CONTACTORS

Electrical contactors, sometimes referred to as motor starters or controllers, are devices that control the electrical currents to a motor, welder, or lighting system. The difference between a contactor and a circuit breaker, which also makes and breaks the circuit current, is the operation and duty cycle of the device. A contactor must be capable of operating one million times mechanically, while a circuit breaker is designed to operate tens of thousands times. A contactor operates as either a normally open or normally closed switch; that is, it has monostable operation, while a circuit breaker has bistable operation. Both devices provide circuit protection under overload and short-circuit currents, but the sensors that trip the contactor are set differently from those of the breakers. The contactor may be part of switchgear or an electrical panelboard used to control a machine or lighting. It can be coordinated with a fuse so that the contactor provides the control

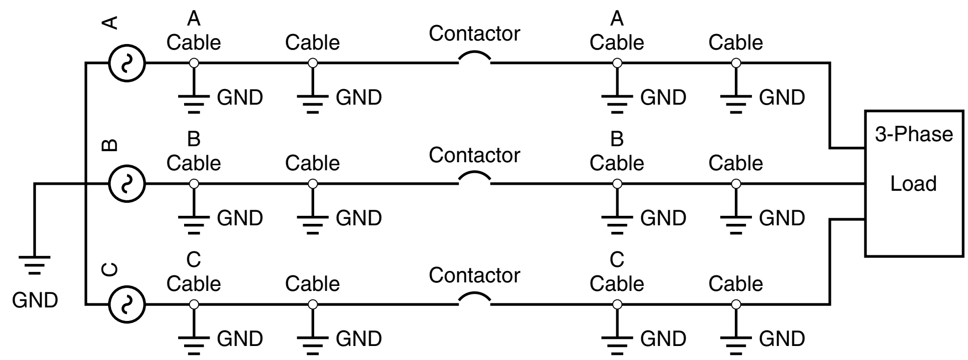


Figure 1. Schematic of a typical three-phase contactor circuit.

and protection while the fuse serves as a backup, in case the contactor fails. Figure 1 is a simplified schematic of a typical industrial circuit in which a contactor connects the voltage source to the load (motor, welder, or lighting). Most industrial power circuits are three phase, as opposed to household circuits, which are single phase. Therefore, a contactor has three sets of contacts to make or break the current in each phase of the circuit, making it a three-phase device. The sets of contacts for each phase are in the current interrupting part (interrupter chamber) of the contactor. The interrupter chamber can be an air chamber or a vacuum chamber. Contactors that have the contacts in an air chamber are called *air* (or *magnetic air*) *contactors,* and those in which the contacts are in a vacuum chamber are called *vacuum contactors.* The above contactors control currents in ac circuits. In addition, there are special types of contactors that will control currents in dc circuits. These contactors usually have only one set of contacts, and are of the air magnetic type.

The operation of a contactor can be controlled by buttons and handles on the contactor body or remotely. Air magnetic motor protectors have built-in overload current sensors and short-circuit current instantaneous sensors that trip the contactor. The overload sensor is a thermal device and has delayed tripping, while the short-circuit current sensor is a magnetic device and has instantaneous tripping. Vacuum contactors can be operated manually or remotely by electronic current-sensing devices (e.g., Westinghouse IQ electronic sensors). The current sensors are adjustable so that the proper current-time characteristics for the contactor application is produced.

Contactors are manufactured by many different companies in the United States, Europe, and Asia. Some of these companies are Cutler-Hammer (Westinghouse products), G.E., Joy Manufacturing, Mitsubishi, and Toshiba. Manufacturers of the vacuum interrupter for the vacuum contactor are Cutler-Hammer (Westinghouse products), G.E., Joy Manufacturing, Jennings, Hitachi, Mitsubishi, and Toshiba. This list of companies is not complete. Please consult the World Wide Web for more information about contactor companies.

INDUSTRIAL APPLICATIONS

Typical applications for contactors are (1) motor starters for large air-conditioning motors in commercial buildings, for manufacturing processes, and for mining operations; (2) in panelboards for lighting and power distribution of commercial buildings; and (3) in high-current welders for assembly operations (e.g., automotive fabrication). For ac induction motor applications, contactors come in various National Electrical Manufacturers Association (NEMA) sizes related to the continuous current of the motor.

An important application of contactors is the control and protection of ac motor circuits. For this application, the air contactors are rated for 240 to 600 V ac and come in different motor starter sizes, ranging from size 0 to size 6, corresponding to motor currents of 3 to 100 A. Table 1 shows the ampere ratings corresponding to the different NEMA motor starter size. However, some contactors have load current ratings up to 1200 A. The short-circuit current interruption capacities of these devices can be high as 200 kA with special current limiters. Short circuits can be caused by shorted cables connecting the contactor to the load or by short circuits in the load (e.g., shorted motor windings).

Dc magnetic air contactors are available in the voltage range of 12 to 250 V to control dc circuits and motors. These are usually single-pole devices, although, for multipole devices, the poles may be connected in series.

Many accessories are available for the molded case circuit protectors. These are shunt trips, undervoltage release mechanisms, handle operating accessories, current limiter attachments, and earth leakage protection modules.

Vacuum contactors come in voltage ratings from 600 to 7200 V, continuous motor load currents up to 800 A, and short-circuit interruption capability of 15 kA. The most popular vacuum contactor NEMA sizes are 5 and 6, although size 4 is available. Nearly all contactors must comply with American, Canadian, and foreign standards to compete in the world market. The American standards are National Electrical Manufactures and Underwriters Laboratory, Inc. (Standard UL489). IEC is the most common foreign standard used. Vac-

Table 1. Ampere Rating versus NEMA Motor Starter Size

Ampere Rating, A	NEMA Starter Size
3	0
7	0
15	1
25	2
30	3
50	4
70	5
100	6
150	

uum contactors are available with different voltage rated solenoid coils and different control modules. The solenoid coils supply the mechanical energy for the contactor mechanism and the solenoid coil voltage corresponds to the control voltage for operating the device.

For lighting and air-conditioning application of large buildings, there are three general categories for contactors used to control lighting. These are power lighting contactors rated up to 1200 A, multipole contactors having up to 12 poles, and single-pole contactors for low-voltage control. These contactors can be manually or computer controlled. The computer control contactors for lighting and air conditioning are part of the energy-management system for a building.

SPECIFIC CONTACTOR OPERATION

Figure 1 shows a typical three phase industrial circuit with a contactor connecting the voltage source to a load. The voltage source is represented by a generator and cables feed the voltage to the source side of the contactor, and the load side of the contactor is connected to a load via cables. Under normal operation, load current is fed to the load when the contactor is in the closed position. To interrupt the load current, the contactor trips and the contacts of the contactor interrupters separate, interrupting the 60 Hz load current. During the interruption of inductive load currents, high-frequency recovery voltage transients appear across the contactor and the load immediately following the current interruption of the first phase to clear. The frequency of this voltage is determined by the capacitances and inductances in the circuit. The high-frequency transient recovery voltage is damped out to the normal 60 Hz recovery voltage by the circuit resistance. These voltages appear across both the interrupter contacts and load to ground of the first phase to clear. The other two phases of the circuit continue to conduct as a single phase current with a delayed current interruption of 90 electrical degrees or less.

As stated previously, there are two types of contactors—air magnetic and vacuum. The elements of both contactors are (1) a current interrupting device or chamber, (2) a mechanism to operate the current interrupter device (such as closing or opening the contacts), (3) a coil or solenoid to activate the mechanism, (4) a frame to house the components, and (5) terminals (line side and load side) to connect the power leads. Figure 2 shows a typical molded case magnetic air motor circuit protector or contactor. Figure 3 shows the internal structure of Fig. 2. The current interruption chamber for the device consists of a set of contacts within an arcing chamber labeled "arc extinguisher." When the contactor is called upon to interrupt a load current, the initially closed contacts separate from each other and an electrical arc is established between the contacts. As the contacts separate, the arc lengthens and is forced magnetically into the U-shaped metallic or ceramic plates of the arc chamber. This magnetic force is created by the current flowing in the contacts and interacting with the current in the arc. Since the arc is a high-temperature plasma, the plates cool the arc and promote current interruption as the current approaches a natural current zero. More details of this process will follow.

The vacuum contactor (shown in Fig. 4) consists of three vacuum interrupters—one per phase, a mechanism to control the contacts contained within the interrupters, and an electri-

Figure 2. Photograph of a three-phase 600 V molded-case motor protector. This device is mounted in a motor starter panelboard. (Courtesy of Cutler-Hammer Co.)

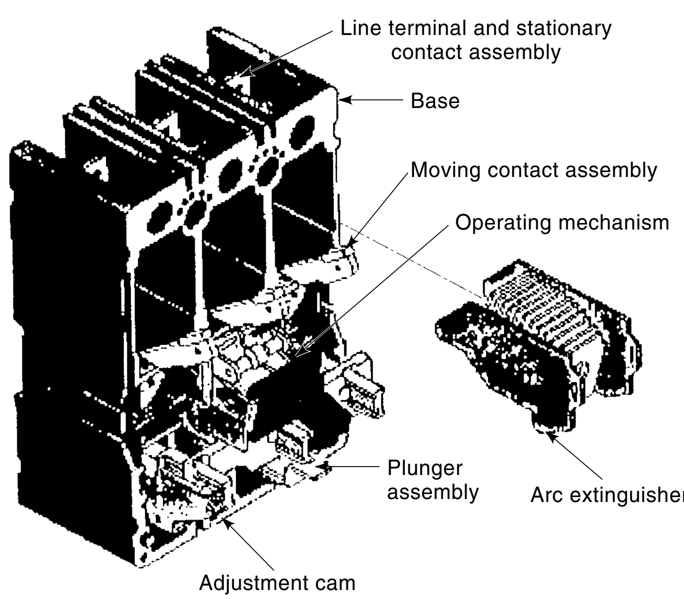
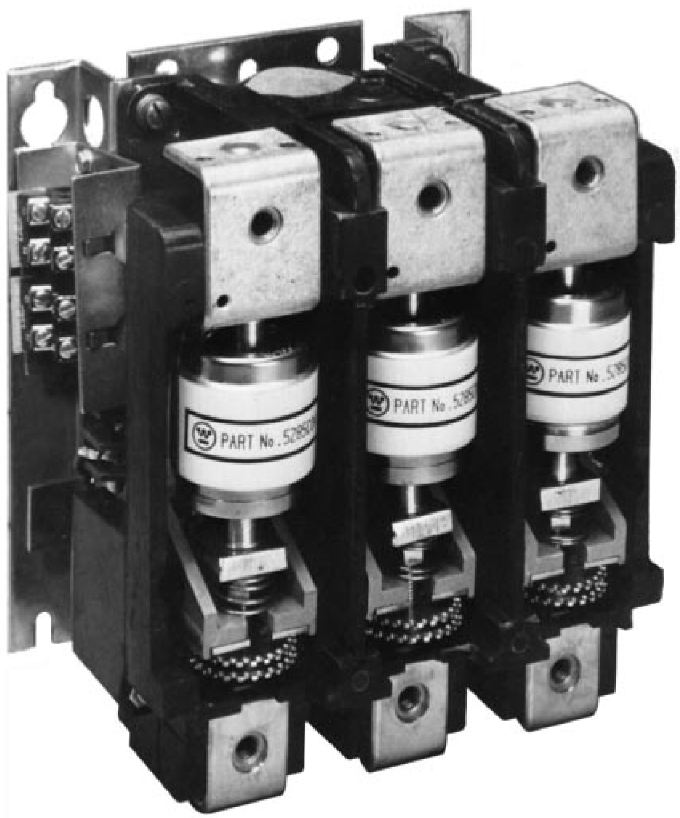


Figure 3. The internal parts of a three-phase molded-case motor protector. Shown are the moving contact assembly in the open position and arc extinguishing chamber. (Courtesy of Cutler-Hammer Co.)



Features:

- Compact, rugged construction
- Interchangeability
- Vacuum bottle installation
- Contact wear indication
- Interlock capability
- Front removable parts
- Permanently adjusted kick-out spring
- Internally rectified coil

Figure 4. Photograph of a three-phase vacuum contactor. Shown are the three vacuum interrupters, connecting terminals, mechanism, and frame. (Courtesy of Cutler-Hammer Co.)

cal means of actuating the mechanism such as a solenoid coil. Figure 5 shows the details of the three-phase vacuum contactor. These parts, as well as two sets of terminals, are supported by a specially designed metal frame. When the solenoid coil is not energized, the contactor is open, representing a normally open switch. To close the contactor, an electric current is passed through the solenoid coil, causing the vacuum interrupter contacts to close and establish the circuit. The contacts remain closed as long as the solenoid coil is energized. Some contactors have the solenoid coil connected to a rectifying circuit so that a dc voltage energizes the coil. More details of the current interruption in a vacuum contactor will follow.

The advantages of the vacuum contactor over the magnetic air contactor are (1) longer service life because of low contact wear due to arcing; (2) lower maintenance; (3) greater safety because the arcing is contained within a vacuum vessel and is not exposed to the ambient (making the device suitable for mining, paper mills, and explosive atmospheres); (4) rugged, compact, and lightweight construction; and (5) quiet operation.

The main disadvantage of a vacuum contactor over air contactors is that a higher probability of overvoltages may occur during switching. These overvoltages are caused by a phenomenon known as *current chop.* That is, when contacts have separated establishing an electric arc between them, the arcing current may become unstable and extinguish before a “natural” current zero (Fig. 6). This current chop can lead to voltage surges when inductive circuits are switched. Voltage surges can be reduced by special vacuum interrupters that have a low chopping current and/or by placing surge suppression devices at the load.

The advantages of air magnetic motor circuit protector contactors are (1) lower current chop associated with them, (2) lower cost, and (3) they can be used to control dc circuits having a voltage range of 12 to 250 V. The disadvantages of these contactors are (1) shorter life, (2) more maintenance, and (3) limited applications.

Air Contactors

When air contactors are used to interrupt inductive loads, the arc of the contactor appears resistive, making the circuit “look” highly resistive. Subsequently, there is very little transient recovery voltage, and the normal recovery voltage is *nearly* in phase with the interrupted current. Since the source voltage is approximately in phase with the circuit current during the arcing time, the instantaneous value of the source voltage is low at current interruption. Subsequently, a low value of recovery voltage occurs at the instant of interruption.

When fault or short-circuit current interruption occurs, again, the high-current arc appearing across the separating contacts is very resistive, and a large arc voltage is developed across the contactor. This voltage limits the amount of fault current in the circuit. Therefore, a 100 kA potential fault current may be limited to a “let through” current of 40 kA or less (see Fig. 7). As a result, the short-circuit current interruption rating of an air magnetic contactor increases with decreasing circuit voltage, because the arc voltage is a function of current. Note that this short-circuit current rating is much higher than for vacuum contactors, because the vacuum arc voltage is much less than that for an air arc at a given current level.

Specially designed dc magnetic air contactors are used to interrupt dc currents. These contactors are similar to the ac contactors, except that they must generate an arc voltage that is equal to or greater than the dc source voltage for current interruption to occur. To achieve a high arc voltage, the contacts of the contactor are separated rapidly and the arc generated between the contacts is forced magnetically into the arc chamber. Since the arc voltage increases rapidly with time and is greater than the recovery voltage, both the times to current interruption and arcing time are shortened. Shorter arcing times means less erosion of the contacts and longer life of the contactor.

The construction of the molded case motor circuit protector (contactor) is shown in Fig. 3. This device is limited to low voltage (240–600 V) applications. It consists of a molded plastic case, a set of movable contacts and a set of stationary contacts, a spring actuator mechanism, plunger assembly, and arc extinguisher plates. The molded case has three compartments, each having a set of contacts and associated “arc extinguisher” plates. Often there are two sets of contacts—“main”

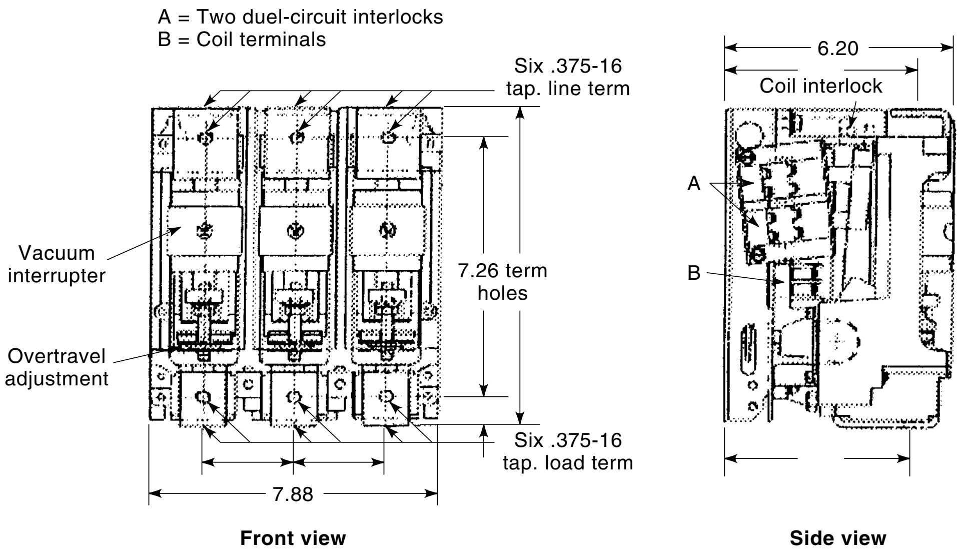


Figure 5. Details of a three-phase vacuum contactor. Front view shows the vacuum interrupters and overtravel adjustment of the contacts. Side view shows the frame. (Courtesy of Cutler-Hammer Co.)

contacts and "arcing" or arc runner contacts (1). The main contacts can be AgCdO or AgW material, and the arc runner is usually Cu. When the contacts separate, an arc is always initiated between the "main" contacts. If the arc current is high, the arc is magnetically transferred from the main contacts to the arc runner contacts.

For motor protection, the sensors of the contactor must detect a 15% motor current overload or a starting current transient equal to six times the load current, without tripping. Thermal bimetal strips are used to detect overload currents, and magnetic trips are used to detect severe overload and short-circuit currents.

The principles of arc interruption discussed here apply to all molded case circuit breakers. During the interruption of the load and overload currents, the breaker mechanism is tripped, either manually, magnetically, or thermally. The movable contact is accelerated from the stationary contact. Immediately upon separation, a thermal plasma is formed between the separating contacts, and the length of the plasma increases rapidly with the fast contact separation. The interaction of the self-induced magnetic field, **B**, with the arc current density, **J**, produces a magnetic force ($\mathbf{F} = \mathbf{J} \times \mathbf{B}$) on the arc column, driving it into the arc chamber plates. In the arc chamber, the arc divides into a series of short arcs, each burning between adjacent U-shaped steel plates of the arc chamber. These short arcs are cooled by heat conduction of the arc to the steel plates, and the arc voltage is $\simeq$25 V/gap (1). With 11 of these plates, 10 series arcs can easily generate an arc voltage of $\simeq$300 V between the separated contacts. As the current approaches zero value, the arc extinguishes and a recovery voltage (described above) appears across the contacts. The steel plates provide further rapid cooling of the arc. This causes additional deionization of the hot gas in the region, with a subsequent increase of dielectric strength or voltage withstand, leading to successful current interruption.

For high-fault current interruption, the arcing process is similar to the above, except that the high arc current produces a larger diameter and hotter arc, which completely fills the arc chamber. Subsequently, it is not broken into a series of shorter arcs. The hot arc consists of an ionized mixture of air, arc chamber materials, and contact material at 10,000 K, with high electrical conductivity ($\simeq$100 S at current crest).

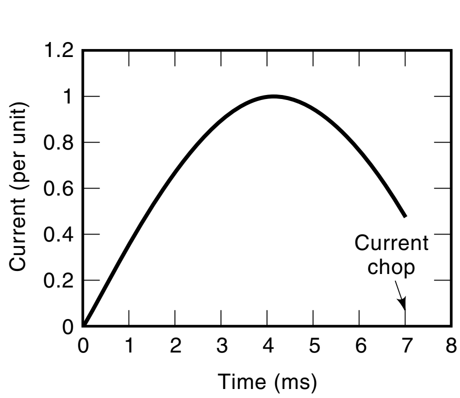


Figure 6. A current waveform versus time with current chop.

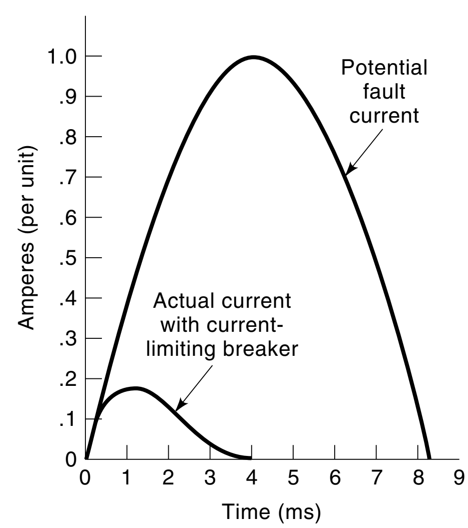


Figure 7. Current waveforms versus time with and without current limiting. The larger current waveform is for the potential fault (without current limiting), and the smaller waveform is the let-through current when current limiting by the motor protector occurs.

The cooling mechanisms for this arc are radial convection and conduction to the steel arc chamber plates, and ablation of material from the arc chamber walls. To promote high arc voltage, some breakers, especially those with current limiters, have means of enhancing the movable contact opening speed with devices such as slot motors. The motor produces additional acceleration force on the contact arm by the interaction of the magnetic field created by current through the contact arms with the U-shaped plates of the slot motor. Because of rapid contact separation, a high-voltage arc is developed quickly, thus limiting the let-through current and making the circuit appear more resistive. Thus the current approaches zero sooner (see Fig. 7), the arcing time is shortened (e.g., from 8.3 ms or longer to 4–5 ms), and contact erosion is reduced. During the recovery voltage period, the conductance of the arc column is decreasing by several orders of magnitude within microseconds via rapid cooling and deionization. Therefore, at current zero, the source voltage is low, making both the rate of rise and the peak of the recovery voltage significantly lower. Thus, the current-limiting effects of the high-current arc lead to easier interruption of fault current.

Vacuum Contactors

Figure 4 shows a typical vacuum contactor, which consists of a rugged frame with three vacuum interrupters mounted (one interrupter per phase), a mechanism to operate the vacuum interrupters, and current sensors. When the solenoid trip coil of the mechanism is not energized, the vacuum interrupter contacts are held open by a spring. Therefore, the contactor is in the normally open position. If a normally closed contactor is required, the mechanism is arranged so that the vacuum interrupter contacts are initially touching. Each interrupter is an insulated vacuum vessel made from a 2-inch diameter ceramic cylinder with metal end plates attached (see Fig. 8). The vessel contains a set of copper-based butt contacts brazed to electrode stems, of which one is fixed to the end plate. A mechanism provides motion (0.2 inches or less) to the movable contact through the opposite end plate via a metal bellows, which serves to maintain a vacuum of 10^{-6} torr or less. Surrounding the contacts is a metal shield, which protects the envelope from metal vapor arc products. This shield is usually brazed to a metal end plate.

When a vacuum contactor is used to interrupt an inductive load, the vacuum arc voltage is low (e.g., 20 V), and the arc current is not interrupted until the natural zero current or less (if current chop exists, as explained above). Therefore, the arc voltage of the vacuum contactor does not affect the circuit. At the instant of current interruption of the first phase to clear, both the transient recovery voltage and the normal 60 Hz recovery voltage appear across the open contactor. The peak value of this transient voltage can be approximately 1.88 times the line to line rms voltage (e.g., for a 600 V circuit, $1.88 \times 600V = 1130$ V). If a current chop occurs, the voltage transient can be even greater than this value, depending upon the surge impedance of the circuit. The other two phases will be interrupted approximately 90 electrical degrees after the first phase to clear. The transient recovery voltages for these two phases are much lower. The resistance in the circuit damps the transient voltages. To suppress high-surge voltages that may appear across the load during load current interruption, capacitor–resistor (R–C) networks can be connected at the load from the load terminal to ground. Other than R–C voltage surge-suppression networks, there are lightning arresters and Zork networks, a device sold by a South African company. The manufactur's application guide that comes with the contactor should be consulted for the recommended means of load protection. Many manufacturers of vacuum contactors claim that the chop current level is low for their product, and so surge protection is not required.

When a fault or short-circuit current interruption occurs, the vacuum arc voltage is low compared with the circuit voltage and the let-through current is approximately equal to the potential fault current. However, the current chop seldom occurs during high-fault current interruption. Since the short circuit current is limited by the inductance of the circuit, the transient recovery voltage can be as high as 1.88 times the rms value of the line-to-line source voltage or less.

Current interruption in a vacuum medium depends on the ionized metal vapor rather than ionized gas, as for the magnetic air contactor. The metal vapor originates from the erosion of the contact material during the arcing process. At low arc currents, this metal vapor arc is not a thermal plasma since strong nonequilibrium conditions prevail. Vacuum arcs consist of three regions—cathode, arc column, and anode. The cathode has many highly mobile arc spots moving rapidly over the surface, and each spot supports about 100 A with a typical current density of 10^8 A/cm^2 (2). The voltage drop of the cathode region depends on the contact material (e.g., typically 18 V for Cu). The anode surface may have a diffuse current collection without anode spots or may have a high-temperature constricted anode spot. The latter causes gross erosion of the anode surface (e.g., 10^{-4} g/C). A constricted anode spot occurs when insufficient number of ions are in the arc column at the anode surface. Subsequently, a space charge is formed, leading to rapid local heating of the anode surface and evaporation of anode material, producing the constricted arc attachment.

The positive column region can be either diffuse or constricted. For arc currents up to several hundred amperes corresponding to load current interruption, the arc column is diffuse and electrons flow from the cathode to anode with a low column voltage (typically 40 V). At higher currents (2000 A or greater, corresponding to fault current interruption) the positive column consists of electrons and ionized metal vapor products generated by the material evaporated from both the anode and cathode. The radius of the column is determined by the outward radial pressure of the ionized and neutral species balanced by the inward magnetic constriction pressure

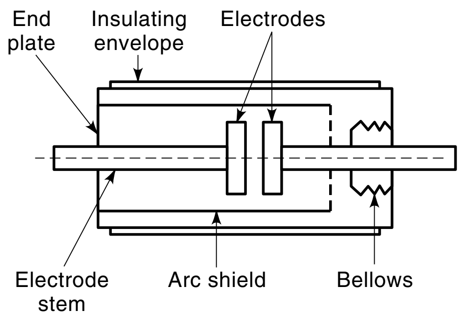


Figure 8. Internal parts of a vacuum interrupter used in vacuum contactors. This is a cut-away of a typical vacuum interrupter.

formed by arc current (*magnetic pinching*). Under these conditions, the metal vapor arc column is nearly a thermal equilibrium plasma that radiates strongly. The arc voltage increases with current and can be as high as 200 V. Cooling of the arc column is primarily by radiation to the surrounding surfaces and by thermal condition to the electrodes.

As the current decays toward a "natural" current zero, the constricted thermal plasma arc becomes a diffuse arc, with the number of cathode spots decreasing as the current approaches a zero value. Close to current zero, the arc can become unstable and suddenly extinguish, producing what is known as current chop, with a recovery voltage appearing across the contacts. Electrons are swept out of the anode region, leaving an expanding ion space charge at the anode surface, producing a post-arc current (several amperes) to flow for several microseconds. The recovery voltage appears across the ion space charge region that is rapidly expanding. If the rate of dielectric recovery of the intercontact region is greater than that of the recovery voltage, interruption will occur. However, if the post-arc current is sufficiently high, causing the electrons to gain enough energy, the electrons will produce additional ionization, leading to the reestablishment of the arc (3).

CONTACTOR SIZE AND FUSE COORDINATION

A contactor is selected by NEMA size number (Table 1) that corresponds to the motor load current or horsepower. When the motor control center has a fuse in series with the contactor, the fuse size must be coordinated with the contactor amp-time characteristics. Therefore, the contactor controls the switching and provides protection for the motor, and the fuse serves as backup protection in case the contactor fails to interrupt a short circuit or excessive overload currents.

Consider a motor control center controlling a three-phase ac induction motor. The motor control center consists of a contactor and fuses. To size the contactor for the motor, the items to consider are (1) the normal full-load current plus 15 percent overload, (2) the maximum short circuit of the circuit, and (3) the voltage of the circuit. To size the fuse, the items to consider are (1) the circuit voltage, (2) the normal full load current plus 15 percent overload and the maximum short-circuit current of the circuit. The contactor sensors for tripping the contactor are based on current-time (I-t) characteristics. The current times the time or number of cycles of current flow determines the delay time for the contactor to be tripped or opened by the sensors, and the time for the fuse to blow. Figure 9 shows typical *I–t* curves for a contactor and a fuse.

For contactor fuse coordination, the *I–t* curve of the fuse must be above and to the right of that for the contactor. Calculation of the three-phase induction motor currents and the maximum short circuit of the circuit are given below.

Motor load current is calculated by knowing the horsepower, the voltage and power factor under a load, as given by Eq. (1).

$$I_{FL} = 746 \frac{HP}{\sqrt{3} V_{L\text{-}L} PF} \qquad (1)$$

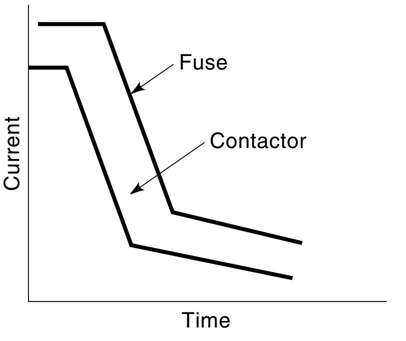


Figure 9. Current-time characteristics of a contactor and a fuse. Typical fuse and contactor coordination are shown. The upper curve is for the fuse and the lower curve is for the contactor control.

where HP is horsepower, $V_{L\text{-}L}$ is the rms line-to-line voltage, and PF is a power factor as a fraction. The 115 percent overload current, I_{OL}, of the motor is

$$I_{OL} = 1.15 x I_{FL} \qquad (2)$$

The maximum short-circuit current, I_{SC}, at the load side of the contactor is

$$I_{SC} = \frac{V_{L\text{-}L}}{\sqrt{3} x Z_s} \qquad (3)$$

where Z_s is the voltage source impedance.

SUMMARY

Contactors are available in many sizes, and of two main types—magnetic air and vacuum. Selection of the contactor depends upon the application, such as for motor control or lighting. Vacuum contactors are excellent for nearly all applications, except for lighting, where more than three poles are required. Then special air contactors must be used. Depending on the manufacturer of the vacuum contactor, switching inductive loads, such as motors, may require special protective circuit elements or networks, to prevent the production of high-voltage transients. However, the reliability and service provided by vacuum contactors are of greater value than the cost of adding a surge-protection network to the circuit.

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CONTACTS, OHMIC. See OHMIC CONTACTS.

CONTAMINANTS IN SILICON. See GETTERING IN SILICON.

CONTAMINATION FREE MANUFACTURING. See SEMICONDUCTOR FACTORY CONTROL AND OPTIMIZATION.