Electric Service Division

INSTRUCTORS' LESSON PLAN

FOR

SYNCHRONOUS MOTOR CONTROL

JANUARY 1970

103.3001

ELECTRIC SERVICE DIVISION

Instructors' Lesson Plan

I. TITLE: Synchronous Motor Control

II. OBJECTIVE: To discuss the function, operation and maintenance techniques of Synchronous Motor Controls.

III. TIME: 4 Hours

IV. TRAINING AIDS:

A. Required (P/O Training Package)

1. Wall Chart #103.300

2. Transparencies / Slides / Drawings

B. Optional - Note: A Practical demonstration using selected typical controls will greatly enhance the value of this lesson.

V. REFERENCES:

A. Westinghouse Motor Controls; Section 7

B. Westinghouse Industrial Controls; SA 9111

C. Instruction Leaflets

11-202-2

11-202-3

14-000-1B

14-000-2A

4230

VI. TEACHING PROCEDURE:

A. <u>Introduction</u>

1. As far as motor control circuits are concerned, the LOW VOLTAGE range is commonly recognized as 3 phase, 60 cycle, 208-220-440-550 volt rated industrial plant

distribution systems usually used for motors up through 200 horsepower.

2. There are many installations where larger horsepower motors are connected to a low voltage system; but because of the associated construction and starting problems faced in powering large horsepower motors on low voltage systems, much consideration is given in this general horsepower area and beyond to the use of higher voltage rated motors.

3. NEMA has defined the maximum voltage of the Industrial Control scope as 5000v and named the voltage range from above 600v to 5000v "Medium Voltage". It follows that the controllers used on voltages in this range be appropriately called "Medium Voltage Starters". Formerly this range was known as high voltage. The medium voltage name was initiated to differentiate it from the voltages above 5000v, which fall outside the Industrial Control Scope.

4. This lesson: **USE WC #103.300**

   A. TITLE: Synchronous Motor Control

   B. OBJECTIVE: To discuss the function, operation and maintenance techniques of Synchronous Controls.

      (1) Synchronous Motor Fundamentals

      (2) Control Characteristics

      (3) Protection Schemes

      (4) Typical Control

      (5) Maintenance Techniques

B. Presentation

DISCUSS WITH CLASS

1. Synchronous Motor Fundamentals

a. Rotating Field

(1) One of the most important things to remember about an electric motor is that rotary motion is produced by the interaction of the magnetic fields of the stator and rotor. Although the specific details are complex, a fundamental understanding of the action involved can be obtained by recalling the basic phenomenon of magnetism ... like poles repel and unlike poles attract.

(2) In a broad sense, an electric motor has a number of north and south magnetic poles on both its stator and rotor. Motor functions require that one set of these magnetic fields be caused to attract the other set continuously. To accomplish this, a-c and d-c motors require different methods.

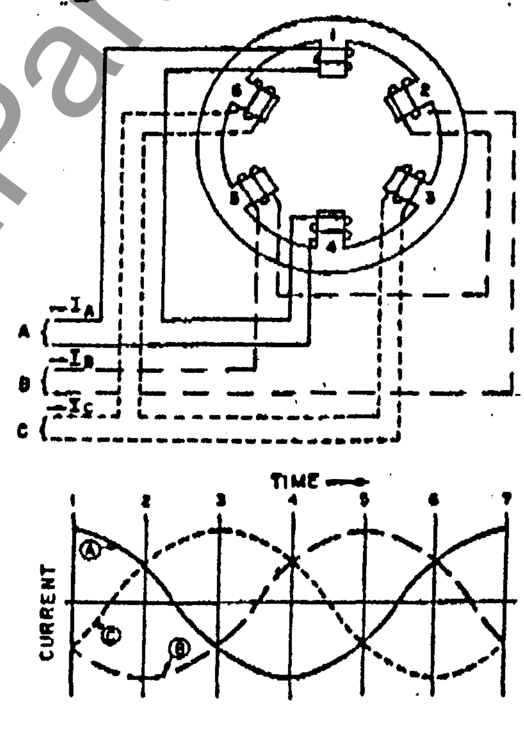
(3) In an a-c motor, the magnetic fields of the stator are created by the a-c current supplied from the power source. By causing these stator fields to rotate, the rotor fields will be "pulled" along and thus cause the rotor to rotate.

USE TD# 103.301

(4) Figure 1 shows how this "rotating magnetic field" is accomplished with polyphase power. Phase A is at greatest intensity, at time 1,

DISCUSS WITH CLASS

producing maximum magnetic flux on motor poles 1 and 4, with pole 1 being the south pole. At time 2, phase B is at greatest intensity with maximum flux now at poles 2 and 5, pole 2 being the south pole. Thus, as each phase of the a-c current rises and falls, the magnetic flux on the corresponding stator poles rises and falls. The result is a rotation of the maximum magnetic flux. It follows that the magnetic fields of the rotor, interacting with the stator poles, will produce torque, causing the rotor to rotate with the magnetic field of the stator.



A-C ROTATING MAGNETIC FIELD
Figure 1 TO103 201
103.301

USE TD# 103.302

(5) Standard motor speeds are shown in Figure 2.

NO. OF POLES	SPEED		
	25 CYCLES	50 CYCLES	60 CYCLES
2	1500	3000	3600
4	750	1500	1800
6	500	1000	1200
8	—	750	900
10	—	600	720
12	—	500	600
16	—	—	450

STANDARD MOTOR SPEEDS

Figure 2 TD 102.202
103.302

This is expressed mathematically as:

WRITE ON CHALKBOARD

$$\text{synchronous rpm} = \frac{120f}{p}$$

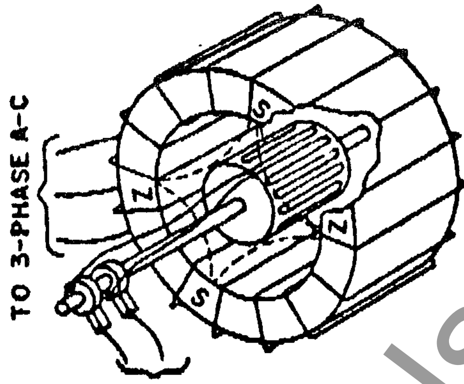
where f = supply frequency in cycles per second

p = number of poles

b. Standard Synchronous Motors

USE TD# 103.303

(1) A simplified drawing of the standard synchronous motors is shown in Figure 3.



STANDARD SYNCHRONOUS MOTOR

Figure-3 TD 103.303

DISCUSS WITH CLASS

(2) The synchronous motor utilizes both a-c and d-c current. The a-c winding is normally on the stator; the d-c winding (field) is on the rotor. In addition to the d-c field, the rotor also contains a small squirrel-cage winding (damper) for starting.

(3) During start-up, the squirrel-cage portion of the rotor receives current by induction from the stator, bringing the rotor to nearly synchronous speed. At that point, application of d-c current to the field winding "pulls in" the rotor to synchronization with the rotating magnetic field of the stator. Running speed is determined by the supply frequency and number of poles only ... there is no slip.

(4) Bear in mind that the synchronous motor requires a source of d-c for excitation. Synchronous motors can be supplied with an

DISCUSS WITH CLASS

exciter generator mounted on the motor ... or a separate d-c source may be used.

(5) Synchronous motors have two advantages:

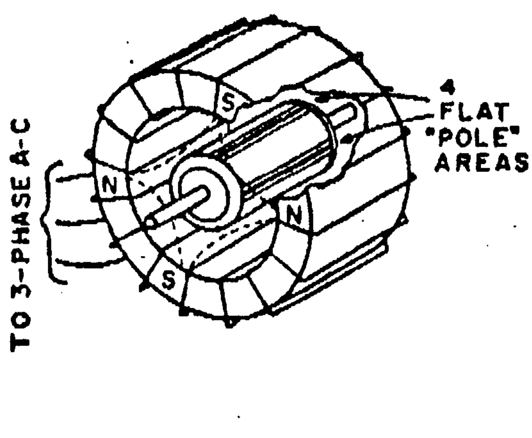
1. Constant speed - no variation in speed with changes in load.
2. Ability to improve plant power factor if operated with high d-c excitation.

(6) If constant speed is the only requirement, motors with 100% power factors can be utilized; and if it is desired to improve the plant power factor, motors with 80% leading power factors can be used.

C. Synchronous Reluctance Motors

USE TD# 103.304

(1) In physical appearance and construction, the synchronous reluctance motor is essentially the same as a polyphase squirrel-cage motor. The stators are identical ... the difference is in the rotors, as shown in Figure 4.



SYNCHRONOUS RELUCTANCE MOTOR

Figure-4 TD 103.304

DISCUSS WITH CLASS

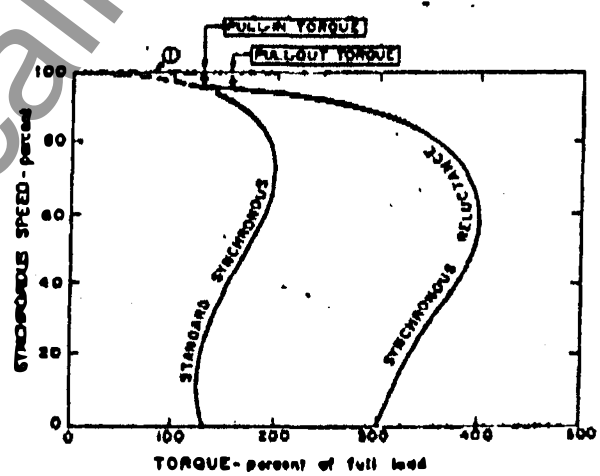
(2) In the synchronous reluctance motor, "poles" are created by milling flats on the rotor, to give flat sides corresponding to the number of stator poles. The result is that the magnetic flux crossing the air gap gathers at these poles, tending to lock the rotor poles in synchronism with the stator field.

(3) The motor starts like a squirrel-cage motor, but locks in and runs at synchronous speed.

d. Speed Torque Curves

USE TD# 103.305

(1) Figure 5 shows typical speed-torque curves of our standard synchronous motor and our relatively new synchronous reluctance motor. The standard synchronous motor is applicable to the full horsepower range while the synchronous reluctance motor is made only in sizes below 30 hp.



SYNCHRONOUS MOTOR CHARACTERISTICS
Figure 5
TD103.305

(2) As would be expected, the running portion of a synchronous speed-torque curve is the straight horizontal line (1) at 100% synchronous speed.

DISCUSS WITH CLASS

This is the same for all synchronous motors. It is referred to as "synchronous torque".

(3) The large "S" portion of these speed-torque curves indicates the motor's starting characteristics. The starting and accelerating torques of the synchronous reluctance motor are about twice as much as those of the standard synchronous motor.

(4) "Pull-in torque" and "pull-out torque" are two terms that are unique to the synchronous motor. Pull-in torque is the value of torque developed at the transition point from slip speed to synchronous speed (zero slip). It is often referred to as the point where the motor pulls into step (with the rotating magnetic field).

(5) Pull-out torque is that value of torque developed at the point where the motor pulls out of synchronization and falls back to the slip speed. This pull-out is caused by an overload created by the driven machine.

(6) Therefore, this pull-out torque is the maximum load that the motor can stand and still remain in synchronization. However, the motor still has a breakdown torque in the slip-speed range. Technically, pull-out torque is defined as the maximum steady-speed torque built up by the motor for one minute before it pulls out of step.

DISCUSS WITH CLASS

(7) Pull-in torque for a given motor is not a fixed quantity ... it depends on the WK^2 of the connected load. The higher the WK^2 of the load, the closer to synchronous speed the motor must accelerate as an induction motor before field excitation is applied. Standard pull-in torques are based on specific values of load inertia established by NEMA.

USE TD# 103.306

(8) Normal torque values for standard synchronous motors are shown in Figure 6.

HP	% OF FULL LOAD TORQUE		
	STARTING	PULL-IN	PULL-OUT
100% POWER FACTOR MOTOR			
200 & below	100	100	150
201 to 1000	60	60	150
1001 & larger	40	60	150
80% POWER FACTOR MOTOR			
150 & below	100	100	175
151 to 1000	60	60	175
1001 & larger	40	60	175

NORMAL TORQUE VALUES

Figure 6 TD103.306

2. Control Characteristics

DISCUSS WITH CLASS

a. Introduction

(1) In order to understand the control for a synchronous motor, one needs a fairly comprehensive understanding of the characteristics of the motor itself. During start-up, the synchronous motor functions much the same as a conventional squirrel-cage motor. Thus, it

DISCUSS WITH CLASS

would follow that the control requirements for this part of starting the motor are the same as those for a single-speed, squirrel-cage motor.

(2) The tough part of the control problem centers on the task of applying the d-c excitation current to the field winding at exactly the right instant for two main reasons:

(a) To minimize and keep the motor's "pull-in" effort within its "pull-in" torque rating

(b) To minimize any high voltage and current disturbances fed back into the a-c line as the motor is locking into step.

(3) To successfully accomplish the "pull-in" operation (synchronizing the motor) and meet criteria (a) and (b) above, the d-c current must be applied only when the stator poles and rotor poles are in favorable relationship. To be more specific, successful synchronizing of a synchronous motor dictates that the control apply the current to the field winding <u>only</u> when the following two conditions are met simultaneously:

(a) The rotor has accelerated to its maximum speed possible on the squirrel-cage winding (usually about 95% synchronous speed or higher)

DISCUSS WITH CLASS

(b) Each rotor pole is lagging slightly behind a stator pole of opposite polarity.

(4) In fulfilling the first requirement, we must start by measuring the speed of the rotor. However, from a control standpoint, it is impractical to make a direct measurement of the speed of the rotor. Instead, we must utilize some inherent effect that is produced in the motor as it accelerates to near synchronous speed.

(5) From our review of synchronous motors, we know that . . .

(a) The "synchronous speed" of the motor is the speed of the stator's rotating magnetic field. For any given number of stator poles, this speed is established by the frequency of the a-c power supply. For example, a two-pole motor operating on 60 cycle a-c has a synchronous speed of 3600 rpm or 60 rps - from the formula:

WRITE ON CHALKBOARD

$$\text{speed (rpm)} = \frac{120 \times \text{a-c frequency}}{\text{no. of motor poles}}$$

(b) The rotating magnetic field causes a voltage to be induced in the rotor poles (conductors being cut by a moving magnetic field). The resultant magnetic field in the rotor poles combines with the stator's rotating magnetic field, causing the rotor to rotate. Because of mechanical inertia,

DISCUSS WITH CLASS

the rotor starts at zero speed and gradually accelerates to a speed which is slightly less than its synchronous speed.

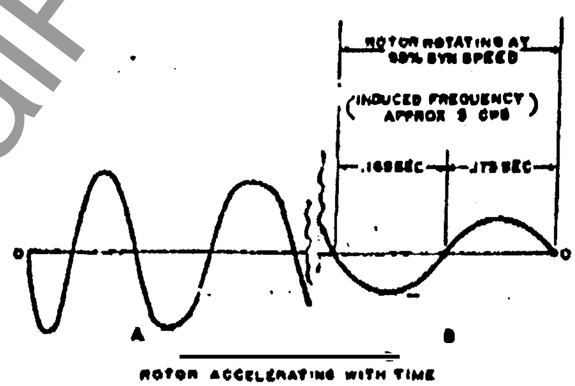
(c) At any given instant, the difference between the speed of the stator's rotating magnetic field and the speed of the rotor determines the frequency of the induced voltage in the rotor poles (field winding). With the rotor at standstill (speed difference 100%), the frequency of the induced voltage in the field is the same as the frequency of the rotating magnetic field in the stator - 60 cps. As the rotor accelerates, the speed difference decreases and thus the frequency of the induced voltage decreases (rotor at 50% synchronous speed = 30 cps induced voltage frequency ... at 95% synchronous speed = 3 cps).

WRITE ON CHALKBOARD

(d) Frequency rate (cycles per second) can be converted to a time value per unit (seconds per cycle). For example, at 60 cps a full cycle is completed in .0167 seconds, a half cycle is completed in half the full-cycle time or .0084 seconds.

USE TD# 103.307

(e) Thus, we can determine the speed of the rotor at any given moment by measuring the time span of one-half cycle of the induced voltage (current) in the rotor field at that moment. Figure 7-A shows the waveform of induced rotor voltage at time zero and through the time interval required for the rotor to reach a little less than .95 synchronous speed. The negative one-half cycle of Figure 7-B displays the conditions which exist when the induced voltage is at .95 synchronous speed and since the rotor is accelerating, the positive portion will necessarily be of a longer time duration.



INDUCED ROTOR VOLTAGE

Figure-7

WRITE ON CHALKBOARD

(f) Rotor at 95% of synchronous speed -

speed difference (slip) = 5%

induced frequency = 5% of 60 cycles/sec

= 3 cycles/sec

time of 1 cycle = 1/3 sec

time of 1/2 cycle = 1/6 sec or .167 sec approximately

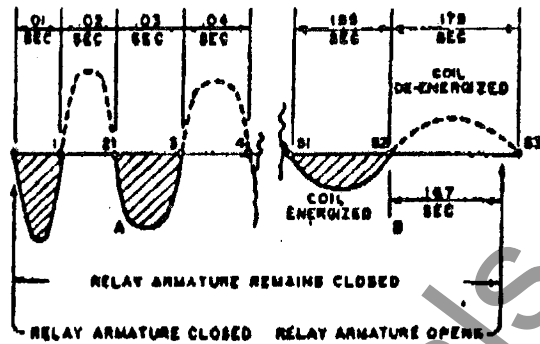
b. Measuring Induced Frequency

DISCUSS WITH CLASS

(1) Another way of stating condition "one" for proper synchronization is: our synchronizing control circuit must keep the d-c excitation off the field winding until such time as the rotor has accelerated to at least 95% of its synchronous speed. In other words, we need a sensing component that will not produce an output signal until the proper induced frequency has been reached. As already stated, this will be when the time span of one-half cycle of the induced voltage and frequency lengthens to more than approximately .167 seconds.

USE TD# 103.308

(2) One of the easiest methods to accomplish this is by means of an accurate time-delay relay. We shall use an off-delay relay so constructed that its armature will open approximately .167 seconds (or some other pre-selected time value depending on the speed selected where synchronizing is to be initiated) after the holding coil has been de-energized. One of the relay's contacts will be normally closed (when coil is de-energized) and will provide the signal for applying the d-c excitation.



TIMING OF INDUCED
VOLTAGE FREQUENCY

Figure-8 TD103.208

DISCUSS WITH CLASS

(3) To make this relay operate so that it can "see" and measure the lengthing time-per-cycle of induced voltage, we will feed its holding coil with only one half of each cycle of the induced voltage. Thus, the holding coil will be energized for one-half cycle, de-energized the next half cycle, energized the next half cycle, etc. It follows that after the relay armature is closed (contact open) it will remain closed during all succeeding OFF half cycles whose time span is less than the time delay setting of the relay (approximately .167 seconds). But, when an OFF half cycle is reached whose time span is greater than the time-delay setting, the armature will open.

(4) As shown in Figure 8, after the relay armature is closed at time 0, the induced voltage is fed to the holding coil. At time 1, the holding

coil is de-energized, but the armature remains closed because of the time-delay factor. Before the time-delay factor can "time out" and release the armature, time 2 is reached and the holding coil is energized once again.

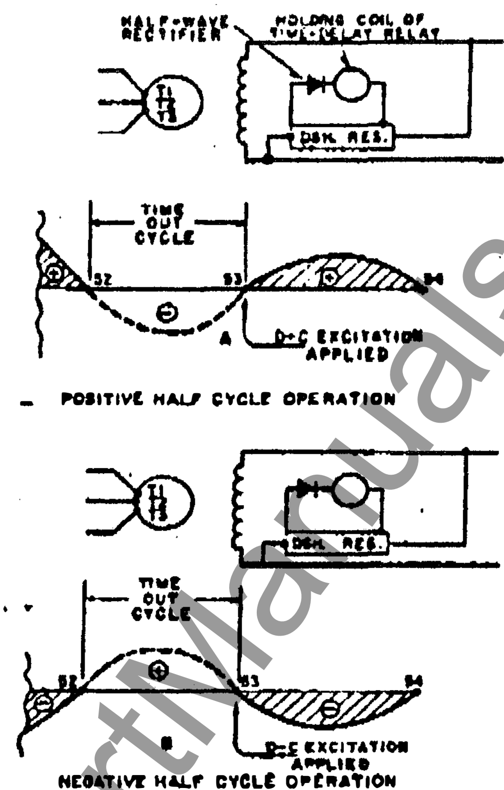
(5) This sequence repeats itself keeping the armature closed until time 52 is reached. Here, the time span between 52 and 53 is long enough for the relay's residual magnetism to decay to the point where the armature opens before Point 53 is reached (when another holding pulse would be available) and signals for the d-c excitation to be applied.

c. Sensing Pole Polarity

USE TD# 103.309

(1) Condition number "two" stated that for proper synchronization, each rotor pole should be lagging slightly behind a stator pole of opposite polarity. When this condition exists, we know the voltage induced in the field winding will be in the negative half cycle, hence this must be the proper time for the d-c excitation to be applied to the field.

(2) Figure 9 shows that portion of the synchronizing control circuit that contains the holding coil of the time-delay relay and the half-wave rectifier which allows current to pass in one direction, but not the other. In Figure 9-A, the diode is positioned so that the positive



HOLDING COIL OPERATION

Figure-9 TD103.309

DISCUSS WITH CLASS

half cycles of the induced current flow in the holding coil and the negative half cycles are used for time-out. Here, when the relay armature would open, the d-c would be applied during a positive half cycle. This we do not want.

(3) Figure 9-B shows the diode reversed so that now the positive half cycles are used for time-out, causing the d-c to be applied during the negative half cycle, as required.

(4) Thus, we see that our second requirement for proper synchronization is met by the proper directional positioning of the half-wave rectifier.

d. Magnetic Controller Operation

WRITE ON CHALKBOARD

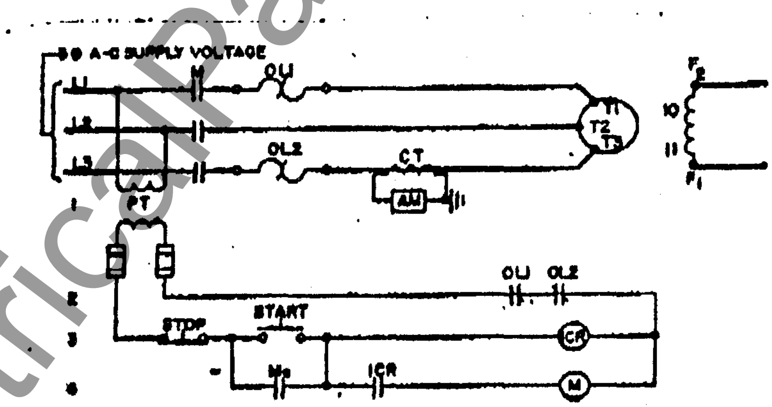
(1) The two main parts of the controller that satisfies the above requirements are:

(a) a-c starting control circuit - applies a-c power to the stator

(b) d-c synchronizing control circuit - determines when to apply d-c to the rotor, sends the signal to apply it, and maintain it.

USE TD# 103.310

(2) The basic a-c induction control circuit (one part of the synchronous motor controller) is very similar to the control circuit utilized for an a-c, single-speed, squirrel-cage motor is shown in Figure 10.



A-C CONTROL CIRCUIT
Figure 10

TD 103310

DISCUSS WITH CLASS

(a) As shown in the diagram,

1) When a momentary input is applied by pushing the "Start" button, the "CR" coil is energized ...

2) closing the "CR" contact and energizing the "M" coil ...

3) which closes "M" contacts in the motor circuit, starting the motor AND

4) which also closes the "Ma" contact (holding interlock), continuing the original output after the "Start" button is released.

(b) Note, too, that we have used:

1) overload relays

2) control circuit transformer (optional)

3) control circuit fuses (optional)

(c) There are two noticeable differences:

1) A current transformer has been added in L3 of the motor circuit to power an ammeter which indicates the value of current (in amperes) the motor is drawing. This combination is standard.

2) A field has been added to the motor symbol to indicate a synchronous motor.

(d) Other devices and symbols will be added later as the scheme is completely developed. Thus far our operation in the

a-c control circuit parallels that used with a standard squirrel-cage motor.

USE TD# 103.311

(3) The d-c synchronizing circuit (SLIPSYN) shown in Figure 11-A is a simple but very accurate method to perform synchronization.

(a) The key component is the ASR relay, which incorporates two separate operating coils:

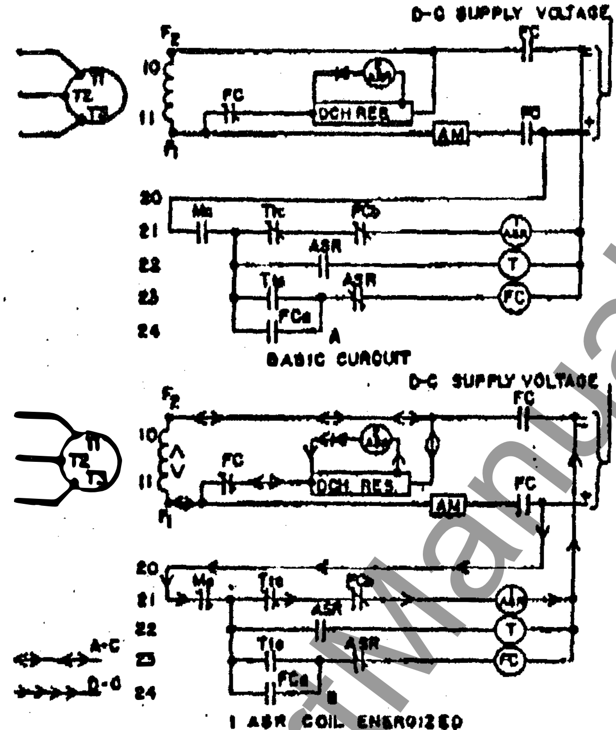
1) 1ASR - the pick-up coil, which closes the relay armature

2) 2ASR - the holding coil, energized only during negative half cycles of induced voltage, which applies d-c to the motor field on timed dropout

(b) In addition, our control also utilizes:

1) T - an inductive timing relay that controls the sequence of the field application components.

2) FC - the field contactor, which connects the motor field winding to d-c excitation source, also connects the field starting and discharge resistor in series with the motor field during start-up and also when the field excitation is removed.



D-C SYNCHRONIZING CONTROL CIRCUIT
Figure 11 TD 103311

DISCUSS WITH CLASS

3) AM - a d-c ammeter, which shows ampere value of d-c current flowing in synchronous motor field when the field in energized. This instrument is standard in the control scheme. While not shown as part of the scheme, a way is always available to adjust the voltage value of the d-c supply. Then the amount of current in the d-c field can be adjusted to the value shown on the motor nameplate. At the same time, the a-c ammeter reading can be matched against the motor nameplate rating, thus determining if the motor is producing its rated output.

(c) When the motor is started (Figure 11-B) an auxiliary contact "Ma" of the a-c motor circuit contactor closes, permitting d-c current to flow ...

1) from "+" ...
2) through "Ma" contact (now closed) (line 21) ...
3) through contact "Ttc" (normally closed) ...

4) Through contact "FCb" (normally closed) ...

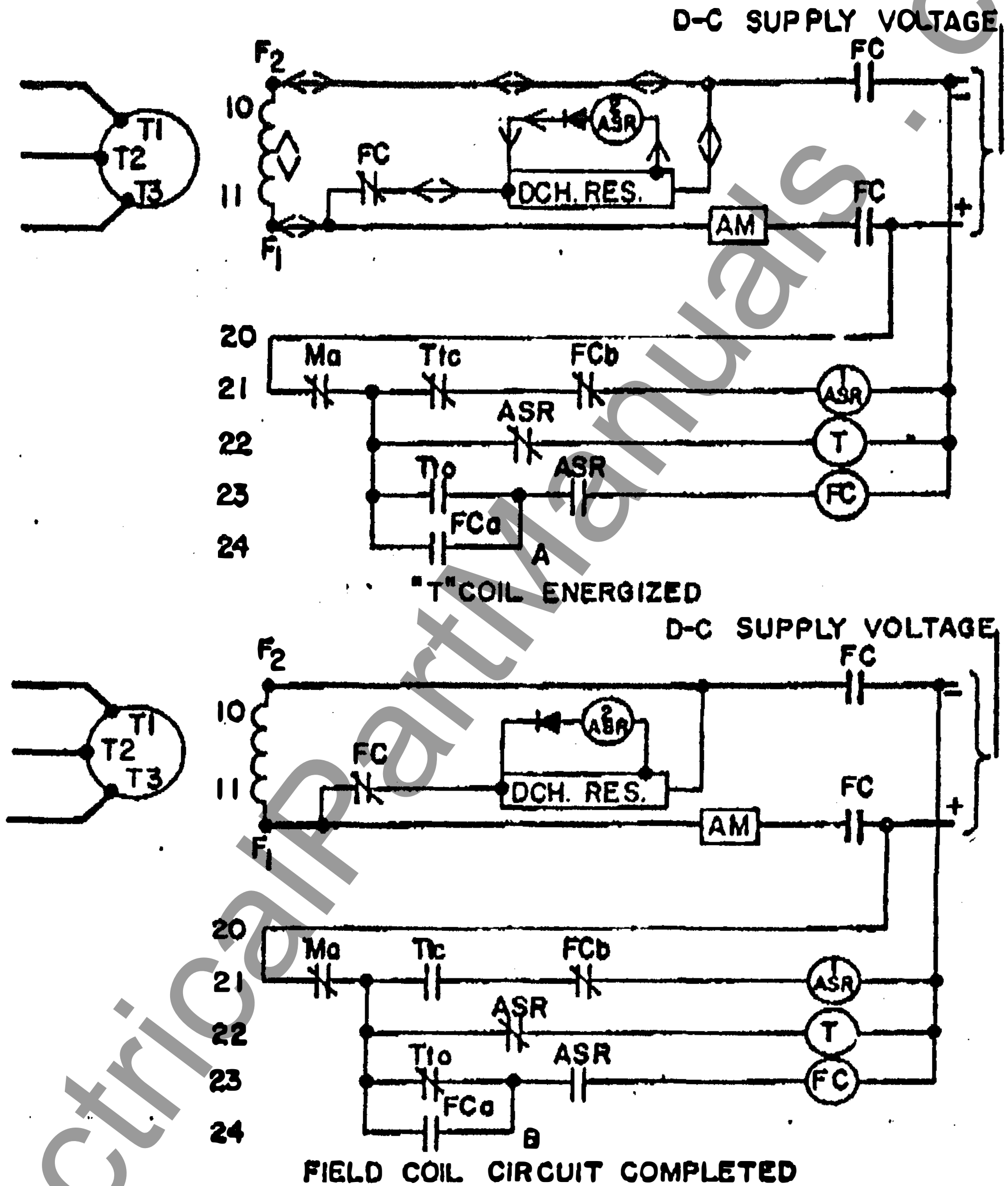
5) energizing pick-up coil "1ASR" of the field application relay. This operating coil provides the main magnetizing force to activate all the ASR contacts.

(d) AT THE SAME TIME, as the rotor starts to turn, an a-c voltage is induced in its field, causing an alternating current to flow through contact "FC" (NC main contact of field contactor) and the discharge resistor. The negative half-wave rectified portion of this current flows in the "2ASR" circuit, causing the "2ASR" holding coil to be energized.

USE TD# 103.312

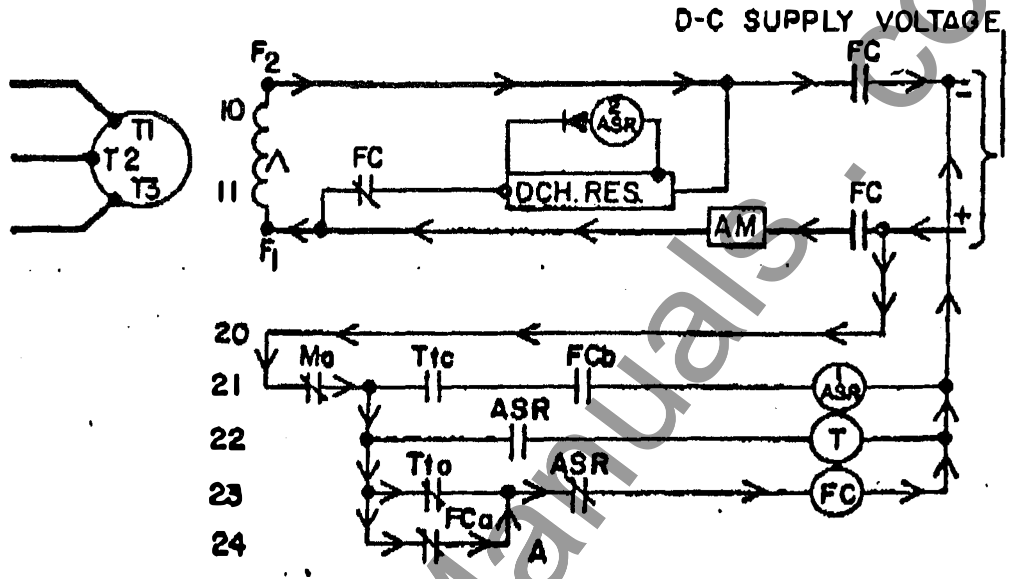
(e) Refer to Figure 12-A. Just as soon as pick-up coil "1ASR" is energized, its normally-closed contacts in line 23 open to block out coil "FC". Also, its normally-open contacts in line 22 close allowing d-c current to flow ...

1) from "+" ...
2) through contact "Ma" (line 21) ...
3) through contact "ASR" (line 22) ...
4) energizing coil "T".

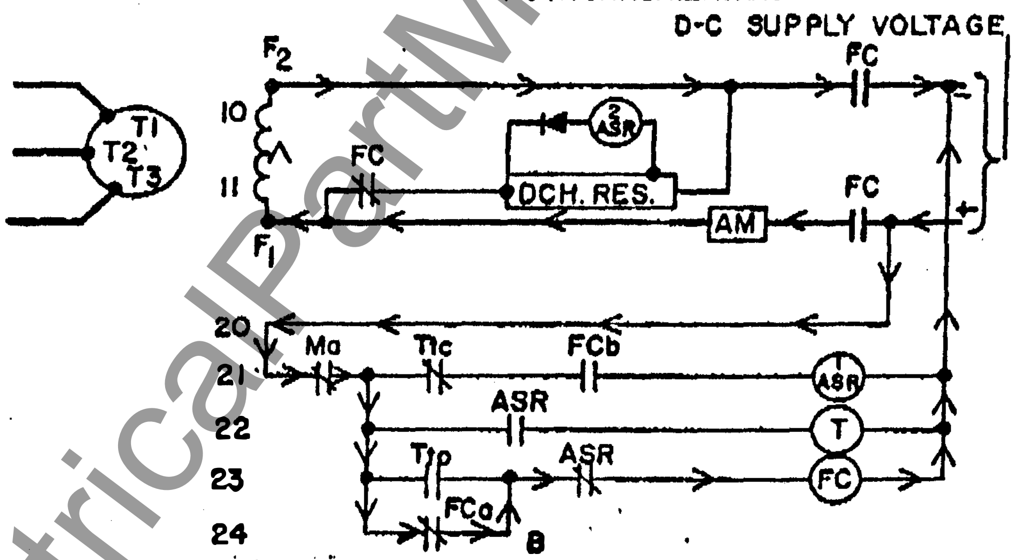


OPERATION OF D-C SYNC CIRCUIT

Figure 12 TD 103312



MOTOR SYNCHRONIZATION



"FC" COIL OPERATION

D-C SYNCHRONIZATION COMPLETE

Figure 13 TD 103313

DISCUSS WITH CLASS

(f) Refer to Figure 12-B. The normally-closed contact "Ttc" in line 21 opens and de-energizes pick-up coil "1ASR", making the "ASR" relay solely responsive to the rectified field current. AT THE SAME TIME, contact "Tto" (line 23) closes and sets up the field contactor coil so that "FC" coil will be energized when "2ASR" coil in line 10 releases its armature and allows "ASR" contact in line 23 to close and complete the field coil circuit.

USE TD# 103.313

(g) Refer to Figure 13-A. When the frequency time span of the induced field current is long enough for the "2ASR" coil to time out, the "ASR" relay drops out ...

1) closing contact "ASR" (line 23) ...
2) energizing coil "FC" ...
3) opening contact "FC" (line 11), canceling both the "2ASR" holding coil (line 10) and the complete field discharge circuit
4) the "FC" coil also closes its two "FC" contacts in the motor field circuit, applying d-c to the field winding, <u>causing the motor to synchronize</u>

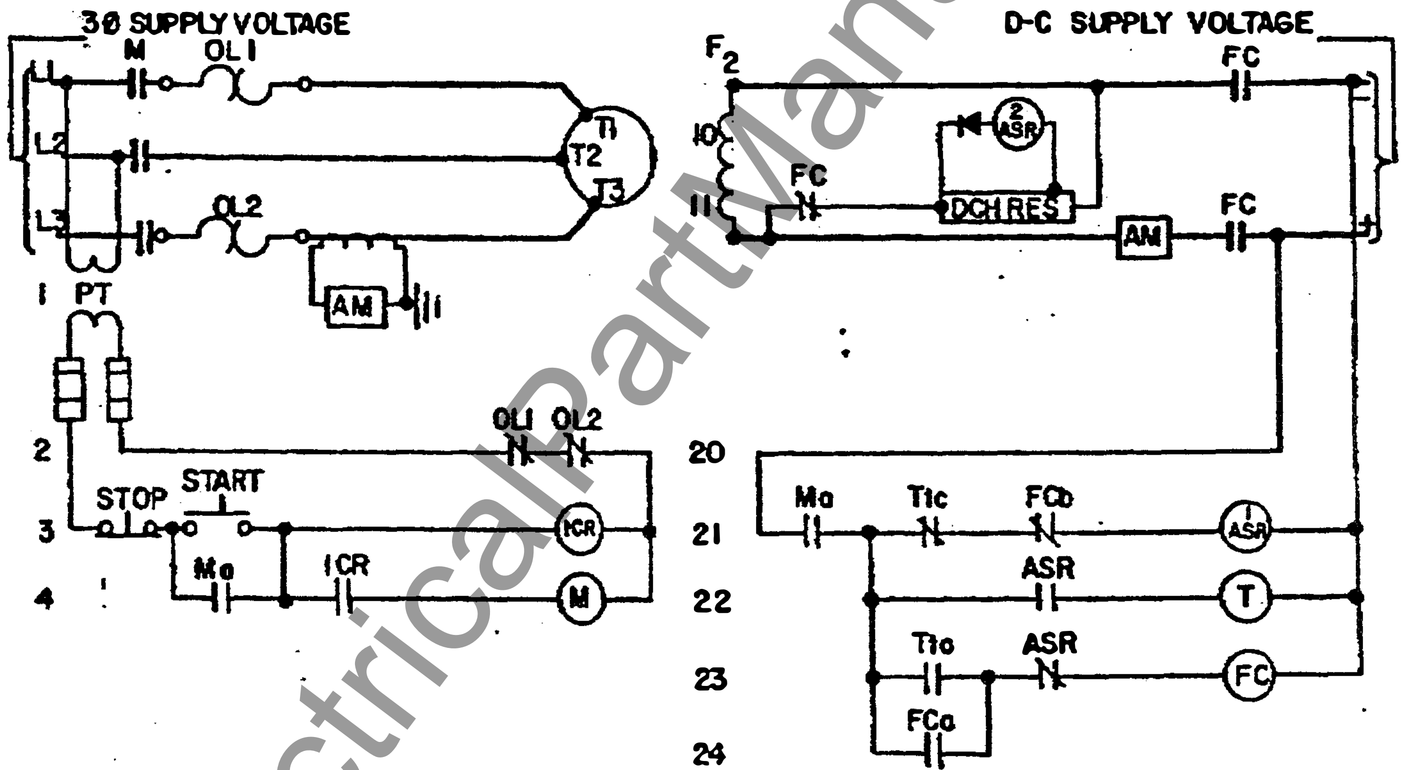
DISCUSS WITH CLASS

5) at the same time, contact "FCa" in line 24 closes maintaining circuit 23 ... and contact "FCb" in line 21 opens to keep coil "1ASR" from being energized again.

(h) Refer to Figure 13-B. When contact "Tto" times out and returns to its normally-open state, the "FC" coil remains energized, allowing its motor field circuit contacts to continue to supply d-c to the field winding of the motor. Simultaneously, as contact "ASR" in line 23 closes, "ASR" in line 22 opens, de-energizing timer coil "T". After the time setting of coil "T" lapses, "Ttc" in line 21 closes and "Tto" in line 23 opens. All the control circuits are now reset ready to repeat the synchronizing cycle as soon as signaled to do so.

USE TD# 103.314

(i) The normal state of the overall basic synchronous motor controller including the a-c control circuit is shown in Figure 14. The actual electrical interlocking between the a-c and d-c control circuits is noted. Only when coil "M" (line 4) is energized can the field be connected to the d-c source. When "M" is open, the field cannot be energized.



BASIC SYNCHRONOUS MOTOR CONTROLLER

Figure 14 TD 103.314

Protective Schemes

—‖—

3. Protection Schemes

DISCUSS WITH CLASS

a. Introduction

(1) As was the case for other types of controls, the synchronous motor control must satisfy the additional requirement of providing protection.

(2) Three types of protection must be built into this control, and are considered to be standard:

WRITE ON CHALKBOARD

(a) Overload Protection

(b) Pull-out Protection

(c) Damper-winding Protection

b. Overload Protection

(1) A motor overload protection unit is, in reality, a device that senses the amount of current being drawn by the motor. When the current drawn by the motor exceeds a predetermined value, this protection unit responds and disconnects the motor from the line. Thus, the motor, the control apparatus, and the associated wires are all protected from excessive heating that can be caused by excessive motor overloads. This device is commonly called an OVERLOAD RELAY.

RE-USE TD# 103.314

(2) It follows that the sensing element of this overload relay must be located in the power lines to the motor, as shown in Figure 14. The schematic shows sensing elements in two conductors of a 3-wire, 3-phase ungrounded supply system.

DISCUSS WITH CLASS

(3) In this particular circuit, the sensing element is a thermal type and it operates through mechanical linkage to open the main power contacts when an overload occurs.

(4) When the motor draws excessive current, the overload relay causes the toggle mechanism to trip, which opens the power contacts and disconnects the motor from the power supply. In addition, power is removed from the control circuit by opening the normally-closed relay contacts OL1 and/or OL2.

c. Pull-Out Protection

(1) When load torque becomes so great that the rotor can no longer keep up with the electrical speed of the magnetic field of the stator, the rotor starts slipping poles, superimposing an a-c current on the steady state d-c in the field winding. This is called "pull-out". NEMA standards call for protection against such be provided in a synchronous motor control system.

(2) The main damage that can be done is to the insulation of the motor. When the shaft is loaded beyond pull-out torque (150% to 250% of rated torque is standard), the rotor starts slipping poles. If the motor is not immediately turned off, high over-current will be drawn, resulting in excessive heat, which will damage the insulation of the motor. Combine this with

the fact that speed of rotation of the rotor (which is the chief means of dissipating heat) is decreasing, and it is fairly obvious why pull-out protection is required. In short -

MOTOR HEAT WILL INCREASE BECAUSE OF INCREASED CURRENT

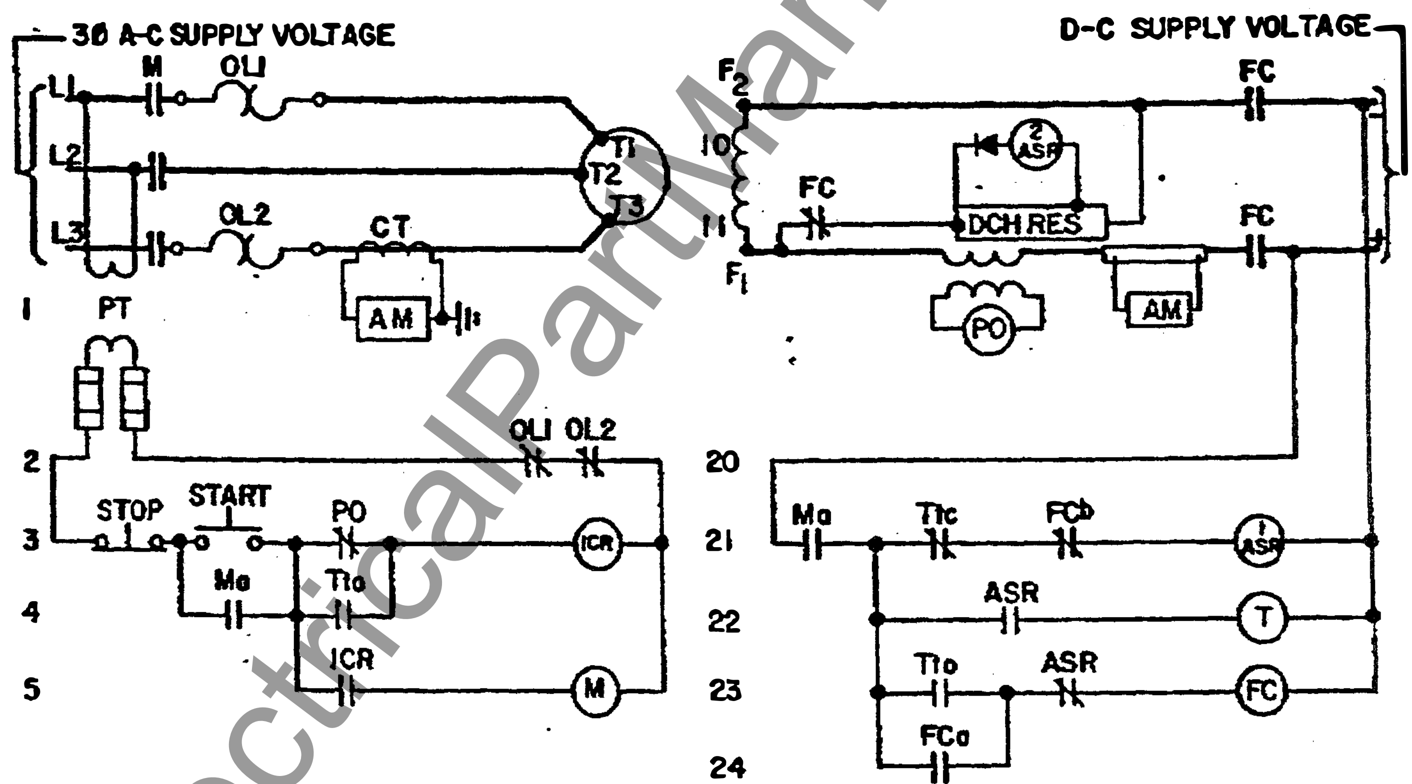
AND

HEAT DISSIPATING CAPABILITY WILL DECREASE BECAUSE ROTOR ROTATION IS SLOWING DOWN

USE TD# 103.315

(3) We accomplish pull-out protection by utilizing a combination <u>pull-out relay and transformer</u> (legend-PO) as shown in Figure 15. The primary of the pull-out transformer is connected in series with the d-c field. Obviously, when only d-c is flowing in this circuit, there is no current induced in the secondary of the transformer, <u>BUT</u> ... when a pull-out condition develops ...

(a) the resultant a-c superimposed on the field is fed into the primary of the transformer
(b) current is induced into the secondary
(c) energizing "PO" coil connected in the "PO" transformer secondary
(d) opening "PO" contact in a-c control circuit (line 3) turning the motor off.



PULL-OUT RELAY AND TRANSFORMER

Figure 15

TD 103315

DISCUSS WITH CLASS

(4) Note, too, that a separate "Tto" contact (line 4) is utilized in the a-c circuit as a holding interlock around the "PO" contact. This contact is employed to prevent the motor from being shut down when both d-c and induced a-c are present in the field winding (similar to pull-out conditions) during synchronizing. Recalling the operation of "T" in line 22 ... immediately after "M" closes, "T" is energized, closing "Tto" in line 4. Since the "PO" transformer is not seeing current during starting, "PO" in line 3 cannot open; but its operation, when "FC" closes, is bypassed by "Tto" in line 4, which then opens so "PO" is affective after the delayed drop-out of "T" following synchronizing and the field current is steady state d-c.

d. Damper Winding Protection

USE TD# 103.316

(1) The motor's damper winding, which is utilized in producing most of the starting torque, has a rather short current-carrying time rating since it is actually in operation only during start-up. If the motor fails to start and accelerate in this short time period, the damper-winding temperature will rise above its safe-limit and cause the winding to burn out or progressively weaken it to the point where it will eventually fail. This is an inherent weakness of any damper winding.

DISCUSS WITH CLASS

(2) As shown in Figure 16, the damper winding relay (legend-DP) provides the required protection. It is a thermal-type relay similar to the overload relays used for motor OL protection. It "sees" the induced current in the field during start-up, which heats its thermal element at approximately the same rate as the damper winding. If the motor hasn't synchronized within a preset time period, it opens its contact ("DP" in a-c control circuit, line 3) shutting down the motor. This relay is rated such that the motor must accelerate in normal time, or the relay contact will open.

e. Summary

(1) So far in our discussion of the control for synchronous motors, we have discussed

(a) the basic theory involved

(b) the overall operation of the:

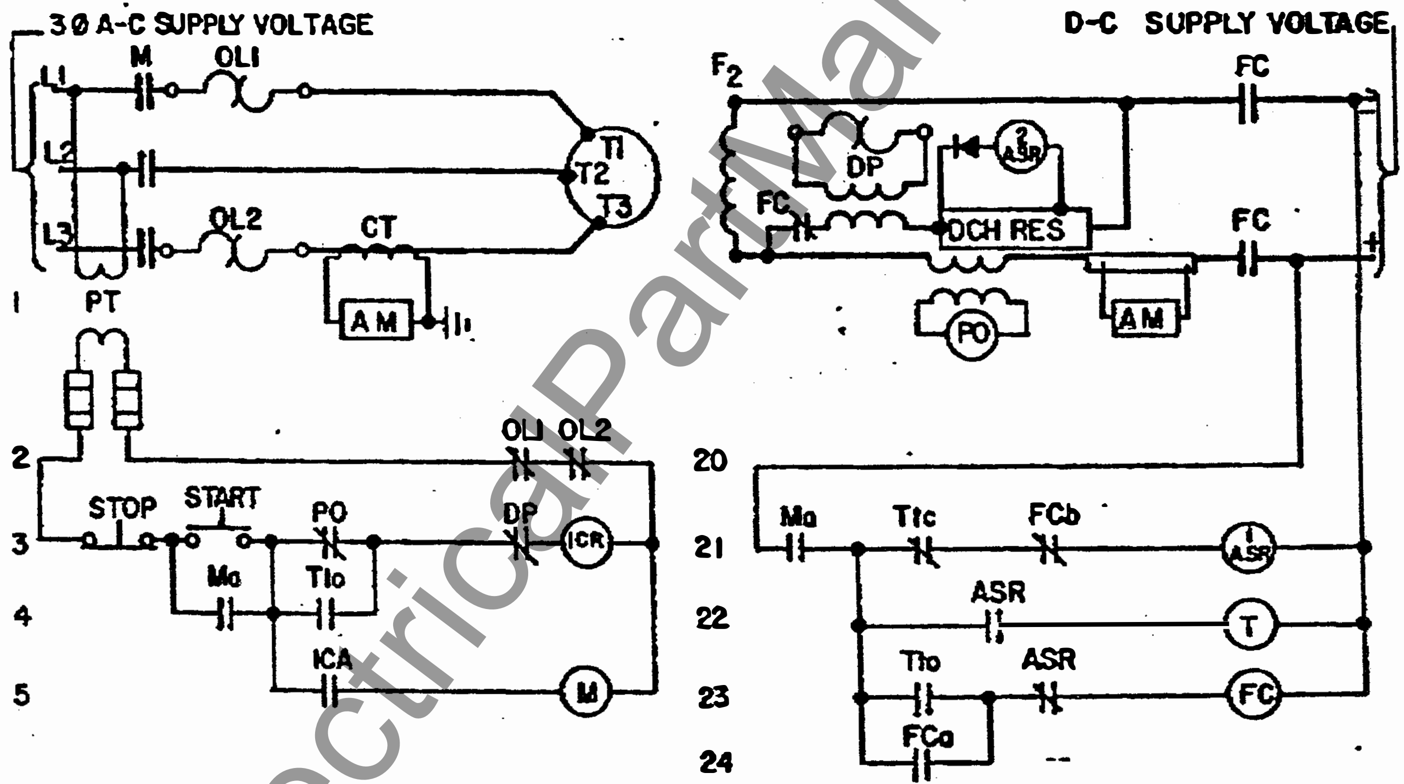
a-c control circuit

d-c synchronizing circuit

(c) the standard protective devices.

(2) The controller as diagramed in Figure 16 is complete and standard. But as is often the case, certain additional control features may be desirable.

f. Modifications - Additional protection schemes are common to the synchronous motor controller. These modifications can be used singly or in any



DAMPER WINDING PROTECTION

Figure 16

TD 103316

combination. They are: Protection Against Loss of Field Current, Protection Against Loss of Field Current and Voltage, Automatic Field Checking for Open Circuit, Dynamic Braking and Incomplete Sequencing.

USE TD# 103.317

(1) Protection Against Loss of Field Current

(a) If d-c voltage is available for the field winding of the motor, but no current can flow when the field contactor closes, the motor can never synchronize. And, if the motor continues running with no d-c field, the already above normal stator currents can overheat and damage the motor.

(b) The damper winding relay cannot be depended on altogether to sense this condition, because by the time motor speed approaches synchronous speed its heating rate has fallen off considerably, since the induced current in the field starting circuit is sharply reduced. The overload relays will eventually trip under these conditions, and their thermal lag may allow undesirable motor overheating before they operate. If the field winding should open abruptly during running, the PO relay may sense the condition and shut down the motor. If the field failed slowly, chances are the PO relay would not operate.

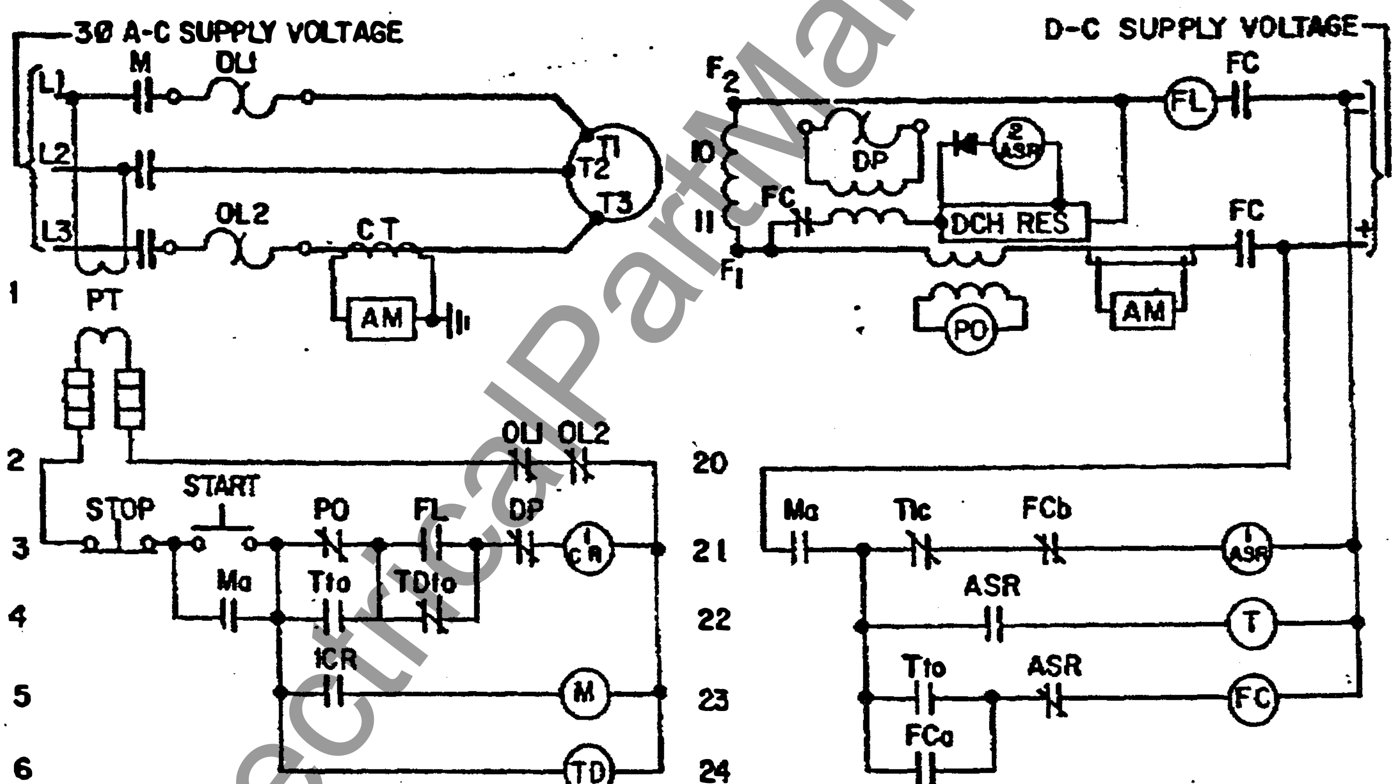
DISCUSS WITH CLASS

(c) One method of providing protection against loss of field current can be seen by examining Figure 17. Here a relay called "FL" with a d-c current-sensitive coil is connected in one side of the d-c power supply and its NO contact is connected in line 3. An on-delay a-c timing relay "TD" is also used. Its coil is added in line 6 and its time-opening NC contact is added in line 4 (around "FL" contact in line 3). Note that coil "TD" is energized when the "Start" button is depressed.

(d) Under normal conditions, the "FL" coil in the d-c circuit will be energized when the field is applied, closing "FL" contact in the a-c control circuit line 3.

(e) A preselected time after the "TD" coil is energized (time enough to allow the d-c to be applied to the field winding and the motor to synchronize), the "TD" contact (line 4) opens, transferring the responsibility for sensing flow of field current by depending upon "FL" coil and its now closed contact (which will stay closed as long as field current is flowing).

(f) In the event that the flow of d-c in the field circuit is not present or interrupted for any reason, the "FL" coil is -



PROTECTION AGAINST LOSS OF FIELD CURRENT

Figure 17

TD 103317

1) de-energized
2) open "FL" contact in line 3
3) shutting down the motor.

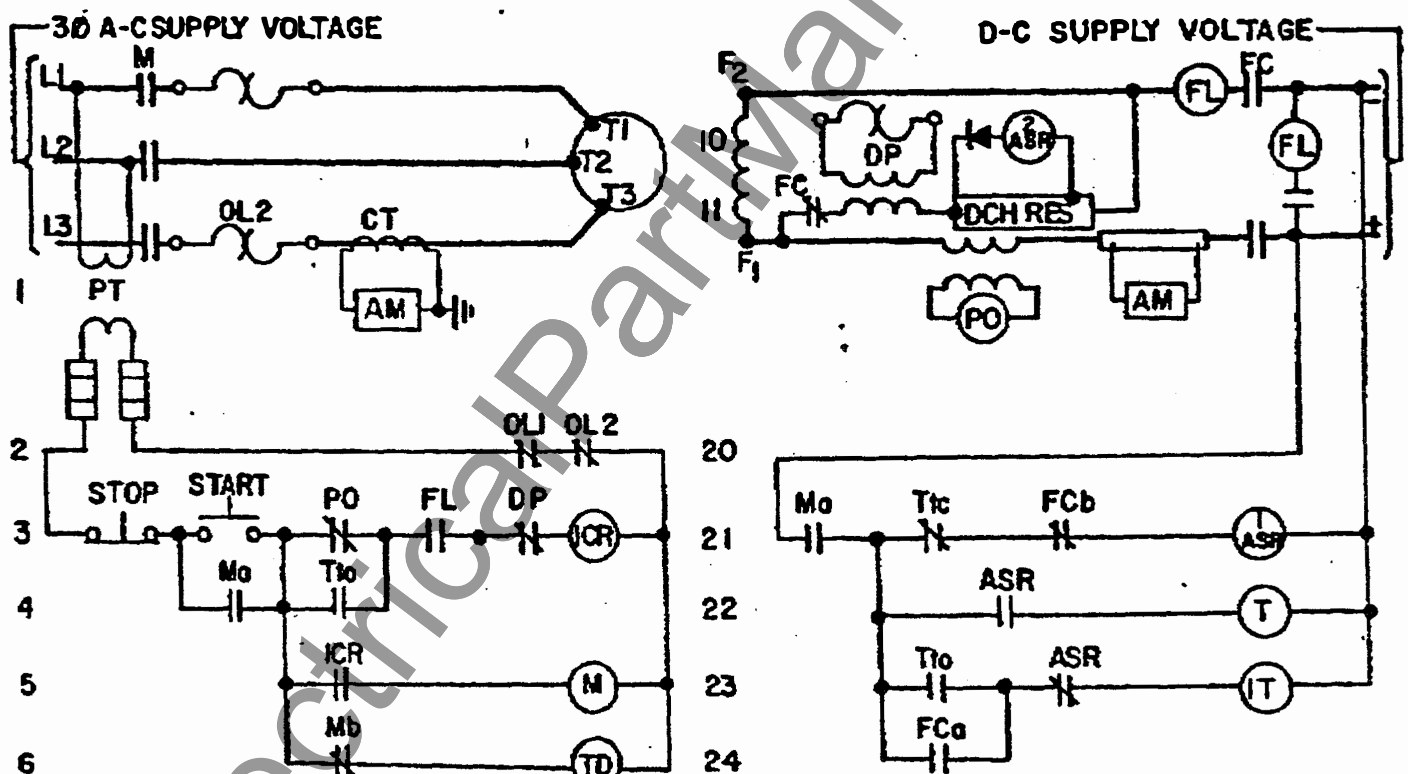
USE TD# 103.318

(2) Protection Against Loss of Field Current and Voltage

(a) Here, additional protection is provided to prevent starting the motor if the d-c supply voltage is not present. This method does not apply when a direct-connected exciter is used to provide synchronous field excitation.

(b) As shown in Figure 18, a voltage-sensitive coil is added to the "FL" relay and connected in series with a NO, time-opening "TD" contact and across d-c supply (+ and -) on the line side of "FC" contacts. A NC interlock of "M" is added to line 6 in series with "TD" coil to provide proper sequence interlocking during start-up.

(c) "FL" relay is set so that when "FL" potential coil is energized from normal d-c excitation voltage supply, its contact in line 3 closes, which allows motor to be started when "Start" button is pushed. "TDto" contact opens after motor is synchronized, allowing "FL" current coil to detect loss of excitation voltage and/or current and to shut down the motor.



LOSS OF FIELD CURRENT AND VOLTAGE

Figure 18

TD 103318

DISCUSS WITH CLASS

(d) It is interesting to note that, in both Figures 17 and 18, the timing relay "TD" is adjusted to operate after the motor synchronizes. Because, in effect, all the control functions have had a chance to perform in their proper sequence to synchronize the motor before "TD" relay operates ... the "TD" relay is also acting as an "incomplete sequence" relay. It is the last relay to operate in the overall synchronizing sequence.

(3) Automatic Field Checking For Open Circuit

USE TD# 103.319

(a) If a synchronous motor is started without a complete circuit to the field through the starting and discharge resistor, a high voltage will be generated in the field during start-up because of the open circuit condition. The most common point of vulnerability which can cause an open circuit is the slip-ring brush assembly on the motor. Maintenance men lift the brushes to clean the rings and sometimes forget to replace the brushes. If the button is pushed in this situation, the motor will start as an induction motor but the d-c can never be applied, and the field winding will be damaged.

DISCUSS WITH CLASS

(b) Our basic requirement then, is to provide a means of detecting an open field-circuit automatically.

(c) The protective scheme which solves this requirement is a Westinghouse exclusive and is shown in Figure 19.

(d) When the start pushbutton is depressed, current will flow in line 3 -

1) through NC contact 1Ttc

2) through the primary of the "field-checking" transformer

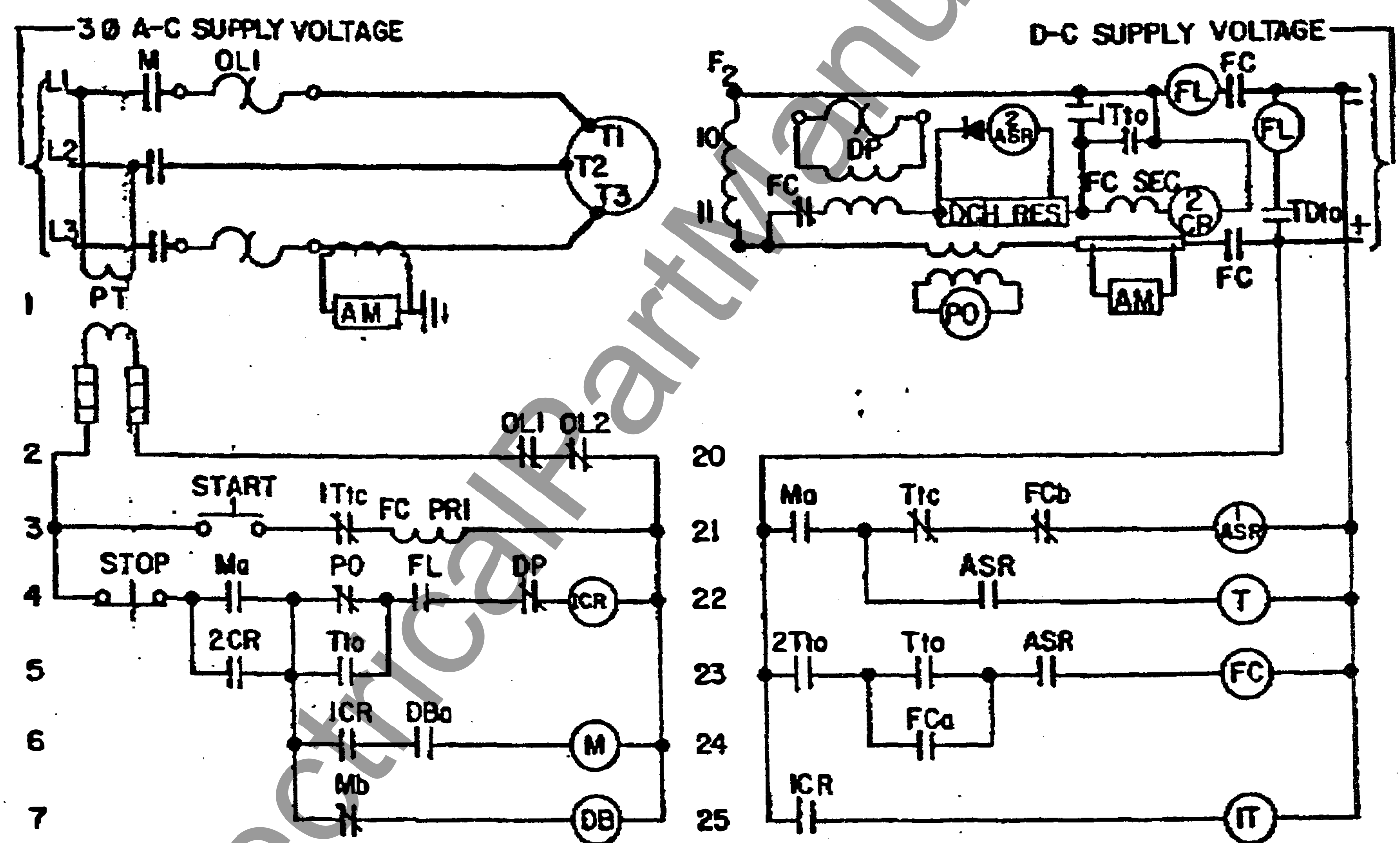
(e) Current will then be induced in the secondary of the transformer located in the field starting and discharge circuit, causing a small current to circulate through the field and discharge circuit and

1) energize coil "2CR" ...

2) closing contact "2CR" in line 5 (to act in place of the start button used in our other applications)

3) energizing coil "1CR" to complete the starting sequence discussed previously.

(f) In addition, when coil "1CR" is energized, contact "1CR" in line 25 also closes - energizing coil "1T" ... instantaneously opening contact "1Ttc" in line 3 to eliminate field checking voltage, and closing contacts "1Tto" connected parallel



AUTOMATIC FIELD CHECKING

Figure 19

TD 103319

DISCUSS WITH CLASS

in the field discharge circuit to short-out "FC" transformer secondary and "2CR" coil (as their design does not permit carrying of currents induced in this circuit during stopping or starting). "2CR" contact in line 5 then opens, but "Ma" in line 4 has closed by this time continuing the circuits established when "2CR" contact closed initially. Note, on stopping line 25, "1CR" opens to start "IT" to time-out, after the time lapse is finished (the field circuit completely discharged) its contacts return to the positions shown.

(g) When there is no open field-circuit, the motor starts through the process just described. But what happens if there is an open field-circuit?

(h) When the start button is depressed in line 3, the induced voltage in the transformer secondary CANNOT cause current to flow because the circuit path is incomplete.

(i) As a result, coil "2CR" is NOT energized and cannot close contact "2CR" in line 5, preventing the motor from starting.

(4) Dynamic Braking

USE TD# 103.320

(a) In many applications, normal motor "coasting" to a stop is not acceptable.

DISCUSS WITH CLASS

~~In~~ these cases, the usual requirement is for special braking. This is particularly true in the Rubber Industry where ALL stops are electrically-braked stops.

(b) Most braking requirements are requested for one of two reasons -

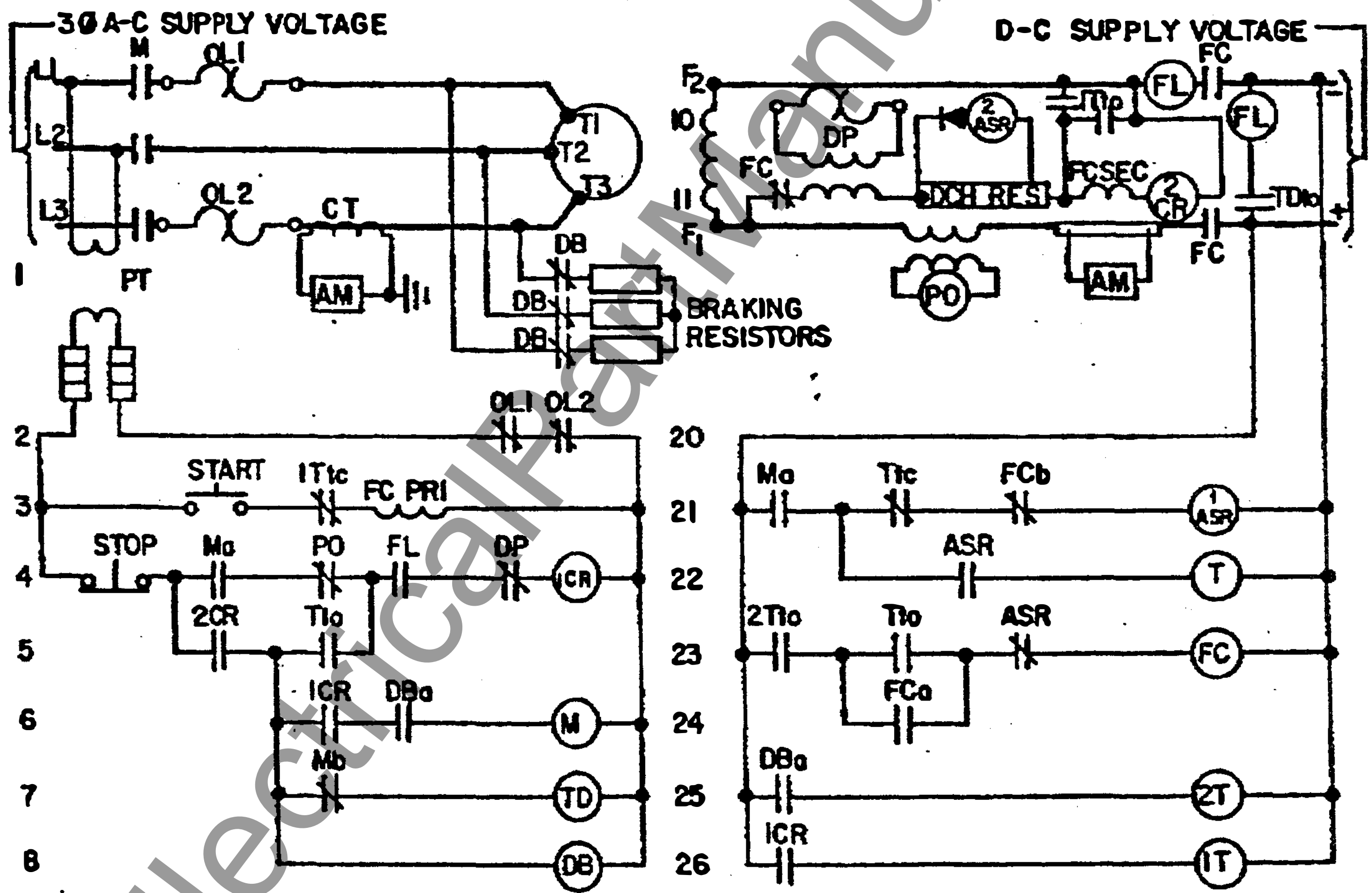
1) for the safety of personnel (can be stopped 99.9% faster than normal coasting)

2) with high inertia load, the motor can be stopped much faster than by normal coasting.

(c) Our basic requirement then, is to provide a means of rapidly braking the motor to a stop.

(d) This can be accomplished best by dynamic braking as shown in Figure 20. The a-c lines are opened, three connections from the motor power lines to resistors across the stator connections are closed. The d-c field must be kept on. As the motor is brought to a stop, it acts as an a-c generator with power fed from the stator to, and dissipated in, the resistors.

(e) When the stop button is pushed, the entire a-c control circuit is opened, de-energizing "M" and "DB" simultaneously. Since "M" and "DB" (spring closed main contacts)



DYNAMIC BRAKING
Figure 20

TD 103.320

DISCUSS WITH CLASS

are mechanically interlocked, "M" motor circuit contacts must be open before "DB" main contacts close ... preventing a short of the a-c power system through the braking resistors. When "DB" main contacts close, the resistors are connected across the motor terminals. (When the motor was started "DBa" in line 25 closed, energizing timing relay coil "1T" and its contact "1Tto" in line 23 closed instantly to set up "FC" coil circuit to perform at its proper time in the synchronizing sequence and allow the field to remain energized for a pre-determined time after "M" opens). "DBa" in line 25 opens, causing "1T" to time-out (3 seconds maximum) and disconnect field from excitation source.

(f) Other control circuitry is possible to accomplish the same result. The particular circuit used here is only typical. Where a field rheostat is used, it must be bypassed during the braking period so that full field current is available for fast stop.

(5) Pull-Out Without Shutdown of Motor

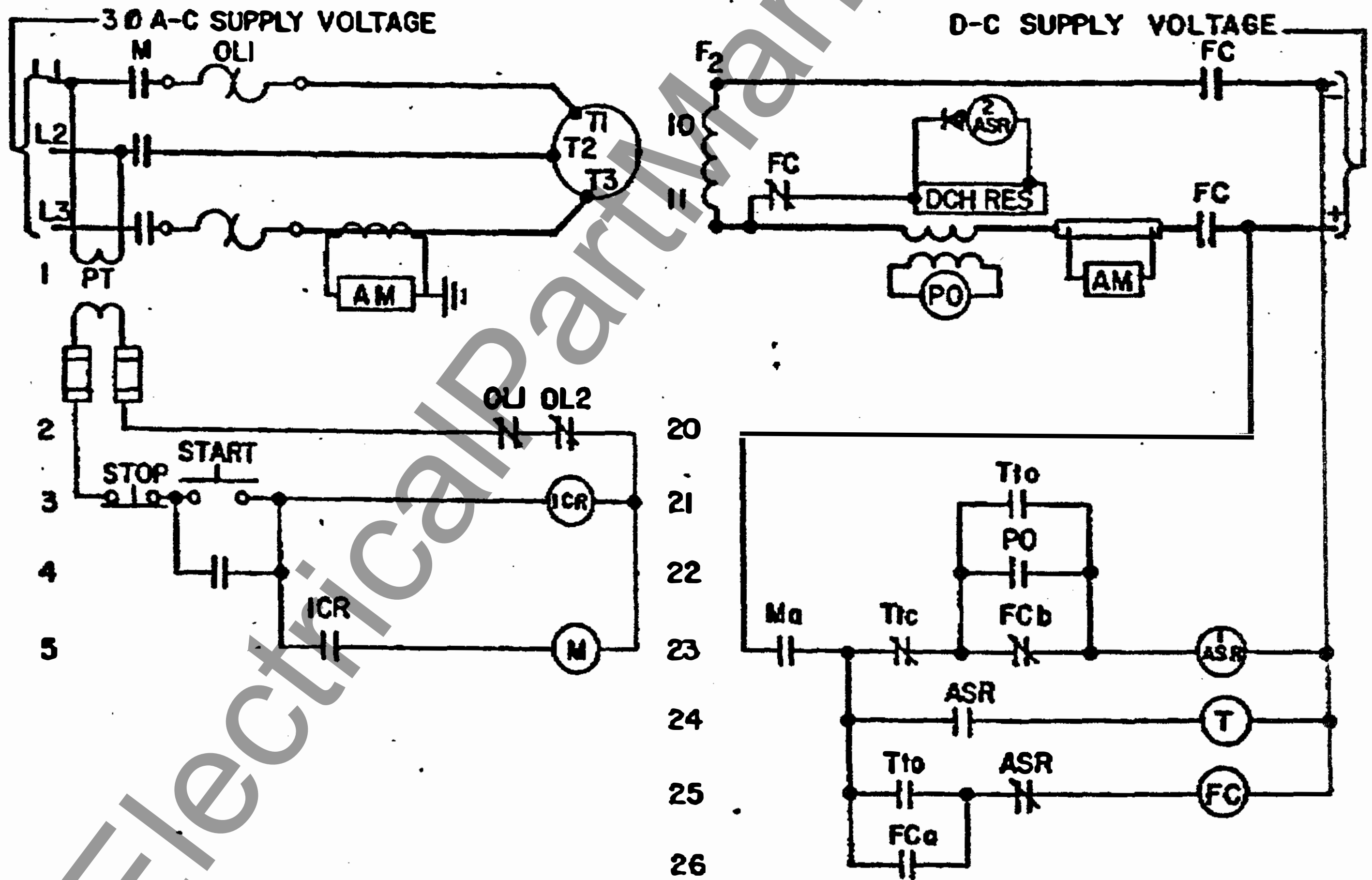
RE-USE TD# 103.315

(a) Normally, synchronous motor controllers are connected to shut down the motor on pull-out, as shown in Figure 15. On rare

USE TD# 103.321

applications, it may be required that the motor not shut down on pull-out, but automatically re-synchronize. This is easily accomplished as shown in Figure 21. Actually the "PO" contact in line 3 is SPDT instead of NCST, as shown. By jumper arrangement this NC "PO" contact in line 4 and the paralleling contact "Tto" of line 5 are moved to the d-c synchronizing scheme and connected in parallel with "FCb" contact (line 21) EXCEPT the NO "PO" contact is used instead of the NC contact. Now on pull-out the a-c control circuit stays energized. The NO "PO" contact closes, bypassing "FCb" now open, and energizes "1ASR" (line 21) whose now closed contact in line 23 opens and cuts off the field, and starts the synchronizing scheme as though the motor was just started. "Tto" bypasses "PO" contact during synchronizing and prevents another re-synchronizing try until after previous try, field current settles down to steady state. Care must be exercised when using the re-synchronizing scheme if other optional protective features are used. For example, if the "FL" feature in Figure 17 were included, the circuitry illustrated in Figure 21 could not differentiate between a "loss of

RE-USE TD# 103.317



PULL-OUT WITHOUT SHUTDOWN OF MOTOR

Figure 21

TD 103321

DISCUSS WITH CLASS

field" and a "pull-out" so as to shut down on loss of field but re-synchronize on pull-out.

(b) Just about everything we have discussed regarding synchronous motor control has related to field application and removal. This is the only thing that differentiates synchronous motor control from squirrel-cage induction motor control.

(c) All of the same basic components can be utilized to perform synchronizing functions in all types of synchronous motor control whether they be low or medium voltage.

(d) Remember, too, that synchronous motor controls, because of their similarity in the a-c motor and control circuits to the squirrel-cage motor controls, can utilize similar reduced voltage starting besides the already illustrated full-voltage starting ... autotransformer and reactor types are the most popular.

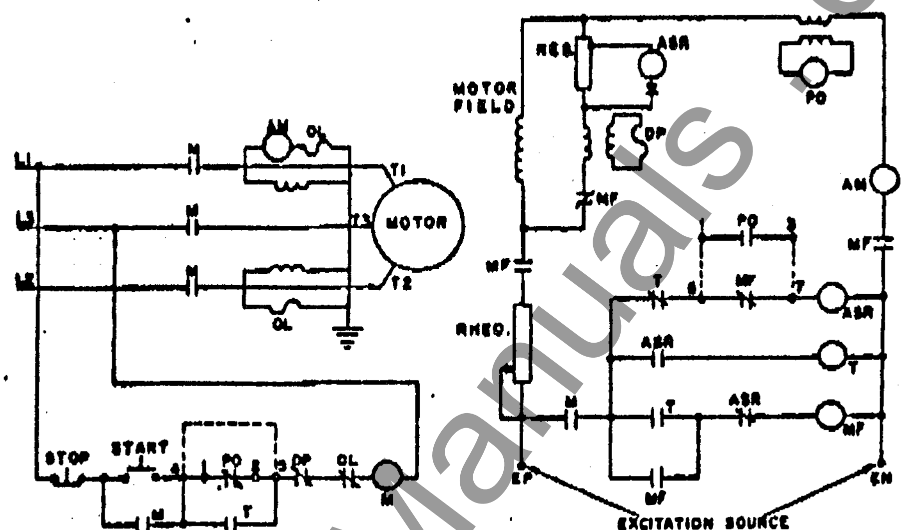
4. Typical Control

a. Magnetic

USE TD# 103.322

(1) The schematic diagram for a typical Westinghouse Class 14-250 Full Voltage Starter is shown in Figure 22.

(2) In summary, the functions of principal devices are:



TYPICAL CONTROLLER
Figure-22

TO 103.522

DISCUSS WITH CLASS

(a) The Line Contactor operates to connect the motor to the a-c line. (This contactor is replaced by starting and running contactors in reduced voltage starters to connect and short out the autotransformer or reactor).

(b) The Thermal Overload Relay protects the synchronous motor from damage due to overload, single-phase operation, and field failure. It operates to trip out the line contactor.

DISCUSS WITH CLASS

(c) The Field Contactor connects the motor field windings to the source of d-c excitation. It also connects the starting-field discharge resistor in series with the motor field during the starting period, and again when field excitation is removed.

(d) The Starting-Field Discharge Resistor is used to improve the motor starting torque and to limit the induced field voltage during starting or when the field excitation is removed.

(e) The Damper Winding Protection Relay protects the damper winding of the synchronous motor against burn-out in the event the motor fails to start and accelerate. It operates to trip out the line contactor.

(f) The Synchronizing Relay controls the field contactor, so that it closes when the motor has reached a sufficiently high speed and the poles are in a favorable relationship for synchronizing.

(g) The Rectox rectifies the component of the induced field current thereby polarizing the holding circuit of the synchronizing relay.

(h) The Pull-Out Relay operates on pull-out of the synchronous motor to trip the line contactor, thus shutting down the motor;

DISCUSS WITH CLASS

or to energize the synchronizing relay, thereby initiating a resynchronizing sequence, depending upon connections used.

(i) The Auxiliary Sequence Relay controls the sequence of the field application equipment and nullifies the pull-out relay during synchronizing.

(j) The Field Rheostat, while usually supplied separately with the motor or exciter, ordinarily may be mounted on the control panel. It is used for adjusting the current flowing to the synchronous motor field. With individual exciters, this is usually accomplished by varying the exciter voltage.

(k) The Master Switch, whether a pushbutton station, float switch, pressure switch, or other device, operates to start and stop the motor.

(l) Ammeters, both a-c and d-c are supplied for use in adjusting the excitation and to give an indication of the currents flowing. Additional meters may be supplied on order.

(m) Current Transformers, where necessary, supply current in direct ratio to line current, to the overload relay, and to the various meters.

DISCUSS WITH CLASS

(n) A Control Transformer is used on all high-voltage starters to supply power at a low voltage to the various control devices. Secondary fuses are provided for this transformer.

(o) An Auxiliary Relay is used with the larger contactors interposed between the master switch and the contactor coil. This is necessary to handle the larger coil current. A similar contactor, together with an anti-pumping relay, is provided to energize the circuit breaker solenoid, when used.

(p) Instantaneous A-C Undervoltage Trip is provided on all starters which use contactors for the line switch. This standard feature is obtained by action of the line contactor, or auxiliary relay if used.

(q) Time Delay Undervoltage Protection may be provided if specified. An auxiliary relay is used with time-opening contacts to maintain the holding circuit for a short time, ½ to 1½ seconds, after voltage failure and thus will initiate a new starting cycle without attention from the operator, provided voltage returns to normal within the time delay period of the scheme. An additional relay is used to provide permanent shutdown on operation of the "Stop" pushbutton.

DISCUSS WITH CLASS

(r) A Time Delay Undervoltage Trip Device is provided for use with all high-voltage starters which are circuit breakers for the line switch. This device operates in conjunction with the regular breaker undervoltage trip attachment, and delays the tripping action for a period of approximately two seconds. This time delay is obtained from energy stored in a condenser which continues to supply power to the trip attachment for a short time after failure of voltage. Instantaneous tripping occurs when the "Stop" control switch or button is depressed.

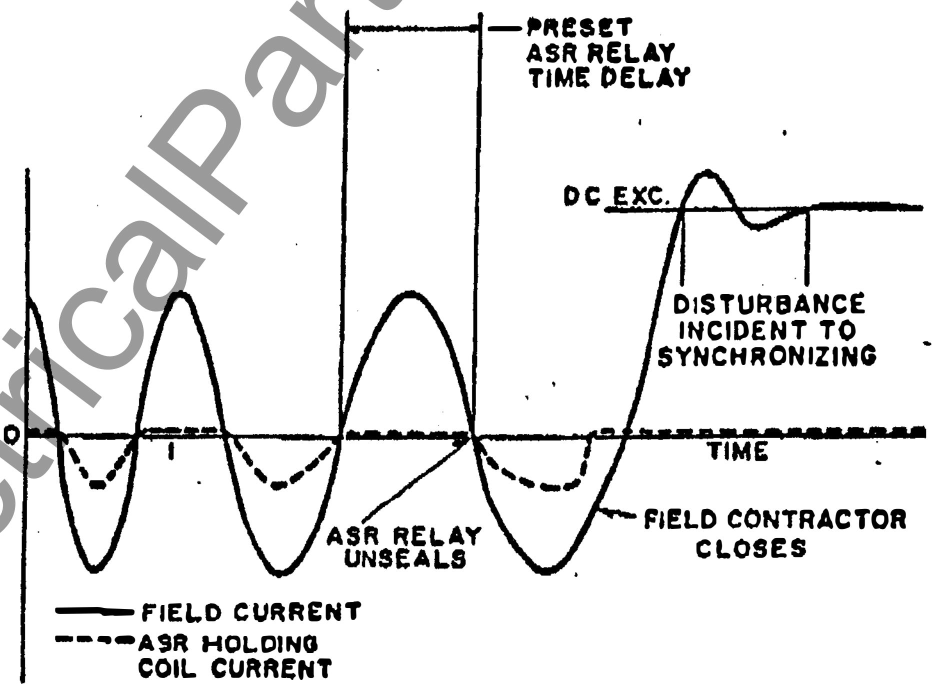
(3) Controller Operation

(a) Referring to the diagram shown in Figure 22, closure of the "Start" pushbutton energizes the line contactor and the motor is connected to the line and is accelerated as an induction motor with its field connected across a starting and discharge resistor through a damper winding protection relay.

(b) At the same time the synchronizing relay "ASR" and auxiliary sequence relay "T" are energized thus nullifying the pull-out relay, setting up the coil circuit of the field contactor, and making the dropout of the synchronizing relay dependent upon its holding coil.

USE TD# 103.323

(c) Operation of the synchronizing relay is based on the variable frequency of the motor induced field current during starting. As shown in Figure 23, a rectified half wave portion of this current is used as a means of holding the relay closed during starting, the time intervals of the no current half of the wave increasing as the frequency of the motor field current decreases with acceleration of the motor. When the time interval between rectified current half waves exceeds the time delay of the relay, the relay operates to close



ASR RELAY OPERATION

Figure-23 TD103.323

the field contactor and apply excitation to the motor. The polarity of the half wave Rectox rectifier is arranged to apply excitation when the motor rotor is in a favorable position for good synchronizing performance.

USE TD# 103.324

(d) As shown in Figure 24, the synchronizing relay can be adjusted to operate over a motor induced field current frequency range of 1 to 3.5 cycles--corresponding to 98 to 94 per cent motor speed based on a 60-cycle machine. This adjustment is made by varying the adjusting nut in the front of the relay. A calibration plate is provided to simplify this setting. The relay should be set to operate at the lowest frequency (highest motor speed) the motor will attain under the most severe starting condition, so that the maximum usable pull in torque is available. This is of special importance in applications involving high inertia loads.

(e) Closure of the field contactor places in the circuit a transformer coupled high speed, highly sensitive pull-out relay for protection against failure to synchronize, or for protection in case the motor pulls out of synchronism after being in step.