Industrial Motor Control Fundamentals

FOURTH EDITION

McIntyre · Losee

INDUSTRIAL MOTOR CONTROL FUNDAMENTALS

Fourth Edition

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Preface

Industrial Motor Control Fundamentals, Fourth Edition, is an introduction to electric motors and their controls. It is written for students training to be industrial electricians or technicians. The text assumes that the reader has a working knowledge of electricity and is able to solve mathematical problems by using simple formulas. The text also provides the reader with the practical foundations of the subject, together with any additional electrical or mathematical theories required to understand the discussions.

Although the text discusses the historical bases of machines and methods, its emphasis is on modern equipment and practices. Wherever appropriate, reference is made to actual equipment likely to be found in the modern industrial environment. Therefore, attention is given to the continuing widespread use of magnetically operated (relay) controls as well as to some of the older solid-state equipment.

A systems approach is used to illustrate the close relationship between rotating equipment and control devices. Process systems are similarly utilized to integrate machines and their controls. Although integrated circuits and microprocessors are rapidly dominating modern controls, their application and operation are closely related to the older relay and contractor equipment and circuits. The use of the microprocessor in programmable controllers has had a dramatic impact on controls of all types. One chapter focuses on this subject and uses a number of well-known commercial P.C.s as examples.

No text on controls would be complete without a discussion of digital logic and boolean algebra. The application of these two subjects is as pertinent to relay and contactor circuits as it is to solid-state electronic circuits. In a carefully sequenced manner, the reader is introduced to the key elements, symbols, and operations of both subjects. Schematic, wiring, ladder, and logic diagrams are used to instruct the reader to progress, step by step, from the written specifications to the final circuit diagram.

The role of an industrial electrician and technician is largely one of "hands on." To aid such a person, this text includes code references applicable to the installation of new control systems and motors, as well as information on systematic maintenance and troubleshooting techniques. Most material in this text has been reviewed and tested in the classroom by both teachers and students, and in the field by electricians and technicians. To everyone involved goes my deepest appreciation.

It is fitting here to acknowledge the groundbreaking work of the originator of this text, the late Robert L. McIntyre. Bob was a master electrician, craftsman, instructor, and author in the field of motor controls. Much is owed him for his pioneering and tireless work and enthusiasm in the field.

Rex L. Losee

Contents

1
Fundamentals of Control

This chapter is concerned with the fundamentals and history of industrial motor control. The meaning of control is discussed. Open-loop, closed-loop, and multiloop control systems are presented. The basic concepts and methods of providing semiautomatic and automatic control are also discussed. Several block diagrams of control systems are illustrated.

In the modern plant many machines are made for fully automatic operation. The operator merely sets up the original process, and most or all operations are carried out automatically. The automatic operation of a machine is wholly dependent upon motor and machine control. Sometimes this control is entirely electrical or electronic, and sometimes a combination of electrical and mechanical control is used. The same basic principles apply, however.

1-1 MEANING OF CONTROL

A modern machine consists of three separate divisions which need to be considered. First is the machine itself, which is designed to do a specific job or type of job. Second is the motor, which is selected according to the requirements of the machine, as to load, duty cycle, and type of operation. Third, and of chief concern in this book, is the control system. The control system design is dictated by the operating requirements of the motor and the machine. If the machine needs only to start, run for some time, and stop, then the only control needed would be a simple toggle switch. If, however, the machine needs to start, perform several automatic operations, stop for a few seconds, and then repeat the cycle, it will require several integrated units of control.

The word *control* means to govern or regulate, so it must follow that when we speak of motor or machine control, we are talking about governing or regulating the functions of a motor or a machine. Applied to motors, controls perform several functions, such as starting, accelerating, regulating speed, protecting power, reversing, and stopping.

Any piece of equipment used to regulate or govern the functions of a machine or motor is called a *control component*. Each type of control component will be discussed in a separate section of this book.

1-2 MANUAL CONTROL

A manual controller is one having its operations controlled or performed by hand at the location of the controller (Fig. 1-1). Perhaps the single most popular type in this category is the manual full-voltage motor starter for lower-horsepower motors. This starter is

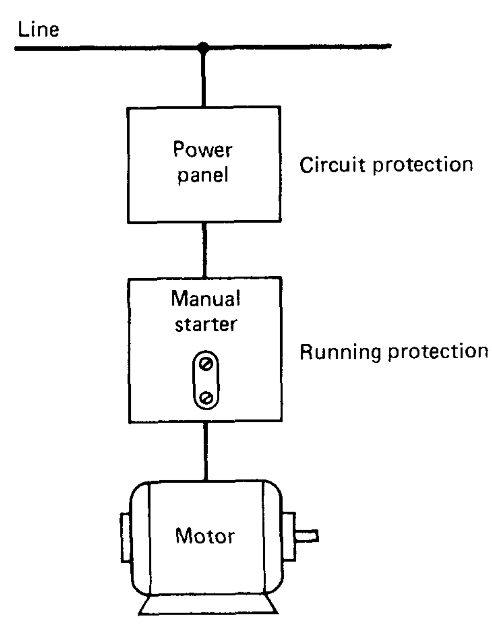

Fig. 1-1 Manual control of a motor.

frequently used where the only control function needed is to start and stop the motor. Probably the chief reason for the popularity of this unit is that its cost is only about one-half that of an equivalent magnetic starter. The manual starter generally gives overload protection and low-voltage release, but does not give low-voltage protection.

Manual control which provides the same functions as those achieved by the manual full-voltage motor starter can be had by the use of a switch with fusing of the delayed-action type, which will provide overload protection for the motor.

Examples of this type of control are very common in small metalworking and woodworking shops, which use small drill presses and lathes and pipe-threading machines. Another example is found in the exhaust fan generally used in machine shops and other industrial areas. In this installation the operator generally presses the START button for the fan in the morning when the plant opens, and the fan continues to run throughout the day. In the evening, or when the plant is shut down, the operator then pushes the STOP button, and the fan shuts down until needed again. The starter for welding machines of the motor-generator type is a very common application of this kind of control.

The compensator, or manual reduced-voltage starter, is used extensively to control polyphase squirrel-cage motors where reduced-voltage starting is required and the only control functions required are start and stop. The compensator gives overload protection, low-voltage release, and low-voltage protection. The compensator-type starter is quite frequently used in conjunction with a drum controller or wound-rotor motors (Fig. 1-2). This combination gives full manual control of start, stop, speed, and direction of rotation.

The compensator, being a reduced-voltage starter, is generally found only on the larger-horsepower motors. A very common use of the compensator and the drum controller combination is in the operation of many centrifugal-type air-conditioning compressors. The reduced-voltage feature is used to enable the motor to overcome the inertia of the compressor during starting without undue current loads on the system. The drum controller, through its ability to regulate the speed of a wound-rotor motor, provides a means of varying the capacity of the air-conditioning system, thus giving a flexibility that would not be possible with a constant-speed, full-voltage installation.

These are just a few examples of manual controllers, but you should have little trouble classifying any unit of this type because it will have no automatic control function. A manual controller requires the operator to move a switch or press a button to initiate any change in the operation of the machine or equipment.

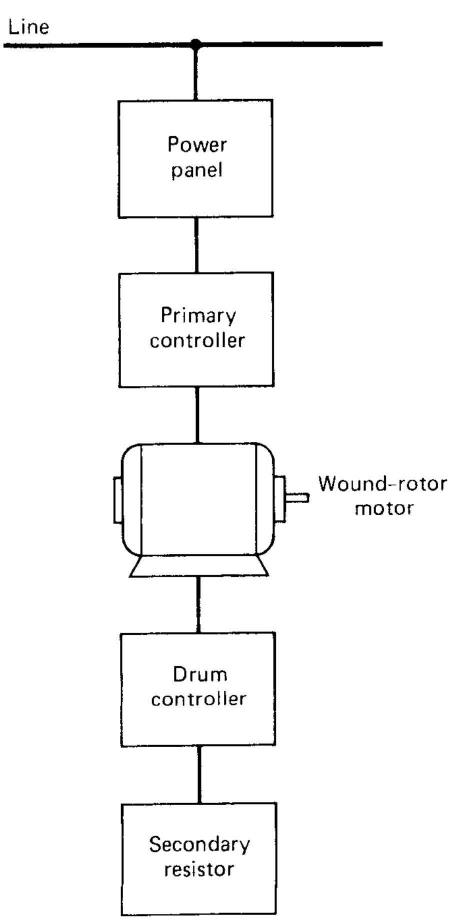

Fig. 1-2 Control for a wound-rotor motor.

1-3 SEMIAUTOMATIC CONTROL

Semiautomatic controllers use a magnetic starter and one or more manual pilot devices, such as pushbuttons, toggle switches, drum switches, and similar equipment (Fig. 1-3). Probably the most used of these is the push-

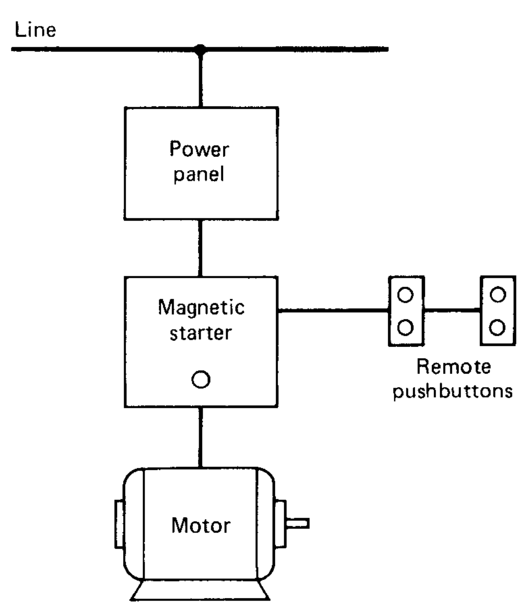

Fig. 1-3 Semiautomatic control for a motor.

button station because it is a compact and relatively inexpensive unit. Semiautomatic control is used mainly to give flexibility to the placement of the control in installations where manual control would otherwise be impractical.

A control system whose pilot devices are manually operated and whose motor starter is magnetic is classified as a semiautomatic control system. There are probably more machines operated by semiautomatic control than by either manual or automatic. This type of control requires the operator to initiate any change in the attitude or operating condition of the machine. Through the use of the magnetic starter, however, this change may be initiated from any convenient location, whereas manual control requires that the control point be at the starter.

1-4 AUTOMATIC CONTROL

In its simplest form, an automatic controller is a magnetic starter or contactor whose functions are controlled by one or more automatic pilot devices (Fig. 1-4). A pilot device provides a source of information to a control system. As an example, a thermostat, level switch, pressure switch, or flow switch can be used to provide information concerning the process variables that are being controlled. Temperature, liquid level, pressure, and flow are examples of process variables that are automatically controlled by magnetic starters, pilot devices, and motors.

Motor control can be classified as open-loop or closed-loop control. A switch that requires manual adjustment to start and stop a motor is an example of open-loop control. Open-loop control is used in manual control systems where an operator is always present to make decisions such as when to start and stop a motor.

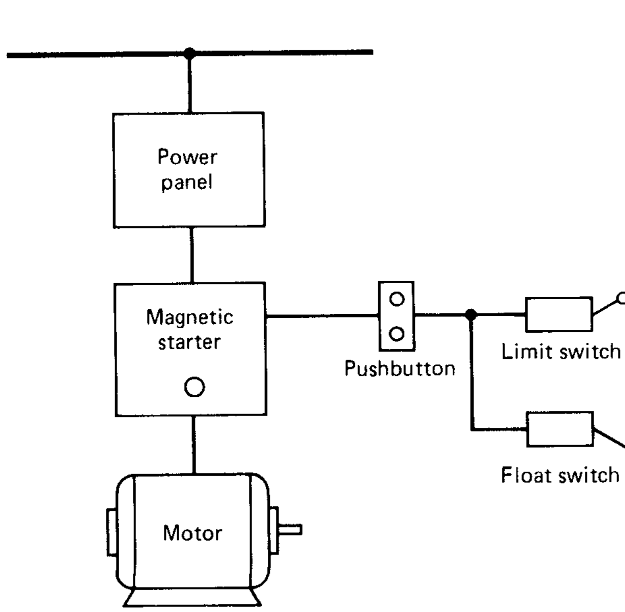

Fig. 1-4 Automatic control for a motor.

Closed-loop control is illustrated by the level-switch control used to regulate the level of liquid in a tank. Block diagrams for closed-loop control systems may appear as in Figs. 1-5 and 1-6.

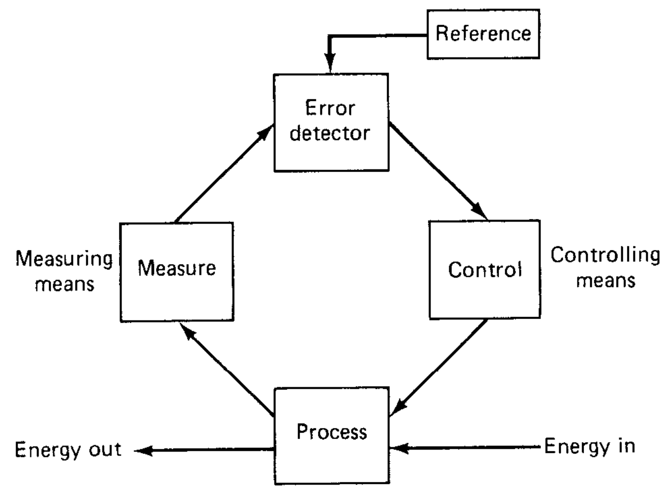

Fig. 1-5 Closed-loop control block diagram.

In a closed-loop system, as illustrated by the block diagrams in Fig. 1-5, it can be seen that by the feedback of information concerning a process parameter (level, for example) and the comparison of that information with a reference (desired level), a decision can be made by the error detector as to when the controlling means (starter and motor) should start and raise the level in the tank. In a closed-loop control system, it is obvious that the process controls itself by the feedback of its condition.

In the block diagram for the closed-loop control system of a refrigerator (Fig. 1-6), notice that the following control action would occur. The thermostat, or temperature-actuated switch, would be adjusted to the desired temperature. The thermostat responds to the actual temperature inside the box. The reference signal (R) is compared with the feedback signal (B). Any error or difference between the reference signal (R) and the feedback signal will produce an actuating signal (E). If the refrigerator temperature is too high, signal E will turn on the control system (motor and compressor)

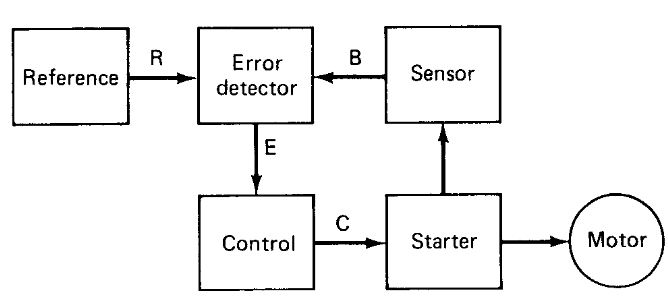

Fig. 1-6 Closed-loop control block diagram for a refrigerator.

to bring the refrigerator to the desired temperature. If the temperature is too low, the signal E causes the control system elements to turn off in order to restore C to the desired value. The blocks in Fig. 1-6 are continuously providing outputs that are fed around and around the loop, making the system a closed-loop control system. Once the start is initiated, the process controls itself in this type of control system.

Regulators are used in many industrial applications to control the voltage output of generators, speed of dc motors, and positions of loads. Regulators are essentially examples of closed-loop systems. In a later chapter we will see how solid-state regulators are used to provide speed control for dc and ac motors. Regulators may be defined as a closed-loop systems that maintain a steady level or value for some quantity, such as voltage, current, speed, temperature, pressure, and the like.

In industry there are control systems responsible for the positioning of large objects. Examples include the positioning of the rolls in a steel-rolling mill and the turning of a rudder on a large ship. The control system that is used for this type of control is called a *servomechanism*, or *servo system* for short. A servomechanism is a closed-loop system that moves or changes the position of the controlled object so that it will follow or coincide with the position of a control device or director. The servomechanism is often located at a location remote from the controlled object. A servo system requires motors to cause mechanical movement. Servos are discussed in greater detail in later chapters.

Automatic control is also illustrated by the system shown in the block diagram of Fig. 1-7.

The information section of the block diagram of Fig. 1-7 will contain pilot or information devices or sensors to initiate control action. The power control block will consist of motor starters and controllers or any other control device that provides power to the action devices. The action devices of the process are motors, generators, solenoid valves, heaters, etc. The block we jumped over, the decision-making block, is what this book is all about. This block is where all the control of the electric motor originates.

In the early automatic control systems decisions in control action were made by relays. The relay soon became unable to keep up with all the demands for high speed, long life, and high reliability that was placed on it. Static switching devices were developed in the 1950s that replaced relays and provided the same logical decisions that relays make. The transistor became the workhorse of the logic and static switching devices of 1960s and early 1970s. Logic control using transistors, printed circuit boards, resistors, diodes, and capacitors were found in many of the various electronic logic systems. In the 1970s integrated circuits, with all the logic of many transistors found on one chip, made great strides in decision-making control systems.

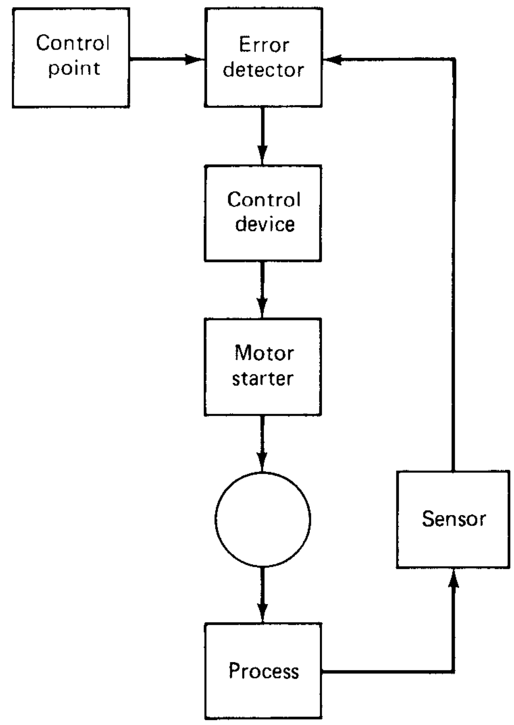

Fig. 1-7 Block diagram of an automatic control system.

In the late 1970s and the 1980s the major advances in solid-state devices for dedicated control systems have been the creation of the microprocessor and programmable controllers. When a control system is designed for a specific application, it is called a *dedicated control system*. The programmable controller by the middle 1980s was the workhorse of industry as far as providing dedicated and programmed control. Programmable controllers became the most popular decision-making devices in the automatic control of electric motors.

With all the changes through the years in automatic control, it is interesting that electric motors have really not changed significantly. Motors and conventional motor control are essentially the same as they have been for years. Automatic control has been through many changes in just a few years' time. A computerized integrated control system produced by General Electric Company will be used to illustrate the elements of automatic control (Fig. 1-8).

In the block diagram of the industrial control system illustrated by Fig. 1-8, each block is given a name. The raw materials enter the system in the lower-right corner. The equipment that converts the raw material to the processed material, or finished product, is indicated by the block labeled "Process Equipment." This equipment may be mills, machines, fabricating equipment, and the like. The motors that drive the process equipment are called *prime movers*. The speed, direction of rotation, time on, time off, sequence of starting and stopping, and other control actions are accomplished by the input to the block labeled Adjustable

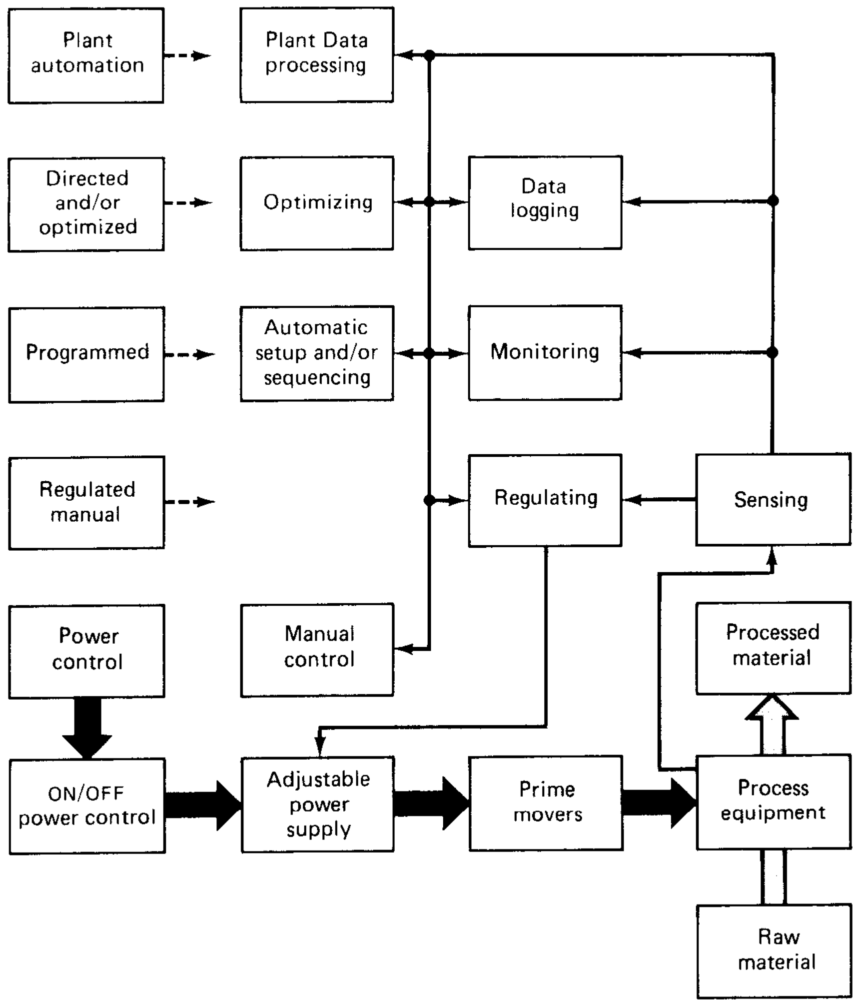

Fig. 1-8 Block diagram of an industrial control system.

Power Supply. All the remaining blocks of the control system in Fig. 1-8 contain many control loops. This type of control system is often referred to as a *multiloop control system.* By looking at only the motor control for large industrial control systems it can be seen that many loops are used to control the machines in a manufacturing process. Multiloop control has many applications in machine control. The following will summarize the function of the blocks in Fig. 1-8:

PROCESS CONTROL

Manual Control. Accepts manual commands and translates them into appropriate signal commands for the other functional blocks and receives control status signals and converts them to manageable information. Examples are

- Pushbutton
- Selector switch
- Rheostat
- Indicating light
- Digital display
- Horn

Regulating. Accepts a reference signal, compares it to a feedback signal, and provides an output to cause the feedback to equal the reference. Examples are

- Voltage regulator
- Position regulator
- Flow regulator

Sensing. Converts a sensible, physical quantity (or quantities) into a usable control signal proportional to a process parameter. Examples are

- Tachometer (converts rate of rotation to voltage)
- Current transformer (converts large current to signal-level current)
- X-ray thickness gage (converts penetration of x-ray to signal proportional to thickness)

Monitoring. Continually measures conditions within the system and communicates any departure of these conditions from predetermined limits. Examples are

- Steam-turbine monitoring system (checking that temperature and pressures have not exceeded limits)

Fault-monitoring system (checking order and occurrence of faults)

Automatic Setup and/or Sequencing. Provides predetermined reference signals for setup and command signals for sequencing in a prescribed order. An advance from one step of output to the next may be initiated by time or by some feedback from the process (such as operation completed). The predetermined program or sequence may be stored on manually operated switches, punched cards, memory, etc. Examples are

Start-up sequence control for a conveyor system

Card program control for a reversing hot mill

Changing control for a batch chemical process

Data Logging. Provides a record of conditions existing within the process. Examples are

Strip chart record of process speed, temperature, position, etc.

Typewriter log of performance data in a power plant

Optimizing. Provides overall direction for the process, taking into consideration what is to be made and how it can best be made under the conditions within the process at that instant in time. Thus, feedback for actual process operating conditions is utilized to determine the optimal manner in which the process is to be operated. Examples are

Adaptive schedule calculation for a reversing hot mill

Optimizing the relationship between temperature and catalyst feed rate in a chemical process

Plant Data Processing. The determination of the schedule of operations for each unit of process equipment in the overall plant complex. In general, the input to plant data processing is the customers' orders and the output to each process equipment control system is what to make, how much to make, and how fast to make it. Examples are

Manual scheduling of a small manufacturing operation

Computer scheduling of a large manufacturing operation

POWER CONTROL

On-Off Power Control. Controls, in a completely on or off manner, the flow of power from the main source to the adjustable power supply or prime movers, or both. Examples are

Motor starter

Valve

Adjustable Power Supply. Converts a constant amount of energy to an adjustable amount of energy such that the prime mover can be given the proper speed, torque, etc. Examples are

Generator

Valve

Static armature supply

Prime Movers. Equipment which converts some form of energy (such as electric) to mechanical energy usable by the process equipment. Examples are

Electric motor

Heat exchanger

Gas turbine

Process Equipment. Equipment which processes or acts on the material in the manufacturing process. The processing may include operations such as shaping, cutting, moving, heating, and distilling. Examples are

Distilling column

Reversing hot mill

Material-sorting conveyor

1-5 BASIC CONCEPTS OF AUTOMATIC MOTOR CONTROL

Automatic control had its beginning with the development of the relay. The design of relays lends itself to automatic control. Relays can perform many functions required by basic automatic control. Their contacts can be normally open or normally closed, or a combination of both. They can provide such timed operation to their contacts as time opening or time closing. They can be designed to provide stepping, sequenced, or latching operations. Many variations of contact arrangements are available to provide automatic motor control. Relays can provide such automatic control as reversing, braking, accelerating, decelerating, plugging, jogging, and the like.

For many years the relay provided adequate control for the automatic machinery of industry. As automatic control became more demanding, the relay was strained to its limits. High-production industries required liberation from the slow-acting, ever-failing, and short-lived relay. While the relay is still adequate for some automatic control systems, it cannot provide the reliability and dependability needed for high-speed, high-production industries. With the development of static and logic control, the relay panels for the conventional automatic control system have been rapidly replaced with this new control system. Static and logic control provides the dependable reliable control for high-production automatic control systems.

The three main divisions of an automatic control system are the information section, action section, and decision-making section.

The information section of the control systems contains such pilot devices as pushbuttons, limit switches, and sensing devices that are used to indicate such variables as pressure, temperature, flow, voltage, current, light, humidity, conductivity, or some other quantity. The information devices found in modern control systems may use solid-state devices to accomplish the measurement or detection of the different process control variables requiring control action.

The action section of automatic control systems contains the motors, starters, solenoids, heaters, coolers, and power devices that provide the regulating action in the control system. The action section may contain individual starters or motor control centers that control many motors at the same time.

With static and logic control devices replacing relays, logic components have become the decision-making devices in this generation of control devices. Static and logic control has opened a vast new system of automatic control for the rapid, fully automated machines and processes of industry.

STATIC CONTROL AND LOGIC CONTROL

Devices found in the earlier Westinghouse Cypak (logic in a package) and General Electric Company static control systems both used magnetic amplifiers in their logic units. Transistor logic systems followed the magnetic amplifier generation; solid-state integrated circuits (ICs) are used in the latest generation of logic and static control. Logic systems using transistors and ICs will be covered in later chapters.

Logic and reasoning are usually associated with the human mental process. However, circuit logic does not imply that circuits possess any mental or intellectual ability. Logic circuits are designed to give a logical response when presented with certain input conditions. Logic devices use two-state (on-off) devices to perform decision-making functions in the control of machines. The essence of a logic control circuit is in recognizing that a certain condition exists and making an appropriate response. The simplest form of logical response is "yes" or "no," or "on" or "off."

Logic circuits need control signals from sensing devices to give them the required information to trigger the logic response. Signals are the basis for all industrial control. They determine the number of operations that must be performed and how they should be performed to produce the required end results. Signals may be amplified, transmitted, or switched.

Signals fall into two general classifications: analog and digital. A digital signal is a sharp, discrete signal of definite short duration. A pulse is an example of a digital signal. An analog signal is a continuous signal that represents some quantity or value over a period of time. A signal from a tachometer generator is an example of an analog signal. The variations in speed indicated by the tachometer take place over an infinite number of steps. Logic functions are primarily concerned with digital signals.

A logic function is a means of expressing a definite condition. Three logic functions are used to express a condition, a set of movements, or a specific arrangement of information. These logic functions are AND, OR, and NOT.

In the AND logic function there is an output only when all of the input signals are present. In the OR logic function there is an output when any one of the inputs is present. In the NOT logic function there is an output when there is no input present. The memory function will give a continuous output after a momentary ON input. The output will cease after a momentary OFF input. Other logic devices, such as DELAY units, NANDS, NORS, amplifiers, signal converters, etc., will be included in logic control systems.

Logic elements are different than relays in several ways. Unlike relays, logic elements have no moving parts. Because they have no moving parts, they are often called *static switching devices*. Static control and static switching are terms that pertain to devices that switch without moving parts. Because static control has no moving parts, it offers a much higher degree of reliability and much longer life than conventional relays. Static switching devices are usually sealed in such a way that atmospheric environment will not have any effect on their operation. They are usually encapsulated in a durable compound that is unaffected by dirt, dust, oils, acid, alkalies, and solvents. Greater system reliability is ensured with the use of static components. Another advantage of static and logic switching is that it provides much higher speeds of operation than relays. Static switching differs from relays also in the number of inputs and outputs. A relay has only one input but several outputs. Static switching devices have several inputs but only one output. This requires a different type of circuitry than conventional relay control.

Binary logic consists of only two states or conditions. The two states can be represented by the numbers 0 and 1. The number 0 can be used to represent "off," "no," "minus," or "down" and the number 1 can be used to represent "on," "yes," "plus," or "up." Binary logic can be used to control basic circuit operations, whose electrical signals can have only one of two states. The principles apply equally well to pneumatic, hydraulic, electrical, electronic, mechanical, and even optical control.