magnetic poles needed to turn it. The rotor is made of a high-retentivity steel such as cobalt steel, These are manufactured in permanent magnet, reluctance and hysteresis designs:

- **Reluctance motors:** These have a rotor consisting of a solid steel casting with projecting (salient) toothed poles, the same number as the stator poles.^{[1][2]} The size of the air gap in the magnetic circuit and thus the reluctance is minimum when the poles are aligned with the (rotating) magnetic field of the stator, and increases with the angle between them. This creates a torque pulling the rotor into alignment with the nearest pole of the stator field. Thus at synchronous speed the rotor is "locked" to the rotating stator field. This cannot start the motor, so the rotor poles usually have squirrel-cage windings embedded in them, to provide torque below synchronous speed. The machine starts as an induction motor until it approaches



A synchronous motor-generator set for AC to DC conversion.

synchronous speed, when the rotor "pulls in" and locks to the rotating stator field.

- **Hysteresis motors:** These have a solid smooth cylindrical rotor, cast of a high coercivity magnetically "hard" cobalt steel.^{[1][2]} This material has a wide hysteresis loop (high retentivity), meaning once it is magnetized in a given direction, it requires a large reverse magnetic field to reverse the magnetization. The rotating stator field causes each small volume of the rotor to experience a reversing magnetic field. Because of hysteresis the phase of the magnetization lags behind the phase of the applied field. The result of this is that the axis of the magnetic field induced in the rotor lags behind the axis of the stator field by a constant angle δ , producing a torque as the rotor tries to "catch up" with the stator field. As long as the rotor is below synchronous speed, each particle of the rotor experiences a reversing magnetic field at the "slip" frequency which drives it around its hysteresis loop, causing the rotor field to lag and create torque. There is a 2-pole low reluctance bar structure in the rotor.^[2] As the rotor approaches synchronous speed and slip goes to zero, this magnetizes and aligns with the stator field, causing the rotor to "lock" to the rotating stator field.

A major advantage of the hysteresis motor is that since the lag angle δ is independent of speed, it develops constant torque from startup to synchronous speed. Therefore it is self-starting and doesn't need an induction winding to start it, although many designs do have a squirrel-cage conductive winding structure embedded in the rotor to provide extra torque at start-up.

- **Permanent-magnet motors:** These have permanent magnets embedded in the solid steel rotor to create a constant magnetic field. At synchronous speed these poles lock to the rotating magnetic field. They are not self-starting. Because of the constant magnetic field in the rotor these cannot use induction windings for starting, and must have electronically controlled variable frequency stator drive.^[3]

Reluctance motor designs have ratings that range from sub-fractions of 735 W to about 22 kW. Motors of sub-fractions of 735 W have low torque, and are generally used for instrumentation applications. Moderate torque, integral horsepower motors use squirrel cage construction with toothed rotors. When used with an adjustable frequency power supply, all motors in the drive system can be controlled at exactly the same speed. The power supply frequency determines motor operating speed.

Hysteresis motors are manufactured in sub-fractional horsepower ratings, primarily as servomotors and timing motors. More expensive than the reluctance type, hysteresis motors are used where precise constant speed is required.

DC-excited motors

Made in sizes larger than 735 W, these motors require direct current supplied through slip rings for excitation. The direct current can be supplied from a separate source or from a DC generator directly connected to the motor shaft

Slip rings and brushes are used to conduct current to the rotor. The rotor poles connect to each other and move at the same speed.

Synchronous motors fall under the category of synchronous machines which also includes the alternator (synchronous generator). These machines are commonly used in analog electric clocks, timers and other devices where correct time is required.

Synchronous speed

The "synchronous speed" n_s of a synchronous motor is the rate of rotation in RPM of the stator magnetic field. After startup it is also the rotation rate of the motor:

$$n_s = \frac{120 \times f}{p}$$

where f is the frequency of the AC supply current in Hz and p is the number of magnetic poles per phase. For example, small 3-phase synchronous motors usually have 6 poles organized as 3 opposing pairs at angles of 120° , each pair powered by one phase, so $p = 2$ per phase. Thus for 60 Hz supply current the synchronous speed is 3600 RPM. (N.B. 'p' can also refer to pole pairs, in which case the equation becomes: Speed of rotation = $60 \times f / p$).

Parts

A typical synchronous motor has the following parts:

- A stator winding, connected to the AC supply, which creates a rotating magnetic field.
- A rotor which turns within the stator field. In excited machines this carries a field winding supplied by DC current from the slip rings. This winding is an electromagnet. In non-excited machines, the rotor is a solid cylindrical steel casting, while in permanent magnet motors there are permanent magnets in the rotor.
- In DC excited machines, slip rings on the rotor supply the DC to the field winding from an external supply (some motors have other arrangements).
- The stator frame contains and supports the other parts and may include bearing housings.

Large machines include additional parts for cooling the machine, supporting the rotor, lubricating and cooling the bearings, and various protection and measurement devices.

Operation

The operation of a synchronous motor is simple to imagine. The 'Stator' winding, when excited by a poly-phase (usually 3-phase) supply, creates a rotating magnetic field inside the motor. The rotor winding, which acts as a permanent magnet, simply locks in with the rotating magnetic field and rotates along with it. During operation, as the rotor locks in with the rotating magnetic field, the motor is said to be in synchronization.

Once the motor is in operation, the speed of the motor is dependent only on the supply frequency. When the motor load is increased beyond the breakdown load, the motor falls out of synchronization i.e., the applied load is large enough to pull out the field winding from following the rotating magnetic field. The motor immediately stalls after it falls out of synchronization.

Starting methods

Small synchronous motors are able to start without assistance due to the low mass of the rotor, and the low *starting current* needed to rapidly accelerate the rotor to full speed from a dead stop. Synchronous motors are commonly used in line-powered electric mechanical clocks that use the powerline frequency to run the gear mechanism at the correct speed.

Three phase and two phase (uncommon) synchronous motors are naturally driven to rotate following the direction of the stepped-overlap phases. Single-phase synchronous motors such as in electric wall clocks can freely rotate in either direction and keep in phase with the rising and falling field strength. Wall clock motors

typically use an anti-reversing mechanism so that the synchronous motor won't start turning the mechanism backwards.

Above a certain size, synchronous motors are not self-starting motors. This property is due to the inertia of the rotor. When the power supply is switched on, the armature winding and field windings are excited. Instantaneously, the armature winding creates a rotating magnetic field, which revolves at the designated motor speed. The rotor, due to inertia, will not follow the revolving magnetic field, but instead acts as a synchronous generator (alternator) and creates a very large counter-current that opposes the rotation. More supply current is needed to overcome this resistance to motion, which results in a power draw so large that it may trip the overcurrent protection. For very large industrial synchronous motor/generators with large power supply capabilities, it may be possible to accelerate the rotor to full speed from a dead stop, but both the motor and the driven equipment may be damaged by the near-instantaneous acceleration.

When synchronous generators are brought online and synchronized, it is important they be closely matched before switched to full current, as the generator can be capable of tearing itself off the foundation or damaging its internal power windings, acting as a motor to accelerate to the correct synchronization.

In practice, the rotor should be rotated by some other means near to the motor's synchronous speed to overcome the inertia. Once the rotor nears the synchronous speed, the field winding is excited, and the motor pulls into synchronization.

The following techniques are employed to start a synchronous motor:

- A separate motor (called pony motor) is used to drive the rotor before it locks in into synchronization.
- The field winding is shunted or induction motor like arrangements are made so that the synchronous motor starts as an induction motor and locks in to synchronization once it reaches speeds near its synchronous speed.
- Reducing the input electrical frequency to get the motor starting slowly, variable-frequency drives can be used here which have rectifier-inverter circuits or cycloconverter circuits.

Special Properties

Synchronous motors show some interesting properties, which finds applications in power factor correction. The synchronous motor can be run at lagging, unity or leading power factor. The control is with the field excitation, as described below:

- When the field excitation voltage is decreased, the motor runs in lagging power factor. The power factor by which the motor lags varies directly with the drop in excitation voltage. This condition is called under-excitation.
- When the field excitation voltage is made equal to the rated voltage, the motor runs at unity power factor.
- When the field excitation voltage is increased above the rated voltage, the motor runs at leading power factor. And the power factor by which the motor leads varies directly with the increase in field excitation voltage. This condition is called over-excitation.
- The most basic property of synchro motor is that it can be used both as a capacitor or inductor. Hence in turn it improves the power factor of system.

The leading power factor operation of synchronous motor finds application in power factor correction. Normally, all the loads connected to the power supply grid run in lagging power factor, which increases reactive power consumption in the grid, thus contributing to additional losses. In such cases, a synchronous motor with no load is connected to the grid and is run over-excited, so that the leading power factor created by synchronous motor compensates the existing lagging power factor in the grid and the overall power factor is brought close to

1 (unity power factor). If unity power factor is maintained in a grid, reactive power losses diminish to zero, increasing the efficiency of the grid. This operation of synchronous motor in over-excited mode to correct the power factor is sometimes called as synchronous condenser.

When used as part of a mechanical clock, a synchronous motor's timekeeping ability is only as accurate as the average line frequency provided by the power source. Although a small amount of frequency drift may occur throughout the course of a day, power companies actively adjust the line frequency to prevent mechanically driven clocks from gradually gaining or losing time. (This topic is discussed in more detail with citations, in the article Utility frequency, in the *Stability* section.)

Uses

- Synchronous motors find applications in all industrial applications where constant speed is necessary.
- Improving the power factor as synchronous condensers.
- Low power applications include positioning machines, where high precision is required, and robot actuators.
- Mains synchronous motors are used for electric clocks.
- Record player turntables

Advantages

Synchronous motors have the following advantages over non-synchronous motors:

- Speed is independent of the load, provided an adequate field current is applied.
- Accurate control in speed and position using open loop controls, e.g. stepper motors.
- They will hold their position when a DC current is applied to both the stator and the rotor windings.
- Their power factor can be adjusted to unity by using a proper field current relative to the load. Also, a "capacitive" power factor, (current phase leads voltage phase), can be obtained by increasing this current slightly, which can help achieve a better power factor correction for the whole installation.
- Their construction allows for increased electrical efficiency when a low speed is required (as in ball mills and similar apparatus).
- They run either at the synchronous speed or they do not run at all.

Examples

- Three-phase AC synchronous motors
- Synchronous brushless wound-rotor doubly fed electric machine

The following have synchronous types, but are frequently not synchronous:

- Stepper motor
- Reluctance motor