CONSTRUCTION ELECTRICIAN APPRENTICESHIP PROGRAM

Level 3 Line I: Install Control Circuits and Devices



LEARNING GUIDE I-2

INSTALL MAGNETIC MOTOR CONTROLS

ita
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THE RIGHT SKILLS ▶ A PROVEN ADVANTAGE

BRITISH COLUMBIA

Foreword

The Industry Training Authority (ITA) is pleased to release this major update of learning resources to support the delivery of the BC Electrician Apprenticeship Program. It was made possible by the dedicated efforts of the Electrical Articulation Committee of BC (EAC).

The EAC is a working group of electrical instructors from institutions across the province and is one of the key stakeholder groups that supports and strengthens industry training in BC. It was the driving force behind the update of the Electrician Apprenticeship Program Learning Guides, supplying the specialized expertise required to incorporate technological, procedural and industry-driven changes. The EAC plays an important role in the province's post-secondary public institutions. As discipline specialists the committee's members share information and engage in discussions of curriculum matters, particularly those affecting student mobility.

ITA would also like to acknowledge the Construction Industry Training Organization (CITO) which provides direction for improving industry training in the construction sector. CITO is responsible for organizing industry and instructor representatives within BC to consult and provide changes related to the BC Construction Electrician Training Program.

We are grateful to EAC for their contributions to the ongoing development of BC Construction Electrician Training Program Learning Guides (materials whose ownership and copyright are maintained by the Province of British Columbia through ITA).

Industry Training Authority
January 2011

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INSTALL MAGNETIC MOTOR CONTROLS

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Learning Objectives

1. The learner will be able to connect and maintain reduced-voltage starters.
2. The learner will be able to connect and maintain wound-rotor motor control circuits.
3. The learner will be able to connect and maintain synchronous motor control circuits.
4. The learner will be able to connect and maintain braking and deceleration control circuits.

Activities

- Read and study the topics of Learning Guide I-2: Install Magnetic Motor Controls.
- Complete Self-Tests 1 through 11. Check your answers with the Answer Key provided at the end of this Learning Guide.

Resources

You are encouraged to obtain the following textbooks for supplemental information:

- *Electrician's Guide to AC Motor Controls*, by Richard A. Cox, Pend Oreille Publications.
- *Industrial Motor Control* 6th edition, 2010, by Stephen L. Herman, Delmar Cengage Inc.

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Industry Training Authority
January 2011

Learning Task 1:

Describe the considerations in selecting motor-starting equipment

There are two fundamental methods of starting polyphase, squirrel-cage motors: full-voltage starting and reduced-voltage starting.

Full-voltage starting

Full-voltage starting offers the simplest control and the lowest component cost. It provides maximum starting torque and minimum acceleration time. But because of large inrush currents, full-voltage starting also disturbs the electrical distribution system to the maximum. As well, the motor and the driven load must be designed to withstand the high torque this starting method produces.

Reduced-voltage starting

Reduced-voltage starting is used where full-voltage starting may cause problems. Since reducing the starting voltage reduces the current, the main function of the reduced-voltage starter is to lower the inrush current drawn by the induction motor. By common usage, all deviations from full-voltage starting have been placed in the category of "reduced-voltage starting." Not all starting schemes grouped under this method actually reduce the voltage at the motor terminals; however, they all reduce the line current the motor coils draw from the supply.

To reduce inrush currents, five types of starters are commonly used:

- Primary impedance starters
- Autotransformer starters
- Wye-delta starters
- Part-winding starters
- Solid-state starters

To accelerate the motor, all reduced-voltage starters have a *starting stage*, which may include one or more steps (or increments). They also have a *running stage* where full voltage appears across the motor. And reduced-voltage starters are usually categorized as either *open transition* or *closed transition*.

Open transition means that the motor is very briefly disconnected from the line as the control transfers from the start position to the run position. This can cause a torque dip for the motor and a further line disturbance.

Closed transition means that voltage is maintained across the motor when the control transfers from the start position to the run position. To maintain the voltage, this control is more elaborate than the control for the open-transition type.

Motor current and torque

The locked rotor current and the resulting torque are the principal factors that determine whether the motor can be started across the line, or whether the current must be reduced to obtain the required performance.

Depending on the motor design, the starting (or locked rotor) current is usually a value between 2.5 to 10 times the full load current. Some motors may have even higher inrush currents when they are started at rated voltage. As such, they require special means of starting.

The torque developed by the induction motor depends largely on the strength of the magnetic field (Φ_S) of the stator and on the induced current (I_R) in the rotor circuit. More precisely, the actual values of the starting torque, the maximum torque and even the starting current are controlled by the design of both the stator and the rotor. The curves in Figure 1 illustrate the torque characteristics of the most common squirrel-cage rotors designed by NEMA, the National Electrical Manufacturers Association.

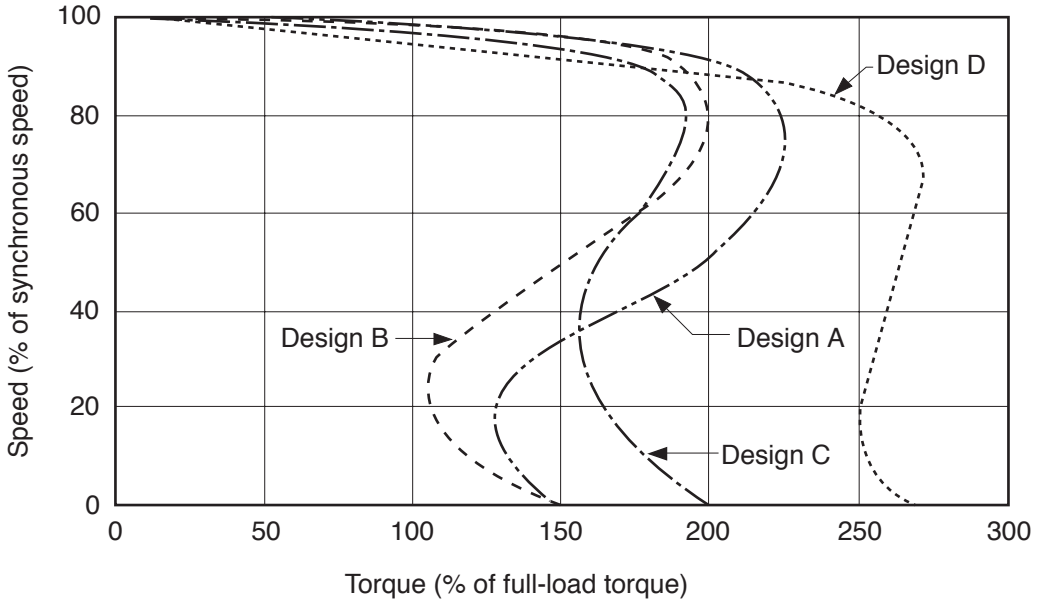


Figure 1—Torque characteristics of common rotor designs

Design A was the original class of squirrel-cage motor. These motors have normal starting torques up to 150% of full-load torque, and relatively high inrush currents (between six and 10 times full-load current).

Design B motors have a high-reactance rotor that limits the starting current to about five to six times the full-load value. The starting torque is comparable to that of a Design A motor.

Design C motors have what is known as a *double-cage rotor*. This rotor combines a high starting torque with a low starting current.

Design D motors have a high-resistance rotor that provides starting torques close to 300% of normal. They have lower starting-current inrush, higher slip under load and lower efficiency compared with the preceding motors.

The starting current of a squirrel-cage motor is directly proportional to the voltage applied to the terminals of the motor at the instant of starting. If rated voltage (100%) is used for starting, rated inrush current will occur. If the starting voltage to the motor is reduced, the inrush current (using Ohm's law) is reduced by the same proportion.

Example 1: A three-phase, 600 V, squirrel-cage induction motor draws a full-load current of 10 A. When it is started across the line, the inrush current is six times its full load value.

What is the inrush current to the motor if the starting voltage is reduced to 300 V?

Solution:

At 600 V, the starting current

$$= 6 \times 10\,\text{A}$$

$$= 60\,\text{A}$$

At 300 V, the starting current is:

$$= \frac{300\,\text{V}}{600\,\text{V}} \times 60\,\text{A}$$

$$= 30\,\text{A}$$

Therefore, if the starting voltage is reduced to 50% of previous voltage, the starting current is also reduced to 50% of previous voltage, or in direct proportion.

Any reduction in starting voltage also reduces the starting torque, since the inrush current to the stator is reduced. This reduces the stator flux (Φ_S) and, in turn, the induced rotor current (I_R) in the same proportion. Since reducing the starting voltage reduces *both* stator flux and rotor current, the starting torque is directly proportional to the square of the starting voltage, as shown in the following formula:

$$T \propto E^2$$

Example 2: A three-phase, 600 V, squirrel-cage induction motor develops a starting torque of 200% of its full-load value when it is started directly across the line. If the starting voltage to the motor is reduced to 300 V, what percentage of full-load torque will the motor develop at starting?

At 600 V, the starting torque = 200% × full-load torque.

Since 300 V is 50% of the rated voltage, and torque is directly proportional to the voltage squared:

$$T \propto E^2$$

$$\propto (0.5)^2$$

$$\propto 0.25$$

This results in the starting torque being reduced to 25% of the normal starting torque, which calculates to:

$$T = 0.25 \times 200\% \text{ full-load torque}$$

$$= 50\% \text{ full-load torque}$$

Since this calculation shows that the motor will develop only 50% of its full-load torque when started with 300 V, it obviously cannot be started under full load at this reduced value of voltage.

Driven load requirements

The torque requirements of different loads may vary widely. The starting torque applied and the rate of acceleration must be desirable for the load. Sometimes it may be difficult to select a motor that satisfies both the running and starting requirements of the load without sacrificing operating efficiency. This problem may be solved by selecting the starter that overcomes the objectionable features.

Starting conditions for motors in industrial applications may vary considerably. The load (or machine) to which the motor is connected may be started under no-load, normal-load or even overload conditions.

Across-the-line starting develops the maximum torque, and the driven load must be capable of safely withstanding high torque and rapid acceleration. For example, if the starting torque on a paper-roll drive is too great, the paper may tear. It may also be necessary to limit the initial surge of starting torque to prevent damaging equipment with gears, belts or chain drives.

Reduced-voltage starting minimizes the shock on the driven load by reducing the starting torque of the motor. The acceleration time, however, may be greatly increased, even to the point where the overload elements (though correctly sized) may trip.



A motor that will not start a load under full voltage will definitely not start a load under reduced voltage.

Duty cycles

Inaccurately determining the intended duty cycle of the motor being controlled can lead to premature failure of the motor's control equipment. Most control manufacturers publish charts and tables to help select the proper contactor. The information is based on motor horsepower and type of use (for example, jogging, plugging, reversing), but the type of load and the frequency of operations must also be considered. In instances where a motor is started and stopped frequently, a larger-than-normal contactor must be used if the normal life expectancy of the contacts is to be obtained.

Control elements such as resistors, reactors and autotransformers are sometimes undersized because they are operated during the brief start-up period only, and usually they have sufficient time to cool down. If the frequency of operation or duty cycle is increased, however, these devices may overheat and fail prematurely.

Even though reduced voltage starters lower the starting inrush current to the motor, this starting current is still considerably higher than the normal running current of the motor. As such, the number of start/stop times in a given interval must be carefully considered.

Refer to the Canadian Electrical Code for the definitions of types of *duty*.

Power source requirements

Probably the most significant factor in determining whether a motor should be started across the line or at reduced voltage is the power source itself.

First, the power source must have sufficient capacity to satisfy the starting demand of the motor and to supply other loads at the same time.

Second, the large, reactive, inrush current drawn by the motor during start-up may create a large line drop, which can cause the voltage to fluctuate severely and affect other loads.

As a result, the power authority (such as BC Hydro) may impose certain restrictive regulations governing the following:

- The maximum amount of starting amperes, either per horsepower or per motor
- The maximum horsepower for across-the-line starting
- The maximum current load for a particular feeder size
- The maximum rate of change-of-line current drawn by the motor (e.g., 200 amperes per half-second)

You should consult the local power authority for specific rules and regulations in effect.

 Now do Self-Test 1 and check your answers.

Self-Test 1

1. State two advantages that across-the-line starting has over reduced-voltage starting for AC motors.

2. State two advantages that reduced-voltage starting has over across-the-line starting for AC motors.

3. List three methods of reduced-voltage starting.

4. What is the difference between a reduced-voltage starter with an open transition and a reduced-voltage starter with a closed transition?

5. When started across the line, a 600 V, three-phase induction motor develops a starting torque that is 300% of its full load torque and draws a starting current that is 600% of its full-load value. If the starting voltage is reduced to 346 V:

   a. What percentage of full-load torque will the motor now develop on starting?

   b. What percentage of full-load current will the motor draw on starting?

6. If an AC motor will not start under load with rated voltage, will you be able to start it with reduced voltage? Briefly explain.

7. Why is it sometimes necessary to provide larger-than-normal contactors for some motors?

8. What type of motor duty is required for a service that must operate for definite, specified, alternate intervals of load and rest?

9. What is the most important consideration in determining whether or not a motor may be started directly across the line?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 2:

Describe the operation of primary-impedance (resistor and reactor) starters

In primary-impedance starters, either resistors or reactors are connected in series with the motor to limit the inrush current. After the motor has accelerated to a predetermined speed, the in-line impedance is removed—either in steps or all at once—and full line voltage is impressed across the motor.

Primary-resistance starters

For this starting method, a power resistor is connected in series with each of the three-phase lines to the motor. When the circuit is first energized, there is a voltage drop across the series-connected resistance and, as a result, reduced voltage across the motor terminals. So the motor draws a reduced current directly proportional to the terminal voltage.

The value of starting resistance is selected to limit the starting current—usually between 65% to 80% of the full voltage value. As the motor accelerates, there is a decrease in the current through the starting resistor, and therefore a lesser voltage drop across the resistor. The result is a gradual transfer of the line voltage to the motor and smooth acceleration. When the motor reaches a certain speed, the resistance is removed (usually it is shorted out), and the full line voltage now appears across the motor. This starting procedure is illustrated in the single-line diagram in Figure 1.

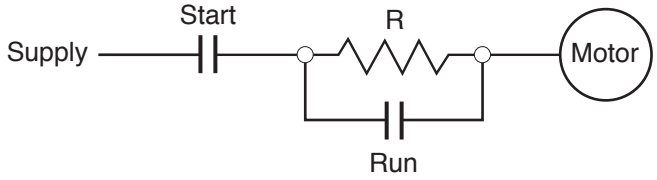


Figure 1—Resistance starting

Depending on the size of the motor, primary-resistance starters may use more than one-step acceleration. And since the motor is never disconnected from the line during the starting process, this starter is a closed-transition type.

A major disadvantage of this type of reduced-voltage starter is the large power loss (I_2R) in the resistors during starting.

Several types of resistors are available. Their construction can be wire-wound, ribbon-type or graphite compression.

Starting resistors can become extremely hot and cause severe burns if they are touched. Use common sense and avoid contact when working with this type of starter.

Figure 2 shows power and control circuits for an automatic, primary-resistance starter with two-point acceleration—that is, one step of resistance.

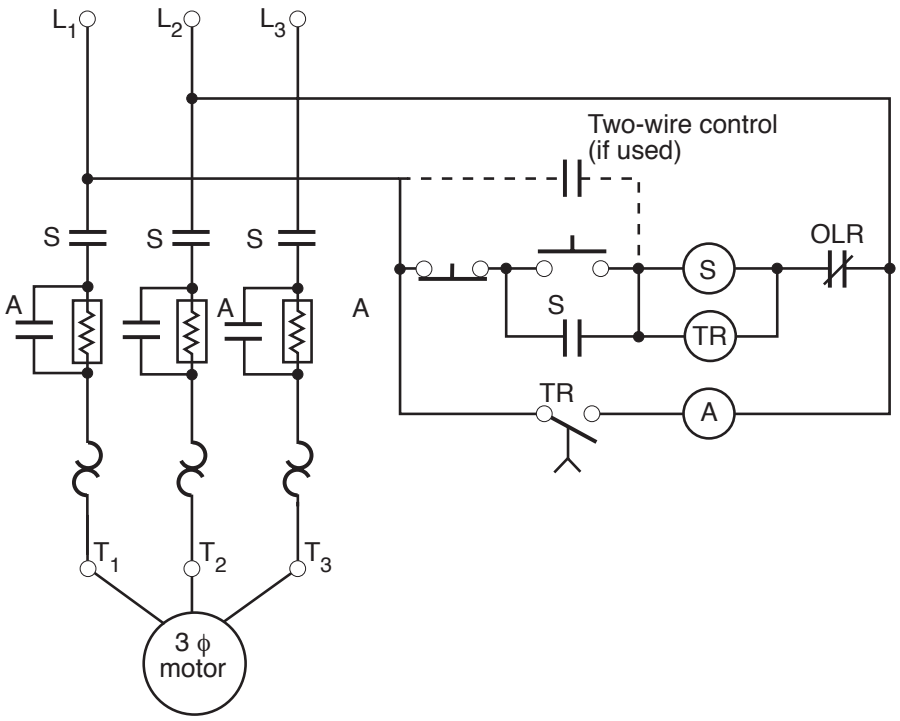


Figure 2—Primary-resistance starter

The control circuit contains the magnetic starter coil (S), the timer relay coil (TR) and the accelerating contactor coil (A).

The control circuit also shows how a two-wire pilot device can be connected for operating the motor automatically.

When the start button is pressed, the magnetic starter coil (S) is energized. In the power circuit, this causes the power contacts (S) to close to connect the power resistors in series with the motor for starting. The seal-in contact (S) also closes to maintain the control circuit, and the timer relay coil (TR) energizes.

After a preset time delay, the normally open timing contact (TR) closes, and the accelerating contactor coil (A) energizes. In the power circuit, this results in the power contacts (A) closing to short out the starting resistors. The motor now runs with full-line voltage across its terminals.

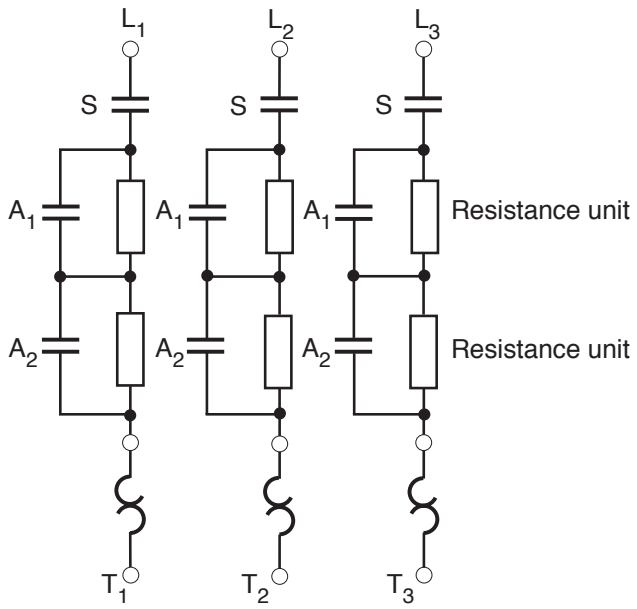


Figure 3—Three-point, primary-resistance starting

Figure 3 shows how additional resistance units can be added to the power circuit to increase the starting steps. Figure 4 shows the simple modification to the control circuit.

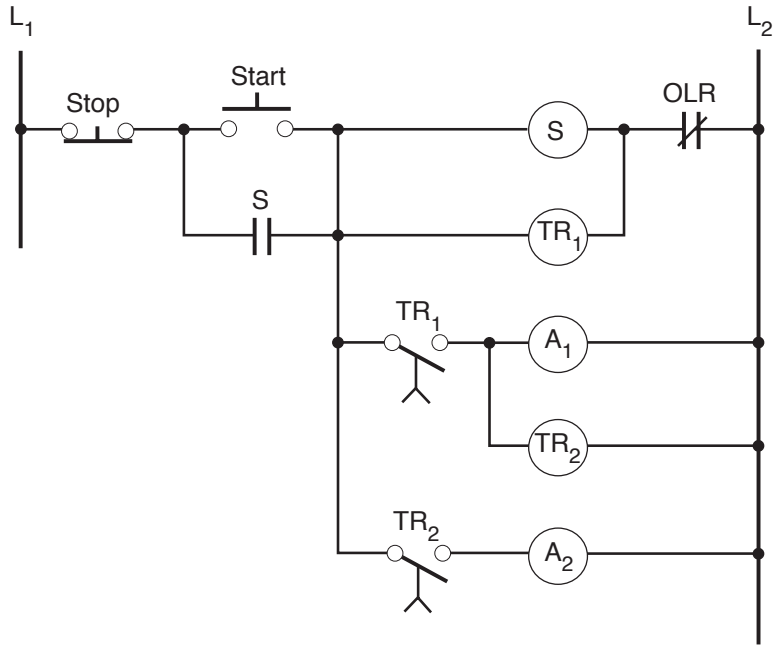


Figure 4—Control circuit for three-point resistance starter

Primary-reactance starters

Primary-resistance starting is usually limited to a maximum of 600 V. For high-voltage or high-current installations, or for situations where the heating or physical construction of resistors is a problem, series reactors may be used as shown in Figure 5.

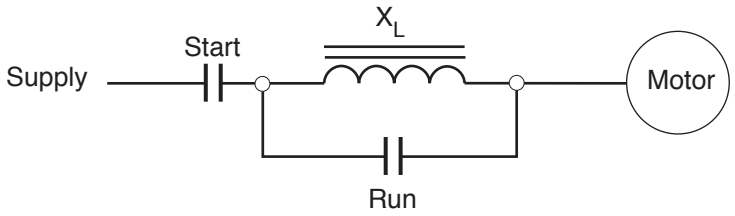


Figure 5—Reactance starting

The control for the primary-reactance starter is essentially the same as that for the resistance starter, except that reactors instead of resistors are used to limit the motor current. In both cases, the motor terminal voltage is a function of the current drawn from the line.

Reactor starting is not commonly used. Primary-reactance starting worsens the already low starting power factor of induction motor circuits. This results in further aggravation of the regulation of system line voltage.

Now do Self-Test 2 and check your answers.

Self-Test 2

1. What type of starter is the primary-resistance starter?

   a. open transition

   b. closed transition _____

2. State two situations where it may be necessary to use starting reactors rather than resistors.

   _____

   _____

3. What is the main disadvantage of using reactors to start induction motors?

   _____

   _____

4. A three-phase induction motor draws an inrush current of 80 A when started at full voltage. If primary resistors are used to limit the initial voltage across the motor terminals to 80% of line value:

   a. What is the initial current drawn by the motor?

      _____

   b. What percentage of starting torque (compared with full-voltage start) will be developed by the motor?

      _____

5. Describe how several steps can be added to the starting stage of the primary resistance starter.

   _____

   _____

   _____

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 3:

Describe the operation of autotransformer starters

In this starter, an autotransformer starts the motor by stepping down the primary line voltage to a lesser value, as shown in Figure 1. After the motor is started, full line voltage is applied. The starter transition may be designed as either open or closed.

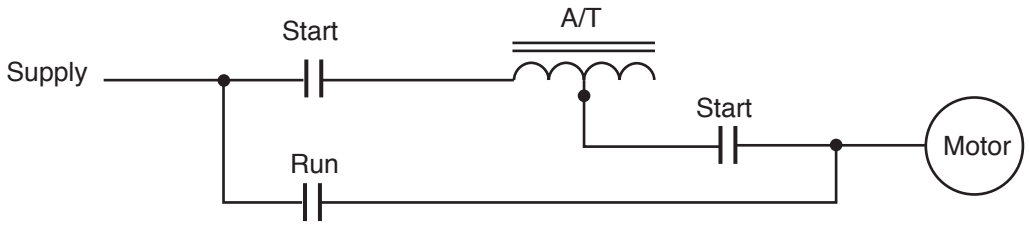


Figure 1—Autotransformer starting

The autotransformer starter provides more starting torque per line ampere of current than any other type of reduced-voltage starter. Autotransformer starters are sometimes called *compensator starters*, even though this term originally applied to the manually operated autotransformer starter.

The autotransformers used for motor starting have *taps*, which normally allow selecting either 50%, 65% or 80% of the primary line voltage for starting as shown in Figure 2. Since the autotransformer is used for step-down operation, the line voltage is applied across the full primary winding. The start of each winding is marked 0 and the finish of each coil is marked 100. The tap selected determines the value of the secondary line voltage used for starting the motor.

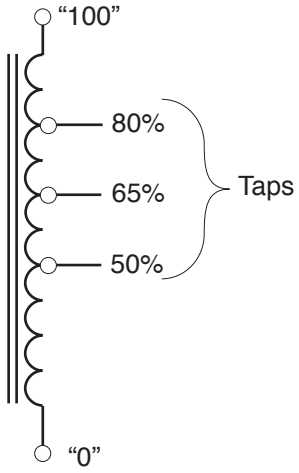


Figure 2—Autotransformer terminal markings

A main advantage of this starting method is that the line current from the supply is a further reduced value of the motor current (through transformer action). This is seen in the single-phase example in Figure 3.

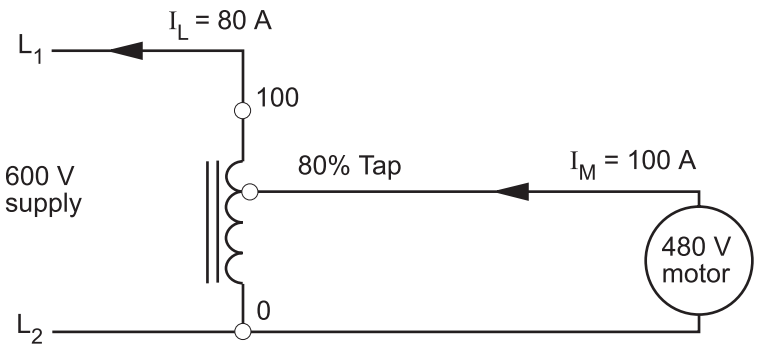


Figure 3—Line current versus motor current

As shown in Figure 3, the 600 V primary line is stepped down (using the 80% tap) to a secondary value of 480 V across the motor. If the motor current (secondary) is 100 A, then the line current (primary) is 100 A × 0.8 = 80 A. Remember that, neglecting losses, the primary VA must equal the secondary VA.

Example 1: A three-phase, 600 V, squirrel-cage induction motor draws a full load current of 50 A. When started across the line, the starting inrush is 500% of the full-load amperes (FLA) and the starting torque is 150% of the full-load value. When using an autotransformer starter set at the 80% tap, what are the following:

a. the initial starting torque

b. the initial current in the supply line

Solution: Since torque is proportional to E_2, the calculation for the starting torque is:

This means that the motor does not develop its full-load value at starting, and must be started under reduced or no-load conditions.

$$T = (0.8)^2 \times 150\%\ \text{FLT} \quad \text{and} \quad \text{FLT} = \text{full-load torque}$$

$$= (0.64) \times 150\%\ \text{FLT}$$

$$= 96\%\ \text{FLT}$$

When started across the line at 600 V, the line current (motor inrush) is

$$I_L = 50\,\text{A} \times 500\%$$

$$= 250\,\text{A}$$

When started at reduced voltage (80%), the motor inrush is:

$$I_M = 250\,\text{A} \times 80\%$$

$$= 200\,\text{A}$$

Since the motor current is on the secondary side of the autotransformer, use the voltage (turns) ratio to calculate the primary line current:

$$I_L = 200\ \text{A} \times \frac{480\ \text{V}}{600\ \text{V}}$$

$$= 200\ \text{A} \times 0.8$$

$$= 160\ \text{A}$$

So, although the motor draws a reduced current of 200 A on starting, the primary line current is further reduced to 160 A through transformer action.

The power circuit for three-phase autotransformer starters can use either three transformers connected in wye (Figure 4[a]) or two transformers connected in open-delta (Figure 4[b]).

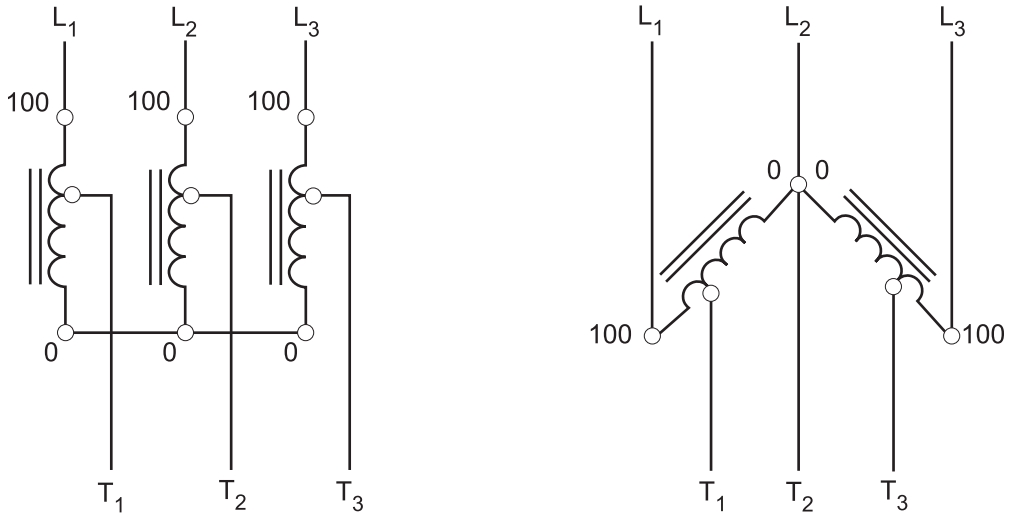


Figure 4—Three-phase autotransformer connections

Although it is more economical to use, the open-delta connection sometimes results in unbalanced phase voltages when larger induction motors are started. If this is unacceptable, the wye connection should be used.

Autotransformers used for motor starting are generally intended for intermittent duty. If they are left in the circuit too long, they may overheat and become damaged. To protect against this, these autotransformers are often equipped with a manually reset temperature switch, which is wired into the motor control circuit.

Open-transition, autotransformer starter

The open-transition starter is the simplest and most economical control. It has one disadvantage in that there is an instant where there is no voltage across the motor as the control transfers from the starting stage to the running stage. It must be determined whether or not this will cause any undesirable transient line surges of current.

Figure 5 shows an open-delta autotransformer starter. For starting, the power circuit has a five-pole contactor (S) for connecting the two autotransformers in open-delta. Using the taps as connected, 80% of the primary line voltage is applied across the motor terminals for starting.

Note that there are several different control circuits for open-circuit transition. To simplify discussion, a very basic control scheme is illustrated in Figure 5.

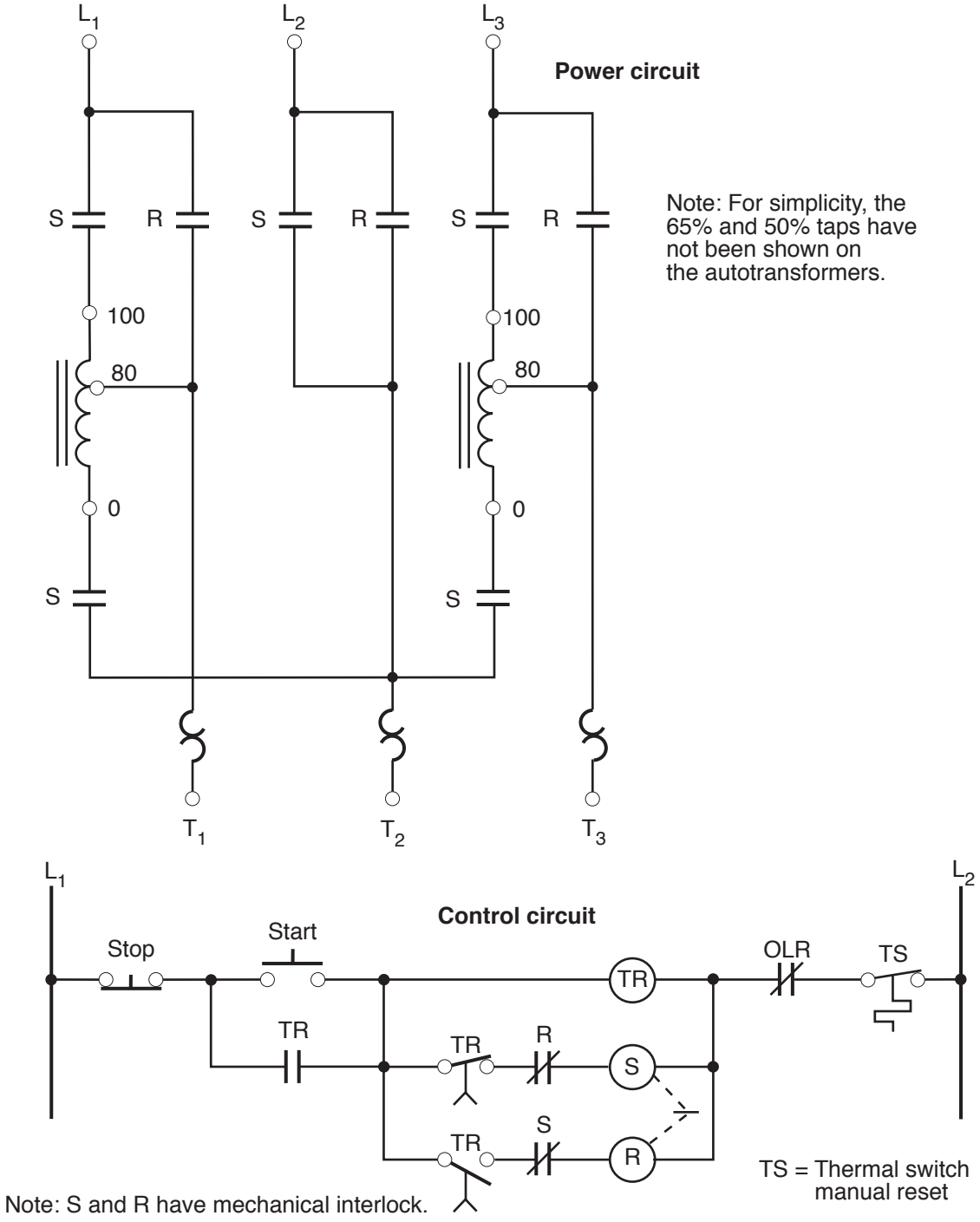


Figure 5—Autotransformer starter with an open transition

When the control circuit is activated by pressing the start push-button, the coil of the timing relay (TR) is energized. At that instant, the starting contactor coil (S) is energized through the NC timing (TR) contact and the NC electrical interlock (R) of the running contactor. The NO instantaneous contact (TR) of the timing relay provides the seal-in circuit. The starting contacts (S) in the power circuit close to apply reduced voltage to the three-phase motor through the autotransformers.

After a preset time delay, the timing contact (TR) opens to de-energize the starting contactor (S) coil, and its electrical (S) interlock in the control circuit returns to the NC position. In the power circuit, the starting (S) contacts open, and the motor is disconnected from the line. At the same instant, the NO timing (TR) contact closes, and electrical continuity is obtained through the coil (R) of the running contactor. The running (R) coil is now energized. In the power circuit, the running (R) contacts close, and full line voltage is applied to the motor terminals.

Although the transfer from start to run results in open-circuit transition, bear in mind that the time span is so brief as to be almost instantaneous.

In the control circuit, notice that the thermal protection (TS) device for the autotransformers has been wired in series with the overload relay (OLR) contact.

Closed-transition, autotransformer starter

The autotransformer starter with a closed-circuit transition is sometimes called the *Korndorfer connection* in honour of its inventor. Figure 6 shows the autotransformers connected in a wye configuration for starting the motor. If the taps are used as connected, 65% of the primary-line voltage is applied across the motor terminals for starting.

When the start push-button is pressed to activate the control circuit, the coil of the timing relay (TR) is energized. At that instant, the first starting contactor (1S) coil is energized. In the power circuit, the first set of starting contacts (1S) close to form the wye-point for the three autotransformers. The seal-in circuit is provided by the NO instantaneous contact (TR) of the timing relay. Also in the control circuit, the NO contact (1S) of the first starting contactor closes to pick up the coil (2S) of the second starting contactor. Notice that a seal-in circuit for this coil is provided by an auxiliary contact (2S). In the power circuit, the second set of starting contacts (2S) close to complete the primary line connections to the autotransformers, and the motor is started with reduced voltage.

After the preset time delay, the timing contact (TR) opens, causing the first starting contactor (1S) to drop out. In the power circuit, the first starting contacts (1S) open, leaving a portion of the autotransformer winding in series with the motor. At the same time, the NO timing contact (TR) closes, and the run contactor (R) coil is energized through the NC electrical interlock (1S). In the power circuit, the run contacts (R) close to apply full-line voltage across the motor terminals.

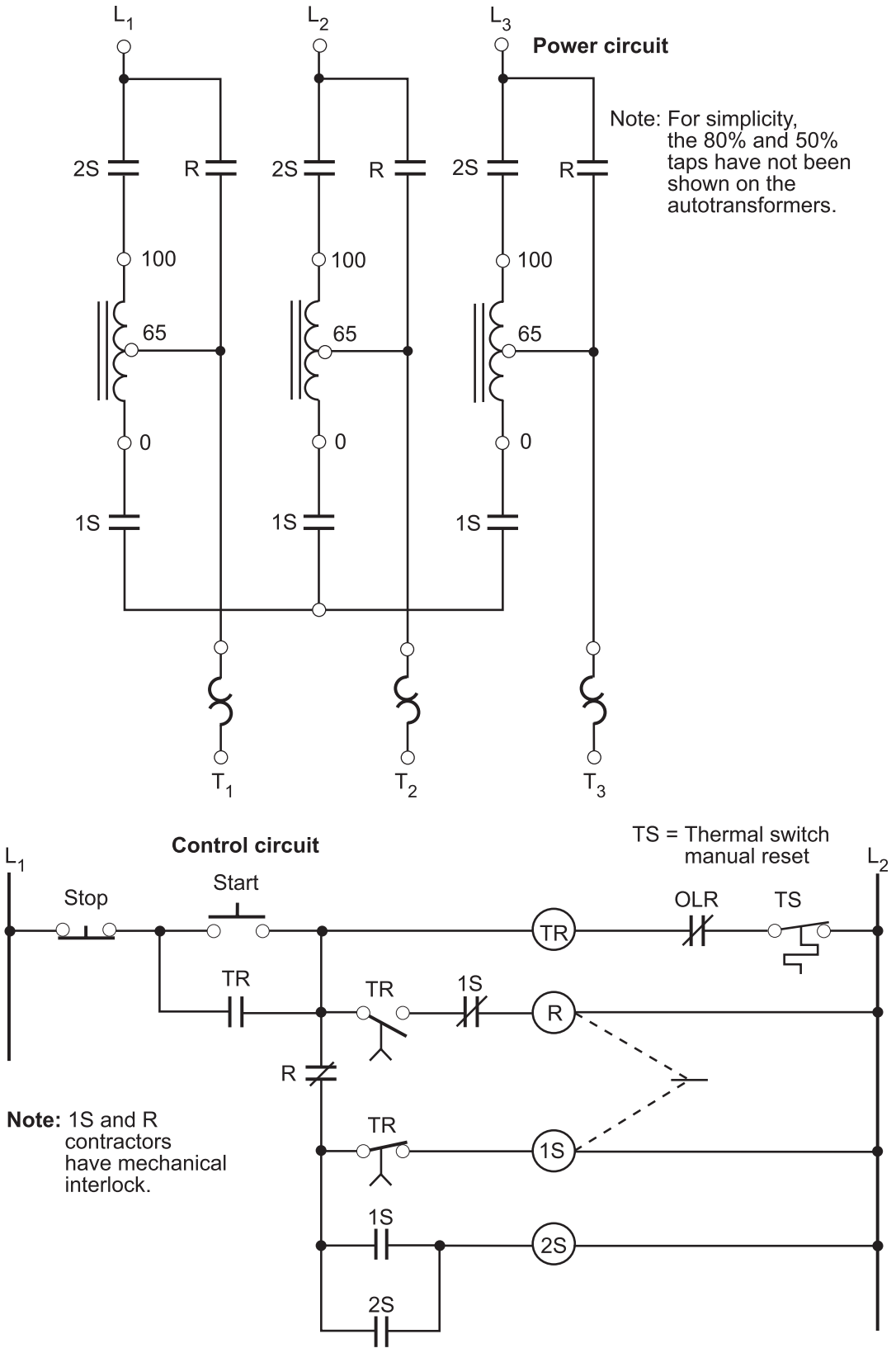


Figure 6—Closed-transition, autotransformer starter

When the run contactor (R) is energized, the NC contact in the control circuit opens to de-energize the second starting contactor (2S). In the power circuit, this causes the second starting (2S) contacts to open and isolate the autotransformers from the primary line.

As you can see from the starting sequence, the power circuit to the motor is not open at any point in the operation. This closed-circuit transition only minimally disturbs the power line.

Note that different control manufacturers may provide slightly different control circuit schemes for closed-transition operation.

 Now do Self-Test 3 and check your answers.

Self-Test 3

1. What standard taps are available on motor-starting autotransformers?

2. Autotransformer starters are sometimes referred to as _____ starters.

3. Autotransformers used for starting motors are generally intended for intermittent duty.
   a. What does this mean?

   b. What protection is usually provided for the autotransformers?

4. What two common three-phase connections are used for starting motors with autotransformers?

5. Refer to Figure 6 of Learning Task 3. Which of the following choices identifies the correct sequence for the power circuit contacts?
   a. 2S closes; 1S closes; R closes; 1S opens; 2S opens
   b. 1S closes; 2S closes; R closes; 1S opens; 2S opens
   c. 1S closes; 2S closes; 1S opens; R closes; 2S opens
   d. 1S closes; 2S closes; 2S opens; R closes; 1S opens _____

6. Why is the autotransformer method of motor starting considered to provide more starting torque per line ampere of current than any other type of reduced-voltage starter?

7. When started across the line, a 600 V, three-phase induction motor draws an inrush current of 400 A and develops a starting torque of 300% of its full-load value. When started by the autotransformer method using the 65% tap settings, what are the following?

   a. percentage of full-load torque developed at starting

   _____

   b. initial starting current in the primary line

   _____

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 4:

Describe the operation of wye-delta starters

The wye-delta (also called the *star-delta*) starting method differs from other starting methods because it requires a three-phase motor that allows access to each phase winding outside the motor enclosure. In other words, it requires a six-lead or a 12-lead motor that can be connected in either wye or delta for normal operation. This type of motor is normally called a *wye-delta motor* (Figure 1).

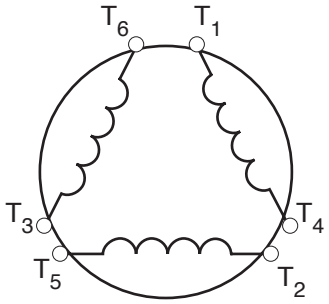


Figure 1—Six-lead wye-delta motor

The wye-delta starter has no adjustment for different operating conditions since it has only one starting step and develops very low starting torque (only 33% of full voltage value). Both open-transition and closed-transition types are available. The closed-transition starter uses resistors to keep the motor energized during transfer to the run position. Although classified as reduced voltage, the wye-delta starter is really a reduced-inrush starter because the line-to-line voltage across the motor terminals is not reduced.

As the name implies, the control for the wye-delta starting method first connects the phase windings of the motor in wye for starting, then reconnects the motor coils in delta for running. Note that the wye-delta motor can normally be connected for either wye or delta operation—that is, the three-phase, six-lead motor is a dual-voltage motor. But the motor must run in delta when it is used with a wye-delta starter.

To compare values, consider the delta-connected motor in Figure 2.

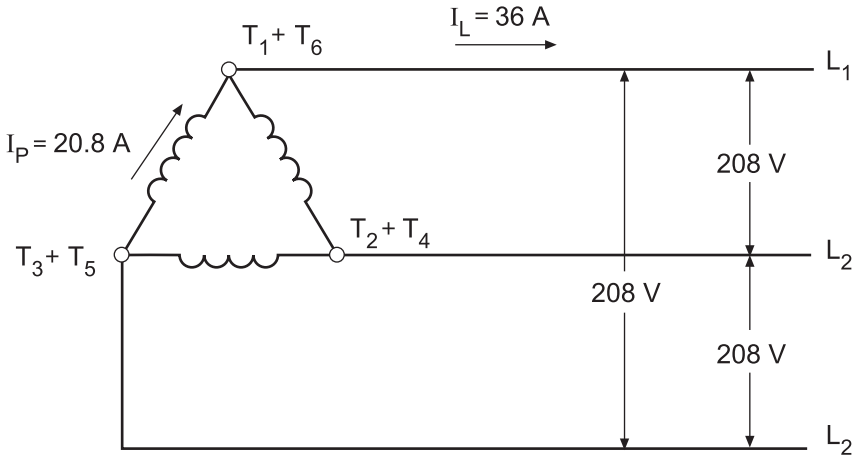


Figure 2—Delta-connected motor at starting

If this motor has a starting impedance of 10 Ω per phase, then, using Ohm's law, the starting current per phase calculates as 20.8 A:

$$I_P = \frac{E}{Z}$$

$$= \frac{208\ V}{10\ \Omega}$$

$$= 20.8\ A$$

Since the motor is connected in delta, across-the-line starting will result in a line current inrush of approximately 36 A.

$$I_L = \sqrt{3} \times I_P$$

$$= 1.732 \times 20.8\,A$$

$$= 36\,A$$

If the same motor is reconnected in wye for starting (as shown in Figure 3), the voltage appearing across each coil will now be 58% $\frac{1}{\sqrt{3}}$ of the line voltage value, or 120 V.

Remember, for a wye connection:

$$E_P = \frac{E_L}{\sqrt{3}}$$

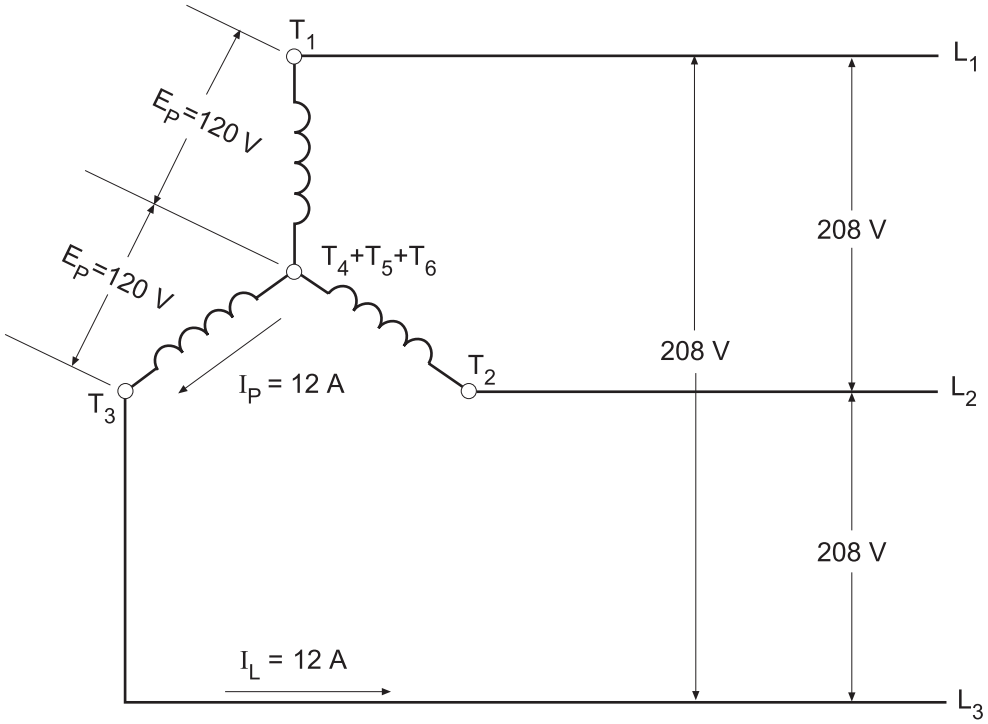


Figure 3—Wye-connected motor at starting

If the same phase impedance is used as before, the starting current per phase calculates as 12 A:

$$I_p = \frac{120\ V}{10\ \Omega}$$

$$= 12\ A$$

For the wye connection, the phase and line currents are the same, so the line inrush current will be 12 A.

In comparing the line inrush current values, the wye versus the delta connection to the same supply is a ratio of:

$$\frac{I_{wye}}{I_{delta}} = \frac{12\ A}{36\ A}$$

$$= 0.33$$

Therefore, in comparing a full-voltage delta start to a wye-delta start for this motor, the starting inrush in the line is reduced to one-third, or 33%.

Similarly, since the starting voltage across each phase is reduced to 58% of its normal running voltage, the starting torque is reduced to 33% of the full-voltage value:

$$T \propto E^2$$

$$\propto (0.58)^2$$

$$\propto 0.33$$

This low value of starting torque restricts the use of wye-delta starters to very light motor loads such as fans and unloaded centrifugal compressor units.

Since each phase lead is brought out from the motor to the controller, the rating of the overload relay protection is based on the *phase value* of the delta-connected motor. It is *not* based on the line value of the current, as with conventional motor control. You will see this by carefully studying the following motor control circuits:

- Open-transition, wye-delta starter
- Closed-transition, wye-delta starter

Open-transition, wye-delta starter

Figure 4 shows a wye-delta starter with an open transition. Note that the starting contactor (S) and the running contactor (2M) are mechanically and electrically interlocked to prevent simultaneous operation and a resulting short circuit.

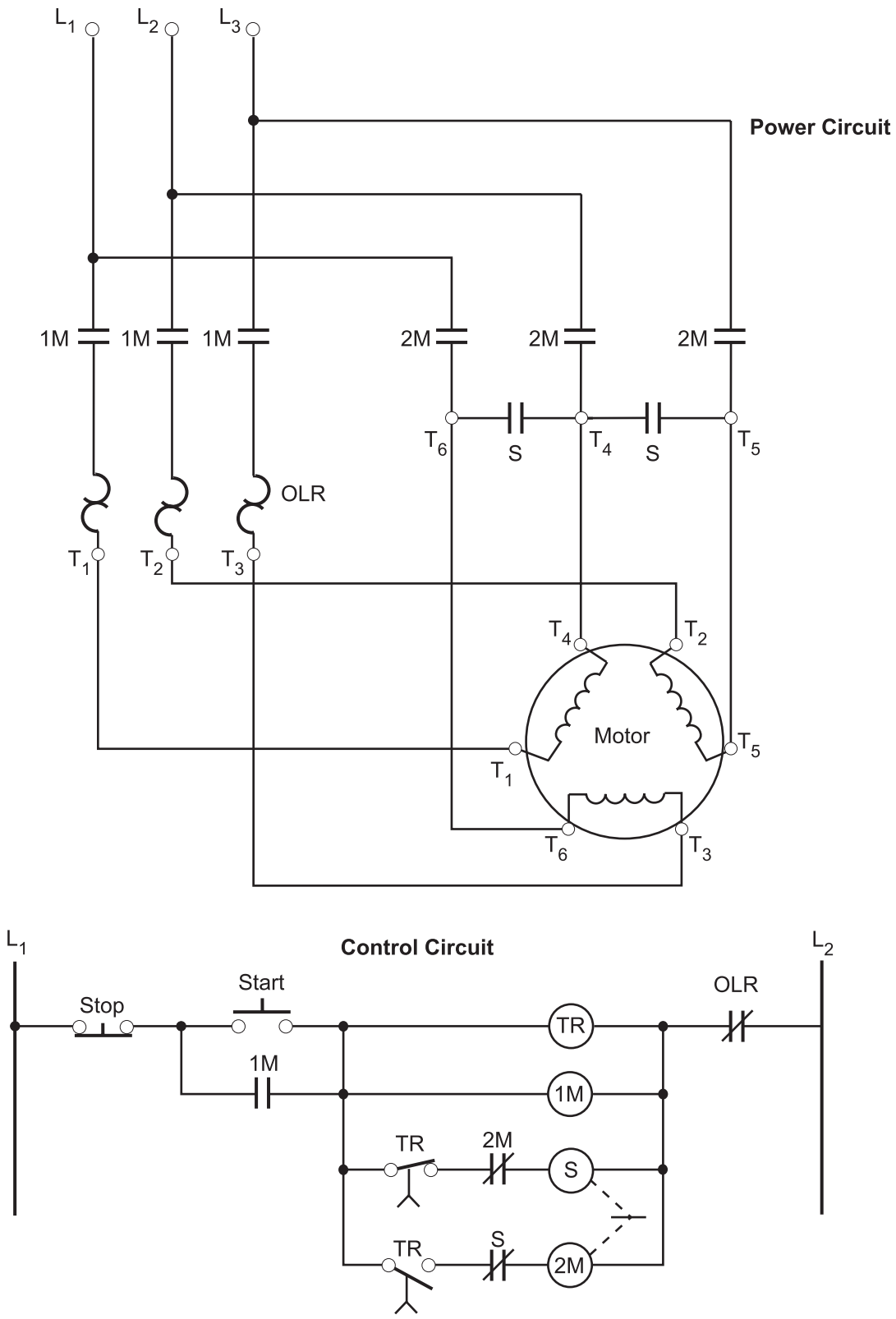


Figure 4—Wye-delta starter with an open transition

When the start button in Figure 4 is pressed, the following control circuit components are activated: the coil (TR) of the timing relay, the coil (1M) of the main line contactor and the coil (S) of the starting contactor. The seal-in circuit is provided by the auxiliary interlock (1M) of the main line contactor. In the power circuit, the starting contacts (S) close to form the wye-point (T_4-T_5-T_6) for the motor coils, and the line contacts (1M) close to energize the stator (L_1-T_1, L_2-T_2, L_3-T_3).

After a preset time, the timing contacts (TR) are activated. The NC contact (TR) causes the coil of the starting contactor (S) to de-energize. Similarly, the NO contact (TR) of the timer now allows the coil (2M) of the second line contactor to energize. Notice that the "interlocking" is such that coil S must de-energize before coil 2M can energize. In the power circuit, the starting contacts (S) open; then the second line contacts 2M close to connect the motor coils in delta to the three-phase supply (L_1-T_1-T_6, L_2-T_2-T_4, L_3-T_3-T_5).

Notice that the current passing through the overload relay heaters in the power circuit is the *phase value*, not the line value, of the delta-connected motor coils.

A note about information on the motor nameplate: the phase value is the lower of the two current quantities listed. The lower of the two voltages listed is the delta-connected (running) line value.

Closed-transition, wye-delta starter

The closed-transition method of starting is achieved by slightly modifying the open-transition circuit. This involves adding an additional starting contactor (2S) and three power resistors (R), as shown in Figure 5.

When the start push-button is activated, the coil of the timing relay (TR) is energized. Two instantaneous contacts (TR) are activated—one acting as a seal-in contact, the other as an interlock to initiate the operating sequence for the control devices. The coil of the first starting contactor (1S) is now energized, and its NO auxiliary contact (1S) allows the coil (1M) of the line contactor to energize. Notice that the second NC auxiliary contact (1S) prevents the coil (2M) of the other line contactor from energizing. An auxiliary contact (1M) of the line contactor provides a seal-in circuit for the coil (1M).

In the power circuit, the starting contacts (1S) close to form the wye point for the motor coils (T_4 -T_5-T_6), and the main line contacts (1M) close to energize the stator (L_1-T_1, L_2-T_2, L_3-T_3).

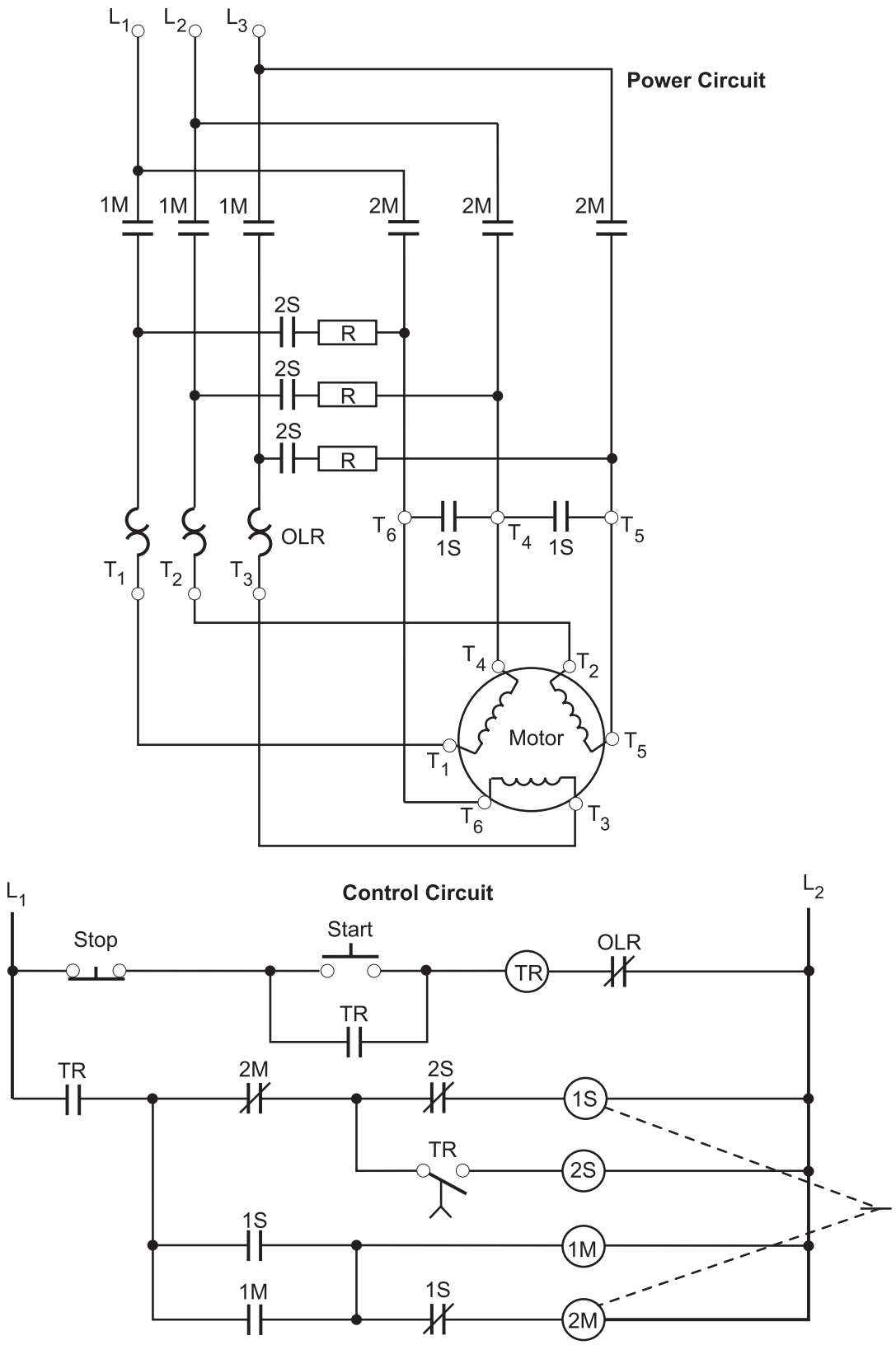


Figure 5—Wye-delta starter with a closed transition

After a preset time, the NO timing contact (TR) closes to energize the coil (2S) of the second starting contactor. This causes its NC interlock (2S) to de-energize the starting contactor (1S). The result in the power circuit is the second set of starting contacts (2S) connecting resistance into the motor circuit. At the next instant, the wye point connection to the motor is opened through the contacts (1S) of the first starting contactor, and the motor is immediately connected in delta to the three-phase lines through the transition resistors (R).

The instant contactor 1S drops out, the second line contactor (2M) is allowed to pick up through the NC interlock (1S). Similarly, the NC interlock (2M) de-energizes the coil (2S) of the second starting contactor. In the power circuit this results in the second line contactor (2M) closing and the second starting contactor (2S) opening. The motor is now connected directly across the line (L_1-T_1-T_6, L_2-T_2-T_4, L_3-T_3-T_5) in a delta configuration.

Although the control circuits of different manufacturers may vary slightly, the closed-transition action in the power circuit is essentially the same.

 Now do Self-Test 4 and check your answers.

Self-Test 4

1. Can all three-phase motors be used for wye-delta starting? Briefly explain.

2. When started across the line, a squirrel-cage induction motor draws 400% full-load current and develops 150% of its full-load torque. If it is started by means of a wye-delta controller, what is the percentage of full-load for the following:

   a. current drawn at starting

   b. torque produced at starting

3. The nameplate of a six-lead, three-phase motor states 120 V/208 V, 15 A/26 A, 60 Hz, 1720 rpm. If this motor is to be installed for wye-delta starting, what will the following be:

   a. the line voltage rating

   b. the full-load line current

   c. the value of motor current used to select the overload relay protection

4. Refer to Figure 5 in Learning Task 4. Which of the following choices is the correct operating sequence of the contacts in the power circuit?

   a. 1M closes; 1S closes; 2S closes; 2M closes; 1S opens; 2S opens

   b. 1S closes; 1M closes; 2S closes; 1S opens; 2M closes; 2S opens

   c. 1S closes; 1M closes; 1S opens; 2S closes; 2M closes; 2S opens

   d. 1M closes; 1S closes; 2S closes; 1S opens; 2M closes; 2S opens _____

5. What additional components are necessary to convert an open-transition, wye-delta starter to a closed-transition type?

6. If the line current to a wye-delta starter measures 42 A, what is the phase current in the motor windings?

7. How many leads are run between the wye-delta starter and the motor?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 5:

Describe basic maintenance and troubleshooting of reduced-voltage starters

Maintaining a trouble-free motor control begins with its installation. The two main requirements here are that:

- The selected equipment be suitable for the intended application.
- It be properly installed.

A properly installed motor control must be correctly matched to the electrical requirements of the motor load. The duty cycle and ratings such as voltage, current and power must be considered, because an inadequate apparatus and improper ratings can lead to premature failure.

When installing equipment, follow the manufacturer's directions to the letter. Typically this includes the following:

- Careful inspection for damage when unpacking equipment
- Proper mounting of enclosures for position and ventilation
- Correct wire sizes
- Proper and tight terminal connections
- Testing insulation resistance on all wires and terminals, using a megger (Instruments or control devices such as semiconductors must be isolated from the circuit.)
- A check of the electrical systems, which may involve adjusting switches, potentiometers and timing relays

After the motor control equipment is installed, a preventive maintenance program should be established. This is a system of routine inspections that involves a checklist of the tasks required and the date performed. The frequency of maintenance will vary with the type of equipment, its application and the environmental conditions.

In maintaining any electrical controls there are four principal rules:

1. Keep the controller clean.

   Dust and dirt must be periodically removed from the controller. Dirt buildup on moving parts and contacts can cause fouling and resultant slow operation, arcing and overheating. Dust may contain conducting materials that cause current leakage to ground or short circuits. Dust is best removed by vacuuming. Excessive dirt is easily removed by wiping the equipment with a cloth and suitable solvent. Observe all safety precautions.

2. Keep the controller dry.

   Moisture can cause short-circuiting and immediate failure. High humidity on copper and iron parts can also cause corrosion or rust, which leads to higher contact resistance and heating. In addition, moisture contributes to the buildup of dirt on electrical parts. If condensation is a problem when the controller is idle, it may be necessary to install heaters.

3. Keep the controller tight.

   Repetitive movements can wear the mechanical parts on controllers and cause an imbalance and vibration that may loosen connecting parts and screws. Contact springs should be checked periodically for proper tension. Terminal screws should also be checked for tightness, since a loose connection may develop at any time.

4. Keep the controller friction-free.

   Moving parts on controllers should operate smoothly, without binding or excessive friction. Check the contactors and relays for loose pins, bolts or bearings. Bearings on electrical controls are designed to operate without lubrication, and oil or grease on bearings will cause dirt to accumulate, with the result that the control is sluggish and may fail. Cleaning off dirt helps to prevent additional friction.

The key element of a maintenance program is visual inspection. In addition to standard tools, maintenance personnel will also require a flashlight. Table 1 lists items to inspect when dealing with motor controls.



Personal safety is a primary consideration when servicing motor controllers. Always observe all standard safety precautions.
When repairing controls, follow proper lockout procedures.

Table 1: Preventive maintenance guide for motor controls

What to inspect	Procedure
1. Exterior and surroundings	• Check for dust, grease, oil, high temperature, rust and corrosion, mechanical damage, condition of gaskets, if any.
2. Interior of enclosure, nuts and bolts	• Do same checks as No. 1, plus investigate excessive vibration that may have loosened nuts, bolts or other mechanical connections.
3. Contactors, relays, solenoids a. General	• Check control circuit voltage. Inspect for excess heating of parts revealed by discoloured metal, charred insulation or odour. • Check freedom of moving parts; check for dust, grease, corrosion and loose connections.
b. Contact tips	• Check for excessive pitting, roughness, copper oxide. Do not file silver contacts.
c. Springs	• Check contact pressure. Is pressure the same on all tips?
d. Flexible leads	• Look for frayed or broken strands. Be sure lead is flexible, not brittle.
e. Arc chutes	• Check for breaks or burning.
f. Bearings	• Check for freedom of movement. Do not oil.
g. Coils	• Look for overheating, charred insulation or mechanical injury.
h. Magnets	• Clean faces. • Check shading of coil. • Inspect for misalignment and bonding.
4. Fuses and fuse clips	• Check for proper rating and snug fit. If copper, polish ferrules. • Check fuse-clip pressure.
5. Overload relays	• Check for proper heater size. Trip by hand. • Check heater coil and connection. Inspect for dirt and corrosion.
6. Push-button stations and pilot devices	• Check contacts. Inspect for dirt, grease and corrosion.
7. Dashpot timers and overload relays	• Check for freedom of movement. • Check oil level.
8. Resistors	• Check for signs of overheating and loose connections. Tighten sliders.
9. Connections	• Tighten main line and control relay conductors. • Look for discoloured current-carrying parts.
10. Control operation	• Check sequence of operation of control relays. • Check relay contacts for sparking on operation. • Check contactors for flash when closing; if there is a flash, adjust to eliminate contact bounce. • Check limit switches, pressure switches, temperature switches and so on.

Troubleshooting

Previously you studied basic troubleshooting procedures for magnetic starters. All the concepts discussed then apply as well to the reduced-voltage motor starter with magnetic contactor and time-delay relay. Table 2 lists tools and equipment that are useful for troubleshooting motor control equipment.

Table 2: Troubleshooting equipment

Tool or Equipment	Application
Voltage indicator	• For measuring circuit voltage up to 600 volts • Portableand rugged.
Multimeter	• For measuring circuit voltage, resistance, and current • Portable
Insulated test leads with alligator clips	• For facilitating jumpering of components during circuit tracing to provide temporary grounding and to extend meter leads.
Electrical diagrams	• Helpful for understanding circuit operation and for locating components. • Essential for rapid troubleshooting.
Troubleshooting charts and maintenance records	• Guide and source of information for efficient troubleshooting.
Insulation-resistance tester	• For testing insulation resistance; detects low-resistance paths.
Tachometer	• For checking rotating machinery speeds.
Variable autotransformer	• For testing circuits at a reduced voltage.
Ground detector and locator	• For locating circuit grounds.
Phase-sequence indicator	• For determining phase sequence of polyphase circuits.
Clamp-on ammeter	• Portable, rugged instrument for taking simple measurements of circuit current.
Potential and current transformers, meter shunt	• For increased range of test instruments to permit reading high-voltage and high-current circuits.
Protective device analyzer	• Simple means of testing protective devices.
Portable capacitance and resistance bridge	• For taking accurate readings of capacitance and resistance.
Electrician's standard tools (fuse pullers, screwdrivers, etc.)	• For troubleshooting, disassembing or repairing electrical equipment.

The schematic and the wiring diagram are essential for troubleshooting motor controls. The schematic shows the operating sequence of the controller. The wiring diagram shows the physical relationship of the components, as well as the connecting wires in the controller enclosure.

Troubleshooting a primary-resistor starter

Figure 1 is a schematic for a primary-resistor starter, showing both the power and the control circuits. From this diagram, the function of each device and the sequence of operation can be identified. These features are important because, once the correct operating sequence is

understood, any deviation from normal can usually be traced to a specific part of the circuit.

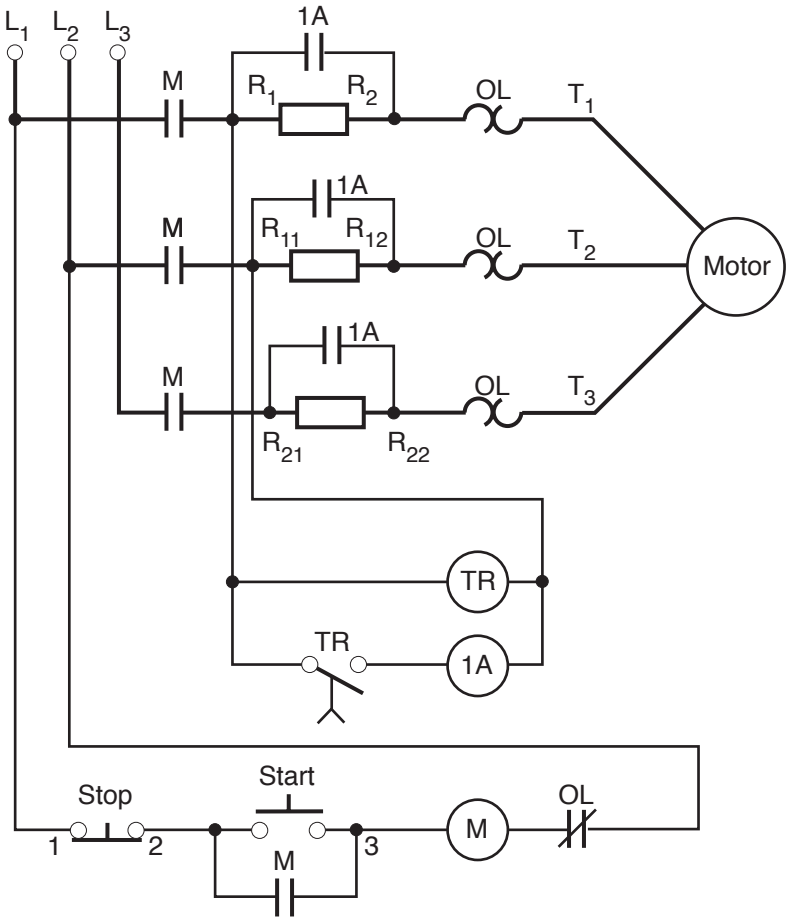


Figure 1—Schematic of a primary-resistor starter

Most manufacturers include a troubleshooting guide in their installation manuals. Refer to this guide for specific equipment problems.

Figure 2 is the wiring diagram for the same primary-resistor starter shown in Figure 1. After the circuit operation has been determined from the schematic, the wiring diagram can be used to identify each component or to trace the connecting wires when trying to locate a fault.

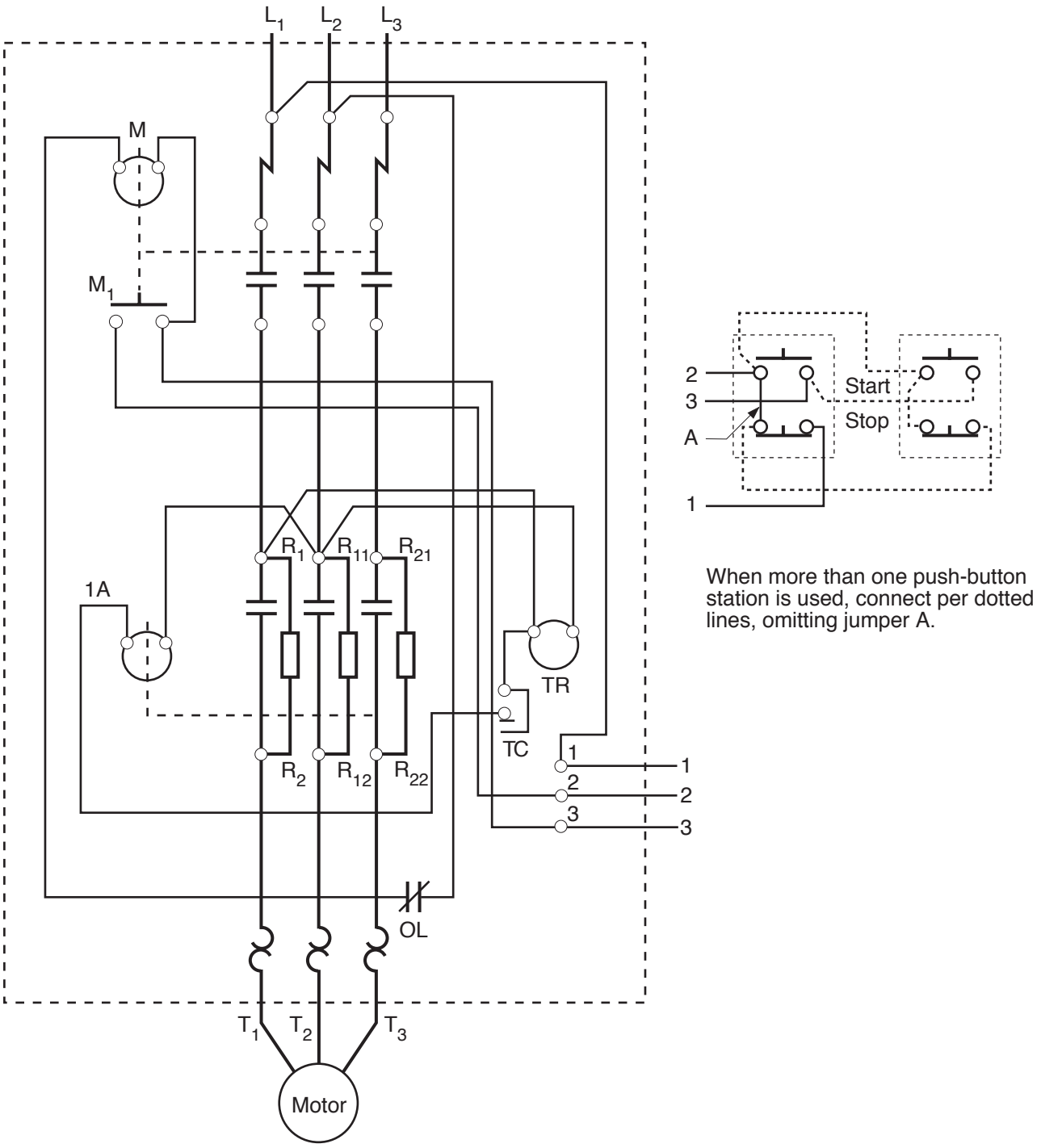


Figure 2—Wiring diagram for a primary-resistor starter

Always check the manufacturer's instructions for the details on specific testing and replacement.

Now do Self-Test 5 and check your answers.

Self-Test 5

1. What are the four key rules for maintaining electrical controls?

2. What should you periodically check on the resistors of a primary-impedance starter?

3. The following questions deal with the wiring diagram of the primary-resistor starter in Figure 2 of this Learning Task.

   a. The start button is pressed, and the M_1 contact wired between points 2 and 3 fails to close. How does the motor in the power circuit operate?

   b. The start button is pressed, and the timing contact of TR fails to close. How does the motor in the power circuit operate?

4. What test equipment would you use to check the speed of a motor?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 6:

Describe methods of automatic acceleration for wound-rotor motors

A wound-rotor motor is normally started with resistance inserted in its secondary circuit. This resistance limits the rotor starting current and improves the rotor power factor. The improved power factor creates a higher starting torque even though the rotor current has been limited.

As the rotor accelerates, the accelerating torque starts to decrease. However, if the rotor *resistance* is decreased as the rotor accelerates, the accelerating torque can be held relatively constant. The relatively constant torque leads to a smoother acceleration.

Normally the resistance is removed in steps as the motor accelerates. The more steps, the smoother the acceleration. The resistance may be removed manually using a drum controller or automatically using contactors.

There are two common methods of *automatic* acceleration for wound-rotor motors:

- Definite-time acceleration, where time-delay relays are used to control the rate at which the resistance is removed
- Speed-sensing acceleration, where frequency-sensing relays are used to determine the speed of the motor and remove the resistance in steps appropriate to the speed of the motor

Automatic, definite-time acceleration

Figure 1 is an example of a wound-rotor motor starter that controls the acceleration of the motor using time-delay relays.

When the start button is pressed, current flows through the M coil, causing the M contactor to pull in. When this happens, three things take place at the same time:

- The three M contacts in the power circuit close, supplying power to the stator of the wound-rotor motor. The motor begins to accelerate with all of the resistance connected into the secondary circuit.
- The instantaneous M contact in the control circuit closes, sealing in the M contactor.
- The time-delay portion of the main contactor begins to time out.

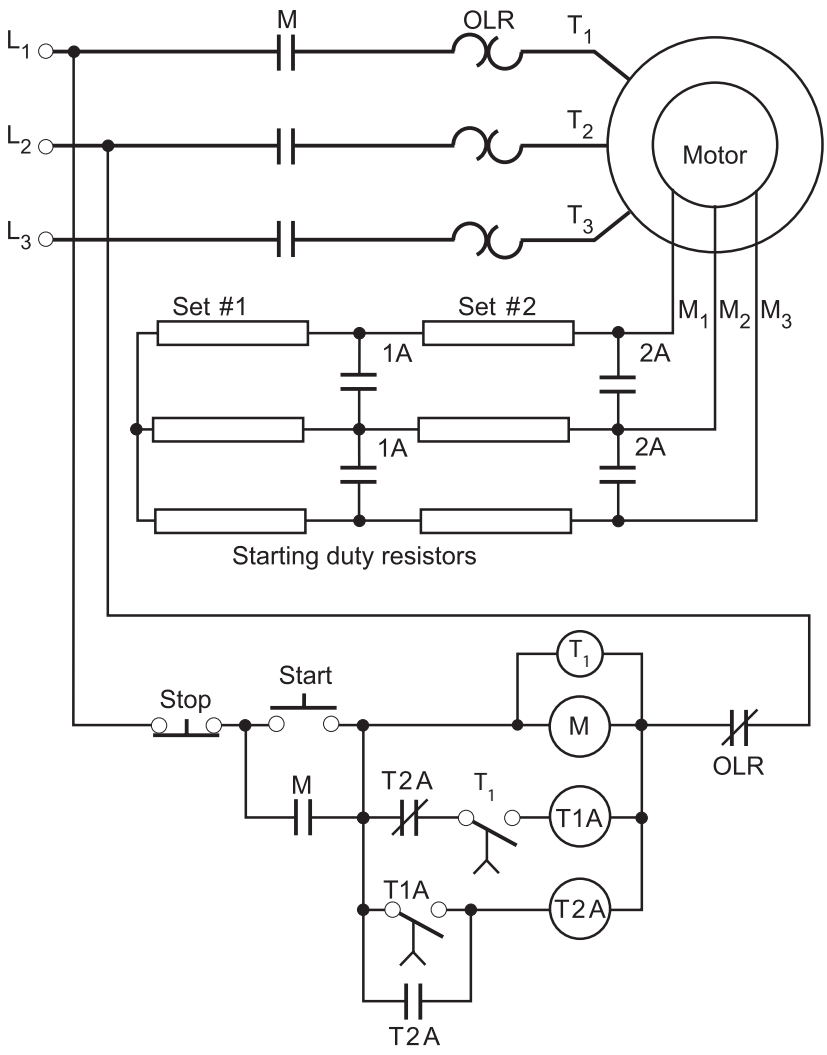


Figure 1—Wound-rotor, motor-starting circuit using time-delay relays

When the timing relay T1 finishes its timing cycle, it closes the T1 NOTC contacts connected in series with T1A timing relay. Current is then permitted to flow through the T1A timing relay, energizing it and causing it to pull in. This now causes two things to happen:

- The instantaneous T1A NO contacts in the secondary rotor circuit close, shorting out part of the secondary resistance, thereby reducing the total rotor resistance.
- T1A timing relay begins its timing cycle.

When T1A completes its timing cycle, the T1A NOTC contacts connected in series with the T2A timing relay close. Current is then permitted to flow through the T2A timing relay. This causes three things to happen:

- T2A timing relay is energized and the instantaneous T2A NO contacts in the secondary rotor circuit close, eliminating the remaining external resistance from the secondary circuit of the motor, improving the efficiency and speed regulation of the motor.

- The instantaneous T2A NO contacts connected in parallel with the T1A NOTC contact close, sealing in the T2A timing relay.
- The instantaneous T2A NC contacts connected in series with the T1A timing relay open, de-energizing the T1A timing relay to prevent wasted energy.

The instantaneous NC and NO contacts of T2A are special "make-before-break" contacts, in order to ensure that the instantaneous T2A NO contacts seal in contactor T2A, before contactor T1A is de-energized by the instantaneous T2A NC contacts opening.

Now the motor will finish accelerating with no external resistance connected in the secondary circuit.

Pressing the stop push-button will interrupt the current to all of the contactors, causing all of the NO contacts to open instantly. This interrupts the power to the stator windings and returns all of the resistance to the rotor circuit. The motor is then ready to be started again.

A disadvantage of time-delay, wound-rotor motor-starters

One big disadvantage of the time-delay type of wound-rotor motor starter is that it is not sensitive to the load on the motor. The time taken for the motor to accelerate will be longer if the load is greater. However, the time-delay relays will operate at the same time to remove resistance from the secondary circuit regardless of whether the load is large or small. This means that the timing for the removal of secondary resistance may not be matched to the requirements of the load.

Automatic, speed-sensing acceleration

Frequency-sensing relays may be used to sense the speed of the rotor and time the removal of the secondary resistance according to the load applied. Figure 2 shows a starting circuit for a wound-rotor motor that uses frequency relays to time the removal of the secondary resistance.

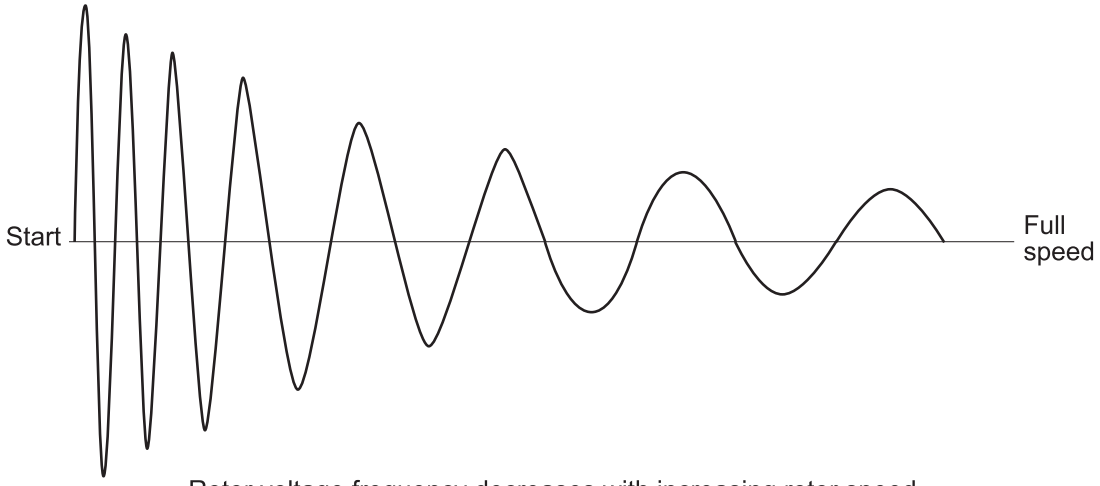
When the wound-rotor motor is first started, the voltage induced in the rotor is at a maximum and has the same frequency as the line voltage. As the motor accelerates, the speed of the rotating stator field relative to the rotor decreases. This causes a proportionate decrease in the magnitude and frequency of the emf induced in the rotor, so:

- At low rotor speeds, the induced emf will be higher in both magnitude and frequency.
- At higher rotor speeds, the induced emf will be lower in both magnitude and frequency.

The circuit shown in Figure 2 monitors the rotor voltage and frequency and uses them to control the timing of the rotor resistance removal. This type of starting circuit ensures that the resistance in the rotor circuit will be removed in the following steps at the same rotor speed no matter what the load on the motor.

1. When the start button is pressed, current is able to flow through the M contactor coil, causing the contactor to pull in. The contactor closes the M contacts in the line to supply the stator of the motor with three-phase power. As well, the contactor closes the M contact in the control circuit to seal itself in.

2. The rotating stator field induces an emf in the secondary rotor circuit that instantly causes the 2A and 1A contactors to pull in. This opens their related contacts in the rotor circuit so that full resistance is inserted in the rotor circuit.



Rotor voltage frequency decreases with increasing rotor speed

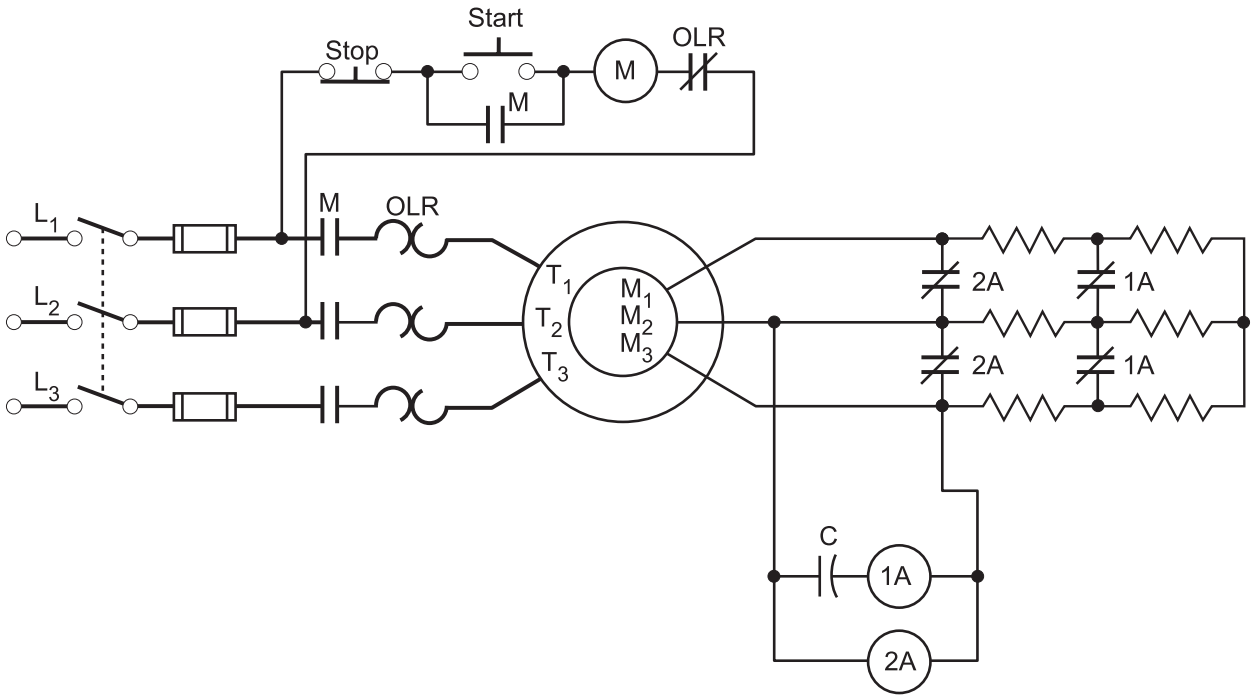


Figure 2—Wound-rotor, motor-starting circuit using frequency relays

3. The current through the coils of contactors 2A and 1A will decrease as the speed of the rotor increases. When the current through these contactors drops low enough, the contactors will drop out, closing the related contacts in the rotor circuit. The reactance of the capacitor connected in series with contactor 1A will cause it to drop out before contactor 2A.

4. The reactance of the capacitor increases as the frequency of the voltage applied across it decreases. This means that, as the speed of the rotor increases, the reactance of the capacitor also increases.
5. When the M contacts close and the 2A and 1A contacts open, the motor begins to accelerate with full resistance connected in the secondary circuit. As the speed increases, the decreasing current in the contactor 1A causes it to drop out at a predetermined speed. This causes the 1A contacts in the secondary circuit to close, which lowers the resistance in the secondary circuit.
6. The motor continues to accelerate with reduced voltage in the secondary circuit. The increasing speed causes the current to decrease through the coil of contactor 2A until it also drops out. This causes the NC contacts 2A in the rotor circuit to close, shorting out the whole of the rotor resistance. The motor will continue to accelerate up to rated speed.

Reversing starters

The direction of rotation in a three-phase, wound-rotor motor is reversed by interchanging any two of the line leads to the stator. This will reverse the direction of the rotating magnetic field in the stator. Since the rotor follows the stator field, it will also reverse direction.

Reversing starters operate exactly the same as non-reversing starters except that they have two interlocked contactors to control two sets of line contacts. Figure 3 shows a circuit for a reversing controller for a wound-rotor motor.



Note that interchanging two rotor leads will have no effect on the direction of rotation since it has no effect on the direction of the rotating stator field.

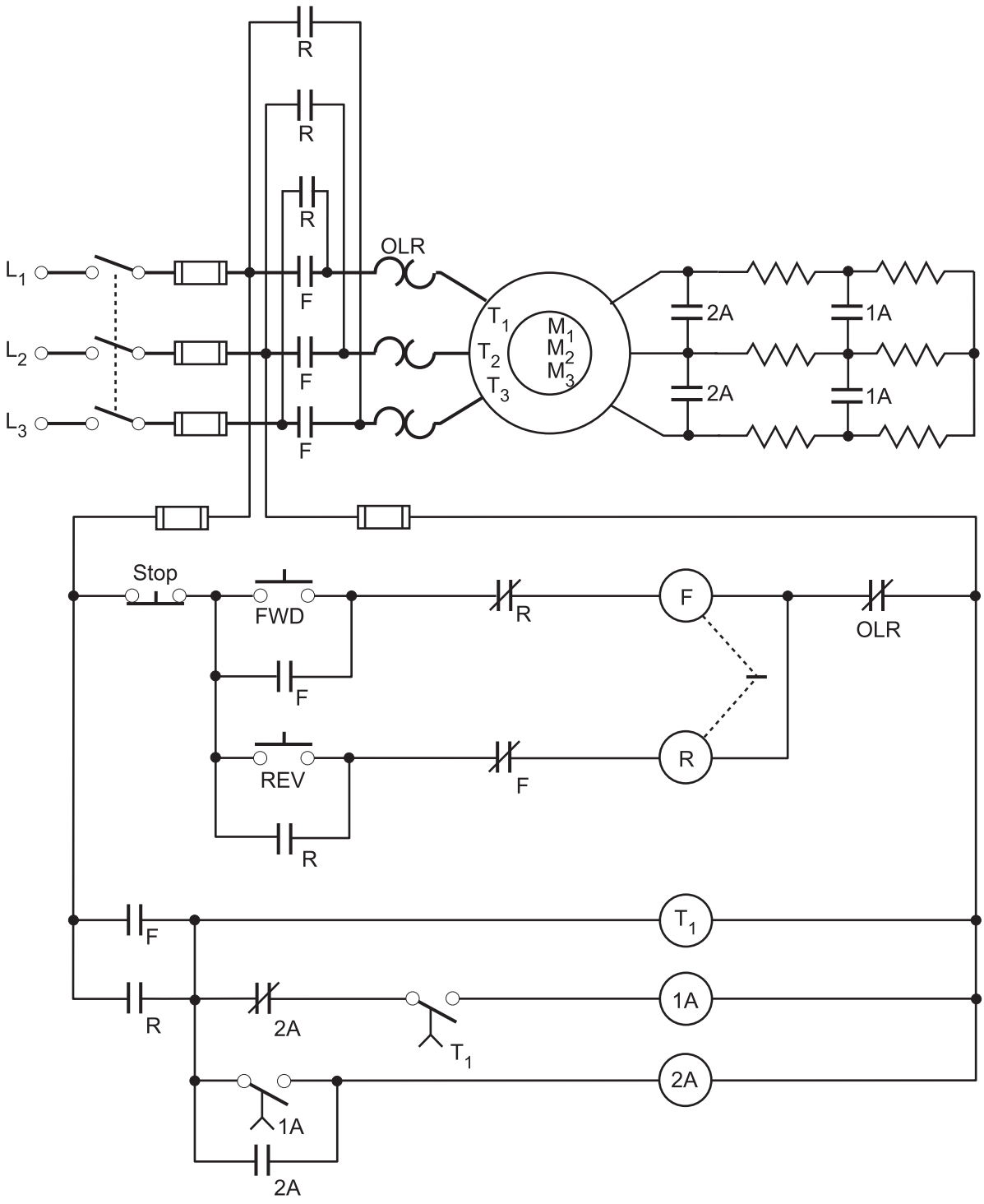


Figure 3—Reversing controller for a wound-rotor motor

Speed regulators

If some of the resistance is left in the secondary circuit, the motor will run with a higher slip speed. In other words, the motor speed will be lower. Some control circuits allow some of the resistance to be left in the circuit to give some speed control to the wound-rotor motor.

The secondary resistors used in this type of control system require a higher power rating. When the resistors are only used for starting, they only require a short time duty cycle; but when they are left in the circuit, their duty cycle is continuous.

Figure 4 shows a speed regulation type of controller for a wound-rotor motor. This controller sets the motor speed to 50%, 75% or 100% of rated full-load speed.

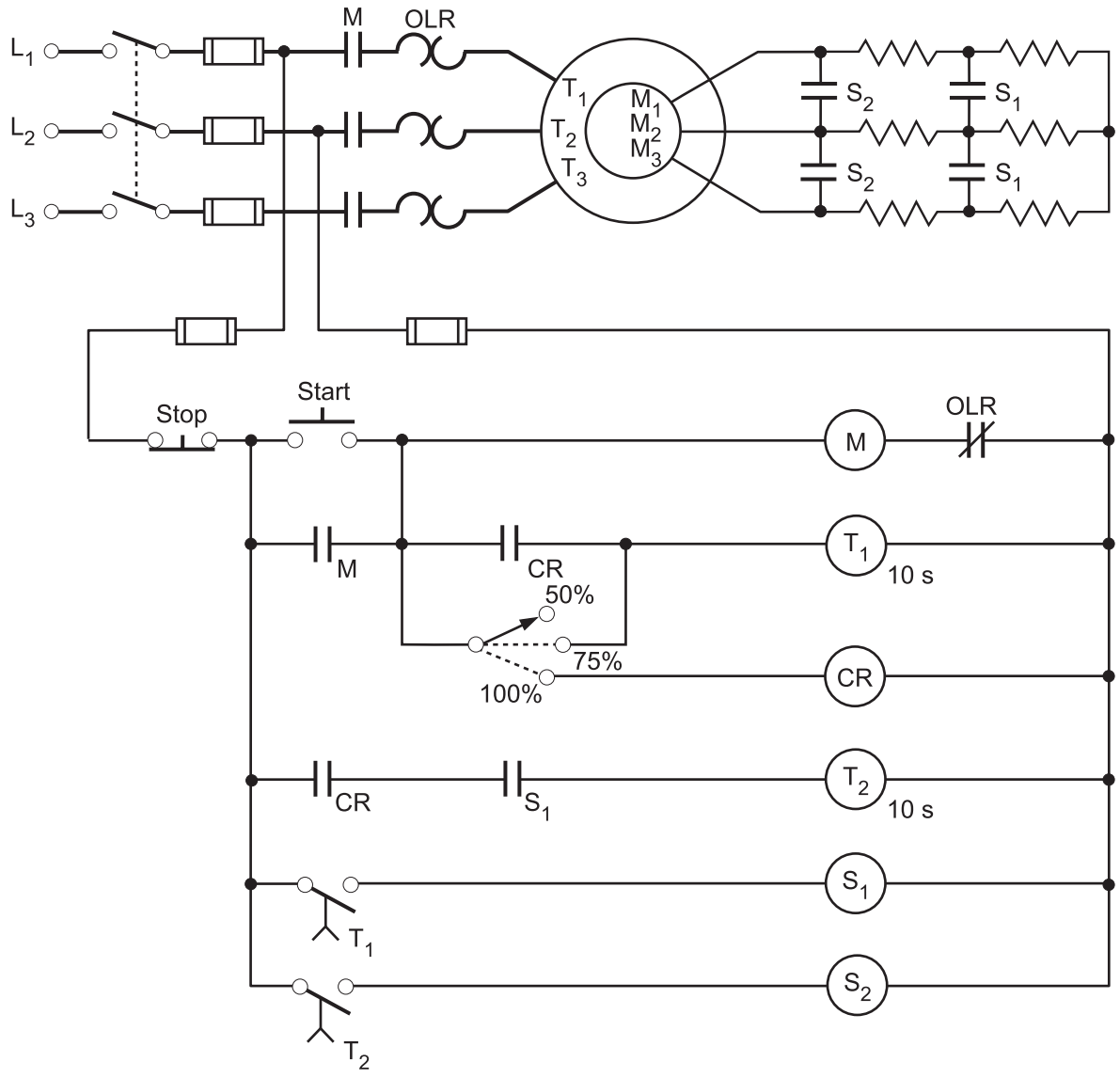


Figure 4—Speed-regulation controller

- When all of the resistance is left in this rotor circuit, the motor speed will be approximately 50% of rated full-load speed.
- When *only* the S_1 contacts close so that part of the resistance is left in this rotor circuit, the motor speed will be approximately 75% of rated full-load speed.
- When *both* the S_1 and S_2 contacts close so that all of the resistance is taken out of the rotor circuit, the motor will run at rated full-load speed.

When the start push-button is pressed, current is able to flow through the M contactor coil. This causes the M contactor to pull in, closing the M contacts in the stator circuit. Also, the M contact across the start push-button will close, sealing in the M contactor. The motor will start to accelerate with all of the resistance in the rotor circuit.

Selector switch in different positions

50% position

With the selector switch in the 50% position, the motor will accelerate to about 50% of full-load speed. At the 50% switch position, the timing relays never receive power. This means that none of the rotor resistance is removed from the rotor circuit.

75% position

With the selector switch in the 75% position, the motor will accelerate to about 75% of full-load speed. At this position, current also flows through timing relay T_1 when the start button is pressed. As soon as this relay times out, the NO, time-closing contact in series with contactor S_1 closes, energizing S_1. This causes the S_1 contacts in the rotor circuit to close, removing part of the resistance in the circuit and allowing the motor to accelerate to about 75% of full-load speed. The motor cannot accelerate further because the circuit to timing relay T_2 is open.

100% position

With the selector switch in the 100% position, the motor will accelerate to 100% of full-load speed. When the start button is pressed, both contactor M and the control relay CR are energized immediately. The CR contacts in series with the timing relays T_1 and T_2 close, allowing it to start its timing cycle. The motor begins to accelerate with all of the resistance inserted in the rotor circuit.

When the T_1 timing relay times out, the NO, time-closing contacts close, energizing contactor S_1. The S_1 contacts in the rotor circuit close, removing part of the resistance. This permits the motor to accelerate further. As well, the S_1 contact in series with the T_2 timing relay closes, allowing the T_2 relay to start its timing cycle.

When the T_2 relay completes its timing cycle, its NO, time-closing contact in series with contactor S_2 closes, causing the S_2 contactor to pull in. The S_2 contacts in the rotor circuit close, removing all the resistance from the rotor circuit and allowing the motor to accelerate to 100% of full-load speed.

When the motor is operating at the 100% setting and the selector switch is turned to the 75% setting, T_2, CR and S_2 will drop out instantly, returning some resistance to the rotor circuit. The motor will slow to 75% of rated full-load speed.

If the selector switch is turned to the 50% setting, T_1 and S_1 will also drop out, returning all of the resistance to the secondary circuit. The motor will slow to 50% of full-load speed.

This type of speed regulation is only effective over a limited speed range. As the speed of the motor is reduced, its speed regulation becomes poorer. Below about 50% of synchronous speed, the speed regulation becomes very unstable as slight load changes occur (Figure 5). The instability arises from the fact that the torque-vs-rotor slip curve becomes very flat with so much resistance left in the secondary circuit.

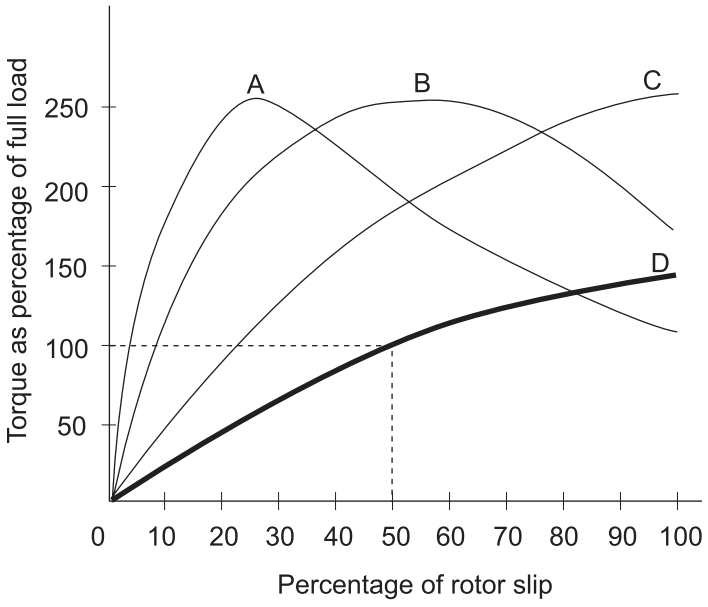


Figure 5—Torque/slip characteristics

Regeneration

One problem with using resistors in the secondary circuit of a wound-rotor motor is that the energy lost through heat transfer from the resistors reduces the efficiency of the motor. This is not a large problem if the resistors are used only for accelerating the motor, but if they are also used for speed regulation, it is very inefficient.

Figure 6 shows an electronic circuit used to replace the resistors. Regeneration occurs because energy is transferred back from the secondary to the primary, improving efficiency.

The current generated in the secondary circuit is first rectified. Then an inverter is used to convert this DC to three-phase AC. The electronic circuit controlling the inverter synchronizes the three-phase AC with the three-phase line and controls the level of voltage out of the inverter. The inverter output is connected across a transformer with its output connected to the three-phase line.

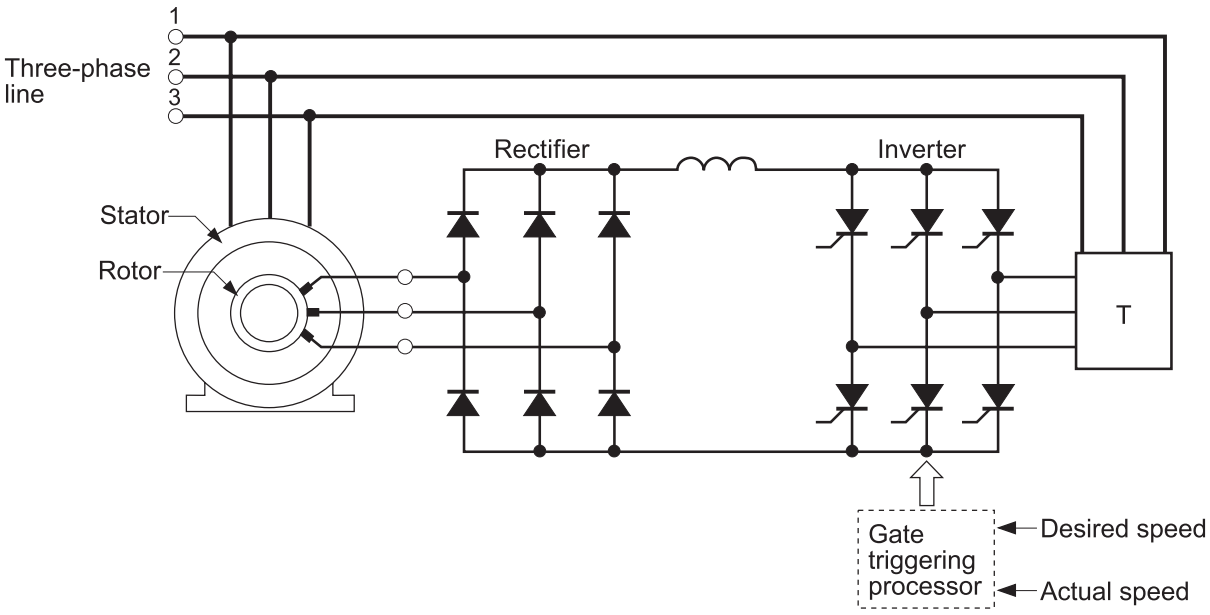


Figure 6—Electronic circuit used to replace resistors

In controlling the output voltage of the inverter by varying the gate pulses, you can control the load current in the rotor circuit (the resistance the rotor sees connected to it).

- Increasing the current has the same effect as lowering the resistance.
- Decreasing the current has the same effect as increasing the resistance.

The speed of the rotor may be controlled very accurately under varying load conditions. The electronics controlling the gate pulses to the inverter can sense the actual speed of the motor and compare it to the desired speed selected by the operator. It can then adjust the pulses to make the two speeds match each other.

Not only is this type of control more efficient than using secondary resistors for speed control, but it is also more accurate.

Now do Self-Test 6 and check your answers.

Self-Test 6

1. Why is a wound-rotor motor normally started with resistance inserted in its secondary circuit?

2. Why is this resistance removed in steps as the motor accelerates?

3. What happens to the magnitude and frequency of the voltage induced in the rotor as the motor accelerates?

4. What type of device do you commonly use to manually control the resistance in the secondary circuit?

5. What is meant by the term *automatic, definite-time acceleration*?

6. How is automatic, definite-time acceleration normally achieved?

7. What is the major disadvantage of automatic, definite-time acceleration?

8. What is meant by the term *automatic, speed-sensing acceleration*?

9. How is motor speed sensing normally achieved?

10. How do you reverse the direction of rotation of a wound-rotor motor?

11. Can a wound-rotor motor be reversed by making changes to the rotor circuit?

12. Explain the difference between a wound-rotor motor starter and a wound-rotor motor-speed regulator.

13. Why does speed regulation of a wound-rotor motor become very unstable below about 50% of synchronous speed?

14. What is the major advantage of a speed regulator that uses regeneration over a speed regulator that simply uses secondary resistors?

15. Which is generally more accurate: a regulator that uses regeneration or one that uses secondary resistors? Why is this so?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 7:

Describe basic maintenance and troubleshooting of wound-rotor controllers

Much of the maintenance and troubleshooting of wound-rotor controllers is similar to the maintenance and troubleshooting of other motor starters. In any type of maintenance you must consider safety first.

It is not always enough just to lock out the electrical system. Other systems, like the hydraulic or pneumatic systems, may also need to be locked out to make the area you are about to work in safe. After you have locked everything out, try the controls so you are sure the lockout procedure has been done properly. Many pieces of equipment are constructed with blocks or pins that must be in place to prevent equipment from moving while you are in the area.



Refer to Level 1, Learning Guide J-2: Install Magnetic Motor Controls, which described basic troubleshooting procedures for both the power and control circuits.

Level 3, Learning Guide J-2: Install Magnetic Motor Controls, Learning Task 5 described basic maintenance and troubleshooting procedures for reduced-voltage starters. The procedures used there also apply to wound-rotor motors. Listed are the things that should be inspected and tools and equipment that are useful for troubleshooting motor control equipment. Review these tables to refresh your memory. (The maintenance table is reproduced here as Table 1.)

Remember the four basic rules for maintaining electrical controls:

- Keep the controls clean.
- Keep the controls dry.
- Keep mechanical parts and electrical connections tight.
- Keep moving parts free of excessive friction.



Remember to use your senses of sight, hearing, touch and smell when performing routine maintenance and troubleshooting.

Maintenance

Referring to Figure 1, read Table 1 to see what a maintenance inspection should include.

Table 1: Preventive maintenance guide for motor controls

What to inspect	Procedure
1. Exterior and surroundings	Check for dust, grease, oil, high temperature, rust and corrosion, mechanical damage, condition of gaskets, if any.
2. Interior of enclosure, nuts and bolts	Same checks as No. 1 plus investigating excessive vibration that may have loosened nuts, bolts, or other mechanical connections.
3. Contactors, relays, solenoids a. General	Check control circuit voltage. Inspect for excess heating of parts revealed by discoloured metal, charred insulation or odour. Check freedom of moving parts; check for dust, grease, corrosion, and loose connections.
b. Contact tips	Check for excessive pitting, roughness, copper oxide. Do not file silver contacts.
c. Springs	Check contact pressure. Is pressure the same on all tips?
d. Flexible leads	Look for frayed or broken strands. Be sure lead is flexible, not brittle.
e. Arc chutes	Check for breaks or burning.
f. Bearings	Check for freedom of movement. Do not oil.
g. Coils	Look for overheating, charred insulation, or mechanical injury.
h. Magnets	Clean faces. Check shading coil. Inspect for misalignment and bonding.
4. Fuses and fuse clips	Check for proper rating and snug fit. If copper, polish ferrules. Check fuse-clip pressure.
5. Overload relays	Check for proper heater size. Trip by hand. Check heater coil and connection. Inspect for dirt and corrosion.
6. Pushbutton stations and pilot devices	Check contacts, inspect for dirt, grease, and corrosion.
7. Dashpot timers and overload relays	Check for freedom of movement. Check oil level.
8. Resistors	Check for signs of overheating and loose connections. Tighten sliders.
9. Connections	Tighten main line and control relay conductors. Look for discolored current-carrying parts.
10. Control operation	Check sequence of operation of control relays. Check relay contacts for sparking on operation. Check contactors for flash when closing; if there is a flash, adjust to eliminate contact bounce. Check limit switches, pressure switches, temperature switches, and so on.

Figure 1 is a schematic diagram of a wound-rotor controller.

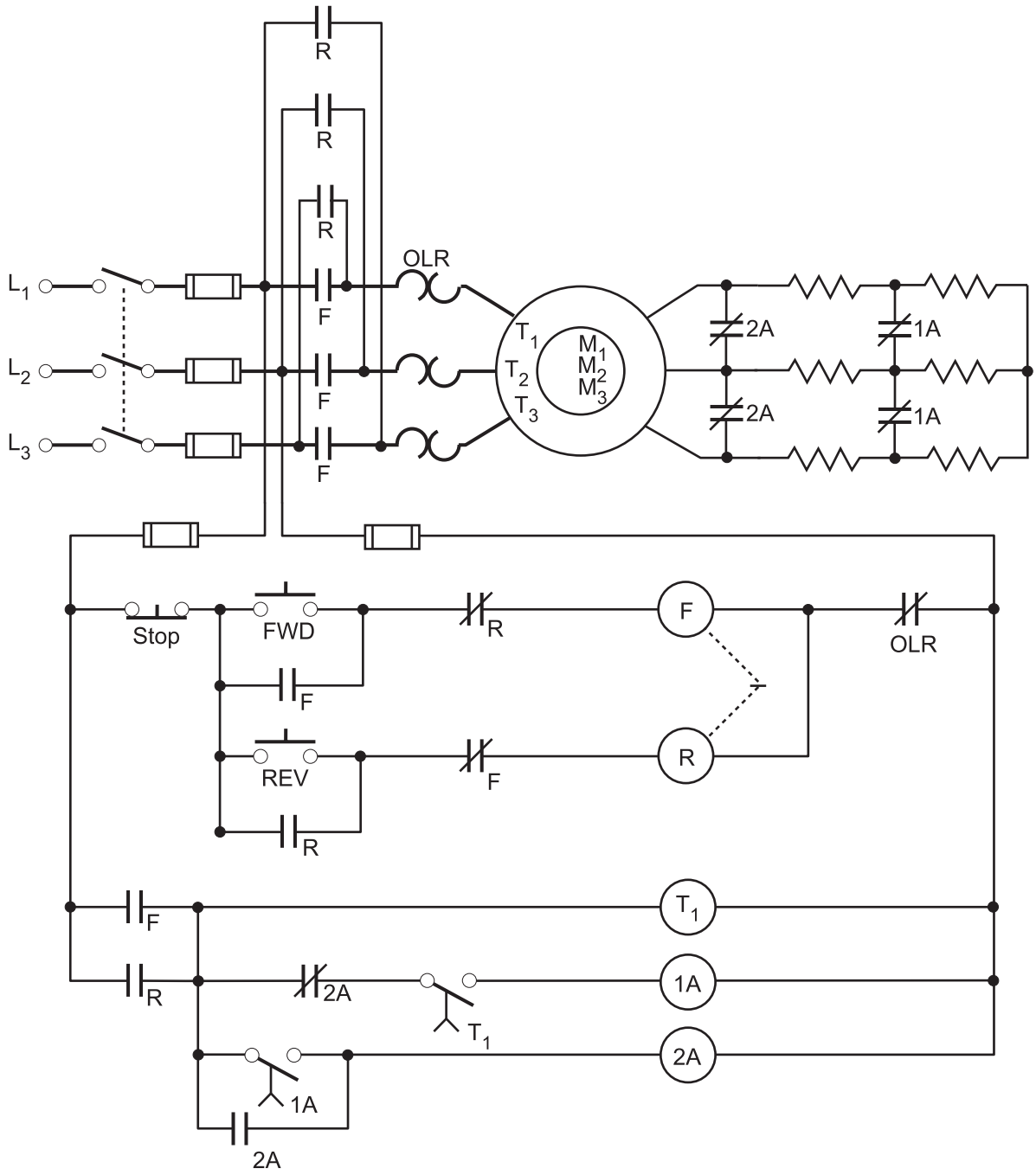


Figure 1—Wound-rotor controller

Since this is a wound-rotor motor controller, there are several areas that should be inspected. These areas are particularly important because of the relatively low secondary voltage:

- The secondary conductors between the motor and the controller, and the secondary conductors between the controller and the resistors:
  - Check for insulation deterioration and for tightness at the connections
  - Examine for signs of hot spots
- The controller connections: check for proper operation as well as soundness
- Contacts in the controller: check for cleanliness, oxidation, pitting and proper contact pressure.
- Resistors: examine for signs of damage, good electrical connections and proper air circulation for cooling

Troubleshooting

To troubleshoot any piece of equipment properly, you must have a good understanding of its normal operation.

- Schematic diagrams are used to explain the operation of electric circuits. If a schematic diagram is not available, it is well worth your time to trace the circuit and create your own schematic.
- Wiring diagrams show the physical relationship between components as well as the electrical relationship. Once you understand the circuit, the wiring diagram is very useful for locating components and connections.

The manufacturer's installation manual is a useful source of electrical diagrams and troubleshooting tips.

Most electrical problems fall into one of the following categories:

- Open circuits (*opens*)
- Short circuits (*shorts*)
- Grounds
- High resistances

Keep these four categories in mind as you troubleshoot electrical circuits. High resistances are not always easy to detect with an ohmmeter. Often, it is much better to try to locate a high resistance by measuring voltage drops around the circuit while it is loaded.

 Now do Self-Test 7 and check your answers.

Self-Test 7

1. List the four principal rules for maintaining electrical equipment.

2. List the four basic human senses you use in troubleshooting.

3. List the four categories into which most electrical faults fall.

4. Which type of electrical diagram is used to explain the operation of electric circuits?

5. What is the difference between a schematic diagram and a wiring diagram?

6. What should you check for when inspecting the enclosure for a motor controller?

7. What should you check for when inspecting the secondary resistors of a wound-rotor motor?

8. What should you check for when inspecting the contact tips in a contactor or relay?

9. What should you check for when inspecting dashpot timers or dashpot overload relays?

10. Explain why a circuit should be loaded when testing for voltage drops across various parts of the circuit.

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 8:

Describe special control features for synchronous motor starters

Figure 1 shows a typical synchronous motor control circuit that automatically senses when to apply the DC excitation to the rotor.

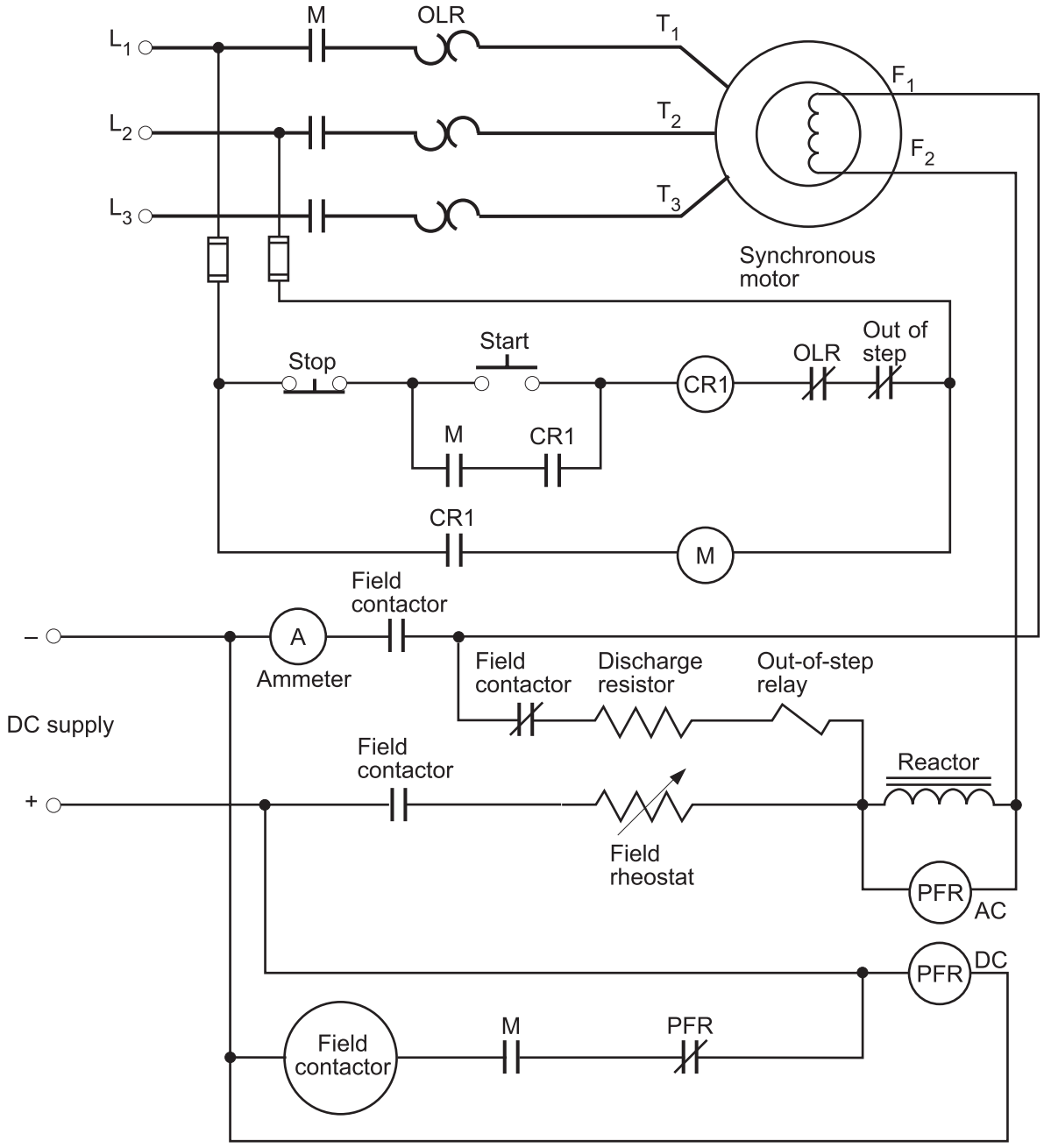


Figure 1—Automatic synchronous motor starter

As you learned earlier, synchronous motors are not self-starting. For this reason, another method must be used to accelerate the synchronous motor to a speed close to synchronous speed. One common way is to use a squirrel-cage winding (called the *amortisseur winding*) to accelerate the motor.

Because of the way synchronous motors must be started, the starting circuit contains devices that are not required in starters for other types of motors. These are:

- Out-of-step relay
- Field discharge resistor
- Field contactor
- Polarized field frequency relay (PFR)
- Field rheostat

Out-of-step relay

The squirrel-cage winding is not designed to carry current for a long period of time. If the motor does not accelerate fast enough, this winding will overheat. The out-of-step relay is designed to protect against this happening. Basically, it is NC time-opening, time-delay relay that is energized anytime the motor is not running at synchronous speed. If the motor runs at less than synchronous speed for too long, this relay times out and opens a set of contacts in the control circuit. This causes the line contactor to drop out, stopping the motor.

Field discharge resistor

During the period of acceleration, the DC excitation is not applied to the rotor circuit. As the rotating stator flux passes by the field windings, high voltages will be induced in the DC field windings. Anytime DC excitation is not applied to the rotor field, a resistor is placed across its terminals. This allows a current to flow in the field circuit, which limits the induced voltage.

Field contactor

At very close to synchronous speed, DC is applied to the rotor field coils to create the fixed rotor poles. When this DC is not being applied, the discharge resistor must be connected in the field circuit. At no time should the field circuit be open.

The field contactor controls the application and disconnection of the DC excitation to the field as well as the connection and disconnection of the discharge resistor. The contactor provides a positive overlap to ensure that the field circuit is never open. This means that when the field is to be excited, the contactor first connects the DC supply and then disconnects the field discharge resistor. When the field is to be removed, the field contactor first reconnects the discharge resistor and then disconnects the DC field excitation.

When the contactor pulls in, the two NO contacts of the field contactor close before the one NC contact opens. When the contactor drops out, the NC contact closes before the two NO contacts open.

Polarized field frequency relay (PFR)

The current induced in the rotor field by the rotating stator flux is AC. As the rotor accelerates, the rate at which the rotor windings are cut by the stator flux decreases. Therefore, the frequency and magnitude of the induced current in the rotor decrease as well.

The timing of the application of the DC rotor field excitation is critical to the proper operation of the synchronous motor starter. The polarized field frequency relay (PFR) is responsible for this timing. This relay does three things:

1. It monitors the rotor speed so that it can time the application of the DC rotor field current to somewhere between 92% and 97% of synchronous speed.
2. It times the application of the DC excitation so that it will create a magnetic field in the rotor circuit, which will reach full strength when two opposite poles are aligned with each other.
3. It disconnects the DC field excitation if an overload or voltage dip causes the motor speed to drop, and reapplies it if the speed returns to within synchronizing speed before the out-of-step relay opens its contacts.

This relay consists of two coils wound on the same core, an AC coil and a DC coil, as shown in Figure 2.

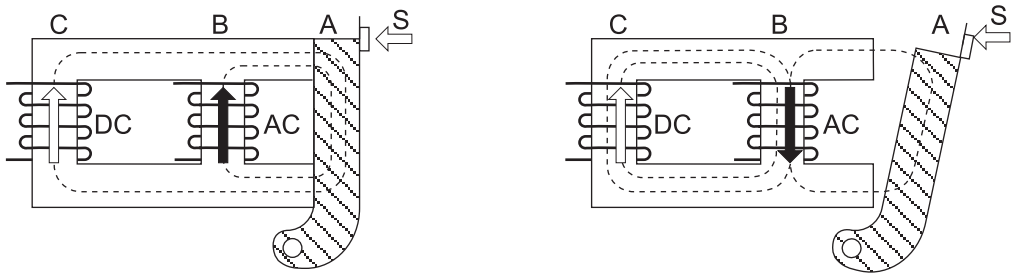


Figure 2—Polarized field frequency relay (PFR)

The AC coil

The AC coil is connected in parallel with the DC field reactor coil, and both are connected in series with the rotor field winding. The reactance of the reactor coil offers very little opposition to the flow of DC but causes a voltage drop across the reactor coil when AC passes through it. In this way, the AC coil of the polarized field frequency relay can sense the AC induced in the rotor field.

The DC coil

The purpose of the DC coil wound on the core is to polarize the core. With the core polarized, the relay is able to determine which half of the cycle in which to close the contacts to apply the DC excitation to the rotor field. The timing of the contact closing is critical to having rotor poles adjacent to stator poles of the opposite polarity when the DC field reaches full strength. If this does not occur, a reverse torque will occur, causing pole slippage, and the pull-in torque may not be sufficient to synchronize the motor.

Field rheostat

The field rheostat is used to control the magnitude of the DC current through the rotor field. The power factor of the motor may be controlled in this way:

- Increasing the rotor field excitation causes a more leading power factor (less lagging).
- Decreasing it causes a more lagging power factor (less leading).

 Now do Self-Test 8 and check your answers.

Self-Test 8

1. What will happen to the amortisseur winding in a synchronous motor if the motor is permitted to operate at less than synchronous speed for an extended period of time?

2. What device in the controls is used to protect the amortisseur winding from the problem stated in the above question?

3. What is the purpose of the field discharge resistor?

4. What is different about a field contactor compared to a normal contactor?

5. What does the abbreviation *PFR* stand for?

6. What are the three main functions of the PFR?

7. What is the purpose of the AC coil on the PFR?

8. What is the purpose of the DC coil on the PFR?

9. Explain the purpose of the field reactor coil.

10. What is the purpose of the field rheostat?

11. What will happen if the resistance of the field rheostat is decreased while the motor is running?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 9:

Describe the operation of synchronous motor starters

The sequences described on the next page occur in operating the synchronous motor starter shown in Figure 1.

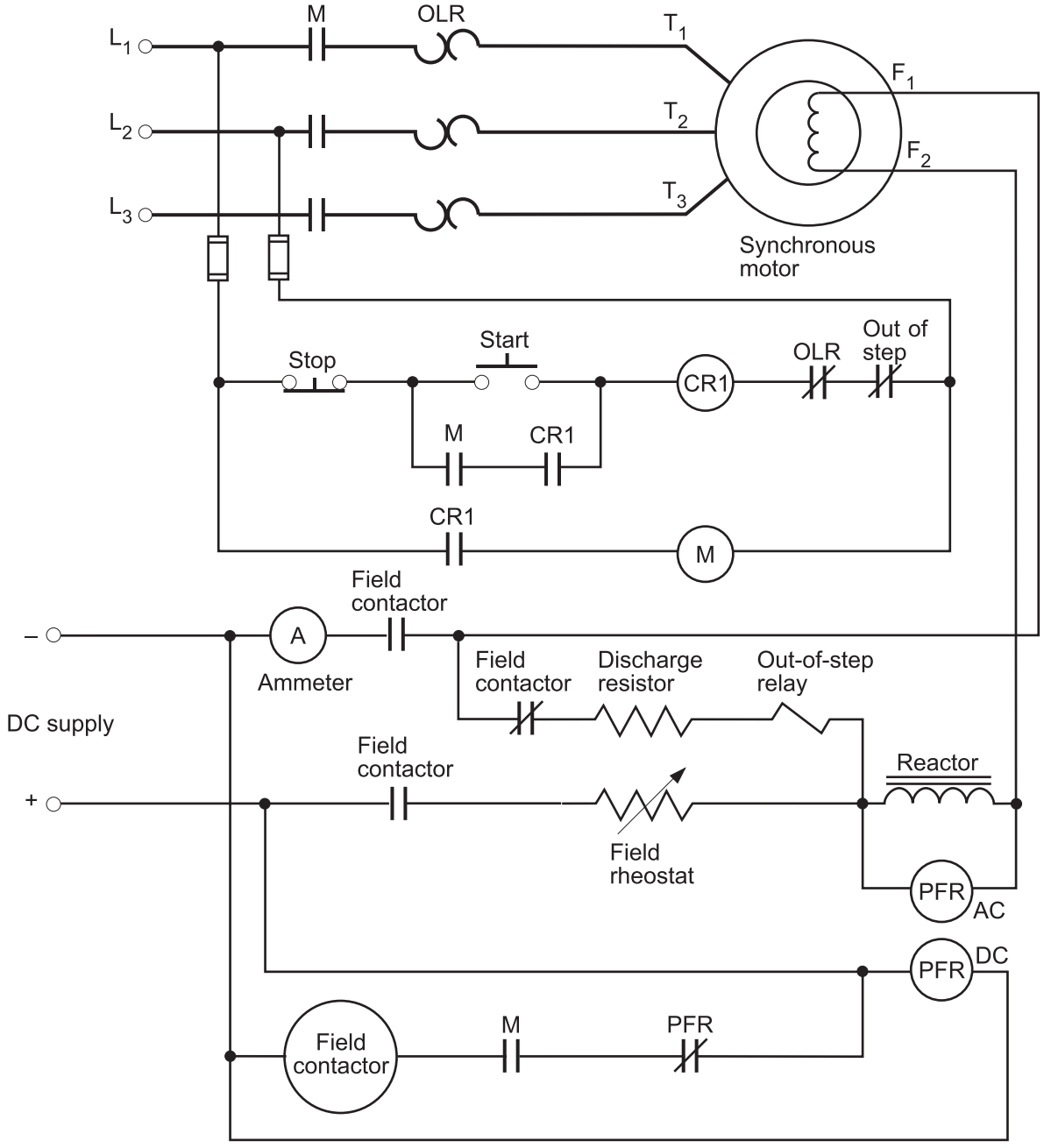


Figure 1—Automatic synchronous motor starter

1. When the start push-button is pressed, current flows as follows:
   - From L_1, through one control circuit fuse
   - Through the NC stop push-button
   - Through the NO, but depressed, start push-button
   - Through the control relay CR1
   - Through the NC overload relay contact
   - Through the NC out-of-step relay contact
   - Through the other control fuse, back to L_2

2. This causes CR1 to pull in. When CR1 pulls in, this closes the NO contact in series with the M coil, causing it also to pull in. The NO contacts M and CR1 in parallel with the start switch also close, so that when the start push-button is released, the circuit remains sealed in.

3. The three M power contacts in the AC lines close, allowing current to flow through the stator windings of the motor. This current produces a rotating magnetic field that induces an AC voltage in both the amortisseur windings and the rotor's DC field windings.

4. The current flowing in the amortisseur windings produces a starting torque that tends to start the rotor turning and begins to accelerate the motor.

5. At the same time, the voltage induced in the rotor field causes the current to flow through the NC field contactor contacts, the discharge resistor, the out-of-step relay coil, the field reactor and the AC coil of the polarized field relay. This causes the relay armature to pull in, opening the NC contact PFR in series with the field contactor coil. This prevents the field contactor from pulling in and applying the DC excitation to the rotor field.

6. DC is being fed to the polarizing coil of the PFR, causing the core of the PFR to polarize. The polarized PFR increases the flux through the armature for one-half of each cycle, while decreasing this flux for the other half of each cycle.

7. As the motor accelerates, the frequency and magnitude of the voltage induced in the rotor windings by the rotating stator field decrease. This decreases the voltage drop across the reactor coil and the AC coil on the PFR. The PFR is adjusted so that the current through the AC coil will produce insufficient flux to hold the armature in any longer at somewhere between 92% and 97% of synchronous speed (depending upon the load applied to the motor). When the armature drops out, it will cause the NC contact PFR in series with the field contactor to close, energizing the field contactor.

8. When the field contactor pulls in, it will first close the two NO field contacts to apply DC to the rotor circuit, and a fraction of a second later, it will open the NC field contact in series with the discharge resistor.

   The DC applied to the rotor will build up a rotor field that will pull the rotor into synchronism with the rotating stator field. The timing of the application of DC to the rotor field is done by the PFR. Since the magnetic field in the rotor takes time to build up because of magnetic inertia, the DC must be applied early so that it will have built up when the rotor poles have the opposite polarity to the adjacent stator poles.

Figure 2 shows a graph of the flux established in the PFR armature by the AC and DC coils. Notice how the DC flux offsets the graph.

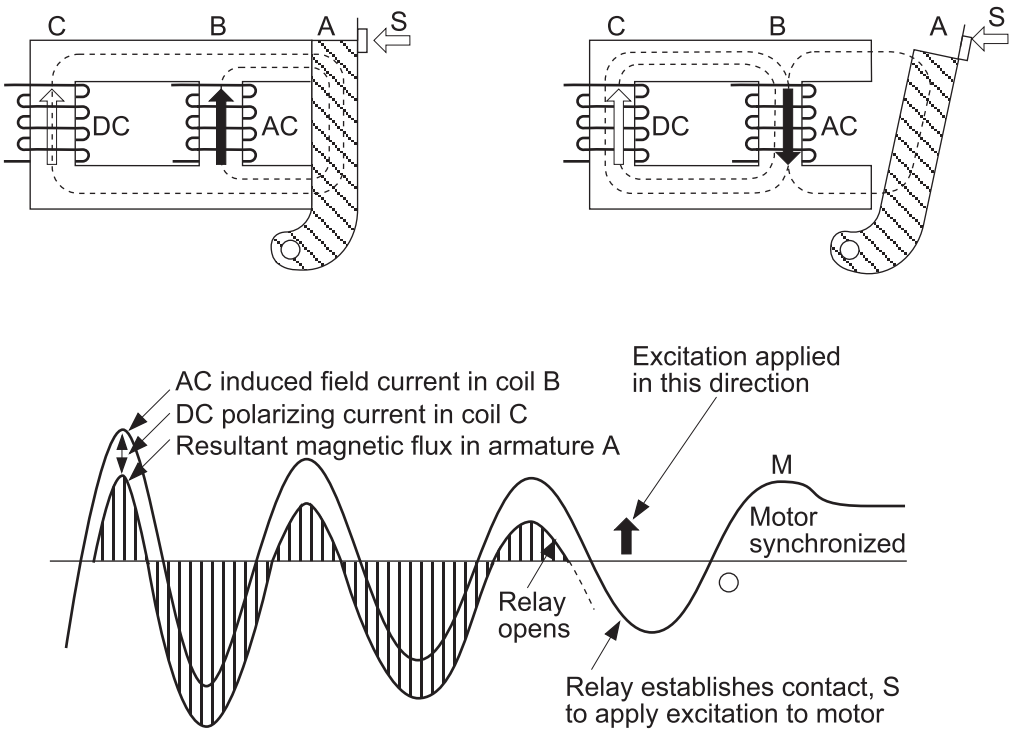


Figure 2—Graph of the flux in the PFR armature

Since the DC coil of the PFR strengthens the armature flux during one-half of the cycle and weakens it during the other, the armature will drop out near the end of one of the weaker half-cycles. This gives a time delay for the contacts to close and a further time-delay for the magnetic inertia to be overcome. More than half a cycle later, the magnetic field reaches its full strength just as the two opposite poles are adjacent. The rotor then is pulled into synchronism with the rotating stator.

Once the rotor is turning at synchronous speed, AC will no longer be induced in either the amortisseur winding or the rotor field windings. If an overload on the motor or a line voltage dip causes the motor to slow down momentarily, currents will once again be induced in the two windings. The current induced in the amortisseur winding as it slips back will be such that it produces a torque that opposes the slip and tries to keep the motor running at synchronous

speed. If the load tries to overdrive the motor, the current induced in the amortisseur winding would also oppose the increase in speed.

The current induced in the DC field winding as the motor slows down would also flow through the reactor coil and the AC winding of the PFR. This would result in the PFR picking up and reconnecting the discharge resistor, and opening the field contacts to remove the DC excitation from the rotor. If the overload or line dip is temporary, the speed of the motor will increase, causing the PFR to drop out and reapply the DC field excitation, which will again pull the rotor into synchronism

Out-of-step relay

Whenever the rotor is turning at less than synchronous speed, current flows through the out-of-step relay coil. This is a time-delay relay. This occurs when the motor is accelerating or when an overload or dip in line voltage causes the motor to pull out of synchronism. The purpose of this relay is to protect the amortisseur winding from overheating. This squirrel-cage winding is not intended to be used for long periods of time. If current flows through this winding for too long, the out-of-step relay will time out and open the NC contact in the control circuit (in series with CR1), causing CR1 and M to drop out and stop the motor.

Starting-duty cycle

Synchronous motors are often rated with a starting-duty cycle, because if they are started too often, the amortisseur winding will be damaged by overheating. If the out-of-step relay causes the motor to stop, a cooling period will likely be required before an attempt is made to restart the motor.

Field rheostat control of motor's PF

The field rheostat can be adjusted to control the power factor of the motor. Often, synchronous motors are used to provide a degree of power factor correction for other inductive loads in the plant. By decreasing the rheostat resistance and overexciting the field, the synchronous motor may be used to provide a leading PF load to offset the lagging PF of other inductive loads.

 Now do Self-Test 9 and check your answers.

Self-Test 9

1. Explain how the out-of-step relay protects the amortisseur winding against overheating.

2. Explain why the NC contact from the PFR is in series with the field contactor.

3. As the motor accelerates, what happens to the magnitude and frequency of the AC induced in the field coils?

4. At what percentage of synchronous speed is the DC excitation normally applied to the field windings?

5. What happens to the voltage induced in the amortisseur winding once the motor is operating at synchronous speed?

6. Why are synchronous motors often rated with a starting duty cycle?

7. How can the power factor of a synchronous motor be made more leading?

8. Which action takes place first when the field contactor pulls in?
   a. The NC contact in series with the field discharge resistor opens.
   b. The NO contacts that apply the DC excitation to the field close. _____

9. Which takes place first when the field contactor drops out?
   a. The NC contact in series with the field discharge resistor closes.
   b. The NO contacts that apply the DC excitation to the field open. _____

10. What is the reason for the positive overlap of the contacts in the field contactor?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 10:

Describe basic maintenance and troubleshooting of synchronous motor starters

Much of the maintenance and troubleshooting of synchronous motor starters is similar to that used in other motor starters. In any type of maintenance, you must consider safety first.

It is not always enough to just lock out the electrical system. Other systems such as hydraulic or pneumatic systems may also need to be locked out to make the area you are about to work in safe. Many pieces of equipment are constructed with blocks or pins that should be in place to prevent equipment from moving while you are in the area. After you have locked everything out, try the controls so you are sure the lockout procedure has been done properly.



Learning Task 5 described basic maintenance and troubleshooting procedures for reduced-voltage starters. The procedures used there also apply to synchronous motor starters.

Remember the four basic rules for maintaining electrical controls:

1. Keep the controls clean.
2. Keep the controls dry.
3. Keep mechanical parts and electrical connections tight.
4. Keep moving parts free of excessive friction.



Remember to use your senses of sight, hearing, touch and smell when performing routine maintenance and troubleshooting.

Maintenance

Referring to Figure 1, read Table 1 to see what a maintenance inspection includes.

Table 1: Preventive maintenance guide for motor controls

What to inspect	Procedure
1. Exterior and surroundings	Check for dust, grease, oil, high temperature, rust and corrosion, mechanical damage, condition of gaskets, if any.
2. Interior of enclosure, nuts and bolts	Same checks as No. 1 plus investigating excessive vibration that may have loosened nuts, bolts, or other mechanical connections.
3. Contactors, relays, solenoids a. General	Check control circuit voltage. Inspect for excess heating of parts revealed by discoloured metal, charred insulation or odour. Check freedom of moving parts; check for dust, grease, corrosion, and loose connections.
b. Contact tips	Check for excessive pitting, roughness, copper oxide. Do not file silver contacts.
c. Springs	Check contact pressure. Is pressure the same on all tips?
d. Flexible leads	Look for frayed or broken strands. Be sure lead is flexible, not brittle.
e. Arc chutes	Check for breaks or burning.
f. Bearings	Check for freedom of movement. Do not oil.
g. Coils	Look for overheating, charred insulation, or mechanical injury.
h. Magnets	Clean faces. Check shading coil. Inspect for misalignment and bonding.
4. Fuses and fuse clips	Check for proper rating and snug fit. If copper, polish ferrules. Check fuse-clip pressure.
5. Overload relays	Check for proper heater size. Trip by hand. Check heater coil and connection. Inspect for dirt and corrosion.
6. Pushbutton stations and pilot devices	Check contacts, inspect for dirt, grease, and corrosion.
7. Dashpot timers and overload relays	Check for freedom of movement. Check oil level.
8. Resistors	Check for signs of overheating and loose connections. Tighten sliders.
9. Connections	Tighten main line and control relay conductors. Look for discolored current-carrying parts.
10. Control operation	Check sequence of operation of control relays. Check relay contacts for sparking on operation. Check contactors for flash when closing; if there is a flash, adjust to eliminate contact bounce. Check limit switches, pressure switches, temperature switches, and so on.

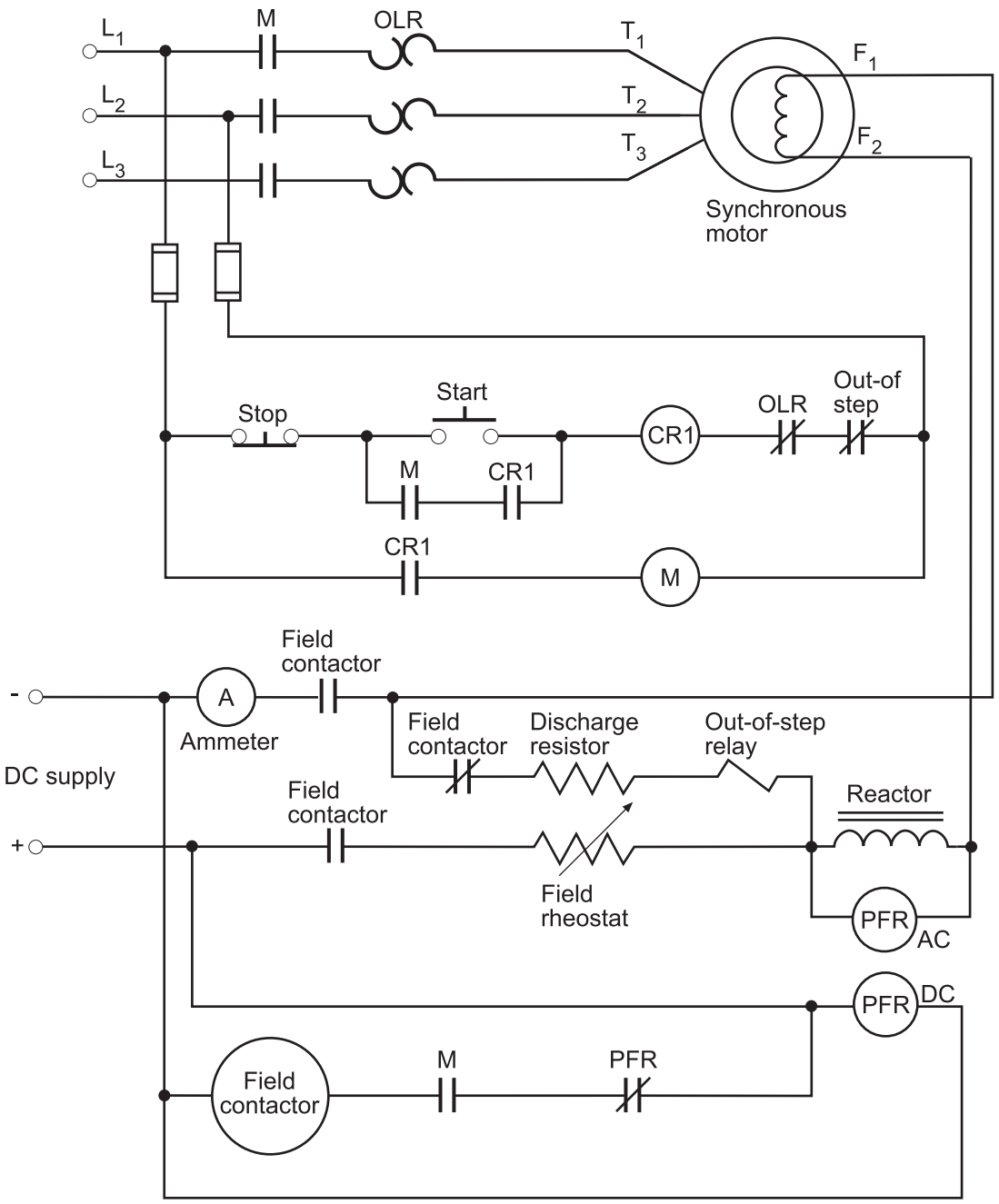


Figure 1—Automatic synchronous motor starter

Troubleshooting

To troubleshoot any piece of equipment properly, you must have a good understanding of its normal operation.

- Schematic diagrams are used to explain the operation of electric circuits. If a schematic diagram is not available, it is well worth your time to trace the circuit and create your own schematic.
- Wiring diagrams show the physical relationship between components as well as the electrical relationship. Once you understand the circuit, the wiring diagram is very useful for locating components and connections.

The manufacturer's installation manual is a useful source of electrical diagrams and troubleshooting tips.

Most electrical problems fall into one of the following categories:

- Open circuits (*opens*)
- Short circuits (*shorts*)
- Grounds
- High resistances

Keep these four categories in mind as you troubleshoot electrical circuits. High resistances are not always easy to detect with an ohmmeter. Often, it is much better to try to locate a high resistance by measuring voltage drops throughout the circuit while it is loaded.

Problems specific to synchronous motor starters

Synchronous motor starters have certain problems that do not occur in other types of starters.

The supplier of the PFR normally adjusts its operation to the application for which it will be used. If the line voltage or load conditions change appreciably, field adjustments may need to be made. The speed at which the PFR drops out and the motor is synchronized may be adjusted by removing or adding non-magnetic shims, or spacers, to the face of the relay core between the stator and the moving end of the armature.

- Adding shims will cause the field contacts to close at a lower speed.
- Removing shims will cause the field contacts to close at a higher speed.

At least one shim should always be left between the stator and the armature of the PFR to prevent the armature from sealing against the stator due to residual magnetism. The adjustment should be made so the field contacts will close at the highest possible speed for the application.

If the armature does not pull in right away when the motor is started or when the rotor falls out of step, this may be caused by too large an air gap or by a sticky mechanism. Check for ease of movement first, and if necessary, reduce the air gap between the armature and the relay core when the armature is dropped out.

When the field is applied to the rotor, the ammeter in the rotor circuit should move slightly below zero and then swing up to the normal excitation level. If, instead, the ammeter swings above zero, then dips back towards zero before it rises to its normal excitation level, the DC applied to the polarizing winding of the PFR must have its polarity reversed.

Commonly, out-of-step relays are dashpot types. The oil level should be checked periodically.

 Now do Self-Test 10 and check your answers.

Self-Test 10

1. List four actions suggested when troubleshooting the control operation of a synchronous motor starter.

2. How are high resistance faults normally located?

3. What might occur if the timing action out-of-step relay fails during startup, and its timed contacts remain closed?

4. What is the next step in a lockout procedure, after all sources of energy have been suitably locked out?

5. How do you adjust the speed at which the field contactor of a synchronous motor starter pulls in?

6. Why should at least one shim always be left in the magnetic circuit of a PFR?

7. When adjusting the speed at which the field contactor pulls in, what speed should you be trying for?

8. If the armature of the PFR does not pull in right away when the motor is started or when the motor speed drops below synchronous speed, what should be checked?

9. When the field is applied to the rotor, the ammeter in the rotor circuit dips slightly below zero and then swings up to the normal excitation level. What does this indicate about the polarity of the DC applied to the field winding?

10. What type of time-delay relay is commonly used for the out-of-step relay?

Go to the Answer Key at the end of the Learning Guide to check your answers.

Learning Task 11:

Describe common methods used for motor deceleration

For the purpose of this Learning Task, the many types of braking methods used in motor deceleration are divided into the following categories:

- Friction or electromechanical braking
- Plugging
- Dynamic braking
- Regenerative braking
- Eddy-current braking

Friction or electromechanical braking

Friction braking is used for retarding the speed of a motor or stopping the motor completely. Friction brakes work by dissipating the energy of the moving machinery as heat. As more of the energy of motion is transferred as heat, the motor slows down. There are three basic types of friction brakes: drum, band and disk.

Most friction brakes are spring-applied and electromagnetically released. In this way, if a power failure occurs, the brake will be applied automatically, making the system fail-safe. However, there are applications where it is preferable to have control over the degree of braking that takes place. In these cases, the brakes may be spring-released and electromagnetically applied. The pressure on the brake linings is controlled by varying the current through the brake coils.

Drum brakes

Pushing a friction material against the motor shaft to stop the motor would not be very effective. The amount of pressure required and the small surface area over which it would be applied would cause the friction material to overheat and fail prematurely. For this reason, a drum is normally attached to the drive shaft. The large diameter of the drum increases the surface area over which the friction material may contact the drum. The increased area of contact between the friction material and the drum means that less contact pressure is required. The heat is also spread over a larger area, giving the friction material a much longer life.

Figure 1 shows a typical spring-applied, electrically released direct-acting drum brake.

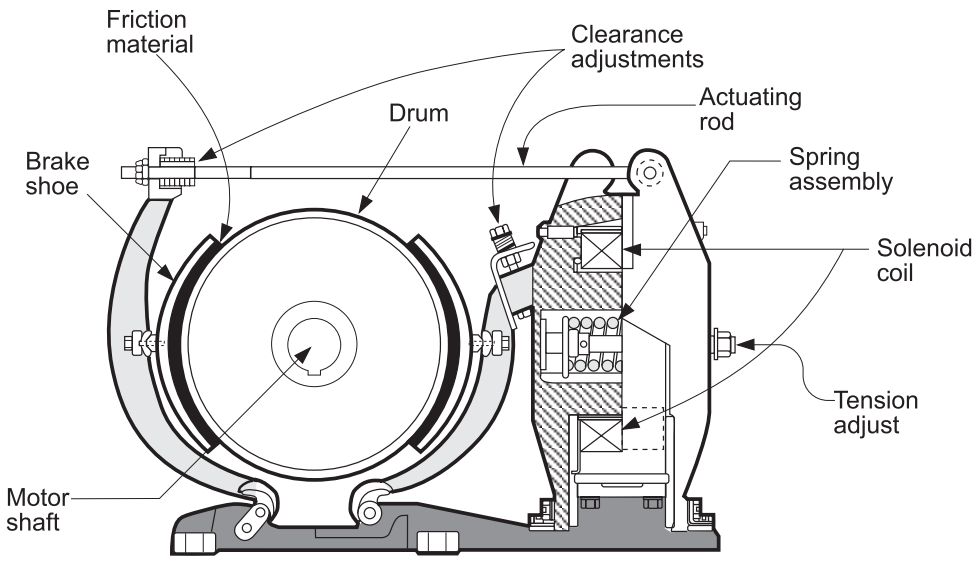


Figure 1—Drum brake

The shoes on this brake are externally applied to the drum by a spring. The shoes are lined with a friction material such as asbestos. The pressure the linings exert on the drum is adjusted by the compression on a spring in the operating solenoid of the brake. Adjustment for wear is made by shortening the actuating rod.

Some provision is also made for separately adjusting the clearance between each shoe and the drum. When voltage is applied to the operating solenoid, it compresses the spring and pushes the shoes away from the drum, allowing the drum to turn freely.

Some AC brakes do not use solenoids to operate the brake but use torque motors or thrusters, which give a steadier force and draw a lower inrush current.

Band brakes

Band brakes also incorporate a drum but, instead of two shoes, they have friction material attached to a band that is anchored solidly at one end and wraps around the drum. When it is pulled tight, it grabs the drum and causes a drag. The brake is smoothest and most effective when the band is being pulled away from the anchor.

Disk brakes

Disk brakes are normally mounted on a motor end bell. A disk lined with friction material is internally splined to the motor shaft so it turns with the motor. This disk is sandwiched between two steel plates that are firmly attached to the stator of the motor so that they cannot turn. Springs apply pressure that squeezes the disk between the two steel plates. A solenoid coil is used to release the spring pressure so that the disk is able to turn freely between the plates.

Figure 2 shows a control circuit for a friction brake. Notice that the brake solenoid coil may be connected in either the power circuit of the motor starter, or in the control circuit.

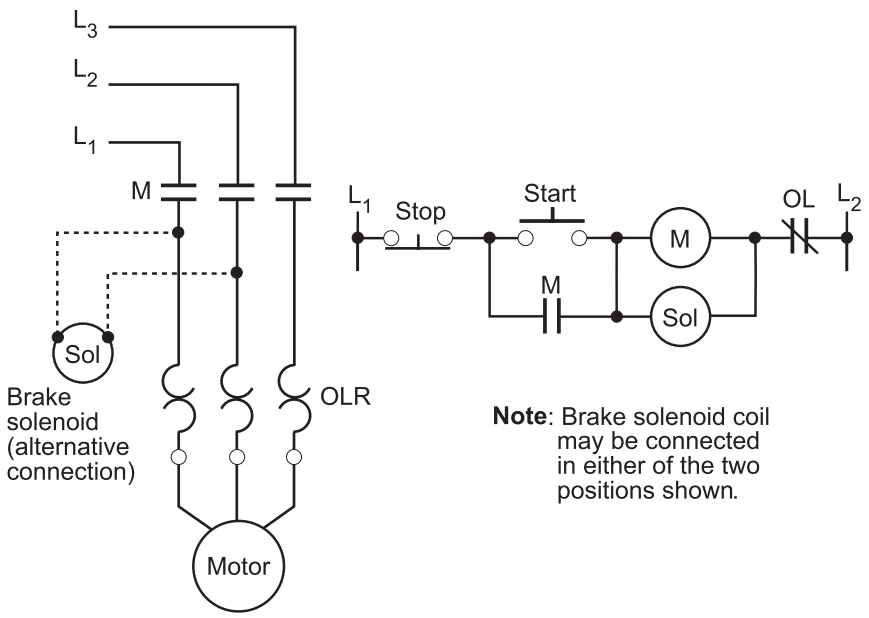


Figure 2—Control of a friction brake

Advantages of friction-type brakes

Some of the advantages of friction-type brakes over other methods of motor deceleration are:

- Friction brakes hold the motor shaft from rotating after the motor has been stopped.
- There are relatively few control circuit components, as Figure 2 shows.
- The brake is automatically applied when a power failure occurs. (This is only true for spring-applied types.)
- The brake cannot reverse the motor.

Disadvantages of friction-type brakes

Some of the disadvantages of friction-type brakes compared to other methods of motor deceleration are:

- The friction parts require periodic maintenance and replacement.
- The brakes themselves can tend to be bulky.
- The initial cost of the brake is high.

Plugging

Plugging is a control function that provides braking by reversing the motor line voltage polarity or phase sequence so that the motor develops a counter-torque that exerts a retarding force. Plugging is used for retarding the speed of the motor, stopping the motor, or even reversing its direction very quickly.

Figure 3 shows a typical plugging control circuit utilizing a time-delay relay.

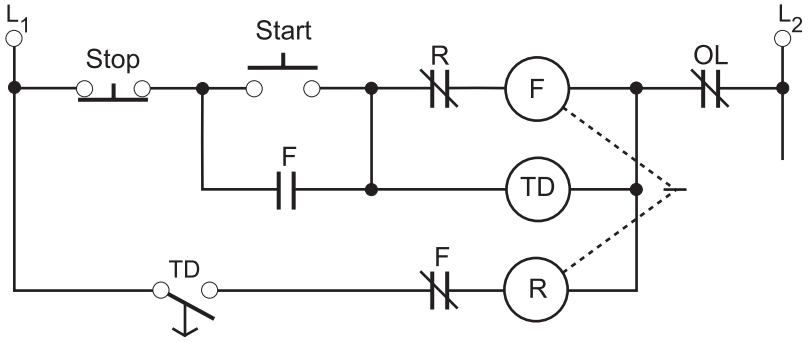


Figure 3—Time-delay plugging circuit

The time-delay plugging circuit has the disadvantage that the circuit does not sense the speed of the motor shaft. It is difficult to use this type of circuit in an application where the inertial load on the motor changes. Each change in load requires a different setting for the time-delay relay.

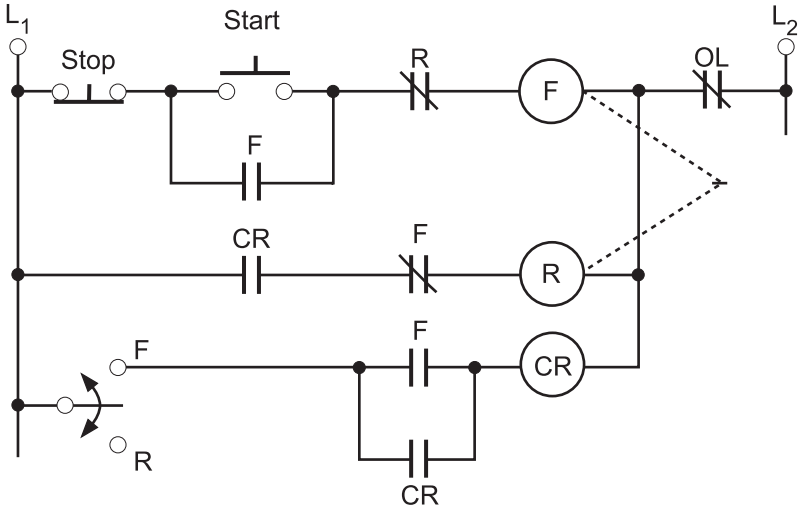


Figure 4—Zero-speed switch plugging circuit

Figure 4 shows a typical plugging control circuit utilizing a zero-speed switch. This type of control circuit monitors the speed of the motor shaft, allowing the plugging to take place for the proper amount of time regardless of load changes. A possible hazard associated with the zero-speed switch is that any physical movement of the motor shaft from standstill could result in a momentary "kickback" of motor rotation. For this reason a control relay (CR) is used in the circuit.

Figure 5 is an example of a plugging circuit used on a motor that operates in both forward and reverse directions. The zero-speed switch used in this circuit incorporates a lockout solenoid (connected across the motor terminals) that must be energized before the control contacts of the switch can be activated. This is to prevent the previously described hazard.

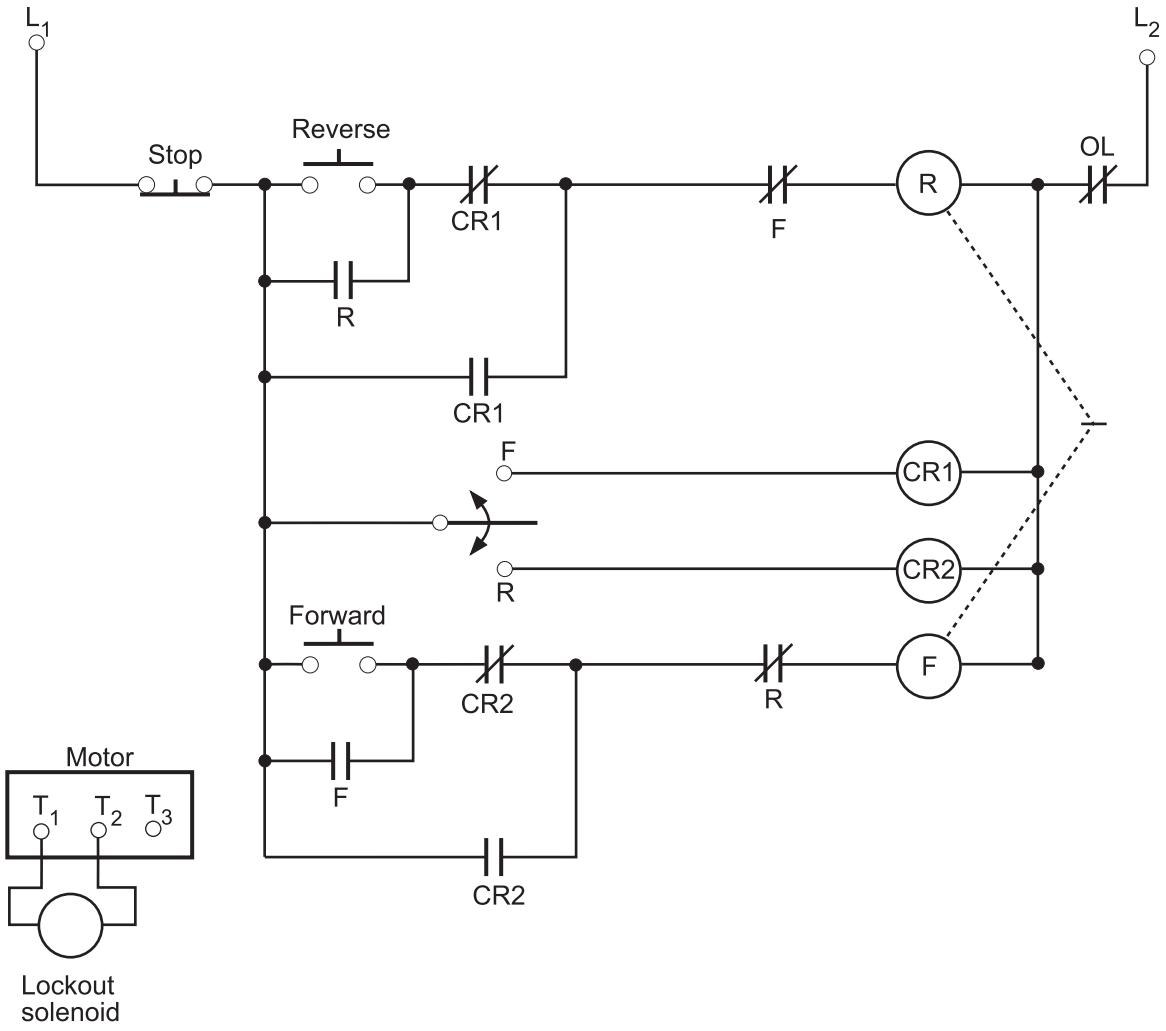


Figure 5—Plugging circuit for motor that operates in both forward and reverse

Advantages of plugging

Some of the advantages of plugging over other methods of motor deceleration are:

- It is the fastest deceleration method.
- It has no friction parts, so there is no real maintenance.
- It is suitable for large motors and severe duty.

Disadvantages of plugging

Some of the disadvantages of plugging compared to other methods of motor deceleration are:

- It requires a reversing controller.
- It requires a zero-speed switch or a consistent time-delay relay.
- It will not operate if a power failure occurs.

- It draws large peak currents.
- The motor windings may require special bracing to handle the high stresses.
- The motor is free to rotate after stopping.
- In the case of the time-delay type, if the plugging is applied for too long, the motor may start to turn in reverse.

Dynamic braking

Dynamic braking (sometimes called *DC injection braking*) is a method of decelerating or completely stopping the motor by making it act as a generator. The energy of the rotating equipment is dissipated as heat in the windings of the motor or in external resistors. Dynamic braking is described for three motor types:

- Squirrel-cage induction motor
- Wound-rotor induction motor
- Synchronous motor

Dynamic braking of a squirrel-cage induction motor

Figure 6 is a schematic diagram of a dynamic-braking setup for a squirrel-cage induction motor.

When the stop push-button is depressed, timing relay (TR) and dynamic-braking relay (DB) are energized. The main contactor drops out, opening the three line contacts. The NO contact TR seals in the TR and DB relays. The NC contact DB in series with contactor M opens, preventing the motor from being started while the dynamic braking is taking place. The NO contacts DB in the power circuit close, feeding the AC input of the rectifier, and the motor stator with the DC output of the rectifier.

The DC current flowing through the stator windings of the motor creates magnetic poles in the stator. As the bars of the squirrel-cage rotor pass the poles, current is induced in the rotor. This current in the rotor causes a counter-torque that tends to slow the rotor, causing the motor to decelerate.

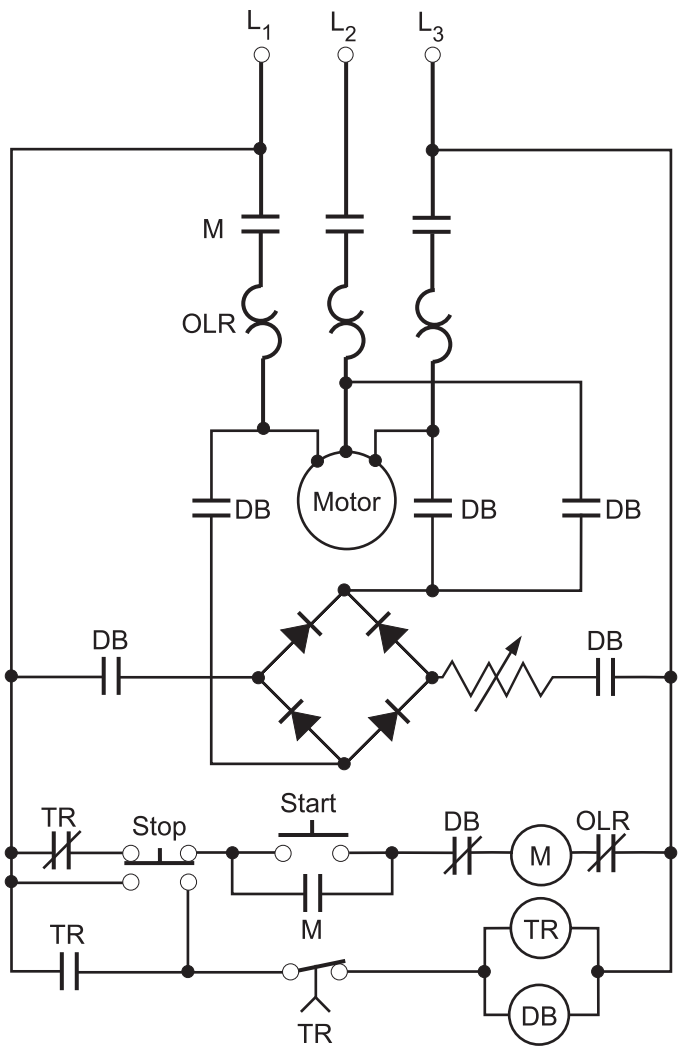


Figure 6—Dynamic braking of a squirrel-cage induction motor

After a predetermined time delay, the NC time-opening TR contact in the control circuit opens. This causes the TR and DB relays to drop out. The AC feeding the rectifier and the DC from the rectifier to the stator field are now disconnected, and the motor control circuit is ready to start again.

Dynamic braking of a wound-rotor induction motor

Figure 7 shows an example of dynamic braking for a wound-rotor motor.

When the start push-button is pressed, the line contactor M and the two timers TD_1 and TD_3 are energized instantly. TD_1 is an on-delay timer, so its contacts do not change state until the timer has timed out. TD_3 is an off-delay timer, so its contacts change state instantly.

The motor starts with full resistance inserted in the secondary circuit. After a period of time, TD_1 times out and energizes S_1. Secondary contactor S_1 pulls in and closes a set of contacts in the secondary circuit, which lowers the resistance in the rotor circuit. At the same time another contact from the S_1 relay closes to start TD_2 timing. When TD_2 times out, it closes a contact,

which energizes S_2. Secondary contactor S_2 pulls in and closes another set of contacts in the secondary circuit. This removes all of the resistance from the rotor circuit, allowing the motor to accelerate to its full load speed.

When the stop push-button is pressed and held for a moment:

- M, TD_1 and TD_3 drop out.
- The M line contacts open.
- TD_2 drops out when S_1 drops out.
- The contacts in the secondary circuit open.
- Since the TD_3 contact in series with the relay DB does not open instantly, the DB relay remains energized.
- The DB maintaining contact seals in the DB relay.
- The DB power contacts close to apply DC to the stator field.
- The DB contact in series with S_2 closes, energizing S_2, which closes contacts in the secondary circuit to short out the rotor resistance.

The DC applied to the stator windings creates poles in the stator that induce currents in the rotor. These currents produce a counter-torque that decelerates the motor. The energy of rotation is dissipated as heat in the rotor. After a period of time, the T_3 contact in series with the DB relay opens, causing the DB relay and the S_2 relay to drop out. The motor is now ready to restart.

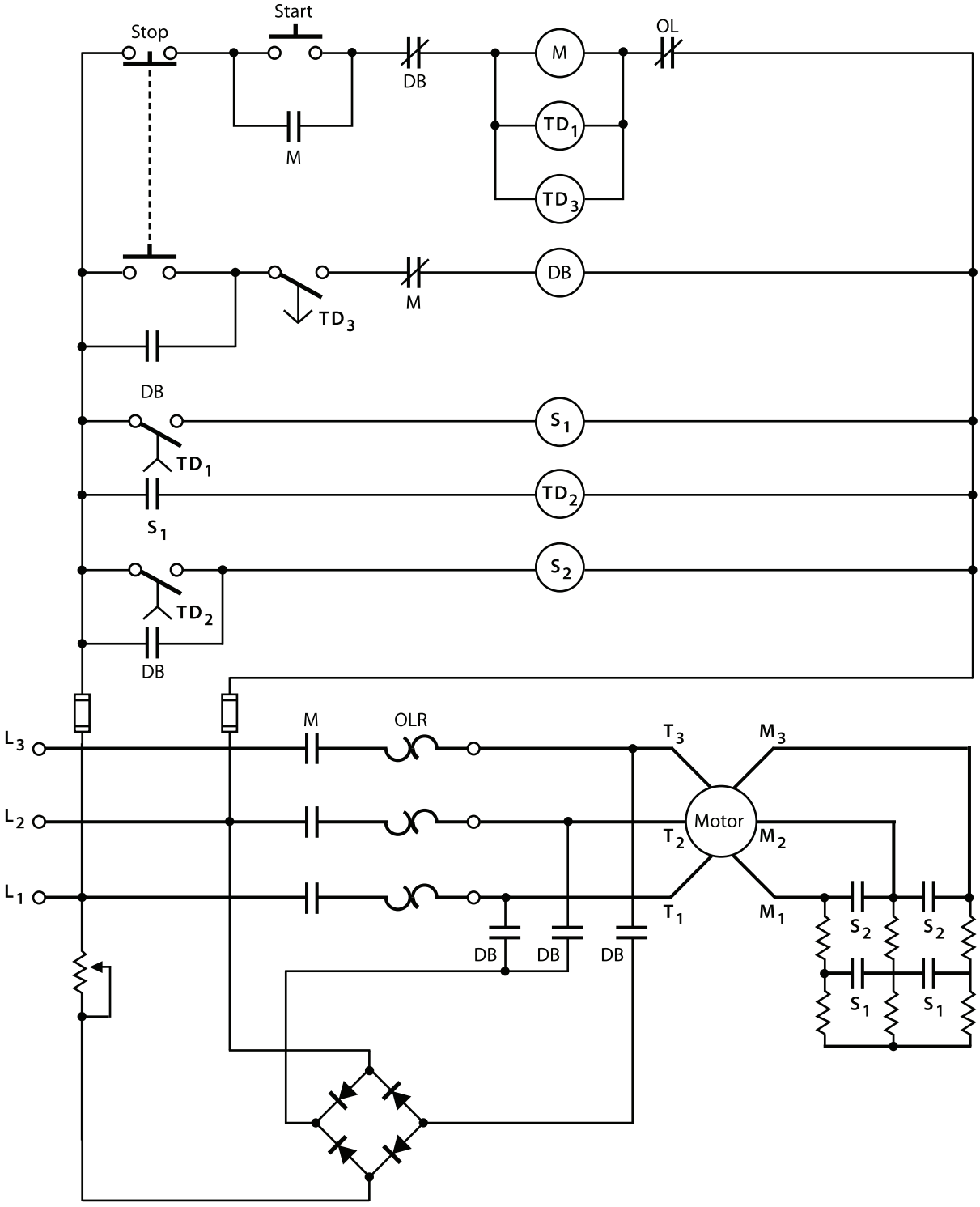


Figure 7—Dynamic braking of a wound-rotor motor

Figure 8 shows another circuit for a wound-rotor motor. This circuit uses frequency relays to accelerate and decelerate the motor. It is far more load-sensitive during acceleration and will provide faster deceleration.

When the start button is pressed, the M contactor pulls in, closing the line contacts to supply three-phase power to the stator of the motor. The maintaining contact closes, sealing in this contactor. Another auxiliary M contact supplies energy to the 1A and 2A relay circuits.

The relays 1F and 2F are frequency-sensitive relays. The frequencies shown are those at which these relays will drop out. At the instant power is applied to the stator, the motor is not turning and the frequency of the voltage induced in the rotor equals the supply frequency. As the motor accelerates, this rotor frequency decreases. This will cause the frequency relays to drop out in steps, which removes the secondary rotor resistance in steps. The result is smoother acceleration of the wound-rotor motor.

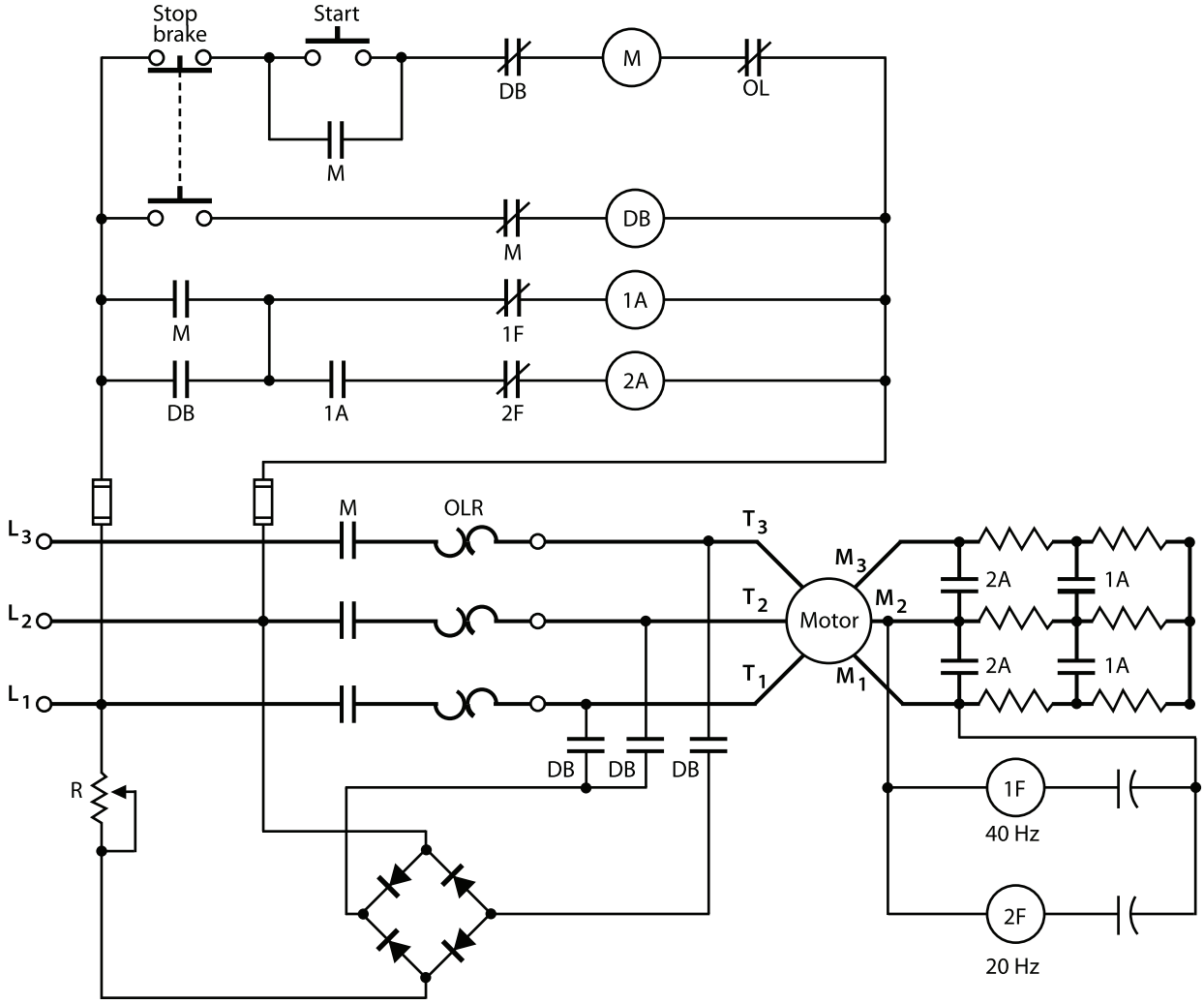


Figure 8—Frequency-sensitive deceleration of a wound-rotor motor

If the stop push-button is pressed and held down, the M contactor will drop out, opening the line contacts. As soon as the M contacts open, the DB contactor will be energized. When it pulls in, it will close contacts to apply DC to the stator of the motor. It will also close a contact in series with relays 1A and 2A.

The motor is still running at rated speed. With DC applied to the stator, a voltage will be induced in the rotor. The frequency of this voltage will be close to that of the three-phase line. Both frequency relays 1F and 2F will pull in, causing 1A and 2A to drop out. All of the resistance will be reinserted in the secondary circuit to improve the power factor of the rotor circuit and increase the decelerating torque.

As the motor slows down, this frequency will decrease. This will cause the frequency relays to drop out in sequence at the frequencies shown. As they drop out, relays 1A and 2A will energize in sequence, shorting out the secondary rotor resistance in steps. This will improve the power factor of the secondary circuit, keeping the decelerating torque higher, which causes the motor to decelerate faster.

When the motor has stopped or slowed down enough, the stop button can be released and the dynamic braking will be de-energized.

Dynamic braking of a synchronous motor

If the AC supply to the stator of a synchronous motor is disconnected but the DC supply is maintained, then the synchronous motor acts just like an alternator. Dynamic braking can be achieved on this motor if a load is connected across the stator terminals after the AC supply is disconnected. The motor will generate a current that will flow through the resistors, taking energy away from the motor and causing it to slow down. The current flowing in the stator windings will produce a counter-torque that will tend to decelerate the motor.

Figure 9 is a schematic diagram of a synchronous motor controller with dynamic braking.

When the stop push-button is pressed and held momentarily, CR1 drops out, which causes M and TD to drop out. This disconnects the M contacts in the supply line. After the M contactor drops out, the DB relay pulls in. The DB relay contacts connect the braking resistors across the stator and allow the field contactor to stay in. The rotating DC field induces a voltage in the stator windings, which causes a current to flow through the braking resistors. The current flowing in the stator windings produces a counter-torque that decelerates the motor.

After a period of time the TD contact opens and the DB relay drops out, removing the resistance from the stator circuit and causing the field contactor to drop out.

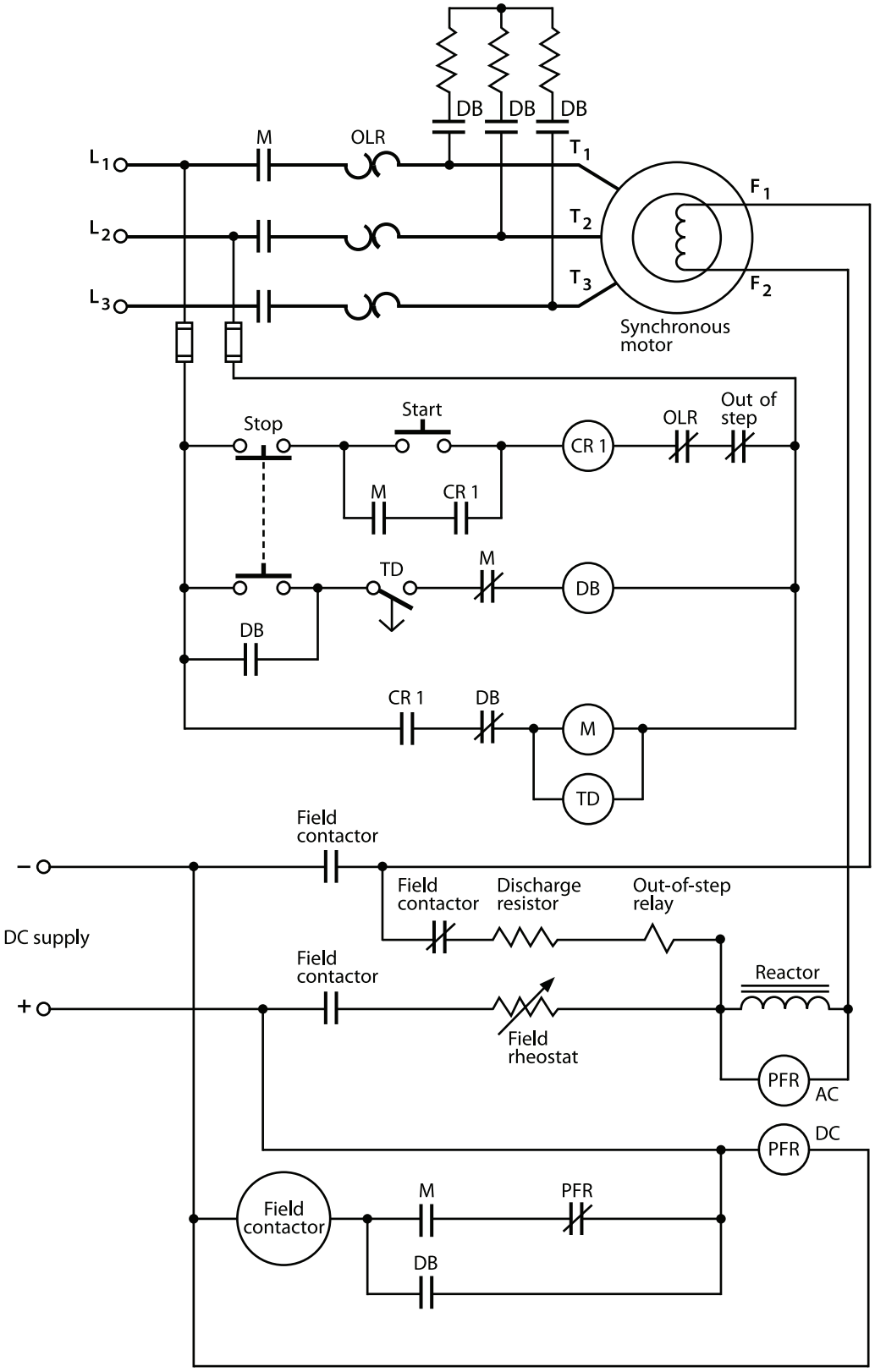


Figure 9—Synchronous motor controller with dynamic braking

Advantages of dynamic braking

Some of the advantages of dynamic braking over other methods of motor deceleration are:

- The control cannot reverse the motor if applied for too long.
- It gives smooth positive retardation.
- Braking torque is easily adjustable by varying the DC applied to the stator.
- There are no friction parts, so maintenance is minimal.

Disadvantages of dynamic braking

Some of the disadvantages of dynamic braking compared to other methods of motor deceleration are:

- DC excitation is required during braking.
- The braking is not available if the source voltage fails.
- The motor is free to rotate after stopping.
- Frequent stopping may cause motor overheating.

Regenerative braking

Regenerative braking is a method by which the motor is made to act like a generator and feed energy back into the system. It is used for retarding but not for completely stopping the motor. This type of braking occurs naturally where motors are being forced by the load to operate at higher than synchronous speed. This can occur in the lowering of hoists or in trains travelling downhill.

At higher than synchronous speed the motor still draws reactive power from the source but delivers active or true power back to the source. When it delivers true power back to the source, the current that flows creates a counter-torque in the motor that tends to try to slow the motor. The motor reaches rated power at about 3% slip above synchronous speed. Regeneration is an inherent property of motors.

Advantages of regenerative braking

The following are some of the advantages of regenerative braking over other methods of motor deceleration.

- Since regenerative braking is an inherent characteristic of the motor, no extra equipment is necessary.
- There are no friction parts, so maintenance is minimal.

Disadvantages of regenerative braking

The main disadvantage of regenerative braking compared to other methods of motor deceleration is that it is only effective at speeds above synchronous speed.

Eddy-current braking

Eddy-current braking is achieved by connecting an eddy-current brake to the shaft of the motor. It may be used to retard or to stop the motor.

Figure 10 is an illustration of how an eddy-current brake operates.

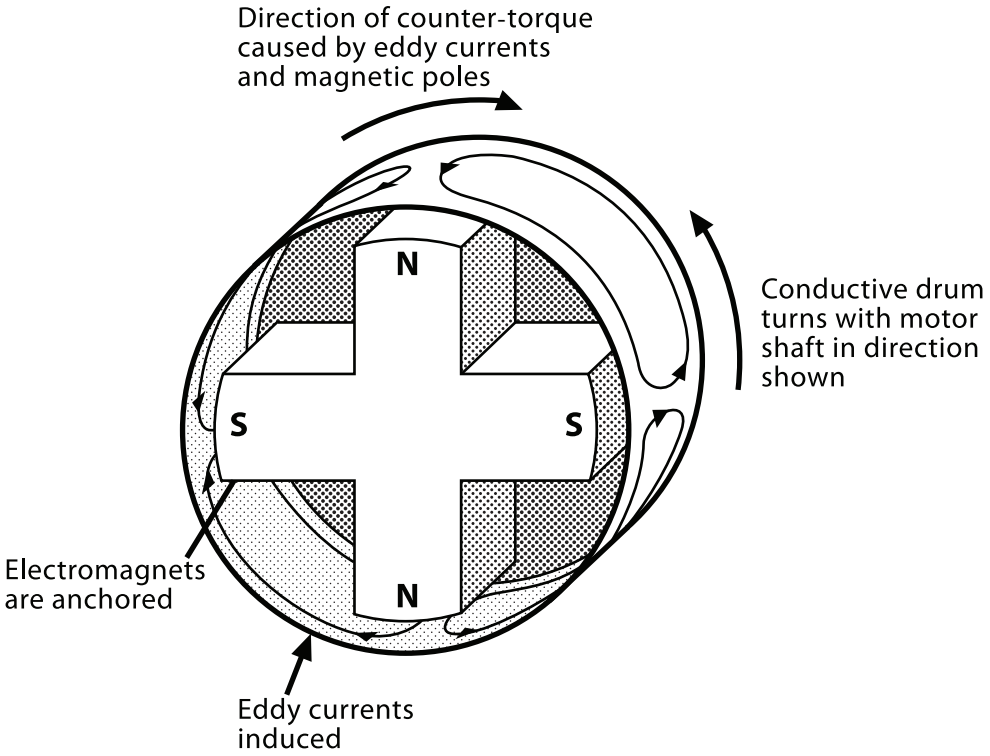


Figure 10—Eddy-current brake

Field poles are set up on a cylindrical core by DC flowing through turns of wire. The strength of these poles may be adjusted by varying the magnitude of the emf applied across the coils. The cylindrical core is anchored and cannot turn.

A conductive drum surrounds the electromagnets. This drum is attached to the motor shaft so that it turns at the same speed as the motor. As the drum moves past the magnetic poles, eddy currents are induced in the drum. The direction of these eddy currents may be determined using the left-hand generator rule. These eddy currents then react with the magnetic poles to produce a counter-torque. Applying the right-hand motor rule identifies that the counter-torque will be opposite to the rotation of the motor. This counter-torque tends to decelerate the motor.

The amount of braking action may be controlled by adjusting the DC through the electromagnets.

Advantages of eddy-current braking

Some of the advantages of eddy-current braking over other methods of motor deceleration are:

- The control cannot reverse the motor if applied for too long.
- Braking torque is easily adjusted by varying the voltage across the brake coils.
- There are no friction parts, so maintenance is minimal.

Disadvantages of eddy-current braking

Some of the disadvantages of eddy-current braking compared to other methods of motor deceleration are:

- It is more expensive than plugging, dynamic braking or regenerative braking.
- The braking is not available if the source voltage fails.
- The motor is free to rotate after stopping.
- The braking action drops off as the speed of the motor decreases.



Now do Self-Test 11 and check your answers.

Self-Test 11

1. List three types of friction brakes.

2. Are friction brakes normally electrically applied and spring-released?

3. Where are disk brakes normally mounted?

4. Explain what is meant by the term *plugging*.

5. Explain what is meant by the term *dynamic braking*.

6. Explain what is meant by the term *regenerative braking*.

7. Which type of brake is automatically applied if there is a system power failure?

8. Which type of braking is generally considered to be the fastest deceleration method?

9. State a disadvantage of friction-type brakes.

10. Which braking method requires a reversing controller?

11. What is the main disadvantage of using the time-delay relay circuit for plugging compared to the zero-speed switch method?

12. When using dynamic braking on a squirrel-cage induction motor, how can the braking torque be adjusted?

13. When using dynamic braking, what can happen when there are too-frequent stops and starts?

14. What is the essential difference between regenerative braking and dynamic braking when comparing energy conversion?

15. When using eddy-current braking, how is the braking torque adjusted?

16. Which of the braking methods is considered to be the most expensive?

Questions 17 to 19 refer to Figure 1 (next page).

17. What is the purpose of the NC contact M in series with the DB coil?

18. What happens to the time-delay contact TD when the stop push-button is pressed?

19. What is the purpose of the rheostat in series with the bridge rectifier?

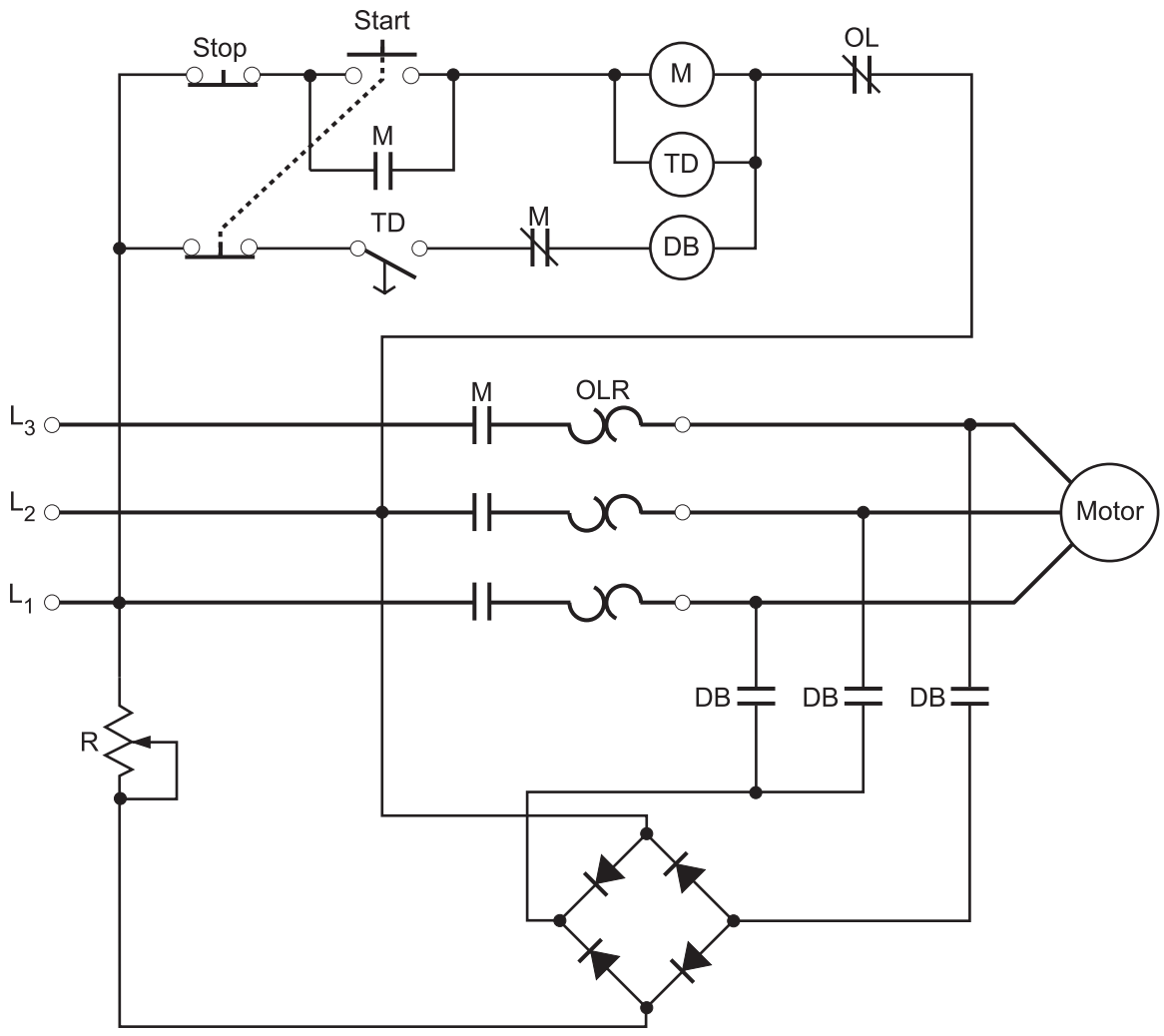


Figure 1—Dynamic braking of a squirrel-cage induction motor

Questions 20 to 22 refer to Figure 2 (next page).

20. Of the three timers, TD_1, TD_2 and TD_3, which are on-delay relays and which are off-delay relays?

21. What is the purpose of the NO contact DB in series with coil S_2?

22. What finally releases the dynamic braking?

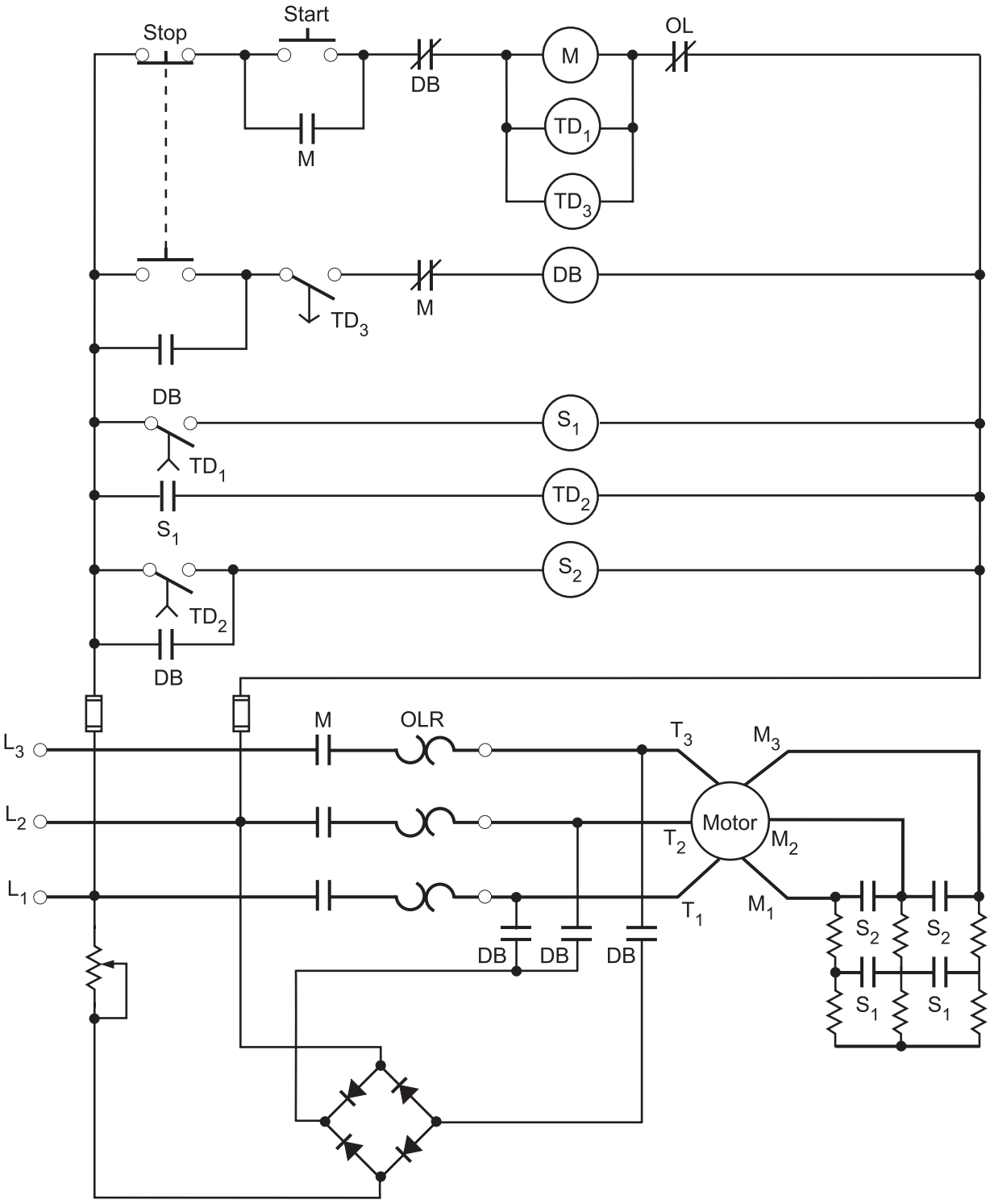

Stop
Start
DB
M
OL
M
TD1
TD3
DB
TD3
M
DB
TD1
S1
TD2
S1
S2
TD2
DB
L3
L2
L1
M
OLR
T3
M3
Motor
T2
M2
T1
M1
DB
DB
DB
S2
S2
S1
S1

Figure 2

Questions 23 to 25 refer to Figure 3.

23. Will dynamic braking occur if the stop button is pressed and then immediately released?

24. What advantage does the dynamic braking in this circuit have over the circuit in Figure 2?

25. When the motor is started, the full resistance is inserted in the secondary circuit and then slowly removed as the motor accelerates. When the motor is braked, is the resistance slowly reinserted in the secondary circuit as the motor decelerates?

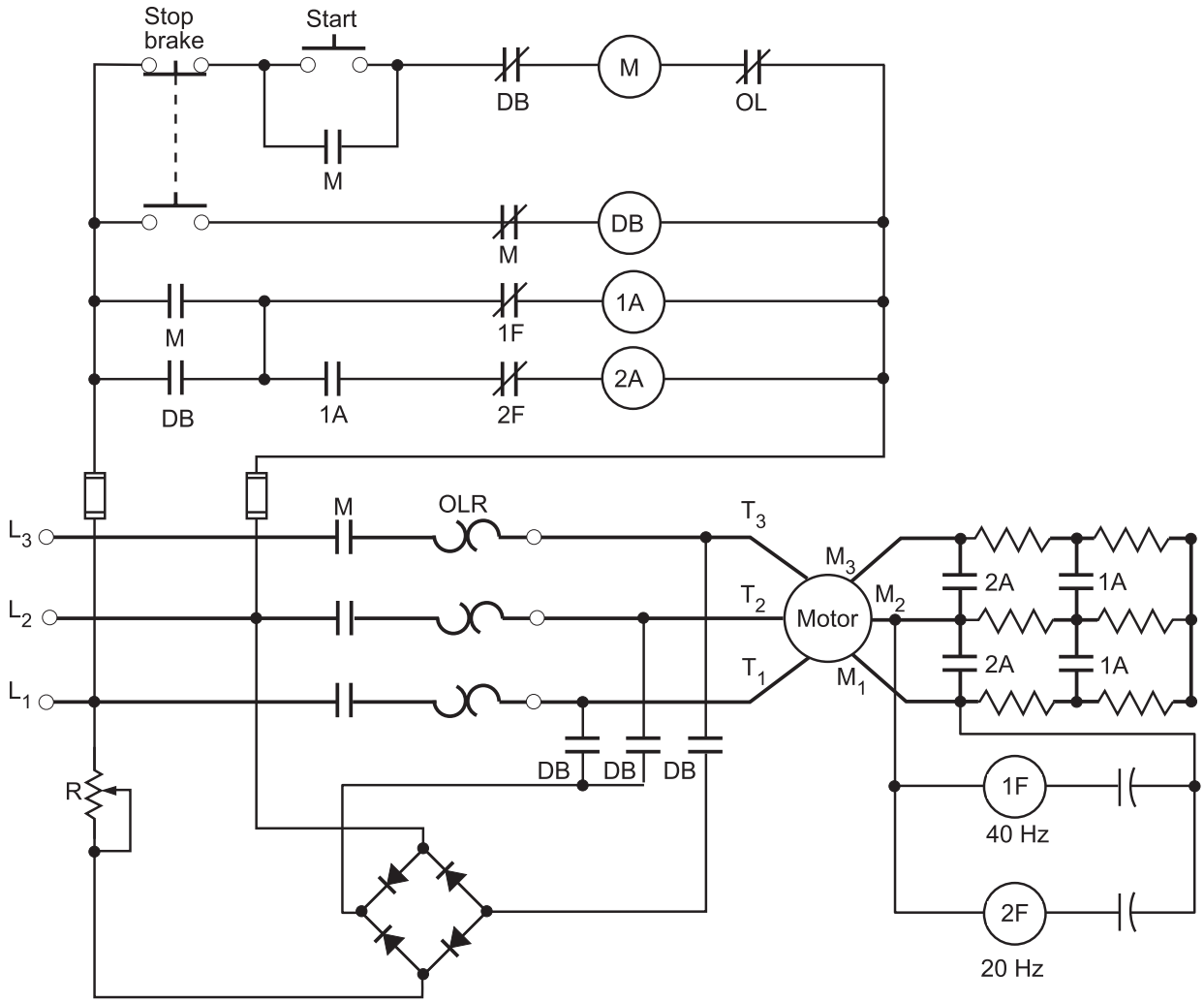


Figure 3

Questions 26 to 28 refer to Figure 4 (next page).

26. Will dynamic braking occur if the stop button is pressed for two seconds and then released?

27. What is the purpose of the TD relay?

28. What is the purpose of the DB contact in series with the field contactor?

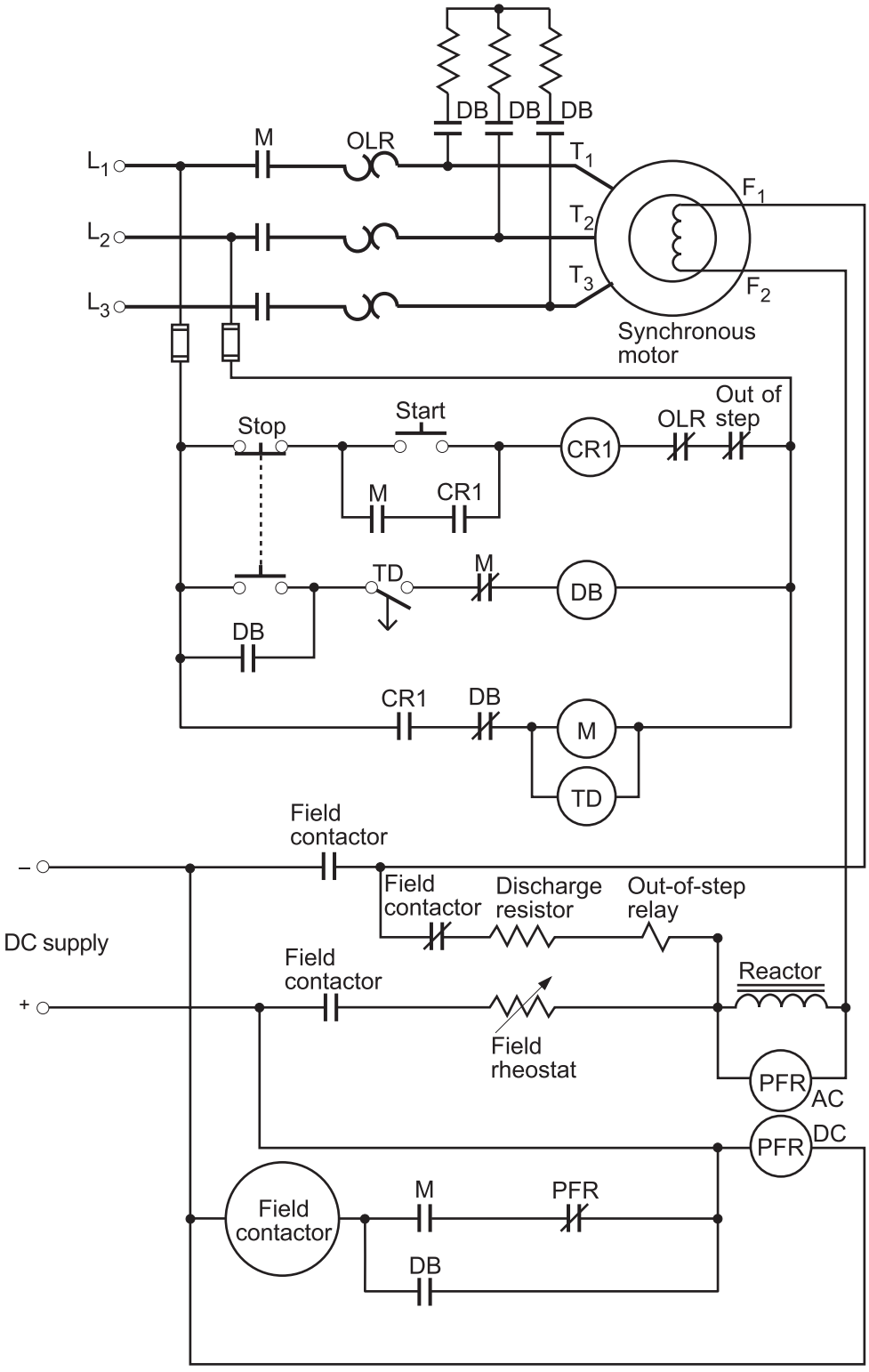


Figure 4

Go to the Answer Key at the end of the Learning Guide to check your answers.

Answer Key

Self-Test 1

1. Any two of the following: simple control; low component cost; maximum starting torque; minimum acceleration time for motor

2. Any two of the following: reduced inrush current on starting; reduced torque on starting; less disturbance (line drop) to the power system

3. Any three of the following: primary impedance starters; autotransformer starters; wye-delta starters; part-winding starters; solid-state starters

4. For open-transition starters, there is a momentary loss of voltage (power) to the motor as the control transfers from the starting to the running stage. But for closed-transition operation, there is no interruption of voltage.

5. a. $T = \left(\frac{346\ V}{600\ V}\right)^2 \times 300\%\ FLT$

$= 0.333 \times 300\%\ FLT$

$= 100\%\ FLT$

FLT = full-load torque value

b. $I = \frac{346\ V}{600\ V} \times 600\%\ FLA$

$= 0.577 \times 600\%\ FLA$

$= 346\%\ FLA$

FLA = 3.46 × full-load amperes

6. No. If the voltage is reduced for starting, then the torque is also reduced (in fact, it is proportional to the square of the voltage). If the motor will not start with full voltage, it definitely will not start at reduced voltage, with the same load requirement.

7. Because frequent (repetitive) operation under large starting inrush conditions will greatly shorten the life of the contacts.

8. intermittent duty (See the Electrical Code section on definitions.)

9. permissible voltage fluctuations (disturbance) to the power distribution system

Self-Test 2

1. b. closed transition

2. • For high-voltage/high-current motors
   • Where heating or physical construction of the resistors creates a problem

3. It worsens the already poor (lagging) power factor of induction motor circuits.

4. a. $I_S = 0.8 \times 80$ A

   $= 64$ A

   b. $T \alpha E^2$

   $T = (0.8)^2$

   $= 0.64$

   $= 64\%$ of the full voltage starting value

5. by adding additional resistors in series, each with an accelerating contactor

Self-Test 3

1. 50%, 65% and 80% of the full-line voltage rating

2. compensator

3. a. *Intermittent duty* means a requirement of service that demands operation for specified alternate intervals of load and no-load, load and rest, or load, no-load and rest. See definitions in CEC Section 0.

   b. Thermal (high-limit) switches equipped with heat sensors

4. three transformers connected in wye; or two transformers connected in open-delta

5. c. 1S closes; 2S closes; 1S opens; R closes; 2S opens

6. For all other starters the line current and the motor current are the same value. In the autotransformer starter, the line current (primary) is a further reduction of the motor current (secondary) through transformer action.

7. a. Since torque is proportional to E^2, the starting torque calculates as:

$$T = (0.65)^2 \times 300\% \text{ full load}$$

$$= 0.4225 \times 300\% \text{ full load}$$

$$= 126.75\% \text{ full load}$$

b. Since the motor voltage is reduced to 65% of normal, the motor-starting current is also reduced to 65% of normal.

$$I_M = 0.65 \times 400 \text{ A}$$

$$= 260 \text{ A}$$

Using the turns-ratio of the autotransformer, the primary line current is further reduced by 65%. The line current is therefore:

$$I_L = 0.65 \times 260 \text{ A}$$

$$= 169 \text{ A}$$

Self-Test 4

1. No. The motor connection box used must allow access to both ends of each phase winding external to the enclosure, since the wye-delta starter starts the motor in a wye connection and switches the windings to a delta connection for running (i.e., six- or 12-lead motor).

2. a. $I_S = \frac{1}{3} \times 400\% \text{ FLA}$

$$= 133\% \text{ FLA}$$

b. $T_S = \frac{1}{3} \times 150\% \text{ FLT}$

$$= 50\% \text{ FLT}$$

3. a. 120 V

b. 26 A

c. 15 A

4. b. 1S closes; 1M closes; 2S closes; 1S opens; 2M closes; 2S opens

5. an additional three-pole starting contactor and three power resistors

6. $I_P = 42 \text{ A} \div \sqrt{3}$

$$= 24.25 \text{ A}$$

7. six

Self-Test 5

1. Keep it clean. Keep it dry. Keep it tight. Keep it friction-free.

2. Check for signs of overheating and loose connections.

3. a. The motor starts with reduced voltage across its terminals and accelerates and runs until the operator releases the start push-button. It will then stop. (No seal-in circuit)

   b. The motor starts as normal, but runs at reduced speed. (The accelerating 1A contacts will not close after the predetermined time delay, and full voltage will not appear across the motor.) If it is heavily loaded, the OLR may trip.

4. tachometer

Self-Test 6

1. With resistance in the secondary circuit, the starting torque is increased and the starting current is reduced.

2. to produce a smoother accelerating torque

3. They decrease.

4. a drum controller

5. Definite-time starters automatically remove the resistance in steps at the same time intervals each time the motor is started.

6. Time-delay relays are normally used to provide the definite-time steps for removal of the secondary resistance.

7. It is not sensitive to the requirements of the load. Under heavy loads, the resistance may be removed too quickly. Under light loads, the resistance may be removed too slowly.

8. Automatic, speed-sensing acceleration is a means of automatically sensing the speed of the rotor in order to determine the proper time for removal of resistance from the secondary winding.

9. by using frequency-sensing relays

10. by interchanging any two of the line leads to the stator

11. No. To reverse the direction of rotation of the motor, you must reverse the direction of rotation of the stator field.

12. With a wound-rotor motor-speed regulator, some of the secondary resistance may be left in the secondary circuit to control the speed of the motor. The resistors used with a speed regulator would have to have a higher wattage rating than those used in a starter.

13. The flat slope of the torque-versus-speed curve means that a small change in torque output of the motor requires a large change in speed.

14. The efficiency of a regeneration type of controller is much higher than that of one that utilizes secondary resistors.

15. A controller using regeneration is generally more accurate because it constantly compares the set speed to the actual speed and adjusts itself to bring the two together.

Self-Test 7

1.
   - Keep the controls clean.
   - Keep the controls dry.
   - Keep mechanical parts and electrical connections tight.
   - Keep moving parts free of excessive friction.

2. sight, hearing, touch and smell

3.
   - Opens
   - Shorts
   - Grounds
   - High resistances

4. schematic diagram

5. The schematic diagram shows only the electrical relationship and is useful in explaining the operation of the circuit. The wiring diagram shows electrical as well as physical relationships between electrical components. The wiring diagram is useful in locating components and connections.

6. See Table 1, points 1 and 2.

7. See Table 1, point 8.

8. See Table 1, points 3B and 3C.

9. See Table 1, points 5 and 7.

10. The voltage drops will only occur when current is flowing through the circuit.

Self-Test 8

1. The amortisseur winding will overheat.

2. the out-of-step relay

3. The field discharge resistor protects the rotor field from having high voltages induced in it when the motor is running at lower than synchronous speed.

4. The field contactor has a positive overlap between the NO contacts and the NC contact, which a standard contactor does not have. That is, when the contactor pulls in, the NO contacts close before the NC contact opens. When the contactor drops out, the NC contact closes before the NO contacts open.

5. polarized field frequency relay

6.
   - It monitors the rotor speed so that it can time the application of the DC rotor field current to somewhere between 92% and 97% of synchronous speed.
   - It times the application of the DC excitation so that it will create a magnetic field in the rotor circuit that will reach full strength when two opposite poles are aligned with each other.
   - It disconnects the DC field excitation if an overload or voltage dip causes the motor speed to drop, and reapplies it if the speed returns to within synchronizing speed before the out-of-step relay opens its contacts.

7. It senses the speed of the rotor.

8. It times the application of the rotor field excitation so the field reaches full strength when opposite poles (rotor and stator) are adjacent.

9. It produces a voltage drop when alternating current is flowing in the rotor circuit. This voltage drop is necessary so the AC coil of the PFR can sense the AC in the circuit.

10. It controls the DC through the rotor field. The power factor of the motor may be varied by adjusting the excitation current in the rotor field.

11. The current through the rotor field will be increased, causing the power factor of the motor to become more leading (or less lagging).

Self-Test 9

1. The out-of-step relay is a timer relay that starts to time out whenever the rotor is turning slower than synchronous speed. If the relay times out, it opens a contact in the control circuit, which causes the line contactor to drop out and the motor to stop.

2. When the motor is first started, or anytime the rotor turns at lower than synchronous speed, the PFR pulls in, opening the NC contact. This prevents the DC field from being applied to the rotor.

3. They decrease.

4. It is normally applied somewhere between 92% and 97% of synchronous speed. The actual percentage depends on the load applied to the motor.

5. At synchronous speed, the relative speed between the rotating stator field and the amortisseur winding is zero. Therefore no voltage is induced in the amortisseur winding.

6. The amortisseur winding is not designed to carry current for long periods of time. The amortisseur winding requires time to cool before restarting.

7. The resistance of the field rheostat must be reduced to allow more excitation current to flow through the rotor field winding.

8. b. The NO contacts that apply the DC excitation to the field close.

9. a. The NC contact in series with the field discharge resistor closes.

10. The positive overlap ensures that the field will never be open-circuited. An open circuit in the field circuit can cause a high voltage to be induced in the DC windings of the rotor field.

Self-Test 10

1.
   - Check sequence of operation of control relays.
   - Check relay contacts for sparking on operation.
   - Check contactors for flash when closing; if there is a flash, adjust to eliminate contact bounce.
   - Check limit switches, pressure switches, temperature switches, and so on.

2. High resistances are not always easy to detect with an ohmmeter. Often, it is much better to try to locate a high resistance by measuring voltage drops throughout the circuit while it is loaded.

3. The purpose of the out-of-step relay is to protect the amortisseur winding. If the motor is started under heavy load, the amortisseur winding may be damaged by the prolonged inrush current if the out of step relay fails to open the circuit.

4. After you have locked everything out, try the controls so you are sure the lockout procedure has been done properly.

5. by adding or removing non-magnetic shims from the face of the PFR stator core

6. to prevent the armature from sealing against the stator core (due to residual magnetism)

7. the highest practical speed for the application

8. The PFR should be checked for a sticky mechanism or too large an air gap.

9. This indicates the proper DC polarity on the PFR.

10. dashpot timers

Self-Test 11

1. drum, disk and band brakes

2. No. Friction brakes are normally spring-applied and electrically released.

3. A disk brake is normally mounted on the end bell of the motor.

4. Plugging is a control function that provides braking by reversing the motor line voltage polarity or phase sequence so that the motor develops a counter-torque that exerts a retarding force.

5. Dynamic braking is a method of retarding the motor speed or completely stopping the motor by making it act as a generator to supply a resistive load.

6. Regenerative braking is a method by which the motor is made to act like a generator and feed energy back into the system.

7. spring-applied type of friction brake

8. plugging

9. Any of the following: The friction parts require periodic maintenance and replacement; the brakes tend to be bulky; the initial cost of the brake is high.

10. plugging

11. The time-delay plugging circuit cannot sense the actual speed of the motor shaft. Therefore, any change in motor load would require a different setting on the time-delay relay.

12. by varying the DC applied to the stator

13. The motor can overheat.

14. Regenerative braking delivers true power back to the electrical supply (recovers braking energy), whereas dynamic braking expends most of the braking energy as heat dissipation in resistors, etc.

15. by varying the DC to the electromagnetic coils of the eddy-current brake

16. the eddy-current brake

17. It prevents the dynamic braking from being applied before the line contacts open.

18. After the TD relay has timed out, the contacts will open, releasing the dynamic braking.

19. It controls the degree of braking by controlling the current through the stator coils.

20. TD_1 and TD_2 are on-delay relays. TD_3 is an off-delay relay.

21. This contact energizes the S_2 contactor, causing the S_2 contacts in the secondary circuit to short-circuit the rotor resistance during braking.

22. The dynamic braking is released by the opening of the TD_3 time-delay contacts.

23. No. The dynamic braking in this circuit will only occur while the stop button is held depressed.

24. This circuit will brake faster than the circuit in Figure 2 because the resistance in the rotor circuit is varied during braking.

25. No. When the motor is stopped, the full resistance is inserted in the rotor circuit and then removed in steps as the motor decelerates.

26. Yes. The DB contacts in parallel with the NO contacts of the stop push-button will seal in and maintain the circuit.

27. The TD relay releases the dynamic braking after a period of time.

28. It maintains the DC to the rotor field during dynamic braking.



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