INDUSTRIAL ELECTRONICS

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McGRAW-HILL BOOK COMPANY, INC.
New York Toronto London

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 Library of Congress Catalog Card Number 62-12483.

Preface

Electronic systems are used by industry to sense, measure, warn, and control. The list of industrial applications is so long that it appears all industry has some use for the magic of electronics.

This book is intended as a text covering the important industrial applications of electronics. Because electronic devices, products, and systems are ubiquitous, perhaps the scope of this book can best be defined by exclusion: no broadcast or entertainment radio or television receivers or transmitters are included. Certain aspects of television, two-way radio, and data processing are included to show how they are related to and used by industry. A minimum of material has been included on motors and generators, as the great detail given them in many other texts is not necessary here.

This book has been prepared for use by students at the technical-institute level. The student should have had courses in basic electronics, vacuum tubes, and possibly AM radio receivers and transmitters to use this book most effectively. No prior knowledge of semiconductors is assumed. A minimum of mathematics is used in this text, and this is limited to algebra and some trigonometry, plus graphs and charts to show interrelationships between variables.

Borderlines for industrial electronics are not easy to draw. Emphasis has been given to broad techniques which have wide applicability to a variety of industrial equipment. Many of the devices and circuits described are those actually used in industrial electronics, but fundamental principles have been given first-order importance. This will permit transfer of knowledge from one circuit, device, or technique to other situations which are related. To provide for a broad understanding of industrial electronics, emphasis has been placed on basic devices and circuits.

Industrial electronics promises to be the fastest-growing segment of the electronics industry in coming years. Widening uses of computers, industrial controls, communications—particularly in microwaves—and testing and measuring equipment have been largely responsible for the past growth in the field. The total sales of equipment are still relatively small, but the impact of electronics on industrial and commercial markets has hardly begun.

As electronics technology progresses and costs of advanced products are reduced, more and more applications of electronics in industry and commerce will be seen. The basic reason for this expectation is the pressure on American industrial management to reduce expenses in the face of constantly rising material and labor costs and increasing foreign competition.

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CHAPTER

1

Industrial Electronics

1·1 Electronics in industry Electronics is an exciting field. The electron stream can warn, inspect, detect, measure, and also do a host of other things in modern industry. At one time, not so long ago, industrial electronics meant only motor control and small switching systems. Now, industrial electronics offers its techniques to almost every industry and process in many ways. The age of automation has brought a new meaning to electronics.

From simple switches and solid-state devices to X-ray beams, solar cells in orbit (Fig. 1·1), and heavy-duty gas tubes, electronics has many roles to play in industry and science.

An electronic counter, for example, as shown in Fig. 1·2, has a number of different applications, such as counting objects, measuring frequency, or measuring time. Counters are also used in modern computers.

In addition to their applications in computers there are many uses in industrial electronics for high-speed, direct-reading electronic counters. These can be used to control any operation or to activate an alarm after a preselected total count has been reached.

Any electrical, mechanical, or optical events which can be converted into electric impulses can be counted and controlled. Devices to effect this conversion may be photocells, magnetic coils, switches, and suitable transducers for pressure, temperature, velocity, acceleration, and displacement.

Many circuits used in electronic counters are similar to those found in radio, TV, and regular test equipment. Counting and frequency measurement are closely related. A number of electronic and electromechanical configurations are possible. Tubes, transistors, and relays are used in multivibrator, flip-flop, staircase, and blocking-oscillator circuits.

Computers, both digital and analog, are significant in their growing importance as tools; both types are shown in Fig. 1·3. They use certain logic circuits for specific functions.

Although logical design is employed for large-scale digital computers, it is not limited to this area. The same principles have a direct bearing on, and increasing importance in, control circuits for other types of electronic devices. The automatic control of manufacturing processes is an area where logic plays an important role. Wherever relays, transistors, or vacuum tubes are used for control, logic is an aid to design and understanding of the circuit operations.

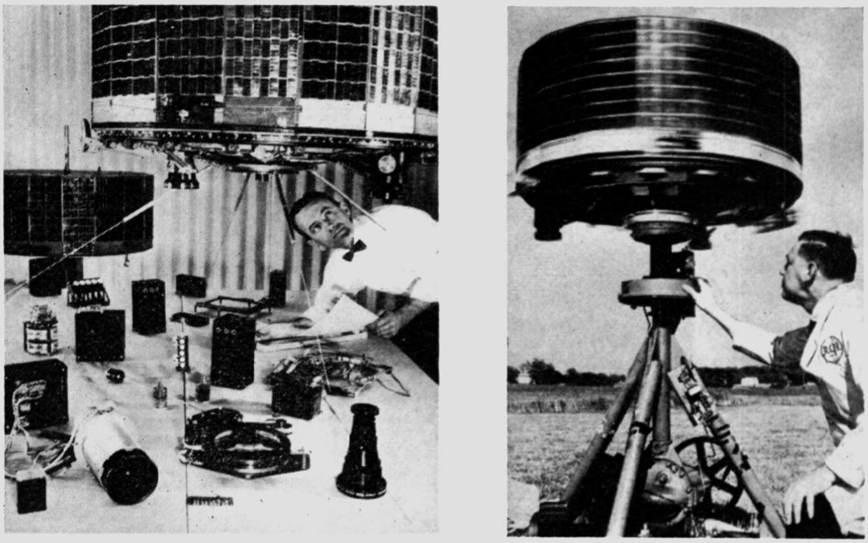


Fig. 1·1 Solar cells used to generate electric current directly from the sun's rays on Tiros satellite. (*International Rectifier Corporation*)

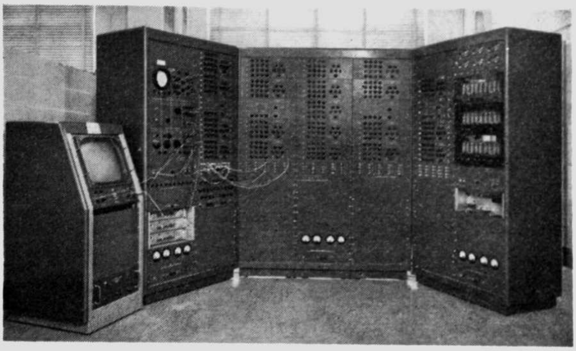
1·2 Electronic control systems Many of the industrial electronic systems discussed in this book may be considered as having three related blocks in a diagram of the system as shown in Fig. 1·4. Something is manufactured, tested, or packed in the process. A transducer monitors this process and creates control signals, which are amplified and acted upon by the control circuits. One of the outputs from the control circuits can be an indicator. Another output is the controlling action itself, which acts upon the process.

One of several ways of classifying automatic control systems is defining their action in terms of proportional, floating, or two-position control.

Two-position control provides full-on or full-off operation of the controlled device. There are no intermediate positions. Many applications such as simple on-off motor control are best served by two-position arrangements.

Fig. 1·2 Counter used to measure units of time, to count events or electric pulses, and to measure frequency. (*Northeastern Engineering*)

A



B

Fig. 1·3 (*A*) IBM 7090 Data Processing System, a large-scale digital computer used for industrial, business, and scientific calculations. (*B*) Philbrick analog computer as installed in the mechanical engineering department of Massachusetts Institute of Technology.

In floating control the position of the controlled device is varied as required to maintain conditions at the control set point. Floating control permits the system to stop at any position between "full on" and "full off," but applications for floating control are limited because of the tendency to overshoot. Overshooting is likely to set up a condition of cycling, also called "hunting," in the system. Both overshooting and hunting are the result of time lags in the overall system.

In proportional control the actuators assume a position proportional to the change in conditions. These conditions can be almost any other controlled variable, such as temperature, pressure, or light. For a given

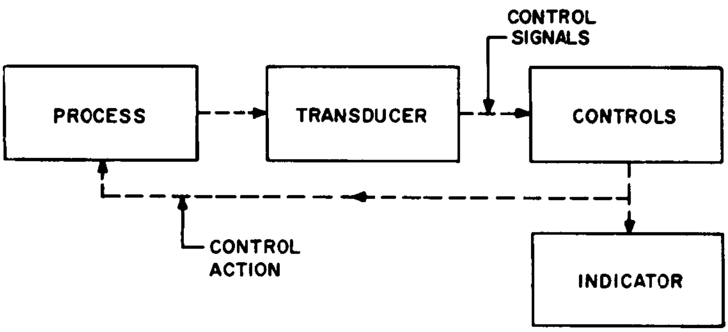


Fig. 1·4 Process-control loop showing the transducer, actuated by the process, feeding control signals which are fed back for control.

increment of change in the variable, the controlled device will move to a definite and corresponding position which is proportional to that increment. In this way the cycling of floating control is avoided since the position reached by the actuator is always the same for any given load on the system. Proportional action uses feedback, which is a link from the actuator to the controlled device. As the actuator moves in response to a change in load, a signal is returned or fed back. The effect of this feedback is opposite to that of the change caused by the load change. When these opposite effects balance, movement in the system is stopped, usually before it can reach the extreme "open" or "closed" position.

Figure 1·5 shows several simple systems. The control in *A* is two-position since closing the switch *S* turns on the load by providing power from the source and opening the switch cuts off power to the load. *B* shows a potentiometer used to vary the amount of power applied to the load; this is a type of floating control. Any amount of power from "full on" to "full off" may be applied. *C* illustrates the principle of feedback and proportional control. Load *L* is a light, part of which goes to a photocell. In darkness, when there is no outside light, the photocell calls for more light from *L*. When there is sunlight, the control turns *L* off.

1·3 Transducers Industrial electronic systems can measure, detect, count, control, warn, and inspect; but for any of these operations, a sensor is required to produce the electric signal. In a home or industrial heating system, for example, closing the switch in a simple open-loop system will cause current flow and the resulting heating of the resistive element, but as long as the switch is closed there will be heat. Adding a bimetallic thermostat makes this a closed-loop system in which the bimetal is a sensor which controls the heating and turns the circuit on and off;

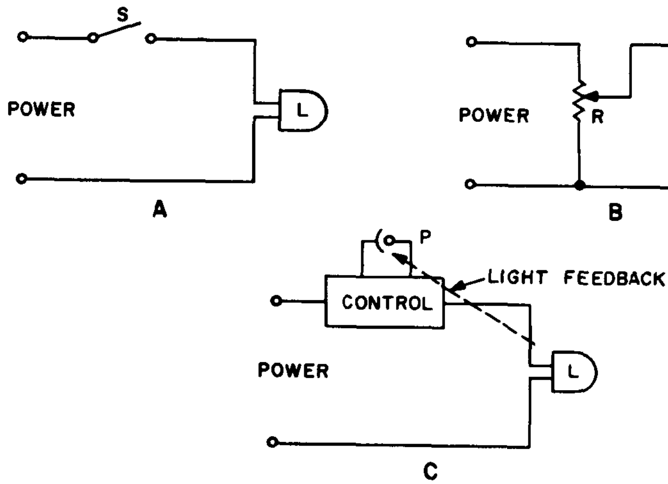


Fig. 1·5 Types of control: (A) a simple off-on switch; (B) a variable power control; and (C) the use of a light-path feedback.

in a manner of speaking it is a "decision maker" since it senses the temperature and either opens or closes the circuit.

This temperature device is a sensor or transducer which changes some physical property such as heat, light, or temperature into an electrical quantity such as current, voltage, or resistance. There is a wide range of possibilities. A transducer, which is somehow mechanically or electrically coupled into an electronic circuit, can vary capacitance, inductance, or resistance to produce a change in current, voltage, or frequency by means of various techniques including the use of piezoelectric, photoelectric, or magnetic devices. By this system it is possible to measure, among other things, pressure, temperature, or humidity.

Many industrial systems use transducers between the process and the electronic control. The control itself has a feedback action to the process and, often, an indicator as well.

The list of transducers is very long and may be divided according to the parameter being measured, the type of measurement, or the technique for producing the electric signal.

Not included specifically in this discussion are the more obvious types such as magnetic pickups, photoelectric sensors, and thermosensitive devices, which are all discussed in detail in other chapters.

Humidity can be measured easily with hygroscopic materials, such as calcium chloride, zinc chloride, or similar compounds in a gridlike structure or an insulating base. As the humidity increases, the material absorbs water from the air and changes its resistance.

The strain gauge is a transducer of special importance because of its wide use. Made of fine wires, about 0.001 in. in diameter, this gauge is usually mounted on a piece of paper for support. The paper is, in turn, cemented onto the structure to be measured. When, under physical stress, the object bends or twists, the wire in the gauge changes its resistance because it is stretched a small amount. As its length is increased the total resistance, of course, is also increased. Typical wires are made of constantan, Nichrome, and nickel. A strain gauge forms one leg of a Wheatstone bridge which is unbalanced to produce an a-c signal output to an amplifier. Strain gauges are in wide use because of their small, flexible, easy-to-use nature and their high stability.

In another transducer, the diaphragm (which can measure barometric pressure) can be used to force a coil core to move. Here alternating current is coupled to the two push-pull tubes. Motion of the core, either in or out, creates an unbalance which can be read, as voltage, on the meter between the anodes of the amplifiers.

1·4 Control signals A variable current or voltage is used to signal the state and action of control systems. Control signals are of three main types: changing d-c levels, a-c sine waves, and complex waveshapes.

Changing d-c levels are amplified by being chopped into a series of segments which are then sent through a-c amplifiers. D-c amplifiers are also used, but not often, because they tend to drift and because they cannot be used for more than two or three stages without serious voltage-supply problems.

Sine-wave signals appear frequently in industrial electronics. Either the sine-wave phase or its amplitude can be varied to cause a change in the signal.

In a simple RC circuit, with applied alternating current, current and voltage are not in phase. They differ by an angle θ whose tangent is X/R. If $X \gg R$, the current leads the voltage by almost 90°. If $R \gg X$, the current and voltage are almost in phase and θ is small.

For a capacitive reactance, current leads voltage; for an inductive reactance, voltage leads current.

To obtain a phase shift, usually R is variable while C is fixed. The amount of phase shift is a function of both X and R, as shown in Fig. 1·6. For example, if $R = 1{,}000$ ohms and $X = 100$ ohms, the phase angle is about 6°.

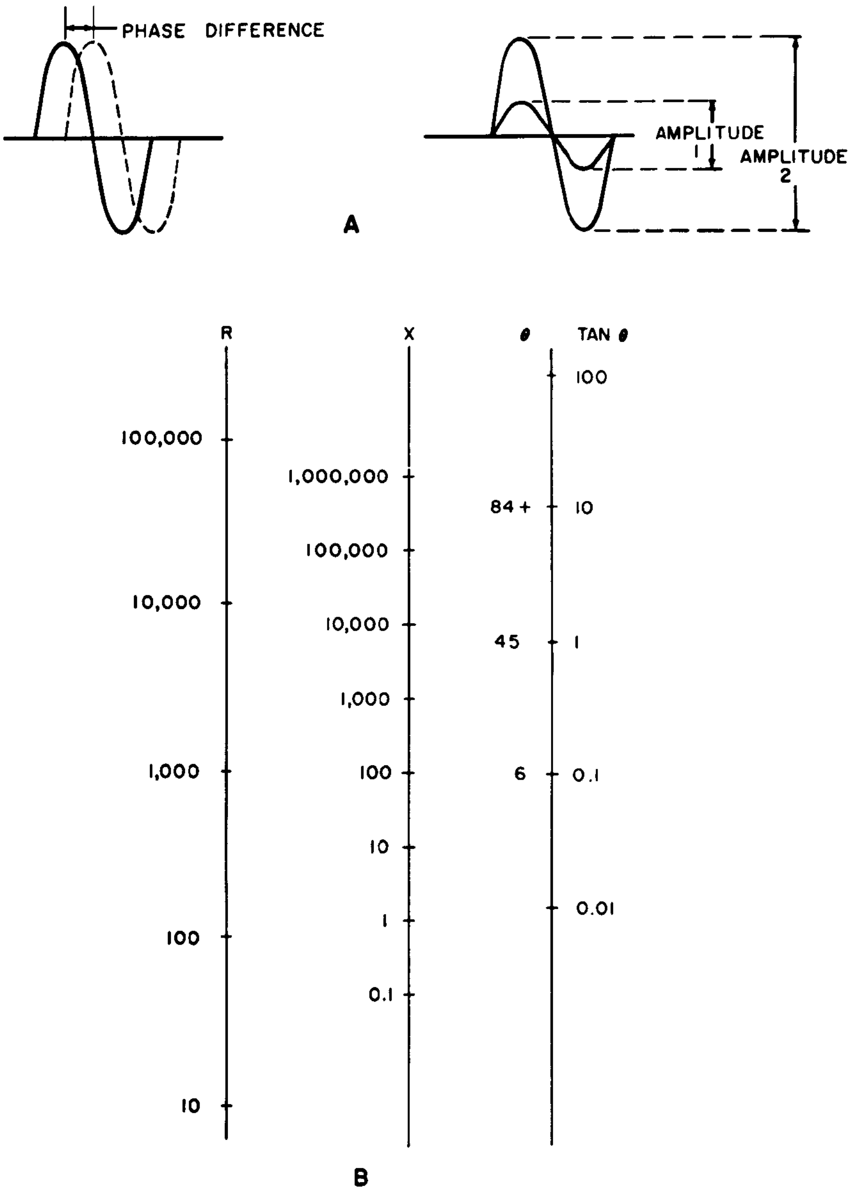


Fig. 1·6 (A) A-c variables: a phase difference and an amplitude difference. (B) Phase-angle nomograph showing the relationship between resistance, reactance, and phase angle.

Complex waveshapes (Fig. 1·7) of various types are used. The most common is the pulse, which is often obtained by the action of the transducer itself.

Pulses can be of different shapes, as shown in Fig. 1·7*A*. They may be rectangular or triangular, or they may appear as half-sine waves.

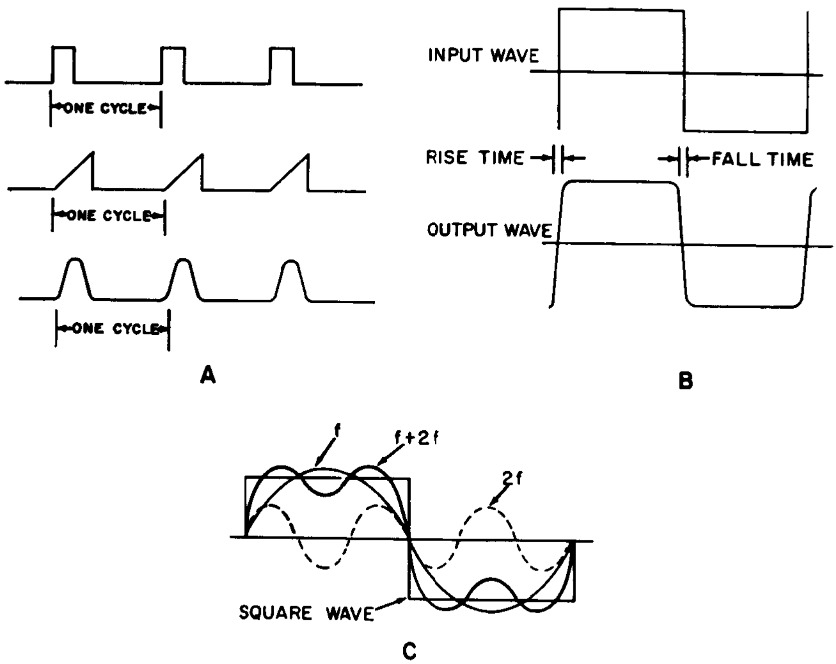


Fig. 1·7 **(A) Three waveshapes which may be used for control signals; these are rectangular pulses, triangular waves, and half-sine waves. (*B*) A bipolar square wave which is between a negative and positive voltage suffers during passage through amplifiers so that the rise time and fall time are not zero but require a certain short time to change from negative to positive. (C) A square-wave control signal of frequency *f* is composed of frequencies *f* and 2*f*, plus other harmonics of *f*. The wave shape of $f + 2f$ only approximates the perfect square wave.**

The square wave (Fig. 1·7*B*) is common. The rise time and fall time are important in some switching applications and must be controlled to ensure sharp switching. Components of this square wave are the harmonics of the fundamental frequency, as in Fig. 1·7*C* where the fundamental, first harmonic, and second harmonic are shown adding to produce a square wave.

1·5 Circuit elements A circuit is made up of active and passive elements. The active elements are electron tubes or solid-state devices.

Electron Tubes. These tubes are in many different forms for various jobs.

One possible classification of vacuum and gas tubes is a primary division into four groups based upon the cathode types, as shown in Fig. 1·8. Four different cathode sources of electrons are shown. Heated cathodes, using direct or indirect heating, emit electrons when their temperature is sufficiently high. Cold cathodes use gas ionization, which frees electrons, as the source of current flow. Photocathodes emit electrons under the excitation of light. The final type has a pool of mercury as the electron source. Most of these tubes are discussed in later chapters.

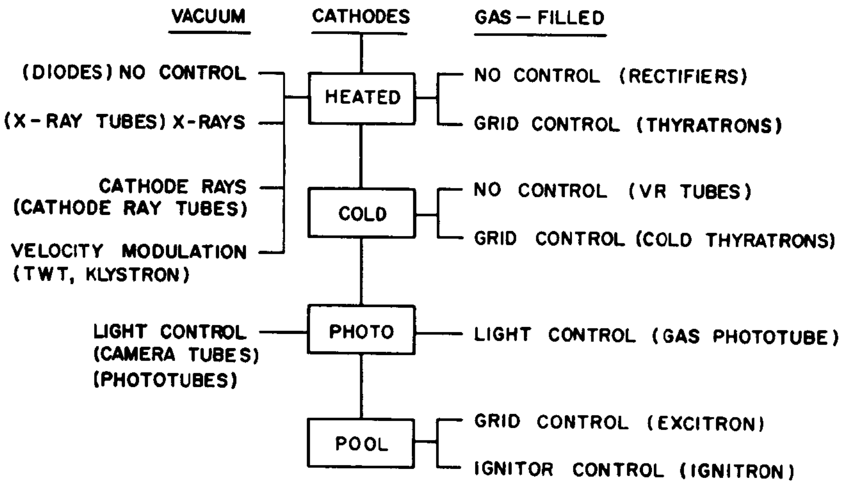


Fig. 1·8 The industrial tube family tree showing vacuum and gas-filled tubes in the four groups with different cathode types.

Solid-state Devices. These include semiconductor devices which cover many active components. There are three states of matter: solid, liquid, and gas. In the vacuum tube, electrons travel through an atmosphere of very thin gas; in a solid-state device such as a diode or a transistor, the electrons travel through a solid.

Transistors are current-operated devices, whereas tubes are voltage-operated devices. The tube plate, grid, and cathode are like the transistor collector, base, and emitter (respectively) in some of their actions. Transistor circuits use both NPN and PNP configurations. NPN transistors, in a grounded-base arrangement, have a negative voltage applied to the emitter and a positive voltage to the collector. In the PNP transistor these voltages (or, more accurately, current sources) are of opposite polarity. A grounded-grid tube corresponds to the grounded-base transistor, the grounded-cathode tube to the grounded-emitter transistor, and the grounded-plate tube to the grounded-collector transistor. These circuits are all used in one way or another in industrial electronics.

One of the greatest uses of transistors is in multivibrator switches, of which there are several variations. A multivibrator may be free-running, which means it produces an output without an input signal. If required, a synchronization signal may be introduced to lock in this self-excited oscillator to a desired frequency. Or the multivibrator may be a flip-flop, which has two stable states. Here each input switches the circuit to the other state. There are also other types.

But the family of solid-state devices grows ever bigger. Both controlled rectifiers and photodevices are used and are important. Diodes have appeared in various types; they can amplify, control, detect, and measure. Magnetics, in their several configurations, are also important and are covered in detail in Chap. 11.

A special form of solid-state device, the field-effect transistor may be considered as a stepping stone between a vacuum tube, which is a voltage-operated device, and the true transistor, which is a current-operated device. The unit consists of an N-type silicon bar with two ohmic contacts (cathode and anode) on either end of the bar. Two PN junctions are built into the middle of the bar and connected in parallel to serve as the grid of the device.

A negative bias applied to the grid increases the effective resistance between the anode and cathode of the unit and produces a triode-type output characteristic. As the anode voltage is increased, the grid junctions are reverse-biased by the voltage drop occurring because of the anode current. At some point, further increase in anode voltage will not result in any appreciable increase in anode current, causing the output characteristics of the unit to closely resemble those of the vacuum-tube pentode.

The anode potential, at which the saturation of anode current occurs, is known as the pinch-off voltage. The anode current flowing through the device after the pinch-off voltage has been reached is known as pinch-off current. With zero grid bias, the pinch-off current is the maximum specified anode current of the transistor. The device is in the triode region before the pinch-off occurs and in the pentode region after the pinch-off potential has been reached.

The anode and cathode terminals of the field-effect transistor are, in a manner quite unlike that of a tube, interchangeable, although a somewhat higher transconductance and lower noise figure are generally obtained if the unit is used in the normal way.

The grid normally requires a negative potential. Positive bias on the grid will increase the anode current, but this potential should remain below 0.6 volt. Substantial grid currents capable of destroying the device will be drawn if the grid is biased with a positive voltage in excess of this.

Circuitry for use of the field-effect transistor as an amplifier is identical with that of triodes and pentodes, except that lower anode voltages can

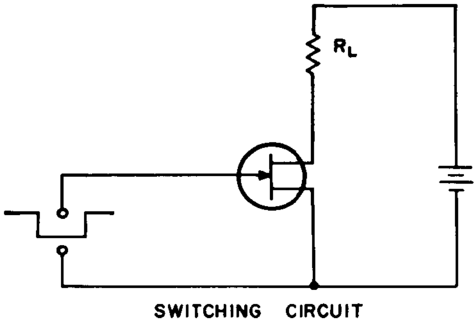


Fig. 1·9 Switching circuit using a field-effect transistor.

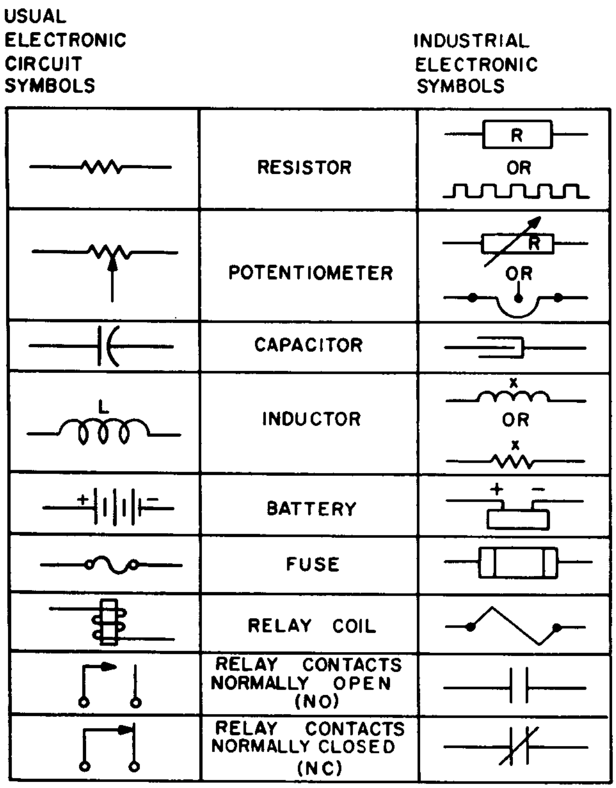


Fig. 1·10 Industrial electronic circuit symbols compared with the more usual electronic circuit symbols.