Synchronous Motor Control

Abstract — This paper provides a detailed discussion of the basic theory of operation and control of the synchronous motor. It describes typical synchronous motor starting and provides information regarding control and optimization of the motor through the use of power factor control or var operation that can be helpful in reducing var penalties and improving voltage stability of the plant. Typical protection is also discussed involving motor pullout and under- and overexcitation concerns.

I. INTRODUCTION

Motors are electromagnetic devices used to convert electrical energy into useful mechanical work. There are two major classifications of ac motors:

- **Induction motors** have fixed stator windings that are electrically connected to the ac power source. Current is induced in the rotor circuit via transformer action. The resulting magnetic field interacts with the stator's 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. No separate power source is required to provide the rotor field.
- **Synchronous motors** have 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 1.

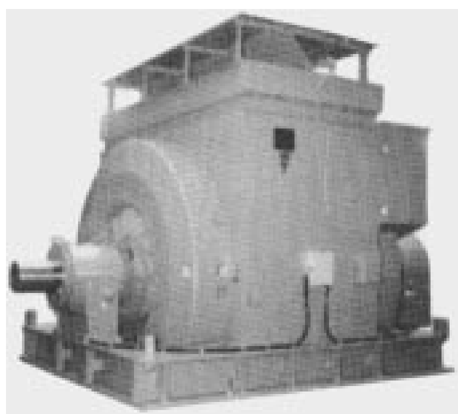

Figure 1: Synchronous Motor

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, but a synchronous motor requires special attention because it starts as an induction motor, then, when rotor speed is near synchronous speed, the rotor is locked in step with the stator by application of field excitation. Various arrangements have been devised for starting synchronous motors and for providing excitation to the field winding at the appropriate time in the starting sequence. When 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 field. These special characteristics of synchronous motors can be understood through an examination of the construction of the motor and a brief review of the machine theory that explains these operating characteristics.

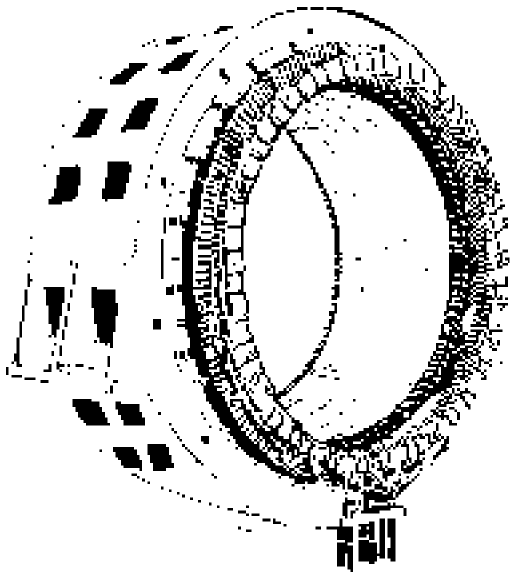

Figure 2: (a) Stator Winding

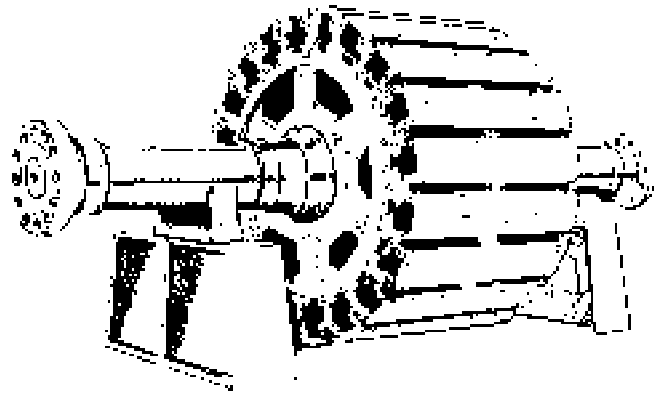

Figure 2: (b) A Rotor for a Synchronous Motor

II. CONSTRUCTION OF A SYNCHRONOUS MOTOR

Referencing Figure 2, synchronous motors, like synchronous generators, 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). 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. 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 ammortiseur 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 3. This squirrel cage winding is also 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.

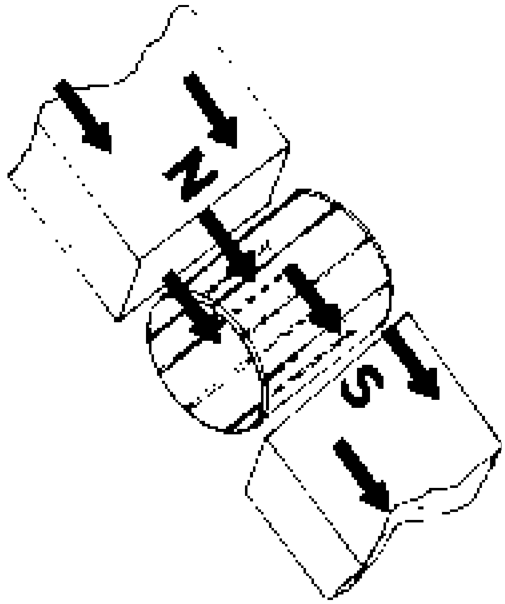

Figure 3: (a) Relation of the Squirrel Cage Conductors to Magnetic Field. Starting Torque Results from Flux Cutting Conductors of Squirrel Cage.

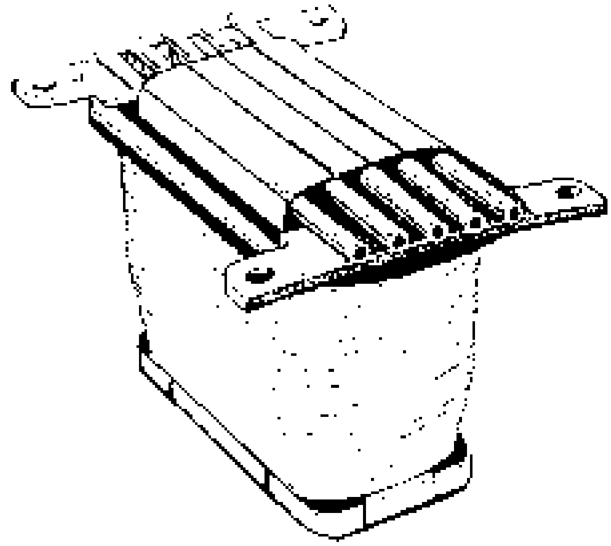

Figure 3: (b) A Rotor Field Pole with Squirrel Cage. Each Pole Will Be Bolted Together Around the Rotor.

The synchronous motor then can be 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, decreases as the rotor accelerates, and approaches zero as 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 windings)
- 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 4, 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, and no external excitation is applied to the field.

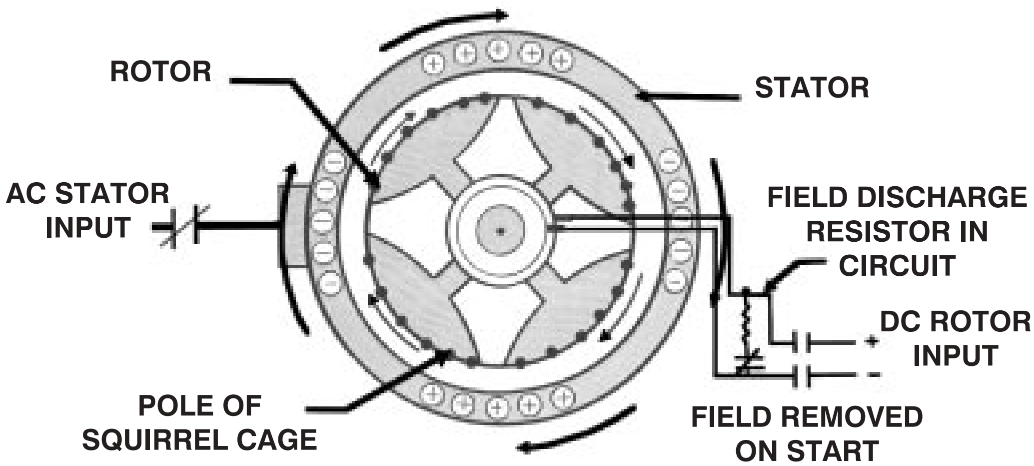

Figure 4: During Start the Rotor Poles will Rotate at a Slower Speed than the Stator Frequency, Inducing a Slip. Voltage is Not Applied to the Rotor Field Input at this Time.

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 starting 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 starting 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 5.
- Insulation limits of the field winding limit the resistor, because field voltage increases with increasing values of discharge resistor.

Sizing the starting resistor is an “art” that balances starting torque and allowable field voltage during startup. In some applications, the load is removed from the synchronous motor during startup and applied only after the motor has reached stable operation at synchronous speed, in order to reduce torque required to start.

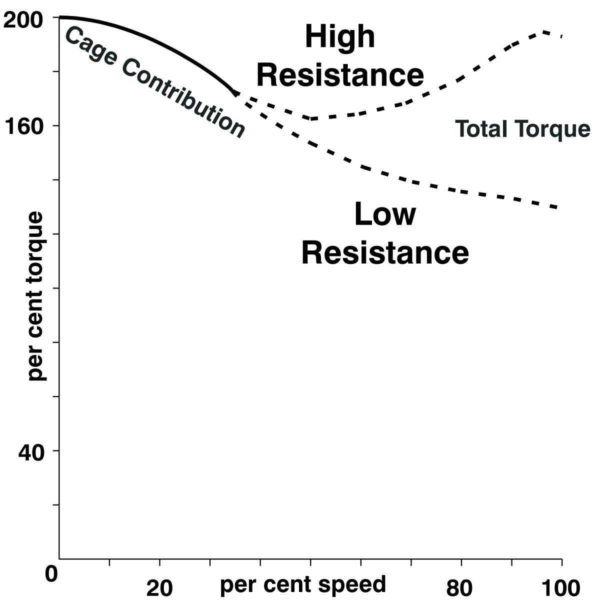

Figure 5: Squirrel Cage at Different Discharge Resistance Values

III. STARTING THE SYNCHRONOUS MOTOR

Synchronous motors are started using several reduced voltage methods. The most common 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 starting 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 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 N and S 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.

Another approach to motor startup is switching out the starting resistor and applying excitation based upon time after the motor ac supply power is applied. Here, a dc contactor closes applying excitation to the field after a fixed time. This approach can be used if the acceleration time of the motor is known and the motor is able to reach nearly synchronous speed without excitation.

In some applications, a speed signal is used to apply excitation when the motor has accelerated to 92 - 95% of rated speed. The precise timing for switching out the starting resistor and applying dc to the main field is monitored by electronics on the rotating field.
The most straightforward approach to synchronous motor starting is to monitor the frequency of the voltage across the field starting resistor, as the motor nears synchronous speed, the slip frequency approaches zero across the resistor. At a specific slip frequency and rotor angle, dc is applied to the main field and the starting resistor is switched out to provide a very smooth transition from “starting” to synchronous operation. Application of the field can be most reliably performed using solid state devices instead of mechanical breakers or contactors. Most brushless excitation systems include such a scheme; similar devices can be used with brush-type systems to perform the same function.

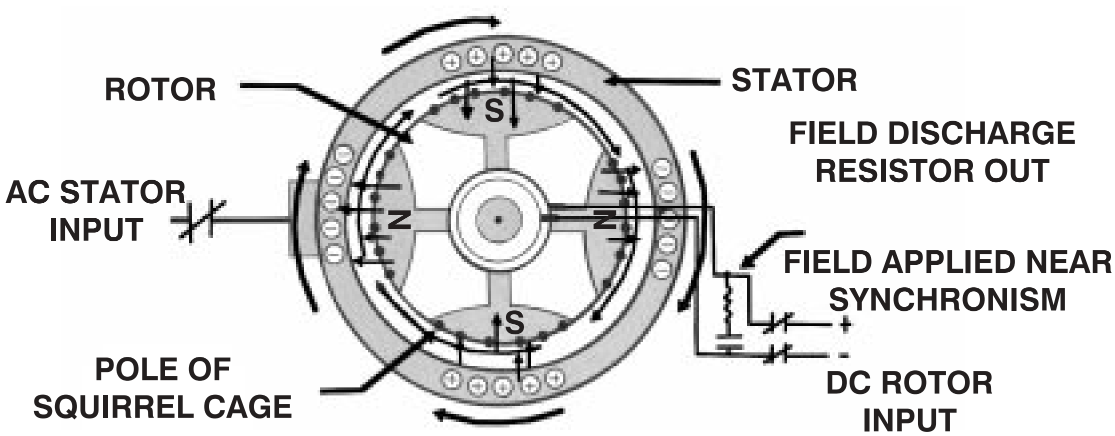

Figure 6: A Synchronous Motor after dc Voltage is Applied to the Revolving Rotor Field and the Field is in Step with the Stator Frequency.

IV. 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 (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 7.

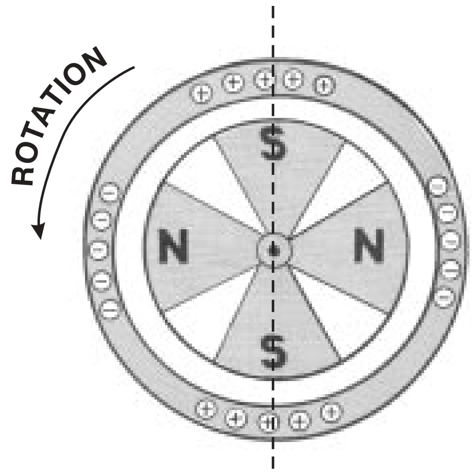

Figure 7: Opposite Polarity Poles are Matched

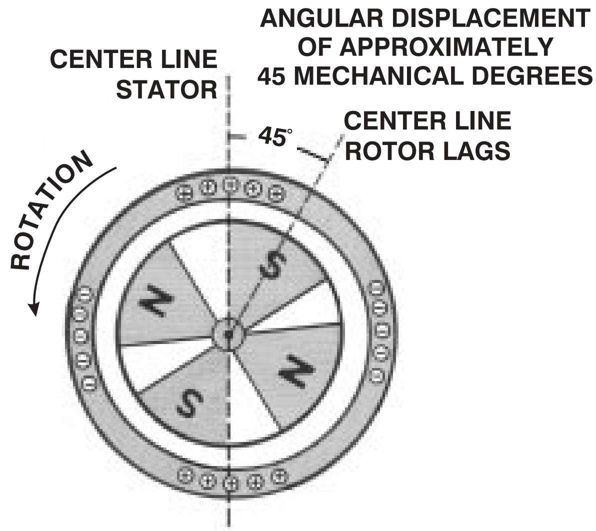

Figure 8: Center Lines of Opposite Polarity Poles with
Angular Displacement Approaching 45 Degrees

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 8, 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; the second is the number of poles in the motor.

$$\text{Speed} = \frac{\text{Freq x 120}}{\text{Poles}}$$

V. START SEQUENCE OF THE SYNCHRONOUS MOTOR

A typical automatic starting circuit for a synchronous motor is shown in Figure 9. The main devices in the system are the main contactor M; a control relay CR; the dc contactor D; a frequency relay FR; and auxiliary relays. In Figure 9, reactance X represents the inductance of the field, and rotor resistance R represents the starting resistance.

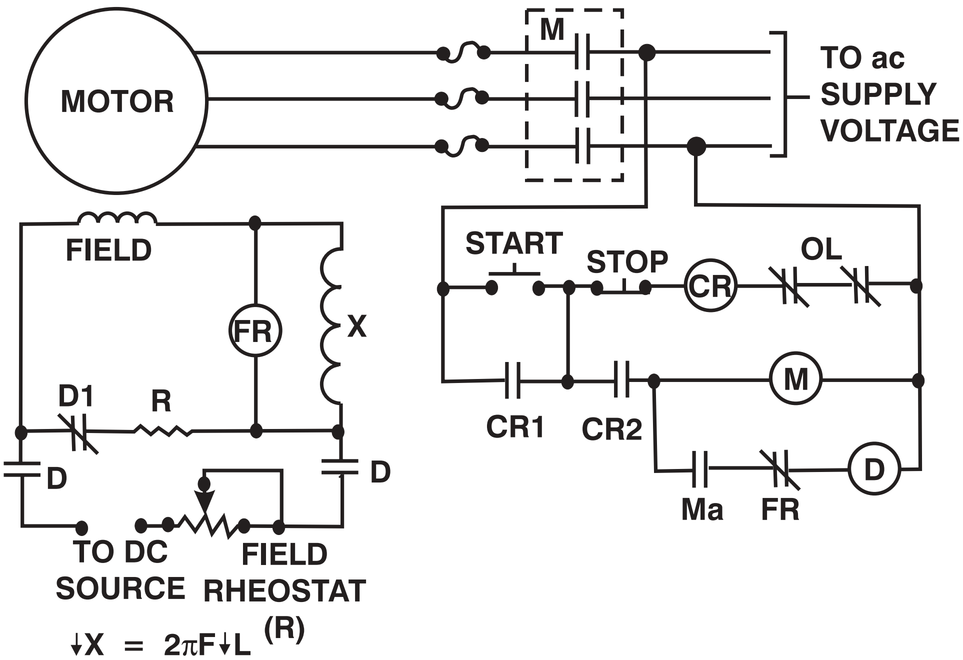

Figure 9: Wiring Diagram of a Simple Start System for a Synchronous Motor

The starting sequence is as follows:

1. When the start button is depressed, the CR relay energizes and CR1 and CR2 close, energizing the close coil of the main contactor M.
2. The main contacts of M close, applying ac power to the motor stator winding before the auxiliary contact Ma can close.
3. An emf is induced in the field winding, causing current to flow through the field winding at synchronous frequency.
4. Since the impedance at supply frequency is high, voltage across X is enough that Frequency Relay FR picks up.
5. The normally closed contacts of FR open before the auxiliary contacts Ma close, so the dc contactor coil D will not be immediately energized.
6. The field begins to rotate.
7. As the speed of the field increases, the slip between the field and the stator decreases. The impedance decreases as the slip frequency decreases. As the impedance of X decreases, voltage decreases to relay.
8. As the slip frequency approaches synchronous, the reactance of X decreases until Relay Fr drops out, closing NC contact FR.
9. Relay D energizes, contact D1 opens and contact D closes, thus switching Resistor R out of the field circuit and applying excitation to the field.
10. The motor pulls into synchronous operation.

In the motor starting circuit shown in Figure 9, a field rheostat is used to adjust the dc voltage applied to the field after the motor has arrived at synchronous operation. Though this is shown as a manual adjustment, various automatic control schemes could be provided to maintain stable operation of the motor, including a voltage regulator to increase excitation when the motor is picking up load, or a var/power factor controller to vary excitation to control the vars absorbed or produced by the motor. These aspects of motor excitation control will be discussed later.

Though the above discussion is based on starting a brush-type motor with a separate external exciter, the functions described are typical of either a brush-type or brushless motor, except for the fact that an automatic controller would be used in a brushless system to excite the motor field, and solid state devices rather than a contactor are often used to switch the starting resistor out of the field circuit. Specific configurations vary greatly between motor manufacturers.

VI. ADVANTAGES OF SYNCHRONOUS OVER INDUCTION MOTORS

One major advantage of a synchronous motor over an induction motor is its ability to operate at a leading or lagging power factor. Many industrial facilities contain motor loads that require substantial var support from the local utility system. 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 imports vars from the system. Local var generation tends to improve overall transmission system efficiency, and in many cases can result in significant savings in utility bills.

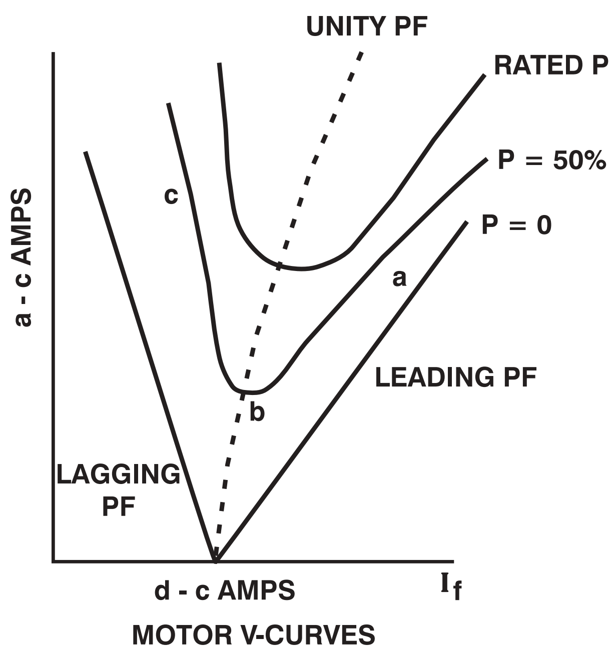

Figure 10: Synchronous Motor Power Factor versus Field Excitation

Figures 11, 13 and 14 show phasor representations and one-line diagrams of a synchronous motor operating at leading, unity, and lagging power factors. When operating in a leading power factor as shown in Figures 11 and 12, 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 13), the supply current and voltage shift into phase; if excitation is further reduced, the motor will operate to lagging power factor, and the system power factor will shift to lagging as well (Figure 14). Under these conditions, the system must carry a larger kVA load than when the motor is operating at unity power factor; and at unity power factor, the system must provide the local var support. Thus, operation of the synchronous motor can substantively affect the power factor of the load as seen from the supply system, and the kVA of the load as seen from the utility system. Many industrial plants use var-producing equipment such as capacitors to adjust their power factor to minimize their power bills, and to provide voltage support for other loads in the plant. Here, synchronous motors can play a key role in optimizing industrial load factors, if the synchronous motor is equipped with controls allowing the motor to relieve the utility of some var load.

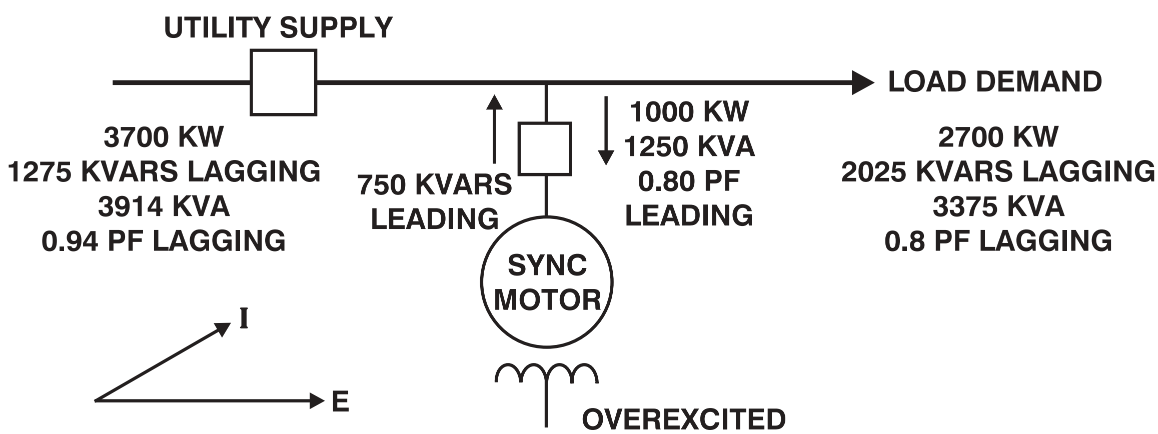

Figure 11: Synchronous Motor in Leading PF

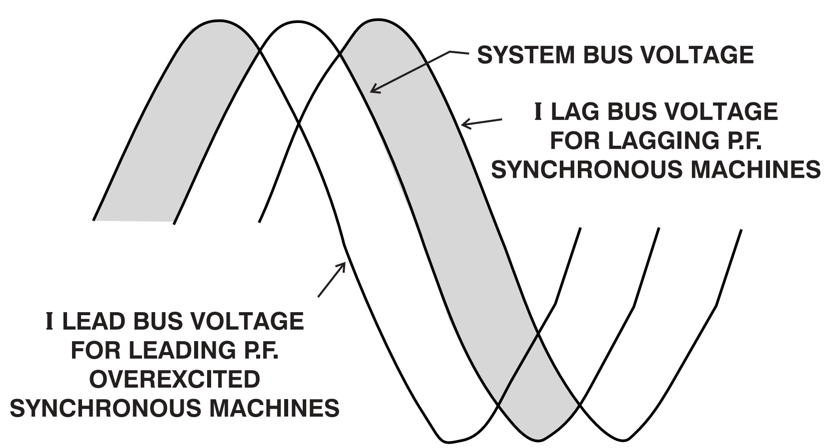

Figure 12: Leading and Lagging Current as Affected by Field Excitation on the Synchronous Motor

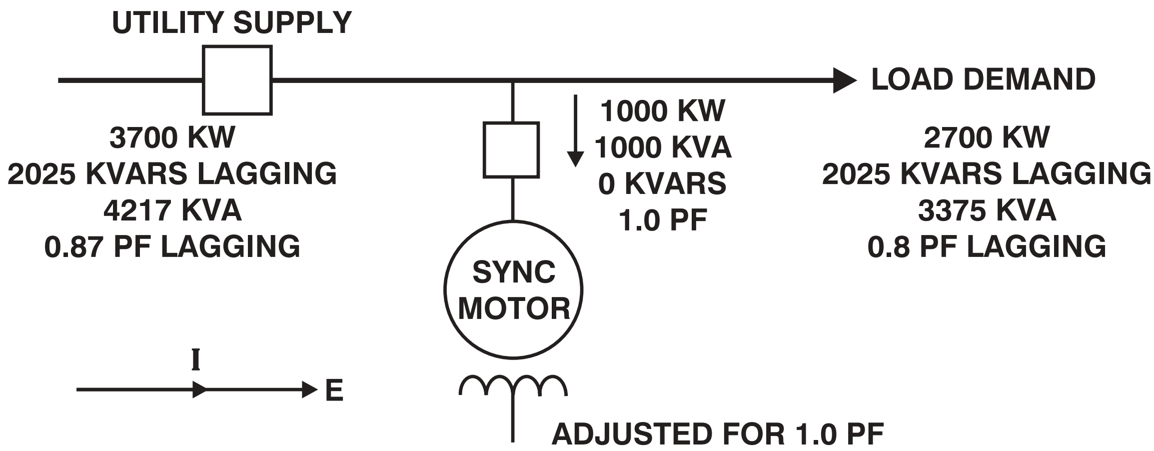

Figure 13: Synchronous Motor at Unity Power Factor

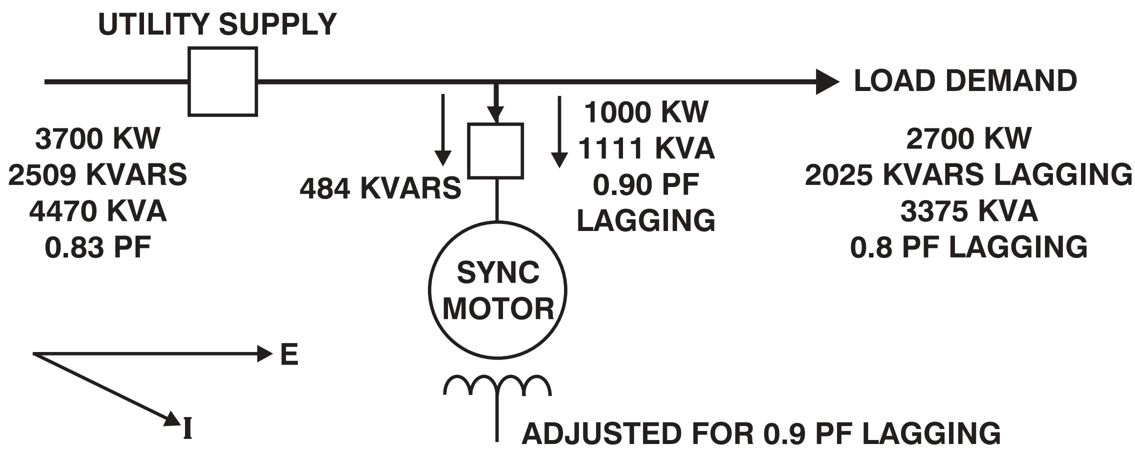

Figure 14: Synchronous Motor at 0.9 Lagging PF

VII. SOLID STATE EXCITATION CONTROL FOR SYNCHRONOUS MOTOR

Excitation systems are of prime importance for the proper operation of synchronous motors. The excitation system can be as simple as a fixed dc power supply connected to the field of the synchronous motor or, with additional sophistication, an automatic controller can be provided with var/power factor control or voltage regulation. When a fixed dc power supply is utilized, the input is generally derived from a tapped transformer whose output is rectified to match the motor full load field requirements. If the supply voltage to the transformer-rectifier changes, the motor power factor must also change. See Figure 15. The automatic controller derives its power from a similar power source, but here, the excitation system output is SCR controlled which automatically changes field excitation based upon loading requirements in the system. See Figure 16.

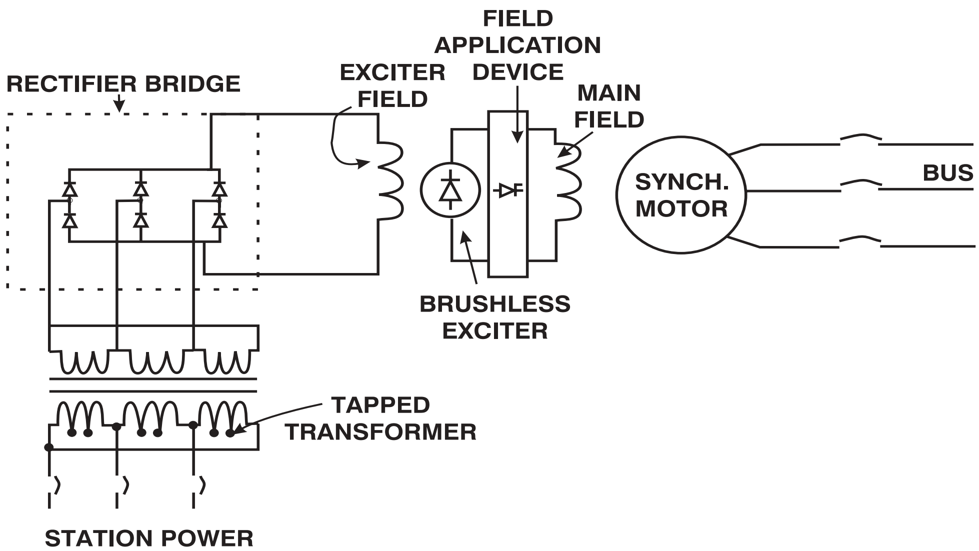

Figure 15: Fixed dc Power Supply with Tapped Transformer Supply Voltage

VIII. WHY SOLID STATE AUTOMATIC CONTROL

The selection of automatic synchronous motor control over a fixed dc power supply offers several benefits. See Figure 15. A fixed dc power supply for excitation is a low cost solution that works reasonably well if motor loads and the power supply voltage remain relatively constant. If motor load varies widely, or if the power supply voltage is subject to significant drops, such as those that occur when other nearby motors are started, a constant excitation source may be unable to maintain the motor in synchronism, resulting in pole slip and asynchronous operation. Pole slip events can seriously damage components of the excitation system due to excessively high voltage transients and asynchronous operation can quickly cause motors to overheat.

During pole slip events, large currents are induced in the field that try to flow in opposition to the normal direction of excitation current. Pole slip events create voltage transients that may exceed the peak inverse voltage rating of the power semiconductors of the brushless rotating exciter or main power semiconductors in a static exciter system. If the semiconductors fail, the remaining semiconductors in the circuit must operate under overload conditions until the power conversion bridge is repaired.

Using a fixed source of excitation also eliminates the possibility of using motors to provide local var support or to assist in controlling power factor on the supply bus. Poor power factor can cause excessive loading on transformers and cabling and usually results in higher than necessary power bills. Proper operation of synchronous machines can provide significant savings in power cost for a small investment in improved motor control. See Table 1.

Both of these potential problems can be addressed by replacing fixed dc motor exciters with excitation control systems that automatically maintain adequate excitation to the motor to prevent pole slip during load or power supply transients, while providing a means to optimize var production by the motor during operation.

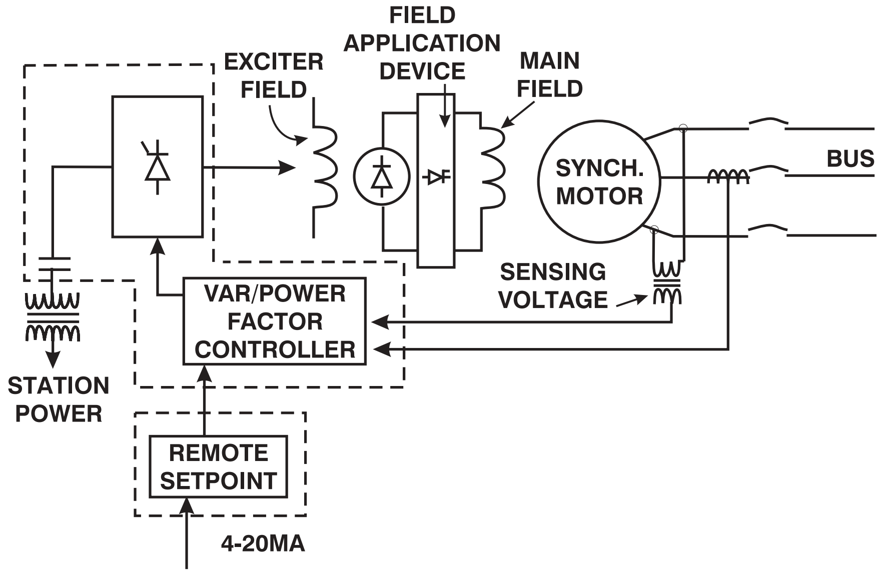

Figure 16: Automatic var/Power Factor Controller Power Supply

IX. AUTOMATIC CONTROL

A synchronous motor controller provides a means to automatically respond to voltage transients and provides a reliable means for controlling the var output or power factor of the motor during normal operation. Referencing Figure 16, a brushless exciter is used for discussion. As noted earlier in the paper, the brushless exciter uses an internal solid state control that determines when the optimum time occurs to apply excitation to the field of the exciter. Various methods are utilized including slip frequency or impedance monitoring of the rotor circuit to determine synchronization. When the slip frequency is minimum, conditions are correct for the power SCRs in the rotor circuits to be gated on to allow excitation to flow from the output of the exciter to the main field.

Type of Excitation System	Conditions	Motor Field Excitation	Synchronous Motor Operation	Affect on System	Economics
Fixed dc supply	- Low Bus voltage - Excessive load on motor	Under excitation	Lagging power factor	- **Increase** KVA loading on plant transformer - Reduce system voltage - Potential pole slip	**Costs** $
Automatic controller		Automatic power factor correction	Unity or leading power factor	- **Decrease** KVA loading of plant transformer - Improves voltage stability of Bus	**Saves** $

Table 1: Benefits of Proper Operation of Synchronous Machines

The excitation system in Figure 16 represents a typical automatic control system to adjust field excitation for the motor field. The excitation system consists of a variable SCR control power supply that is connected with a var/power factor controller. The var/power factor controller monitors the phase angle between the motor terminal voltage and the motor armature current to regulate the motor and maintain a programmed level of var or power factor at the machine terminals. As the load varies at the output of the motor, the excitation system increases or decreases the field excitation to keep the motor vars or power factor constant. The var level at the motor terminals can be set for a fixed value of motor power factor or can be adjusted for a leading power factor based on the needs of the plant. See Figure 17. For example, if the plant power factor is 0.7 due to a large inductive load, the excitation system can be adjusted to overexcite the synchronous motor to produce vars and improve plant power factor.

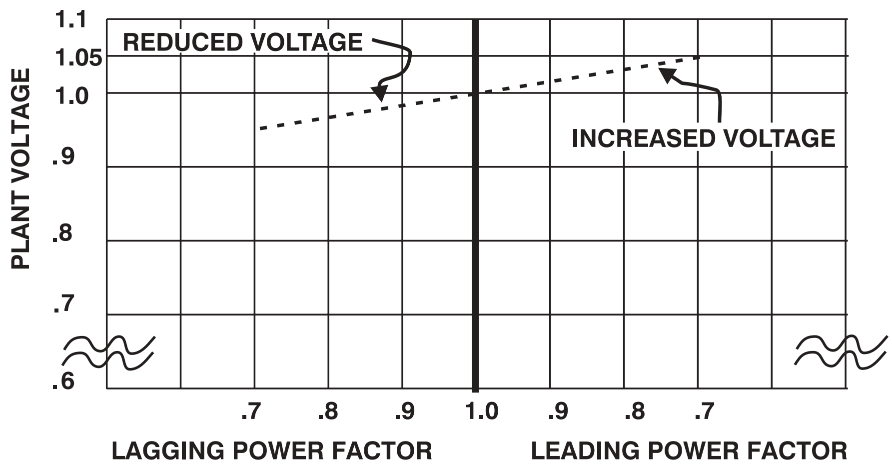

Figure 17: Plant Voltage versus System Power Factor

The result of reducing plant var demand on the utility source will be a voltage increase, as illustrated by the curve in Figure 17.

Why is this important? Low lagging power factor in the plant can overload transformers, cabling, and can cause undesirable voltage drops in the plant. Low bus voltage can overheat motors and cause misoperation of voltage sensitive equipment. The low lagging power factor can also result in var penalties that the electric utility will charge. When synchronous motors are overexcited vars, or the magnetizing currents required by the inductive loads are no longer provided from the electric utility but from the overexcited synchronous motor. The net result becomes lower plant operating cost and longer operating life for electrical equipment.

X. CHOOSING MODE OF OPERATION

If an automatic control system is selected, a choice of regulating motor vars or power factor may be made. The selection depends on the application. For synchronous motors with large step changes in load, such as ball mill grinders and chipper motors, the priority may be to keep the motor from losing synchronism. By using var regulation and by setting the var operating point to produce rated leading vars, the motor excitation should always be sufficient to keep the rotor in step. This mode also provides for maximum var support to the plant bus, allowing the utility power factor to be reduced.

For synchronous motors with relatively steady mechanical load, the power factor mode will maintain a preset motor power factor, keeping the vars produced at a level proportional to the real power needs of the motor.

If the primary purpose of the excitation automation is to improve plant power factor and reduce energy cost, operation in the var mode, regulating the var production of the motor would allow setting the control to the var level required to offset utility-supplied vars. Another possible configuration uses the var/PF controller connected to monitor utility power factor, allowing the controller to adjust motor excitation to keep utility power factor to a maximum level, supplying additional vars from the synchronous motor.

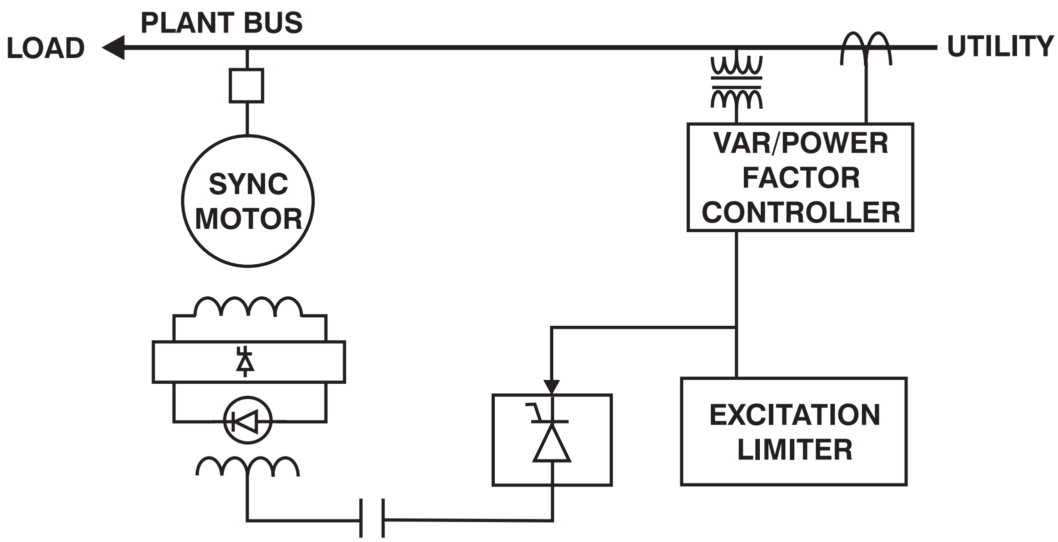

Figure 18: Synchronous Motor or Condenser Supplying vars to Keep Utility PF Constant

This arrangement works well as long as the var supply does not exceed the maximum or minimum limits of excitation. To make certain these limits are respected, an excitation limiter can monitor the motor and override the var/PF controller if excitation exceeds the limits.

XI. REMOTE VAR CONTROL

Plant optimization of energy consumption is an important goal for many industrials. Controlling the plant power factor can offer a major area in energy savings. Remote control of the excitation system can provide the means to automate the operation of the synchronous motor to maintain optimum power factor for the plant by using energy monitoring instruments. Remote control can be accomplished through a 4-20 ma input that adjusts the setpoint of excitation controller. The input for the 4-20 ma signal can be provided from a computer that measures power factor to determine how to adjust the excitation controller, keep energy cost minimum, and motor operation at peak efficiency. See Figure 16.

XII. SYNCHRONOUS MOTOR APPLICATION AS A SYNCHRONOUS CONDENSER

A synchronous condenser is another form of a synchronous motor. The term ”condenser” comes from the older terminology for capacitor. A synchronous condenser is a synchronous motor running without a mechanical load. See Figure 19. Depending on the amount of excitation on the machine, it can either absorb or generate reactive power to improve the power factor of the system or provide better voltage stability. Capacitors are used for the same application, but must be switched on and off in large steps and may be more costly to install. Since there is no mechanical load, the ac input power for the synchronous condenser is only enough to supply the watt losses of the machine during operation. By adjusting the field current, the synchronous condenser is operated at leading or lagging power factor. As the synchronous condenser picks up reactive load, the bus voltage will increase, depending on the system impedance. Condensers are most often connected to the transmission system to improve voltage stability of the line in large industrial areas.

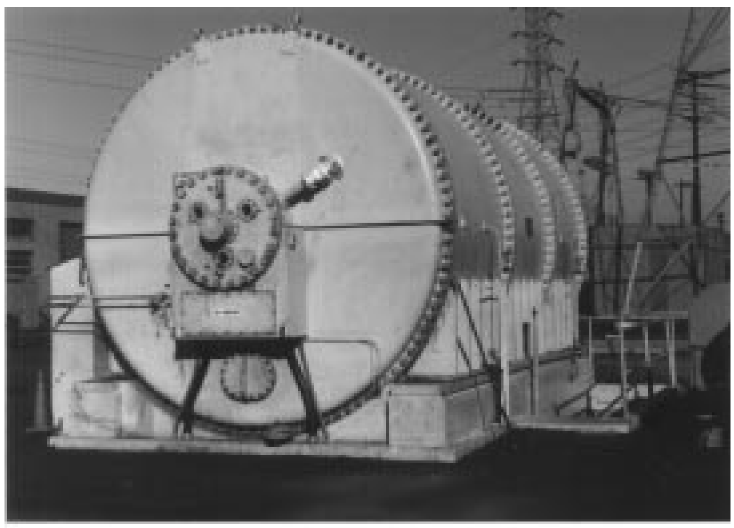

Figure 19: Synchronous Condenser

XIII. CONTROLLING THE SYNCHRONOUS CONDENSER

The synchronous condenser utilizes various methods for starting. One common method is using a pony motor that brings the condenser up to rated speed. As the condenser reaches synchronous speed, the excitation system applies power to the field, which builds terminal voltage to rated output much like a generator. Synchronization to the bus occurs after the phase angle of the condenser matches the system bus voltage. The condenser’s breaker then closes and the system is synchronized. Once synchronized, the output can be controlled by either a var/power factor controller or terminal voltage regulator depending on the needs of the system. If terminal voltage regulation is chosen, the voltage regulator will adjust the field excitation to maintain the system voltage. See Figure 20.

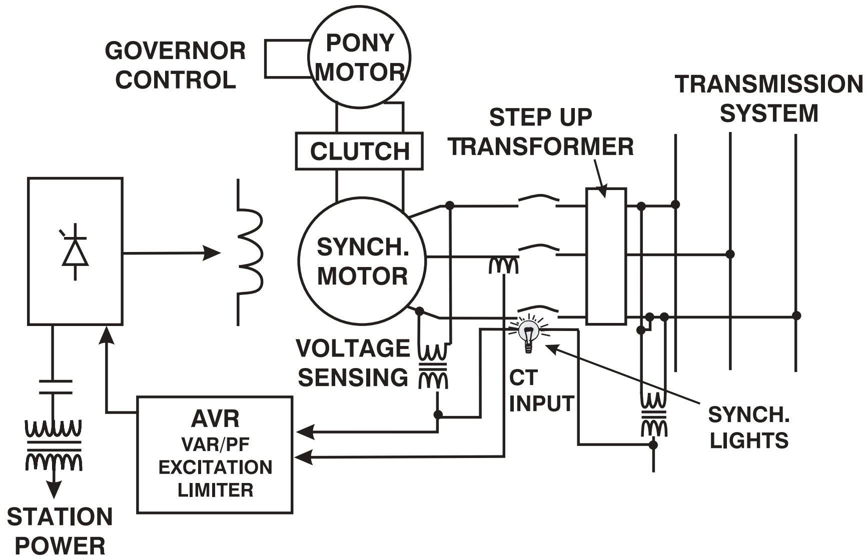

Figure 20: Synchronous Condenser with Voltage Control

Synchronous condensers are often located where large industrial loads exist. Here, the system voltage often varies throughout the day due to inductive loads in the vicinity. Having the system operate in either voltage or var control will boost the system voltage during the day when loads are at their maximum. In the evening, system voltage tends to be higher as industrial loads are shed. Here, the synchronous condenser voltage controller reacts by reducing excitation, hence drawing vars off of the system and bringing system voltage back to normal. See Figure 20.

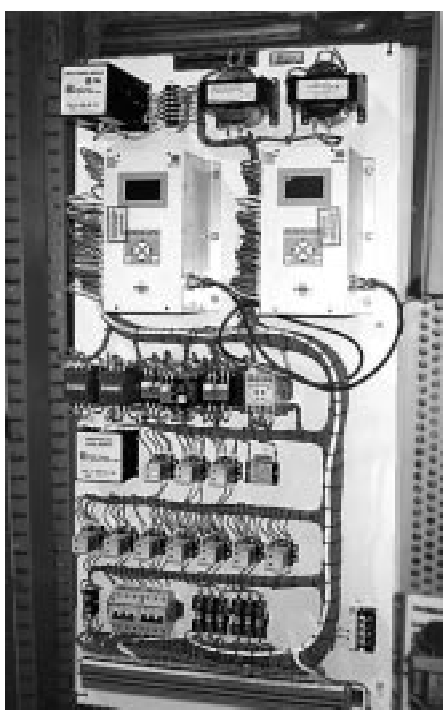

Figure 21: Digital Excitation for Motors

XIV. SYNCHRONOUS MOTOR PROTECTION

Figure 22 highlights multiple functions used to monitor the status of the synchronous motor. These devices include field over and under current, motor pullout protection and incomplete sequence.

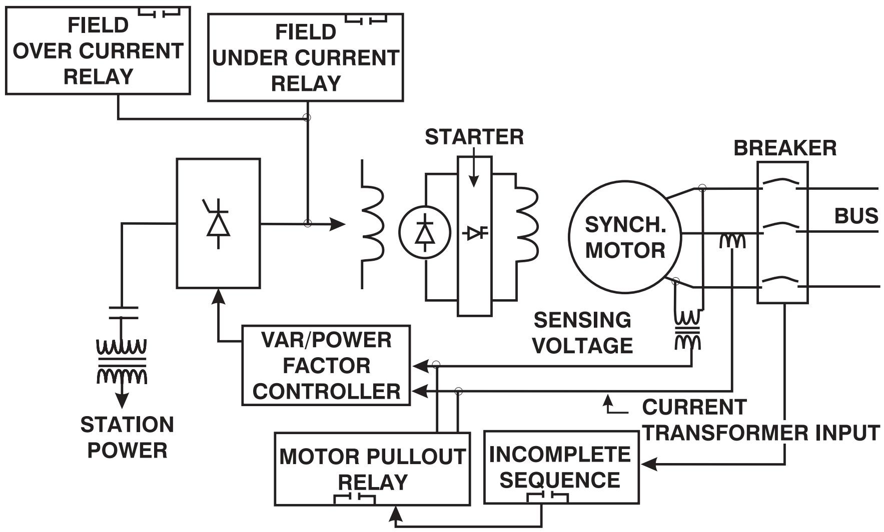

Figure 22: Synchronous Motor Controller with Motor Protection

As the synchronous motor builds to rated speed, a maximum allowable time is defined by the motor manufacturer for excitation to be applied. Should the motor take longer than the defined time, the rotor squirrel cage winding will overheat. The fail to synchronize relay is set to trip the motor in time to protect the squirrel cage winding. The motor pullout relay monitors for lagging power factor at the motor output to indicate loss of or low excitation. The lagging phase angle occurs when insufficient excitation fails to provide the needed synchronizing torque to keep the rotor locked in step with the stator rotating magnetic field. Figure 23 shows the motor line current lagging the impressed armature voltage when the synchronous motor is operating as an induction machine. When the power factor drops below .8 to .9 lagging, the motor pull out relay will trip the system.

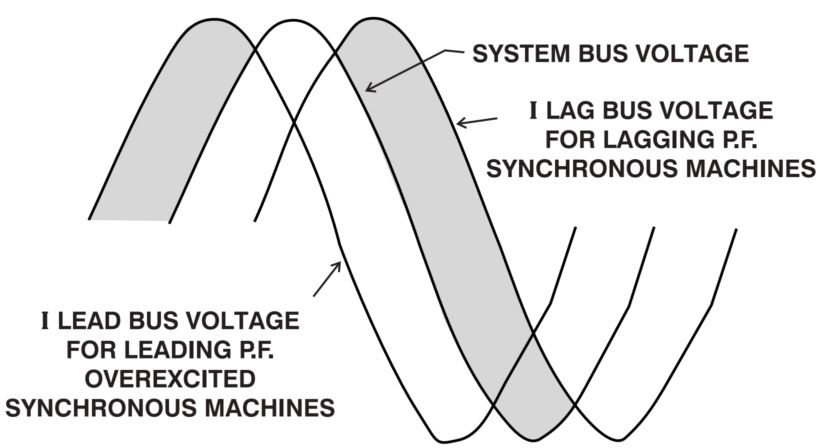

Figure 23: Leading and Lagging Current as Affected by Field Excitation on the Synchronous Motor

In addition to the motor pullout relay, the field undercurrent relay monitors for insufficient field current from the excitation system. Too little field excitation to meet loading requirements for the synchronous motor can result in pole slip, hence serious damage to the motor and associated excitation system. The undercurrent relay threshold detector is set slightly below the normal field current of the motor. When field current drops below the threshold, an output contact provides alarm to trip the system.

The field overcurrent relay is used to detect excessive rotor or exciter field current. Field current levels that remain higher then acceptable for extended periods of time, can cause severe heating of and damage to the rotor. ANSI C50.13 provides acceptable field overcurrent levels based upon time and magnitude. See Table 2.

Field Voltage (Percent of Rated)	Time (Seconds)
140%	35
160%	21
200%	11
260%	5

Table 2: Permissible Short Time Duty for Cylindrical Rotor Synchronous Generators

Coordinating the thermal heating limits of the motor field with the excitation system field forcing limits is important to ensure long life of the motor.

XV. CONCLUSION

Selecting the appropriate excitation system for a synchronous motor depends on the field current required for the motor field. Automatic excitation control can be applied to the exciter field for the brushless exciter system and to the main field for any slip ring brush type systems. Automatic control can be retrofitted to any existing motor application to help optimize plant performance and reduce energy cost.

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