CONTROLS AND SENSORS

Together, controls and sensors regulate the transmission of power. Through switching devices, power controls regulate the energy that motors use to turn shafts, heaters use to heat, etc. Through sensors, process controls fine tune or adjust performance parameters to regulate machine and process operations and are part of a system that is either open or closed loop.

Open loop systems

The main characteristic of an open loop system is that there is no feedback of a process control variable. Machines and processes that work well with open loop control include those that:

- Have predictable behavior and are self-regulating through the use of timers, cams, or switches.
- Are insensitive to outside disturbances.
- Do not cause harm if the desired result deviates widely from command.
- May be simple, slow in operation, do not affect other process sections, or are under the supervision of an operator.

Step motors, Figure 1A, are commonly used in open loop control systems. An indexer receives a command signal from an operator, programmable controller, or computer. The indexer then provides the driver with acceleration, deceleration, velocity, and position information. Signals to the driver continue unaltered until the indexer's program is changed.

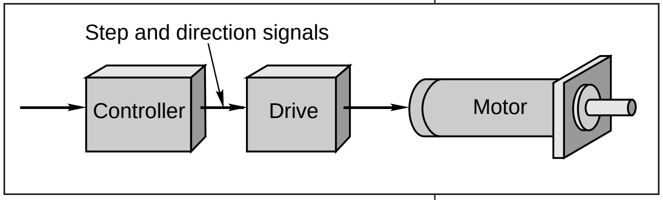


Figure 1A — An open-loop system does not use a tachometer, encoder, or resolver for feedback.

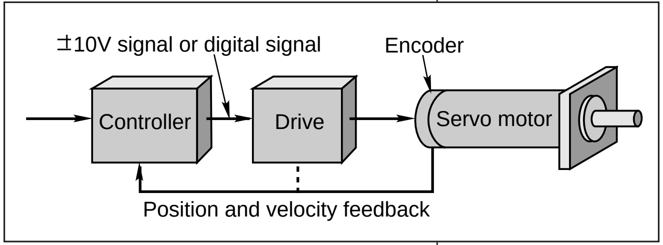


Figure 1B — Closed-loop systems use feedback for velocity and position control. A traditional servo system may use a tachometer for velocity control and an encoder for position information. Current systems typically use an encoder to provide velocity and position feedback. Some systems use a resolver in place of an encoder.

Closed loop systems

Closed loop systems, Figure 1B, use feedback from the work process to control an operation. Servosystems are typical of closed loop control. The digital controller in this system compares position feedback from an encoder to a programmed motion profile. The error between the two signals is used to alter the velocity signal.

OPERATOR CONTROLS AND DISPLAYS

With the increased use of automatic devices and the need for personal safety, an almost infinite number of operator's controls and displays are available.

In most cases, before any operation starts, the operator must initiate a start command — usually through a push-button or a computer keyboard command. Pushbuttons come in many configurations, from hard contact systems that operate by closing one contact against another, to units with Hall-effect devices and saturable ferrite cores.

Switches

Pushbuttons are available with normally open and normally closed contacts, and with a combination of both. Some selector switches, for instance, let the operator select a particular operation or sequence of operations with over 30 combinations.

For digitally controlled units, thumb-wheel switches and operator keyboards are available, which let operating personnel give specific digital commands to the control system.

Other operator controls include potentiometers that provide an analog output voltage, determined by the position of a contact wiper attached to the shaft. These units come in single-turn units that operate over a 270 deg arc, to multiple-turn units that require 100 turns to go from zero to full voltage.

Displays

Two basic types of displays are used to keep operating personnel informed of machine conditions: analog and digital.

Analog — These devices are frequently voltage or current sensing units that consist of a dial or meter calibrated in the desired units of measure (volts, amperes, rpm, etc.). They may offer a charting or graphing function, as well as a visual display. Complex models also incorporate a controlling function that converts a specific low level signal — such as thermocouple input — to a 4 to 20-mA output signal for controlling process systems.

Digital — Built with either LEDs, or more recently LCDs, these displays provide digital or alphanumeric indications. Some units with microprocessors combine visual display with control functions and are programmed in much the same manner as a programmable controller. These displays are usable as stand-alone controllers for simple operations, or to augment a programmable controller function.

Cathode ray tubes — Common to television and computer terminal use, CRTs are rapidly expanding into the industrial environment and are frequently included with equipment containing microprocessors. The systems provide a graphic display of machine operating parameters.

Figure 2 — Liquid crystal displays are a recent development. With a depth of only a few inches, they are particularly useful for applications where space is a premium, and they are light weight and not subject to conducted EMI and radio interference.

Liquid crystal displays — A recent development, Figure 2, the main benefit is a depth of only a few inches, particularly useful for applications where space is a premium. They are light weight and not subject to conducted EMI and radio interference. Monochrome gas plasma and electroluminescent (EL) displays are the most common.

LOGIC AND PROCESS CONTROLS

Process controls make shafts turn smarter. They use reference signals provided by sensors to adjust or regu-

Always a PLC?

PLCs aren't the only solution for motion control, particularly those applications that need few I/O points. The industrial personal computer (PC) is often a competitor with the PLC.

When choosing between a PC and PLC, keep in mind the benefits and limitations of each.

For the PC, features and limitations include:

- An open architecture. Add-in boards let engineers add hardware features such as sensor interfaces, special math capabilities, sound, and others.
- Communications. Ability to network with other PCs, PLCs, and other computer products.
- Large availability of software. Programs exist for analysis, programming, business functions, and some control functions. Also, large availability of programming languages.
- Flexibility. Users can alter PC functions in software or add-in hardware boards.
- Easy-to-use operator interface. The PC set the standard for windows-based, pull-down menus, and icon-graphics style operator interface.
- Single-tasking operating system. DOS and Windows are not real-time operating systems. They are oriented toward file handling and operator interface.
- Does not fail in a predictable manner. When a PC fails, it "crashes" regardless of the step in the control process. The PC does not leave clues to possible causes of failure and thus, is not easily, or quickly, diagnosed and repaired.
- I/O limitations. PCs lack I/O points and are limited in their ability to operate with a large number of I/O. Some motion-control applications, such as driving labeling machines, may require at least 64 I/O points, which are not readily available on an industrial PC. The cost of I/O for industrial PCs can be high. An industrial PC, excluding software, can cost up to $1,000/point.

For the PLC, features and limitations include:

- Semi-open architecture. Openness in hardware and software is growing in PLCs, although it is not yet the same as PC openness. Most PLCs, though — even micro and nano versions — can interface with wide-bit, high-speed, single-board computers that use standard software and graphical user interfaces. Motor parameters can be set up on a control panel, giving an operator the ability to adjust parameters "on-the-fly."
- Communications. Ability to network to many manufacturing operation and control devices from sensors to motors to mainframe computers.
- Limited software. Traditionally, only ladder logic was available. The IEC-1131 standard, however, increases the number of programming languages to five. Software is geared to controlling a process rather than displaying status.
- Limited flexibility. PLCs are optimized for factory control.
- Operator interface is usually a PC.
- Multitasking and interrupt handling capabilities.
- Predictable failure. PLCs shut down in a logical manner that safeguards the process. Specific memory registers record the last functions executed for easier diagnosis of why the system shut down. This feature makes it easy to bring a PLC back on line.
- I/O. A small 14 I/O PLC, can be bought for about $16/point. The price advantage between PCs and PLCs changes with mid-size PLCs. A complete mid-size PLC can cost $4,000 to $5,000, while a 486 industrial PC can cost less than $2,000.

Despite the limitations, PC benefits have made it a strong competitor in many motion applications. To compete, PLC vendors often embed single-board PCs in their products. Software is loaded on these PC boards through modules that plug into a PLC's VME backplane. This gives users a product that combines PC flexibility in a PLC environment, and eliminates the need to integrate one to the other. *Information courtesy of Aromat Corp.*

late machine operations. Control-level signals are low-voltage, low-current signals often measured in milliamperes. Logic and process controls range from simple relays that control one function to sophisticated programmable logic controllers (PLCs) and personal computers (PCs) that control and monitor every facet of a manufacturing process. The abbreviation "PLC" is often used for programmable (logic) controllers to differentiate from "PC" for personal computers.

Relays

Relays are used to control other devices in the same or another circuit, and are either electromechanical or solid-state units.

Magnetic relays — Many types of relays exist, each having unique mechanical and electrical construction. The most common magnetically operated types are covered here.

Reed relays — are basically an assembly of reed switches within an operating coil. The reeds can be any type or configuration, but the quantity is limited by the coil size. Most manufacturers limit the size of the coil to handle a maximum of 12 switches. To obtain additional contacts, relays are connected in parallel.

Mercury-wetted contact relays — consist of one or more glass switch capsules surrounded by a coil. When two contacts wetted with mercury are separated, the mercury stretches and then breaks at two points, leaving a thin rod of mercury in the middle that drops to the bottom of the switch. The loss of mercury from the contacts disturbs the system equilibrium, and more mercury is fed up the armature from the pool. Thus, in effect, the relay provides a new contact surface for every operation.

Armature relays — are a large class of relays with armatures that carry or actuate electrical contacts in response to small control signals.

AC relays are the most readily available, but ac is the least flexible power source for relay operations. However, most ac relays designed for 120 V line operation tolerate line fluctuations from 102 to 132 V.

DC relays have inherently greater mechanical life expectancy than ac relays. Of the many sources of dc, the most frequent is probably rectified ac. Often ac ripple influences relay operation. Some dc relays can tolerate ripple; others need filtering.

Solid-state relays (SSRs) — These devices control load currents through solid-state switches such as triacs, silicon-controlled rectifiers (SCRs), or power transistors. These switch elements are controlled by input signals coupled to the switching devices through isolation circuits such as transformers and reed relays. Since the semiconductor switch can dissipate significant amounts of power, solid-state relays are generally heat-sinked to minimize the operating temperature.

Solid-state relays are used in applications where rapid on/off cycling would quickly wear out conventional electromechanical relays. General-purpose SSRs have on/off cycle lifetimes as high as 100,000 actuations. SSRs can be actuated with conventional CMOS and TTL logic level voltages.

Transistor-transistor logic — (TTL) devices operate with 5-V power supplies, and recognize voltages between 2 and 5 V as logical 1 level, and voltages between 0 and 0.8 V as logical 0 level. When these devices are connected to form digital circuits, the two most important characteristics are called fan-out and propagation delay. Fan-out is the maximum number of logic gate inputs that can be fed from any given logic gate output. Propagation delay is the amount of time a gate takes to react to a change in state at its input. This delay time is caused primarily by capacitive delays induced by components making up the gate.

Complementary metal-oxide semiconductors — (CMOS) can operate from power supply voltages ranging from 3 to 15 V. These devices are generally slower than equivalent TTLs, however, they dissipate much less power. Propagation delay times are set primarily by supply voltage; the higher the supply voltage, the longer the propagation delay. Since these devices dissipate so little power, fan-out is essentially unlimited.

Programmable controllers

A programmable logic controller (PLC) provides many of the advantages of computer control in industrial applications. PLCs are solid-state control devices that withstand tough factory environments and can be located near the equipment or processes they control.

A typical PLC consists of a central processing unit (CPU), a programmable memory, input/output (I/O) interfaces, and a power supply, Figure 3.

The CPU is the "brain" of the PLC, where all logic operations are performed. The CPU compares inputs to a program stored in memory and alters the output signals in accordance with instructions in the program.

Digital signal processors

Motion control products previously used ordinary microprocessors to calculate and execute motion algorithms. Today, most use a "screamingly fast" new microprocessor — the digital signal processor (DSP). This computer-on-a-chip executes motion algorithms up to ten times faster than previous controls.

It consists of an arithmetic and logic unit, address generation and management units, and sequencers to control the flow of data and instructions. It has two distinct sets of memory — one for data, one for instructions — and two busses. One bus grabs data operands while the other grabs instructions. This ability to do two things at once is part of what gives a DSP its speed.

All microprocessors execute instructions in a measure of time known as a cycle. In a DSP, most instructions take one cycle. Depending on how multiplication is implemented in the motion algorithms, execution can take one or two cycles, including floating point numbers.

Microprocessors such as the Pentium family or the Power PC chips may compete with DSPs in motion control. Both types of microprocessor chips are moving to a design where they have one large memory outside and two memory channels inside, similar to DSPs. But unlike these microprocessors, DSPs can directly process sensor inputs because they can operate in the same microsecond time frame, and they have a software program that users can access and alter.

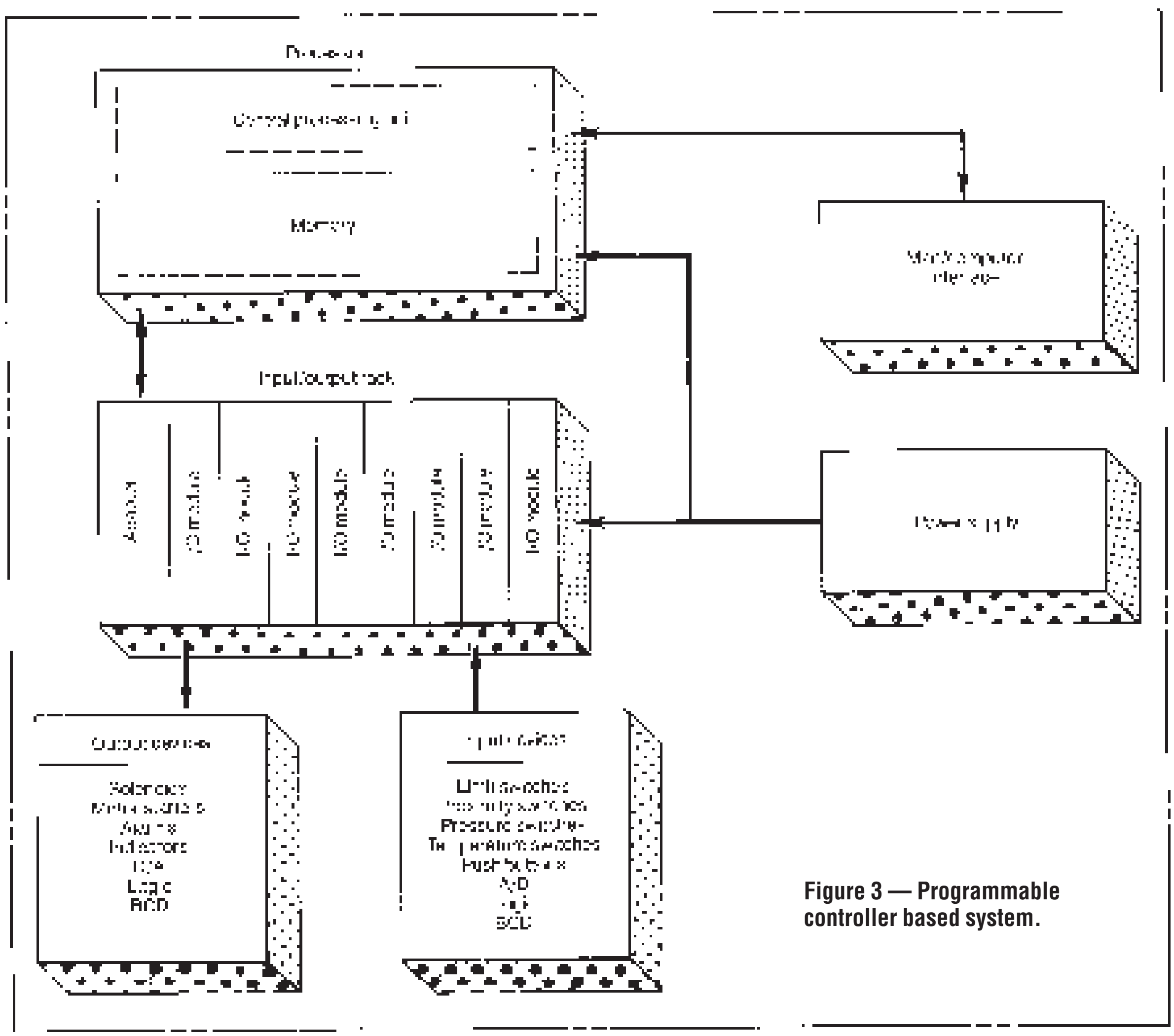


Figure 3 — Programmable controller based system.

Most CPUs perform mathematical operations on the input data or use lookup tables in order to alter the output signal. Other capabilities include remote input/output, run-time diagnostics, and high-speed communication networks that link one PLC to other PLCs, supervisory computers, and sensing and monitoring devices.

During operation, the CPU continually scans all I/O circuits, compares input to memory, performs logic operations, and directs output. Scan times run from less than 1 to 200 milliseconds, depending on the size of memory and the number of I/Os that must be read.

Memory in a PLC is divided between executive and user. The executive memory is usually read only memory (ROM) and often programmed by the PLC manufacturer. This memory is permanent. It cannot be altered nor will it be lost if power is interrupted or removed. Its program contains instructions and algorithms for its specific operation.

Programmable read only memory (PROM) is more versatile in that it can be programmed (once) by the user. Thereafter, it effectively becomes ROM. Often, users purchase several PROMs and program each for a different operation.

Erasable programmable read only memory (EPROM) permits data erasure when it is exposed to an intense source of ultraviolet light. Electrically erasable programmable read only memory (EEPROM) is another non-volatile memory that can be erased electrically and reprogrammed. Both EPROM and EEPROM provide long-term program retention without battery backup.

Random access memory (RAM) is user memory that is easily accessed and altered. Should power be removed, the contents in RAM will be lost. It can be protected from power outages by lithium batteries having service lives of up to several years. Non-volatile random access memory (NOVRAM) acts like RAM but stores data like EEPROM. No battery back-up is required.

The amount of memory that a PLC contains determines its size. Generally, PLCs are available with 1K to 8 or more Megabytes of memory. Many are expandable so that users can increase memory size.

Input/Output (I/O) devices are either digital or analog types. Digital inputs are typically supplied by on/off devices such as switches, analog-to-digital converters, and counters. Analog signals are provided by process instrumentation and transducers. Generally, PLCs handle digital signals as high as 125 Vdc and 230 Vac. Analog signals are converted to digital signals by input modules. Standard analog inputs are 4-20 mA, 10-50 mA, 0-5 Vdc, and 0-10 Vac.

I/O systems can be rack mounted or remote (also termed distributed) and contain from 4 to 8,000 I/O points. Maximum remote mountings typically run to 2 miles away from the CPU.

Power supplies provide all of the voltages required for a PLC's internal operations. These supplies can be mounted directly inside the PLC or remotely mounted and connected to the PLC by cable. The power supply converts 120 or 240 Vac line power to regulated dc power required by the CPU and I/O modules.

Programming devices range from small hand-held keypads to personal or mainframe computers. In the latter case, the PLC is connected to a larger PLC, a PC, or a mainframe computer through a data bus. Programs and lookup tables can be downloaded into the PLC from the larger computer. Thus, one PLC can control hundreds of types of operations.

Programming languages for PLCs are moving towards true portability — enabling engineers to use various languages on any PLC regardless of manufacturer. The IEC 1131 programming standard is responsible for this increased level of portability.

IEC 1131 has been in development since 1981. It consists of five parts: General information, specifications for equipment and test requirements, specifications for programming languages, user guidelines, and communications. The third part on programming languages, 1131-3, received international approval in 1993.

The standard defines two graphical languages — ladder diagram and function block diagram — and two text-based languages — instruction list and structured text. Each of these languages also uses an organization language commonly known as sequential function chart. This language is similar to the European standard graphical language Grafcet. Sequential function chart helps organize the sequences of functions in a PLC program.

Ladder diagram logic is the oldest PLC programming language, and the one most electricians and maintenance people know. Instruction list is a low-level language, similar to an assembler language for computers. For simple applications, it executes only one operation per line. Structured list is a high-level language that offers Boolean and arithmetic statements as well as statements using IF...THEN...ELSE...and WHILE. It can be used to represent analog and digital values. Function block language defines code that is common to several applications or repeated in several segments of a program, e.g., PID loop control, counters, timers, and similar algorithms.

A programmer can use any one or all five languages in one PLC program. The benefit: programmers will have the freedom to program in the most suitable language for each function or application segment, eliminating many of the limitations typical of using only one language for PLC programming.

This standard also forces vendors to use a standard "look," or common operator interface for each language, which will lessen the amount of training required to use PLCs.

With this common interface, all ladder programs will use the same graphic objects for rungs, open and closed symbols, the same names for functions, and so on. All Structured lists will have the same Boolean and arithmetic statements and programming constructs. Once an engineer knows a language, he or she can go to any vendor's PLC and program it.

Communications. In 1994, control manufacturers introduced a new type of communications product for connecting switches, sensors, small motor starters, and other such devices to PLCs or personal computers (PCs). These buses cut wiring, cabling costs, and device installation time in half, while they increase uptime and reliability of automated systems. They offer an alternative to discrete, proprietary I/O solutions and fieldbuses.

One four-wire cable connects the above-mentioned devices to PLCs.

These buses take advantage of advances in microprocessor technology, especially application specific integrated circuits (ASICs). A bus's protocol, or the rules governing data format, transmission format, and network housekeeping details, are coded onto an ASIC chip or chips. These chips are small enough that sensor and switch manufacturers can embed them in their 18-mm diam products.

Device-level buses exist in three versions: bit, byte, and packet. Bit-type buses, such as Seriplex and ASI, transmit a few bits at a time, typically one to four bits. They send on/off, there/not there signals, or simple counting data. They transmit at the fastest rate — usually less than 5 msec/bit — because they don't send several bytes of format coding with the data.

Byte-type networks send bytes of data. Data transmission speeds typically range from 125 to 500 Kbaud. A few can go higher. These buses typically handle mid-level automation functions such as process or cell-level control. Byte-type buses include CAN-based buses such as DeviceNet and SDS, and low-level versions of Profibus and Interbus-S.

The packet buses include Ethernet and TCP/IP, which send large amounts of data, called packets, to various computing systems.

Selection tips:

- Select a bus that connects with the sensors you use, or plan to use.
- Be sure the bus meets your speed and data throughput requirements.
- Select a bus that communicates over the distances you require.
- If you have other buses or networks, be sure the topologies, i.e., a ring configuration vs. a trunk-drop configuration, are compatible.

Personal computers

Personal computers (PCs) are frequently found with programmable logic controllers (PLCs) on the factory floor. They often work side-by-side to optimize automation and motion control solutions, generally with the PLCs controlling production processes, and the PC collecting and managing information. More recently, PCs are used in direct motion-control applications in addition to data acquisition and manipulation, data trending for production schedules and quality control, logic solving, handling of screen and operator functions, and interfacing with other devices such as printers and graphics terminals. Through I/O modules and PLCs, they control and monitor industrial devices such as motors and sensors. In addition, PCs are used to create ladder-diagrams off-line, then program PLCs and debug programs on-line.

Compared to PLCs, PCs generally have more memory and greater calculation capabilities.

Programming languages for PCs in-

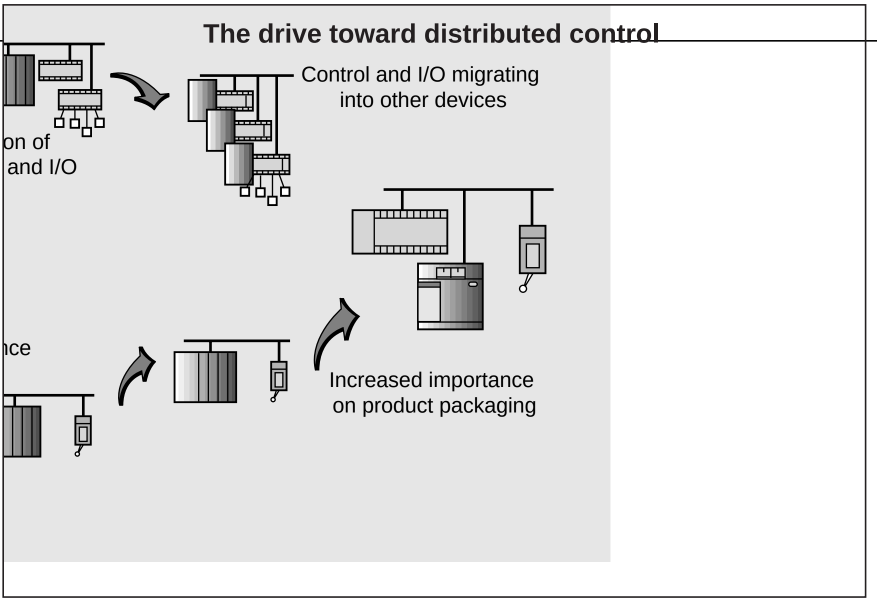


Figure 4— Part of the reason open, modular controls are in demand now is because customers are seeing the benefits of distributing microprocessor control and I/O to other devices and of connecting these components through innovative network strategies such as device-level networks.

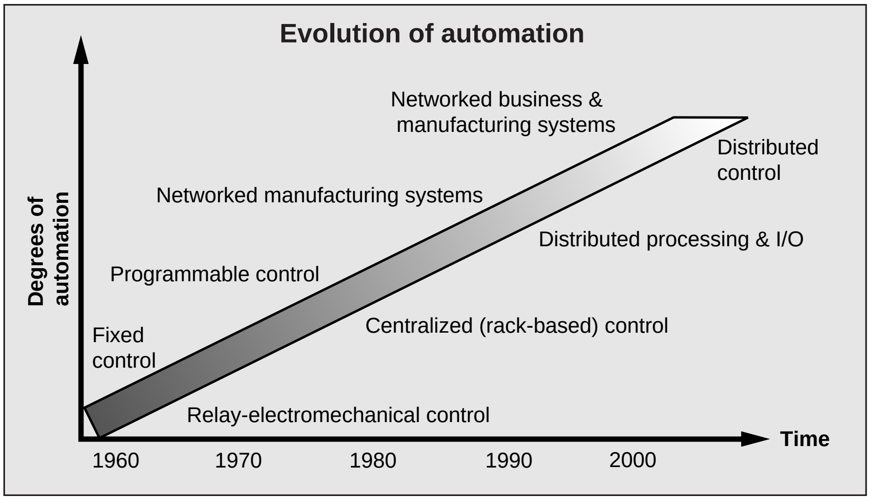


Figure 5 — Several manufacturers are moving from a present control strategy of distributed processing to a new strategy of distributed control.

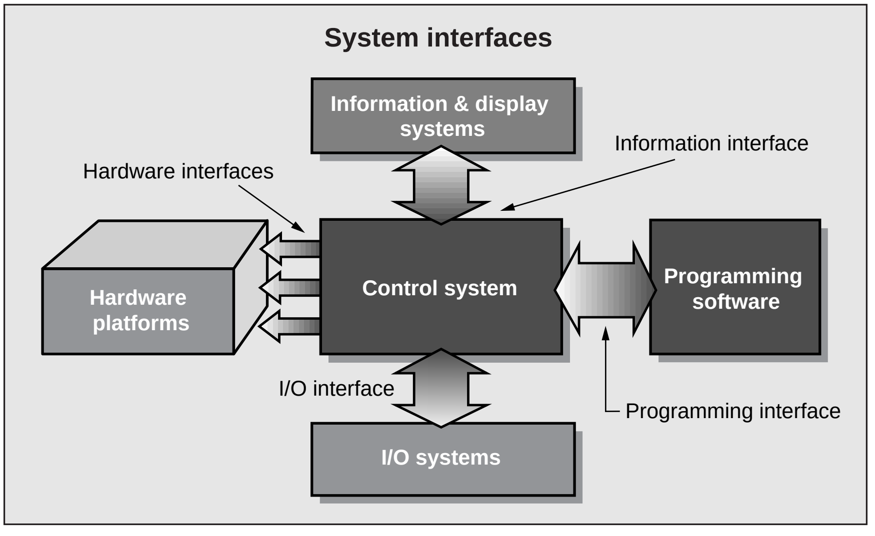


Figure 6 — These modular control components will be connected through application interfaces (APIs), software or hardware that will send data back and forth yet it will be as easy to install as a new program on an office PC.

clude conversational languages such as Windows, BASIC, PASCAL, and C, plus various assembly languages.

Industrial controls

The PLC and the PC have reduced cycle times, improved productivity, and met the information gathering needs of production and manufacturing processes. But as each goal is reached, customer requirements change.

In 1996, the requests were for controls that offer open, modular architectures that enable users to gain lifecycle economies. The goal of this open, modular industrial control is to enable users to:

- Run control software on any hardware platform.
- Purchase peripheral equipment that will plug and play into any hardware platform.
- Reduce the amount of time it takes to change a control's capabilities
- Reduce the costs of retraining, installation, and spare parts.

In 1994, engineers at General Motors reviewed their manufacturing operations and came up with strategies to cut their development and manufacturing time. But to implement these strategies, the engineers needed a control that they could upgrade with minimal additional investment. They developed a specification for this control, which ignited development of the open architecture, modular, industrial control. Eventually, such a control would facilitate the same rapid revolution of capabilities for the shop floor that has occurred in office computing applications.

While GM is one of the primary drivers for this open architecture concept, other drivers include relatively small firms:

- Searching for ways to meet customer needs of mass production while simultaneously manufacturing a highly custom product.
- Searching for the best-of-breed among computer-control components. Users want to choose from the best I/O modules, the best peripheral interfaces and the best software programs — not just those components that work with a specific control.
- Demanding solutions that seamlessly integrate control and information throughout a company.
- Distributing microprocessor control and I/O to other devices.

• Developing innovative network strategies such as device-level networks, Figure 4.

• Seeking to leverage the technology shifts found in electronic component, software, and network technologies, Figure 5.

Because there is such a huge installed control base, the opportunity for open, modular systems revolves around application interfaces (APIs). These consist of software or hardware that will let logic engine, I/O, and human-interface components send data back and forth, Figure 6.

Control manufacturers are investigating several approaches:

• A control that incorporates an operator display with a look and feel common with other controls. Yet, operators can tailor the display to their preferences, eliminating retraining. It also uses a common set of core features and interfaces to enable load-and-run software. This software links Windows-based programs to the control's real-time operating system. An electronic message system shuttles communications among the modules and add-on software and hardware.

• A control with a PC compatible software-hardware system. Cost reductions will result from easier system design, less installation, and less downtime when compared to traditional control systems.

• A control that consists of open modules that can be packaged together or sold as individual pieces. These modules offer communications, I/O drivers, a real-time control engine, human-machine interface, and interfaces to other PCs, networks, and information systems.

SENSORS AND TRANSDUCERS

Sensors and transducers can be classified by the machine or process variable detected (such as temperature), or by the method used to detect a machine or process variable (such as photoelectric).

Temperature sensors

Temperature sensors range from simple conventional thermometers to sophisticated solid-state devices. Some are used merely to sense and provide a visual indication; others, combine sensing with control capabilities.

Mercury thermometers — A mercury in glass thermometer is a simple industrial sensor used only to indicate temperature. Mercury rises and falls within a capillary tube with a calibrated scale in response to temperature changes.

Bimetallic thermometers — These devices have a sensing element that consists of two strips of different metals bonded together. Each metal has a different thermal expansion coefficient. Consequently, the metals expand at different rates as temperature rises, and bend in the direction of the metal that expands least. Some bimetallic sensors are formed into a helix with one end attached to a shaft. A pointer is attached to the shaft and, as temperature changes, the pointer moves along a calibrated scale. The shaft could be attached to a position sensor (such as a potentiometer) to produce an output signal that can be used for process control.

Thermocouples — Two wires, such as iron and constantan, are joined to form a measuring junction and a reference temperature junction. A thermocouple produces a voltage proportional to the temperature difference of the two junctions. This voltage difference is only a few millivolts, but is amplified for control applications.

Thermistors — A semiconductor that provides high sensitivity and quick response to temperature changes. Thermistor resistance decreases with temperature increases. Because a large change in resistance occurs per degree of temperature change, thermistors provide very sensitive indications of temperature when used in a bridge circuit. Often, bridge output is fed to an amplifier, and then to a control circuit, such as a relay.

Radiation pyrometers — A noncontact sensor used to measure extremely hot (700 to 3,500°C) temperatures. Because they do not have to contact an object to measure its temperature, the object can be in a corrosive atmosphere, in a vacuum, or moving. The radiation pyrometer senses temperature by measuring an object's radiation of thermal energy. Optical or brightness pyrometers compare the radiation from the surface of an object with the radiation emitted from a filament of a calibrated lamp. The brightness of the object is matched to the reference bulb. Then the reference bulb current is measured and translated to temperature.

Position sensors

Position sensors may be simple mechanical devices like switches that require physical contact with the object whose position they are sensing, or electronic devices like photoelectric scanners that determine position through the use of a light beam.

Limit switches — These devices translate mechanical position into an electrical indication of position. Several types are available and usually referred to by their physical configuration.

Push rollers are actuated by direct thrust or the vertical component of a linear or rotary cam. Side forces can cause binding and should be minimized, Figure 7.

Rotary switches are one of the most commonly used due to the variety of heads available, Figure 8.

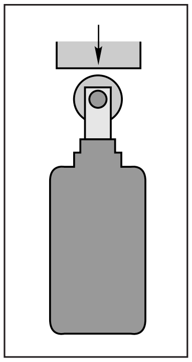


Figure 7 — Typical push roller limit switch.

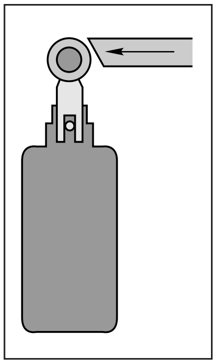


Figure 8 — Typical rotary limit switch.

Cam limit switches consist of one or more rotating cams shaped to actuate limit switches during part of the cam's rotation in order to initiate a specific action. Several switches can be arranged in parallel to actuate a sequence of actions, Figure 9. Both mechanical and electronic programmable types are available. The electronic type, Figure 24, can provide multiple functions with digital and

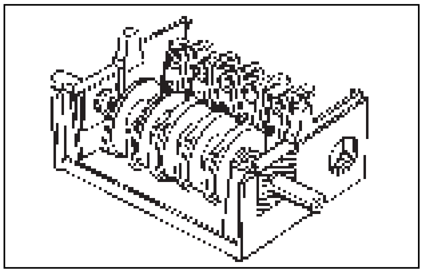


Figure 9 — Typical rotating cam limit switch. Cam switches are also available in solid-state versions, Figure 19.

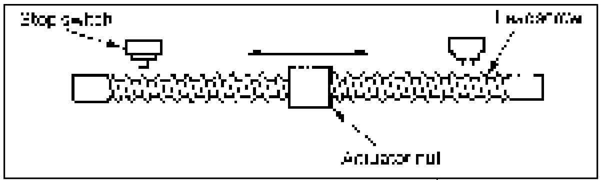


Figure 10 — Typical lead screw limit switch.

analog outputs. These electronic units can be reprogrammed to change functions without stopping the machine, and have diagnostic capabilities. (For more on electronic programmable cams, see Smart Sensors later in this section.)

Lead screw types use an actuator nut to trip stop contacts at each end of travel, Figure 10. Intermediate switches can be located between stops for position indication or circuit switching.

Potentiometers — Available in rotary and linear configurations, potentiometers change the value of the voltage output. By moving a slide across a resistor material, output voltage changes and indicates the measured object's position. A typical use for potentiometers is in measuring fluid levels. A float is attached to the potentiometer shaft and, as fluid level changes, voltage output varies proportionately.

Proximity sensors — Actuated by the presence of objects without physical contact, proximity sensors can be used as limit switches, positioning devices, speed controls, and counting devices, Figure 11. Their speed generally varies from 5 to 1,000 pulses per second. Different types of sensors detect either metallic or nonmetallic materials.

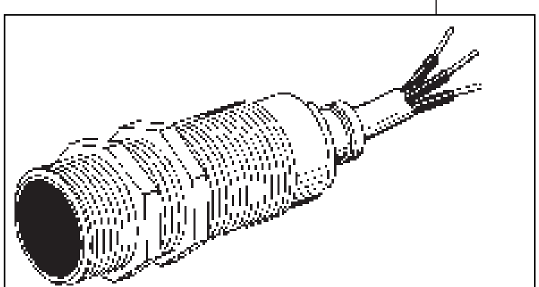


Figure 11 — Typical proximity sensor.

Inductive proximity sensors detect metallic objects by means of changes in the characteristic of an inductive electrical circuit. These sensors generally have a sensing range of a few thousandths of an inch to several inches.

Other types of proximity sensors include capacitive and sonic designs, which sense nonmetallic materials.

Some of the advantages of proximity sensors include high speed actuation, solid-state reliability, ability to sense motion from any direction in any sequence, and a capacity to sense small parts without hindering flow.

Ultrasonic sensors — Able to detect ferrous and non-ferrous objects without physical contact, these sensors use sound waves to detect the presence, distance, and orientation of objects. Operating at ultrasonic frequencies (typically 140 kHz), the sensor emits pulses in a concentrated beam from a cylindrically shaped housing, Figure 12. A receiver, within the same housing, senses returning (reflected) pulses.

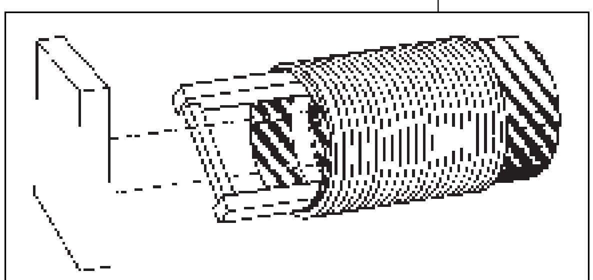


Figure 12 — Typical ultrasonic sensor measures about $4\frac{1}{2}$ in. long and $1\frac{3}{4}$ in. in diameter.

Photoelectric scanners — These noncontacting sensors detect nonferrous objects. They operate by sensing the completion or interruption of a light beam. Photoelectric scanners can be used to fine tune automated machine processes by manipulating the timing and duration of their output signal. Five types of sensing methods are available.

Retroreflective types depend on a target breaking a beam of light between the scanner and a retroreflector. This method is usually the least expensive of the five methods. Surface properties and color of the object are not critical, but it must be large enough and sufficiently opaque to break the beam, Figure 13.

Through-beam is used to indicate that an object broke a beam of light between a sender and receiver, Figure 14. Restrictions are similar to retroreflective types, and precise alignment of sender and receiver is necessary. Through-beam sensors offer the longest range (about 300 ft), but have the highest cost.

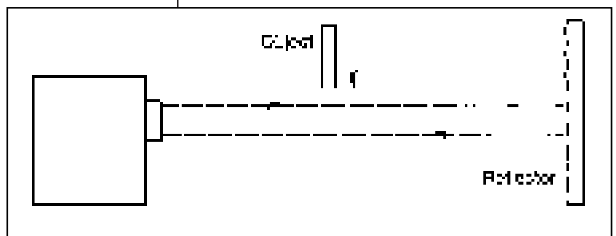


Figure 13 — Retroreflective principles.

Diffuse reflective/proximity types sense an object when the object completes a beam by reflecting any element of the beam back to the sensor, Figure 15. This method requires a distinct difference in reflectivity between the object and background area that is in visible range. If this is not possible, a retroreflective or through-beam type should be used.

Specular reflective/proximity types are similar to diffuse types, but require that a highly focused beam be returned to the sensor. This type is usually used for sensing glossy and other highly reflective surfaces.

Color mark sensing types differentiate between colors and are used for detecting registration marks, parts inspection, and color sorting. Extreme sensitivity lets them sense ripe/un-

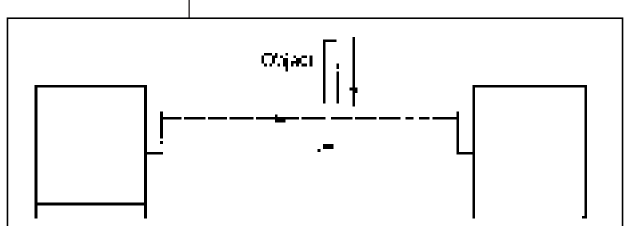


Figure 14 — Through-beam.

Improve encoder performance

During the selection process, motion system designers generally focus on encoder resolution, overlooking the electronics associated with an encoder. But the operating bandwidth, the type of output driver, and the length and type of cable have an equal affect on system performance.

Resolution. Resolution is the number of up-down cycles produced on one channel within one revolution of the encoder shaft, referred to as counts per turn or pulses per revolution (ppr). The number and accuracy of the patterns or slots on the code disc and the rigidity and stability of the mechanical assembly affect encoder accuracy.

Discs with the highest accuracy have photolithographically produced patterns on glass. Common accuracy is a few ppm, or 5 arc seconds. Less accurate are chemically milled holes in metal discs. Errors can be as high as 100 ppm, or 2 arc minutes.

The direct-read (native) resolution value is dictated by the number of optical slots on the disc. Too many lines or slots decrease the percentage of light that can pass, which can produce fringing effects and crosstalk.

The bearing and spindle design determine the mechanical stability of any industrial encoder. Resolutions higher than 20 ppm (50,000 counts per turn) will reflect bearing noise in the form of position error. Thermal mismatches between mating components in the bearing assembly can also degrade performance over temperature, and reduce encoder life.

Techniques to obtain better resolutions than through the direct-read value include quadrature decoding and electronic interpolation.

Using a 2.5-in. diameter encoder with 2,500 slots per turn as an example, the quadrature technique improves resolution because it uses both up and down transitions of a channel to get up to 5,000 counts per turn, or both up and down transitions of both channels to get up to 10,000 counts per turn. Most common controller chips have these functions built in, so it is a matter of setting a few hardware or software switches to activate these higher resolutions.

The choice of direct-read resolution or electrical interpolation is a design decision made by the manufacturer. A common method for electronic interpolation is to use a voltage divider circuit to subdivide the raw analog signal into the desired number of interpolation steps. Interpolations as high as 20 times are possible. This is usually done internally to the encoder and is transparent to the motion system designer. It pushes the practical upper limit to about 200,000 counts per turn (10,000 direct × 20 = 200,000) which will handle most common industrial applications.

When specifying encoder resolution for any system, look at the error analysis for the system and choose an encoder that will read two to four times better resolution than the maximum error source. In the above example on the encoder, the error sources are typically about 20 ppm (26 arc seconds) and the maximum resolution available is about 5 ppm (6.5 arc seconds), or four times better.

Bandwidth. It is not possible to entirely separate the design parameters of resolution and bandwidth. They are related, through operating speed, by the formula:

$$F = \frac{N \times R}{60}$$

where:
F = Frequency, Hz
N = speed, rpm
R = Resolution, counts per turn

The bandwidth is dictated by the type of output driver (line driver vs. open collector), length and type of cable, and the type of terminations used at the controller end.

Line drivers. Consisting of two transistors with collectors connected, line drivers ensure a low impedance output, typically less than 50 ohms. They can be used with cable lengths to 1,000 ft and operating frequencies to 1 MHz. However, their high switching speeds mean that they are prone to ringing while their low impedance makes them more noise immune.

For highest performance, the signals for these outputs should be specified to include the channel complements and be carried in shielded, twisted pairs. These signals should be fed to a high impedance differential-line receiver, or opto-isolator, which offers common mode noise rejection. Cable termination resistors match the receiver to the cable impedance to minimize signal ringing. This is usually done through trial and error.

Open collectors. Due to their higher impedance, open collectors are more bandwidth limited. A good rule of thumb is to use them at a maximum of 50 kHz with a maximum of 50 feet of cable. Their advantage is that they are the least expensive type of output. The pull-up resistors can be user supplied or factory installed within the encoder, or both. The arrangement is often dictated by the controller or the need to operate the encoder at a different voltage than the supply voltage.

Encoder bearing assemblies and load. To ensure a high quality, reliable output, code disc and spindle assemblies for encoders must be mounted in a bearing assembly. There is a common misunderstanding regarding encoders that since they have a bearing structure, they can carry significant loads such as those that result from installation misalignment. They can carry some loads, however, even a good installation can have a 0.003-in. parallel misalignment. The relationship between bearing loading and life is:

$$n = \left(\frac{C}{P}\right)^3 \times \left(\frac{1665}{L_H}\right)$$

where:
n = bearing life, revolutions
C = dynamic capacity (from manufacturer's data)
P = bearing load, lb
L_H = design life of bearing, hr

If the encoder is hard mounted to the motor shaft and the encoder housing is hard-mounted to a base plate, the bearing assemblies could experience side loads of several hundred pounds. Bearing life is approximately inversely proportional to the third power of the load. Therefore, doubling the side loads results in 1/8th the useful life.

The most common encoder mechanical failure is caused by excessive bearing load.

Standard, high quality bearing assemblies operate well at speeds to 10,000 rpm. At higher speeds, bearing operation is limited by a combination of heat generation in the races and surface micro-cracking caused by the high relative speeds between the races and the balls.

Bearing assemblies can be built with tolerances that allow their use at higher speeds, to 30,000 rpm. However, temperature can still be a problem. Most industrial encoders are built with shaft seals to protect the internal assemblies from dirt, oil, metal chips, etc. As spindle speeds increase, these seals can be a source of heat generation. Manufacturers take different approaches to shaft sealing techniques, so be sure to check with the particular manufacturer to ensure that they have addressed this concern.

Installation. All encoders must have a means to couple directly to the drive shaft to be controlled or measured. Because the center of rotation of the encoder is never exactly co-aligned with the center of rotation of the driving shaft, use a coupling or flexible mounting scheme to resolve the misalignment.

Excerpted from an article by the Industrial Encoder Div., BEI Sensors & Systems Co., in the September, 1996 issue of PTD.

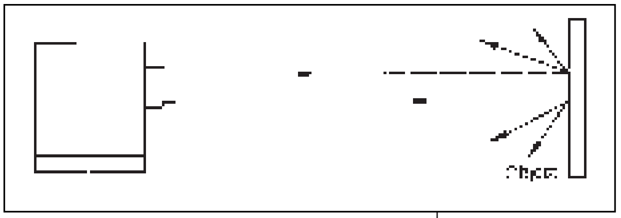


Figure 15 — Diffuse reflective.

ripe fruit, and quality of miniature electronic components.

Vision systems — Industrial vision systems aid manufacturers in identifying, measuring, and inspecting parts for defects. Each system consists of a camera, lights, processor, and computer. In operation, the video camera scans the object line-by-line, sending video signals for each line to the processor for conversion into a form understood by the computer. The processor digitizes these signals in the form of a grid where each square in the grid is a picture element called a pixel. Light intensity is determined for each pixel and expressed as a number from zero to 256 in a system called gray scale.

The gray scale data is sent to the computer for analysis of the image, using one of several techniques:

- Feature analysis — the determination of characteristics such as size, shape, and location of holes.
- Edge detection — finding the edge of an object based on a change in gray scale level. Edges can be used to derive other information such as part dimensions.
- Template matching — comparing features (pixel by pixel) of an object with a standard image.

Rotary encoders and resolvers — Sometimes referred to as incremental encoders, these devices produce discrete electrical pulses during each increment of shaft rotation, and provide high-resolution feedback data on shaft position, velocity, and direction. Available in a range of resolution capabilities from 1 to 30,000 pulses/rev, four types are commonly used.

Optical encoders use one or more light sources and a set of photo detectors, separated by a rotating disk and a stationary reticle. Advantages to optical encoders are: operation down to zero speed, low cost, high resolution (2,500 pulses/rev), excellent immunity to shock and vibration, low moment of inertia, high reliability, and the capability to operate over a wide temperature range.

Magnetic encoders consist of a variable reluctance probe, an iron gear, and housing, Figure 16. The probe consists of a strong permanent magnet wrapped with electrical wire to form a magnetic coil. The reluctance path of the magnet is varied by the presence or absence of teeth. The continuously changing magnetic field induces a voltage in the coil that produces a sine wave output from the encoder. Advantages to this type of encoder are: lowest in cost, no external power requirements, highest reliability, and widest operating range. Disadvantages are: resolution is limited to 360 counts/rev, relatively high moment of inertia, and cannot be operated at zero or low speed.

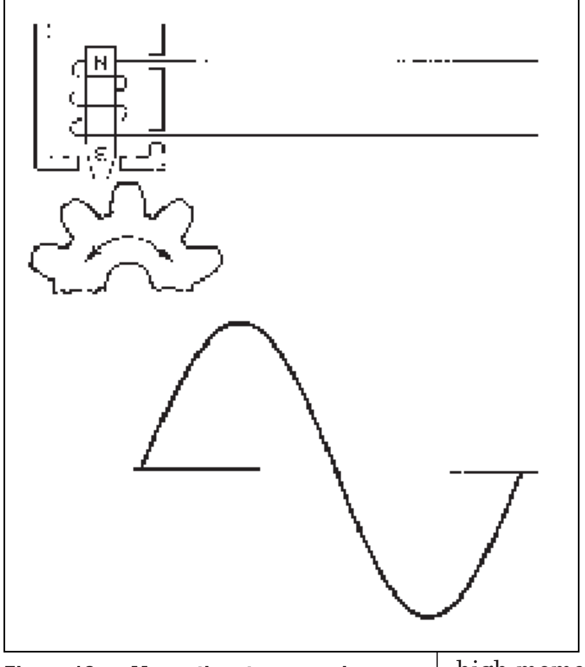


Figure 16 — Magnetic rotary encoder consists of variable reluctance probe, iron gear, and housing. Output is a sine wave.

Magneto-resistive encoders are similar to magnetic encoders except for the probe. The probe is a differential magneto-resistive element attached to a powerful permanent magnet. Its output is connected to an amplifier and drive transistor. The imbalance of the magnetic field caused by the gear tooth passing under the legs of the sensor produces an output signal. Advantages and disadvantages of this type are similar to that of magnetic types; however, they can operate to zero rpm.

Resolvers look like small motors and are, in some respects, similar in construction. A resolver contains single winding rotors that revolve inside fixed stators with two windings mounted 90 deg apart. The rotor winding is typically driven by a reference voltage at a frequency ranging from 400 Hz to several kHz. The resolver circuitry contains a resolver-to-digital converter that compares output to a fixed reference frequency to determine shaft speed. In most cases, an analog output proportional to the shaft velocity eliminates the need for a separate tachometer feed. Resolvers are rugged, wide-temperature-range devices that operate reliably to zero rpm. Disadvantages of resolvers are the relatively high moment of inertia and the complexity of the electronic circuitry.

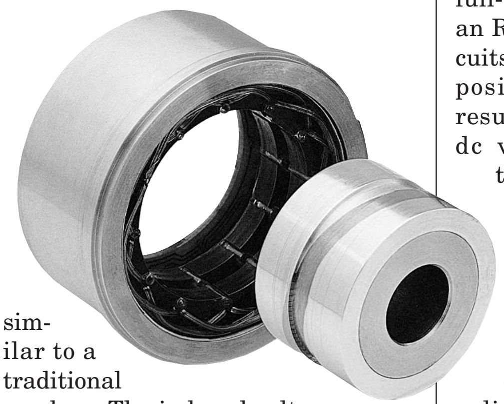
Recent design innovations, however, may reduce or eliminate these disadvantages.

A new design uses a solid rotor without windings, which makes the resolver less complex and less costly to manufacture. The primary and secondary windings are in the stator, therefore it does not need a rotating magnetic coupling, Figure 17. The design is inherently brushless.

The rotor contains a diagonal section (not perpendicular to the shaft) of high permeability material that varies the magnetic field across the stator as the rotor turns. Transferred energy remains magnetic from the primary coil through the air gap to the sinusoidally shaped poles of the solid rotor. The total flux through the gap is constant—the rotor determines the angular position within the stator bore where the coupling occurs, and thus, the relative amplitudes of the output signals.

The primary coil is wound circumferentially between the two stators. The secondary windings are wound in the stator slots in space quadrature,

Figure 17 — A new resolver design has primary and secondary windings in the stator and a solid rotor.



similar to a traditional resolver. The induced voltage amplitudes correspond to the sine and cosine of the rotor angle as in a traditional resolver.

This design is mechanically and electrically compatible with traditional resolvers, Figure 18. Because there are no coils in the solid rotor, it is rated to 30,000 rpm. Higher speeds are a matter of mechanical balance. The top speed (100,000 rpm) is limited by the excitation frequency, and the burst strength of the rotor.

The single-stage magnetic design means low source impedance, so the resolver is less susceptible to noise pickup and tolerant of long cable runs. It can be excited at frequencies to 40 kHz.

Linear variable differential transformers — LVDTs are frequently used as position sensors because they provide excellent linearity, infinite resolution, and high sensitivity, Figure 19. The oscillator converts dc input to ac, exciting the primary winding of the differential transformer. Voltage is induced in the secondary windings by the axial core position. The two secondary circuits consist of a winding, a full-wave bridge, and an RC filter. The circuits are in series opposition so that the resultant output is a dc voltage proportional to core displacement from the electrical center. Voltage polarity is a function of the direction of core displacement from the electrical center.

Figure 18 — In traditional brushless resolvers, a rotary coupling transformer transfers energy from the stator to the rotor.

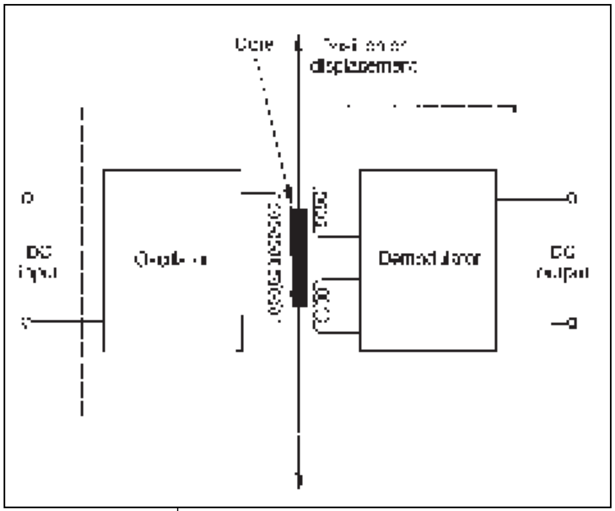


Figure 19 — Principle of a dc-to-dc LVDT.

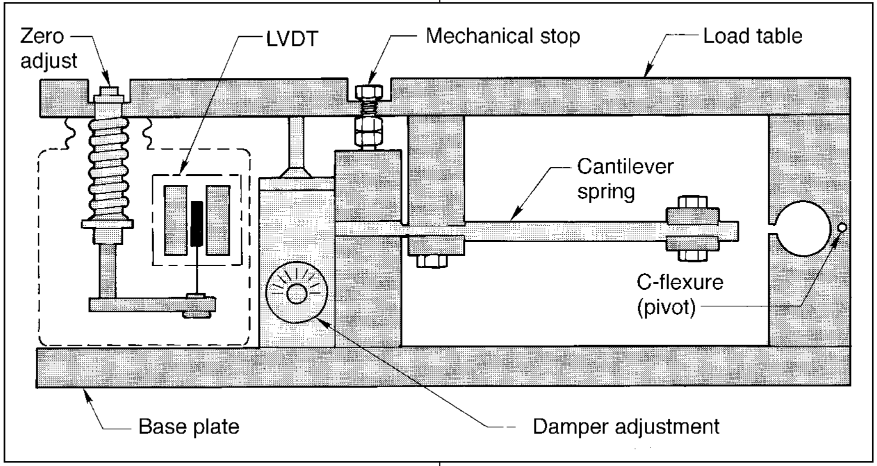


Figure 20 — Typical LVDT-type force transducer.

Today, LVDT circuits built on a single chip greatly simplify interfacing. These chips contain a programmable frequency oscillator, a synchronous demodulator, and an amplifier that produces a buffered voltage output.

Force transducers

A force transducer produces an output signal proportional to applied force. LVDTs and strain gages are multi-purpose electrical devices that can measure a variety of physical quantities, including force. In force measurement applications, these devices convert mechanical displacement due to applied force into an electrical signal.

LVDTs are often used in load tables containing an internal spring and flexure, Figure 20. The load moves the load table, which moves the core in the LVDT. DC output signal is linear within 0.2% of rated voltage over a 20:1 range and offers repeatability of ±0.1%, of maximum rating. Response is adjustable from 600 μs to 250 ms through the operation of a damper. Load cells with dual LVDTs offer ranges to 125:1.

Strain gages — These devices undergo a change in electrical resistance when subjected to strain—a material's change in length due to applied force. Strain gages are also used to measure physical quantities such as load, torque, pressure, tension, and weight. In industrial process control, strain gages are probably the most common devices used to measure force.

They are also used for static and dynamic measurements. They can respond quickly to minute displacements. However, they may lose accuracy due to hysteresis, when the gage

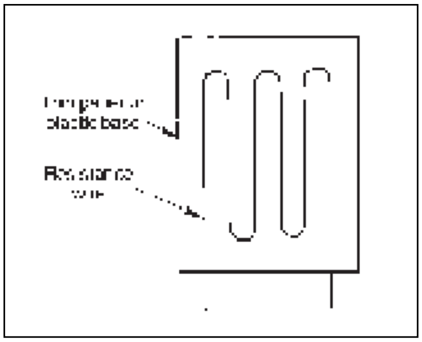


Figure 21 — Bonded resistance-type strain gage

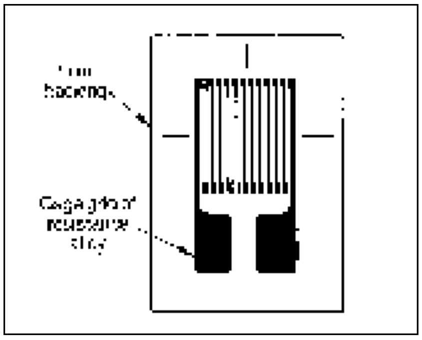


Figure 22 — Foil strain gage.

must measure the same displacement for many cycles, or due to overload. Strain gages are available in three basic types: bonded, unbonded, and semiconductor.

Bonded gages are generally available in two types. One type, Figure 21, uses thin metallic filaments bonded to a thin paper or plastic base. Another type, Figure 22, uses a foil (thin film) design. These gages have resistive elements that are vacuum deposited on a ceramic film. Pressure applied to the pressure summing diaphragm deflects the diaphragm and changes the resistance of the foil strain gages that are wired into a Wheatstone bridge.

Unbonded gages are generally smaller than bonded types, but are not as rugged, nor as stable as thin-film pressure types. They differ from bonded types in that the filaments are attached between movable and fixed supports. Unbonded gages can be made to measure very low and very high pressures — from less than 0.05 to 20,000 lb/in.[2]

Semiconductor gages include bonded bar and diffused types that offer important advantages such as small size and high output signal (about 100 mV).

Bonded bar gages are similar to bonded foil gages in that they are bonded with epoxy to the mechanical structure (cantilever beam or diaphragm). The bonded bar gage is a piece of pure single-crystal silicon into which an impurity such as boron is introduced during the growth of the silicon crystal. The entire piece of silicon serves as the strain gage.

Diffused gage transducers are formed from a piece of pure silicon with boron diffused areas that are strain sensitive. Because the strain gages are an integral part of the silicon wafer, which also serves as the diaphragm, no bonding is required. The result is a structure whose stability is superior to that of unbonded wire, bonded foil, and bonded semiconductor strain gage transducers.

Torque transducers

A torque transducer consists of a mechanical structure that distorts when subjected to a torsional force. Strain gages, which are bonded to the structure, deform with the structure and produce corresponding stress or strain values. The two most widely used structures are hollow-cruciform and square-section, Figure 23. Hollow-cruciform types produce high strain values at low torque and are used extensively in low-capacity (below 500 lb-in.) applications. Square sections are used for high capacity (500 to 500,000 lb-in.). Torque transducers are accurate to 0.1% or better and operate up to 35,000 rpm.

When used in rotating applications, a signal transmission path is established between the stationary and rotating components of the transducer, usually by means of slip rings or rotary transformers. Where application constraints such as space, configuration, or speed prohibit the use of these types, other designs may be used, such as the torsional variable-differential transformer (TVDT), phase-shift transducer, or reaction transducer. Torque transducers are used in quality control to check completed motors for rated torque, and for process control to maintain constant motor torque on production lines.

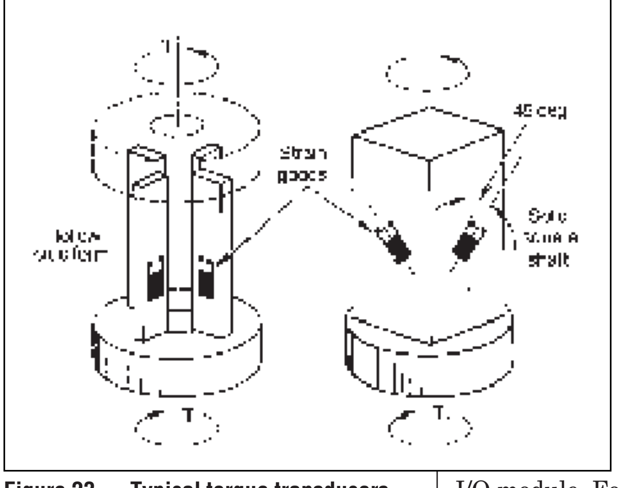


Figure 23 — Typical torque transducers consist of a physical structure and strain gages.

Smart sensors

In distributed control systems, operation logic is often placed close to the application being monitored by combining a sensor and microprocessor into one unit, commonly called a smart sensor. This reduces response time and interference from noise, and allows a smaller, less expensive PLC to be used because routine, repetitive operations are controlled by the sensor's own microprocessor. Functions performed by smart sensors include correcting for environmental conditions, diagnosing operation, and making decisions.

One type of smart sensor, an electronic programmable cam switch includes a position sensor and a microprocessor, sometimes in one enclosure, Figure 24. An encoding disc converts shaft position data into binary coded decimal data (BCD). A microprocessor compares the BCD data to user-defined dwell settings stored in an EEPROM chip, and then determines the on/off status of several outputs. The outputs are programmed into the switch with a built in keypad or a hand-held programmer. Dwell settings can be maintained to within plus or minus 1 deg at 2,000 rpm.

Because it is programmable, the switch can be integrated into an automated factory system through an intelligent I/O module. For example, a host computer can direct a controller (PC or PLC) to adjust machine parameters

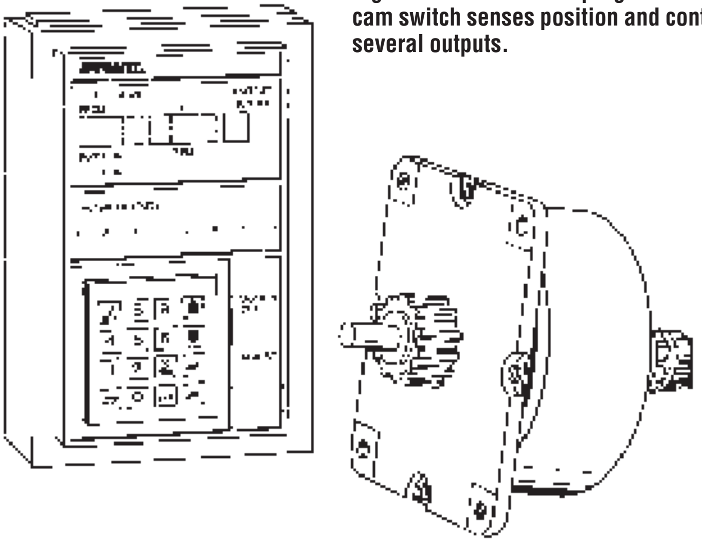


Figure 24 — Electronic programmable cam switch senses position and controls several outputs.

for a product changeover. The controller downloads instructions through the intelligent I/O module which receives position feedback data from the switch to fine tune machine operations.

Flow sensors

Flow rate is a common process variable that must be controlled in the petrochemical, food-processing, and similar industries. Many flow rate sensors are actually pressure sensitive devices. They respond to changing fluid pressure. Generally, flowmeters are classified as head flowmeters, positive displacement flowmeters, and variable area flowmeters.

Head flowmeters measure flow by passing the fluid through a restriction. Pressure on both sides of the restriction is measured, and flow rate is directly proportional to the square root of the difference of the static head (high pressure before the restriction) and dynamic head (low pressure after the restriction). Commonly, orifice plates; flow nozzles, and venturi tubes comprise head flowmeters.

Positive displacement flowmeters and metering pumps measure fluid flow directly, not indirectly like head flowmeters. The positive displacement flowmeter has a measuring chamber between inlet and outlet ports. A vane, disc, or piston in the measuring chamber displaces a fixed fluid volume with each revolution. The fluid volume passing through the flowmeter is a function of the meter's rotational speed. Fluid flow is a product of displacement and chamber cross-sectional area. Typical applications include water, gas, and gasoline flow.

Variable area flowmeters include rotameters and piston-type meters. Variable area flowmeters operate on the same principle as other differential headmeters. They have a variable orifice and relatively constant pressure drop.

Rotameters are the most common type of variable area flowmeter. They consist of an upright tapered glass tube containing a float, usually made of metal. When fluid flows through the rotameter, the float's weight opposes the upward force exerted by fluid flow. You can determine flow rate by reading the float position of the rotameter's calibrated scale. Some rotameters are designed for direct viewing; others are coupled magnetically or hydraulically to allow automatic recording of flow rate.

Piston types consist of a fitted piston in a sleeve or cylinder, held in a cast body. The cylinder has inlet and outlet orifices cast into it. The piston indicates the flow rate. These flowmeters can be used to measure highly viscous or corrosive fluids. However, they should not be used with fluids containing sediment.

Viscosity sensors

Viscosity is a measure of a fluid's resistance to flow. It should be considered in industries where fluid must be pumped, such as petrochemical, pharmaceutical, and food processing applications. Typical viscosity sensors include the capillary and rotating disc viscometers.

Capillary types force fluid through a small diameter tube at a constant flow rate. The pressure drop across the capillary tube is proportional to viscosity. This viscometer requires close temperature regulation. It cannot be used with fluids that have non-Newtonian viscosity characteristics. With a non-Newtonian fluid, the ratio of shear rate (velocity per unit thickness) to shear stress (force per unit area) is not constant.

Rotating disc viscometers measure the torque required to rotate the disc in a fluid at constant speed. With one type, a strain gage measures the force exerted by a spring loaded wormgear that drives the rotating disc spindle. The signal generated by the strain gage can be fed to a recorder to monitor viscosity.

POWER CONTROLS

Power controls direct energy to power consuming devices, such as heaters, lights, and other similar items that can be associated with power transmission products. Three of the most common elements used in controlling electrical energy to these items include switches, circuit breakers, and contactors. Motor controls are covered separately in the next section.

Switches

Usually operated manually, switches provide one of the simplest means of turning electric power on and off, and are rated from 10 through several thousand amperes. Having an internal design similar to early knife switches, modern switches are frequently enclosed in a protective housing and operate in a snap-acting manner to reduce sparking. Enclosures are available in general purpose NEMA 1 through NEMA 7 for explosive atmospheres, and NEMA 12 for common oil and dust environments. Frequently termed disconnect switches, these units come with or without fuses depending on application requirements. They are also available as transfer switches, for transfering the source of power from a main power system to an emergency system. Typically, these units are simply power rated multiple-pole, double-throw devices. In addition to being manually operated, they can come with different types of operating schemes — such as magnetic units that will automatically switch to a standby power system should the main supply fail.

Switches are available for switching ac and dc power. Typically, the dc switch will include blow-out coils (typically permanent magnets), which help extinguish the arc of high current dc to increase contact life.

Circuit breakers

Circuit breakers are usually contained in a single enclosure and are available in fractional through several thousand amp ratings. Thermal and compensated-thermal breakers depend on heat for tripping. The thermal tripping range is usually 101 to 120% of their current rating and offers an inverse time delay characteristic. Their characteristics differ only slightly when used on dc or 60 Hz ac.

Circuit breakers with a magnetic trip feature offer instantaneous response, tripping whenever a predetermined value of overload occurs. Some breakers contain both thermal and magnetic trip functions. Typically, the magnetic portion is set to trip when the overload exceeds 600% of rating. The relationship between magnetic and thermal trip characteristics can be varied, usually through an adjustment screw.

Circuit breakers can also come with ground fault interrupters that cause the breaker to open whenever a high amount of current flow to ground is detected. This feature is especially important when the circuit breaker controls devices operated by personnel. Many types of ground fault detectors are available to meet a range of applications. Consult manufacturers with the specific application requirements to assure proper personnel protection.

Circuit breakers are not designed for a high number of operations. If it is desirable to open or close a power circuit several hundred-thousand times, use a magnetic contactor.

Contactors

These are magnetically controlled devices for controlling electric heaters, large banks of lights, and other power consuming devices. Unlike magnetically operated circuit breakers, contactors are designed for hundreds of thousands of operations.

Contactors are available in many enclosures, including explosion-proof and NEMA 12 industrial use. Available for operation on ac or dc (which usually include blow-out magnetics for rapidly extinguishing the arc) these units should be specified based upon the type of load they are controlling. For example, units designed for controlling incandescent lights and highly inductive loads are derated to give reliable operation for long periods of time, even if the contacts must open or close under abnormally high currents. Contactors are available with normally open or normally closed contacts, or a combination of both.

The most common type of contactor is built to operate with ac powered coils for controlling ac power devices. Many manufacturers offer various combinations of coil voltages and types, including 4,160 Vac and several hundred ampere rating.

MOTOR CONTROLS

Motor controls are usually referred to as starters or drives. Motor starters start and stop motors by applying or removing electric power. Drives are more complex than simple starters, in that they condition the electrical power prior to delivering it to the motor. Motor starters and reduced voltage starters represent the simplest form of motor control.

AC motor starters and controls

AC motor starters and controls are grouped into two broad classifications: full voltage (across-the-line starters), and soft start (reduced voltage starters). Both offer two functions — turn the motor on and off, and provide overload protection, as required by the National Electrical Code. This code also requires that almost all motor branch circuits contain a disconnecting means and short circuit protection. These functions are provided by circuit breakers and fused disconnects. If a single enclosure contains the motor starter plus the disconnect and short circuit protection, the unit is a combination starter.

Full-voltage starters

These starters apply full line voltage directly to the motor terminals and come in two basic types: manual and magnetic. Other types, such as

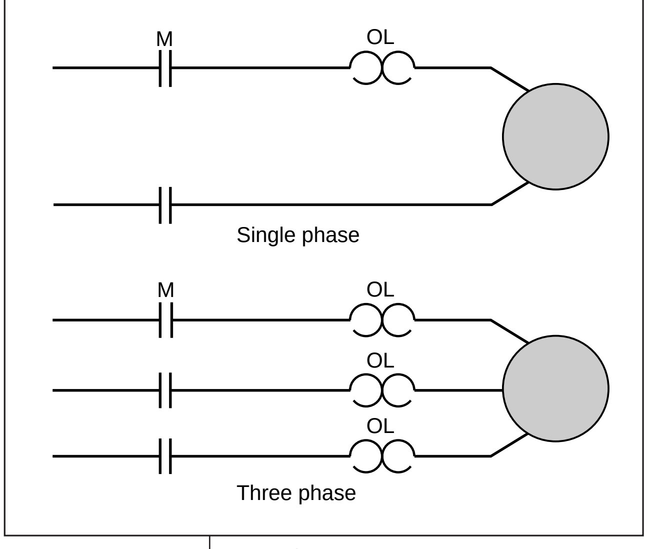


Figure 25 — Across-the-line manual starter.

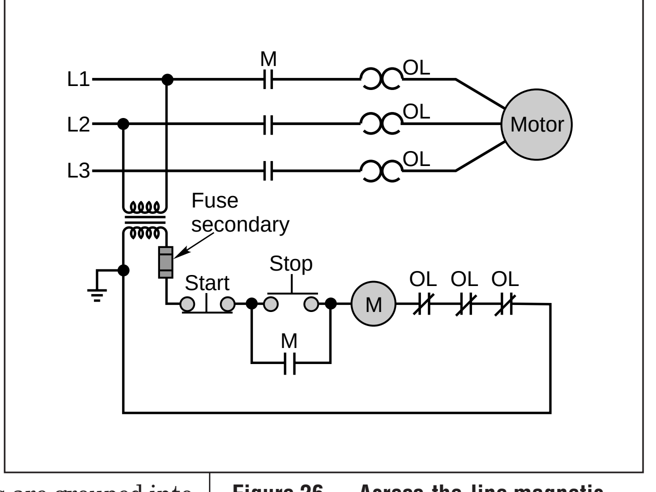


Figure 26 — Across-the-line magnetic starter.

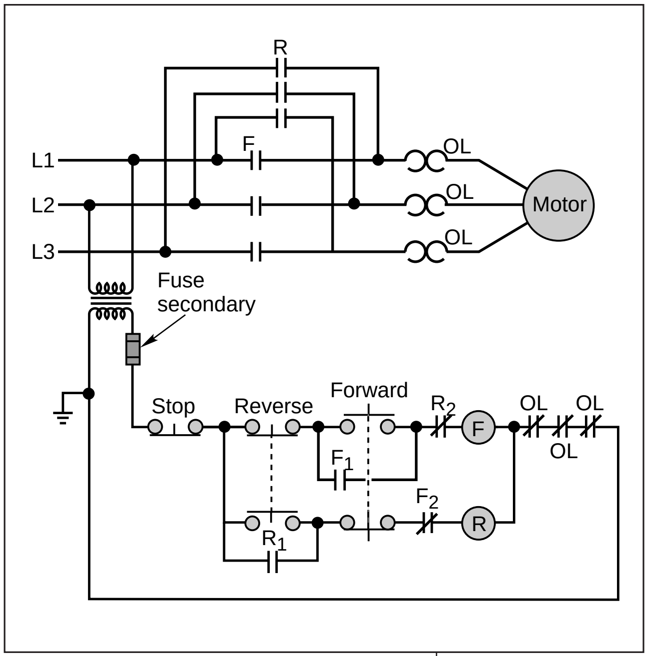


Figure 27 — Across-the-line reversing starter.

reversing starters, are magnetic starters with added control functions.

Manual starters are hand operated mechanisms that connect or disconnect the motor circuit. A thermal protective circuit in the starter guards against excessive motor temperature conditions. Manual starters are limited to single-phase motors up to 5 hp at 230 V, and three-phase motors up to 15 hp at 600 V, Figure 25.

Magnetic starters are similar to manual starters but the electrical connection to the motor is made through a set of contacts, which are controlled by a coil. De-energizing the coil opens the circuit, Figure 26.

Reversing starters switch two of the power leads going to a three-phase squirrel cage motor to reverse its direction of rotation. Reversing starters are usually magnetic and switch the two leads through another set of contacts, Figure 27.

Reduced voltage starters

These starters apply less than rated voltage during the starting sequence of ac motors. During starting, ac motors typically draw 600% of full load current and develop 150 to 200% of rated torque. This high current can cause the power line voltage to drop, which can make lamps flicker, and cause sensitive instruments to give false indications. The high starting torque can break belts and damage other mechanical devices.

By reducing the applied voltage to motors during starting, the initial line currents and torque surges are reduced. The line current reduction is approximately proportional to the voltage reduction. However, the torque is approximately proportional to the square of the voltage change.

Three methods are commonly used to reduce the motor starting voltage: resistors, auto-transformers, and solid-state controllers.

Resistors — Connected in series with the motor during starting, resistors are shorted out to apply full voltage during running. A timer frequently determines the duration of the starting phase.

Auto-transformers — Connected in the motor circuit to supply reduced voltage during starting, full line voltage is supplied to the motor after the starting sequence.

Solid-state — Also termed soft start controls, these use SCRs to increase the applied motor voltage from zero to rated. This increase can be current limited so the motor does not exceed a selected value, on a current limit ramp, or, by using tachometer feedback, on a linear motor speed ramp. This solid-state method offers many advantages, including a high degree of controllability and stepless acceleration, Figure 28.

Any application of reduced voltage starters must be carefully engineered to assure proper coordination of required starting torque, starting duration, starter capabilities (current and time), and motor heating characteristics.

MOTION CONTROL SOFTWARE

Recent developments in programming software let engineers concentrate on designing a motion control solution rather than writing lines of code. The most frequently executed programming task for the engineer is to point and

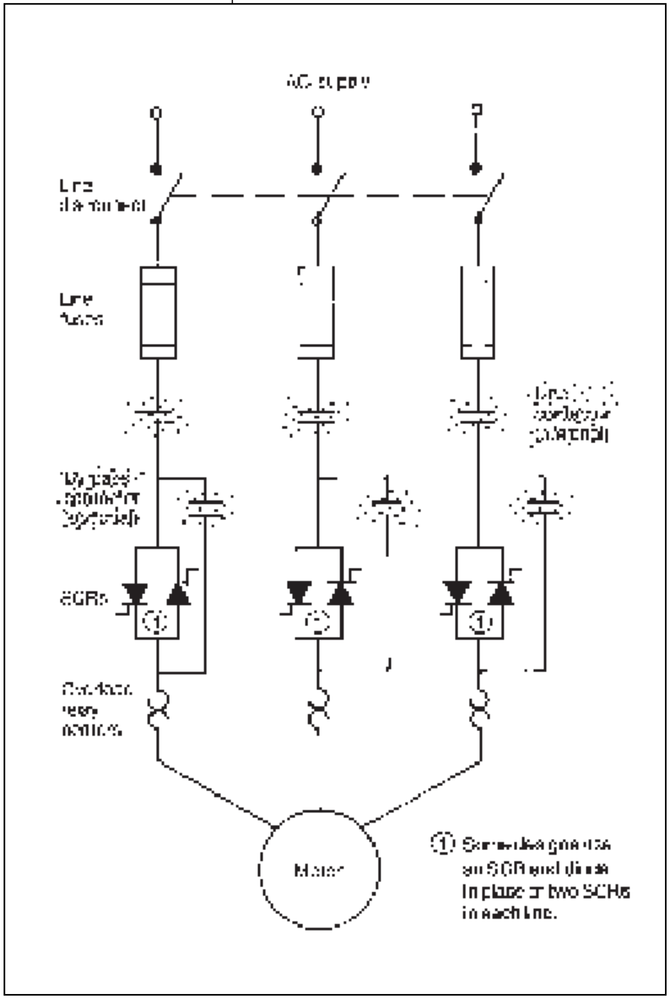


Figure 28 — Power circuit of typical solid-state, reduced-voltage starter. SCRs control motor voltage during starting sequence only. After starting sequence, motor runs at line voltage.

click. Engineers can use prewritten routines, or fill in the blanks, or keystroke parameter data such as desired final position, speed, number of axes, and position points; the software does the rest of the programming.

The popular Windows operating system is a large part of the reason why motion control software has become easier to use then earlier versions. Windows offers program-development tools and programming aids (such as Visual Basic, DDE, and others) that manufacturers can use to create application programs that almost write themselves.

Some motions must be programmed with more sophisticated software. For 85 to 90% of programmed motion, however, the Windows-based software works well.

Typical features of the easier-to-use software include:

Graphic icons. Engineers link these icons to describe the motion system in flow chart form. The software converts the icon flowchart into code and transmits that code to the drive or motion system.

Integrated diagnostics. These programs offer digital versions of oscilloscopes, spreadsheets, and real-time signal plots, which aid motion system diagnostics. For example, using the oscilloscope version to set up servo drives can be a one key-stroke operation. Such a feature eliminates the time an engineer needs to find cables and wire up the scope, and reduces the time needed to measure the correct signals.

Dynamic Data Exchange (DDE). The Windows operating system is too slow for motion control applications. DDE is an addition that helps alleviate this limitation. It captures and quickly transmits data from a device, such as a motion controller, to software applications such as spreadsheets, plotting routines, and operator interfaces.

File management. Some programs will also manage file uploading and downloading, and archive the application programs.

CAD interface. A few programs can receive files from a CAD system. These programs will take the CAD data and create lines of code to manipulate the axes to trace the pattern.

In addition, most software offers automatic tuning of drives to the motion system. You enter in a few parameters and the software does the rest. Most programs also offer *Help* functions for on-line explanation or instruction. ■