Plant efficiency benefits resulting from the use of synchronous motors

SYNCHRONOUS

VERSUS

INDUCTION MOTORS

NDUCTION MOTORS ARE OFTEN the choice for various industrial production processes. Use of an induction motor, however, will result in increased lagging power-factor burdens in the plant. This burden often must be corrected by adding capacitors. If not, the result is the penalty of larger kilovoltampere burdens to the interconnected system. For low-speed applications, synchronous motors may be a better choice when equipped with accessories that offer power-factor control. The synchronous machine, with the aid of an intelligent excitation controller, can control power factor to reduce the plant reactive loading to the connected system.

BY JIM PARRISH, STEVE MOLL, & RICHARD C. SCHAEFER

This article will discuss the application of the synchronous motor at the Lion Oil refinery and the digital excitation system used to control the machine power factor.

Background

Lion Oil is a refinery in El Dorado, Arkansas, that processes petroleum products. Environmental mandates that go into effect June 2006 include new clean-air regula-

tions requiring a reduction in sulfur emissions for diesel fuel from 500 parts to 15 parts per million.

Current refining equipment is not designed to process the petroleum product at the increased pressures and higher temperatures needed to meet the U.S. Environmental Protection Agency (EPA) regulations. To meet the refining requirements, a new, higher-rated motor connected to a hydrogen-reciprocating compressor would be needed to drive the refining process.

Lion Oil currently utilizes induction motors ranging in size from 100–3,500 hp (Figure 1). With such a large number of induction motors, power factor is an issue at the plant. Capacitors are used for correction to minimize penalties from the electric utility. The decision to use a synchronous motor instead of an induction motor was based upon the need to have an optimally efficient plant with low operating cost.

Decision for Selection of Synchronous Motor

The induction motor has fixed stator windings that are electrically connected to the ac power source. Current is induced in the rotor circuit via transformer action,

resulting in a magnetic field that interacts with the stator field causing rotation.

The rotor must rotate slower than the stator field for the induction to occur, thus an induction motor operates at less than synchronous speed using no other power source to excite the rotor's field.

Motors, especially those operating at 600 r/min and below, have lower operating efficiency and, inherently, a lagging power factor that draws exciting current from the connected source. Since an induction machine draws all exciting current from the ac source, it may take in the range of 0.3 to 0.6 p.u. reactive magnetizing kilovoltamperes per horsepower of operating load.

The synchronous motor has fixed stator windings electrically connected to the ac supply with a separate source of excitation connected to a field winding on the rotating shaft. Magnetic flux links the rotor and stator windings, causing the motor to operate at synchronous speed (see Figure 2).

While induction motors can be started and accelerated to steady-state running condition simply by applying ac power to the fixed stator windings of the motor, a synchronous motor starts as an induction motor. Then, when rotor speed is near synchronous speed, the rotor is locked in step with the stator by the application of dc voltage and current applied to the rotor of the motor.
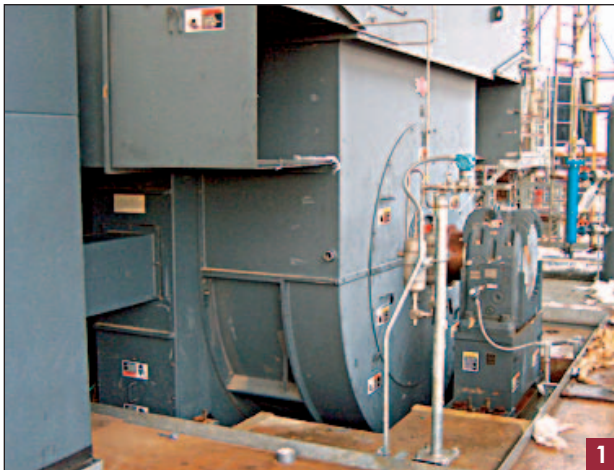
The Lion Oil induction motor.
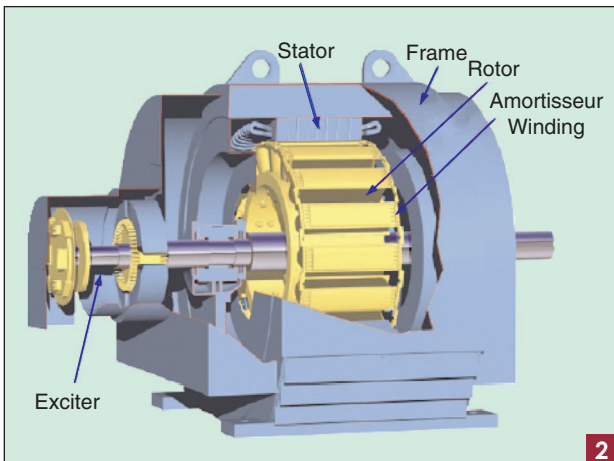
A synchronous motor.

Once the synchronous motor is operating at synchronous speed, it is possible to alter the power factor of the motor by varying the excitation supplied to the motor's field. Since power-factor correction could be provided, a synchronous motor was chosen.

This article will describe the characteristics of the synchronous motor, field application, and the excitation system selected for this application. For Lion Oil, the new synchronous motor would be rated for 5,000 hp, 13,800 Vac, operating at 327 r/min.

Construction of a Synchronous Motor

Synchronous motors consist of a fixed stator and a field that rotates concentric with the stator. The stator contains armature windings that are electrically connected to the ac supply system while the rotor contains a field winding that is electrically connected to a source of excitation (dc) (see Figure 3).

Since the primary purpose of the field winding is to create a rotating magnetic field, the field winding is wound around poles attached to the rotor in a configuration that produces magnetic north and south poles that are 180 electrical degrees apart (see Figure 4).

During starting of the motor, the field winding is not effectively coupled with the armature windings in the stator, and no net torque is produced in the field when ac power is connected to the stator winding.

To produce starting torque, a supplementary winding is provided on the rotor that effectively couples electromagnetically with the armature windings. This winding is a squirrel-cage arrangement of bars placed across each poleface that are electrically shorted at each end. The squirrel cage winding on the rotor is formally known as the damper or amortisseur winding.
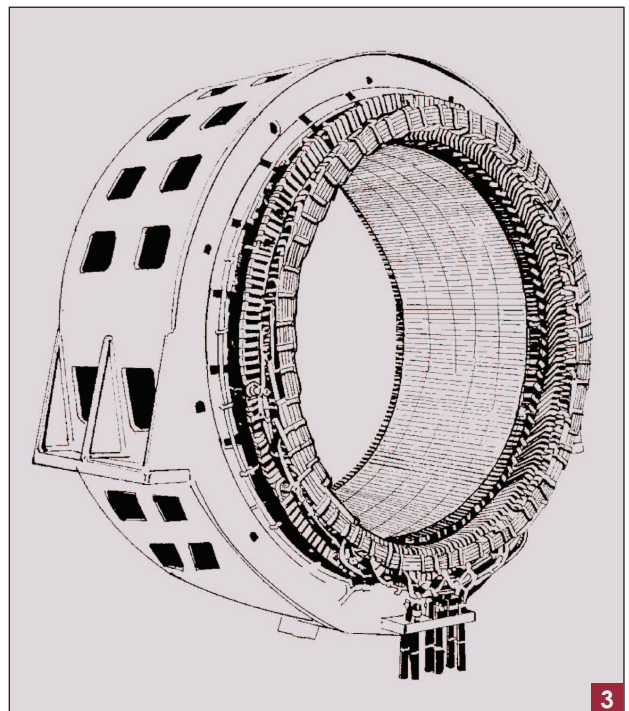
A stator winding.

When ac power is connected to the stator, current is induced in the squirrel-cage winding. This results in a net torque that is applied to the rotor, as shown in Figure 5(a) and (b).

This squirrel-cage winding also is used in the induction motor to produce motor torque during starting and running operation. Torque is produced by the electromagnetic interaction of stator and rotor only when a slip speed exists. Thus, the induction motor speed increases from zero until just below synchronous speed as torque decreases with increasing rotor speed.

As noted, the synchronous motor is started like an induction motor, with the torque on the rotor dependent on the difference between the rotor speed and the frequency of the power being applied to the stator winding. The torque supplied by the squirrel cage is at a maximum when ac power is first supplied to the stator winding and decreases as the rotor accelerates until it reaches zero torque when the rotor approaches synchronous speed. The absolute value of the accelerating torque is a function of the resistance of the bars in the squirrel cage. Higher resistance bars produce higher starting torque (and hotter squirrel-cage winding), while lower resistance bars produce lower starting torque with less heat generation.

If the starting torque produced by the squirrel-cage winding is not adequate to roll the rotor, the rotor is said to be locked, and ac power must be quickly removed from the stator windings to avoid overheating both the armature and the squirrel cage windings. As shown in Figure 6, the stator winding is connected to the ac supply system at startup, and the bars of the squirrel-cage winding on the rotor produces an accelerating torque on the rotor. The field winding is connected to a field discharge resistor during startup, while no external excitation is applied to the field (see Figure 6).

As the rotor accelerates, the field winding is coupled to the stator field via the armature winding. AC current is induced into the field based upon the difference between the frequency of the applied ac voltage to the motor and the frequency associated with the instantaneous speed of the rotor. If the field winding were open circuited during startup, dangerously high voltages could be induced in the field winding, hence, a discharge resistor is used to limit the voltage seen by the field winding during startup while dissipating the energy induced in the field. The resistance of the discharge resistor also affects the synchronizing torque available as the rotor approaches rated speed. Synchronizing torque increases with the resistance of the field discharge resistor.

A low resistance produces lower synchronizing torque, as shown in Figure 7. Insulation limits of the field winding limit the size of the resistor, because induced field voltage increases with increasing values of the discharge resistor. Sizing the discharge resistor is an art that balances starting torque and allowable field voltage during startup.

Starting the Synchronous Motor

Over the years, several methods have been used to start synchronous motors. The most common approach is starting across the line, with full ac voltage to the armature windings.

The squirrel-cage windings begin the task of accelerating the motor from zero speed. As the motor speed increases, the discharge resistor provides the torque required for the motor to reach synchronous speed. When the synchronous speed is reached, the discharge resistor is switched out of the field circuit, and excitation can be applied to lock the stator and field poles into synchronism. It is important to properly time the application of
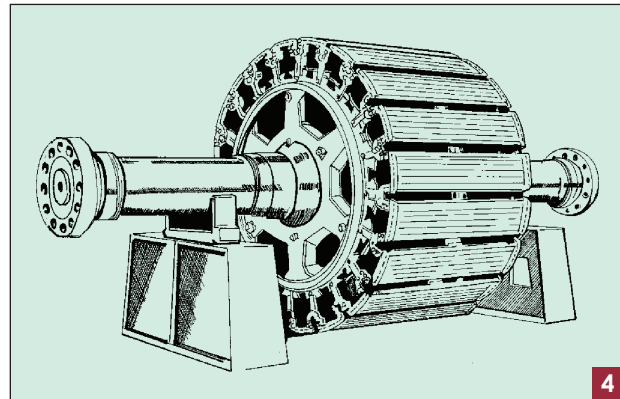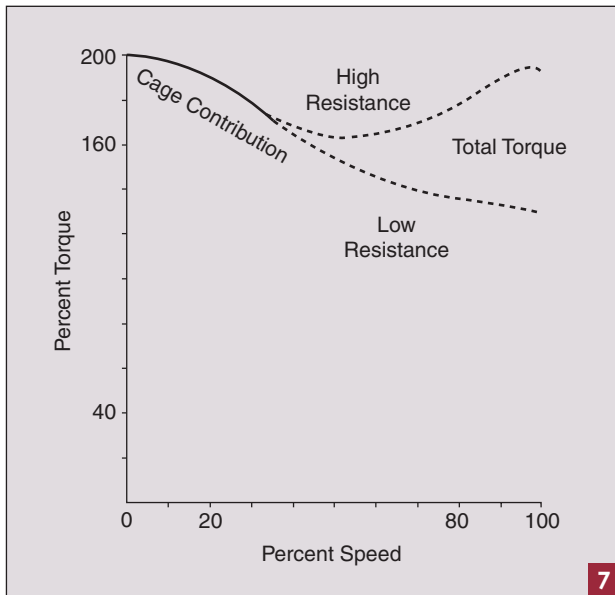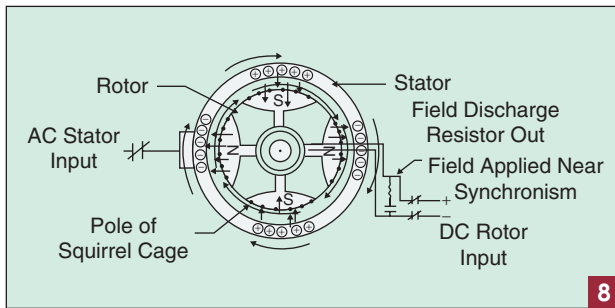

A rotor for a synchronous motor.
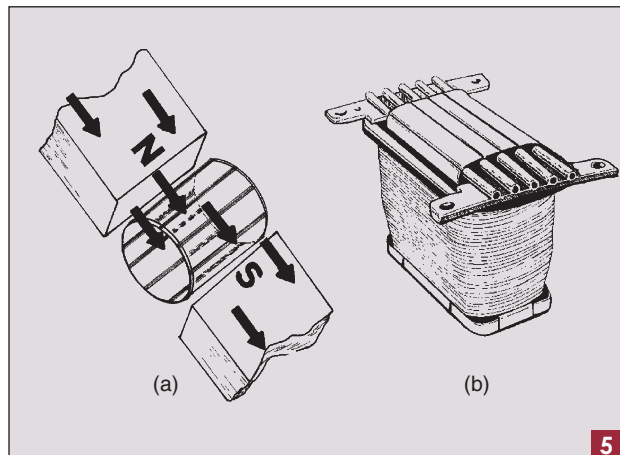
**(a) Relation of the squirrel-cage conductors to the magnetic field. (b) A rotor field pole with a squirrel cage.**
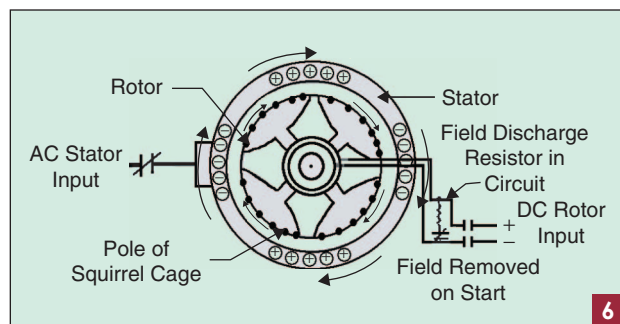
During start, the rotor poles will rotate at a slower speed than the stator frequency, inducing a slip.

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The squirrel cage at different starting resistance values.

8

A synchronous motor after dc voltage is applied to the revolving rotor field and the field is in step with the stator frequency.

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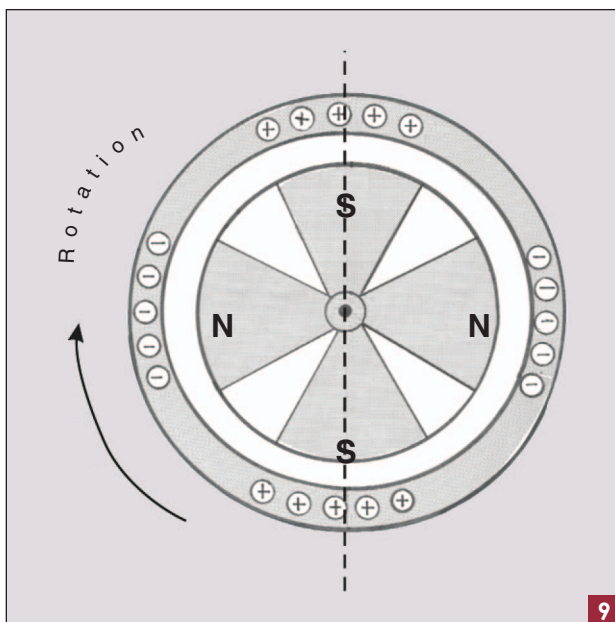
Opposite polarity poles are matched.

excitation to the main field. The purpose of the dc excitation system is to apply current to the field winding, creating a rotating electromagnet field that couples the rotor field to the rotating ac field in the armature winding when the motor is operating at synchronous speed. When dc excitation is applied to the motor field, the position of the rotor with respect to the stator magnetic field determines the reaction of the rotor.

If the north and south rotor and stator poles are aligned, such that the magnetic flux lines flow easily from the rotor through the airgap, the rotor flux will lock in step with the stator flux, and the motor will become synchronous. If the rotor poles are 180 electrical degrees out of phase with the stator poles, but motor acceleration is decreasing the angle of displacement, it is likely that accelerating torque plus magnetic attraction will combine to draw the rotor rapidly into pole alignment with the stator. Synchronizing additionally depends on the slip frequency between rotor and stator. Synchronizing torque from the magnetic linkage of rotor and stator must be sufficient to accelerate the rotor to keep it locked in step.

The most straightforward approach to synchronous motor starting is to monitor the frequency of the voltage across the field discharge resistor. As the motor nears synchronous speed, the slip frequency approaches zero across the resistor (see Figure 8).

At a specific slip frequency and rotor angle, dc is applied to the main field, and the discharge resistor is switched out to provide a very smooth transition from starting to synchronous operation. Modern application of the field for synchronous motors utilizes solid-state devices that control the removal of the discharge resistor and apply the excitation at the proper time in lieu of the breakers or contactors that have been used historically in the past.

Synchronous Operation

To understand normal operation of the motor, it is important to understand why the field rotates at synchronous speed. Each set of field poles is matched with an equivalent set of stator poles. Since like poles, for example north and north, repel, and unlike poles attract, the poles of the rotating field tend to align themselves with opposite poles produced in the stator by the ac power applied to the armature windings of the motor, as shown in Figure 9.

When this condition is achieved, the motor is said to be in step. When the motor is lightly loaded, the centerline of the rotor poles will nearly align across the air gap between the pole face and the stator with the center line of an opposite polarity stator pole.

As the motor is loaded, the angular displacement of the center lines will increase. As the angular displacement approaches approximately 45 mechanical degrees (90 electrical degrees), as shown in Figure 10, the motor is approaching pullout torque. Beyond this point, the rotor poles will no longer be in step with the stator poles, and the rotor poles will slip, producing a sudden increase in current draw from the ac system.

Once the synchronous motor's field poles are in step with the stator frequency, two factors determine the synchronous speed of the motor: the first is the frequency of

the applied voltage, and the second is the number of poles in the motor.

$$\text{speed} = \frac{\text{frequency} \times 120}{\text{poles}}.$$

Benefits of the Brushless Excited Synchronous Motor

The brushless excited synchronous motor is the most common type of exciter supplied today for use with synchronous motors, requiring no brushes or collector-ring maintenance. The exciter is physically direct-connected to the motor shaft. The brushless exciter has a three-phase ac armature winding (see Figure 11). The stationary field winding is on poles on the stator and is connected to an excitation supply source. The generated ac current is directly connected along the shaft to a rotating three-phase diode wheel, where the ac is rectified to dc before going to the motor's main field. The magnitude of the motor field current is adjusted by changing the current to the stationary exciter field by a dc source.

Solid-State Field Application Systems

The efficiencies of solid-state field application control has provided an economical and reliable means of applying excitation to the motor's field at the precise moment that insures optimum synchronization (see Figure 12).

The function of the field-application system provides three important elements:

- It provides a discharge path for the current induced in the field of the motor during starting and opens this circuit when excitation is applied.
- It applies field excitation positively when the motor reaches an adequate speed. The excitation should be applied with such polarity that maximum torque will be obtained at the time of pull-in.
- It removes excitation and reapplies the field discharge resistor immediately if the motor pulls out of step.

Referring to Figure 11, the field-discharge resistor protects the motor field winding from the high voltage induced during starting and provides the voltage source for the control circuit. The ac output of the exciter is converted to dc by the *rotating* rectifier diodes. This output is switched on or off to the motor field winding by a silicon controlled rectifier, SCR-1, which is gated by the control circuit.

The solid-state field application system shown in Figure 11 has a control circuit that keeps SCR-1 from firing until the induced field-current frequency is very low, representing a close approach to synchronous speed, and then fires the rectifier SCR-1 at the proper time and applies excitation to the synchronous motor field. At the same time, the field discharge resistor is removed from the circuit. This is done by the inherent operating characteristics of silicon controlled rectifier SCR-2. This frequency-sensitive part of the control circuit ensures that field excitation is applied at the proper pull-in speed for successful synchronizing and at the proper polarity to give maximum pull-in torque with minimum line disturbance.
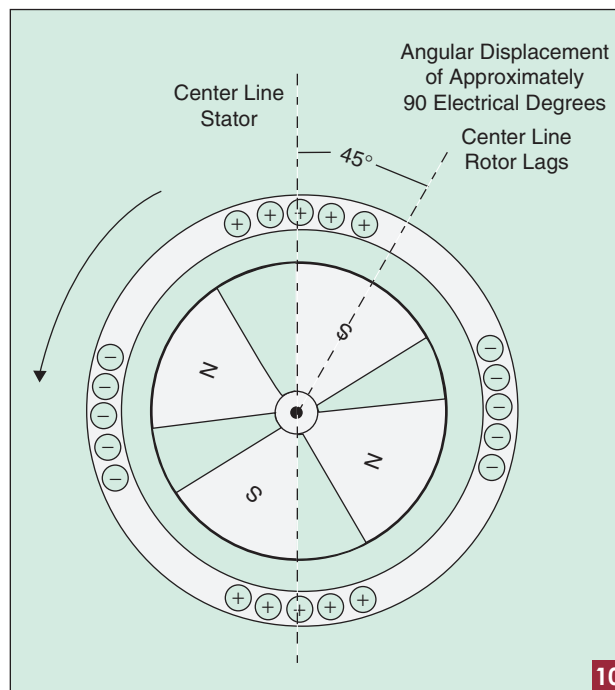
Center lines of opposite polarity poles with angular displacement approaching 45°.
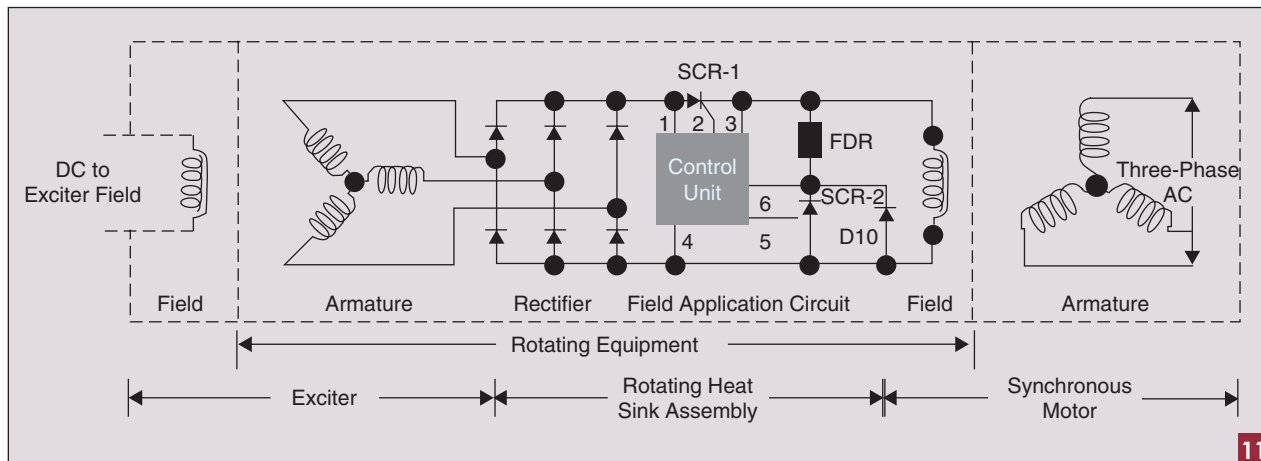

**A field application circuit drawing.**

The control circuit operates to remove excitation should the motor pull out of step due to a voltage step or excessive mechanical load. On the first half cycle after pull-out, the induced field voltage causes the net field current to pass through zero, turning SCR-1 off, automatically removing excitation. SCR-2 operates to connect the field discharge resistor back in to the circuit. During this time, the motor operates as an induction motor.

When conditions permit, the field is then reapplied as during starting. In Figure 11, the voltage from the exciter rectifier is blocked by SCR-1 until the point of synchronization. The field has an alternating voltage causing current to flow first through SCR-2 and the discharge resistor. On the next half cycle, current flows through the diode and discharge resistor. The control circuit waits until the frequency drops to the preset value, indicating the rotor is at an adequate speed. Then, after a north pole on the stator is in the right position to be attracted to what will be a south pole on the rotor, it triggers SCR-1 to apply excitation.

If the rotor does not synchronize, it will slip a pole, and the induced field voltage will oppose the exciter voltage, causing the current to go to zero, turning SCR-1 off. SCR-2 is Figure 11 turned on only at a voltage higher than the exciter voltage, so it will not be on when SCR-1 is on.
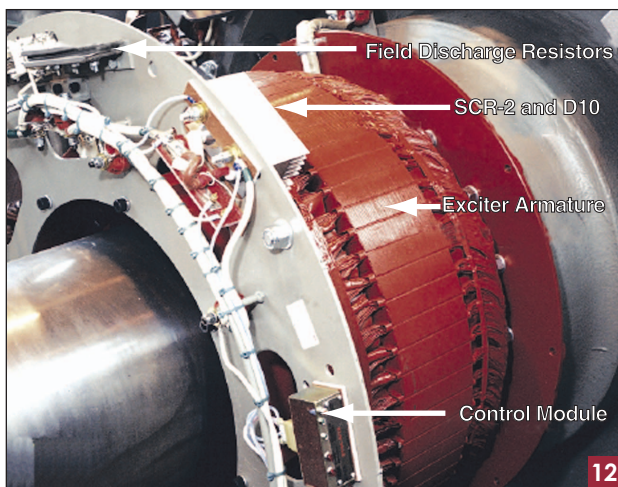
A brushless exciter.
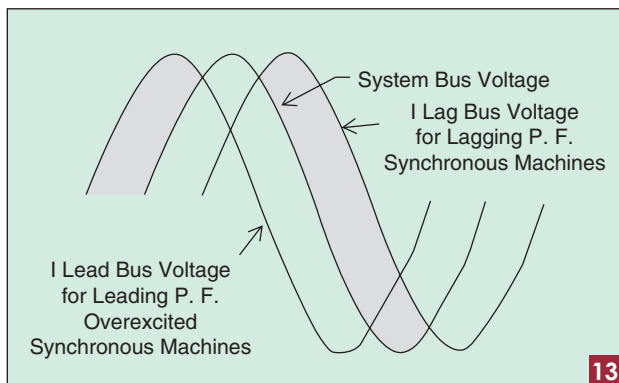
Leading and lagging current as affected by field excitation on the synchronous motor.

Synchronous Motor Controls Power Factor

Power factor is the factor by which apparent power, or kilovoltamperage, is multiplied to obtain actual power, or kilowatts, in an ac system. It is the ratio of the in-phase component of current to total current. It also is the cosine of the angle by which the current lags (or leads) the voltage. The conversion of electrical energy to mechanical energy in a motor is accomplished by magnetic fields. The poles rotate around the stator. When voltage is applied to a motor, an armature current flows to provide the necessary magnetic push {magnetomotive force (mmf) or ampere turns] to produce a flux that in turn, produces a voltage {back electromotive force (emf)} that opposes the applied voltage. This mmf is a magnetizing current. It is lossless, except for the I^2R losses in the winding and any core loss due to the changing flux in the iron. The magnetic energy is transferred from the line to the motor and back again each half cycle. The net power is zero, and the power factor is zero.

The power factor of a synchronous motor is controllable within its design and load limits. It may operate at unity, leading, or in rare cases, lagging power factor.

Once the synchronous motor is synchronized, the field poles on the rotor are in line with the rotating magnetic poles of the stator. If dc is applied to the rotor pole windings, the rotor can supply the necessary ampere turns to generate the flux that produces the internal motor voltage. Thus, the field current can replace part or all of the magnetizing current. In fact, if more dc field current is supplied, the increased flux will try to increase the line voltage. To increase the line voltage, the motor will supply ac magnetizing current to all "magnets" on the system to increase their magnetic flux. This is leading power factor. The synchronous torque developed is roughly proportional to the angle of lag (load angle) of the motor rotor with respect to the terminal voltage, which, at full load, is in the area of 20–30 electrical degrees. If a restraining force is applied to the motor shaft, it will momentarily slow down until a torque is developed equal to the applied restraint. The motor will then continue to operate at synchronous speed.

Figure 13 illustrates how the change in the excitation causes the ac line current to either lead the ac source voltage, be in phase with the source voltage, or lag the source voltage, depending upon whether the synchronous motor is over or underexcited.

V Curves

It is generally assumed that the line voltage will be substantially constant, and it is apparent from the preceding discussion that load, excitation, line amperes, and power factor are closely related. This relationship is readily expressed by a family of characteristic curves known from their shape as "V" curves. These are represented in Figure 14; for each curve, the power is constant and the excitation is varied to give different magnetizing currents. The minimum value of line amperes for each load condition is at 1.0 or unity power factor. As excitation is decreased, the line current will increase, and the motor will operate at lagging power factor.

System Power Factor Correction

By operating synchronous motors with a leading power factor, the overall system power factor can be shifted toward unity. The power factor of a synchronous motor can be controlled by varying the amount of excitation current delivered to the motor field during operation. As the dc field excitation is increased, the power factor of the motor load, as measured at the motor terminal, becomes more leading as the overexcited synchronous motor produces vars. If excitation is decreased, the power factor of the motor shifts toward lagging, and the motor will import vars from the system.

The decision for Lion Oil to go with a synchronous motor was based on the need to minimize economic penalties due to poor power factor at the utility connection. An example of how penalties can occur is illustrated in Figures 15–17.

Figures 15–17 show one-line diagrams of a synchronous motor operating at leading, unity, and lagging power factors. When operating at leading power factor as shown in Figure 15, the field excitation is increased above the level required to produce unity power factor.

If the power supply system is being operated to maintain a fixed voltage at the terminals of the motor, var production by the motor reduces the vars required from the system to maintain the preset terminal voltage.

As the motor excitation is reduced until the motor operates at unity power factor (Figure 16), the supply current and voltage shift in phase. The kilovoltampere burden supplied to the utility increases from 3,914 to 4,217 kVA. If excitation is further reduced, the motor will operate at lagging power factor, and the system power factor will shift to lagging as well. Notice the kilovoltampere burden from the utility is now 4,470 kVA (see Figure 17).

Under these conditions, the system must carry a larger kilovoltampere load than when the motor is operating at unity or leading power factor. At 0.8 lagging power factor, the system must provide the local var support. Thus, operation of the synchronous motor can substantially affect the power factor of the load as seen from the supply system, and the kilovoltamperage of the load as seen from the utility system resulting in penalties because of low incoming power factor.

Excitation System Controls the Power Factor

To take full advantage of the synchronous motor, it is necessary to have an excitation system that will maintain constant power factor regardless of load and ac supply variations to the excitation controller. Today's excitation systems are designed with features to help improve the quality of machine control. For this system, a digital controller was specified by the engineering consultant with the following features:
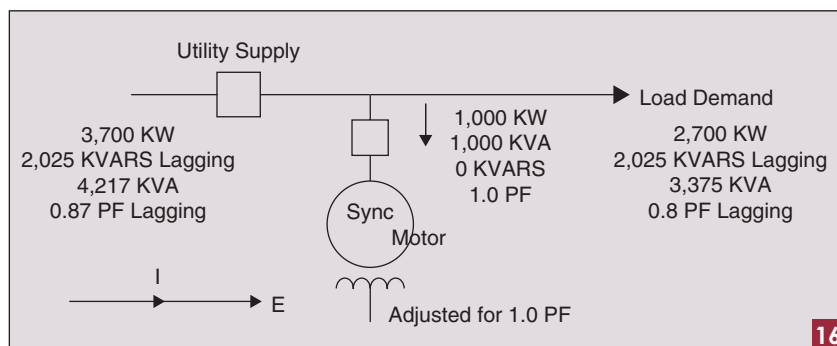
- power-factor control
- underexcitation limiting
- overexcitation limiting
- manual control.
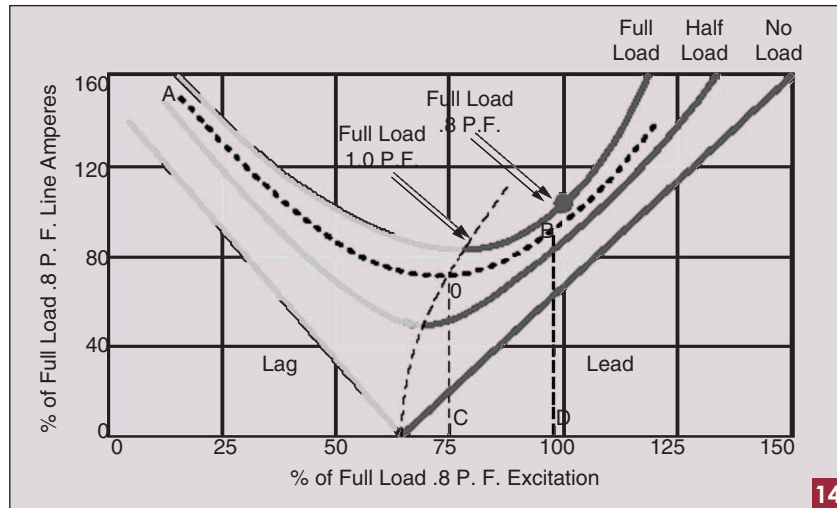
Characteristic V curves.
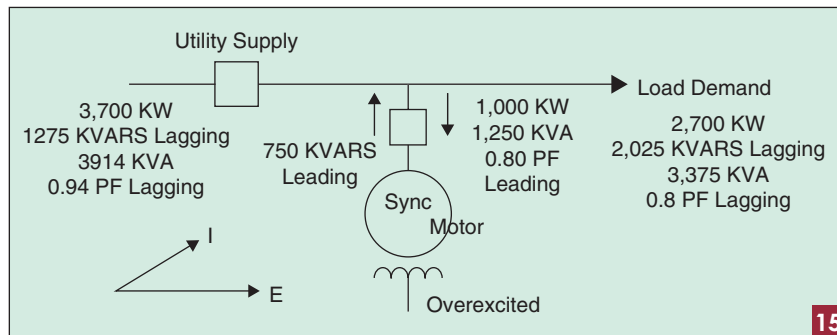
A synchronous motor in leading PF.
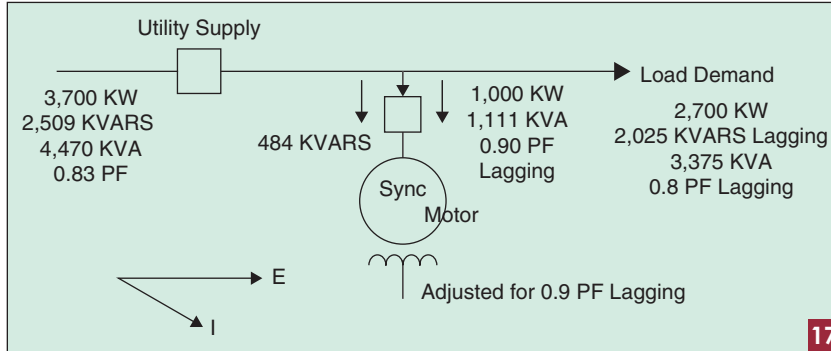

A synchronous motor at unity power factor.

The digital control, however, also includes functions to provide added value to the plant and the maintenance personnel who are responsible for the system. These features include:

- loss of voltage sensing and automatic transfer to manual control to prevent a machine trip caused by a loss of PT fuse at the controller input
- autotracking between power-factor mode and manual control to avoid bumps and a system disturbance during a unit transfer

A synchronous motor at 0.9 power factor lagging.

- oscillography, a diagnostic tool to evaluate plant issues such as a machine trip to help determine and locate the problem
- sequence of events that tabulates all events that occur from the time the motor is started to the time the machine is shutdown.

Automatic Power-Factor Control

The digital controller is designed to maintain a specific cosine angle by measuring the real power into the motor and adjusting the excitation into the field to provide the correct amount of kilovars to maintain the cosine angle. Figure 18 illustrates the constant angle as a function of kilowatts into the machine versus kilovars out of the machine. Any voltage variation to the system or load change that would affect the power factor is immediately modified via the excitation system to restore the cosine angle and power factor of the machine.

The automatic control eliminates the concern with an ac supply variation to the excitation system that could otherwise result in pole slip due to too little excitation for the motor field. Additionally, digital systems are equipped with safeguards to prevent pole slip from occurring. These include:

- field forcing margins
- underexcitation limiting
- overexcitation limiting.

Field Forcing

Field forcing provides a means to maintain constant voltage into the field, even when the ac supply voltage drops as much 30–40%. Hence, if the field voltage required by the motor were 100 Vdc at 0.9 power factor lead, and the digital controller were selected to provide 150 Vdc maximum ceiling voltage, the digital controller would be able to provide 100 Vdc to the field even if the supply voltage into the controller were to drop 50%. The additional margin could mean the difference between continue process control or a machine trip and plant outage.

Underexcitation Limiting

Digital controllers also are equipped with underexcitation limiters. These devices have always been popular for generators but also very practical for synchronous motors using digital controllers. The underexcitation limiter monitors the kilowatts into the synchronous machine as compared to the kilovars being supplied. Should the kilovars drop below acceptable levels needed to maintain synchronism, the underexcitation limiter will cause an increase in excitation to prevent a machine trip. Figure 19 illustrates an apparent drop in machine vars. Notice how the kilovars drop to a level but are limited to any further reduction because of the underexcitation limiter.
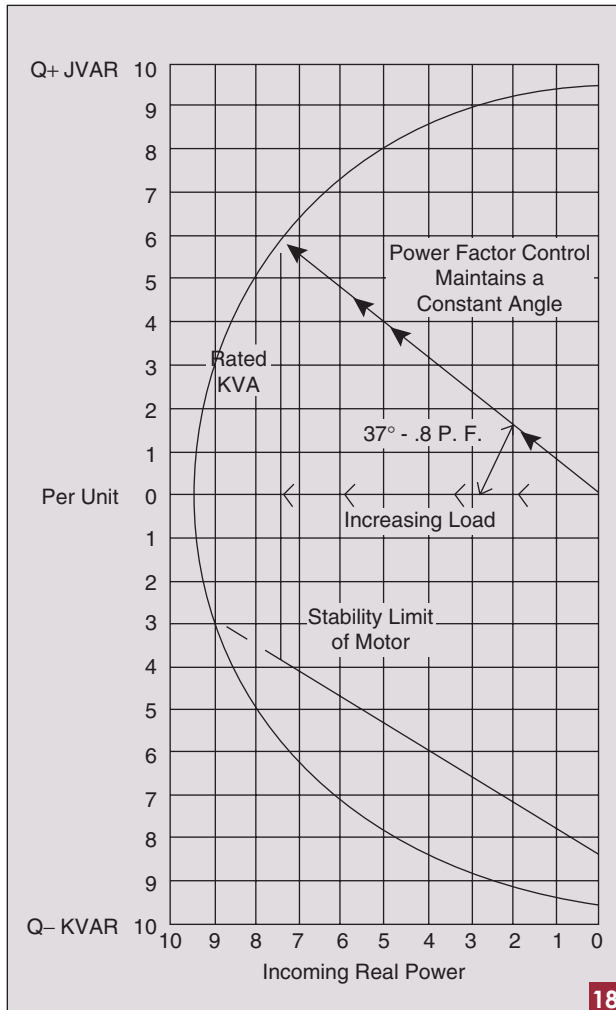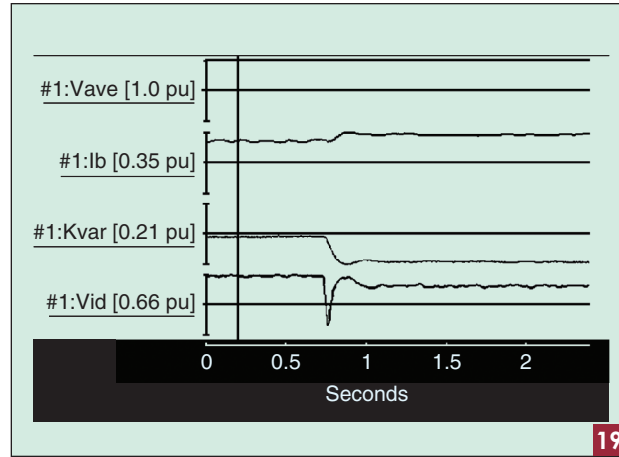

The motor capability curve.
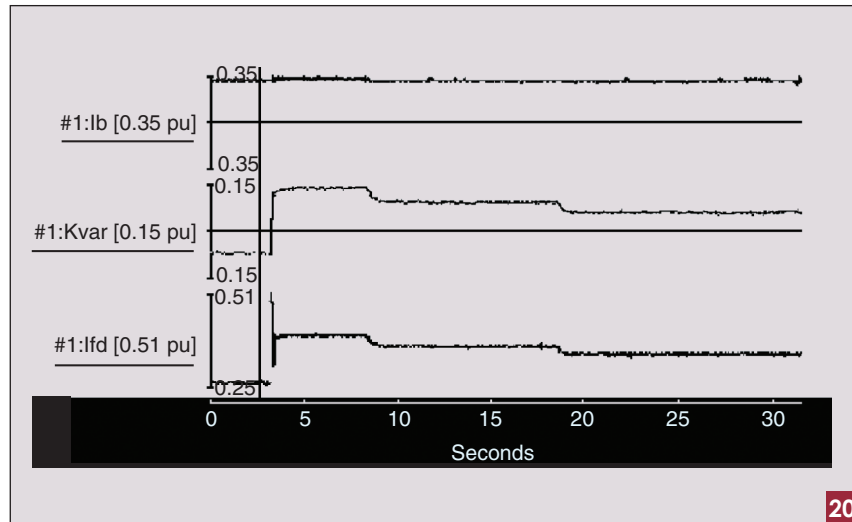
Overexcitation Limiting

To ensure that too much excitation is not applied into the rotor for extended periods of time, the excitation system is equipped with an overexcitation limiter. The overexcitation limiter monitors the field current, and if it should remain too high for extended periods, the excitation limiter will react by restricting any further increased field current and restore the level within a safe operating region for the machine. Figure 20 illustrates how a bump in the system has occurred, and kilovars are limited because of the overexcitation limiter limiting any further increases. Observe that the overexcitation limiter limits at three levels to allow short time var boosting that could benefit the system.

Other Features

Today's digital excitation controllers, such as the type provided for Lion Oil, also include field protection that might otherwise have been neglected or provided by other discreet devices. These additional features include field overvoltage and field overcurrent as well as over and under terminal voltage monitoring. Since brushless motors use diodes to rectifiy the ac to dc from the exciter output, failure of these diodes can lead to a faulted exciter phase and subsequent overload and excessive vibration of the exciter (see Figure 21). New digital controllers are equipped with diode-failure detectors for the brushless exciter that will alarm should failure occur and allow for a timely shutdown to repair faulted devices.

Underexcitation limiter operation for a synchronous motor.

The overexcitation limiter operation on a synchronous motor.
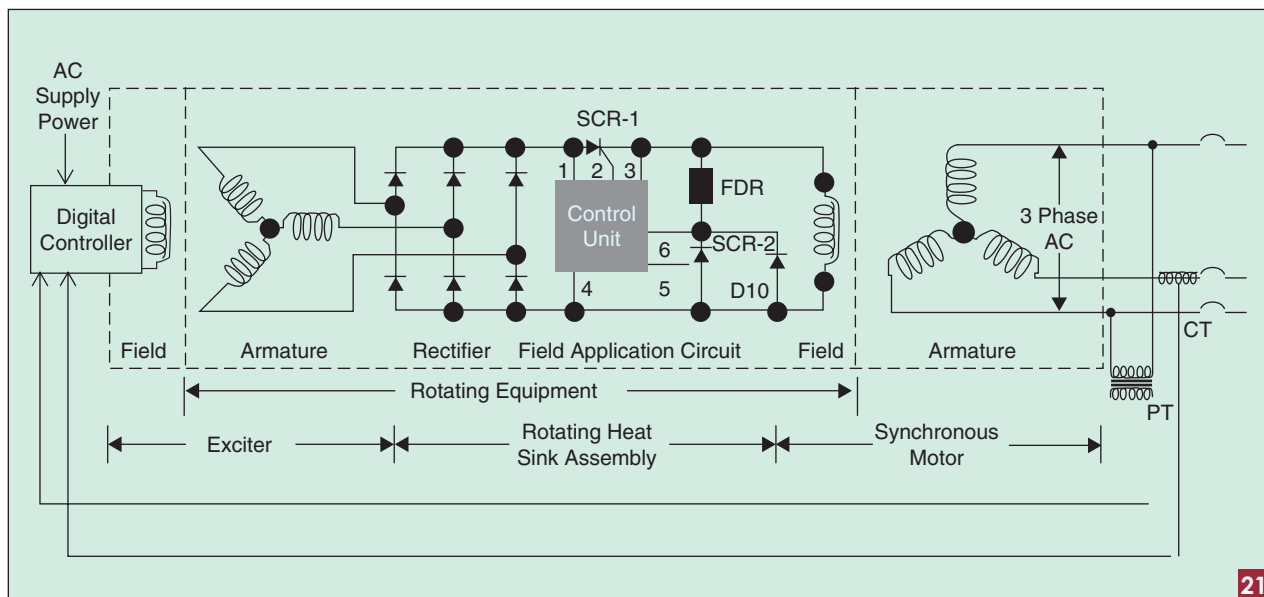

**The system one-line interconnect.**

Excitation System Interconnection

Unlike constant voltage supplies that require only an ac voltage source to provide a fixed dc into the field, the automatic control system requires inputs from instrument PTs for measuring motor line voltage and a current transformer signal input for measuring the reactive current out of the motor (see Figure 21).

Inputs for starting the excitation systems are interfaced with the motor control, so when the motor breaker closes, the excitation system will apply excitation into the exciter field. The excitation system initially is enabled in manual control with a fixed dc current level to the field. Once the motor field is synchronized to the line, the system switches to power-factor control for automatic operation.

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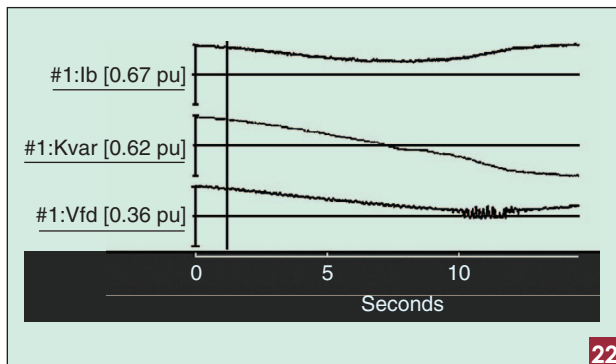
Testing the synchronous motor operation using V curves.

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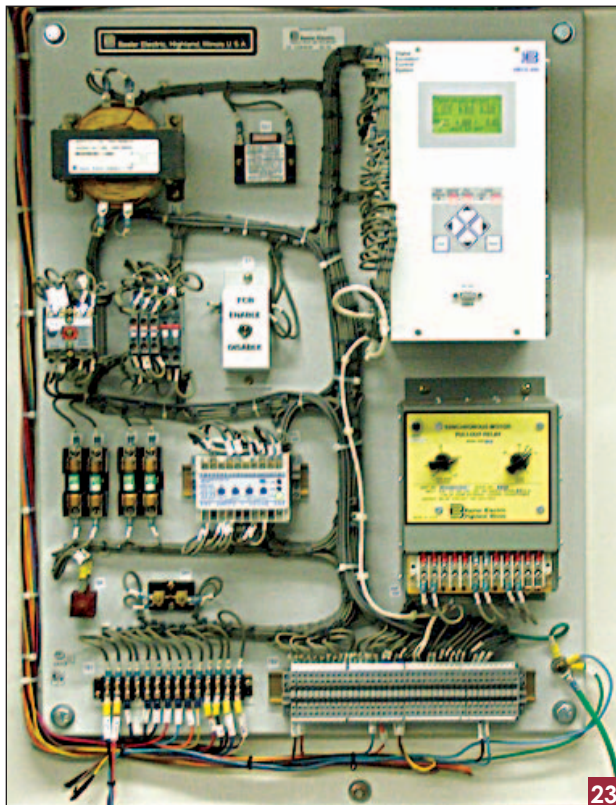
A picture of the new excitation system.

Outputs are available to monitor any operation of the excitation limiters and general annunciation of any protection alarms either by hard contact or by a Modbus RS 485 serial port.

Testing and Evaluating

During testing, V-curve checks are performed to evaluate motor characteristics. Historically, the V curve was obtained by installing chart recorders and appropriate transducers to measure watts and vars. In the digital excitation system, curves can be obtained using the oscillography that can speed commissioning time and provide permanent records of the motor's history. Figure 22 illustrates kvars and ac line current when field excitation is changed, forming a V curve of the synchronous machine. Notice how the kvars increase with increasing excitation. As the motor line current valleys between the two ac line current peaks, the kvars are zero. A further reduction in field current now causes the kvars to further decrease, causing a lagging ac line current and lagging power factor in the system.

Conclusion

For low speed applications and power factor concerns, the benefits offered by the synchronous motor can provide long-term improvements that can represent cost savings to the plant. The brushless exciter favors a more streamlined control via a solid-state device to apply excitation to the field with increased reliability and economic benefits. Accurate control of the synchronous motor power factor as implemented by a digital excitation system (Figure 23) offers more efficient control of the machine to help avoid potential machine trips due to low ac power supply variations to the excitation system. Features included in the excitation system also provide more complete monitoring of the synchronous machine to safeguard the unit under abnormal operating conditions. Special attention should be provided for long time storage of the motor prior to installation to be sure the motor is adequately protected from moisture.

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