

# Synchronous motor

From Wikipedia, the free encyclopedia

A **synchronous electric motor** is an AC motor in which, at steady state,<sup>[1]</sup> the rotation of the shaft is synchronized with the frequency of the supply current; the rotation period is exactly equal to an integral number of AC cycles. Synchronous motors contain multiphase AC 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 with permanent magnets or electromagnets turns in step with the stator field at the same rate and as a result, provides the second synchronized rotating magnet field of any AC motor. A synchronous motor is only considered doubly fed if is supplied with independently excited multiphase AC electromagnets on both the rotor and stator.

The synchronous motor and induction motor are the most widely used types of AC motor. The difference between the two types is that the synchronous motor rotates in exact synchronism with the line frequency. The synchronous motor does not rely on current induction to produce the rotor's magnetic field. By contrast, the induction motor requires "*slip*", the rotor must rotate slightly slower than the AC current alternations, to induce current in the rotor winding. Small synchronous motors are used in timing applications such as in synchronous clocks, timers in appliances, tape recorders and precision servomechanisms in which the motor must operate at a precise speed; speed accuracy is that of the power line frequency, which is carefully controlled in large interconnected grid systems.



A synchronous motor-generator set for AC to DC conversion, circa 1909



Small synchronous motor and integral stepdown gear from a microwave oven

Synchronous motors are available in sub-fractional **self-excited** sizes<sup>[2]</sup> to high-horsepower industrial sizes.<sup>[1]</sup> In the fractional horsepower range, most synchronous motors are used where precise constant speed is required. These machines are commonly used in analog electric clocks, timers and other devices where correct time 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.

## Contents

- 1 Type
  - 1.1 Non-excited motors
    - 1.1.1 Reluctance motors
    - 1.1.2 Hysteresis motors
    - 1.1.3 Permanent magnet motors
  - 1.2 DC-excited motors
- 2 Synchronous speed
  - 2.1 Example
- 3 Construction
- 4 Operation
- 5 Starting methods
- 6 Features of Synchronous Motor<sup>[27]</sup>
- 7 Applications, special properties, and advantages
  - 7.1 Use as synchronous condenser
  - 7.2 Steady state stability limit
  - 7.3 Other
- 8 Subtypes
- 9 See also
- 10 References
- 11 External links

## Type

Synchronous motors fall under the more general category of *synchronous machines* which also includes the synchronous generator. Generator action will be observed if the field poles are "driven ahead of the resultant air-gap flux by the forward motion of the prime mover". Motor action will be observed if the field poles are "dragged behind the resultant air-gap flux by the retarding torque of a shaft load".<sup>[1]</sup>

There are two major types of synchronous motors depending on how the rotor is magnetized: *non-excited* and *direct-current excited*.<sup>[3]</sup>

## Non-excited motors

In non-excited motors, the rotor is made of 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:

[4]

## Reluctance motors

These have a rotor consisting of a solid steel casting with projecting (salient) toothed poles. Typically there are fewer rotor than stator poles to minimize torque ripple and to prevent the poles from all aligning simultaneously—a position which cannot generate torque.<sup>[2][5]</sup> 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



Single-phase 60 Hz 1800 RPM synchronous motor for Teletype machine, non-excited rotor type, manufactured from 1930 to 1955.

torque below synchronous speed. The machine starts as an induction motor until it approaches synchronous speed, when the rotor "pulls in" and locks to the rotating stator field.<sup>[6]</sup>

Reluctance motor designs have ratings that range from fractional horsepower (a few watts) to about 22 kW. Very small reluctance motors 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**

These have a solid smooth cylindrical rotor, cast of a high coercivity magnetically "hard" cobalt steel.<sup>[5]</sup> This material has a wide hysteresis loop (high coercivity), 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  $\delta$ , 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.<sup>[5]</sup> 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  $\delta$  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.

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.

## Permanent magnet motors

A permanent magnet synchronous motor (PMSM) uses permanent magnets embedded in the steel rotor to create a constant magnetic field. The stator carries windings connected to an AC supply to produce a rotating magnetic field. At synchronous speed the rotor poles lock to the rotating magnetic field. Permanent magnet synchronous motors are similar to brushless DC motors.

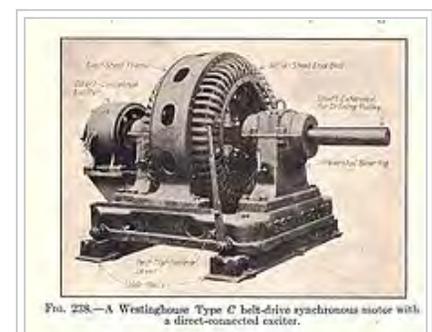
Because of the constant magnetic field in the rotor these cannot use induction windings for starting. These motors require a variable-frequency power source to start.<sup>[7][8][9][10][11]</sup>

The main difference between a permanent magnet synchronous motor and an asynchronous motor is the rotor. Some studies seem to indicate that NdFeB permanent magnet synchronous motors are around 2 percent more efficient than the highest-efficiency (IE3) asynchronous motors—using the same stator laminations and similar variable-frequency speed controllers.<sup>[12]</sup>

Permanent magnet motors have been used as gearless elevator motors since 2000.<sup>[13]</sup>

## DC-excited motors

Usually made in larger sizes (larger than about 1 horsepower or 1 kilowatt) these motors require direct current (DC) supplied to the rotor for excitation. This is most straightforwardly supplied through slip rings, but a brushless AC induction and rectifier arrangement may also be used.<sup>[14]</sup> The direct current may be supplied from a separate DC source or from a DC generator directly connected to the motor shaft.



DC-excited motor, 1917.

The exciter is clearly seen at the rear of the machine.

## Synchronous speed

The synchronous speed of a synchronous motor is given:<sup>[15]</sup>  
in rpm, by:

$$N_s = 60 \frac{f}{p}$$

and in  $\text{rad} \cdot \text{s}^{-1}$ , by:

$$\omega_s = 2\pi \frac{f}{P}$$

where:

$f$  is the frequency of the AC supply current in Hz,

$p$  is the number of poles per phase.  $P$  is the pair number of poles per phase.  $P = p/2$

If  $p$  is the number of pole pairs per phase (rarely called 'planes of commutation') instead, simply divide both formulas by 2.

## Example

A 3-phase, 12-pole (6-pole-pair) synchronous motor is operating at an AC supply frequency of 50 Hz. The number of poles per phase is  $12/3 = 4$ , so the synchronous speed is:

$$N_s = 60 \times \frac{50}{4} = 750 \text{ rpm}$$

## Construction

The principal components of a synchronous motor are the stator and the rotor.<sup>[16]</sup> The stator of synchronous motor and stator of induction motor are similar in construction.<sup>[17]</sup> With the wound-rotor synchronous doubly fed electric machine as the exception, the stator frame contains *wrapper plate*.<sup>[18]</sup> *Circumferential ribs* and *keybars* are attached to the wrapper plate.<sup>[18]</sup> To carry the weight of the machine, *frame mounts* and *footings* are required.<sup>[18]</sup> When the field winding is excited by DC excitation, brushes and slip rings are required to connect to the excitation supply.<sup>[19]</sup> The field winding can also be excited



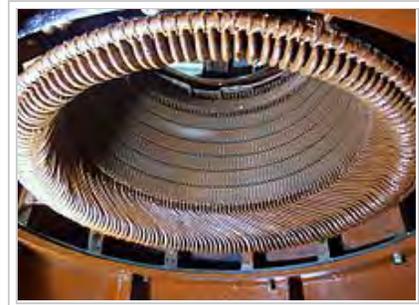
Rotor of a large water pump. The slip rings can be seen below the rotor drum.

by a brushless exciter.<sup>[20]</sup> Cylindrical, round rotors, (also known as non salient pole rotor) are used for up to six poles. In some machines or when a large number of poles are needed, a salient pole rotor is used.<sup>[21][22]</sup> The construction of synchronous motor is similar to that of a synchronous alternator.<sup>[23]</sup>

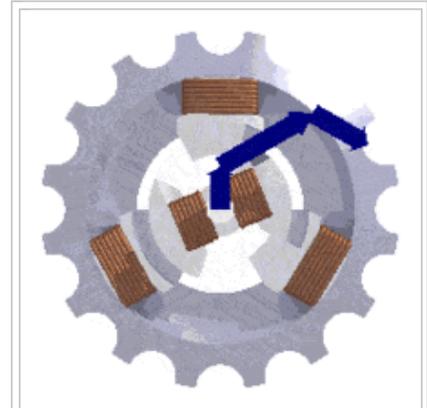
## Operation

The operation of a synchronous motor is due to the interaction of the magnetic fields of the stator and the rotor. Its stator winding, which consists of a 3 phase winding, is provided with a 3 phase supply, and the rotor is provided with a DC supply. The 3 phase stator winding carrying 3 phase currents produces 3 phase rotating magnetic flux (and therefore a rotating magnetic field). The rotor locks in with the rotating magnetic field and rotates along with it. Once the rotor locks in with the rotating magnetic field, the motor is said to be in synchronization. A single-phase (or two-phase derived from single phase) stator winding is possible, but in this case the direction of rotation is not defined and the machine may start in either direction unless prevented from doing so by the starting arrangements.<sup>[24]</sup>

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 and the field winding no longer follows the rotating magnetic field. Since the motor cannot produce (synchronous) torque if it falls out of synchronization, practical synchronous motors have a partial or complete squirrel-cage damper (amortisseur) winding to stabilize operation and facilitate starting. Because this winding is smaller than that of an equivalent induction motor and can overheat on long operation, and because large slip-frequency voltages are induced in the rotor excitation winding, synchronous motor protection devices sense this condition and interrupt the power supply (out of step protection).<sup>[24]</sup>



Stator winding of a large water pump



The rotating magnetic field is formed from the sum of the magnetic field vectors of the three phases of the stator windings

## Starting methods

Above a certain size, synchronous motors are not self-starting motors. This property is due to the inertia of the rotor; it cannot instantly follow the rotation of the magnetic field of the stator. Since a synchronous motor produces no inherent average torque at standstill, it cannot accelerate to synchronous speed without some supplemental mechanism.<sup>[2]</sup>

Large motors operating on commercial power frequency include a "squirrel cage" induction winding which provides sufficient torque for acceleration and which also serves to damp oscillations in motor speed in operation.<sup>[2]</sup> Once the rotor nears the synchronous speed, the field winding is excited, and the motor pulls into synchronization. Very large motor systems may include a "pony" motor that accelerates the unloaded synchronous machine before load is applied.<sup>[25]</sup> Motors that are electronically controlled can be accelerated from zero speed by changing the frequency of the stator current.<sup>[26]</sup>

Very small synchronous motors are commonly used in line-powered electric mechanical clocks or timers that use the powerline frequency to run the gear mechanism at the correct speed. Such small synchronous motors are able to start without assistance if the moment of inertia of the rotor and its mechanical load is sufficiently small [because the motor] will be accelerated from slip speed up to synchronous speed during an accelerating half cycle of the reluctance torque."<sup>[2]</sup> Single-phase synchronous motors such as in electric wall clocks can freely rotate in either direction unlike a shaded-pole type. See Shaded-pole synchronous motor for how consistent starting direction is obtained.

## Features of Synchronous Motor<sup>[27]</sup>

Some characteristic features of Synchronous Motor are as follow :

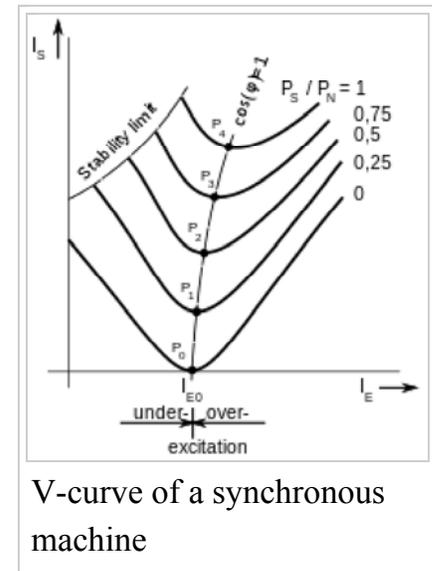
1. It runs either at synchronous speed or not at all. That is, while running it maintains a constant speed. The speed is independent of load.
2. It is not inherently self-starting. It has to be run at synchronous speed by some means before it can be synchronized to supply.
3. It can be operated under wide range of power factors both lagging and leading.

4. It will stall if, while running, counter torque is increased beyond the maximum torque that machine can develop.
5. speed of the synchronous motor can be controlled by inverter units

## Applications, special properties, and advantages

### Use as synchronous condenser

By varying the excitation of a synchronous motor, it can be made to operate at lagging, leading and unity power factor. Excitation at which the power factor is unity is termed *normal excitation voltage*.<sup>[28]</sup> The magnitude of current at this excitation is minimum.<sup>[28]</sup> Excitation voltage more than normal excitation is called over excitation voltage, excitation voltage less than normal excitation is called under excitation.<sup>[28]</sup> When the motor is over excited, the back emf will be greater than the motor terminal voltage. This causes a demagnetizing effect due to armature reaction.<sup>[29]</sup>



V-curve of a synchronous machine

The V curve of a synchronous machine shows armature current as a function of field current. With increasing field current armature current at first decreases, then reaches a minimum, then increases. The minimum point is also the point at which power factor is unity.<sup>[30]</sup>

This ability to selectively control power factor can be exploited for power factor correction of the power system to which the motor is connected. Since most power systems of any significant size have a net lagging power factor, the presence of overexcited synchronous motors moves the system's net power factor closer to unity, improving efficiency. Such power-factor correction is usually a side effect of motors already present in the system to provide mechanical work, although motors can be run without mechanical load simply to provide power-factor correction. In large industrial plants such as factories the interaction between synchronous motors and other, lagging, loads may be an explicit consideration in the plant's electrical design.

### Steady state stability limit

$$\mathbf{T} = \mathbf{T}_{\max} \sin \delta$$

where,

$\mathbf{T}$  is the torque

$\delta$  is the torque angle

$\mathbf{T}_{\max}$  is the maximum torque

here,

$$\mathbf{T}_{\max} = \frac{3\mathbf{VE}}{\mathbf{X}_s \omega_s}$$

When load is applied, torque angle  $\delta$  increases. When  $\delta = 90^\circ$  the torque will be maximum. If load is applied further then the motor will lose its synchronism, since motor torque will be less than load torque.<sup>[31][32]</sup> The maximum load torque that can be applied to a motor without losing its synchronism is called steady state stability limit of a synchronous motor.<sup>[31]</sup>

## Other

Synchronous motors are especially useful in applications requiring precise speed and/or position control.

- Speed is independent of the load over the operating range of the motor.
- Speed and position may be accurately controlled using open loop controls, e.g. stepper motors.
- Low-power applications include positioning machines, where high precision is required, and robot actuators.
- They will hold their position when a DC current is applied to both the stator and the rotor windings.
- A clock driven by a synchronous motor is in principle as accurate as the line frequency of its power source. (Although small frequency drifts will occur over any given several hours, grid operators actively adjust line frequency in later periods to compensate, thereby keeping motor-driven clocks accurate (see *Utility frequency#Stability*)).
- Record player turntables
- Increased efficiency in low-speed applications (e.g. ball mills).

## Subtypes

- Three-phase AC synchronous motors
- Synchronous brushless wound-rotor doubly fed electric machine
- Stepper motor (may be synchronous or not)
- Reluctance motor (may be synchronous or not)

## See also

- Short circuit ratio
- Doubly fed electric machine

## References

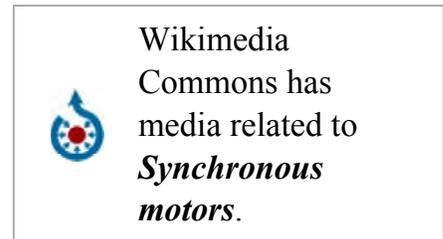
1. Fitzgerald, A. E.; Charles Kingsley, Jr.; Alexander Kusko (1972). "Chapter 6, Synchronous machines, steady state". *Electric Machinery, 3rd Ed.* USA: McGraw-Hill. pp. 283–330. Library of Congress Catalog No. 70-137126.
2. Fitzgerald, A. E.; Charles Kingsley, Jr.; Alexander Kusko (1971). "Chapter 11, section 11.2 Starting and Running Performance of Single-phase Induction and Synchronous Motors, Self-starting Reluctance Motors". *Electric Machinery, 3rd Ed.* USA: McGraw-Hill. pp. 536–538. Library of Congress Catalog No. 70-137126.
3. James G Stallcup, *Stallcup's Generator, Transformer, Motor and Compressor*, page 15-13, Jones & Bartlett, 2012 ISBN 1-4496-9519-1.
4. William Yeadon (ed.), *Handbook of Small Electric Motors*, McGraw-Hill 2001 ISBN 0-07-072332-X, Chapter 12 "Synchronous Machines"
5. Gottlieb, Irving M. (1997). *Practical electric motor handbook, 2nd Ed.* USA: Newnes. pp. 73–76. ISBN 0-7506-3638-6.
6. Michael A. Laughton (2003), "19.2.5 Reluctance motors", *Electrical Engineer's Reference Book*, Newnes, p. 19/8, ISBN 978-0-7506-4637-6
7. R. Islam; I. Husain; A. Fardoun; K. McLaughlin. "Permanent-Magnet Synchronous Motor Magnet Designs With Skewing for Torque Ripple and Cogging Torque Reduction" (<http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=4757411>). Industry Applications, IEEE Transactions on. 2009. doi: 10.1109/TIA.2008.2009653 (<https://dx.doi.org/10.1109%2FTIA.2008.2009653>)
8. Ki-Chan Kim; Seung-Bin Lim; Dae-Hyun Koo; Ju Lee. "The Shape Design of Permanent Magnet for Permanent Magnet Synchronous Motor Considering Partial Demagnetization" (<http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=1704668>). Magnetics, IEEE Transactions on. 2006. doi: 10.1109/TMAG.2006.879077 (<https://dx.doi.org/10.1109%2FTMAG.2006.879077>)

9. P. Pillay; R. Krishnan. "Application characteristics of permanent magnet synchronous and brushless DC motors for servo drives" (<http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=90357>). Industry Applications, IEEE Transactions on. 1991. doi: 10.1109/28.90357 (<https://dx.doi.org/10.1109%2F28.90357>) quote: "The permanent magnet synchronous motor (PMSM) and the brushless DC motor (BDCM) have many similarities; they both have permanent magnets on the rotor and require alternating stator currents to produce constant torque."
10. Y. Honda; T. Nakamura; T. Higaki; Y. Takeda. "Motor design considerations and test results of an interior permanent magnet synchronous motor for electric vehicles" (<http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=643011>). Industry Applications Conference, 1997. Thirty-Second IAS Annual Meeting, IAS '97., Conference Record of the 1997 IEEE. 1997. doi: 10.1109/IAS.1997.643011 (<https://dx.doi.org/10.1109%2F2FIAS.1997.643011>)
11. M.A. Rahman; Ping Zhou. "Analysis of brushless permanent magnet synchronous motors" (<http://ieeexplore.ieee.org/xpl/login.jsp?tp=&arnumber=491349>). Industrial Electronics, IEEE Transactions on. 1996. doi: 10.1109/41.491349 (<https://dx.doi.org/10.1109%2F41.491349>)
12. Markus Lindegger. "Economic viability, applications and limits of efficient permanent magnet motors" (<http://www.circlemotor.ch/downloads/summaryinenglish.pdf>). p. 7, p. 21
13. Mehri, Darius Mehri (2000-09-18). "Belts lift performance". Design News.
14. H.E. Jordan, *Energy-Efficient Electric Motors and Their Applications*, page 104, Springer, 1994 ISBN 0-306-44698-7
15. "Motor speed". Electrician's toolbox etc.
16. "Electrical machine". University of Alberta.
17. Finney, David. *Variable Frequency Ac Motor Drive System*. B (1991 reprint ed.). Peter Peregrinus, Ltd. p. 33. ISBN 978-0-86341-114-4.
18. Isidor Kerszenbaum, Geoff Klempner. *Handbook of Large Turbo-Generator Operation and Maintenance* (Second ed.). Wiley.
19. Gerald B. Kliman, Hamid A. Toliyat. *Handbook of Electric Motors* (Second ed.). p. 302.
20. Jordan, Howard E. *Energy-Efficient Electric Motors and Their Applications*. B (Second ed.). Plenum press. p. 104. ISBN 0-306-44698-7.
21. Theraja, B.L. *Electrical technology*. II (2010 reprint ed.). S. Chand. p. 1404. ISBN 81-219-2437-5.
22. Isidor Kerszenbaum, Geoff Klempner. *Handbook of Large Turbo-Generator Operation and Maintenance* (Second ed.). Wiley.
23. Theraja, B.L. *Electrical technology*. II (2010 reprint ed.). S. Chand. p. 1490. ISBN 81-219-2437-5.
24. IEEE Standard 141-1993 *Recommended Practice for Electric Power Distribution for Industrial Plants* pages 227-230
25. Jerry C. Whitaker, *AC Power Systems Handbook*, page 192, CRC Press, 2007 ISBN 0-8493-4034-9.
26. David Finney, *Variable Frequency AC Motor Drive System*, page 32, IEE, 1988 ISBN 0-86341-114-2.
27. Hussain, Ashfaq. *Electric Machines*. Dhanpat Rai and Co.

28. Bhattacharya, S. K. *Electrical Machines* (third ed.). Tata - McGraw Hill. p. 481. OCLC 808866911.
29. Kosow, Irving L. *Electric Machinery And Transformers* (second ed.). Pearson Education. p. 230. OCLC 222453.
30. Theraja, B L; Theraja, A K. *Electrical technology*. II (2010 reprint ed.). S Chand. p. 1524.
31. Dubey, G K. *Fundamentals of electrical drives*. Narosa publishing chennai. p. 254.
32. Pillai, S K. *A First Course On Electrical Drives* (second ed.). New age international. p. 25.

## External links

- Synchronous motor animation



(<http://www.animations.physics.unsw.edu.au/jw/electricmotors.html#ACmotors>)

Retrieved from "https://en.wikipedia.org/w/index.php?title=Synchronous\_motor&oldid=756748015"

Categories: Electric motors | Synchronous machines | Synchronous motors

- 
- This page was last modified on 26 December 2016, at 16:07.
  - Text is available under the Creative Commons Attribution-ShareAlike License; additional terms may apply. By using this site, you agree to the Terms of Use and Privacy Policy. Wikipedia® is a registered trademark of the Wikimedia Foundation, Inc., a non-profit organization.