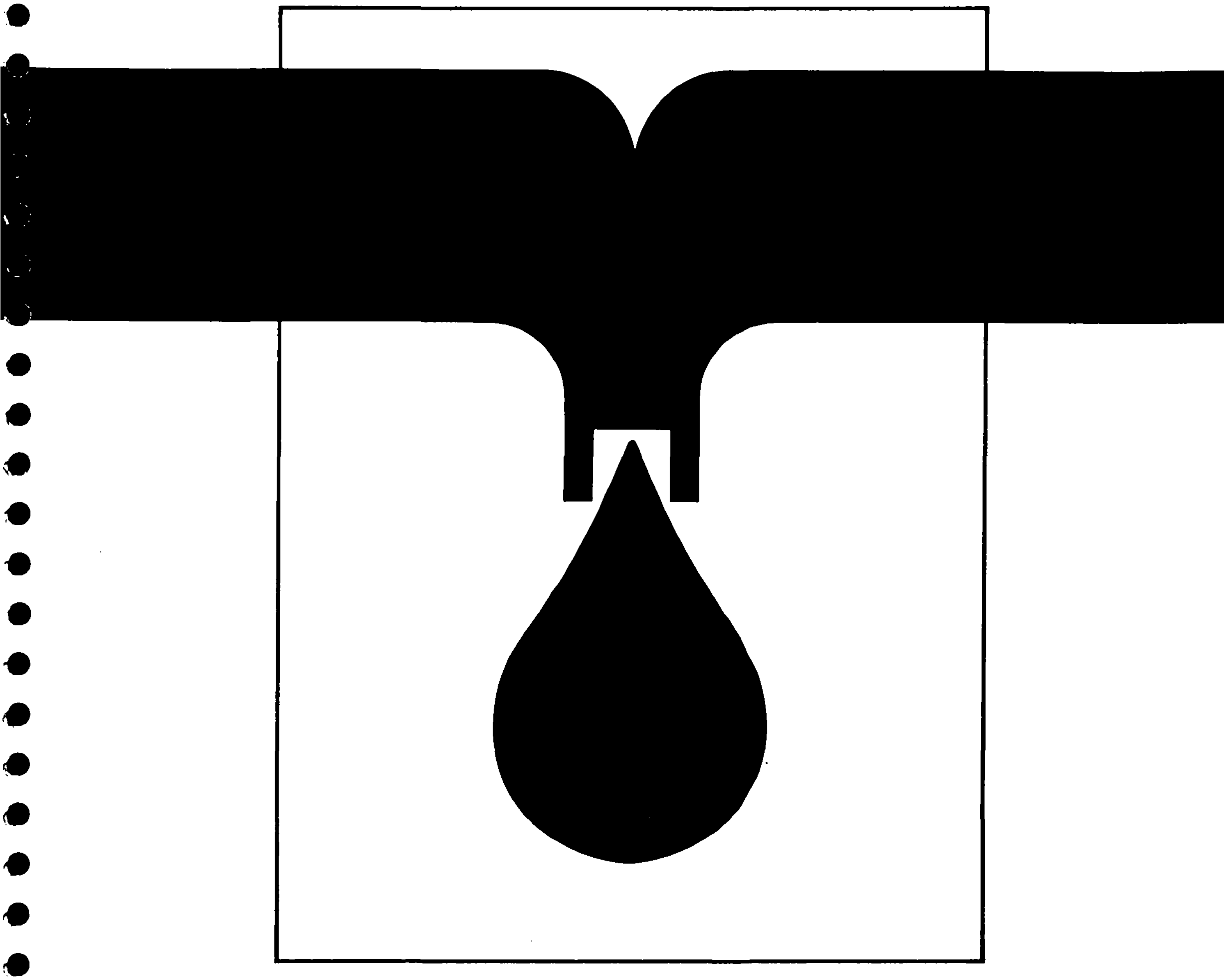
TRAINING MODULES FOR WATERWORKS PERSONNEL



Special Knowledge

2.3 i

Maintenance and repair
of electrical motor controls and protective equipment

Foreword

Even the greatest optimists are no longer sure that the goals of the UN "International Drinking Water Supply and Sanitation Decade", set in 1977 in Mar del Plata, can be achieved by 1990. High population growth in the Third World combined with stagnating financial and personnel resources have led to modifications to the strategies in cooperation with developing countries. A reorientation process has commenced which can be characterized by the following catchwords:

- use of appropriate, simple and – if possible – low-cost technologies,
- lowering of excessively high water-supply and disposal standards,
- priority to optimal operation and maintenance, rather than new investments,
- emphasis on institution-building and human resources development.

Our training modules are an effort to translate the last two strategies into practice. Experience has shown that a standardized training system for waterworks personnel in developing countries does not meet our partners' varying individual needs. But to prepare specific documents for each new project or compile them anew from existing materials on hand cannot be justified from the economic viewpoint. We have therefore opted for a flexible system of training modules which can be combined to suit the situation and needs of the target group in each case, and thus put existing personnel in a position to optimally maintain and operate the plant.

The modules will primarily be used as guidelines and basic training aids by GTZ staff and GTZ consultants in institution-building and operation and maintenance projects. In the medium term, however, they could be used by local instructors, trainers, plant managers and operating personnel in their daily work, as check lists and working instructions.

45 modules are presently available, each covering subject-specific knowledge and skills required in individual areas of waterworks operations, preventive maintenance and repair. Different combinations of modules will be required for classroom work, exercises, and practical application, to suit in each case the type of project, size of plant and the previous qualifications and practical experience of potential users.

Practical day-to-day use will of course generate hints on how to supplement or modify the texts. In other words: this edition is by no means a finalized version. We hope to receive your critical comments on the modules so that they can be optimized over the course of time.

Our grateful thanks are due to

Prof. Dr.-Ing. H. P. Haug
and
Ing.-Grad. H. Hack

for their committed coordination work and also to the following co-authors for preparing the modules:

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It is my sincere wish that these training modules will be put to successful use and will thus support world-wide efforts in improving water supply and raising living standards.

Dr. Ing. Klaus Erbel
Head of Division
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Eschborn, May 1987

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1 Motor Controls - Alternating Current

1.1 Introduction

The five major functions of a motor-control system are:

- Start and stop the motor.
- Protect personnel, motor, and control equipment.
- Govern motor speed, torque, horsepower and other characteristics.
- Maintain proper sequencing of motors, equipment and operations.
- Sense and correct errors in operation of a motor or process.

The first three functions are provided by the basic units in the block diagram shown in Fig. 1 for a simple control system. How these functions are obtained and what kind of equipment is being used will be covered in this chapter.

Unit 1 in the diagram protects the motor from starting or running under overcurrent conditions which could cause overheating and damage to the windings.

Unit 2 starts and stops the motor and also provides the desired operating characteristics of the drive. Usually units 1 and 2 are combined.

Unit 3 protects the branch circuit, motor and associated control from short circuits.

Unit 4 permits the entire branch circuit to be deenergized and disconnected from the power supply. It can be a seperate unit or be combined with unit 3.

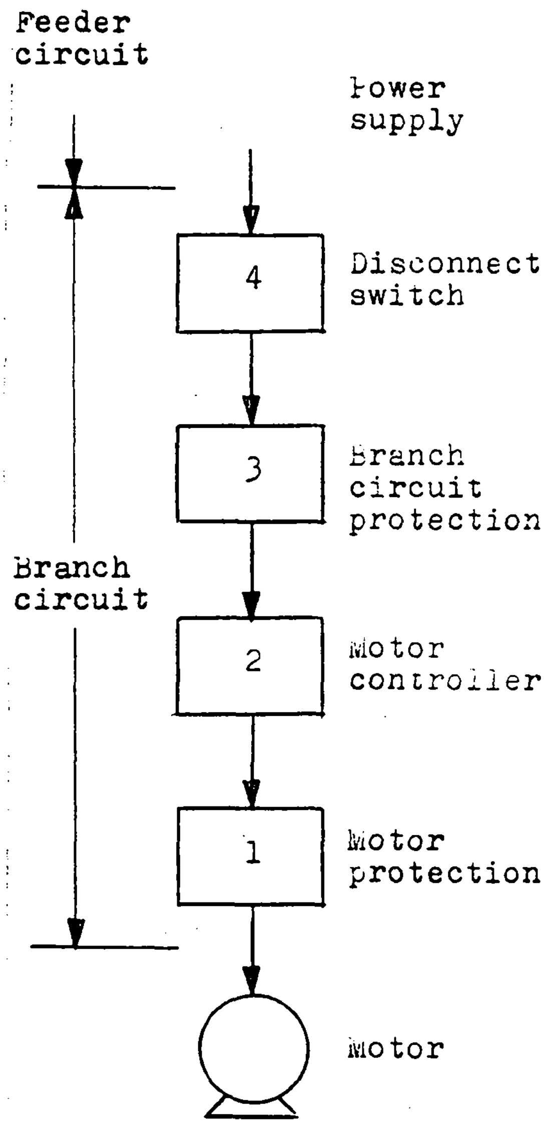


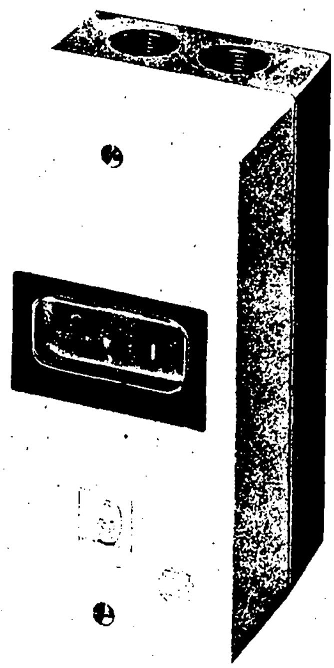
Fig. 1
Block diagram of typical motor branch circuit.

1.2 Squirrel-Cage Motor Starters - Across-the-Line.

Controls for single speed drives are available in several basic types of starters namely manual, magnetic, combination and reversing starters. As indicated by the term "across-the-line", these starters are designed to apply full line voltage directly to the motor windings.

Controls for simple small motor applications consist normally of manual type starters Fig. 2. The motor being small, involves no special operating characteristics or power supply problem such as heavy starting current. Special situations such as reversing, multi-speeds, duty cycling, remote control are not encountered. Also because of the nature of the machine, there is no necessity for frequent starting and stopping.

a) Manual Starters: The manual starter is simply a hand operated contact or switch mechanism that makes or breaks the motor electric circuit. A thermal protective device included in the starter automatically guards the motor against excessive currents due to overloads. A magnetic tripping device can be provided to insure rapid operation of the manual starter in case of a short circuit, Fig. 3b.



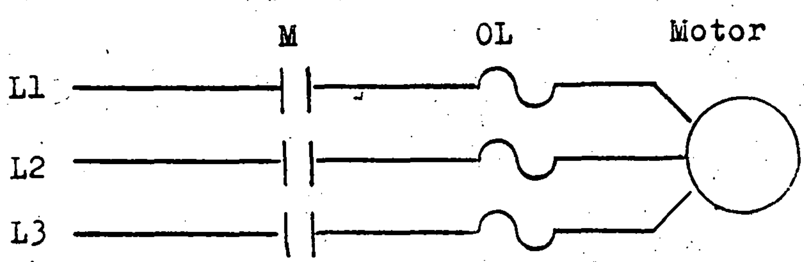


Fig. 2
Typical manual starter and representative circuit application.

The thermal protective device which is normally an integral part of all motor starters is designated by the symbol "OL" (overload-relay) on the circuit diagrams. It consists of two to three heaters in series with the motor circuit to be protected, above these heaters are strips of bimetallic material, which act as latches for the contact members. Bending of the bimetallic strips under heating of overload current will release the latches and allow the contacts to open.

Characteristics of a typical thermal-overload-relay are shown in Fig. 3a. It has the tripping characteristic which corresponds closely to the heating characteristics of a motor, and therefore provides an ideal protective means.

Resetting of the thermal-overload-relay may be accomplished either manually or automatically. Manual reset requires the operator to go to the starting panel and thus assures inspection of the machine and correction of the trouble which caused the overload. Automatic reset relays are arranged so that their contacts reclose automatically a short time after the relay has tripped.

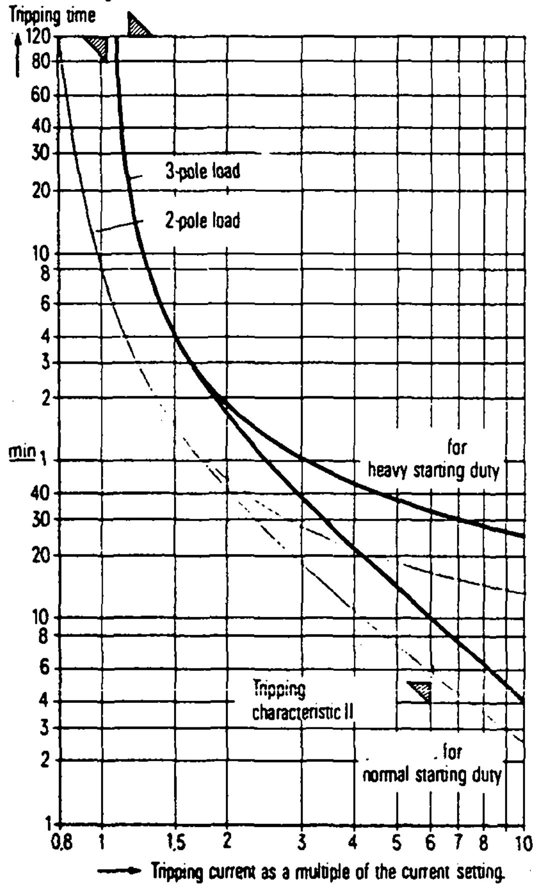


Fig. 3a
Characteristics of a thermal overload relay for motor overload protection.

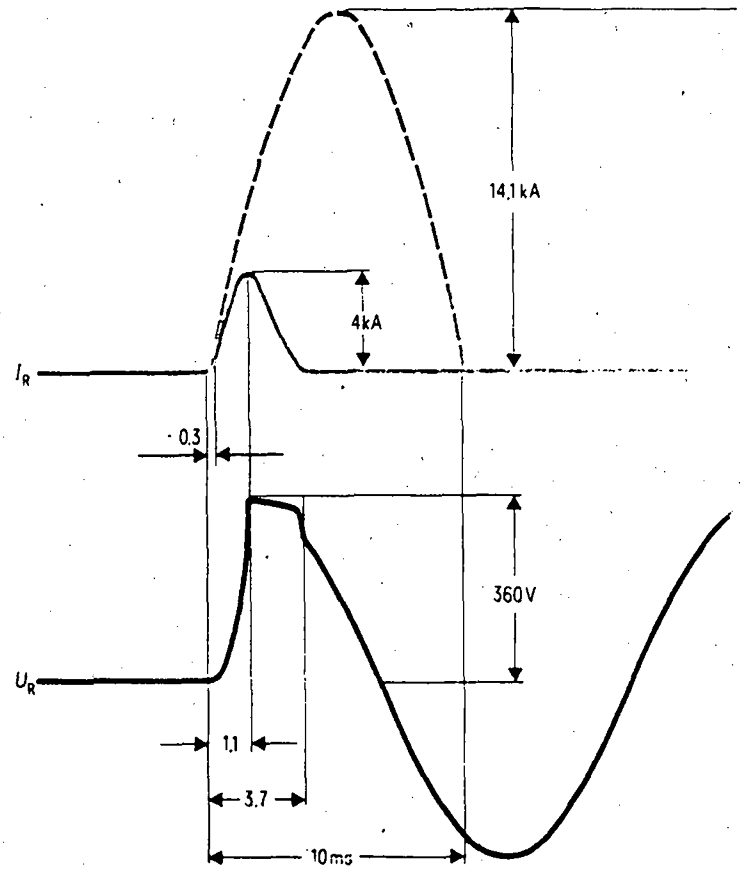


Fig. 3b
Clearing time of manual starter with current limiting feature to prevent high short circuit currents, thereby limiting high thermal and dynamic stresses.

b) Magnetic Starters: The magnetic starter is the most desirable alternative to the manual starter. The magnetic starter (Fig.4) can be used to control squirrel cage motors in many different ways, including provisions for overvoltage or undervoltage protection. In addition it is capable of withstanding frequent, hard use.

The design of a magnetic starter is quite simple in principle. Like the manual starter, it contains a mechanism for opening and closing a set of contacts in the motor circuit and a thermal overload protective device or devices. However, while the contact mechanism of a manual starter is actuated by an operator, contacts of a magnetic starter are operated by an electric signal from some control device such as a push-button.

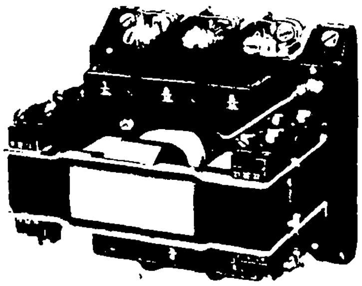
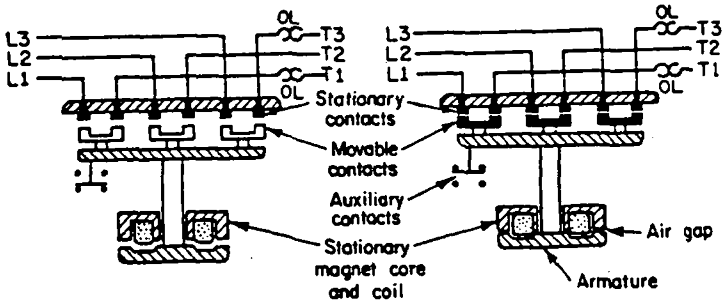


Fig. 4
Typical magnetic starter and cross-sections of contactor and magnet assembly.



(a)—Coil de-energized, main contacts open.

(b)—Coil-energized, main contacts closed.

As shown in Fig. 4, the mechanism of a magnetic starter consists of two sets of main contacts (stationary and movable) and a magnet structure. The magnet structure includes a stationary magnetic core, a coil that fits on the core and an armature.

When the contactor coil is energized, a magnetic flux is established. This flux concentrated in the iron core, draws the armature against the stationary magnetic core. Since the movable contacts are fastened to the armature, they also move toward the stationary contacts, thereby closing the circuit to the motor through appropriate thermal overload devices.

When the coil is deenergized, the weight of the armature or the tension of a built-in spring will drop the armature and open the contacts in the motor circuit. A slight air gap is maintained between the magnet core and armature in the closed position to prevent residual magnetism from holding the armature closed when the coil is deenergized.

Circuit application of a magnetic starter is illustrated in Fig. 5. Low voltage release is provided by a maintained contact push-button. When the start button is pressed to complete the control circuit, the starter coil is energized and closes the main contactor in the motor circuit. If a low voltage condition occurs in the power supply, the magnetic strength of the coil is sufficiently weakened to permit the contacts to open and stop the motor. When the voltage returns to the proper value and since the push-button contacts remain closed, the coil again closes the main contacts in the power circuit.

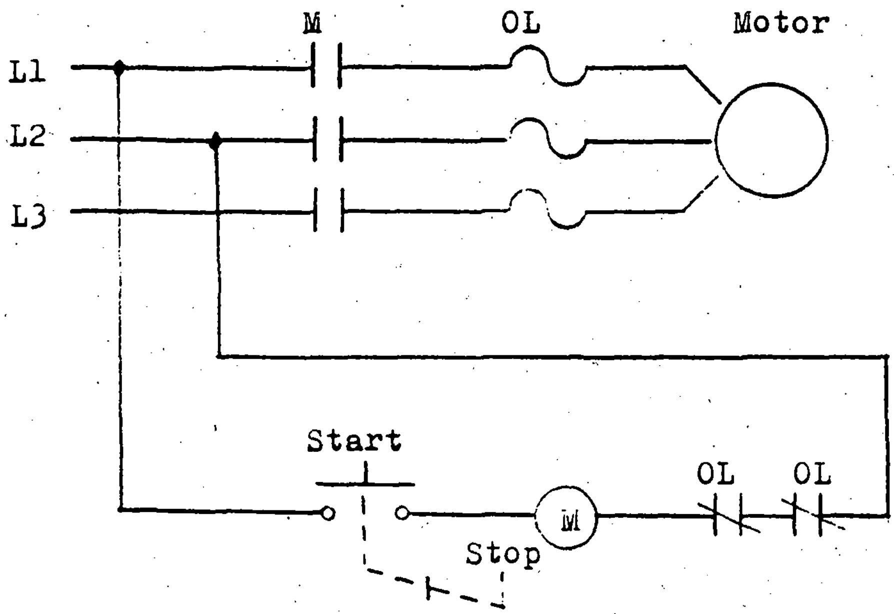


Fig. 5
Circuit diagram of across-the-line magn. starter and maintained contact push-button for providing low voltage release.

There are some isolated applications where low voltage release is desirable but most of the time it is not desirable because it threatens the safety of operating personnel. If a pump for instance were to stop because of low voltage and the operator began to troubleshoot the difficulty without remembering to press the stop button, he could be inj red if voltage returned to normal. To eliminate this danger, another method of motor control is employed.

A momentary contact push-button is used in combination with a set of normally open auxiliary contacts in the starter (Fig. 6). When the start push-button is pressed, the control circuit is energized and causes the starters main and auxiliary contacts to close, when the start button is released an its contacts open, the starter auxiliary contact, which is wired in parallel continues to maintain the circuit. Consequently, the circuit containing the auxiliary contact is commonly refered to as the "holding circuit".

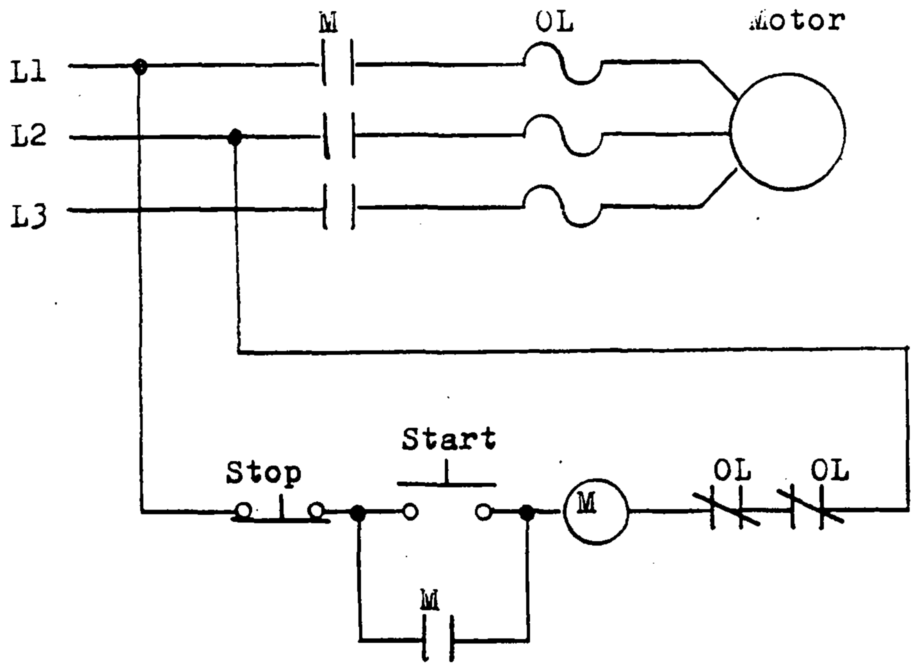
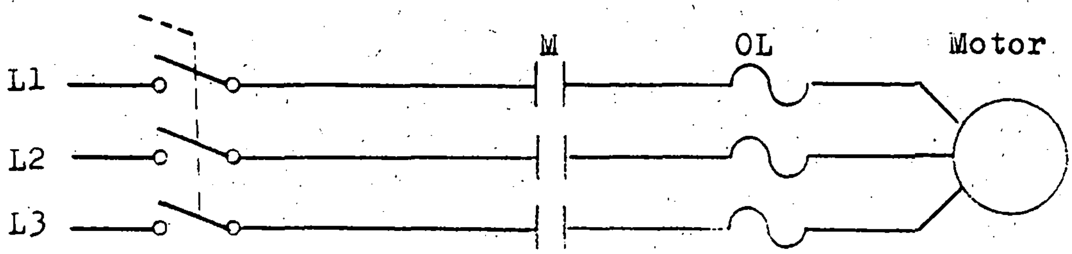


Fig. 6
Circuit diagram of across-the-line starter and momentary-contact push-button for providing low voltage protection.

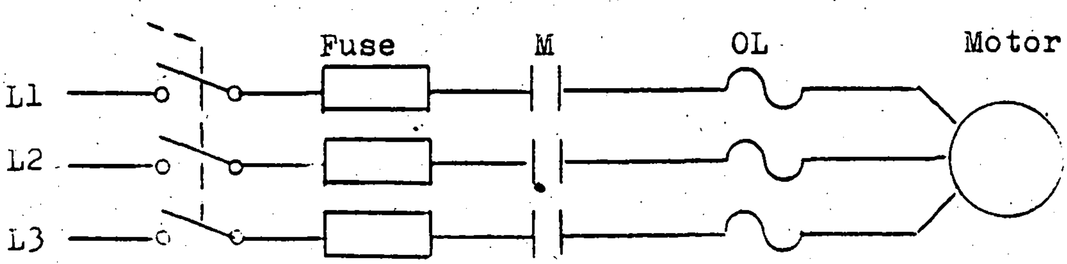
Power interruption or reduced voltage will deenergize the coil in Fig. 6, thus dropping the contactor out and opening the holding-circuit. When power is restored, the motor cannot restart automatically. The start button must again be pressed. The safety feature provided by this arrangement is called "low voltage protection" and is one of the advantages of magnetic control.

Flexible control is another feature of the magnetic starter. A push-button for energizing starter coil can be located any distance from the starter. Also the use of several push-buttons can provide multiple-location operation of the same starter and motor. Instead of a push-button, a limit switch, relay, pressure switch, level indicators or float switches can be used to provide automatic operation in addition to remote control (see also module 0.5 section 5).

c) Combination Magnetic Starter/Disconnect Switch: As illustrated in Fig. 1, a complete basic motor-control system includes: 1-motor protection. 2-Motor controller. 3-Branch circuit protection. 4-branch disconnect switch. A magnetic starter normally consists of a magnetic contactor and an overload relay, thus combining items 1 and 2. If a branch disconnect switch is added to a basic starter, the entire package is called "Combination starter/disconnect". If item 3 is also included, the result is called a "Combination starter fused-disconnect". Power circuits of these combinations are shown in Fig. 7. The control circuit, of course, is unaffected.



Circuit for combination starter with disconnect switch.

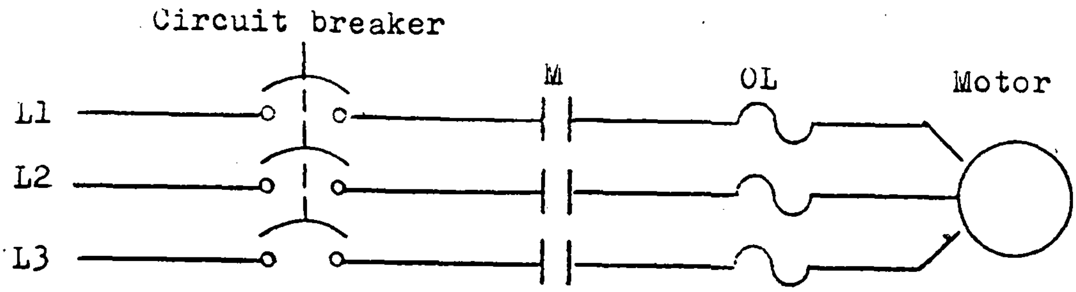


Circuit for combination starter with fused disconnect swith

Fig. 7

d) Combination Magnetic Starter/Circuit Breaker: A circuit breaker provides both, branch circuit protection and branch circuit disconnect in a single package as shown in Fig. 8. If a predetermined, abnormal current develops in the circuit, the device will automatically trip without damaging itself and open the circuit. This non-destructive feature is its main advantage, for it can easily be reset without the nuisance of replacing the fuse.

Circuit breakers are generally selected on the basis of a continuous current rating of not less than 115%, and a thermal trip element rating of approximately 250% of full load motor current.



Circuit for combination starter with circuit breaker

Fig. 8

Ordinarily, each breaker contains two types of trip mechanisms. One is the thermal trip which has a time lag characteristic to provide protection against persistant overloads of comparatively small values. The other mechanism provides protection against short circuit currents through an instantaneous magnetic tripping device which opens the circuit instantly in the event of high value overcurrents. The magnetic tripping device is usually adjustable.

e) Three Phase Reversing Starters: One of the basic characteristics of squirrel cage motors is, that the direction of rotation can be changed by reversing any two incoming power leads. On small motors this can be done with a three-pole double-throw knife switch, Fig. 9. The third pole is used for disconnecting purposes only.

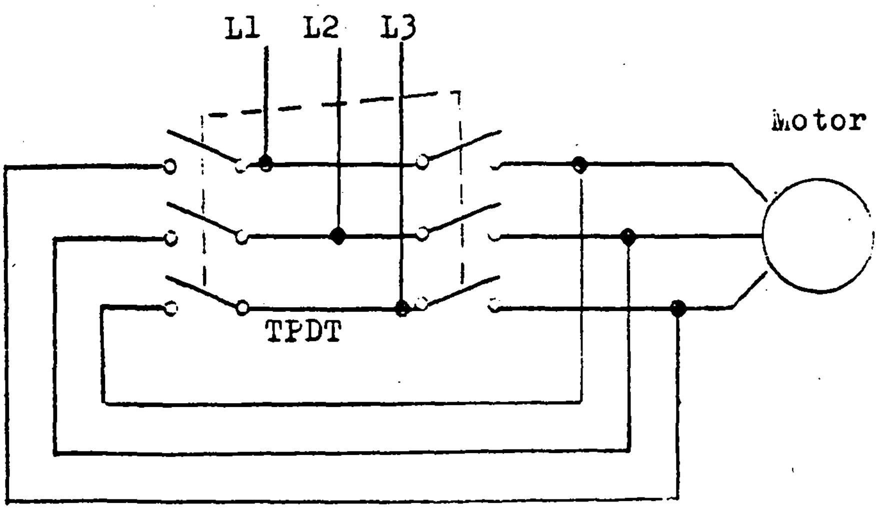


Fig. 9
Three-pole double-throw knife switch used for reversing rotation of squirrel cage, three phase motor.

Reversing motor rotation can also be accomplished with a standard magnetic starter plus a contactor with the proper electrical and mechanical interlocks, Fig. 10. The interlocking feature prevents both sets of contacts from being closed at the same time - even for an instant - so that there is no possibility of short circuits.

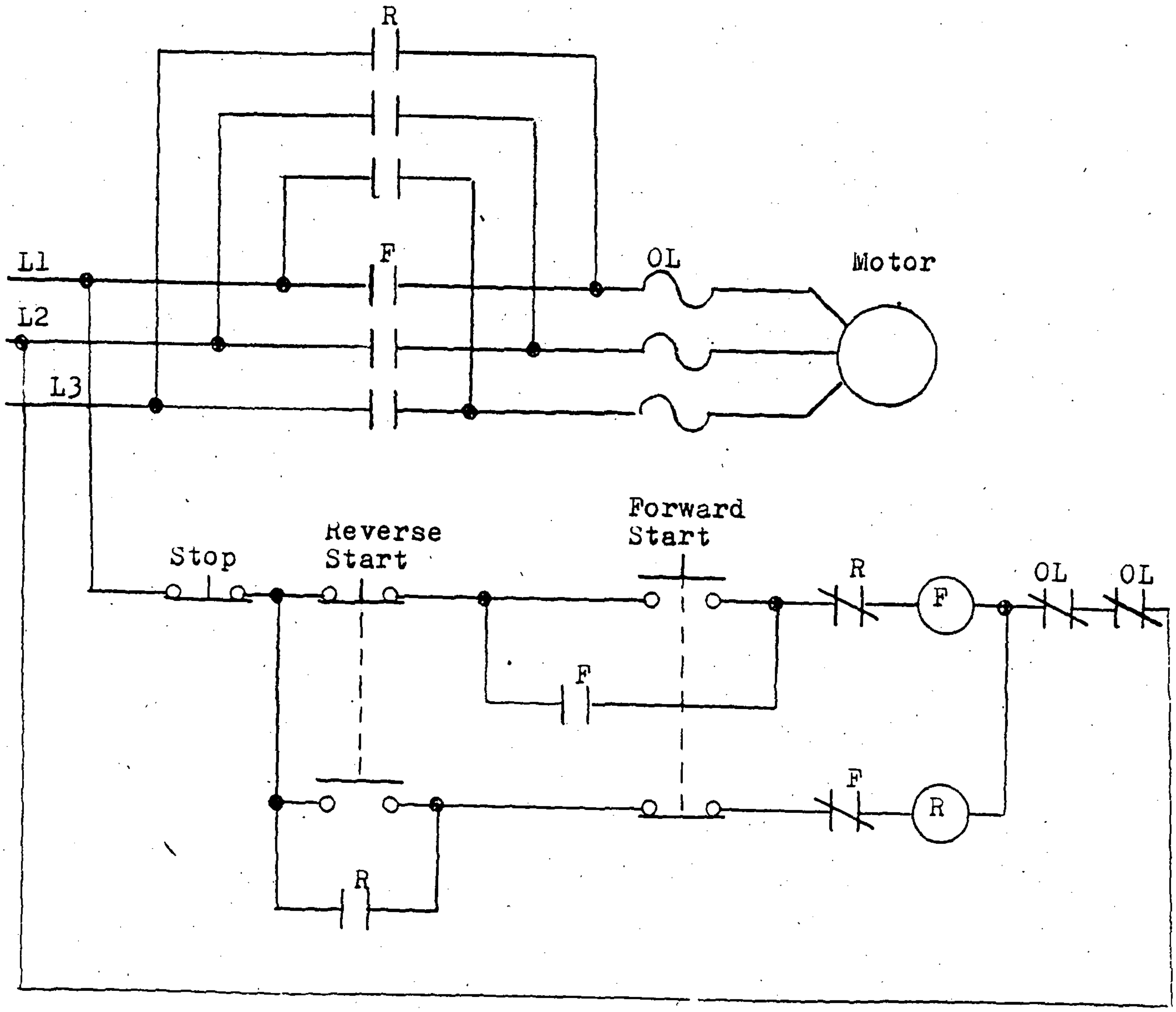


Fig. 10
Typical reversing starter with double electrical interlocking

A system of double electrical interlocking is provided in the control circuit of Fig. 10 by two normally closed auxiliary contacts F and R on the main contactor. This circuit functions as follows:

When the forward button is pressed, forward contactor coil is energized through the stop button, upper contacts of the reverse button, and normally closed contact R of the reversing contactor. The three main contacts of the forward contactor close to energize the motor. Coil F is kept energized when the forward button is released by the holding circuit contact.

If the reverse button is pressed, the forward circuit opens through the normally closed contacts of the reverse push-button. The forward circuit opens by deenergizing the forward contactor coil. Auxiliary contact R in the forward holding circuit opens, and normally closed auxiliary contact F in the reverse circuit closes. The reversing circuit is thus completed through the normally closed lower contacts of the forward button and auxiliary contact R. Reverse contactor coil R is energized, and reverse contacts in the motor circuit are closed. Auxiliary contact R opens in the forward circuit for added safety. The reverse contactor is kept energized by contact R in the holding circuit until either the forward button or stop button is pressed.

In addition to electrical safeguards it is standard practice in some countries to provide also mechanical interlocks which positively prevent one contactor from closing before the other is open. Also note that only one set of overloads is used in a reversing starter.

f) Electric Braking: A standard across-the-line reversing starter can also be used for quick stopping an electric motor. With the motor running forward, the operator presses the reverse button. At the instant the motor reaches zero speed, the operator shuts off the power with the stop button. This action is called "plug stopping". It is also possible to mount a zero speed switch on the motor shaft which will assure power cut-off at zero speed. Sometimes torques developed during plugging may be too high, and series primary resistance in the form of "plugging resistors" is required to limit the torque to a safe value.

The main disadvantage of plug stopping is power-line disturbance. When this presents a problem, another practical method that is frequently used for quick stopping a squirrel cage motor is dc dynamic braking.

The general principle of dynamic braking is to make the drive motor function as a heavily loaded generator by cutting off ac power and applying dc across the stator winding. Principal requirements are a dc source capable of supplying about two or three times full load current, and a two pole contactor to switch the dc in as soon as the main contactor cuts off ac power. Resistors are generally included in the dc power line to limit braking force. A timer drops out the dc contactor after the drive has come to rest. Fig. 11 shows how a simple power circuit could be wired.

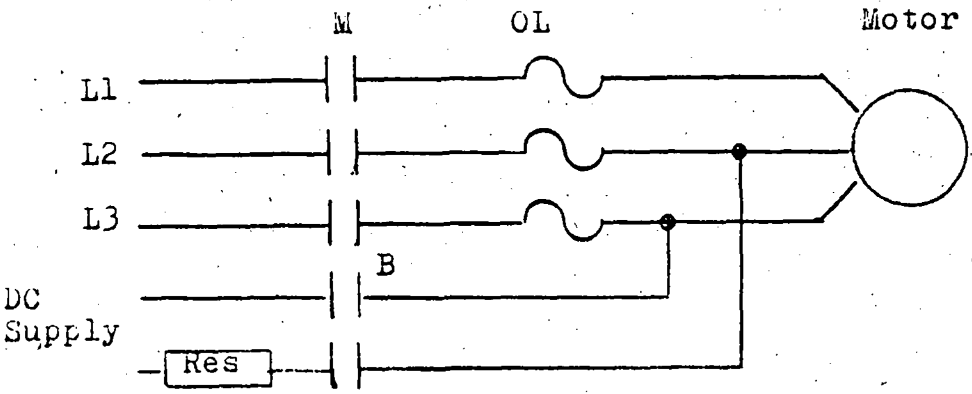


Fig. 11
Simple power circuit for dynamic braking of a squirrel cage motor.

A typical dynamic braking schematic is shown in Fig. 12. When the start button is pressed M contactor is energized and closes its contacts starting the motor. Closing of auxiliary contact M energizes timer coil T which closes the timers instantaneous auxiliary contact T in the holding circuit for coils M and T. The timers normally open delay contact closes instantly as the timer coil is energized. However, normally closed auxiliary contact M has opened to prevent energizing of braking contactor B.

The motor continues to run until the stop button is pressed. Then, contactor M and timer T coils are deenergized thus cutting ac pow r to the motor. Contact M returns to closed position and energizes coil B. The dynamic braking contacts B are closed, applying dc power to the motor. DC is applied only until the timer setting returns the delay contact T to its normally open position.

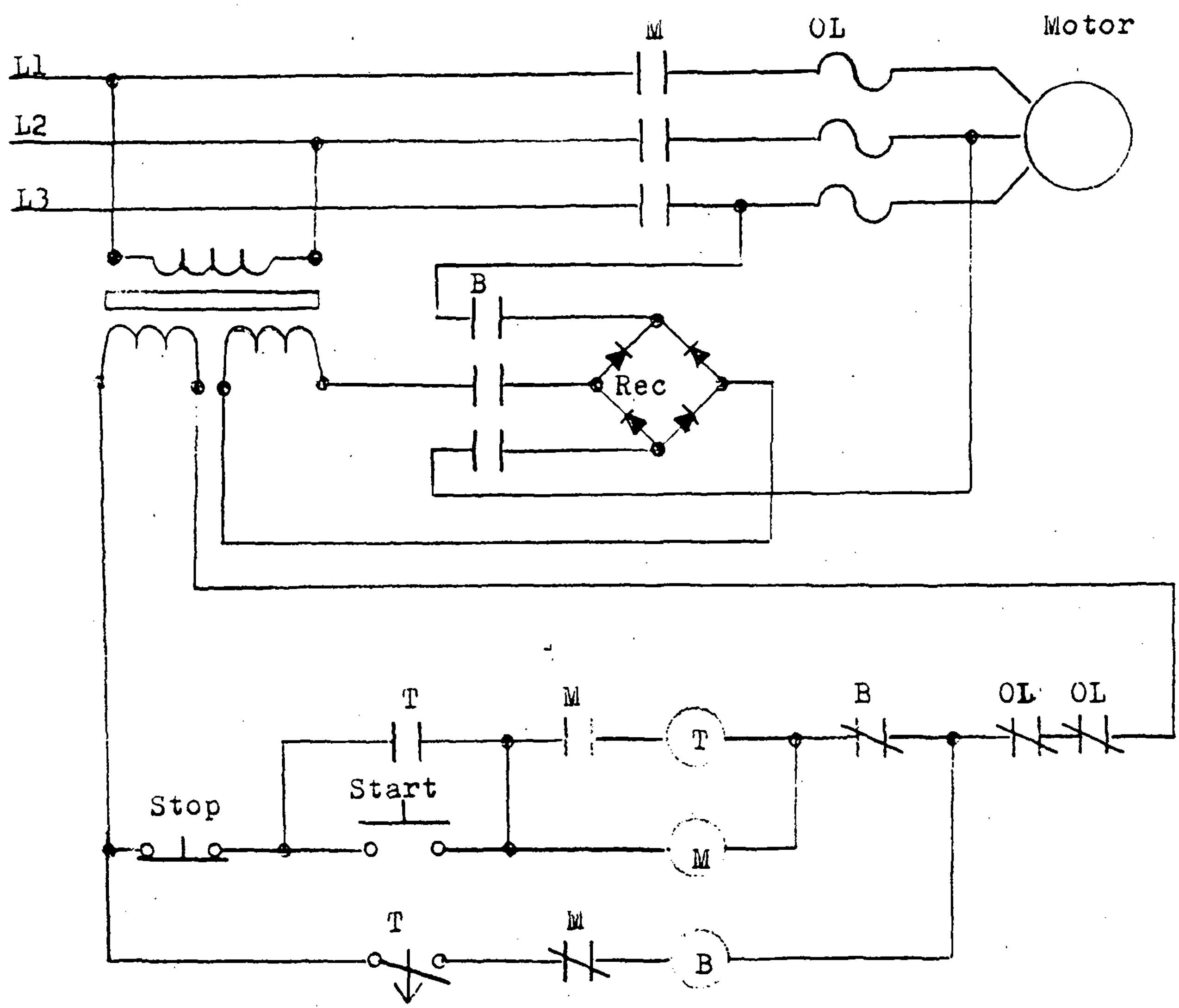


Fig. 12 Typical circuit for application of dynamic braking to squirrel cage motors.

Dynamic braking does not affect line current because the motor is completely disconnected from the power supply during the braking operation. It also produces high maximum torque with low losses, while high losses are incurred during plugging.

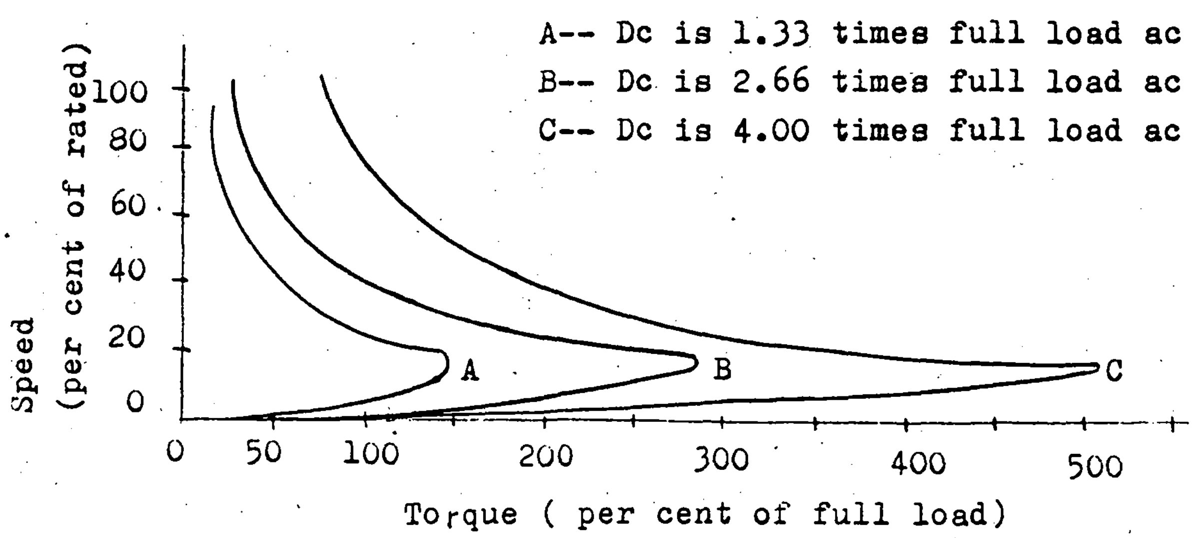


Fig. 13 - Speed-torque curves for dynamic braking of typical squirrel cage motor.

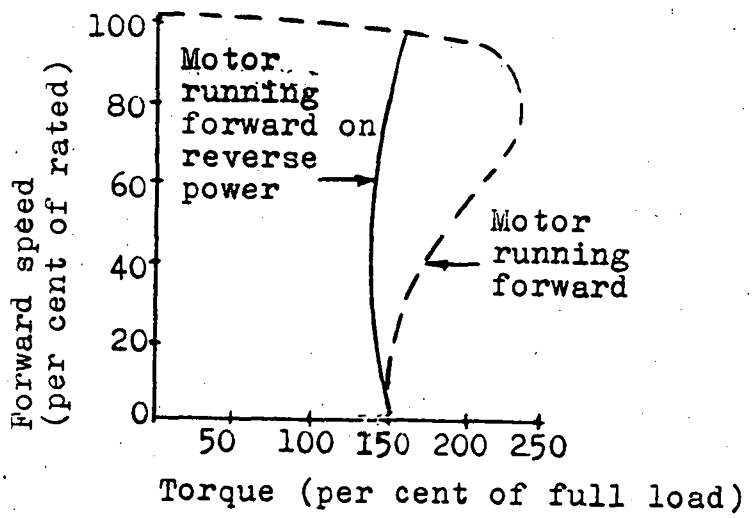


Fig. 14 - Typical speed-torque curve for squirrel cage motor during plugging.

1.3 Squirrel Cage Motor Starters - Reduced Voltage.

Putting certain pumps in motion may require a gentle start and smooth acceleration up to full speed. In addition to such requirements, power company regulations may limit the current surge or voltage fluctuation that may be imposed on the power supply during motor starting.

Four types of starters which are designed to meet these requirements by applying reduced voltage to the motor windings during start-up.

- Primary resistor starter
- Primary reactor starter
- Autotransformer starter
- Star-delta Starter

a) Primary Resistance Starter: One of the most common types of reduced voltage starter is the primary resistance starter. The basic operation of this starter is illustrated by the schematic of Fig. 15.

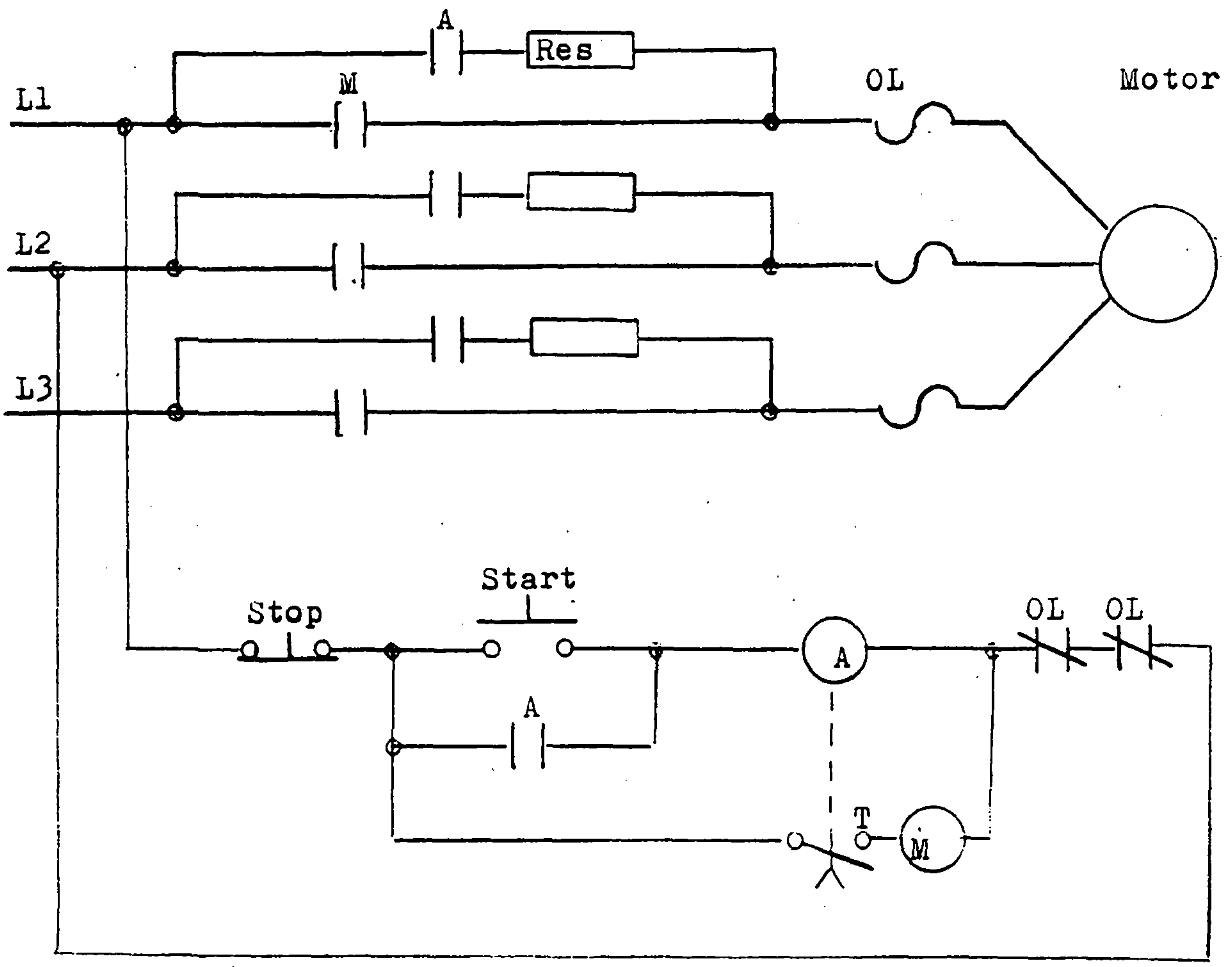


Fig. 15 - Typical primary-resistor starter schematic for a three phase squirrel cage motor.

When the start button is pressed, contactor A closes and applies power to the motor through the resistors. Timer A begins to time out and closes after the proper time interval. When the timer contacts close, M contactor is energized. The M contacts short out the resistors and apply full voltage to the motor.

The primary resistor, reduced voltage starter, especially smaller versions, is after the star-delta starter the least expensive type of reduced voltage starter. It provides a relatively high breakdown torque. The motor torque is constantly increased as the motor speeds up.

Smooth, cushioned starting and acceleration are obtained without transition periods (during which the motor would be disconnected from the line). Acceleration is smooth because the motor draws less current as it gains speed. As current decreases, voltage drop across the resistor also decreases, while voltage at the motor terminals increases. When extra smooth acceleration is desired, multipoint starting is possible by using additional contactors and possibly additional resistors.

b) Primary Reactor Starter: The main advantage of the primary reactor starter over other types of reduced voltage starting are the somewhat higher maximum starting torques and lower starting losses. Ordinarily these advantages are not sufficient to warrant use of the primary reactor starter. It is used mainly on large high voltage pump motors because the reactor is self-contained and presents none of the insulation problems that would be involved in mounting resistors in such applications. A schematic diagram for this type of starter is essentially the same as shown in Fig. 15, except that the reactors are substituted for the resistors.

c) Autotransformer Starters: When limitation of the starting current is of prime consideration, an autotransformer type of starter is used. A typical schematic is shown in Fig. 16.

When the start button is pressed, contactor S is energized. Closing the S contacts places reduced voltage on the motor and opens electrical interlock S in the coil circuit of run contactor R.

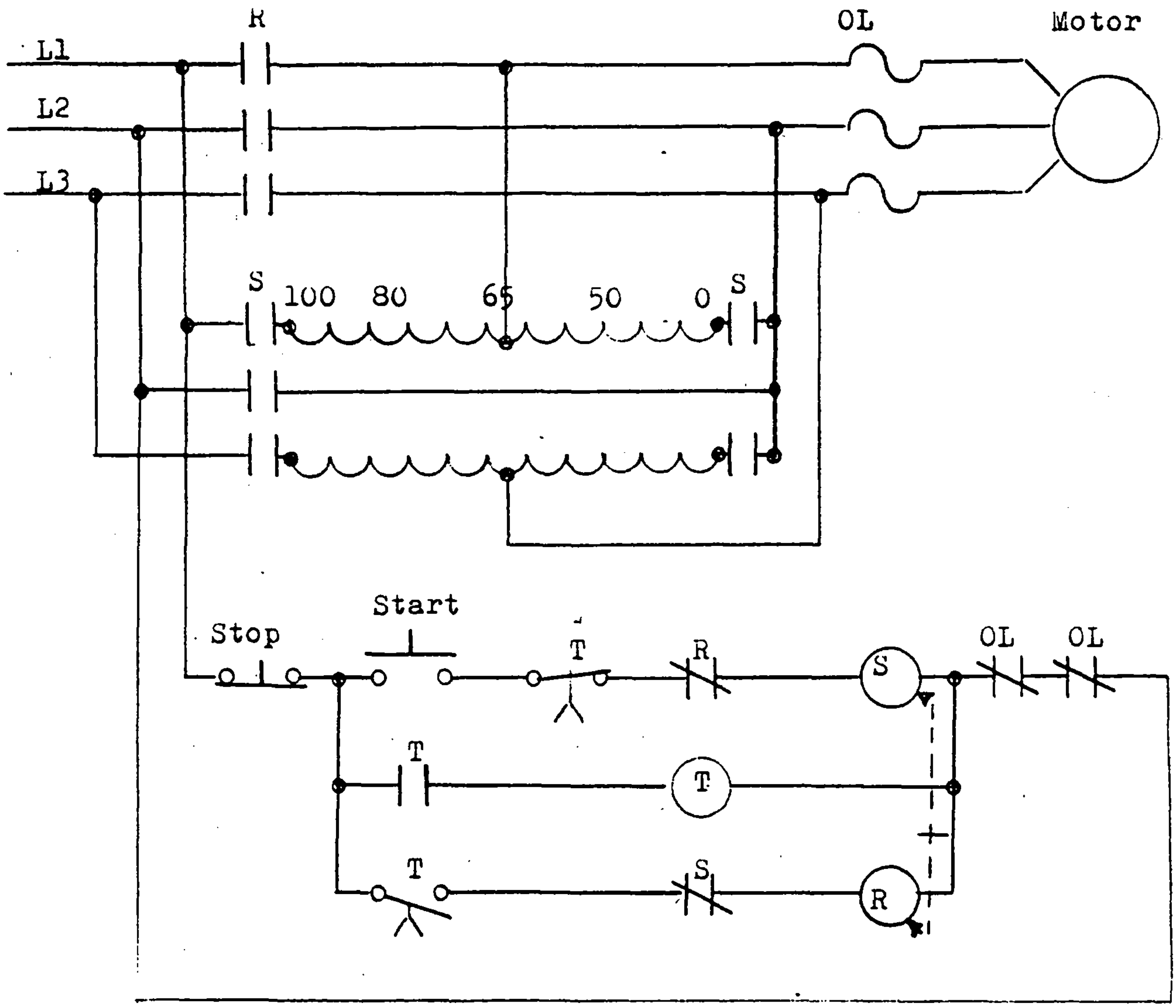


Fig. 16 - Typical autotransformer starter schematic for a three phase squirrel cage motor.

Simultaneously timing relay T is energized and its instantaneous contact closes the holding circuit for both S and T coils. Also, the two time-delay contacts start to time out. At the end of the time interval, T normally closed, opens to deenergize contactor S and disconnect the transformer. Normally open contact T closes the coil circuit of contactor R. After S has dropped out, the normally close contact S closes, then R closes and applies full voltage to the motor. Electrical interlock R opens as a safeguard. Mechanical interlocks are also incorporated in the control assembly between start and run contactors.

The autotransformer starter provides low line currents and low losses during starting. Maximum starting torque is low, but transformer action provides sufficient torque per ampere of line current for starting heavily loaded equipment such as compressors, with minimum drain on the supply.

In the standard autotransformer circuit there is a moment of transition which occurs just after the transformer is disconnected from the line and prior to the closing of the main contactor. During this moment the motor is actually disconnected from the power line. When the main contactor closes and applies full voltage to the motor, a high transient current can be produced which might be excessive for either the power supply or the driven equipment. This momentary transition, however, can be eliminated with a special circuit known as the Krondorfer circuit.

d) Star-Delta Starter: The most common type of reduced voltage starter for small pump drives on weak power supplies is the star-delta starter. Its main advantages are its inherent simplicity and its low cost. Its main disadvantages are the limited torque and KVA values during the starting period when the motor is star connected. Similar to the autotransformer starter, the star-delta starter also has a moment of transition which occurs just after the star contactor opens and before the delta contactor closes. During this moment the motor is disconnected from the power line and high transient currents can be poduced when the delta contactor closes and reconnects the motor to the supply.

This starter requires no external resistors, reactors or transformers.

When the start button shown on schematic diagram Fig. 17 is pressed, contactor A is energized, connecting the motor in star. Auxiliary contact A closes and energizes contactor B which connects the star-connected motor to the power-line. Auxiliary contacts of contactor B complete the holding circuit for contactor B and energize timing relay T through normally closed auxiliary contact C; At the end of the time interval, time contact T opens, deenergizing coil A thus opening the star connection of the motor. When con-

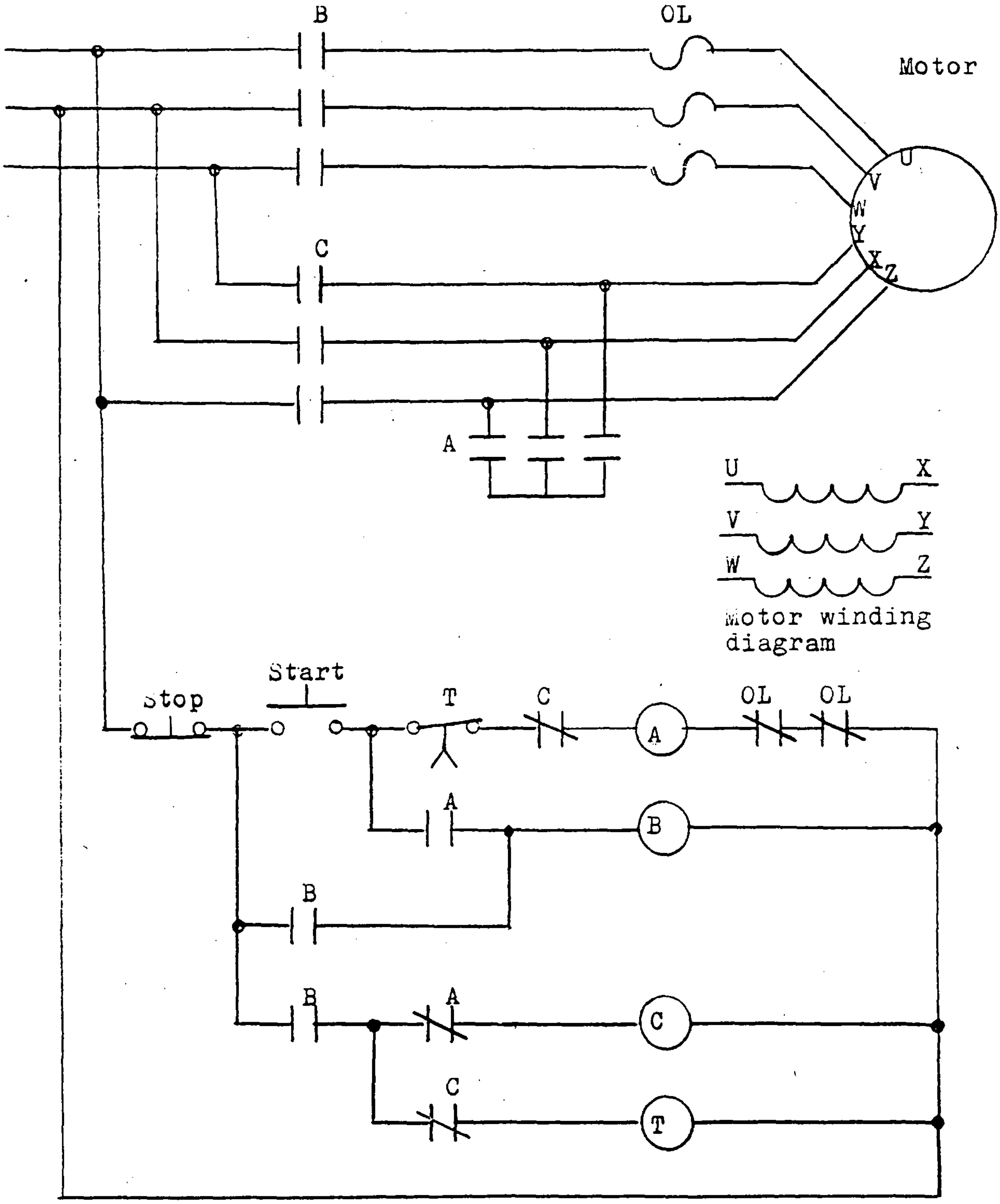
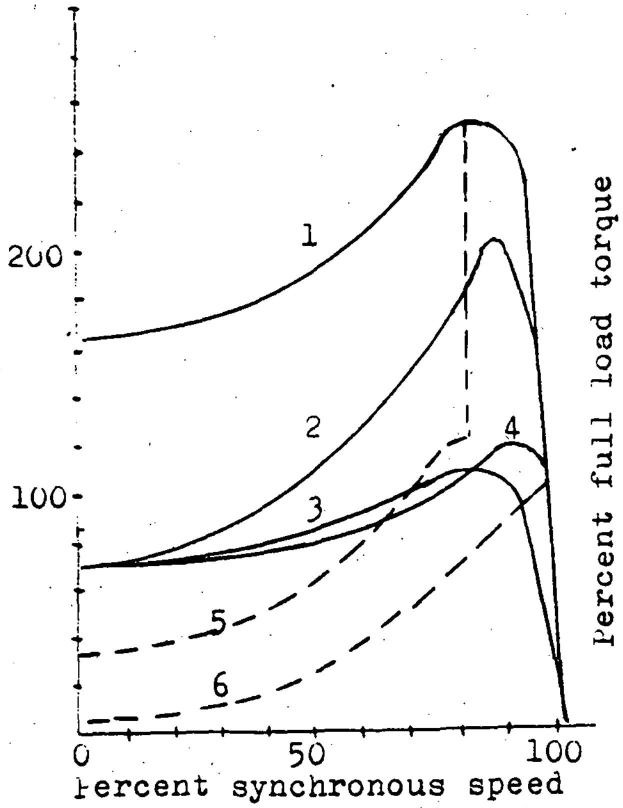


Fig. 17 - Typical star-delta starter schematic for a three phase squirrel cage motor.

tactor A is fully open, normally closed auxiliary contact A closes, energizing contactor C connecting the motor in its running (delta) mode

e) Comparison of Reduced-Voltage Starters: All reduced-voltage starters function to cushion the drive against mechanical shock and the power system against high starting currents. Because of its low cost, the star-delta starter is prefered for small motors provided its limited torque developed during starting is ample to accelerate the load and provided the current surges during the open transition from star to delta are not objectionable.

Because of its closed transition and smoother start, the primary resistor starter is next in the line of preference if it can furnish ample torque within allowable current limits. If open transition is acceptable, the autotransformer starter, which develops more toque per ampere of line current is used. Primary reactor starters are mainly used to start high voltage motors because of the inherent insulation benefits.



1--Full Voltage
2--Reactor with 65% tap
3--Autotransformer with 65% tap
4--Resistor with 65% tap
5--Star/Delta
6--Loaded centrifugal pump

Fig. 18
Comparison of speed-torque characteristics for starting a typical squirrel cage motor with reduced-voltage and across-the-line.

Torque requirements of a centrifugal pump increase to the square of the speed. Fig. 18 shows that the torque developed by any one of the reduced voltage starting methods is well above the requirements of a centrifugal pump start.

Fig. 18 also shows the torque characteristics of a star-delta starter when the transition from star to delta is made too soon in the starting cycle (at about 80 to 85% synchronous speed). The resulting surge of current could very well eliminate the advantages of a star-delta starter. The torque requirements of a loaded centrifugal pump show that a transition from star to delta could be delayed until almost full motor speed is reached. It should be delayed to save the equipment and to eliminate unnecessary current surges.

Starting Method	% volts applied	kva % f.v.+	Torque % f.v.+
Full Voltage	100	100	100
Autotransformer	80	64	64
	or 65	42	42
Resistor or Reactor	80	80	64
	or 65	65	42
Star-Delta	57	33	33

Fig. Squirrel cage motor starting - comparison of starting torques and starting kva.

+ f.v. = full voltage

1.4 Wound-Rotor Motor Starters

As already covered in other modules, adding resistance to the rotor (secondary) circuit of a wound-rotor motor, reduces rotor current and stator (primary) current is reduced proportionally. The effect of added rotor resistance on starting current gains special importance in relation to its simultaneous effect on starting torque. Although starting current decreases with each added increment of resistance, starting torque increases up to point no. 4 Fig. 20, then drops off rapidly.

This characteristic - increasing torque with increasing current - frequently determines the selection of a wound-rotor motor when starting current limitations are severe. For example, if power company regulations were to limit peak values of current to 150% of full load, this type of motor would still produce a locked rotor torque of 150% of full load torque. By contrast, a typical squirrel cage motor might require 600% of full load current for equivalent locked rotor torque. If starting current for a squirrel-cage motor were limited to 150%, a locked rotor torque of only about 10% of full load torque would be obtained.

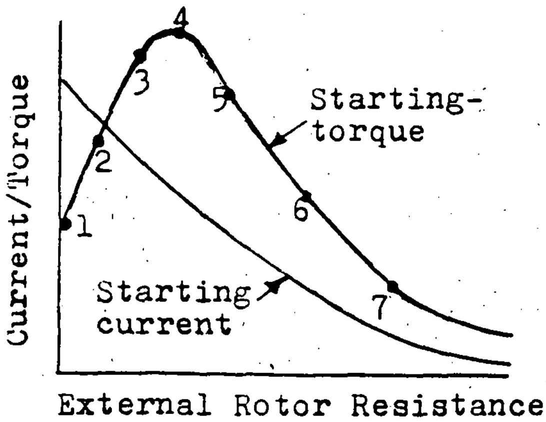


Fig. 20
Relationship of starting current and torque for various values of resistance in the secondary circuit of a wound rotor motor;

Speed-torque curves in Fig. 21 have been plotted from the seven starting points on the torque curve in Fig. 20 to give a more complete picture of the effect of resistance on motor torque. These curves show that locked rotor torque can be increased only until it equals break-down torque at point no. 4. Further increases in resistance reduce starting torque but prevent the motor from reaching maximum or breakdown torque.

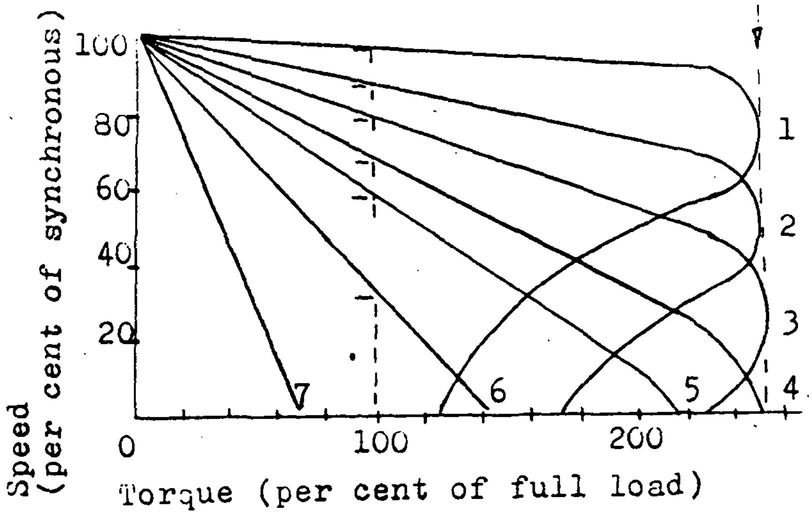


Fig. 21
Speed-torque curves for values of resistance indicated on curve of starting torque in Fig. 20

The curves in Fig. 21 show that each addition of resistance in the rotor circuit (from point no. 1 through 7) reduces motor speed. Speed reduction is practical only to 50% of synchronous speed. Beyond this point speed becomes unstable because high slip characteristics are produced in a rotor that operates with a high resistance in its circuit. For this reason, speeds corresponding to resistance points no. 6 and 7 would be practical only where constant loads are involved.

The basic control for a wound-rotor motor consists of an across-the-line starter in the stator circuit and a resistor bank in the rotor circuit. Multipoint control of the resistance may be manual or magnetic. In a manual system a drum controller is generally used with a resistor bank, although a face plate rheostat may be used for small motors.

Where magnetic control is used, especially for fully automatic operation in starting, a contactor and a acceleration device must be added for each step of resistance in the rotor circuit, Fig. 22. The motor size determines the energy the resistor must absorb. Resistor design is also based on motor load and on the relationship of speed-torque characteristics of the motor and load.

When the start button shown on schematic diagram Fig. 22 is pressed, coil M is energized and the main contactor in the primary circuit closes. It is held closed through the auxiliary contact of M in the holding circuit.

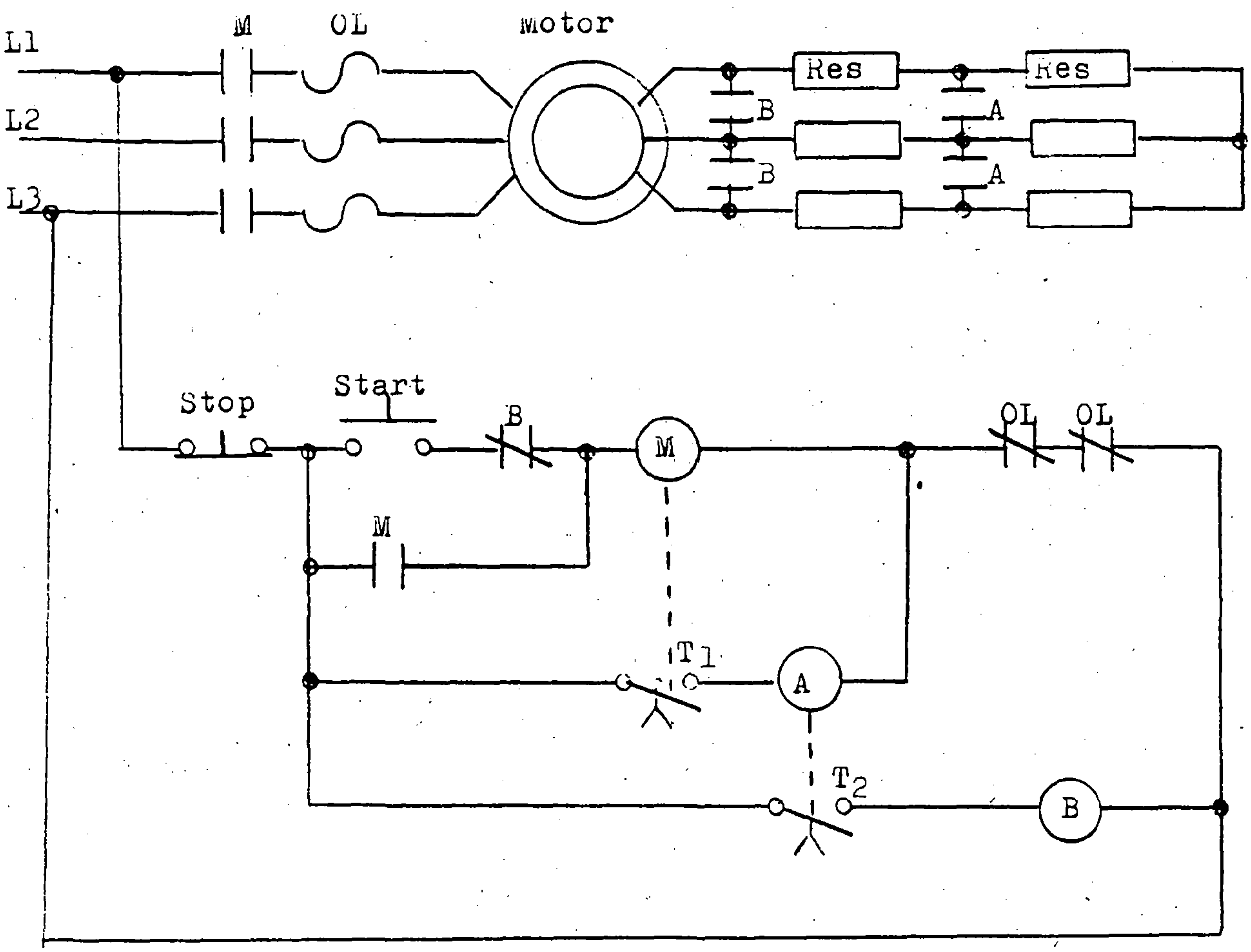


Fig. 22 - Typical magnetic starter schematic with 3 step acceleration for wound-rotor motors.

Both secondary resistor banks are now connected to the rotor circuit. At the end of the first time interval after closure of contactor M, contact T1 closes, energizing contactor A. Contactor A closes and short circuits the first external secondary resistor bank. At the end of the second time interval, contact T2 closes, energizing contactor B. Contactor B closes and short circuits the second external resistor bank. This condition remains until the stop button is pressed.

1.5 Synchronous Motor Starter

The synchronous motor is not inherently self starting. For this reason some synchronous motors of early design were equipped with a special motor designed for use during the starting period only. Nowadays, synchronous motors are generally provided with a squirrel cage type rotor. The field winding, located physically on the same rotor, is designed to carry direct current. The stator winding is connected to the main ac power supply during both starting and running. The squirrel cage winding is used to start and accelerate the motor to approximately 95% of synchronous speed. When this speed is attained, the field winding is energized from a dc supply. A strong polarized rotor field is developed which "locks" into synchronism with the rotating stator field.

A basic synchronous motor starter incorporates four components:
- A three pole magnetic starter for the ac stator circuit.
- A contactor for the dc field circuit.
- An automatic synchronizing device to control the dc field contactor.
- A squirrel cage winding protective relay to open the ac circuit if the motor operates too long without synchronizing.

Because a synchronous motor requires ac power during both starting and running, the main contactor M is always closed when the motor is operating. The dc winding of the rotor is energized by the field contactor as the motor approaches synchronous speed. Two normally open poles on the field contactor FC make the connection for the dc excitation, and one normally closed pole permits dissipation of induced field current (through a discharge resistor) during any period of non-synchronous operation.

For smooth synchronisation, two conditions determine the instant that the dc field is energized:
- the motor must be running at the proper speed - usually 93 to 98% of synchronous speed.
- The rotor poles must be lagging slightly behind stator poles of opposite polarity.

Any of several different synchronizing devices can be used to apply dc to the rotor field. Its function can best be illustrated with an explanation of the circuit shown in Fig. 23.

Pressing the start button closes main contactor M and connects the motor stator to the line. The motor accelerates as an induction motor. An induced alternating current flows in the motor field circuit with a frequency proportional to the slip of the motor (the frequency of the induced field current is the same as line frequency when the motor is at a standstill and approaches zero as the rotor nears synchronous speed).
The synchronizing relay PFR responds to declining frequency in the field discharge circuit so that dc excitation is applied at the correct motor speed and with proper polarity.

The out-of-step protective relay for the squirrel cage winding is usually a conventional thermal overload device (OSP). It is energized whenever the motor is running without rotor field excitation. If, during the start, the motor does not synchronize within a given period of time (usually 15 to 20 sec.) the OSP relay operates and opens the main contactor M.

Synchronous motors can be stopped quickly by methods similar to those used with induction motors. Plug stopping requires a reversing control. Dynamic braking requires a set of braking resistors and a contactor to connect the resistors across the motor stator. The dc field winding remains excited. The motor then functions as a generator and dissipates the internal energy through the resistor bank. The degree of braking can be varied by changing resistance values.

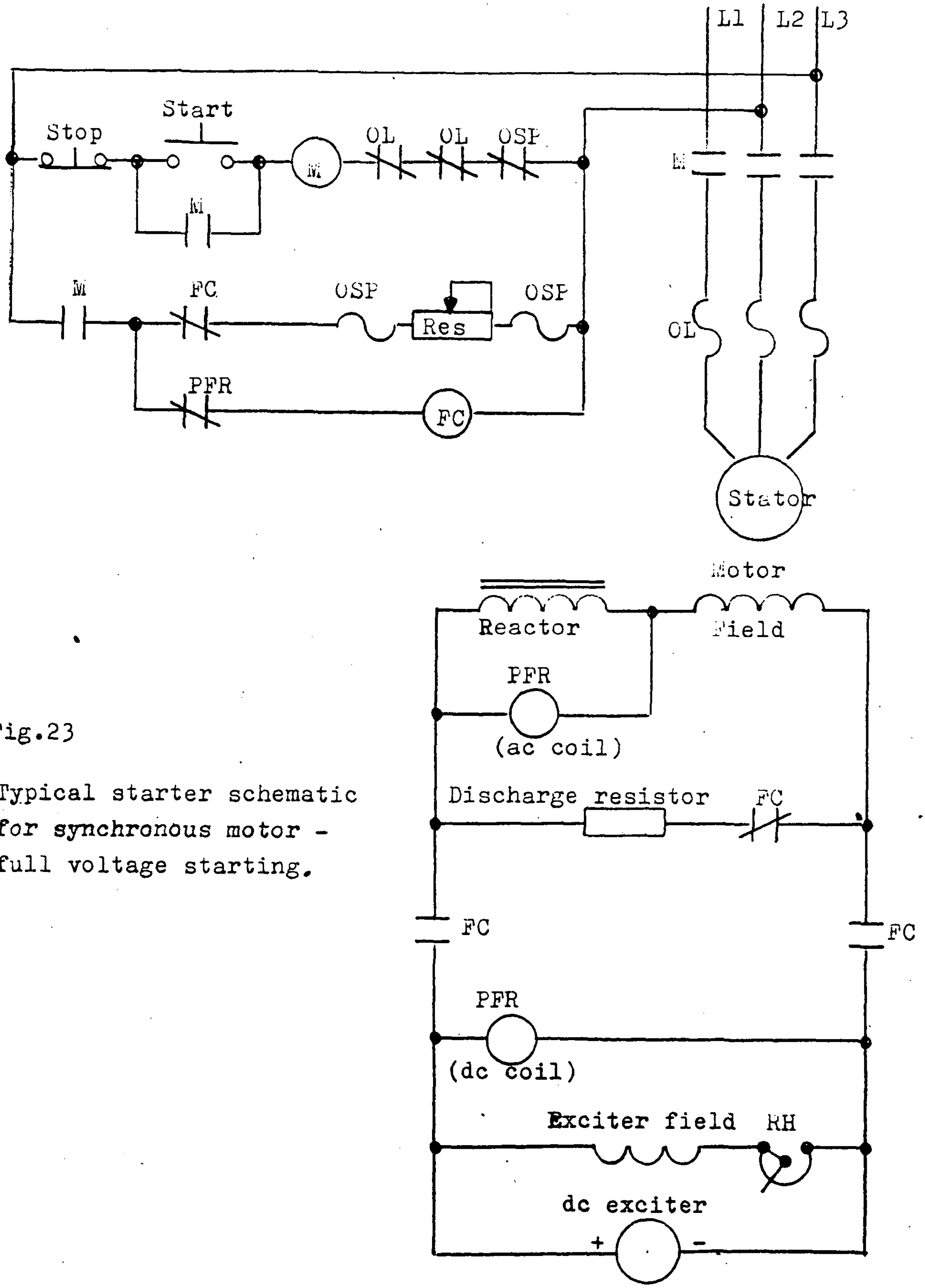


Fig.23

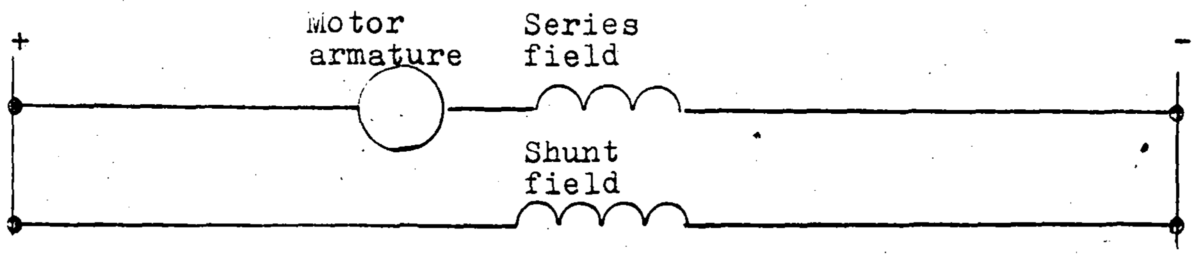
Typical starter schematic for synchronous motor - full voltage starting.

2 Motor Controls - Direct Current

2.1 Introduction

Few dc motor applications require only that the motor run. A minimum of two connections to a suitable source of dc power would normally accomplish this. But when such features as motor protection, controlled acceleration or deceleration, reversed rotation, or operating sequence are involved, control devices and additional electrical connections are required. These components and their related circuitry are provided by motor controllers.

The purpose of the controller is to control (or to connect) electric power to the motor. This basic result is represented by the circuit shown in Fig. 1 below



With the motor connected to the power source, various components commonly used in dc controllers can be added in building block fashion. "Creating" a dc controller in this manner is a convenient means for describing the electrical connections and functions of dc control devices.

2.2 Circuit Function and Control Devices

a) Line Disconnect

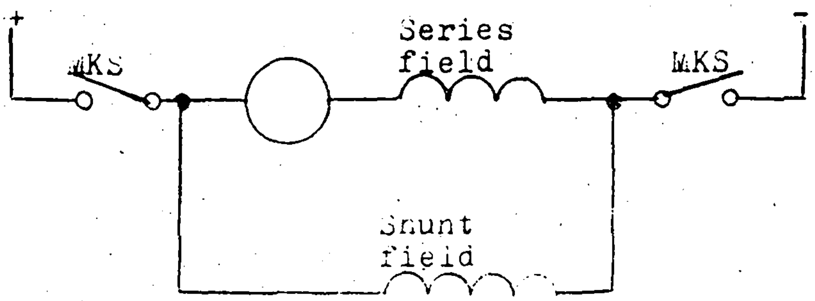
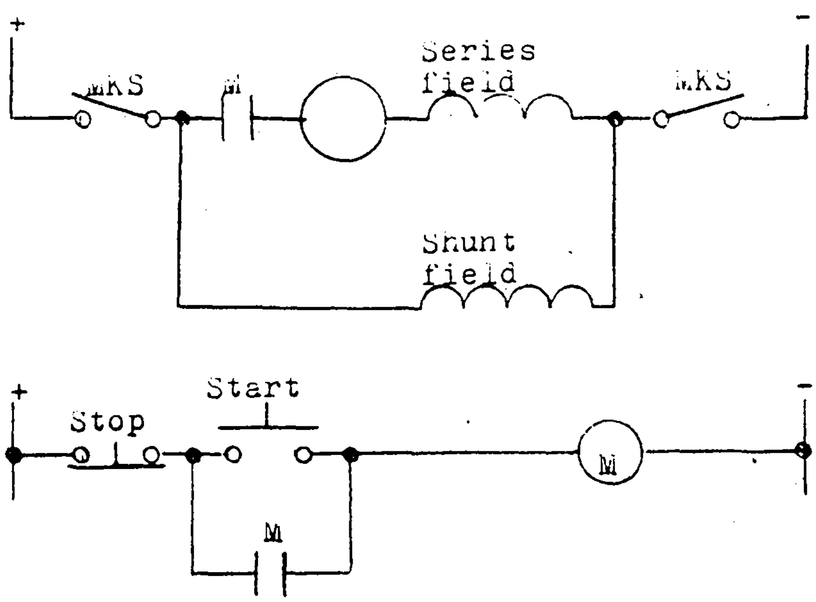


Fig.2

The simple circuit representing the end result of a controller does not include means to obtain that result or to thereafter disconnect the motor from the power source. Therefore, the first device to add is a two-pole main knife switch, MKS. Although some other disconnect device could be used, such as a circuit breaker, a safety switch, or even some type of snap switch, conventional practice in dc control is to use a knife switch.

This amount of equipment can be considered a minimum basic controller of the manually operated or non-magnetic type. Manual starters which contain a suitable interrupting mechanism can be used with dc motors having power ratings of 2 hp or less.

b) Line Contactor - Fig. 3



Because even the most basic dc controller uses magnetically operated devices, a main line contactor, M, is the next logical addition. Since a coil operates this device, a control circuit and its supply must be added.

To complets the circuit to the contactor coil, a pilot-type device such as a push-button or master switch is required. For simplicity, a two-unit start-stop push-button is shown.

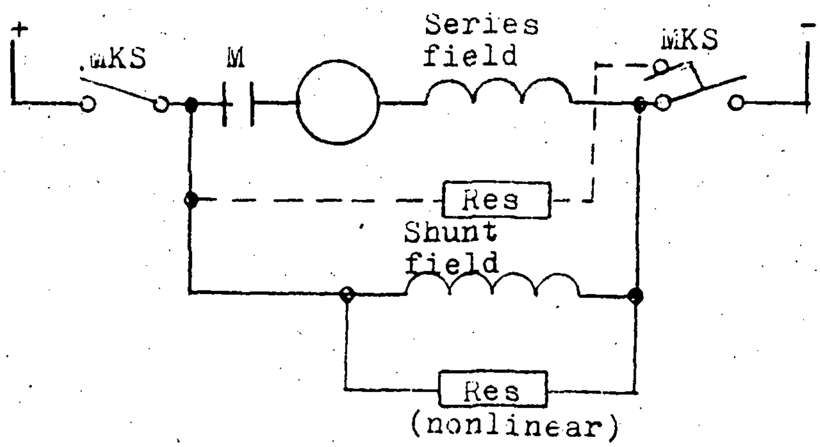
Pressing the start button energizes the contactor coil and thereby closes the main power contacts of the contactor to complete the power circuit to the motor armature.

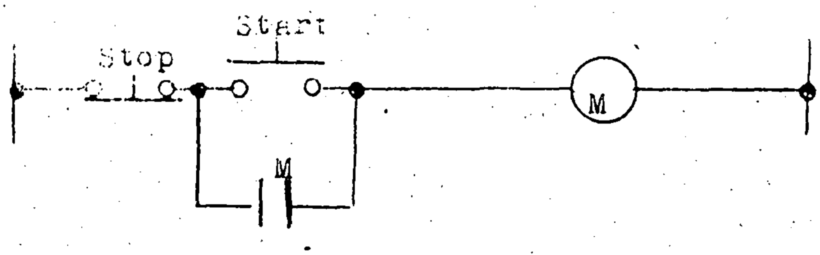
Revised:

To prevent the contactor from dropping out as soon as the start button is released, an auxiliary contact, or control-circuit contact is provided on the contactor to by-pass the start push-button.

To stop the motor, all that is necessary is to momentarily press the stop push-button. This deenergizes the operating coil of the contactor, opens the contactor, and removes power from the motor armature circuit.

c) Field Discharge Means - Fig. 4





If MKS in the previous circuit is opened, the shunt-field circuit is also opened. However, under these conditions, the highly inductive shunt-field winding can induce such a high voltage that the winding insulation is damaged. Therefore a path must be provided so that the induced voltage can produce a current flow. This path prevents the discharge voltage from rising too high.

Two different methods of providing a means for field discharge are shown. One method (dashed circuit) uses a resistor so connected to an auxiliary blade on MKS that, when the switch is opened, the resistor is connected across the shunt-field to provide a discharge path.

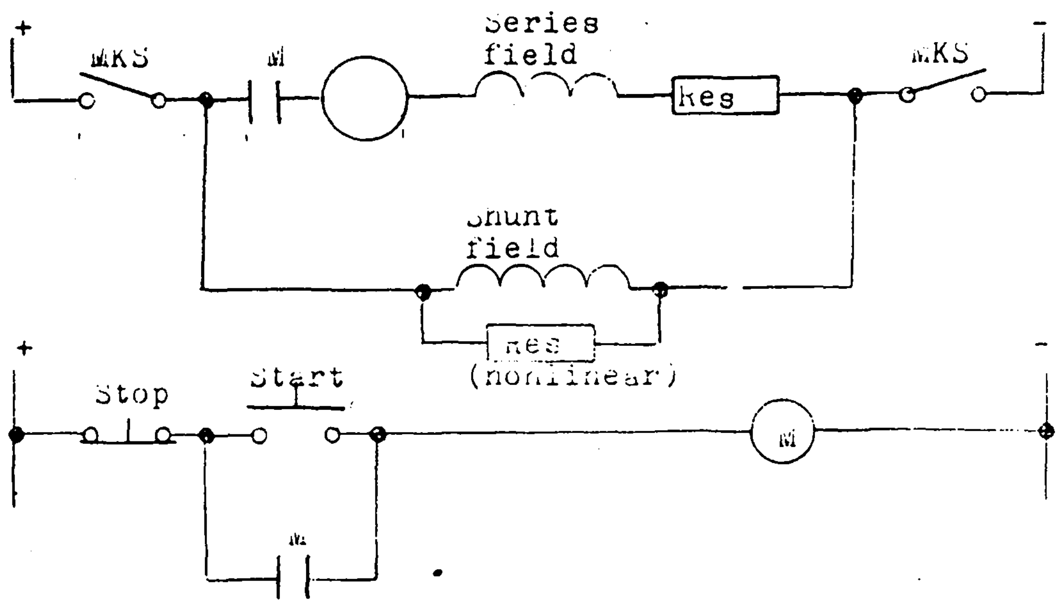
The other method uses a nonlinear resistor connected directly across the shunt field. Resistance of this special device decreases as the voltage impressed upon it increases. Commercial units for this praticular use are so designed that, with a supply of 230 v, resistance is high and little current flows. When the field is disconnected and its induced voltage tries to rise, resistance of the unit decreases, current is allowed to flow, and the discharge peak voltage is held to a safe value.

Either of these two methods is practical.

Other methods also are operationally satisfactory. A conventional resistor unit can be permanently connected across the shunt field in place of the non-linear unit. A disadvantage is the amount of resistor material required. Also, appreciable current is drawn from the line all the time the controller is in operation. This current, in turn, produces heat which can sometimes be a problem. Consequently, this method is rarely used.

Another possibility is to use a rectifier valve or diode connected across the shunt field to block current flow during normal operation. However, during field discharge when polarity is reversed, current is allowed to flow. This method is comparatively expensive and is used only under special circumstances. As semiconductors are improved and reduced in cost, this method may find wider use in the future.

d) Accelerating Resistor - Fig. 5



To prevent a dangerously high current inrush when the motor armature is connected to the power supply, a resistor is placed in the armature circuit. The necessity for adding a resistor can be illustrated with a typical 50-hp motor which has a full-load current rating of 180 amp and an armature resistance of 0.13 ohm. If the armature of this motor is directly connected to a 230-v source of power, inrush current would be 230/0.13, or 1770 amp. This is almost 10 times the rated full-load current of the motor and would surely cause "flashing" of the commutator and damage to the armature. In addition, the torque produced by the surge of current might also cause mechanical damage either to the motor or the connected load.

A resistor in the armature circuit can reduce this abnormally high inrush current to a reasonable level. Usual practice is to select a resistor which limits inrush current to 150 to 200 per cent of the full-load current rating of the motor.

For the same typical motor, limiting current inrush to 150 per cent of 180 amp would permit a current of 270 amp to flow. Then, the total resistance that must be added to the circuit is 230/270, or 0.85 ohms. This resistance value includes the internal resistance of the armature, but for simplicity, armature resistance will be neglected here.

e) Accelerating Contactors - Fig. 6

If the accelerating resistor is allowed to remain in the motor armature circuit, the motor at full load would never be able to reach its speed. This can best be shown with the same motor used as an example in discussing the accelerating resistor.

If the motor draws a full-load current of 180 amp, voltage drop across the accelerating resistor would be 180 x 0.85, or 153 v. Since line voltage is 230 v, the voltage appearing across the armature would be the difference between 230 and 153, or 77 v. Therefore, the resultant maximum speed that the motor could attain would be 77/230, or approximately 1/3 rated speed of the motor.

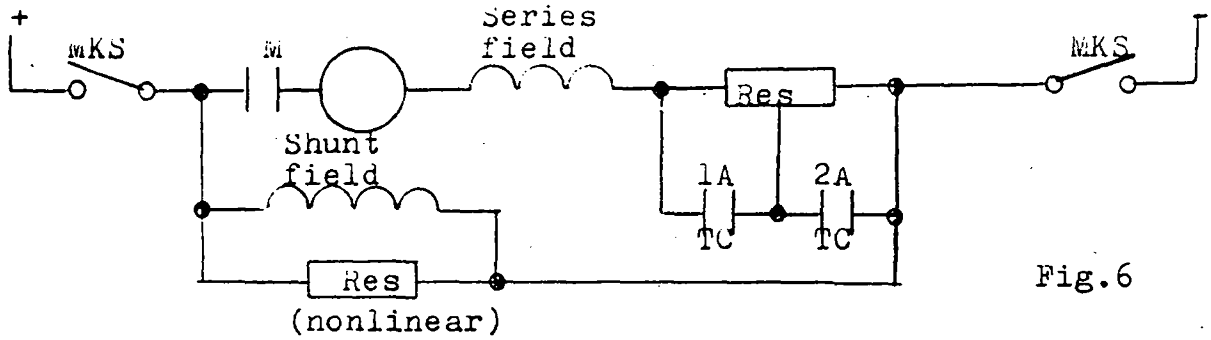
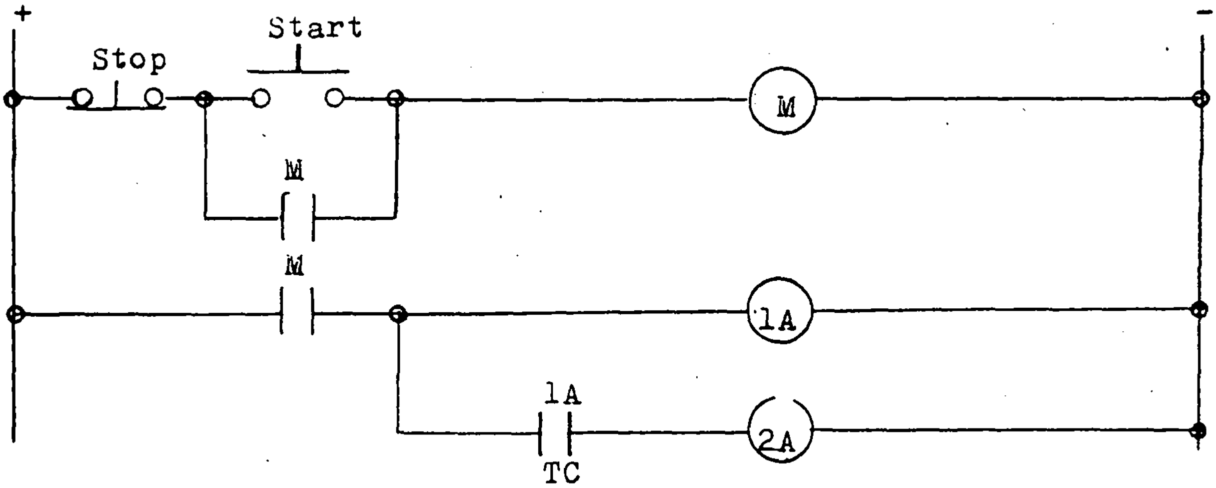


Fig.6



This condition would be unacceptable in most cases. The solution would be to reduce, or cut out, resistance after the motor had reached an appreciable speed. Thus, the motor would eventually be able to attain normal speed when no external resistance remained in the circuit. This result is accomplished with accelerating contactors.

From one to six accelerating contactors may be used, but usually two or three are sufficient for most applications. Two, the first and second accelerating contactors, 1A and 2A, are shown in the accompanying circuit. Because these "accelerators" are magnetically operated, they have operating coils which must be added to the control circuit.

For satisfactory operation, contactor 1A must close at a certain interval after M closes, and 2A in turn must close at a suitable interval after 1A closes. The intervals may be determined by such methods as definite time, motor speed, motor counter-emf, or decrease in current flowing through the motor armature. Conventional practice is to base the interval on a definite time period, usually in the order of one second per interval.

Although the time periods can be determined in various ways, the accelerating contactors shown in the circuit have a time delay built into them. Hence, separate relays or sensing devices are not necessary. The control-circuit contacts on M and 1A insure the proper order or sequence of operation.

After both accelerating contactors have closed, all of the resistor is by-passed or shorted out so that, effectively, no resistance remains in series with the motor armature. Therefore, the motor will run at its rated speed, having been "accelerated" by the successive closing of contactors M, 1A, and 2A.

f) Overload Relay - Fig. 7

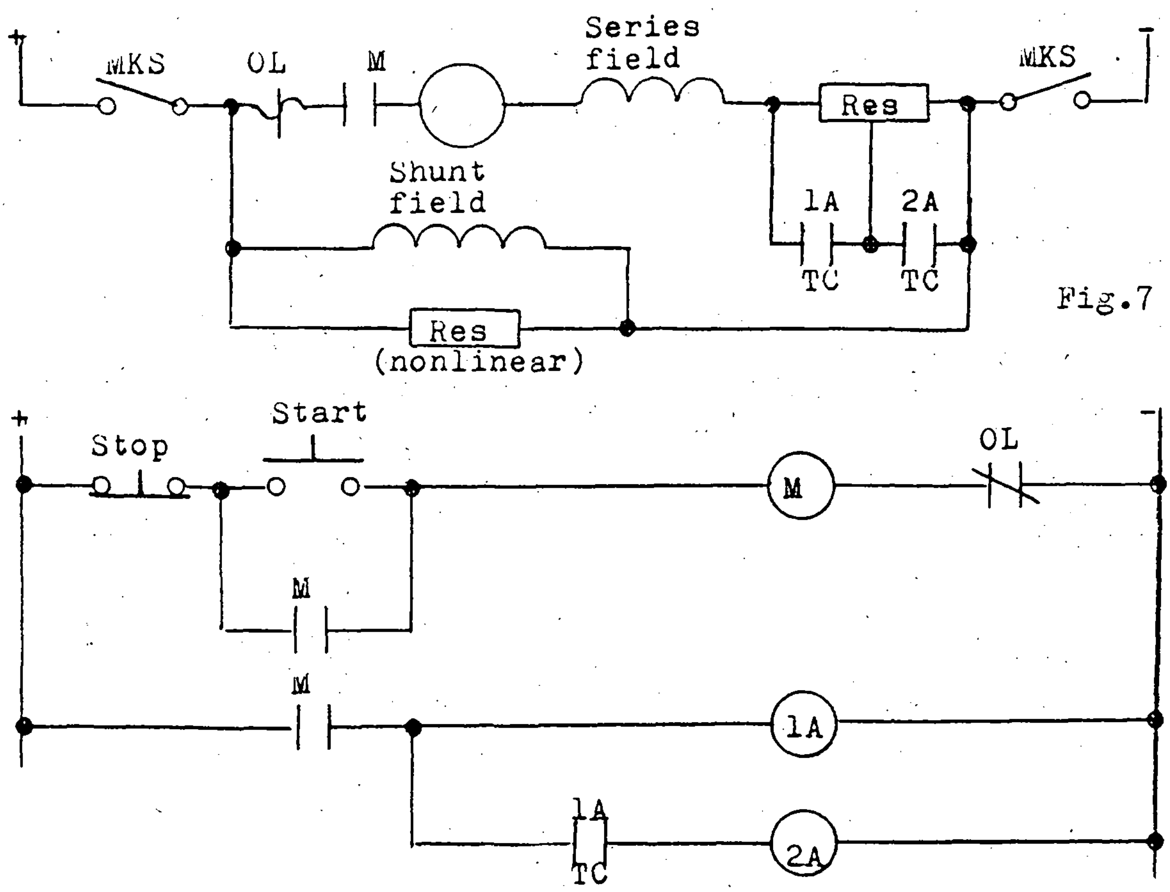


Fig.7

Up to this point, a controller has been "built" which has all the elements required for successful and basic operation. However, it does not include any devices for sensing unusual or undesirable conditions and for subsequently initiating corrective action.

A grater than normal load thrown on the connected machinery, either by operator fault or mechanical fault in the equipment, represents one type of undesirable condition. This overload would increase the current through the motor as the motor attempted to support the load. Such a condition might result in damage to either the driven machinery, the motor, or both, especially if allowed to continue for an indefinite period of time.

Detecting an overload condition and acting to remove the motor from the source of power is the function of an overload relay, OL. This relay is a current-sensing device and has its operating coil connected in the armature circuit. It has normally closed contact which is connected in series with the operating coil of contactor M.

g) Field-Loss Relay - Fig. 8

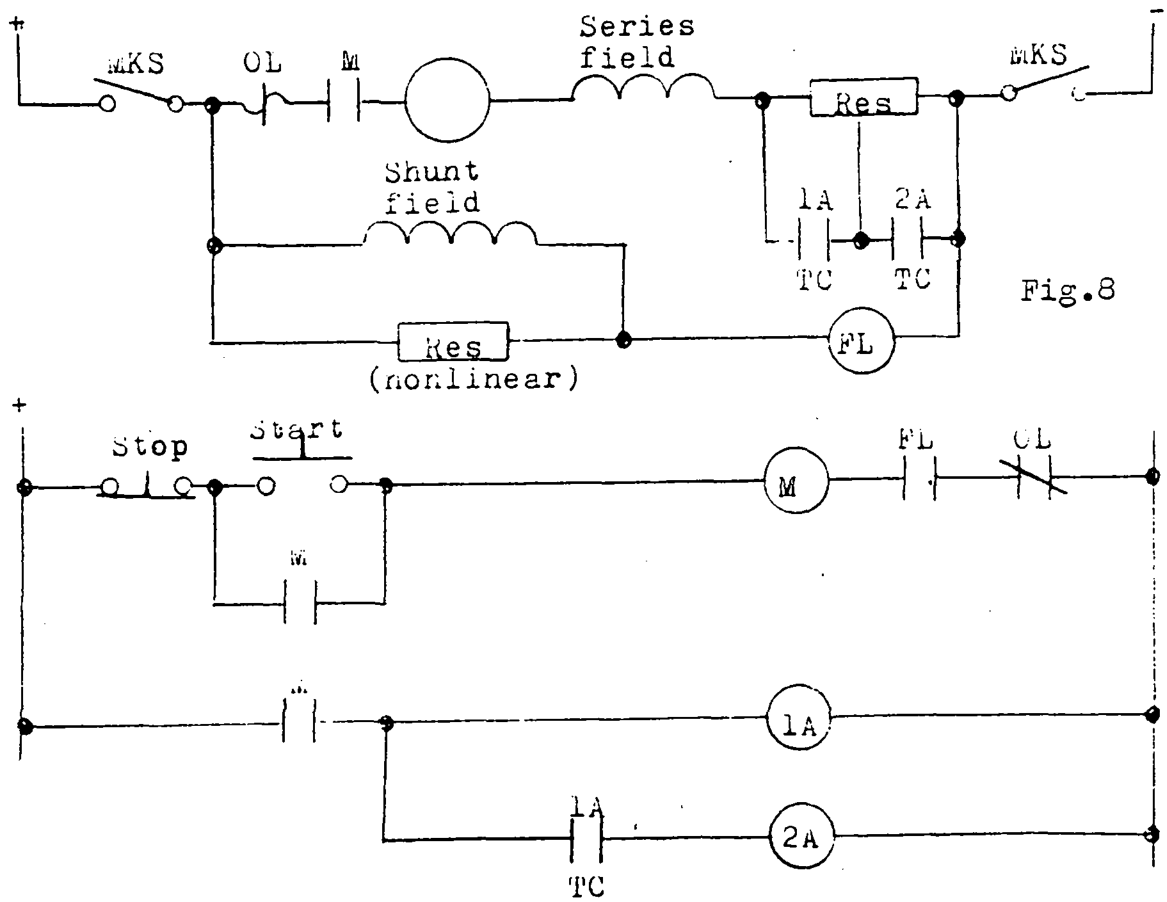


Fig.8

Another fault condition that must be sensed and acted upon is the loss of shunt-field excitation. Otherwise, the motor will tend to run away. At the same time, the motor will draw a high current from the power supply. Either mechanical damage or electrical damage, or both, could result from this condition.

A field-loss relay, FL, protects against this fault. The relay operating coil is connected in series with the shunt-field circuit. A normally open contact is connected in series with the operating coil of contactor M in the control circuit. Therefore, if the shunt-field circuit is broken or opened, no current flows through the coil of the FL relay, its contact opens, and contactor M is de-energized and removes the motor from the source of power.

h) Field Rheostat - Fig. 9

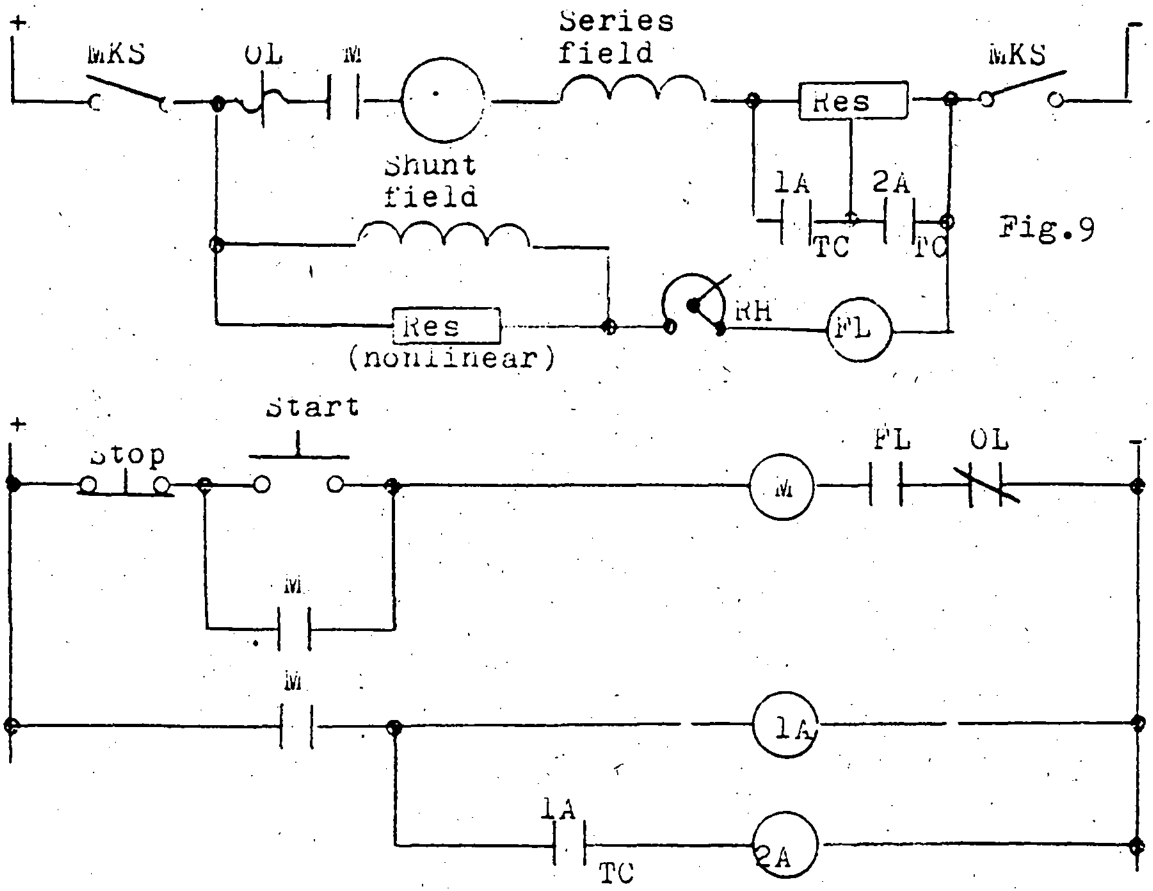


Fig.9

When a motor is shunt wound or lightly compound wound, its speed can be increased above rated base speed by decreasing the strength of its shunt field. Accordingly, shunt-field current can be varied, primarily from rated value to reduced values, with a field rheostat.

Essentially, a field rheostat is an easily operated adjustable resistor. Although it may be driven by a pilot-type motor, in which case it is known as a motor-operated rheostat, the conventional field rheostat is manually adjusted by the operator.

i) Field Accelerating Relay - Fig. 10

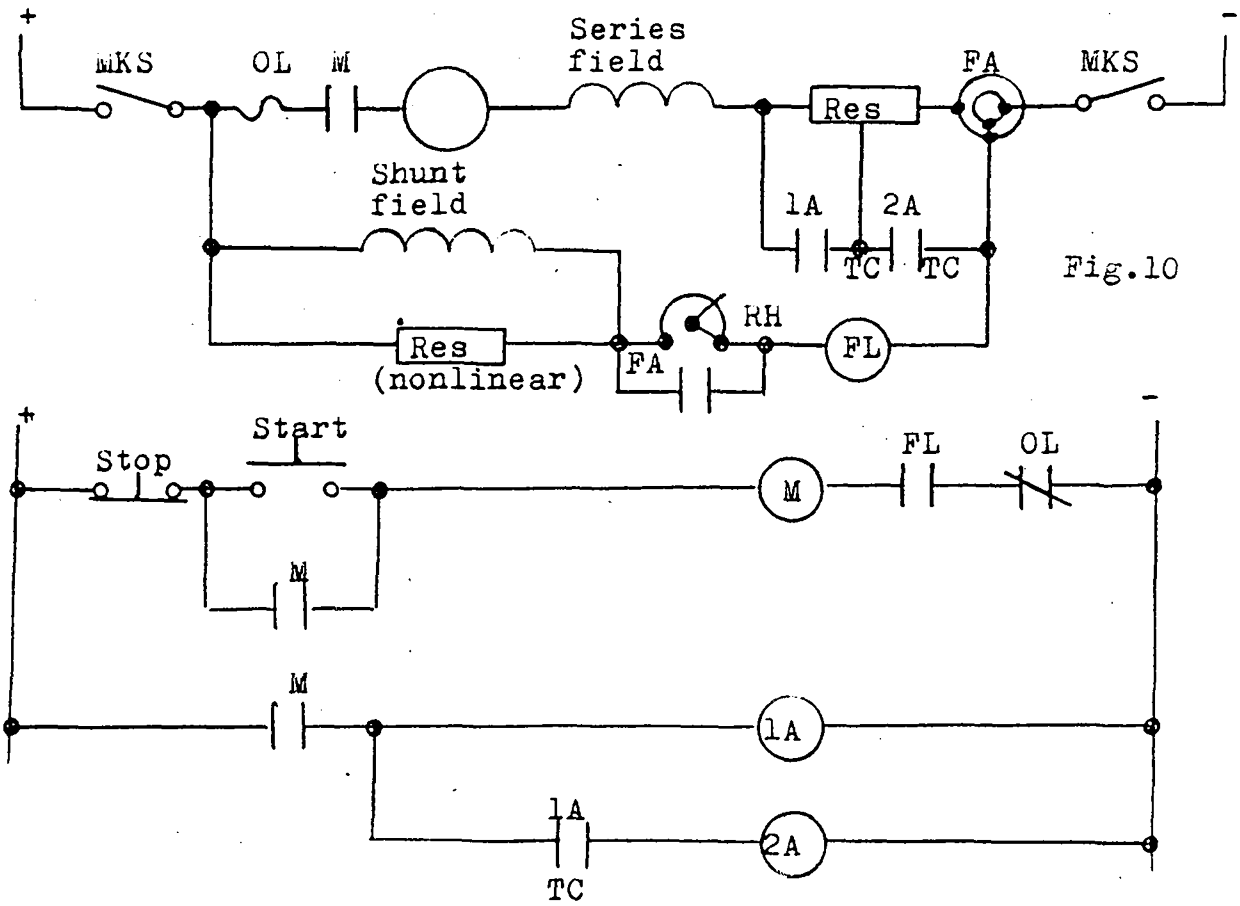


Fig.10

If the motor speed range is more than 2 to 1, the presence of a field rheostat creates two demands on the controller.

1. To provide rated, and often required, torque when accelerating from standstill to base speed, the shunt field must be at full strength.
2. If the motor is running at base speed because the rheostat is

in its all-resistance-out position, and the rheostat is then rapidly moved toward, or to its all-resistance-in position, an excessive current will be drawn by the motor from the source of power. To avoid this high armature current condition, it is desirable that the field strength be weakened slowly, or in a multiplicity of steps, or by some manner which accomplishes the same result.

Both of these demands can be satisfied by a field accelerating relay, FA. The design indicated in the circuit has a series coil with an intermediate tap. The relay has a normally open contact which is connected across the field rheostat. Thus, when the relay and its contact are closed, the rheostat is by-passed or shorted out.

The double-coil construction permits the relay to close on comparatively low currents while the motor is accelerating to base speed, and to close only at higher currents when the motor is accelerating above base speed. This relay and the last accelerating contactor, 2A, are so interconnected that operation of accelerator 2A shorts out one of the two relay coils.

Other methods of accomplishing this dual-purpose function are possible. Some may require two separate relays, or one relay plus additonal auxiliary contacts on the last accelerating contactor. If the proper result is obtained, the method is not important.

j) Field Decelerating Relay - Fig. 11
If a motor is running at a speed considerably above its base speed because the field rheostat is in its all-resistance-in position, the motor field is correspondingly weak. Then, if the shunt field is rapidly strengthened by some means such as rapidly moving the rheostat to it all-resistance-out position, the counter-emf generated by the motor will also rise rapidly. This counter-emf might exceed the voltage of the power supply and result in a reversal of current through the motor armature.

Usually, if the value of the reversal current is not too high, and if the speed range is less than perhaps 2 to 1, the condition is not harmful. However, if the speed range is greater, the magnitude of the reversal current might be high enough to cause flashing at the commutator, a reaction on the driven machine, or possibly a disturbance of the power supply.

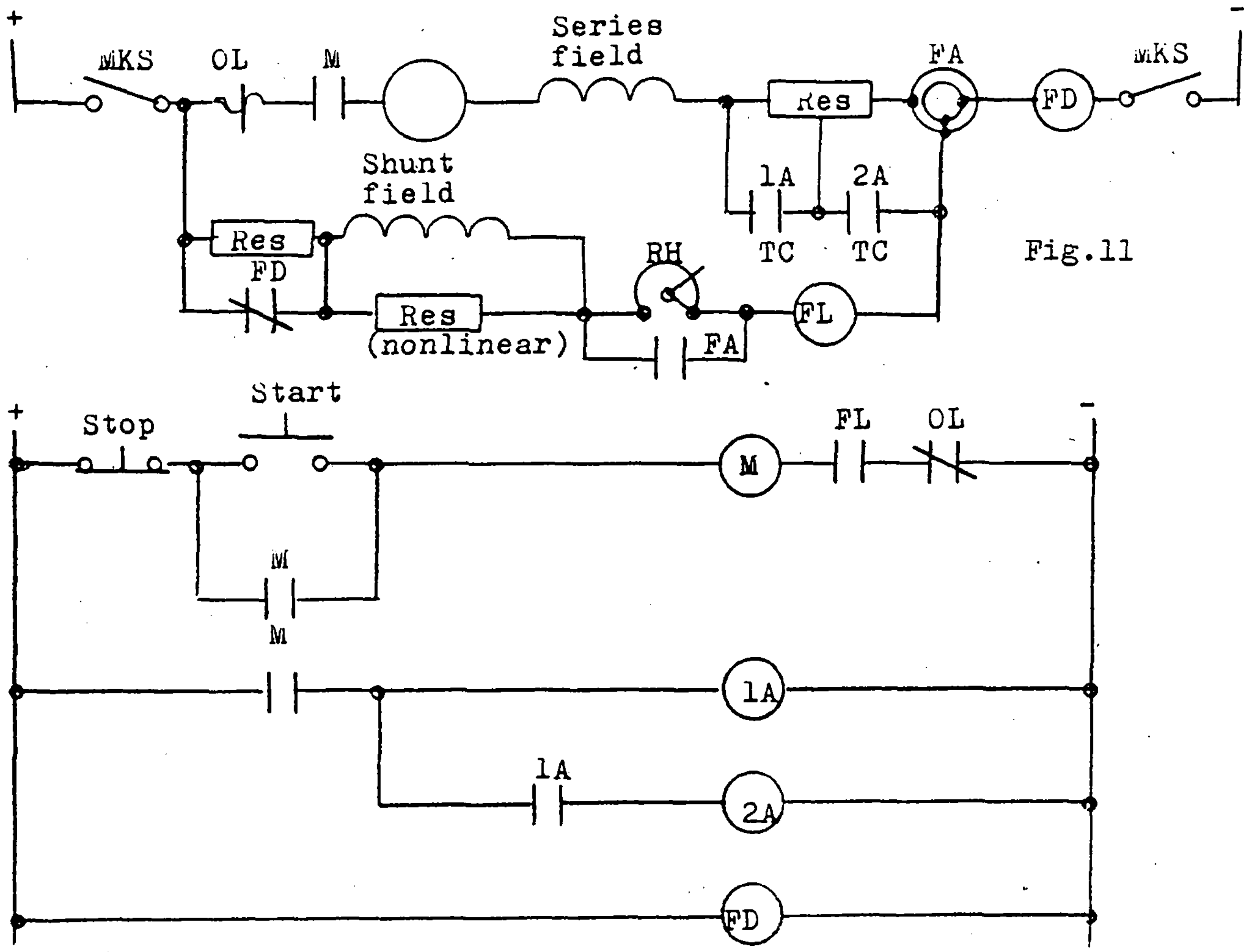


Fig.11

Reversal current can be held to an acceptable value with a field decelerating relay, FD and an associated resistor. The type of relay shown in the circuit has a series coil, which is connected in the armature circuit, and a shunt coil, which is connected across the control-circuit supply. The relay also has a normally closed contact which is connected across the resistor in the shunt field circuit.

The two relay coils are so polarized and proportioned, relative to the flux each produces, that the relay will not operate on currents flowing in the normal direction. But the relay will operate when armature current is reversed and exceeds a predetermined magnitude. When the relay does operate, its normally closed contact opens and inserts resistance in the field circuit. This additional resistance reduces the conter-emf and, thus, the magnitude of the reverse current.

Here again, other methods or devices can be used, but the end result should be the same.

k) Field Protective Relay - Fig. 12

Some motors are so designed that the shunt field is not suitable for continous duty at full field excitation when the motor is at standstill. When the motor is running, however, sufficient movement of air is caused to prevent the shunt field from overheating. The controller must therefore provide protection for the shunt field when the motor is at rest.

A field protective relay, FP, and its associated resistor, usually called the field economizing resistor, can provide shunt-field protection. The relay is a conventional type and has a normally open contact. The operating coil is located in the control circuit, while the resistor and relay contact are connected in the shunt field circuit. When the motor is stopped, the relay is de-energized and the resistor is inserted in the circuit. When the motor is

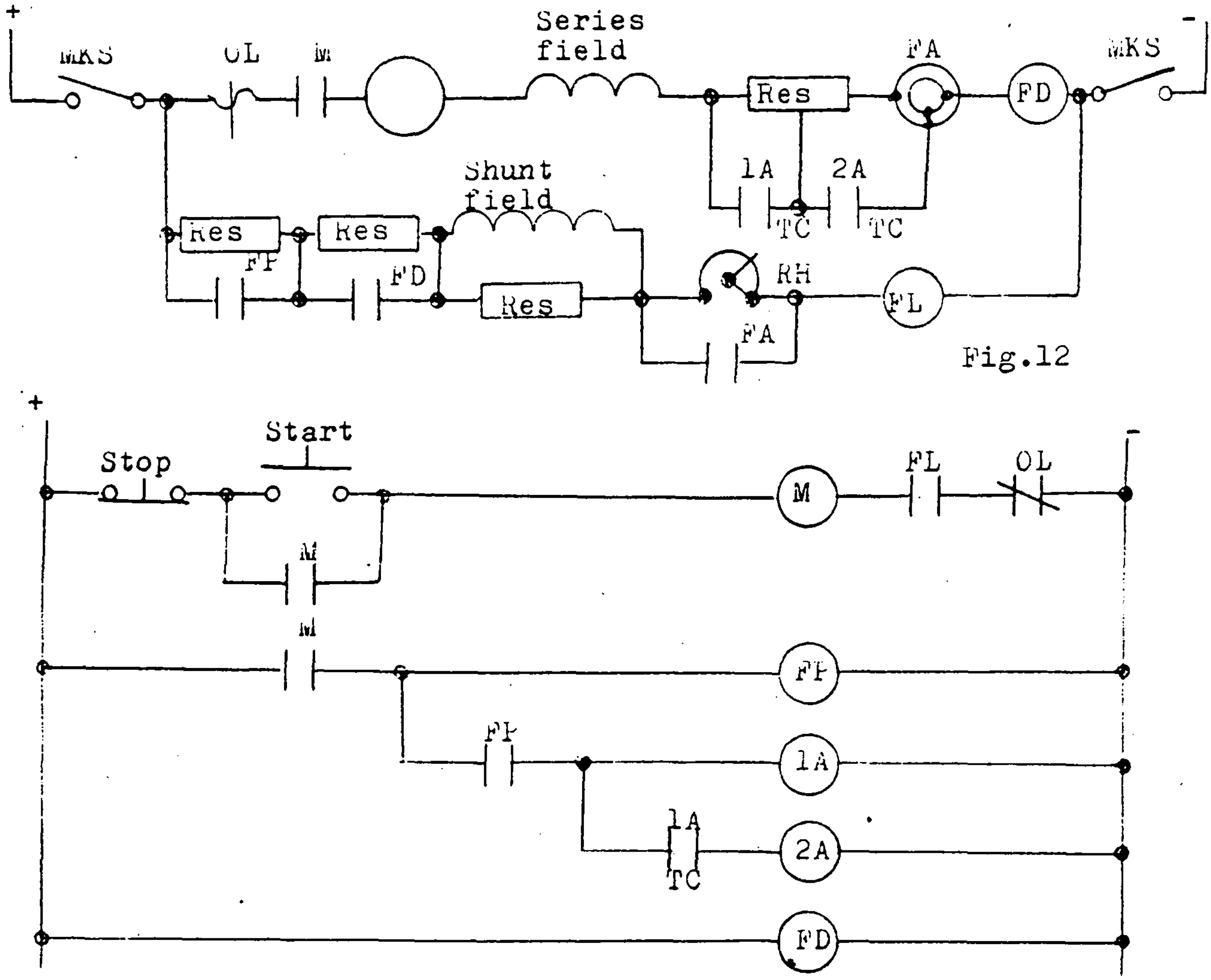


Fig.12

started and running, the relay coil is energized, thereby shorting out the economizing resistor.

A typical resistor allows about 70 per cent of base-speed field current to flow. Thus, the power, I^2R, which must be dissipated by the shunt-field winding is reduced to about 49 per cent of the normal value. In general, the value of resistance is statisfactory if field current is reduced to between 80 and 60 cent of the base-speed value, resulting in a heating effect of 64 to 36 per cent of the normal value.

1) Self Contained AC - DC Converters and Motor Controls - Fig. 13, 14

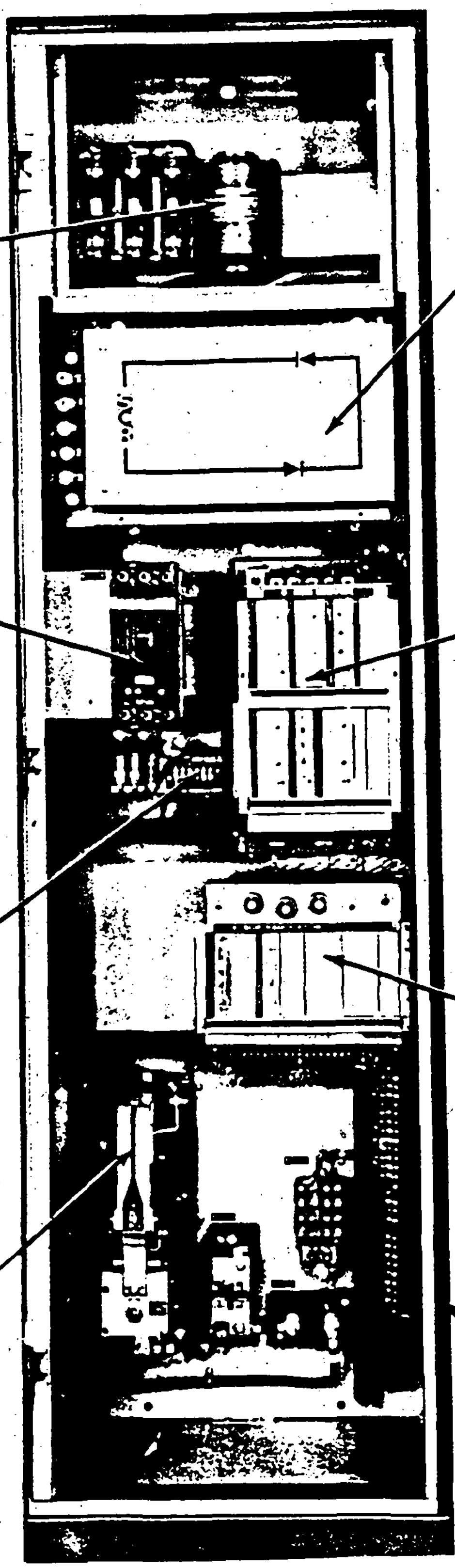


Fig. 13 - Front view, self contained ac-dc converter and motor controller.

The dc motor control devices covered in this section so far, are for connection to an already existing dc source. Unfortunately, dc power is not as readily available as ac power and it was at times cumbersome and relatively expensive to provide and maintain dc generating or conversion equipment for dc drive motors within a water supply system for instance. Dc drive motors were therefore only seldom used to drive centrifugal water pumps, even though the speed variation characteristics of the dc motor makes it ideally suited for certain applications as pump drive motor.

The dc motor however, did gain more importance in recent years as variable speed, centrifugal pump drive motor. This was mainly brought about by the advance in semi-conductor technologies, which permitted the low cost construction of self contained dc motor controllers in combination with variable output ac-dc converters.

These units are available for almost any motor size with any combination of the control features described in items a) through k). The conversion from ac to dc is accomplished by Thyristors (also known as SCR's - Silicone Controlled Rectifiers).
Fig. 13 shows the front view of such a control cubicle for a 150 hp dc motor.

The one line diagram of Fig. 14 shows the block function principles of a basic unit. The desired preset speed is set by the speed adjustment potentiomenter, which is supplied from the regulator power supply. The timing circuit applies the linearity increasing reference signal to the control amplifier during acceleration.

A tachometer is used for feedback. This speed feedback signal is compared with the reference signal from the timing circuit at the input to control amplifier. The output of this amplifier controls the driver which in turn controls the firing of the Thyristor module. The output of the Thyristor conversion module supplies variable controlled voltage to the dc motor armature. Motor starting and stopping is accomplished by means of a main contactor M. Thermal protection of the dc motor is provided by the thermal overload relay OL in the armature circuit.

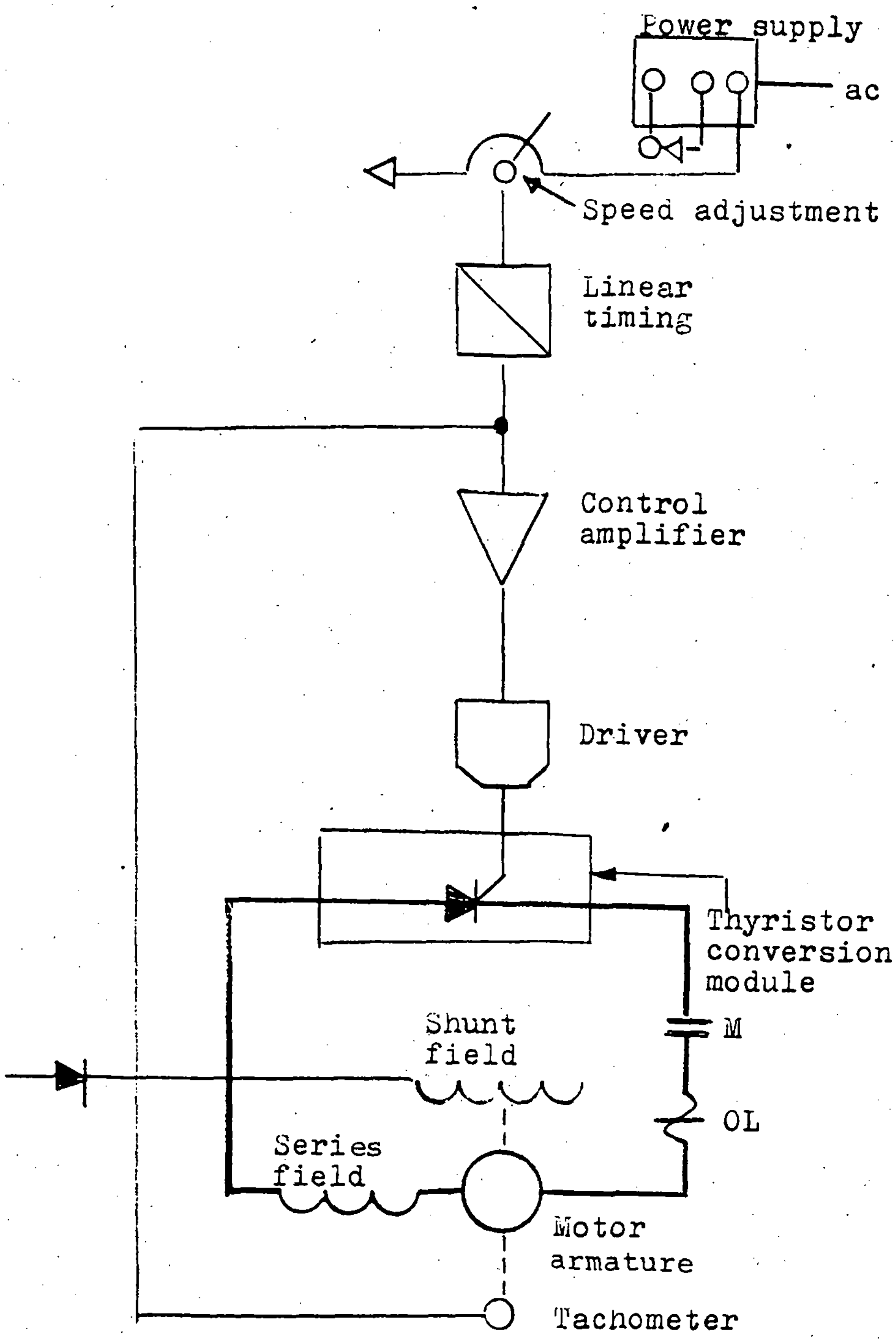
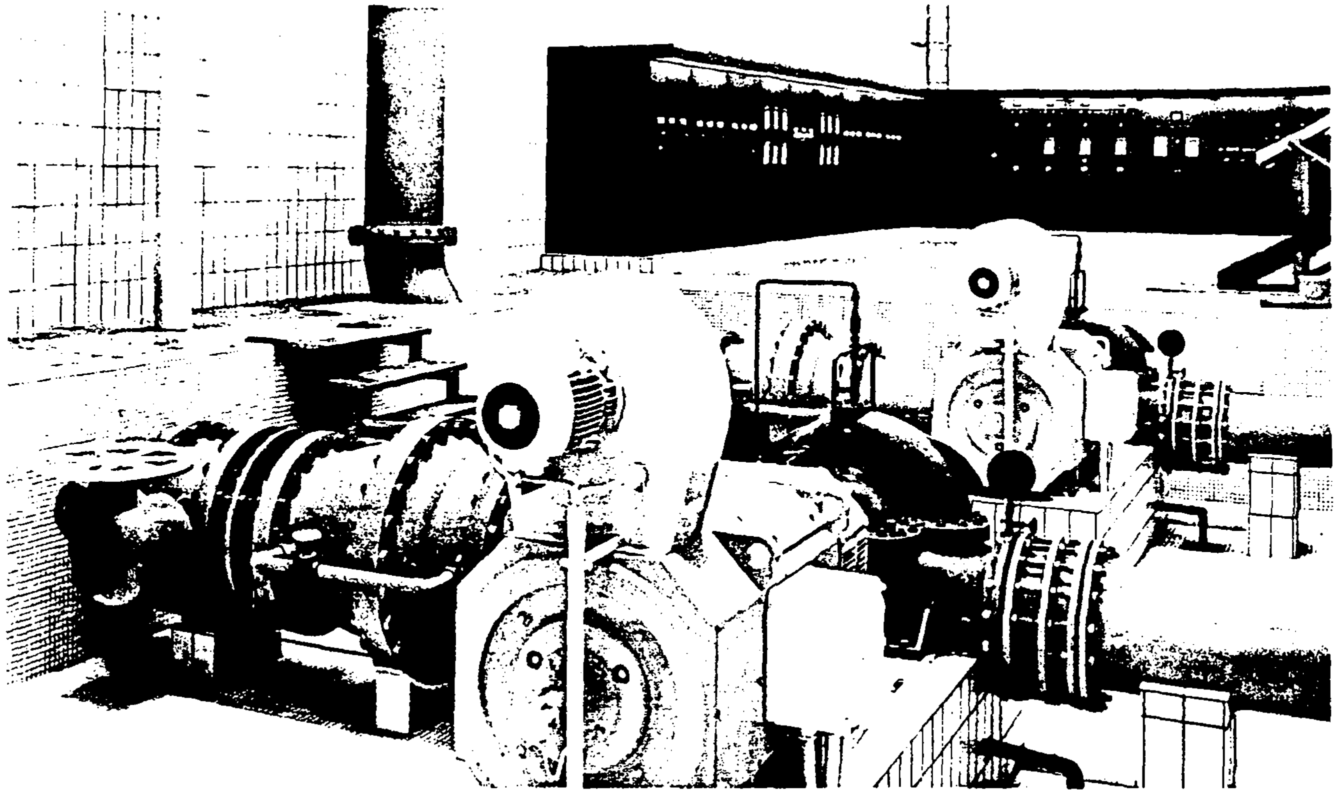


Fig. 14
One-line-diagram showing self-contained dc Motor controller with ac-dc conversion and variable dc voltage control.



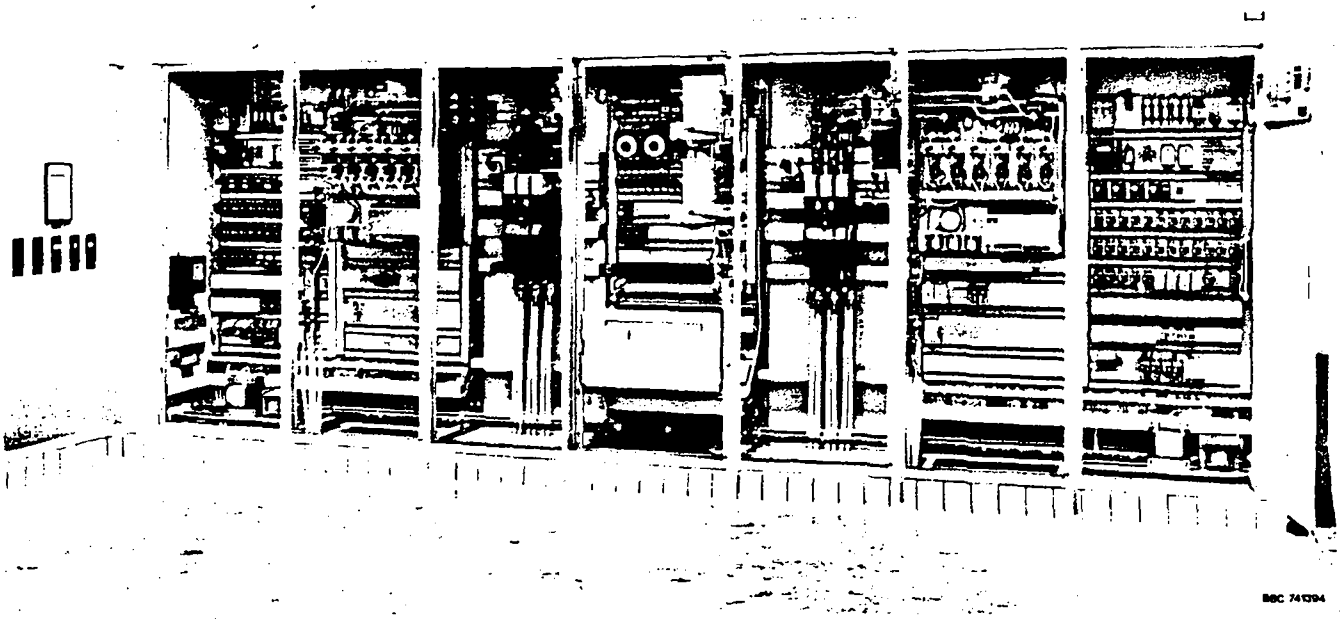


Fig. 15 - Pumping station with associated electrical equipment. The pump motors are 530 KW direct current, the controllers are self-contained similar to the units shown in Fig. 13 and 14. Note external top mounted fans on pump motors to provide adequate cooling at low rpm.

Illustrations shown in this module by courtesy of:

Fig. 2,3	The Siemens AG	Erlangen W Germany
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Fig. 15	The Brown Boveri Cie	Mannheim W Germany

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- management of all financial obligations to the partnercountry.

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TRAINING MODULES FOR WATERWORKS PERSONNEL

List of training modules:

Basic Knowledge

- **0.1** Basic and applied arithmetic
- **0.2** Basic concepts of physics
- **0.3** Basic concepts of water chemistry
- **0.4** Basic principles of water transport
- **1.1** The function and technical composition of a watersupply system
- **1.2** Organisation and administration of waterworks

Special Knowledge

- **2.1** Engineering, building and auxiliary materials
- **2.2** Hygienic standards of drinking water
- **2.3a** Maintenance and repair of diesel engines and petrol engines
- **2.3b** Maintenance and repair of electric motors
- **2.3c** Maintenance and repair of simple driven systems
- **2.3d** Design, functioning, operation, maintenance and repair of power transmission mechanisms
- **2.3e** Maintenance and repair of pumps
- **2.3f** Maintenance and repair of blowers and compressors
- **2.3g** Design, functioning, operation, maintenance and repair of pipe fittings
- **2.3h** Design, functioning, operation, maintenance and repair of hoisting gear
- **2.3i** Maintenance and repair of electrical motor controls and protective equipment
- **2.4** Process control and instrumentation
- **2.5** Principal components of water-treatment systems (definition and description)
- **2.6** Pipe laying procedures and testing of water mains
- **2.7** General operation of water main systems
- **2.8** Construction of water supply units
- **2.9** Maintenance of water supply units Principles and general procedures
- **2.10** Industrial safety and accident prevention
- **2.11** Simple surveying and technical drawing

Special Skills

- **3.1** Basic skills in workshop technology
- **3.2** Performance of simple water analysis
- **3.3a** Design and working principles of diesel engines and petrol engines
- **3.3b** Design and working principles of electric motors
- **3.3c** –
- **3.3d** Design and working principle of power transmission mechanisms
- **3.3e** Installation, operation, maintenance and repair of pumps
- **3.3f** Handling, maintenance and repair of blowers and compressors
- **3.3g** Handling, maintenance and repair of pipe fittings
- **3.3h** Handling, maintenance and repair of hoisting gear
- **3.3i** Servicing and maintaining electrical equipment
- **3.4** Servicing and maintaining process controls and instrumentation
- **3.5** Water-treatment systems: construction and operation of principal components: Part I - Part II
- **3.6** Pipe-laying procedures and testing of water mains
- **3.7** Inspection, maintenance and repair of water mains
- **3.8a** Construction in concrete and masonry
- **3.8b** Installation of appurtenances
- **3.9** Maintenance of water supply units Inspection and action guide
- **3.10** –
- **3.11** Simple surveying and drawing work

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