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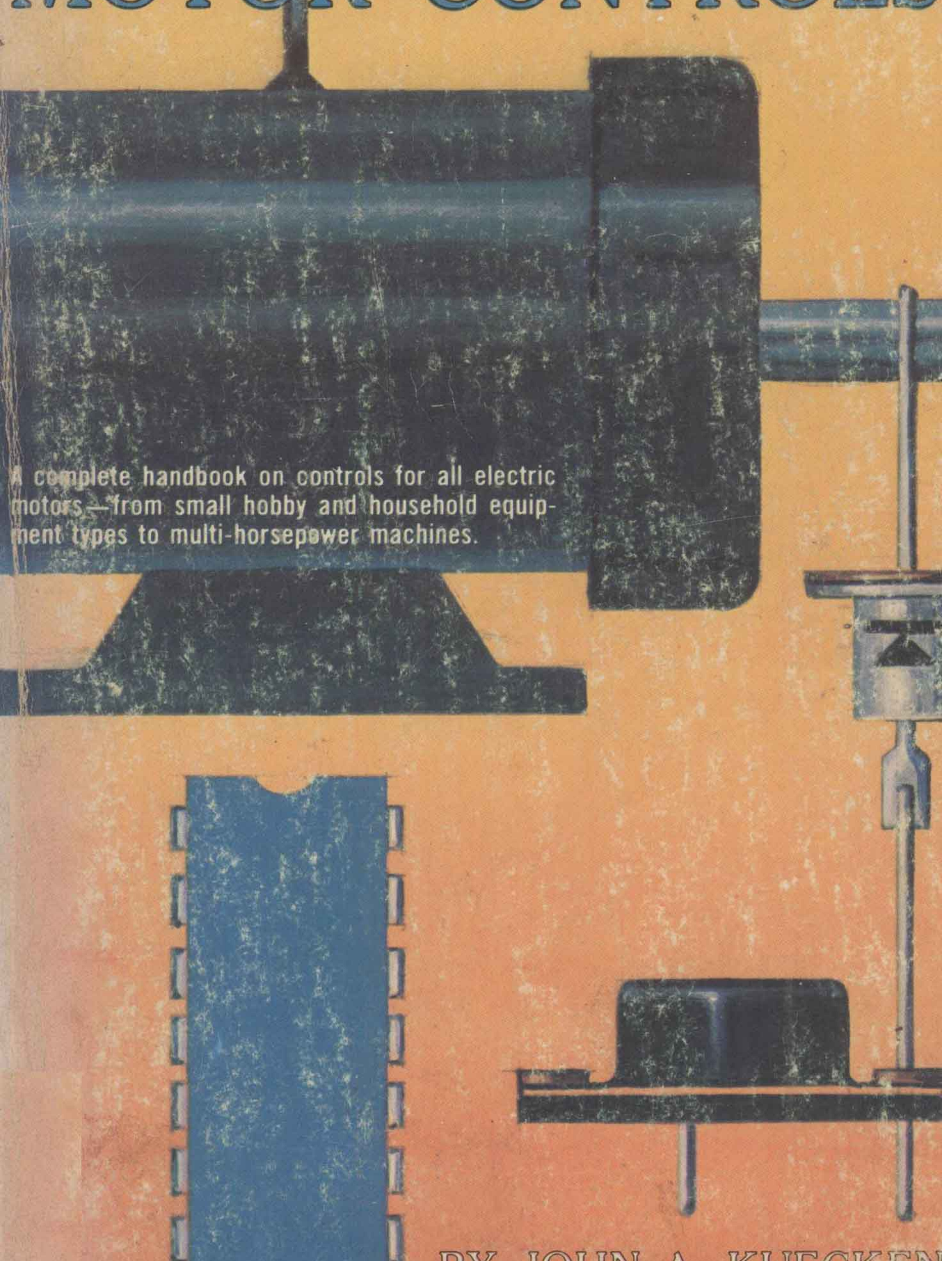
SOLID-STATE MOTOR CONTROLS



A complete handbook on controls for all electric motors—from small hobby and household equipment types to multi-horsepower machines.

BY JOHN A. KUECKEN

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Foreword

Beginning with the invention of the transistor in 1948, solid-state devices began to displace electronic functions long held by vacuum tubes, metallic rectifiers, electromechanical relays, photosensitive chemicals, and other similar devices. The new solid-state packages not only displaced these old standbys but also went far beyond their capabilities—in certain applications. In receiving functions, transistors soon became the favorite active element of design engineers. The rigorous demands of transmitting tubes, however, precluded the use of transistors in all but "flea powered" units for many years. While today the output stages of many commercial high-powered transmitters use transistors, tubes still hold the market for the really high power stations.

The metallic rectifiers and photochemical devices of the past have largely given way to solid-state products. With rectifiers it is relatively easy to build junctions able to carry high currents and to withstand large reverse voltages. The photoproperties of semiconductor junctions proved to be much more useful than the meager photodevice field of pretransistor electronics.

But when solid-state devices were first investigated as control replacements for industrial motors, generators, relays, and other heavy duty machines, engineers soon learned that the harsh environment of industrial equipment required far greater ranges of parameters than the new technology could provide. Thus, solid-state control of these products had to wait for the technology to advance, to provide devices capable of handling large currents and voltages, extremes of temperature and vibration, and multiple control functions and versatility.

Today, absolute maximum ratings for power transistors and thyristors have reached the point where these devices are able to displace the electromechanical controls on many of the large-horsepower motors in common use. With the cost of these control devices being competitive with older control methods, and with the proven high reliability and performance of solid-state controls, the designer of any new control system would do well to investigate the latest offerings of the manufacturers before deciding whether to go mechanical or solid state. Specifications continue to improve, and costs continue to fall for solid-state control devices.

The author provides a complete course on motor controls—from the principles of control to the use of microprocessors for obtaining maximum efficiency in complex installations.

The three basic types of motors—ac, dc, and universal (ac/dc)—are treated in detail so that the designer has a complete understanding of all parameters before deciding on the best approach to a control system. Supporting these discussions of motors are chapters reviewing principles of dc and ac circuits. Inductor, transformer, and capacitor circuits illustrate many of the principles used in motors.

With an understanding of magnetic flux density, magnetic potential gradient, poles, and other characteristics, a control designer gains an understanding of the inner workings of motors, enabling him to understand the reasoning behind control techniques given later in the book. Ultimately the hope is that the reader will learn to appreciate the superiority of solid-state motor controls in many applications and will design and use them in his own applications.

John A. Kuecken

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Principles of Control

The progress of civilization is measured, at least in part, by the means man has devised to control and harness its forces. Abraham rode a saddle ass (Genesis 22:3) and the Pharaoh of Egypt could summon up 600 chariots to chase the Children of Israel (Exodus 14:6—8). By 1500 B.C. the Egyptians were sailing 70-foot papyrus ships with a single sail and 30 oars for propulsion and two for steering. The significance of the 15 pairs of propulsive oars is that they were not only for propulsion but also for control. The wind would move the ship very well but not always in the direction the captain wanted her to go; therefore, the oars.

CONTROL CATEGORIES

Our world is populated with a tremendous variety of controls, devices intended to harness and direct the use of energy. Of these the simplest, fastest, and most flexible are usually electrical. This text intends to explore some of the major categories of these controls and to discuss the means by which solid state devices can be applied.

In the discussions to follow, controls will be divided into two broad categories:

1. Open-loop controls
2. Servo (closed-loop) controls

Some very fundamental differences exist in these categories which tend to influence the design of the components and the principles of operation. Indeed, each category is populated with a number of subcategories, which will also require definition. For the sake of simplicity, we shall try to employ some rather commonplace examples in the definitions.

OPEN LOOP CONTROLS

Open loop controls are defined here as those controls in which there is no direct sensing of the accomplishment of the end goal of the system by the system itself.

For example, the vacuum cleaner is turned on and off at the discretion of the person using it. There is nothing built into the mechanism to tell whether the rug is actually clean. This is a simple on/off control and will be referred to as a *manual control*. Other manual controls can be a good deal more sophisticated and still remain in this category. For example, a blender, a cake mixer, or a fan may be equipped with a variable speed control (the speed control itself may contain a closed-loop servo). However, in each case, the unit is turned on and off and the speed is regulated only at the discretion of the operator and not by having the device sense that the job is accomplished.

A second type of open-loop control is the *automatic open loop control*. This type generally takes the form of a *sequencer*. A good example of this is the automatic dishwasher and the automatic clothes washer. These machines generally have been built to operate in a time sequence. Fill, wash for 10 minutes, pump out, rinse for 5 minutes, pump out, and so forth. Here again the device does not sense the cleanliness of the clothes or dishes but rather assumes that if all of the steps in the sequence have been adequately performed, the clothes and dishes will be clean. In the past these sequencer controls have consisted of some rather elaborate clockwork schemes to turn on pumps, valves, and motors. If the device is relatively simple and has only one set sequence, this sort of thing works out relatively well. However, more-modern washers tend to be supplied with a choice of cycles for various wash and wear fabrics, delicate lingerie, sensitive cotton cloths, and other washable items. Provisions for a flexible cycle selection tend to multiply the complexity of the sequencer. It is particularly in these areas that the use of an electronic sequencer is attractive. A very modest microcomputer or microprocessor chip combined with the simplest of read only memory (ROM) and random access or read/write memory (RAM) permits an unprecedented amount of flexibility in the cycle control and in a very simple package. Ultimately, the cost of the solid state or electronic sequencer should be smaller than that of the simplest mechanical unit.

The use of the open-loop system is by no means confined to the relatively simple applications described. One of the most important and sophisticated members of this family is the *direct numerical control*. This is the system commonly found in numerically controlled (NC) machine tools. In these machines, *stepper motors*, which produce a precise angular shaft rotation for each input stimulus, are used to position the table, carriage, or tool. For example, stepper motors are available that provide a shaft rotation of 7.2° for each input pulse. It requires 50 input pulses to make the shaft rotate through a full revolution. If the machine is provided with a 20-thread-per-inch lead screw, the tool or carriage propelled by the lead screw will advance 0.001 inch with each input pulse.

The convenience of this arrangement in digital programming of the machine tool is relatively obvious. The sequencer need only provide a train of pulses numerically equal to the desired travel in thousandths of an inch. Most machines of this type read sequencing instructions from a punched paper or Mylar tape. The tape sequentially addresses the various table motion or tool motion drives and the machine produces the piece with little or no operator intervention. The original tape can be punched out by a programmer from the drawings.

One of the reasons for the popularity of this system for machine control over the closed-loop system is the fact that the system can be easily made to operate with essentially zero overshoot. This is particularly important in machine tools and plotters. If the drill or mill were to go a little too far and then move back, the damage would be done because the taking-off tools work better than the putting-back-on tools. On the plotter, the ink would be on the paper beyond the point where the line should have ended.

SERVO CONTROLS

The term *servo* stems from the Latin servus—meaning servant. The dictionary definition indicates that the term is applied to any device permitting control of large forces with negligibly small ones. In technical usage, though, this definition is too broad since it could be applied to nearly any valve, switch, or amplifier. The common technical usage of the term *servo system* is usually reserved for devices in which the control input is construed by the system as an error and the machine acts to remove the error.

Perhaps the simplest example available is the refrigerator. The operator sets in a desired temperature in the control dial and the thermostat senses the actual temperature within the box. If this temperature is more than a few degrees warmer than the set level, the motor starts and operates until the temperature is slightly less than the set level. The machine then shuts down and waits until the temperature again rises to the upper limit whereupon the cycle repeats. The system is called a closed loop because it actually senses the accomplishment of the task at hand.

The refrigerator cooling system and thermostat form a unidirectional closed loop servo. The system is unidirectional in the fact that the compressor system is able only to cool the box and not to warm it. The warming action, of course, comes from leakage through the walls and the requirement to freeze or cool the contents. In other closed-loop systems, this unidirectional property would not be acceptable.

An important property can be defined in terms of the refrigerator example. The system possesses an important property termed *hysteresis*. This property is carefully engineered into the product, forms an important part of the operating principle, and is very necessary to ensure the life of the machine.

Most refrigerators are equipped with single-phase induction motors, which require the use of a starting winding. During the starting operation the torque of the motor is very limited, and the motor cannot start the compressor against the back pressure of the refrigerant. You may have had the experience of having the refrigerator stopped by a brief power interruption during a storm. When the power came back the motor, perhaps, attempted to resume the refrigeration cycle, but couldn't start against the charged compressor cycle, so the unit groaned until the thermal overload switch kicked out due to the excessive current being drawn. If the thermal overload had not interrupted the current, the motor would have burned out. Sometime later the thermal overload re-closed and the motor tried again. If the refrigerant had an opportunity to pass from the cooler into the evaporator during the idle period, the back pressure was reduced and the unit started and ran successfully.

From the example, we can see that it is neither possible nor desirable to have the refrigerator attempt to hold the temperature absolutely constant. The practical mode of operation is to have the unit run until the box is cooled to some low temperature, for example 34°F, then shut off. The thermostat then waits until the box warms to some higher temperature, for example 36°F, before attempting to restart the compressor. This gives some time for the refrigerant to pass from the cooler through the evaporator and relieve the back pressure. The difference between the 34° shutoff point and the 36° turn-on point is termed hysteresis. An important aspect of hysteresis is that it is directional; the thermostat switches off at 34° with a falling temperature and switches on at 36° with a rising temperature.

There are two other terms that we may define here. When the motor shuts off at the 34° level, there is still a certain amount of refrigerant left in the cooler. As this passes into the evaporator, the cooling process continues so that the box temperature will actually fall below the turnoff point to perhaps 33°. This is termed *overshoot*. A similar case of overshoot takes place on the warming cycle. As the box warms beyond 36°, the compressor starts; however, it takes a little while before the cooling process begins. The box temperature will actually overshoot and get to be warmer than 36°, perhaps to 37°, before the cooling process takes over. In this example the system would have a hysteresis of 2°F, with a 1°F overshoot at each limit. A good quality refrigerator would have much tighter limits, but the principle is the same, and some amount of overshoot will be noted, and a measurable hysteresis will be built in.

It is a general rule that switching mechanisms should cleanly toggle on and off and not be allowed to halt at a halfway point.

THE BIDIRECTIONAL CLOSED LOOP SERVO

Many servo systems have the requirement that they operate in both directions. For our example of this type system we shall examine an oversimplified power steering system shown in Fig. 1-1. As the discussion progresses, we shall see some of the properties of the system and learn why the system is oversimplified.

In our illustration we see that the system consists of a steering wheel which is attached to a driven gear with a springy insulated joint. The gear carries two batteries, A and B, with opposite poles grounded and a pair of contact pins attached to the floating, or "hot," battery terminals. A permanent magnet electric motor is connected with a slip contact to the switch rod. Now the property of permanent magnet dc motors is that they reverse their direction of rotation when the polarity is reversed, and we can see that this is accomplished with the directional switch.

We arrange the motor such that when the steering wheel is twisted clockwise (cw), the switch rod swings over and touches the B contact, which causes the motor to drive the driven gear also in the clockwise direction. This rotates the gear and pulls the B contact

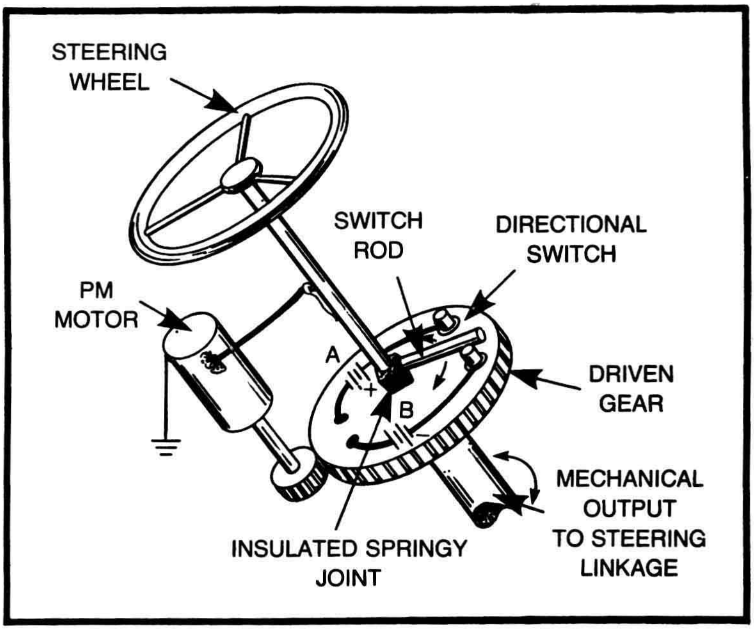

Fig. 1-1. An oversimplified power steering system.

away from the rod. If the motor coasts a little, and the system has the right amount of friction, the driven gear rotates through the same angle that the steering wheel was turned and coasts to a stop with the switch rod not touching either the A or B contacts. If the wheel is turned counterclockwise (ccw), the switch rod touches the A contact and the motor drives the gear in the ccw direction.

This is obviously a full closed-loop servo system. The operator need only supply enough torque to the steering wheel to keep the switch rod in contact with the pin and the output torque is supplied almost entirely by the motor. The output shaft can be made to rotate through the same angle as the steering wheel with essentially no effort on the part of the operator. The system is said to have ***negative feedback*** in that the action of the system tends to cancel the effect of the input (by rotating the contacts on the driven gear away from the switch rod).

Now note the fact that it is always necessary to have some small angle where the steering wheel may be moved without touching either contact. This *deadband* is necessary so that the rod cannot contact A and B simultaneously since this would short circuit the two batteries. In addition, there are other factors which necessitate some amount of deadband.