Electrical Tech Note — 316

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Synchronous Motors

There are numerous applications where an electric motor must have an exact shaft rotation. Timing devices and tape drives are applications where exact shaft rotation is necessary. An ac synchronous motor is one where the shaft rotation is exactly the same as the magnetic field rotation. For a 60 Hz 2-pole motor the field rotates at 3600 rpm and for a 4-pole motor the field rotates at 1800 rpm.

There are three basic types of synchronous motors based upon the type of rotor used. The rotors for a synchronous motor are different than for a squirrel cage induction motor. One type has windings on the rotor excited by direct current to crate a magnetic field independent of the stator field. The second has a reluctance type rotor. It is similar in construction to the dc excited rotor but without any windings. The third type uses the principle of magnetic hysteresis in a special steel shell that surrounds the rotor.

The power supply to the synchronous motor can be single-phase or 3-phase. The stator design is similar to that of a conventional squirrel cage induction motor. There will be natural magnetic field rotation with 3-phase power. Typical single-phase motor methods of obtaining a rotating magnetic field use split-phase starting, capacitor starting, permanent split capacitor starting, or magnetic pole shading. The basic operation of the various types of synchronous motors is discussed in this Tech Note. Typical synchronous motors have multiple poles, but for the purpose of simplicity this discussion will be limited to 2-pole motors.

Direct Current Excited Rotor: The rotor is designed in an elongated shape as far as the magnetic steel portion is concerned. The rotor has an aluminum squirrel cage like a conventional induction motor except the steel core in elongated as shown in Figure 316.1. Windings are placed on the rotor and energized with direct current. This produces a North pole at one end of the rotor and a South pole at the other end. Direct current is fed to the rotor through slip rings and brushes on one end of the shaft.

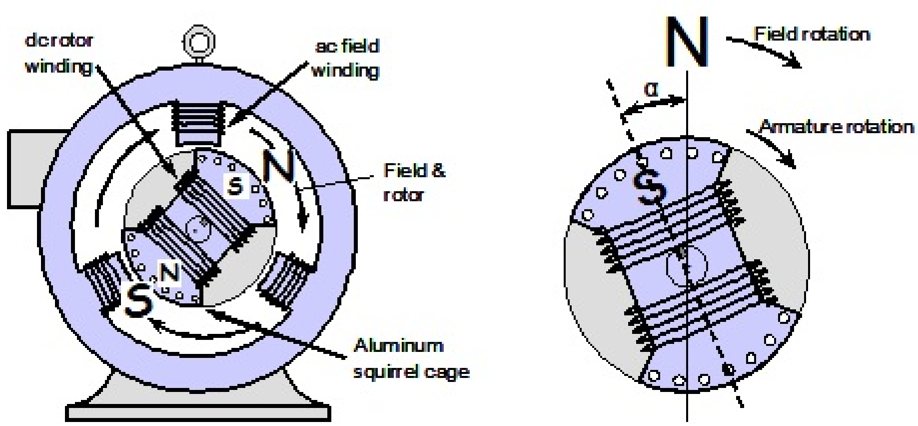

Figure 316.1 One type of synchronous motor supplies direct current to the rotor to create a rotor magnetic field independent of the stator magnetic field.

When the rotor is first energized, it acts like an ordinary squirrel cage induction motor. Current is induced into the rotor squirrel cage which produces a magnetic field in the rotor that results in rotation. As with induction motors, there must be slip between the rotor and the rotating field. This means as an induction motor the rotor can never catch up with the rotating field. This is where the dc winding on the rotor comes into play. By energizing the rotor winding, magnetic poles are produced on the rotor that are not dependent upon induction. When the rotor gets to within about 50 rpm of the field rotation, the magnetic attraction is great enough to pull the rotor up to synchronous speed. Now the rotor South pole is locked to the rotating field North pole and vice versa for the other end of the rotor. This attraction is somewhat like a rubber band. As the load increases the rotor falls back a few degrees but still continues to rotate at synchronous speed. If the load gets too great the magnetic bond between the rotor and stator fields is broken and the rotor drops out of synchronization.

The dc excited rotor synchronous motor requires a supply of direct current as well as a supply of alternating current. These motors typically range from a few horsepower in size up to several thousand horsepower. Because the rotor is dc excited and has a fixed magnetic field, it can be used as a generator if a prime mover is connected to the shaft. For example, a synchronous motor can be used to pump water into a storage lake and then later used as a generator when the water is released.

The rotor with windings and dc current flow is a rotating magnet that induces a voltage *(counter voltage)* in the stator windings that opposes the supply voltage. If there is no load on the motor, the counter voltage will be 180° out-of-phase of the supply voltage. Theoretically it is possible to adjust the excitement of the rotor winding so that the counter voltage is exactly the same as the supply voltage and the motor runs with no current draw. This is illustrated in the left hand diagram of Figure 316.2. There is always some friction and air resistance so there will be some current flow. Note in the right hand diagram of Figure 316.1 that when load is applied, the rotor falls behind the field by an angle alpha (α). This results in the counter voltage vector being less than 180° out-of-phase of the supply voltage by alpha (α) degrees. The right hand diagram of Figure 316.2 illustrates the supply voltage, and induced counter voltage of a synchronous motor powering a load. By adding the supply voltage to the counter voltage, a net or *effective voltage* results that is responsible for current flow through the stator.

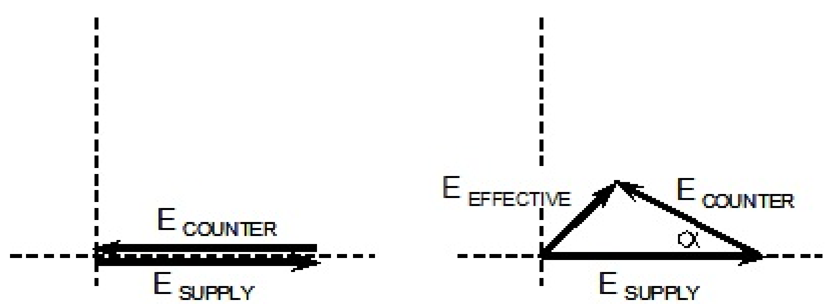

Figure 316.2 The rotating magnetic field of the rotor creates a counter voltage in the stator windings that subtracts from the supply voltage to give the effective voltage that is responsible for current flow through the stator windings. The angle alpha (α) increases as the load on the motor increases. The magnitude of the counter voltage can be increased by increasing the strength of the rotor magnetic field.

The current through the motor windings (I_{MOTOR}) will lag behind the effective winding voltage ($E_{EFFECTIVE}$) usually by 50° to 70°. The circuit supplying the motor provides the supply voltage (E_{SUPPLY}) and carries the motor current. The power factor of the circuit is the cosine of the angle theta (θ) between the supply voltage and the motor current as shown in Figure 316.3. By increasing the dc excitation of the rotor, the amount of counter voltage will increase thus changing the angle of the effective voltage with respect to the supply voltage as shown in the right hand diagram of Figure 316.3. As the angle of the effective voltage increases, the angle theta (θ) between the supply voltage and the motor current will change. The angle theta (θ) can be changed from a typical negative angle to a positive angle with respect to the supply voltage. It is the angle theta (θ) that determines the power factor of the circuit. Note that for a dc excited rotor synchronous motor the angle between the circuit current and the supply voltage will be quite small and the power factor will be close to one.

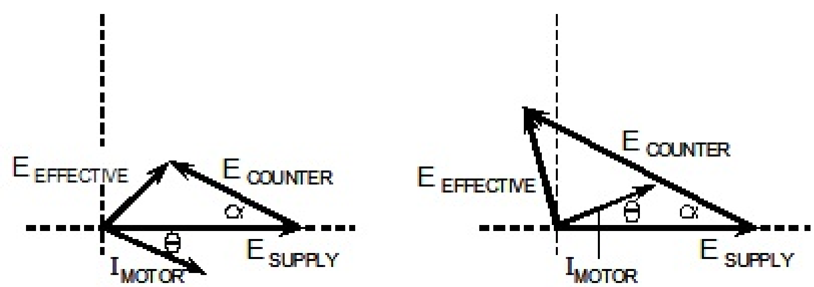

Figure 316.3 Increasing the excitation of the rotor field can result in a shift in the supply current angle with respect to the supply voltage and the current can be changed from lagging the supply voltage to leading.

Since the synchronous motor rotates at a constant speed, increasing the rotor current will strengthen the rotor flux thus resulting in increased counter voltage. If the load remains the same, the angle alpha (α) will remain unchanged. Note that increasing the dc excitation of the rotor results in a change in the angle of the effective voltage. This will also result in a change in the angle of the motor current as can be seen in the right hand diagram of Figure 316.3. The motor current is now leading the supply voltage by some angle theta (θ). Because the dc excited rotor synchronous motor line current is leading the supply voltage, the synchronous motor acts like a power factor correcting capacitor. Synchronous motors can actually be used to correct power factor in industrial plants with many induction motors that cause a lagging current. The amount of power factor correction is controlled by the level of dc excitation of the rotor winding.

Reluctance Type Rotor: A special rotor is installed in synchronous motors where a portion of the steel is cut away and replaced by a nonmagnetic material. This nonmagnetic material has a high reluctance where steel has a low reluctance. Magnetic flux will seek a path of low reluctance and it can create a force in the process. In the case of a solenoid with a movable steel core offset to the side as shown in Figure 316.4, a force will be exerted to move the core to the center of the magnetic flux of the coil. A similar process occurs with a reluctance type synchronous motor.

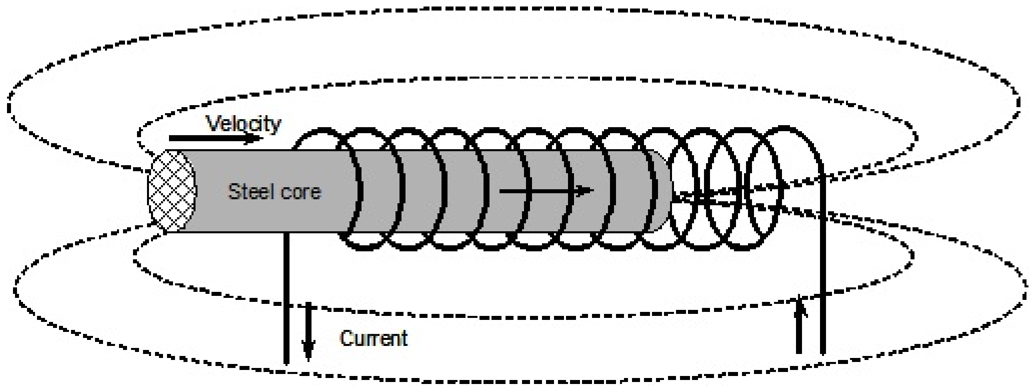

Figure 316.4 The steel core of a solenoid if permitted to move will attempt to center itself in the magnetic flux.

A reluctance type synchronous motor has no winding on the rotor. It starts as an induction motor. An induction motor must have slip between the rotor speed and the field rotational speed, and the rotor will never catch up to the rotation of the stator field. In the case of the 2-pole reluctance motor, there is only one low reluctance (high permeability) path for the magnetic field to take through the rotor as shown in Figure 316.5. As the rotor begins to catch up with the field rotation, the rotor will be pulled into line with the rotating field in a manner similar to the solenoid. This magnetic force to keep the rotor magnetic flux path in line with the field flux will keep the rotor turning at synchronous speed and induction is no longer needed. As in the case of the dc excited rotor, the reluctance type rotor will drop back as load is increases by an angle alpha (α). An advantage to this type of synchronous motor is that a source of direct current is not needed, but the attraction between the stator field and the rotor is not as strong as in the case of the dc excited rotor.

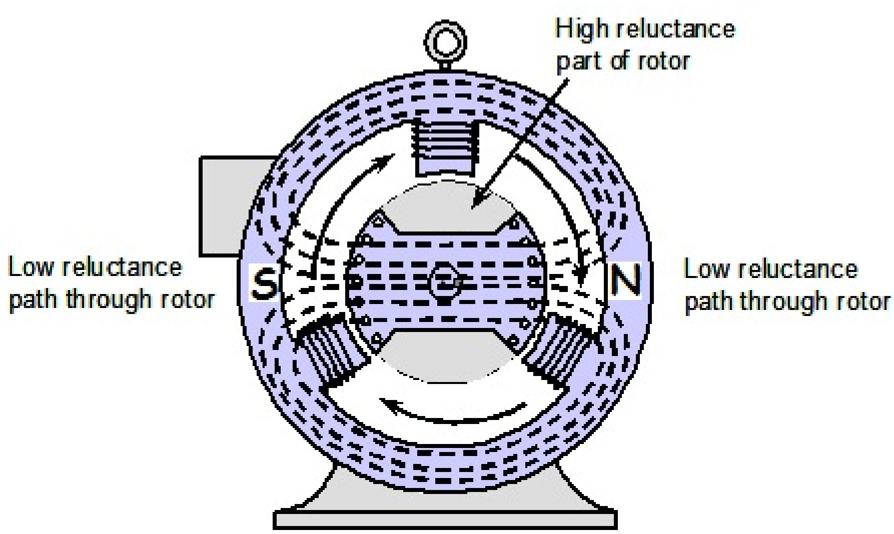

Figure 316.5 The elongated rotor with a low reluctance path will pull into the rotating magnetic field and turn at the same synchronous speed.

Hysteresis Rotor: Hysteresis is the phenomenon that causes residual magnetism. Most everyone has experienced the magnetism of a screwdriver. Sometimes it is helpful and sometimes it is very annoying. Figure 316.6 shows the process of producing a magnetic flux in a steel core by wrapping a winding around the core. The vertical axis is the flux density (B) in the steel core and the horizontal axis is the current flow in the winding necessary to create the flux. Start with the left hand diagram and a flux produced by a positive current flow. When the current is reduced to zero, the flux density does not go to zero. There is a residual magnetic flux in the steel core. The core remains magnetized. In order to get the flux to zero, it is necessary to apply a negative current flow to the coil as seen in the middle diagram of Figure 316.6. Increasing the negative current flow even further will now result in a negative flux. Now as seen in the right hand diagram, stopping the current flow does not result in zero flux. It is now necessary to apply a positive current flow to force the flux back to zero. Further increasing the positive current flow will bring the flux density back to the starting point. The right hand diagram is called a hysteresis loop. This principle can be used to get a specially designed rotor to catch up to the rotating magnetic field of a motor.

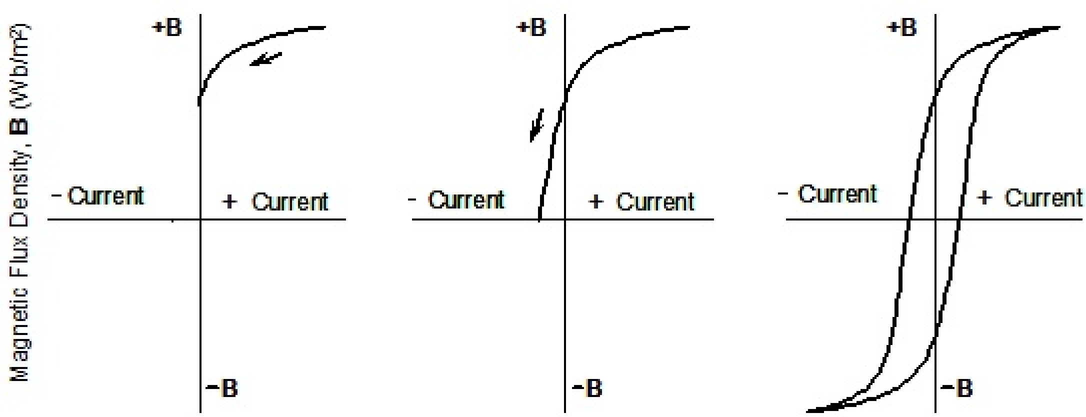

Figure 316.6 Magnetic materials experience hysteresis where reducing the current to zero will not result in a zero magnetic flux density in the material. Magnetic materials experience a property called residual magnetism.

The rotor of a hysteresis type synchronous motor is different than other types of rotors. The rotor is composed primarily of a nonmagnetic material with a thin outer shell (cylinder) made of a special steel alloy. The rotor will start by induction with current loops in the thin steel outer shell. In induction motors and other types of synchronous motors these currents flow in an aluminum (nonmagnetic) squirrel cage. Because the outer shell of the rotor is a magnetic material, due to residual magnetism, the rotor will remain magnetized when the induction current decreases to zero. As the rotor accelerates, it will get pulled into synchronization by the attraction of the residual magnetic field of the rotor and the rotating magnetic field. Figure 316.7 shown the rotor of a hysteresis type synchronous motor. This is a single-phase synchronous motor with shaded-pole starting.

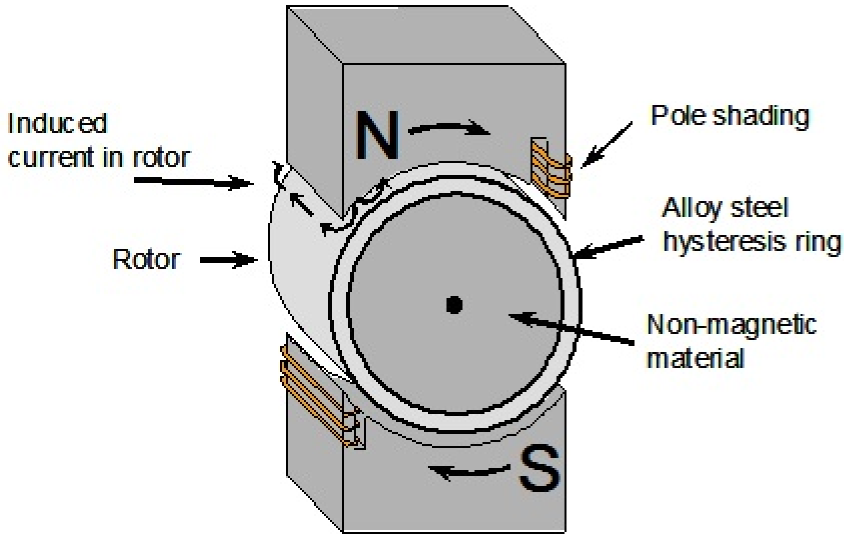

Figure 316.7 Hysteresis in the thin magnetic cylindrical shell of the rotor of this single-phase shaded-pole motor permits the rotor to achieve synchronous speed.