CIRCUIT BREAKERS

Circuit breakers are two-terminal devices similar to switches and are used for controlling the power flow in electrical power circuits and protecting power circuits from excessive currents

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caused by overload and high fault currents. Overload currents are caused by having too many electrical devices connected to a given power source. Fault currents are caused by trees falling across power lines, people accidentally putting metal objects across bus bars, cutting power cords or lines, or faults in electrical apparatus connected to the system. The input to the circuit breaker is connected to the source side and the output of the breaker is connected to the load side of the circuit. Circuit breakers come in many different sizes and shapes depending on the voltage and application of the power circuit. Breakers are characterized as

- Residential molded-case, single-phase 115 V and 230 V circuit breakers located in power distribution boxes in homes and offices.
- Industrial three-phase, low-voltage (240 V to 1000 kV) circuit breakers used in industrial, distribution, and transmission applications. These can be either molded-case circuit breakers or power breakers.
- Industrial, three-phase, medium-voltage (5 kV to 38 kV) circuit breakers used in factories and office buildings. These are indoor metal-clad breakers.
- Local power utility company for supplying power to factories, office buildings and residential homes uses distribution, three-phase, high-voltage (5 kV to 38 kV) circuit breakers. These are outdoor breakers and reclosers.
- Transmission, three-phase, high voltage- (>72 kV) breakers used between the power generating plant and the distribution substations. These are outdoor breakers.
- Specialty breakers for mining, shipboard (Navy breakers), generator, and aircraft applications.

All circuit breakers are required to meet specified ratings set forth by standards. These ratings are maximum voltage (three-phase breakers rated for line–line voltage), ac voltage withstand, high-impulse voltage (basic-impulse voltage–BIL) that simulates a lightning voltage and a switching voltage. Transmission, distribution, and metal-clad circuit breakers are design to withstand (1) continuous load current, (2) high momentary close and latch current that lasts only for several cycles, and (3) high short-circuit currents. Low-voltage, molded-case breakers and power breakers must have the above duties plus carry 115% overloads and in-rush circuits of six times normal load currents without tripping. The latter current, which lasts only a very short time, represents the in-rush current that flows when transformers are energized or induction motors are started.

The function of a circuit breaker is to conduct current when it is closed, interrupt current when it is tripped to open, and isolate one section of an electrical circuit from another when it is in the open position. Depending on the size and application, breakers are mounted in panel boards (e.g., home use), are free-standing, or are placed in metal-clad switchgear compartments. Circuit voltage, continuous current and fault current interruption ratings, and interrupter interrupting media (oil, air, or vacuum) categorize circuit breakers. Types of breakers are oil, compressed-gas (e.g., air and SF_6), magnetic air, and vacuum. The operation of circuit breakers in a network must be coordinated with the other breakers and fuses in the network so that they trip at the proper currents and times ensuring the maximum protection and availability for the network.

CIRCUIT BREAKER DETAILS

The primary components of any circuit breaker are the interrupters, the mechanism to actuate the interrupters, energy storage means for the mechanism (e.g., springs, compressed gas, etc), a housing to contain the breaker components, and bushings to feed the current to the interrupters. The interrupter consists of a set of electrodes surrounded by an arc chamber and a medium to support the arc. One electrode of the set is usually stationary, and the other electrode is movable. When the breaker is in the "closed," position, the electrodes touch and conduct current. For the breaker to interrupt current, the mechanism separates the movable electrode from the fixed electrode establishing an electric arc between the separating electrodes. Because the current is sinusoidal, it goes through periodic zero values. When the arcing current reaches a "natural" current zero, the arc is extinguished and the current ceases to flow. Immediately following current interruption, a high-frequency recovery voltage (TRV) appears across the separated electrodes and tries to make the current flow again. If the arc products (e.g., hot gases for a gas breaker) are sufficiently cooled, the arc does not reignite, and the current interruption process is complete.

A mechanism is linked to the movable electrodes of a circuit breaker to actuate the motion of the movable electrodes. This mechanism is spring-operated, compressed-gas-operated, or solenoid-operated. A cutaway of a molded case, three-phase circuit breaker, shown in Fig. 1, shows how the mechanism is linked to the movable electrodes (denoted as contacts). When the breaker handle is moved from the tripped or off position to the closed position, the spring mechanism toggles the movable electrodes so that they are held against the stationary electrode with a certain force. This operation also charges an opening spring of the mechanism. Tripping of this breaker is initiated by three methods (1) a high fault magnetic trip, (2) a bimetal thermal overload trip, and (3) a manually operated trip. For high-voltage (5 kV to 38 kV) outdoor and medium-voltage metal-clad breakers, the mechanism is spring-operated to both close and open the breaker. Some newer medium-voltage breakers use capacitor storage and a solenoid to actuate the electrodes. Very large distribution and transmission circuit breakers may have a compressed air mechanism to actuate the contacts.

Different types of circuit breakers are shown in Figs. 1, 2, 3, and 4. Note that the circuit breaker housing configuration and construction depend on the current interrupting medium. As mentioned previously, Fig. 1 shows a cutaway view of a small, low-voltage (e.g., 600 V) molded-case circuit breaker (1). The high-voltage (5 kV to 38 kV) outdoor breakers and oil reclosers have three interrupters within one tank, as shown in Fig. 2, whereas very high voltage breakers may have three separate tanks, each containing an interrupter. For either style of breaker, the actuating mechanism is external to the breaker. Figure 3 shows a high-voltage 500 kV compressed-air, circuit breaker. The interrupter housing is a live tank and is mounted on top of the support insulator. Note that there is a separate insulator and interrupter for each phase because of the high voltage. The outdoor vacuum circuit breaker is

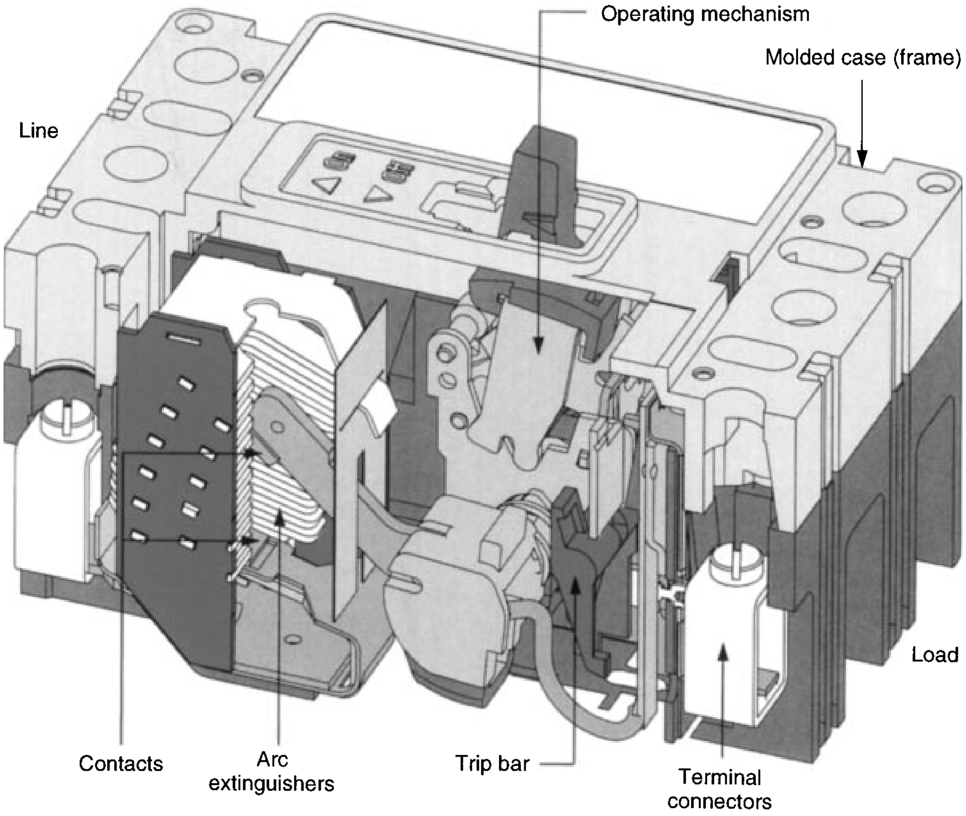

Figure 1. Molded-case circuit breaker. Cutaway view shows the arc chamber, electrodes, mechanism, and terminals. The breaker is shown in the open position (courtesy of Cutler-Hammer).

shown in Fig. 4. The figure shows the breaker is free standing and with the front removed to show the insulators, linkages, and vacuum interrupters. The mechanism and controls are contained in the low part of the breaker.

Overvoltage or overcurrent sensors, such as potential transformers or current transformers, provide information about the circuit, needed to decide when to trip breakers. High-voltage and medium-voltage breakers have signals from these transformers fed to relays which are programmed to open the breaker at the proper time. The open time of the breaker is a function of the magnitude of the fault current through it. The relays are set to coordinate with the relays of either the upstream or downstream breakers, so that power is removed from the faulted or overload parts of the circuit. Subsequently, the rest of the circuit can continue to operate normally. Low-voltage, molded-case circuit breakers have self-contained electronics to sense the overcurrents or overvoltages. When a high fault current flows through the breaker, a magnetic trip actuates the breaker contacts instantaneously. For overload currents, a thermal or bimetal trip actuates the electrodes of the breaker. Some single-phase, low-

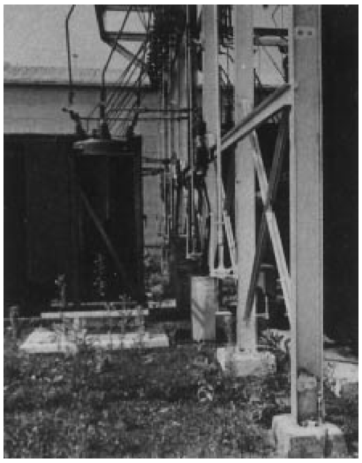

Figure 2. 14.4 kV, 600 A, oil circuit breaker (courtesy of Marcel Dekker).

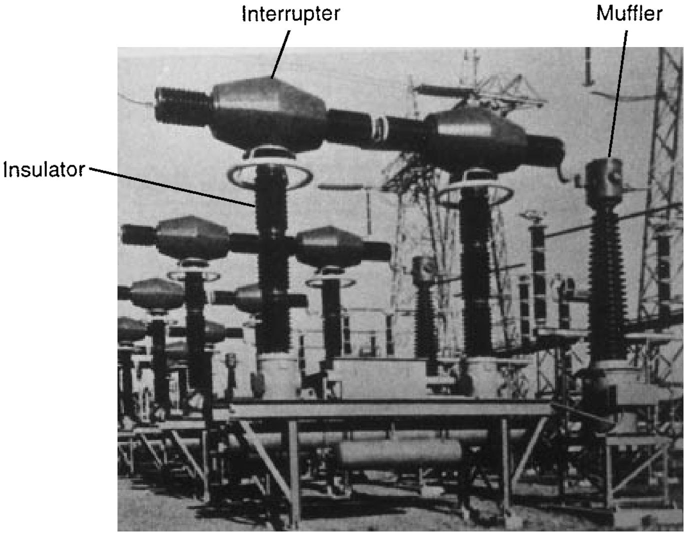

Figure 3. 500 kV compressed-air circuit breaker (courtesy of MIT Press).

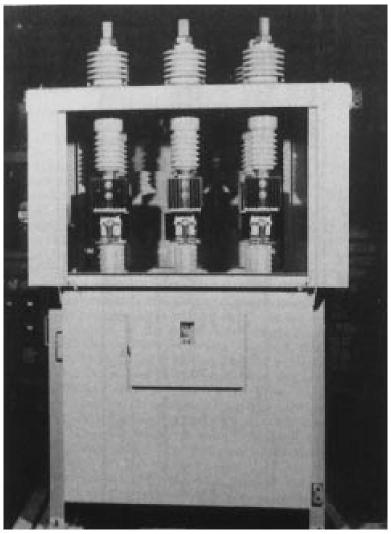

Figure 4. Outdoor vacuum circuit breaker. The circuit breaker is shown with the side cover removed (courtesy of Marcel Dekker).

voltage breakers have electronics that detect ground fault currents and trip the breaker. These are "smart" breakers containing microprocessors, that are unlike "smart" MCCBs and LVPCBs which detect overcurrents and faults as well as clearing them when they occur. High-voltage circuit breakers are generally dependent on the highly sophisticated relaying control circuits that deteriorate to the point where a breaker should trip.

RATINGS

Voltage Ratings

The important ratings for all circuit breakers are the rated maximum voltage, the transient recovery voltage, the 60 Hz withstand voltage, and the basic-impulse voltage (BIL). In addition, there are chopped-wave voltage ratings for outdoor breakers and switching-surge voltage ratings for breakers of 362 kV and higher. Medium-voltage metal-clad breakers have an additional fault-current rating known as MVA (million-volt ampere).

Previously, indoor metal-clad breakers were rated by constant MVA for fault-current interruption capability. Then the same "*K*" factor was used over a wide range of circuit voltages. In 1997, the American standards revised this *K* factor to one for indoor breakers. The maximum operating voltage is the maximum safe circuit voltage at which the circuit breaker is designed to operate reliably. The one minute 60 Hz withstand voltage is used as a dielectric test to determine whether a breaker withstands an overvoltage condition (e.g., source-side and load-side voltages are 180° out of phase) for a period of time across the separated electrodes.

The transient recovery voltage (TRV) is the peak of the recovery voltage across the circuit breaker contacts immediately following current interruption. This voltage is a high-frequency voltage superimposed on the power-frequency source. The time to crest for the TRV depends on the inductance, capacitance, and cable effects of the breaker circuit. For medium-voltage 15 kV industrial circuits in which cables are used, the time to voltage crest is typically 60 μs. For breakers connected to overhead line circuits, the time to crest is typically 30 μs. The reason for the difference in the times to crest is that cables have much higher capacitance per length than overhead lines.

The basic-impulse voltage (BIL) is a rating required of all power equipment. This voltage simulates a lightning strike voltage. The voltage waveform has a rise time of 1.2 μs to 90% of peak voltage and a decay time of 50 μs to half of the peak value. Outdoor breakers require a chopped-wave voltage test in which the time to peak is 1.2 μs and a voltage peak slightly higher than for the BIL. The tail of the wave is chopped to zero 2 μs to 3 μs after the peak to simulate the effect of a lightning arrestor operating to protect the circuit from an overvoltage condition. Circuit breakers rated for 362 kV and higher are subjected to a switching-surge test in which the front and tail times are longer than the BIL.

Fault Currents

Fault currents are caused by short circuits in power circuits, such as single-phase, low-voltage circuits encountered in the home or office and three-phase shorts encountered in power transmission, distribution, and industrial operations. A fault current occurs when a low impedance suddenly exists between two wires and one or both wires are at a high voltage. These fault currents are interrupted by the circuit breaker upstream from the short.

Overload Currents

Circuits and breakers are required to withstand a given continuous overload current without damaging the circuit or causing the breaker to trip. These overload currents are caused by

1. In-rush currents of transformers when they are energized. In-rush currents can be as high as six times the normal load current of the transformer. However, the circuit losses damp these currents quickly (e.g., <0.1 s) to the normal operating value.
2. In-rush currents of induction motors when first energized from a stop position, known as locked-rotor currents. These currents can also be as high as six times the normal full load current and are damped to normal operating currents within 0.1 s.
3. Induction motors operated continuously at 115% of normal rated current.

The electronic trip or relaying determines the time-current trip characteristics of circuit breakers. These characteristics must also match the required continuous load current, overload current, and fault current of the circuit.

Momentary Currents

A circuit breaker must withstand close and latch currents when the breaker is closed-in on a high fault current. The high momentary current may be beyond the capability of the breaker to interrupt. However, the breaker structure must not fail under these high peak momentary currents which are 2.6 times rated short-circuit current and last for 10 cycles. When this occurs, a downstream breaker having a higher current interruption capability interrupts the current. When a breaker is blocked from opening, it must also withstand the rated fault interruption current for 10 s without mechanical or electrical damage to the breaker structure.

ELECTRICAL SPECIFICATIONS

The electrical specifications for a circuit breaker are determined by industrial standards and by customer needs. The standards used depend on the voltage class of the breaker and the country where the breaker will be installed. Table 1 gives a listing of the numbers and usage of ANSI standards used in the United States and IEC standards used in Europe (2).

High Voltage

High-voltage (72 kV to 1000 kV) circuit breakers must meet ANSI/IEEE C37.04 and C37.06 specifications. Medium-voltage (5 kV to 38 kV) metal-clad breakers are classified as indoor breakers, and high-voltage (15 kV to 72 kV) breakers and reclosers as outdoor breakers. Each has a different standard and different duty cycle (i.e., close-open sequence). In addition, a recloser is a circuit breaker that is used in a substation or on a pole. It has voltage ratings of 15 kV to 38 kV and a different duty cycle from a breaker.

The US standards that apply to high-voltage (5 kV to 38 kV) outdoor breakers are ANSI/IEEE C37.04, -.06, and -.09. Medium-voltage switchgear breakers meet ANSI/IEEE C37.09, C37.54, and UL specifications. High-voltage outdoor breakers produced for the European market must at least meet the IEC 56, and medium-voltage metal-clad switchgear must meet the IEC 298 standards.

Medium-voltage breakers and reclosers also have capacitor switching specifications. To be classified as Definite-Purpose breakers, they must switch capacitor banks, such as load-dropping, and back-to-back capacitor banks. Back-to-back capacitor switching occurs when the circuit has a capacitor bank on the source side of the breaker and the breaker switches a capacitor bank on the load side. Such switching causes high current and high-frequency in-rush currents to flow through the breaker upon closing. The other classification is General Purpose which indicates that the breaker can switch capacitor banks only on the load side of the breaker.

Table 1. Applications of ANSI and IEC Standards

Breaker Class	ANSI	IEC	Application
High Voltage CB	C37.04	694	General rules
Switchgear	C37.20.2	694	General rules
All	C37.06	56, 694	Preferred ratings
High Voltage CB	C37.09	56	Design tests
Switchgear	C37.20.0	298	Design tests
All	C37.010	NA	Application guidelines
High Voltage	C37.54 and UL	By labs[a]	Conformance
Switchgear	C37.55 and UL	By labs[a]	Conformance
High Voltage CB	C37.09	56	Production tests
Switchgear	C37.20.2	298	Production tests
All	C37.100	50, 56, 694, 298	Definitions

[a] Conformance testing only; may or may not include Follow-up Services.

Low-Voltage Breakers

In the United States, low-voltage, molded-case circuit breakers (MCCB) are tested to the UL 489 standard, and low-voltage power circuit breakers (LVPCB) are tested to ANSI/IEEE C37.13, -.16, and -.20. MCCB must be built according to NEMA and also UL specifications (3).

Some of the major foreign standards are Australian Standards, British Standards Institute (BSI), Canadian Standards Association (CSA), International Electrotechnical Commission (IEC), Japanese Industrial Specification, South African Bureau of Standards, Swiss Electro-Technical Association, and Verband Deutscher Elektrotechniker (VDE).

US specifications for molded-case circuit breakers are given in Table 2. Note that the voltage range is 240 V to 600 V, the continuous current range is from 150 A to 2000 A, and the current interruption is as high as 200 kA (rms).

The customer may have particular specifications for a breaker. For example, (1) the electric utility of South Korea has special TRV requirements for a medium-voltage circuit breaker, and (2) other countries have special applications, such as ring main circuits, with limited duty for the breaker.

Power Circuits

Four different power circuits for circuit breaker applications are three-phase transmission, distribution, industrial circuits, and single-phase, light commercial (e.g., office) and residential circuits.

Transmission

A circuit originates at a power generating plant in which typical generator voltages are three-phase, typically, 22 kV, 50 Hz or 60 Hz. Bus bars connect the generator to a transformer via a special circuit breaker known as a generator breaker. Line currents in the bus can range up to 20 kA (rms) of continuous current. Because the generator transformer is a step-up transformer, the output voltage may be 240 kV or higher which reduces the line current from 20 kA to 2000 A via the turn ratio of the transformer. Overhead lines transmit the power to substations. High-voltage circuit breakers may be placed at the secondary of the generator transformer and also at the inputs to the substations. The breakers for this application are oil, compressed-air, or SF_6 breakers.

Distribution

The voltage output of the substation is transformed from very high transmission voltages to distribution voltages of 5 kV to 38 kV. If the substation supplies urban power, the voltage is 5 kV or 15 kV and feeds power to factories, offices, and hospitals via either overhead lines or cables. Each feeder line is protected by an outdoor distribution circuit breaker. Distribution to urban homes is via overhead lines or cables. This voltage is stepped down by feeder transformers in which the transformer secondary is a three-wire 220 V/110 V circuit. Each line to the neutral voltage is 110 V and 180° out of phase. This power is fed to homes via either overhead lines or cables.

Table 2. Molded-Case Circuit Breaker Rating Chart

	Max. Current, A Standard	Voltage, V	150 kA	250 kA	400 kA	600 kA	800/1200 kA	1600/2000 kA
	NEMA/UL	240, ac				65–200		
	NEMA/UL	480, ac				25–100		
	NEMA/UL	600, ac				25–50	65–200	65, 200
	NEMA/UL	260, dc					25–100	65, 100
	IEC 157[a]	240, ac					25–50	25, 50
	IEC 157[a]	380, ac						
	IEC 157[a]	415, ac						
	IEC 157[a]	250, dc						
I_{CU}	IEC 947	240, ac	65–200	65–200	65–200	65–200		
I_{CS}	IEC 947	240, ac	25–100	25–100	25–100	17–50		
I_{CU}	IEC 947	380, ac	18–35	18–35	25–50	40–100	65–200	125, 200
I_{CS}	IEC 947	380, ac	10–22	10–22	10–22	10–25	17–50	32, 50
I_{CU}	IEC 947	415, ac	65–200	65–200	65–200	40–100	50–100	65, 100
I_{CS}	IEC 947	415, ac	35–100	35–100	40–100	10–25	15–25	17, 25
I_{CU}	IEC 947	250, dc	35–100	35–100	40–100	10–20	50–100	65, 100
I_{CS}	IEC 947	250, dc	10–22	10–22	10–22	3–5	15–25	17, 25

[a] Obsolute, superseded by IEC 947-1.

Industrial Circuits

Industrial circuits are usually three-phase, medium-voltage circuits (5 kV to 38 kV). The circuits consist of a bus fed from an input transformer. Feeder lines are fed from this bus to the load via metal-clad feeder breakers and cables between the load side of the breaker and the load. Typical industrial loads may be motors, transformers connected to welders, lighting, air conditioners, or electric arc furnaces (e.g., steel mills). The continuous current for these feeder circuits ranges from 250 A to 3000 A. Faults that occur close to the load side of the circuit breaker may produce currents as high as 63 kA. Faults close to the load produce reduced fault currents because of the cable impedance. Medium-voltage (e.g., 5 kV) feeder circuit breakers are either air magnetic or vacuum. In Europe, these breakers can be air magnetic, SF_6, limited oil, or vacuum. If the feeder loads are 600 V or less, either molded-case circuit breakers or power circuit breakers are used for protection. Both types of circuit breakers use air as the interrupting medium.

These circuits may have capacitor banks connected for power factor correction especially if the load is highly inductive, such as in an electric arc furnace. Circuit breakers are used to switch capacitor banks in and out of the circuit as the power factor needs to be corrected.

FAULTS—VOLTAGES AND CURRENTS

Fault Currents

Different types of fault currents occur. Three-phase shorts are encountered in power transmission, distribution, and industrial settings. Such faults immediately trip circuit breakers, which clear the fault current within one to five current cycles depending on the type of breaker. Three-phase breakers must protect for line-to-line, line-to-neutral, and line-to-ground fault currents. Three-phase circuits usually have the neutral of a wye-connected source, e.g., transformer or generator, grounded via a resistor, and the load may either be grounded, as in a four-wire system, or neutral ungrounded, as in a three wire system. Figure 5 is a simplified schematic of these circuits.

Fault currents for low-voltage circuits (600 V to 1000 V) can be as high as 200 kA. These are theoretically available potential fault currents, and the arcing resistance of the breaker usually limits the current let through to less than 100 kA. For medium- and high-voltage circuits (5 kV and up), symmetrical fault currents are rarely higher than 63 kA. Following the interrupted short-circuit current, a transient recovery voltage appears across the breaker contacts. The ANSI and IEC standards give typical values of these transient recovery voltages for different circuit voltages.

Figure 5(a) shows a simplified ungrounded three-phase circuit with a three-phase, line-to-line fault. The magnitude of the fault current depends on the circuit voltage and impedance of the line from the voltage source to the load. However, the fault current can be either a symmetrical or asymmetrical sinusoidal waveform depending on when the fault occurred relative to the source voltage and the resistance of the circuit. For example, a fully offset wave can have a peak value of 2.88 times the rms value of the symmetrical fault current. Losses in the circuit quickly damp the envelope of this asymmetrical current. Immediately after the breaker interrupts the fault current, the TRV appears across the electrodes. This voltage has a transient component determined by the circuit parameters and a steady-state sinusoidal component. The peak of the TRV is higher for an ungrounded neutral circuit because when the current of the first phase clears, the neutral point of the circuit shifts to 0.5 p.u., where 1.0 p.u is given by

$$1.0\,\text{p.u.} = V_{L-L} \times (2/3)^{0.5} \tag{1}$$

where V_{L-L} is line to line rms voltage.

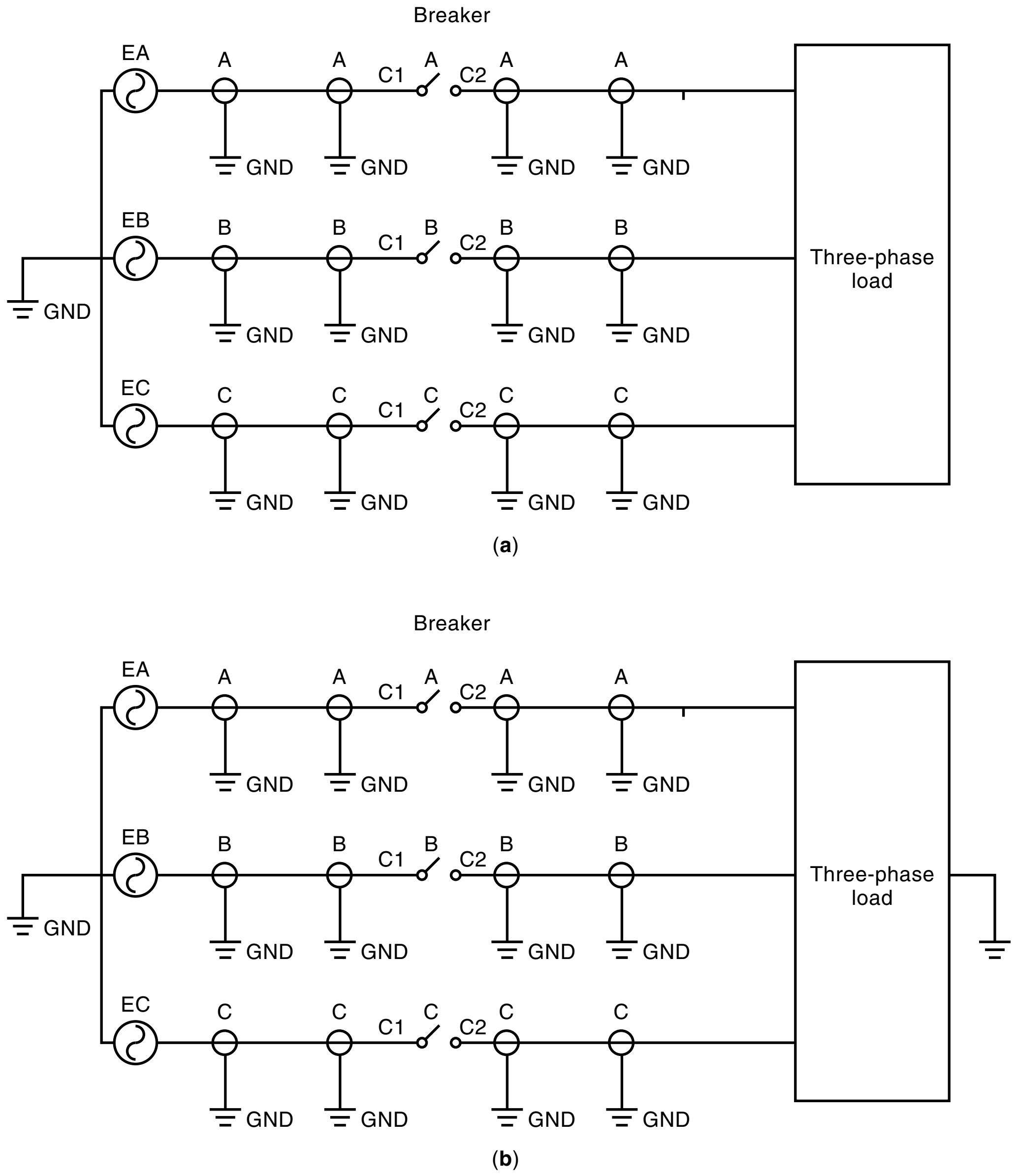

Figure 5. Schematic of a simplified three-phase circuit showing the source, breaker, and load. (a) An ungrounded wye circuit; (b) A grounded wye circuit.

This neutral shift is added to the source voltage giving typical peak values of the TRV equal to

$$\mathrm{TRV} = 1.88 \times V_{\mathrm{L-L}} \tag{2}$$

The 1.88 factor is for ANSI standard circuits and 1.76 for IEC standard circuits. After the first phase clears, the currents in the other two phases are in series, and therefore are equal and are interrupted 90 electrical degrees later. Subsequently, the peak of the TRV takes about half of the first phase to clear.

Figure 5(b) shows a simplified, grounded, three-phase circuit with a three-phase fault. This circuit is similar to three single-phase circuits connected together. Each circuit can be treated independently except for the opening time of the breaker, which is the same for all three phases. The fault currents can be the same as previous. However, the TRV is lower because there is no neutral shift. Subsequently, this voltage can be as high as 1.25 × $V_{\mathrm{L-L}}$, as each phase is interrupted.

Overhead Lines

Overhead lines are used to transmit power over long distances by high-voltage (i.e., 69 kV and higher) transmission lines which can be hundreds of miles long. These lines are protected by circuit breakers close to the voltage source.

Consider when short circuits occur between overhead lines, which are protected by a high-voltage circuit breaker. If the fault is line-to-line, the upstream breaker interrupts the fault current. Immediately following the current interruption, a TRV consisting of a sawtooth wave superimposed on the (1 − cos) voltage wave begins to appear across the breaker contacts. A transient voltage traveling back and forth on the transmission line between the breaker and the short circuit causes the sawtooth waveform. If the fault is approximately one mile from the voltage source, the rate of rise of the TRV, known as RRRV, can be very steep (e.g., 14 kV/μs). Such a fault is known as a short line fault and produces the most severe RRRV of any fault to interrupt. The RRRV is given by

$$\mathrm{RRRV} = \omega I Z_\mathrm{s} \tag{3}$$

where ω is 2π times the power frequency, I is the peak value of the short-circuit current, and Z_s is the surge impedance.

Cables

For medium-voltage (5 kV to 38 kV) industrial circuits, cables are used to connect a bus to a feeder circuit breaker and to connect from the load side of the breaker to the load. These power cables have low surge impedance (20 Ω to 40 Ω) and a relatively high capacitance per 1000 ft, compared to overhead lines. When a short circuit occurs in a cable circuit, the upstream circuit breaker interrupts the fault current, and the TRV associated with the interruption has a much slower rate of rise compared to that of overhead lines. However, when a circuit breaker energizes an uncharged cable, high in-rush currents occur charging the capacitance of the cables.

Some high-voltage circuits have gas-insulated substations which contain gas-insulated cables and breakers. These high-voltage substations are smaller than conventional outdoor substations and are usually located in areas where real estate is at a premium.

TRANSMISSION BREAKERS

Transmission circuit breakers are designed for voltages of 72 kV to 1000 kV, 600 A to 4000 A continuous currents, and 20 kA to 63 kA interruption current ratings. These breakers are either oil or compressed-gas and are used to protect the high-voltage transmission lines between the generating plant and the substations. The power leads to the breaker are made to the outside terminals of high-voltage feed-through bushings, and the inside terminals of these bushings are connected to interrupters located within the breaker tank. Two high-voltage bushings per phase isolate the high-voltage wires from the tank of the breaker. Current transformers are usually placed around the feed-through bushings to monitor the current flowing through the breaker and send this information is sent to relays for use in controlling the power system.

Oil Breaker

The oil breaker consists of an oil tank with a current interrupting element in it, known as the interrupter. The current interrupter consists of a pair of electrodes (one stationary and one movable). The stationary electrode is "tulip"-shaped. The movable electrode has a cylindrical shape which is inserted into the tulip electrode when the breaker is in the closed position. The advantage of the tulip-cylinder electrode configuration is that, during high fault currents, inward magnetic contact forces develop so that the electrodes do not "pop" open (4). These electrodes are surrounded by an arc chamber consisting of deionizing plates.

During current interruption, the movable electrode separates from the stationary electrode establishing an arc between the electrodes. The hot arc plasma burning between the electrodes decomposes the oil surrounding it into carbon, hydrogen, and oxygen. The gaseous mixture fills the interelectrode region. Cooling of the arc is accomplished by convection, evaporation, and dissociation of the oil and by heat conduction to the deionizing plates. The arc continues to burn until the current reaches a "natural" current zero upon which the arc plasma is quickly deionized by the cooling effects. Hydrogen has excellent heat capacity and dielectric properties, which provide rapid cooling to the arc and excellent dielectric recovery of the interelectrode region. Subsequently, the breaker can withstand the high transient recovery voltage following the current interruption.

Grounded-tank or dead-tank breakers (e.g., 72 kV) have two interrupters connected in series by a cross-bar per phase. The crossbar connects the movable electrode of each interrupter. The interrupters for all three phases are contained within a single tank. The three crossbars are connected to insulating linkages and to the mechanism. For higher voltage circuits, one tank with a single interrupter is used per phase because of the high-voltage insulation distances needed between the interrupters and the tank. But the interrupters of all three tanks are operated by a single mechanism. Some European breakers are so-called "limited oil" or "minimum oil" breakers, that is, the interrupters and oil media are contained within a small vessel.

The mechanism to actuate the interrupters is operated by compressed air. A compressor fills an air storage tank with air under pressure so that the compressed air has enough energy stored to open and close the breaker to fulfill several Close–Open operations of its duty cycle without recharging the tank. Linkages connect the mechanism's actuating air piston to the movable electrode of the interrupter. The tripping and closing of the breaker are performed on site or remotely through relays.

Compressed-Gas Breaker

The compressed-gas breaker may contain either compressed air or SF_6. The vessel that contains the compressed gas is metal, and it is either grounded, called a dead tank, or ungrounded, called a live tank. Figure 3 shows a 500 kV live-tank, compressed-air breaker and Fig. 6 shows a 362 kV live-tank SF_6 breaker. Here a vertical insulating post supports the live tank. The current interrupters are within the tank. The

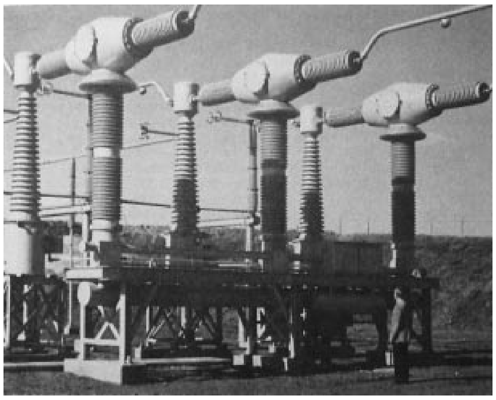

Figure 6. 362 kV SF_6 circuit breaker (courtesy of Marcel Dekker).

interrupter consists of "tulip"-shaped hollow electrodes consisting of the movable electrode and a stationary cylindrical electrode. The interrupters can be either single-flow or double-flow. Upon current interruption, the movable electrode separates from the stationary electrode producing an electric arc between the electrodes. Compressed gas blasts through the electrodes with a tremendous radial velocity, several times the speed of sound. This radial gas flow cools the axially burning arc. As in all breakers, the current electric arc burns until a natural current zero is reached, and the arc is extinguished. Compressed air and SF_6 gas both have excellent heat capacity to deionize the arc plasma and excellent dielectric resistance, so that the breaker can withstand the high transient recovery voltage. The compressed gas is supplied from a compressor or by a piston connected to the movable electrode. The former breaker is called a "two-pressure" breaker. The latter normally uses SF_6 and is called a "puffer" breaker which uses a piston and electrode arrangement. In this arrangement the electrodes separate, the piston is activated simultaneously to produce a blast of SF_6 through the electrodes which flows radially outward through the burning arc. The interruption mechanism is the same as previous. Compressed-gas and puffer breakers use a pneumatically operated mechanism similar to the one described previously for oil breakers.

DISTRIBUTION BREAKERS

High-voltage outdoor distribution breakers and reclosers are used to protect lines and cables from substations to a factory or commercial power distribution centers. The main differences between a breaker and a recloser are the duty cycle and the magnitude of fault current. The recloser performs more open and close operations before lockout, mainly to burn the fault off the line. However, the construction of both is similar. These breakers are rated for 5 kV to 72 kV, 250 A to 2000 A continuous current, and 12 kA to 41 kA fault current interruption. In the United States, these breakers can be oil or vacuum. Some breakers used in power stations have special ratings.

Reclosers normally interrupt lower fault currents than breakers. Also, reclosers normally receive all their control power from the power lines, but circuit breakers normally operate from control room battery banks.

Oil Breakers or Reclosers (Distribution Class)

High-voltage oil breakers or reclosers have three sets of current-interrupting elements immersed in an oil tank. Rods connect the mechanism to the current-interrupting elements and actuate the movable electrodes of the interrupting elements. The stationary electrode is "tulip"-shaped, and the movable electrode has a cylindrical shape which inserts into the stationary electrode when the breaker is in the closed position. A spring mechanism simultaneously provides motion to all three movable electrodes. A typical electrode stroke is a motion of several inches within tens of milliseconds. Each set of electrodes is surrounded by pots or "de-ion" grids similar to those used with high-voltage oil breakers. The current interruption process is the same as for the oil transmission breaker described previously.

A spring-operated mechanism operates the movable electrodes of the breaker or recloser. The mechanism consists of energy storage springs that are wound either by a solenoid, an electric motor or are wound manually. There are closing springs and opening springs. When the breaker is in the open position and is tripped to close, the solenoid or the initially charged closing spring releases some of its energy to close the movable electrodes via linkages and transfers some of its energy to charge the opening springs. When the breaker is tripped to open, the opening springs activate the linkages to open the movable electrodes. These mechanisms are operated electrically by remote signals from relays to trip coils or are manually operated. The current is usually interrupted within five cycles after the trip signal is received at the breaker (known as a five-cycle breaker). Reclosers sometimes have the relays mounted to the utility pole where the recloser is.

Vacuum Circuit Breakers and Reclosers

The distribution vacuum circuit breaker or recloser contains current-interrupting elements that are vacuum interrupters or vacuum bottles. Figure 4 shows a typical 15 kV three-phase outdoor vacuum circuit breaker. The interrupter modules are vacuum interrupters that are mounted horizontally on post insulators. This figure shows the heat sinks connected to the electrode stems for cooling the structure. The vacuum bottles have an electrically insulating cylindrical envelope made of glass or ceramic and are typically 10 cm to 18 cm (4 in to 7 in) in diameter and 15 cm to 31 cm (6 in to 12 in) long. Metallic end plates are attached to the insulating envelope. The vessel contains a set of electrodes brazed to electrode stems of which one is fixed to an end plate and the movable electrode stem is connected to the other end plate via a metal bellows. The metal bellows provides a hermetic seal and contacts stem motion. Therefore, the vacuum interrupter is sealed completely, and the pressure within it is maintained at 10^{-6} torr or less. Surrounding the contacts is a metal shield that protects the insulating envelope from the deposition of arc products (metal vapor).

A mechanism similar to that described previously provides a much smaller motion (20 mm [0.78 in] or less) to the movable electrode through the opposite end plate via a thin metal bellows. The mechanism is connected to the interrupters by linkages. In the breaker closed position, a retentive force of approximately 350 lbs. is applied to each interrupter electrode to prevent the electrodes from "popping" apart when high current passes through them and also to maintain low contact resistance. Upon opening, the mechanism through the linkages provide an impact opening force to break any contact welds and produce fast opening speeds (e.g., 1 m/s). The current is usually interrupted within three cycles of current from the time the trip signal is received from the relay to the current interruption by the breaker. These breakers are known as three-cycle breakers.

INDUSTRIAL BREAKERS

Medium-voltage metal-clad switchgear circuit breakers are used to protect industrial circuits in factories, hospitals, schools, and offices. These breakers are in a substation or in the basements of buildings. Metal-clad switchgear is also found within power generating plants. The voltage and cur-

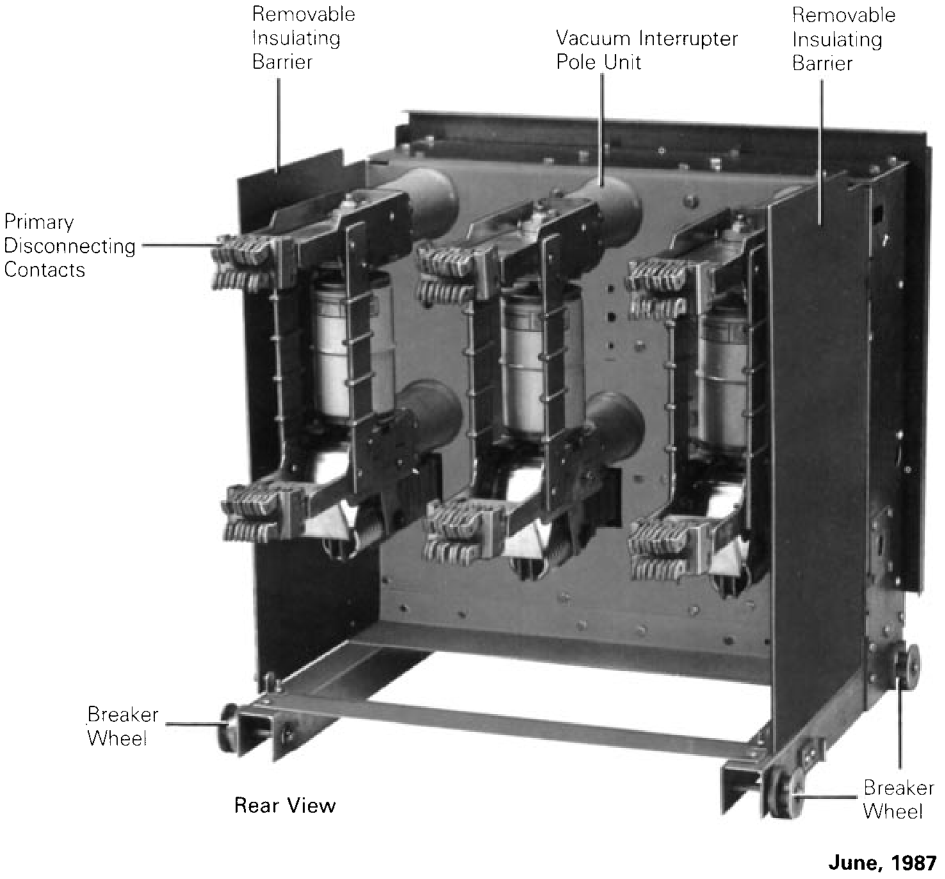

Figure 7. 15 kV medium-voltage metal-clad air magnetic circuit breaker. The breaker is withdrawn from the switchgear cabinet and the arc chamber of one phase is tilted to expose the electrodes (courtesy of Marcel Dekker).

rent ranges for these breakers are 5 kV to 38 kV, 250 A to 4500 A continuous current, and 600 A to 50,000 A fault current. Magnetic air and vacuum metal-clad circuit breakers are available in the United States. Other countries have these types as well as SF_6 breakers.

Air magnetic or vacuum breakers consist of a frame that is drawn from the switchgear unit by a set of rails.

LV Power Air Breaker

The construction of the magnetic air breaker for indoor metal-clad switchgear is similar to that of the metal-clad vacuum breakers except for the current-interrupting elements. The construction of the breaker is shown in Fig. 7. The arc chamber of one phase is angled to expose the electrode construction. Each interrupter consists of two electrodes (one stationary and one movable), a mechanism, an arc chamber, and overcurrent detecting circuits. There are two sets of electrodes—"main" electrodes and "arcing" electrodes. Surrounding the electrodes is an arc chamber consisting of a series of electrically insulated U-shaped deionizing metal plates. With the breaker closed, the main electrodes touch, and current passes through them. But during high fault current interruption, the main electrodes separate initiating an arc between them. The self-induced magnetic fields $\boldsymbol{B}$ produced by the current from the conductors to the electrodes (1) causes transfer of the high current arc to the arcing electrodes or arc runners and (2) blows the arc into the arc chamber. In some breakers this is aided by a puff of air onto the arc.

During interruption of load and overload currents (less than twice the load current), the breaker is tripped, and the movable electrode is accelerated from the stationary electrode, forming an electric arc of increasing length between them. The interaction of the magnetic field $\boldsymbol{B}$ with the arc current density $\boldsymbol{J}$ produces a magnetic force, $\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B}$, on the arc column driving it into the arc chamber plates. 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 conducted to the steel plates, and an arc voltage of 25 V/gap is generated (5). If the arc chamber contains 11 plates, the arc voltage may be as high as 300 V when the electrodes are fully separated. As the current approaches zero, the arc is extinguished, and a recovery voltage appears across the electrodes. The steel plates provide additional rapid cooling of the plasma in the arc chamber. Subsequent additional rapid deionization of the hot gas in the region occurs increasing the dielectric strength of the gap needed for successful interruption.

Current interruption of high fault current is similar to that of load currents except that the arc completely fills the arc chamber and the interelectrode region and is usually not broken up into a series of shorter arcs as described previously. The arc is larger in diameter and much hotter (e.g., $>10{,}000$ K) and has electrical conductivity on the order of hundreds of Siemens. The cooling mechanisms for this arc are radial thermal convection and conduction to the steel plates of the arc chamber and ablation of the material from the arc chamber walls. Then the current is interrupted, and the TRV appears

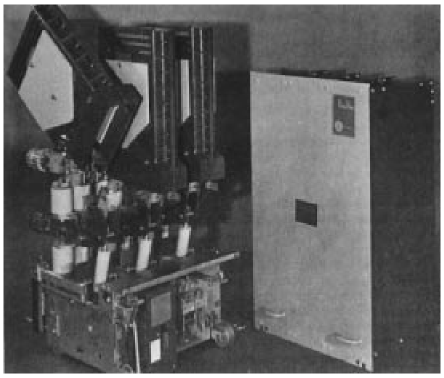

Figure 8. 15 kV medium-voltage metal-clad vacuum circuit breaker. The breaker is withdrawn from the switchgear cabinet (courtesy of Cutler-Hammer).

across the separated electrodes. These are usually classified as five-cycle breakers, that is, the current is interrupted five cycles after the breaker receives the trip signal from the relays.

Vacuum Breakers

Figure 8 shows a typical metal-clad vacuum breaker withdrawn from the switchgear cabinet. The metal-clad vacuum circuit breaker is similar in construction to the air magnetic except that vacuum interrupters are used instead of electrodes in air surrounded by an arc chamber with deionizing plates. The vacuum interrupters are very similar to those described previously, and the theory for current interruption in vacuum is the same. Note that the vacuum interrupters are mounted vertically and separated by glass polyester barriers between phases. Each phase has primary disconnect contacts connected to the vacuum interrupters by vertical bus bars. These primary disconnect contacts connect the breaker to the bus work of the metal-clad cabinet when the breaker is inserted into it. A spring-operated mechanism similar to that described for the HV outdoor vacuum breakers and reclosers actuates the vacuum interrupters via linkages. This mechanism is located in the rear of the structure and cannot be seen.

The time from receiving the trip signal to current interruption is three cycles, which is shorter than that for magnetic air breakers. Consequently, these breakers are known as three-cycle breakers.

MOLDED-CASE CIRCUIT BREAKERS

Molded-case circuit breakers are low-voltage breakers (240 V to 1500 V) with continuous current from 150 A to 2000 A, and 10 kA to 200 kA interruption current. These ratings determine the frame size of the breaker. The number of poles varies from one to four. Within the molded case, the breaker construction, shown in Fig. 1, consists of two sets of electrodes (one main and one arcing), a mechanism, an arc chamber, and an overcurrent detection circuit. The operation of these breakers is similar to the magnetic air breaker described in the previous section. During high fault current interruption, the electrodes separate, initiating an arc between the "main" electrodes, and a magnetic outward force transfers the arc rapidly to the "arcing" electrodes by and into the arc chamber. The theory of current interruption is the same as that for the magnetic air breaker except that the arc voltage of the molded-case breaker is significant compared to the circuit voltage. The arc voltage is large enough to influence current interruption by (1) causing a lower "let through" arcing current and (2) reducing the arcing time to the natural current zero.

Molded-case circuit breakers, known as current limiting breakers, are very fast actuating and have a means of generating high arc voltages to cause deliberate current limiting. Such breakers quickly accelerate the movable contacts via a "slot motor."

A charged spring mechanism actuates the moveable electrode. A handle is provided to reset the breaker, close the movable electrodes, and charge the opening spring. The breaker can be tripped open manually by operating the handle or automatically by the overcurrent circuits. A remote electrical trip is optional. Self-tripping of the breaker is caused by overload currents, known as thermal delayed trips, and by high fault currents which are magnetic instantaneous trips. The overcurrent trips of the breaker have an adjustable

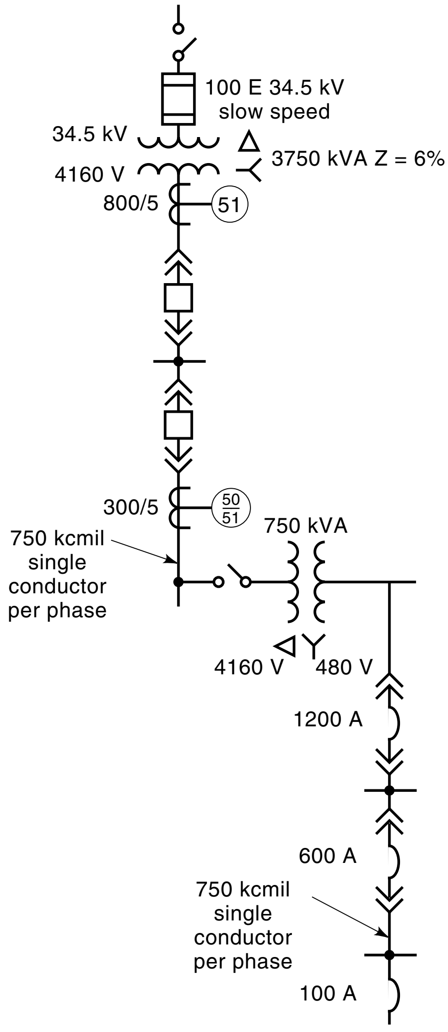

Figure 9. A simplified one-line diagram of a typical industrial power distribution circuit (courtesy of Marcel Dekker).

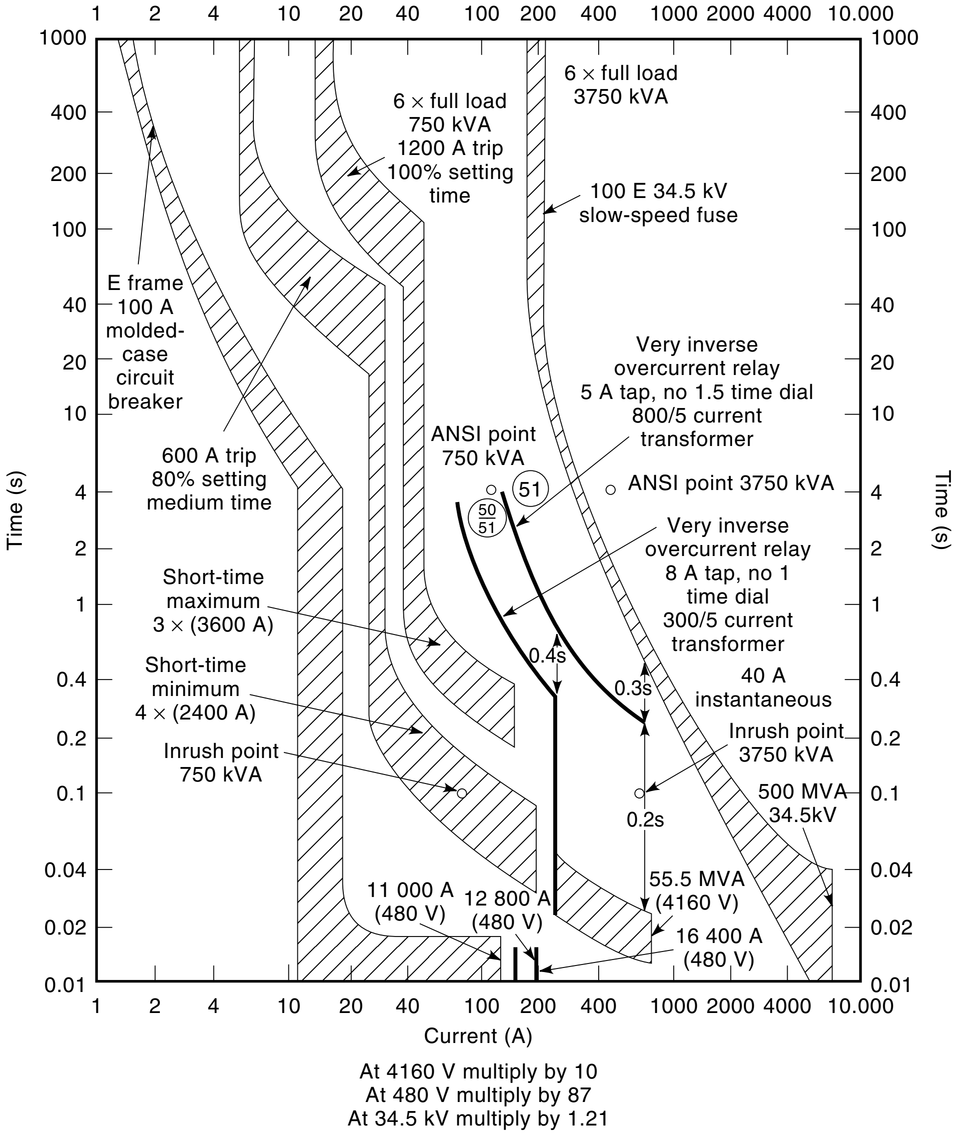

Figure 10. Time–current graph of breakers and fuse of an industrial power distribution circuit (courtesy of Marcel Dekker).

current-time relationship. The higher the overload or fault current, the shorter is the delay in the trip time of the breaker.

Molded-case circuit breakers are used for low-voltage distribution in factories, hospitals, and offices; aboard ships (Navy breakers); in aircraft where 400 Hz is the power frequency; and in mining operations. Special breakers made for ships because of the corrosive atmosphere and do not trip under severe mechanical shock and vibration. Breakers for mining applications must be enclosed so that they do not ignite in an explosive atmosphere.

Switching Surges

Switching currents in circuits always cause some voltage transients or surges regardless of the type of circuit breaker. For medium- and high-voltage power circuit breakers, the phenomenon that causes voltage surges is chop current which occurs during the current interruption process. Current chop occurs when the arc current suddenly goes to zero as the arc current approaches the "natural" current zero. In this period of arcing, the arc voltage becomes very unstable and exhibits high-frequency oscillations. Typical current chop values range from tenths of amperes to several amperes. The value is statistical and is influenced by the circuit parameters. The probability of significant current chop is higher when the breaker interrupts low currents, such as the magnetizing current of transformers, than with interrupting fault currents. Vacuum circuit breakers also have a higher chop-current level than gas or oil breakers.

Upon current interruption of inductive loads (e.g., transformers or motors), a significant current chop current of the breaker leads to voltage escalation across both the breaker and across the load. Such escalations may cause damaging high surge voltages at the load terminals. Perkins analyzed typical industrial circuits that are switched by vacuum breakers and found that inductive loads need surge protection under certain conditions (6). Manufacturers of circuit breakers publish application guides. The user should consult the guide for the particular breaker that is being installed to determine whether surge protection is recommended.

BREAKER COORDINATION

Figure 9 shows a one-line diagram of a power distribution circuit that may be used in an industrial plant. Breakers are used in the upstream 34.4 kV source side of the transformer, the 4160 V medium voltage side, and in the downstream low-voltage 480 V feeder circuits within the plant. Coordination among the downstream breakers with the upstream breakers and fuses is very important. This is a typical factory power circuit fed by a 34.5 kV high-voltage transformer with a 4160 V low-voltage secondary connected to a bus. The bus has feeder lines connecting it to various loads. Only one load is shown here. Note that the feeder circuit has a transformer with a 480 V secondary voltage. The secondary is protected by a 600 V molded-case circuit breaker. Therefore the primary of the main transformer and each feeder line are protected by circuit breakers. Tripping of the breakers between the primary breaker and the feeder breakers must be coordinated so that when a fault occurs downstream on a feeder line, that feeder breaker interrupts the fault rather than the main breaker. Subsequently, only the faulted feeder line is isolated rather than interrupting power to the whole factory.

To accomplish this coordination, the tripping time-current (t-i) characteristics for each breaker and fuse must be known and plotted on a common time-current graph, as shown in Fig. 10. For breakers and fuses operating at different voltages, the *t–i* characteristics of each breaker and fuse must be normalized so that they can be plotted on the same curve. The *t–i* characteristics of the 480 V downstream breaker are plotted to the left of the graph because it is the first breaker to trip if the fault occurs on its load side. The *t–i* characteristics of the 34.5 kV main breaker are plotted to the right of all the other breakers and fuses because that is the last breaker to trip. Chen gives an excellent discussion of coordinating breakers (7). He states that the data required for a coordination study are (1) a one-line diagram of the system, (2) short-circuit studies, (3) time-current characteristics of the breakers and fuses, and (4) maximum loading.

Larger industrial plants have a main control room in which the close, open, or trip status of each breaker in the network is displayed. Status signals from the breaker are sent to the display panel, and the operator may have the capability of operating a breaker remotely. Utility companies have such a breaker status panel of their distribution system so that they can dispatch power flow over the power grid and observe and correct any problems of the grid before they become too serious.

EQUIVALENT CIRCUIT

A high-frequency model can be developed for nearly all circuit breakers. All circuit breakers have source-side connections, load-side connections, and conductors internal to the interrupters. Figure 11 is a simplified circuit breaker model. The model consists of a source-side capacitance C_1 to ground, a switch S, a series resistance R, representing the contact resistance of the electrodes and of the busses, a series inductance L, representing the bus and interrupter inductance, a capacitance C_2 across the switch, and a load side capacitance C_3 to ground. In most cases, at low frequencies, this equivalent circuit can be neglected. However, the model is useful for analyzing the high-frequency transient response of a circuit when switched by a breaker. The capacitance and inductance are responsible for high-frequency parasitic arcs created during the arcing process of current interruption.

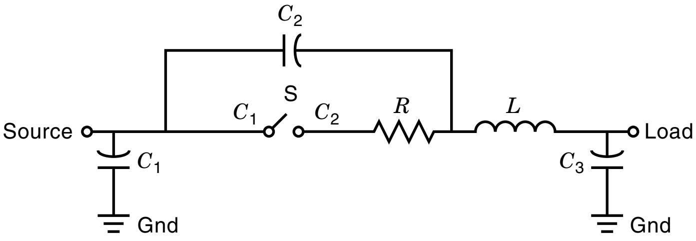

Figure 11. A high-frequency equivalent circuit of a circuit breaker. This circuit is for one pole of the breaker.

CONCLUSIONS

Breakers are very reliable protective devices to prevent excessive overloads and fault current from damaging power lines, transformers, motors, and sensitive circuits.

The older, high-voltage circuit breakers used oil or oil as the current interrupting and insulating medium. If this type of breaker fails to operate properly, fire or explosion is possible. Subsequently, the more reliable and safer compressed-air or SF_6 breakers are replacing these breakers. Where oil reclosers or air breakers were used for high-voltage operations (15 kV to 72 kV), they are being replaced by vacuum circuit breakers. The vacuum breaker is not a fire hazard, requires less maintenance, has longer life, and is safer.

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CIRCUIT BREAKERS. See CONTACTORS.

CIRCUIT, DEFECT TOLERANT. See WAFER-SCALE INTEGRATION.

CIRCUIT (FREQUENCY), IDLER. See MICROWAVE PARAMETRIC AMPLIFIERS.

CIRCUIT MAGNIFICATION METER. See Q-METERS.