SWITCHGEAR PROTECTION

Switchgear is generally considered to be switching and interrupting equipment that is normally equipped with controls, instruments, metering, protective, or regulating devices. It is primarily employed in electric power distribution systems in connection with the generation, transmission, and distribution, of power. The voltage range is from 4.76 kV to 38 kV. The most common switchgear in the industry is known as metal-clad switchgear, with a voltage range from 4.16 kV to 15 kV. One of the unique features of the metal-clad switchgear is its drawout-type interrupting unit. Its arc-interrupting medium can be air, vacuum, or SF_6-type gas. In North America, air interrupters have gradually been phased out, and SF_6 interrupters are more frequently used above 69 kV and less used below 38 kV. Therefore, this article will concentrate on describing vacuum-type metal-clad switchgear.

METAL-CLAD SWITCHGEAR FEATURES

A switchgear assembly is completely enclosed with 11-gauge sheet metal, except for ventilating openings and inspection windows. It contains a high-voltage section that includes primary circuit switching or interrupting devices or both, with buses and connections. The assembly may also contain a low-voltage section that includes control and auxiliary devices. Access to the interior of the enclosure is provided by doors or removable covers or both. To meet the ANSI C37.20.2 standard, metal-clad switchgear must have the following features (1):

1. The main switching and interrupting device must be a drawout type, arranged with a mechanism for moving it physically between “connected” and “disconnected” positions. It must also be equipped with self-aligning and self-coupling primary disconnecting devices. Its control wiring must be disconnectable.
2. Major parts of the primary circuit—that is, the circuit switching or interrupting devices, buses, voltage transformers, and control power transformers—must be completely enclosed by grounded metal barriers that have no intentional openings between compartments. A metal barrier must be included in front of or as part of the circuit interrupting device to ensure that, when in the “connected” position, no primary circuit components are exposed by the opening of a door.
3. All live parts must be enclosed within grounded metal compartments.
4. Automatic shutters must be installed to cover primary circuit elements when the removable element is in the “disconnected/test” or removed position.
5. Primary bus conductors and connections must be covered with insulating material throughout.
6. Mechanical interlocks must be provided for proper operating sequence under normal operating conditions.
7. Instruments, meters, relays, secondary control devices, and their wiring must be isolated by grounded metal barriers from all primary circuits elements, with the exception of short lengths of wire such as at instrument transformer terminals.
8. The door through which the circuit interrupting device is inserted into the housing may serve as an instrument or relay panel and may also provide access to a secondary or control compartment within the housing.

METAL-CLAD SWITCHGEAR CONSTRUCTION

Structure

Metal-clad switchgear can consist of one or more vertical sections that are mounted side-by-side and connected electrically and mechanically. Each vertical section, 36 in. wide, 95 in. high and 94 in. deep, is a self-supporting structure consisting of a bolted steel frame with reinforcing gussets as shown in Fig. 1. The external cover and doors are 11-gauge steel.

A vertical section can house up to two circuit breakers, or three of the voltage transformer, control power transformer, fuse drawout trays or certain combinations of these three units. Figures 2, 3, and 4 present some of the typical arrangements.

Breaker

As shown in Fig. 5, breakers can be removed from the switchgear by either a manually operated or motor-operated jackscrew racking mechanism. As a breaker is removed, grounded metal safety shutters will automatically isolate the primary disconnecting contacts from the rest of the compartment.

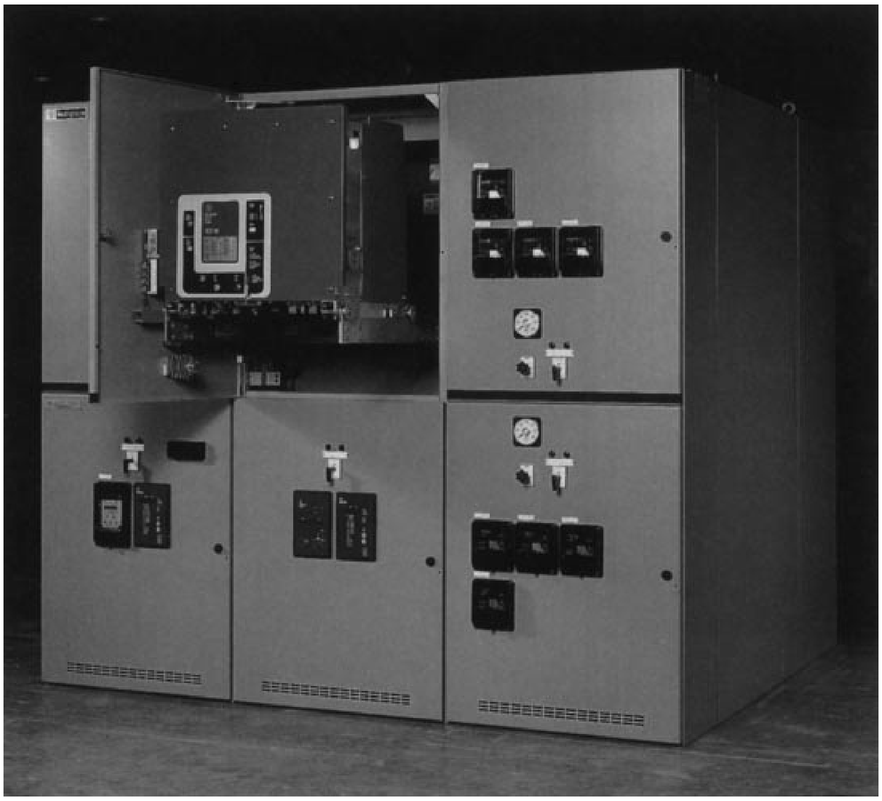


Figure 1. Metal-clad switchgear (2). Reprint-Permission by Cutler-Hammer.

When the breaker primary disconnecting contacts are fully engaged and locked in with the main bus, this is called the "connected" position. When the breaker primary disconnecting contacts are completely withdrawn from the "connected" position and the grounded metal safety shutters are actuated to cover the stationary primary studs, this is called the "test/disconnected" position. Mechanical interlocks are provided in the switchgear to:

1. Prevent the breaker moving to or from the "connected" position when the breaker interrupters are in the "closed position."

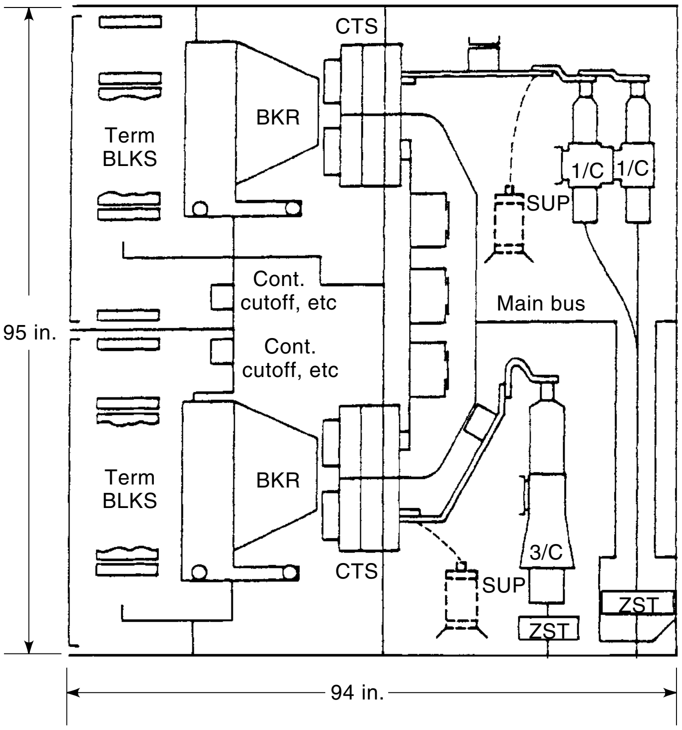


Figure 2. A 36-in.-wide typical breaker/breaker vertical section (7). Reprinted-Permission by Cutler-Hammer.

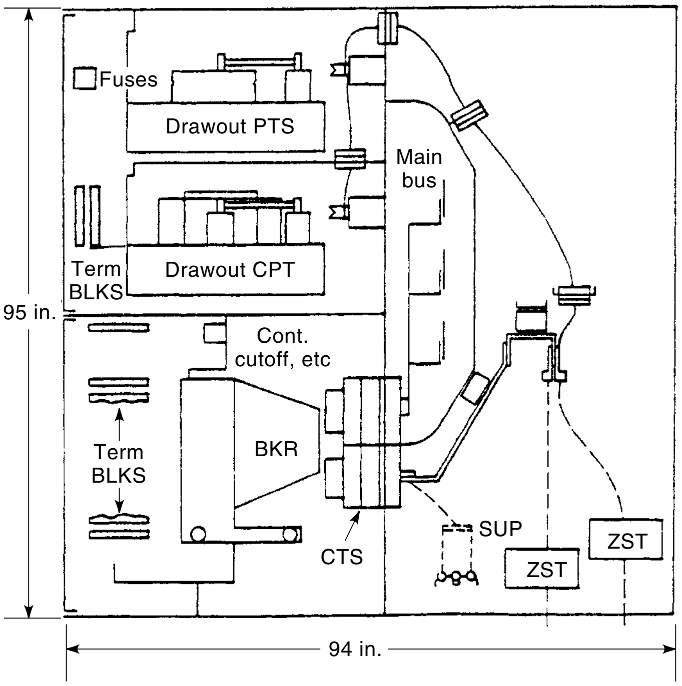


Figure 3. A 36-in.-wide typical auxiliary/breaker vertical section (7). Reprinted-Permission by Cutler-Hammer.

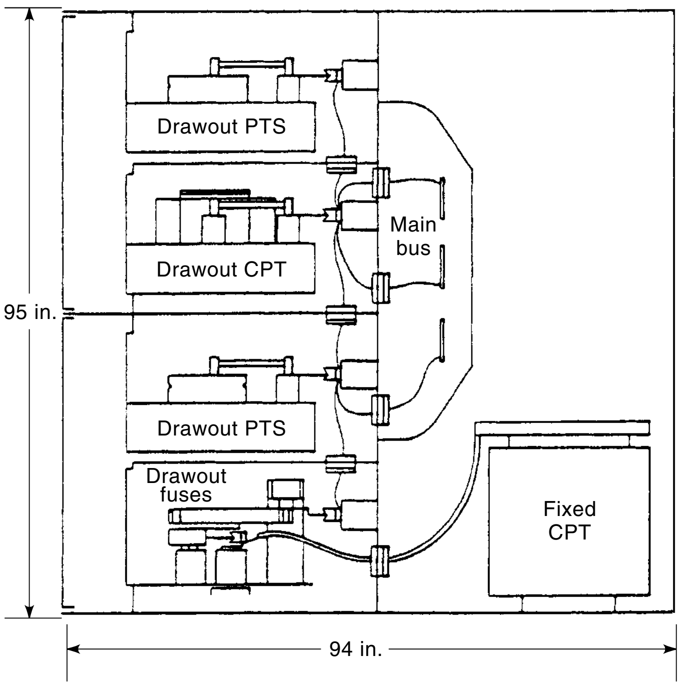


Figure 4. A 36-in.-wide typical auxillary/auxiliary vertical section (7). Reprint-Permission by Cutler-Hammer.

Figure 5. Removable vacuum breaker (2). Reprint-Permission by Cutler-Hammer.

2. Prevent the breaker to close unless the breaker is at either “connected” or “test/disconnected” position.
3. Discharge the closing springs automatically when the breaker is moving between the “connected” and “test/disconnected” position.

In addition, control power transformer primary fuses are not accessible, unless the control panel power transformer primary and secondary recording circuits are opened.

Primary Compartments

The primary compartments (i.e., breaker compartments, main bus compartment, power termination compartment, and auxiliary compartment) of each vertical section are isolated by grounded metal barriers. In addition, each breaker and drawout tray is furnished with a front plate that isolates the control from the primary compartment. Control circuit wires are armored or enclosed in grounded metal troughs where they pass through primary compartments.

Power termination compartments are located at the rear of the section, and they are accessible through bolted rear covers.

As shown in Fig. 6, barriers and cable pass-through boxes of 11-gauge steel are provided to isolate the circuit terminations in the event that there are two cable termination compartments in the same vertical section. Each termination compartment can accommodate up to 2 750-MCM stress cones (or two potheads) per phase without the addition of a rear extension.

The power termination compartment can be used for mounted stationary CPTs, wound primary CTs, ground sensor CTs, surge arrestors, and other auxiliary devices.

Ventilation is provided by inlet openings through slots in the bottom flange of each front door and louvers in the rear covers. Exhaust vents through openings in the top covers,

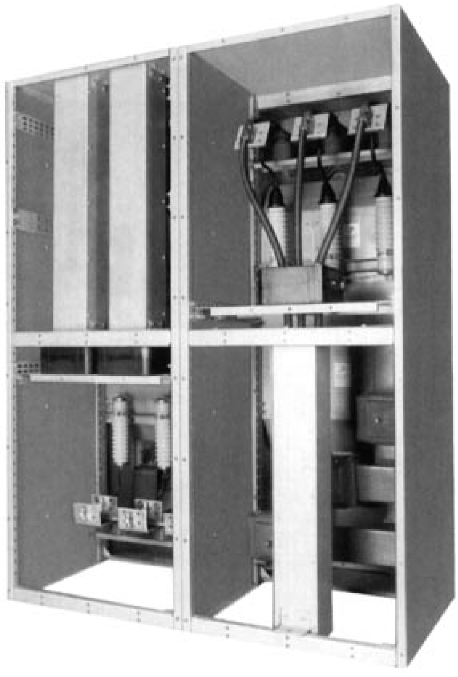


Figure 6. Rear view showing cable compartments (8). Reprint-Permission by Cutler-Hammer.

which are not used for power or control cable entry. Top exhaust vents are equipped with dust guards to keep dirt off the top breakers.

Additional design features include:

1. The rating interference plate which allows only a breaker of the correct type and rating to be inserted into any specific breaker compartments.
2. Closed-door drawout design which allows breaker racking to and from the "connected" position with the front door closed.

Main Bus

The main bus is completely enclosed by grounded, metal barriers and feeds both the upper and lower compartment in a vertical section. Standard main bus materials are A STM B317 aluminum alloy No. 6101 for 1200 A rating ($\frac{1}{4}$ in. by 6 in. bar) and 2000 A rating ($\frac{1}{2}$ in. × 6 in. bar), and A STM B187 Type ETP copper for the 3000 A rating ($2\frac{3}{8}$ in. × 6 in. bars). All main bus joints are silver-plated and utilize at least two $\frac{1}{2}$ in. zinc-plated, bronze iridescent chromate conversion coated steel bolts per joint. Provision for future extension of the main bus is standard.

Bus bars are mounted edgewise on 11 in. centers and are insulated with flame-retardant, track-resistant epoxy that withstands the dielectric tests specified in ANSI-C37.20. The bus bars are supported on track-resistant, molded-polyester-glass supports which also serve as interlock bus barriers. Bus supports have strength suitable to withstand the forces caused by a peak short-circuit asymmetrical current of 80,000 A (50,000 symmetrical amperes). All bus joints are insulated with preformed vinyl boots secured by nylon hardware.

Secondary Control

Protection, instrumentation, and control devices which provide indication or manual control are mounted on the front door.

Secondary control devices that are not door-mounted are surface-mounted in their predesignated locations in the equipment. Included in this class are fuse blocks, terminal blocks, some auxiliary relays, and stationary auxiliary switches.

Ring-type current transformers are mounted over the stationary primary stubs and are accessible through the front of the breaker compartment. Primary CTs, when required, are voltage transformers, and their associated fuses are mounted on drawout trays.

Secondary control wiring is No. 14, extraflexible, stranded, tinned-copper control wire, Type SIS rated 600 V, except for some specific circuits for which a larger wire size is required. Crimp-type, uninsulated spade terminals are furnished on all wire ends, except where noninsulated ring terminals are used to connect to fuse blocks, instrument studs, or terminal block points which have two or more wire connections. Secondary control wires are armored or enclosed in grounded metal troughs where they pass through primary compartments.

Grounded Bus

A ground bus of $\frac{1}{4}$ in. by 2 in. copper extends throughout the lineup with connections to each breaker grounding contact and each cable compartment ground terminal. All joints are made with at least two $\frac{3}{8}$ in. zinc-plated, bronze iridescent chromate conversion coated steel bolts per joint. Station ground-connection points are located in each end section.

Space Heaters

A heating element is isolated in each breaker or auxiliary compartment and each cable compartment. Heaters are applied at half-voltage for extended life and are protected by perforated metal guards to prevent inadvertent contact with the heater element.

Heaters should be energized at all times to guard against condensation caused by wide ambient temperature excursions. There is no switch or thermostat in the heater circuit.

Finish and Paint

Indoor switchgear enclosure parts are protected with a cathodic electrodeposition of ANSI 61 gray epoxy after pretreatment of the metal. This process results in high corrosion resistance, uniform and thorough paint coverage (which is more attractive), and exceptional hardness, yet it exhibits greater flexibility and impact resistance than former painting methods.

Outdoor switchgear is given the same "E coat" process as indoor equipment followed with an additional coat of light gray (ANSI 61) acrylic enamel. Other options include dark gray (ANSI 24), sky gray (ANSI 70), or Berkshire medium green (ANSI 45).

VACUUM INTERRUPTER

The heart of a switchgear is its interrupter. As shown in Fig. 7, the vacuum interrupter is usually contained in a hermetically sealed ceramic enclosure and consists of a stationary contact, a moving contact with flexible metallic bellows, and a metal vapor condensing shield. A series connected coil is sometimes placed around the interrupter near the contacts to provide an axial magnetic field. This would increase the interrupting capability. The vacuum chamber has a pressure in the range of 10^{-8} torr to 10^{-6} torr.

When a fault occurs and interruption is required, the contacts on all three phases are quickly separated. An arc is drawn between the contact surfaces and is rapidly moved around the slotted electrode surface by self-induced magnetic effects; this prevents gross electrode erosion and the formation of hot spots on the surface. The arc burns in an ionized metal vapor, which continually leaves the contact area and condenses on the surrounding metal shield.

At current zero, the arc extinguishes, vapor production ceases, and very rapid dispersion, cooling, recombination, and deionization of the metal vapor products cause the vacuum condition to be quickly restored. Hence the separated contacts withstand the transient recovery voltage (2).

However, when the current is in the range of 0.2 A to 20 A, arcs may be prematurely extinguished prior to a current zero due to plasma instability. This condition is known as "current chopping." During this interrupting period, the chopping current may resonate with load side of the circuit and oscillate on the order of 100 kHz. The oscillating current may reach current zero numerous times. If the interrupter achieves dielectric recovery, then the current will finally remain at zero. This would trap stored energy within load side of the circuit, which then results in transient overvoltage. The transient overvoltage is proportional to the product of the chopped current and the surge impedance of the circuit.

Current chopping depends on many factors, including the characters of circuit current levels, contact separate timing, and contact material. There has been a significant amount of development in contact material, and the overvoltages created by current chopping and multiple reignitions have been greatly reduced. The need for additional circuit suppression shall depend upon the length of cable and the amount of line-to-ground capacitance of the circuit.

Table 1 illustrates overvoltage probabilities for vacuum circuit breakers of recent design, and it lists selected typical overvoltages under conditions of chopping and multiple reignitions, as given by J. F. Perkins (3).

Table 1 illustrates that overvoltages, under the conditions specified, can exceed 4 pu, or 45 kV, for a 13.8 kV system. Since the peak of the normal dielectric test is on the order of 50 kV, it can be seen that some form of protection is reasonable to consider. Arrestors and surge capacitors are typically used for the purpose.

Cables of different lengths and loads of different size have an effect on the magnitude and numbers of reignitions. In some instances there is sufficient length of cable, or the load is of a certain nature, to ignore the concern for overvoltage protection. It appears, however, that the consideration for suppression of one form or another is more prudent in the application of vacuum breakers.

Table 1. Overvoltage Probabilities for Vacuum Circuit Breakers (4)

Load	Cable Length (ft)	Surge Protection	Maximum Transient Voltage Line-to-Ground	Typical Number of Restrike/Phase
Transformer 10 MVA	300	None	4.0 pu	10.0
		ZnO at breaker	3.4 pu	10.0
		Capacitors at load	2.0 pu	0.3
Transformer 1.5 MVA	300	None	2.3 pu	5.0
Motor 8000 HP running	100	None	1.6 pu	0.4
		Capacitors at load	1.1 pu	0.1
Motor 8000 HP inrush	100	None	4.6 pu	1.3
		Capacitors at load	2.8 pu	0.3

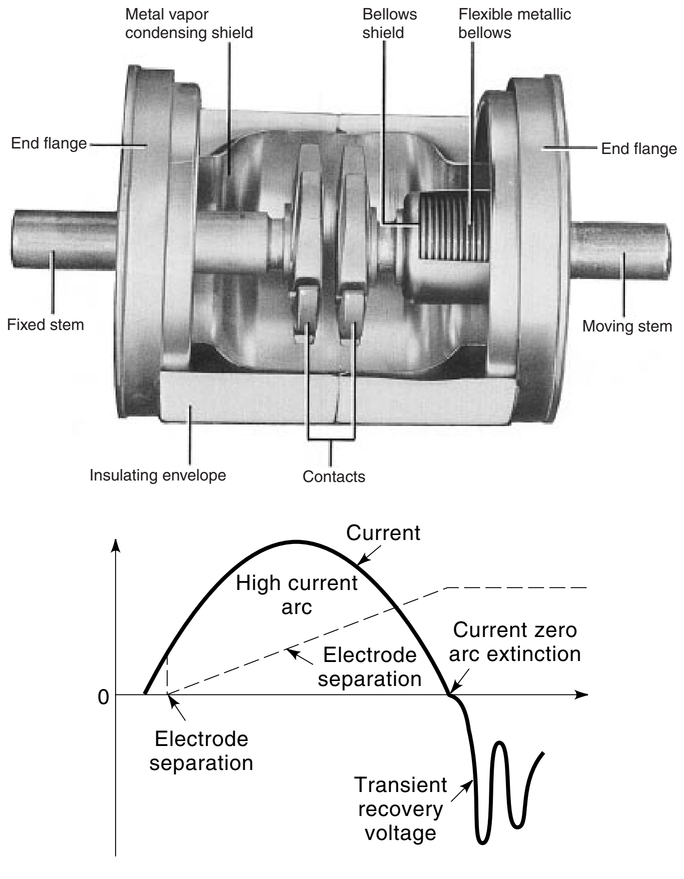


Figure 7. Current, voltage, and contact separation interrelationship (2). Reprint-Permission by Cutler-Hammer.

One of the minor concerning characteristics of vacuum equipment is its possibility to become involved in a three-phase virtual chop, or, as it is sometimes called, a simultaneous interruption, where all three poles interrupt at the same time. The usual interruption involves the process where the first pole interrupts at a current zero, with the other two poles recombining into a singe phase. At a point 90 electrical degrees later, the single phase interrupts with the last two poles in series. In the simultaneous interruption, if the first pole chops at a significantly high current level and the surge impedance is high, a high-frequency current disturbance is created in the other two poles by capacitive coupling. If the disturbance is sufficient, it can drive the current to a premature zero in the other two phases, at which time the other two vacuum interrupters may also interrupt almost instantaneously. The virtual chop current levels in the last two poles to clear can be very high, as compared to the normal chop levels of 3A or 4A. The resulting overvoltage as a result of a virtual chop can exceed the BIL rating of the equipment. For this reason it is advisable to have an arrestor somewhere in the circuit. Virtual chopping tends to be isolated to those systems having high surge impedances (4).

RATINGS

General

The design criteria for metal-clad switchgear shall be full compliance with American National Standard Institute (ANSI) and National Electrical Manufacturers Association (NEMA) to ensure high level of performance and accuracy.

The applicable industry standards are:

ANSI C37.010	Application guide for alternating-current (ac) high-voltage circuit breakers rated on a symmetrical current basis.
ANSI C37.04	Rating structures for ac high-voltage circuit breakers.
ANSI C37.06	Preferred ratings for ac high-voltage circuit breakers as rated on a symmetrical current basis.
ANSI C37.07	Factors for reclosing service.
ANSI C37.09	Test procedure for ac high-voltage circuit breakers.
ANSI C37.11	Power circuit breaker control.
ANSI C39.20	Switchgear assemblies including metal-enclosed bus.
ANSI C37.24	Guide for evaluating the effort of solar radiation.
ANSI C37.100	Definitions for power switchgear.
NEMA SG-4	Power circuit breakers.
NEMA SG-5	Power switchgear assemblies.

Service Conditions

American National Standards for the design and performance of metal-clad switchgear are based on the following conditions:

1. The temperature of the cooling air (ambient air temperature) surrounding the enclosure of the metal-clad switchgear is within the limits of −30°C and +40°C.
2. The altitude of the installation does not exceed 3300 ft (1000 m).
3. The effort of solar radiation is not significant.

Ratings

Switchgear under the service conditions specified in the section entitled "Service Conditions" shall have the following ratings:

Rated Maximum Voltage. The highest root-mean-square (rms) voltage for which the switchgear is designed and is the upper limit for operation.

Rated Frequency. The rated frequency is 60 Hz.

Rated Insulation Level. The rated insulation level shall consist of two items:

1. Low-frequency 1 minimum withstand voltage. The switchgear shall be able to withstand a voltage with crest value equal to 19 kV, 36 kV, and 36 kV for switchgear rated maximum voltage rated 4.76 kV, 8.25 kV, and 15 kV, respectively, for 1 minimum at ±20% of the rated frequency—that is, 60 Hz.
2. Impulse withstand voltage. The switchgear shall be able to withstand a full 1.2/50 MS impulse voltage of 60 kV, 95 kV, and 95 kV for switchgear rated maximum voltage rated 4.76 kV, 8.25 kV, and 15 kV, respectively.

Rated Continuous Currents. The rated continuous current is the maximum current in rms amperes at rated frequency, which a switchgear can carry continuously without causing temperatures in excess of specified limits. The rated continuous currents are 1200 A, 2000 A, and 3000 A.

Table 2. Temperature Limits for Insulating Materials as Used in Switchgear Assemblies (1)

Class of Insulating Material	Limit of Hottest-Spot Temperature Rise (°C)	Limit of Hottest-Spot Total Temperature (°C)
Class 90	50	90
Class 105	65	105
Class 130	90	130
Class 155	115	155
Class 180	140	180
Class 220	180	220

Note: For additional information on temperature limits see ANSI/IEEE Std. 1-1986.

Table 2 and Table 3 summarize the temperature limits for insulating materials and bus/connectors, respectively.

Temperature limits for air within an enclosed assembly shall be in a range of −30°C to +40°C.

Rated Short-Time Current. The rated short-time current is the average rms current that a switchgear can carry for a period of 2 s.

Rated Closing and Latching. The rated closing and latching is the maximum rms total current that a switchgear is required to close and immediately thereafter to latch on any normal-frequency-producing current which does not exceed $1.6K$ times the rated short-circuit current or $2.7K$ times rated short-circuit peak current. K is the rated voltage range factor, which is the ratio of rated maximum voltage to the lower limit of the operating voltage range.

Rated Interrupting Time. The rated interrupting time of a breaker is the time between trip circuit energization and

Table 3. Temperature Limits for Buses and Connections as Used in Switchgear Assemblies (1)

Type of Bus or Connection	Limit of Hottest-Spot Temperature Rise (°C)	Limit of Hottest-Spot Total Temperature (°C)
Bus connections with unplated copper-to-copper connection joints	30	70
Buses and bus connections with silver-surfaced, tin-surfaced or equivalent connection joints	65	105
Connections to insulated cables (unplated copper to copper)	30	70
Connections to insulated cables with silver-surfaced, tin-surfaced, or equivalent connection joints	45	85

Note: All aluminum buses shall have silver-surfaced, tin-surfaced, or equivalent connecting joints. Welded bus connections are not considered connecting joints.

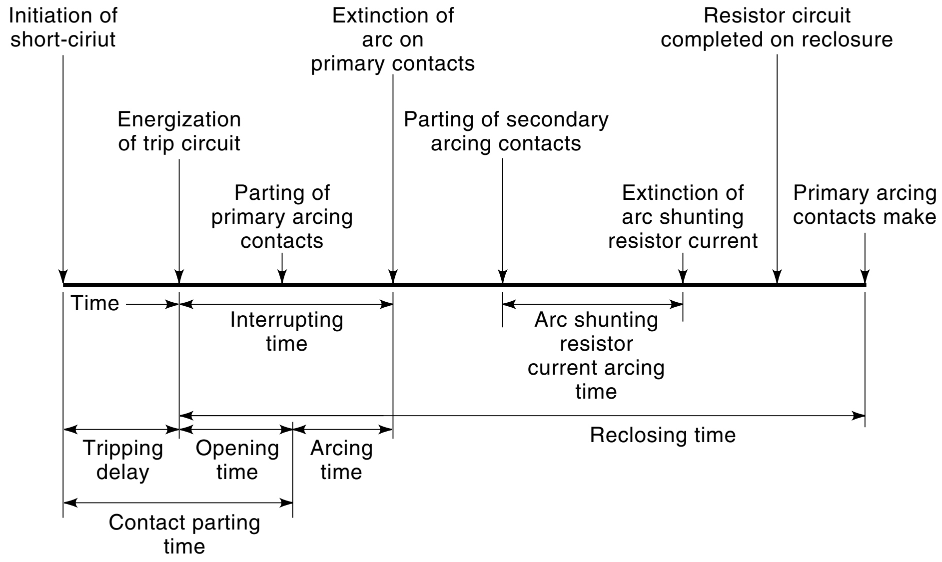


Figure 8. Operating time (9). *Reclosing time is the time interval between energization of the trip circuit and making of the primary arcing contacts, where low ohmic resistors are used; making of the resistor contact in reclosure may be more significant. (© 1979 IEEE)

power arc interruption on an opening operation, and it is used to classify breakers of different speeds.

The rated interrupting times are 2 cycles, 3 cycles, 5 cycles, and 8 cycles. Figure 8 shows the sequence of events in the course of a circuit interruption and reclosure.

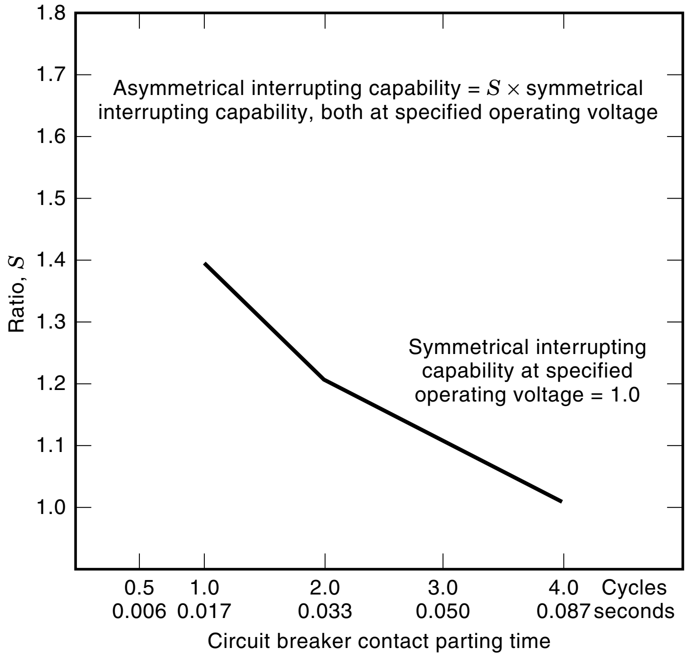
Rated Symmetrical and Asymmetrical Interrupting Currents

Rated Symmetrical Interrupting Current. The rated symmetrical interrupting current is the highest value of the symmetrical component of the short-circuit current in rms amperes at the instant of primary arcing contact separation which the breaker shall be required to interrupt at a specified operating voltage on the standard operating duty and irrespective of the direct current component of the total short-circuit current. The numerical value at an operating voltage between $1/K$ times rated maximum voltage shall be determined by the following formula (5):

$$\begin{array}{c}\text{Required}\\ \text{symmetrical}\\ \text{interrupting}\\ \text{capability}\end{array} = \begin{array}{c}\text{Rated}\\ \text{short-}\\ \text{circuit}\\ \text{current}\end{array} \times \frac{\text{Rated maximum voltage}}{\text{Operating voltage}}$$

In no case shall the required symmetrical interrupting capability exceed K times short circuit current.

Rated Asymmetrical Interrupting Current. The rated asymmetrical interrupting current is the highest value of the total short-circuit current rms amperes at the instant of primary arcing contact separation which the breaker shall be required to interrupt at a specified operating voltage and on the standard operating duty. The numerical value shall be equal to the product of a ratio S, specified below and illustrated in Fig. 9, times the required symmetrical interrupting capability of



Sum of 1/2 cycle tripping delay plus the opening time of the individual breaker (refer to 5.10.2.2.2)

Figure 9. Ratio of circuit-breaker asymmetrical-to-symmetrical interrupting capabilities (5). *Note:* For relation of symmetrical interrupting capability at specified operating voltage to rated short-circuit current, see Fig. 10. (© 1985 IEEE)

Table 4. Related Required Transient Recovery Voltage Capabilities of Circuit Breakers at Various Interrupting Levels for Terminal Faults (13)

	Multipliers for Rated Parameters	
	72.5 kV and Below	
Percent of Interrupting Rating	E_2	T_2
100	1.00	1
60	1.07	0.67
30	1.13	0.4
7	1.17	0.4

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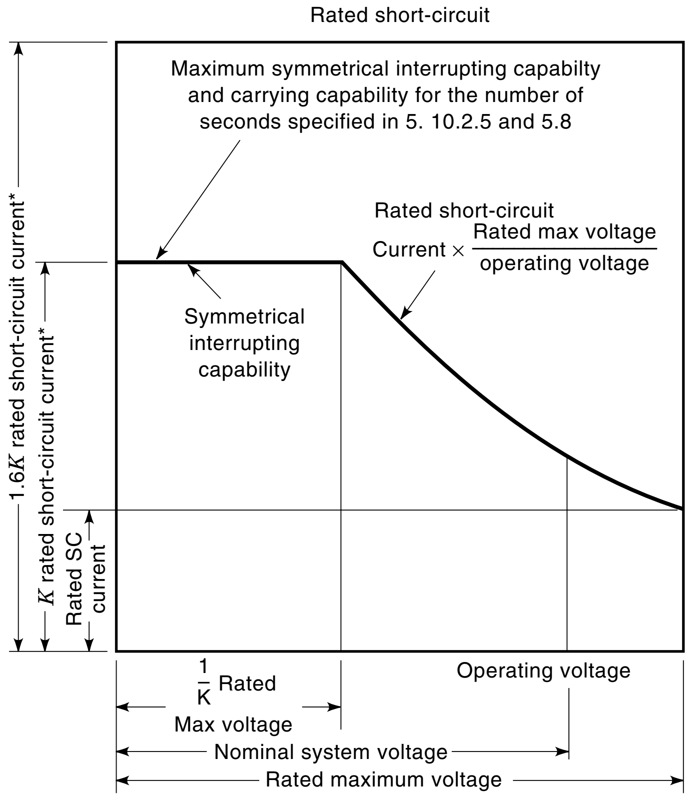

Figure 10. Relation of symmetrical interrupting capability, closing capability, latching capability, and carrying capability to rated short-circuit current (5). *Or 2.7*K* times rated short-circuit current if current is measured in peak amperes. *Note: K* equals voltage range factor. (For preferred standard values see ANSI C37.06-1979.) (© 1985 IEEE)

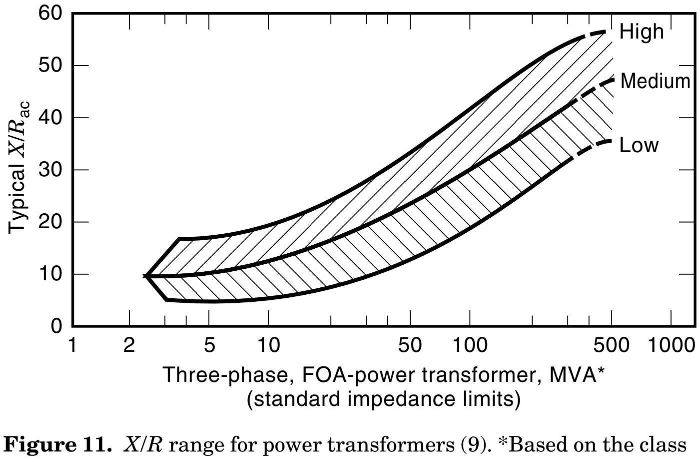

Figure 11. *X*/*R* range for power transformers (9). *Based on the class of transformer, obtain the proper factor from the table below. Multiply the transformer MVA rating by this factor before using Fig. 4 to obtain typical *X*/*R* values. (© 1979 IEEE)

Class	Rating in MVA	Factor
OA	All ratings	1.67
FA	Up to 14.9	1.33
FA	16 and up	1.25
FOA	All ratings	1.0

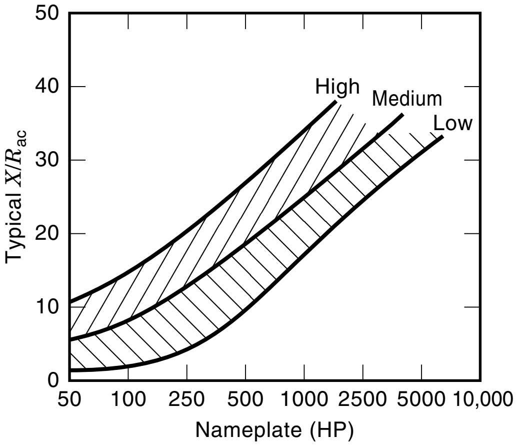

Figure 12. *X*/*R* range for three-phase induction motors (9). (© 1979 IEEE)

the breaker determined for the operating voltage. The values of *S* shall be 1.4, 1.3, 1.2, 1.1, or 1.0 for breakers having primary arcing contact parting times of 1, 1.5, 2, 3, 4, or more cycles, respectively. The values of *S* for primary arcing contact parting times between those given above shall be determined by linear interpolation. The primary arcing contact parting time shall be considered equal to the sum of one-half cycle (present practical minimum tripping delay) plus the lesser of (1) the actual opening time of the particular breaker or (2) 1.0, 1.5, 2.5, or 3.5 cycles for breakers having a rated interrupting time of 2, 3, 5, or 8 cycles, respectively.

Rated Transient Recovery Voltage. During the short-circuit interrupting process, the system voltage [called the transient recovery voltage (TRV)] oscillates with its natural frequency. This TRV is impressed across the opening breaker contacts and stresses the gap insulation. The interrupting media following current extinction is attempting to return from a state of good conduction to one having the attributes of a good insulator. The interrupting media becomes a good insulator while the system is applying increasing TRV to the gap in an attempt to reignite or restrike the arc. If the insulation recovers more quickly than the TRV, then a successful interruption occurs. If not, then the arc is reestablished, another half-cycle or loop of current occurs, and the interruption process is again attempted. This process continues until successful interruption occurs (6).

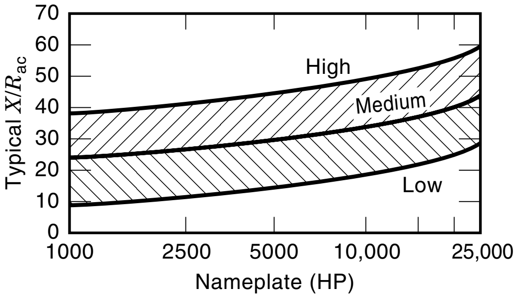

Figure 13. *X*/*R* range for small solid rotor and salient-pole synchronous generators and motors (9). (© 1979 IEEE)

Table 5. Summary of Metal-Clad Switchgear Rating (Basis ANSI C37.06) (13)

Identification (6 & 7)		Rated Values								Related Required Capabilities			
		Voltage		Insulation Level: Rated Withstand Test Voltage		Current					Current Value		
Nominal rms Voltage Class (kV)	Nominal 3-phase Class (MVA)	Rated Maxi-rms Voltage (kV) (1)	Rated Voltage Range Factor *K* (2)	Low-Freq-uency rms Voltage (kV)	Crest Impulse Voltage (kV)	Con-tinuous rms Current Rating at 60 Hz (amperes)	Short-circuit rms Current Rating (at Rated Max kV) (kV) (3) (4)	Rated Inter-rupting Time (Cycles)	Rated Per-missible Tripping Delay, *Y* (seconds)	Rated Maxi-mum rms Voltage Divided by *K* (kV)	Maximum symmet-rical Inter-rupting Capability (5) — *K* Times Related Short-circuit rms Current (kA)	3 Sec Short-Time Current-Carrying Capability — *K* Times Related Short-circuit rms Current (kV)	Closing and Latching Capability rms Current (kV)
4.16	250	4.76	1.24	19	60	1200	29	5	2	3.85	36	36	58
4.16	250	4.76	1.24	19	60	2000	29	5	2	3.85	36	36	58
4.16	250	4.76	1.24	19	60	3000	29	5	2	3.85	36	36	58
4.16	350	4.76	1.19	19	60	1200	41	5	2	4.0	49	49	78
4.16	350	4.76	1.19	19	60	2000	41	5	2	4.0	49	49	78
4.16	350	4.76	1.19	19	60	3000	41	5	2	4.0	49	49	78
7.2	500	8.25	1.25	36	95	1200	33	5	2	6.6	41	41	66
7.2	500	8.25	1.25	36	95	2000	33	5	2	6.6	41	41	66
7.2	500	8.25	1.25	36	95	3000	33	5	2	6.6	41	41	66
13.8	500	15	1.30	36	95	1200	18	5	2	11.5	23	23	37
13.8	500	15	1.30	36	95	2000	18	5	2	11.5	23	23	37
13.8	500	15	1.30	36	95	3000	18	5	2	11.5	23	23	37
13.8	750	15	1.30	36	95	1200	28	5	2	11.5	36	36	58
13.8	750	15	1.30	36	95	2000	28	5	2	11.5	36	36	58
13.8	750	15	1.30	36	95	3000	28	5	2	11.5	36	36	58
13.8	1000	15	1.30	36	95	1200	37	5	2	11.5	48	48	77
13.8	1000	15	1.30	36	95	2000	37	5	2	11.5	48	48	77
13.8	1000	15	1.30	36	95	3000	37	5	2	11.5	48	48	77
High Close and Latch Capability Circuit Breakers (These Ratings Exceed ANSI-C37.06) (13)													
4.16	250	4.76	1.24	19	60	1200 2000 3000	29	5	2	3.85	36	36	78
7.2	500	8.25	1.25	36	95	1200 2000 3000	33	5	2	6.6	41	41	78
13.8	500	15	1.30	36	95	1200 2000 3000	18	5	2	11.5	23	23	58
13.8	750	15	1.30	36	95	1200 2000 3000	28	5	2	11.5	36	36	77

For breakers rated 72.5 kV and below, the rated transient recovery voltage shall be defined as the envelope formed by the 1-cosine curve obtained by using the rated values of E_2 and T_2 from ANSI C37-06, and it shall apply for the rated short-circuit values. E_2 is the peak value that may reach. In ANSI standard, E_2 is 1.88 times the rated maximum voltage for breakers rated 72.5 kV and below. T_2 is the time for TRV to reach the peak value after current zero. The value of T_2 is a variable dependent upon the voltage rating, the type of breaker, and the short-circuit current level. For 15 kV, an indoor class circuit breaker at 100% rated short circuit, the value of T_2 is 75 MS. For other short-circuit levels the breaker-rated TRV capabilities is shown in Table 4.

Relationship of Ratings

The relationship of rated short-circuit current to the other current ratings is illustrated graphically in Fig. 10.

Summary of Metal-Clad Switchgear Ratings (Basis ANSI C37.06)

The rated continuous current, short-circuit capability, maximum voltage, *K* factor, low-frequency voltage, impulse voltage (BIL), and interrupting time for symmetrical rated metal-clad switchgear are summarized in Table 5.

1. The rated maximum breaker voltage is the upper limit of the breaker operation.

Table 6. General-Purpose Switchgear Capacitance Current Switching Duties (13)

			Rated Capacitance Switching Current				
				Shunt Capacitor Bank or Cable			
					Back-to-Back		
						Inrush Current	
Rated Max Voltage (kV, rms)	Rated Short-Circuit Current (kA, rms)	Rated Continuous Current (amperes, ms)	Overhead Line Current (amperes, rms)	Isolated Current (amperes, rms)	Current (amperes, rms)	Peak Current (kV)	Frequency (Hz)
4.76	8.8	1200	1	400			
4.76	29	1200	1	400			
4.76	29	2000	1	400			
4.76	41	1200	1	400			
4.76	41	2000	1	400			
4.76	41	3000	1	400	(Not recommended)		
8.25	33	1200	1	250			
8.25	33	2000	1	250			
15.0	18	1200	2	250			
15.0	18	2000	2	250			
15.0	28	1200	2	250			
15.0	28	2000	2	250			
15.0	37	1200	2	250			
15.0	37	2000	2	250			
15.0	37	3000	2	250			

2. K is the ratio of rated maximum voltage to the lower limit of the range of operating voltage in which the required symmetrical and asymmetrical interrupting capabilities vary in inverse proportion to the operating voltage.
3. To obtain the required symmetrical interrupting capability of a circuit breaker at an operating voltage between $1/K$ times rated maximum voltage and rated maximum voltage, the following formula shall be used:

Required symmetrical interrupting capability

$$= \text{Rated short-circuit current} \times \frac{\text{(Rated max. voltage)}}{\text{(Operating voltage)}}$$

Table 7. Definite-Purpose Switchgear Capacitance Current Switching Duties (13)

			Rated Capacitance Switching Current				
				Shunt Capacitor Bank or Cable			
					Back-to-Back		
						Inrush Current	
Rated Max Voltage (kV, rms)	Rated Short-Circuit Current (kA, rms)	Rated Continuous Current (amperes, ms)	Overhead Line Current (amperes, rms)	Isolated Current (amperes, rms)	Current (amperes, rms)	Peak Current (kV)	Frequency (Hz)
4.76	8.8	1200	1	630	630	15	2000
4.76	29	1200	1	630	630	15	2000
4.76	29	2000	1	1000	1000	15	1270
4.76	41	1200	1	630	630	15	2000
4.76	41	2000	1	630	630	15	2000
4.76	41	3000	1	1000	1000	15	1270
8.25	33	1200	1	630	630	15	2000
8.25	33	2000	1	1000	1000	15	1270
15.0	18	1200	2	630	630	15	2000
15.0	18	2000	2	1000	1000	15	1270
15.0	28	1200	2	630	630	15	2000
15.0	28	2000	2	1000	1000	15	1270
15.0	37	1200	2	630	630	15	2000
15.0	37	2000	2	630	630	18	2400
15.0	37	3000	2	1600	1600	25	1330

Table 8. Rated Operation Endurance Capabilities of Metal-Clad Switchgears (13)

Circuit-Breaker Ratings	Between Servicing	No-Load Mechanical	Continuous Current Switching	Inrush-Current Switching[a,b]
4.76 kV, 1200 A, 29 kA and below 8.25 kV, 1200 A 15 kV, 1200 A, 28 kA and below	2000	10000	1000	750
4.76 kV, 2000 A, 29 kA and below 8.25 kV, 2000 A 15 kV, 2000 A, 28 kA and below	2000	10000	1000	750
4.76 kV, 1200–3000 A, 41 kA 15 kV, 1200–3000 A, 37 kA	1000	5000	500	400
15.0 kV, 1200–3000 A	250	500	100	50

[a] When closing current is equal to 600% of rated continuous current at rated maximum voltage with power factor of 30% lagging or less and when opening current is equal to rated continuous current at rated maximum voltage with power factor between 80% leading and 80% lagging.

[b] If a short-circuit operation occurs before the completion of the listed operations, maintenance is recommended, and possible functional part replacement may be necessary, depending on previous accumulated duty, fault magnitude and expected future operations.

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For operating voltages below 1/*K* times rated maximum voltage, the required symmetrical interrupting capability of the circuit breaker shall be equal to *K* times rated short-circuit current.

4. With the limitation stated in 5.10 of ANSI-C37.04, all values apply for polyphase and line-to-line faults. For single phase-to-ground faults, the specific conditions stated in 5.10.2.3 of ANSI C37.04 apply.
5. Current values in this column are not to be exceeded even for operating voltages below 1/*K* times rated maximum voltage. For voltages between rated maximum voltage and 1/*K* times rated maximum voltage, follow step 3 above.

Switching Duties for Unusual Applications

Application of metal-clad switchgear for usual duty may require either derating of the breaker or an increase in maintenance. For unusual applications, first select a breaker based on basic duty requirements. Then consider the switchgear duty and redetermine the breaker capabilities and choose one next-higher-rated breaker if necessary. Repeat the derating or rating adjustment process to confirm that the new breaker has the adequate capability.

Switching Duty for Capacitance Current. Capacitance current switching includes the switching of an unload transmission line or cable, or the switching of a shunt capacitor bank. A circuit breaker may be modified or especially designed for such a purpose. This is called "definite-purpose circuit breaker." When more than one transmission line or cable or shunt capacitor bank is connected to the system in parallel with the one being switched, this is called back-to-back switching, which shall require higher breaker switching duty. Tables 6 and 7 represent the rated capacitance current switching duty for "general-purpose switchgear" and "definite-purpose switchgear."

Table 9. Altitude Correction Factors (ACF) (5)

Altitude Feet	Altitude Meters	ACF for Voltage	ACF for Continuous Current
3300	1000	1.00	1.00
5000	1500	0.95	0.99
10000	3000	0.80	0.96

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Repetitive Switching Duty. Repetitive switching such as arc furnace switching shall impose higher stress on the breaker. This would require more frequent maintenance service than that of normal switching duty. The maintenance service includes the adjustment, clearing, lubrication, lightning and changing parts if necessary. Table 8 represents the rated operation endurance capabilities of metal-clad switchgear.

Correction Factors for Altitudes Above 3300 feet (1000 m). For applications at altitudes higher than 3300 ft (1000 m), rated dielectric strength and rated maximum voltage shall be multiplied by an altitude correction factor for voltage, and the rated continuous current shall be multiplied by an altitude correction factor for continuous current to obtain values at which applications may be made. These correction factors are shown in Table 9. Rated interrupting time are not affected by altitude.

SHORT-CIRCUIT CALCULATIONS

To properly select a new switching device, or to evaluate the adequacy of an existing switching device in a power distribution system, a detailed short-circuit calculation is essential. There are two ANSI application standards for ac high-voltage circuit breakers as follows:

ANSI 37.5	Application of ac high-voltage circuit breakers rated in a total current basis.
ANSI 37.010	Application of ac high-voltage circuit breaker rated on a symmetrical current basis.

Table 10. Rotating-Machine Reactance Multipliers (9)

	Positive-Sequence Reactances for Calculation Networks (per unit)	
Type of Rotating Machine	Interrupting	Closing and Latching Duty
All turbine generators; all hydrogenerators with amortisseur windings; all condensers	$1.0X_{d''}$	$1.0X_{d''}$
Hydrogenerators without amortisseur windings	$0.75X_{d'}$	$0.75X_{d'}$
All synchronous motors	$1.5X_{d''}$	$1.0X_{d''}$
Induction motors		
(a) Larger than 250 hp at 3600 r/min or 1000 hp at slower speeds	$1.5_{d''}$	$1.0X_{d''}$
(b) Others 50 hp and larger	$3.0X_{d''}$	$1.2X_{d''}$
(c) All smaller than 50 hp	∞	∞

$X_{d''}$ of synchronous rotating machine is the rated-voltage (saturated) direct-axis subtransient reactance.
$X_{d'}$ of synchronous rotating machines is the rated-voltage (saturated) direct axis transient reactance.
$X_{d''}$ of indication motors equals 1.00 divided by per unit locked-motor current at rated voltage.

The total current basis of circuit breakers are mainly applied to breakers manufactured prior to 1964, and its interrupting rating was established as "the highest rms current to be interrupted at the specific operational voltage including the direct-current (dc) component at the instant of contact separation as determined from the envelope of the current wave." Since 1964 a new standard has been established.

The principal change from the previous "total current" standard was in the basis of rating. The new standard established the rated short-circuit current as "the highest value of the symmetrical component of the . . . short-circuit current in rms amperes, measured from the envelope of the current wave at contact separation, which the circuit breaker is required to interrupt at rated maximum voltage . . .". Certain related capabilities were also required, including operation under specified conditions of asymmetry based on typical circuit characteristics and circuit breaker timing. This rating structure became known as the symmetrical current basis of rating as compared to the previous total current basis of rating.

The rated short-circuit current for symmetrical current basis circuit breakers was tabulated for rated maximum voltage rather than for nominal voltage for circuit breakers under the total current basis. However, the short-circuit calculation procedures used for both standards are basically the same.

Table 11. Range and Typical Values of *X*/*R* Ratios of System Components (9)

System Component	Range	Typical Values
Large generators and hydrogen-cooled synchronous condensers	40–120	80
Power transformers	see Fig. 11	—
Induction motors	see Fig. 12	—
Small generators and synchronous motors	see Fig. 13	—
Reactors	40–120	80
Open wire lines	2–16	5
Underground cables	1–3	2

Note: Actual values should be obtained if practical.

Calculation Procedures

First we perform an E/X current calculation, and then it is necessary to adjust the E/X current value for both the ac and dc decay based on the system X/R ratio at the time of breaker contact parting. The calculating procedures for symmetrical current rated and total current rated circuit breakers are described in sections entitled "Symmetrical Current-Rated Circuit-Breaker Short Current Calculation Procedures" and "Total Current-Rated Circuit Breaker Short-Circuit Current Calculation Procedures."

Symmetrical Current-Rated Circuit-Breaker Short Current Calculation Procedures

Step 1. E/X Value of Symmetrical Short-Circuit Current. The network is reduced to a single equivalent reactance at the

Table 12. Equivalent System *X*/*R* Ratio at Typical Locations (for Quick Approximations) (9)

Type of Circuit	Range
Synchronous machines connected directly to the bus or through reactors.	40–120
Synchronous machines connected through transformers rated 100 MVA and larger.	40–60
Synchronous machines connected through transformers rated 25 MVA to 100 MVA for each three-phase bank.	30–50
Remote synchronous machines connected through transformers rated 100 MVA or larger for each three-phase bank, where the transformers provide 90% or more of the total equivalent impedance to the fault point.	30–50
Remote synchronous machines connected through transformers rated 10 MVA to 100 MVA for each three-phase bank, where the transformers provide 90% or more of the total equivalent impedance to the fault point.	15–40
Remote synchronous machines connected through other types of circuits, such as: transformers rated 10 MVA or smaller for each three-phase bank, transmission lines, distribution feeders, and so on.	15 or less

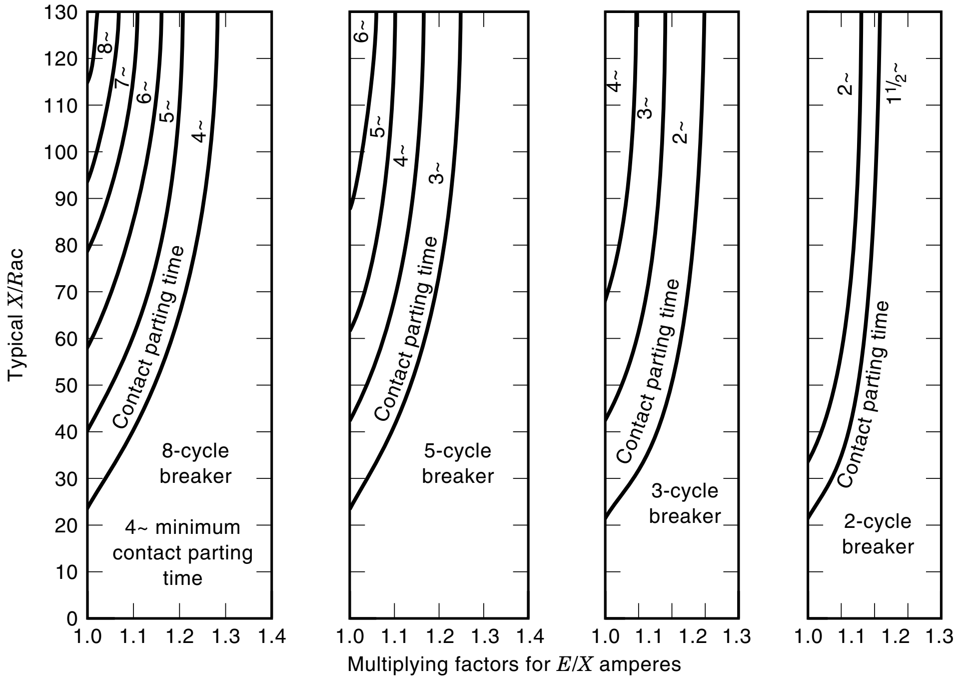

Figure 14. Multiplying factors (symmetrical rating basis) for three-phase faults fed predominantly from generators through not more than one transformation (local) (10). (© 1969 IEEE)

fault point, and the prefault operating voltage is divided by this reactance to obtain an *E*/*X* value of symmetrical short-circuit current.

The reactances representing rotating-machine performance in the network are shown in Table 10.

The *E*/*X* result of the network solution is the symmetrical short-circuit duty to be compared with the circuit-breaker symmetrical interrupting capability, provided that the circuit *X*/*R* ratio is 15 or less. When the circuit *X*/*R* ratio is 15 or less, the asymmetrical short-circuit duty never exceeds the symmetrical short-circuit duty by a proportion greater than that of the circuit-breaker asymmetrical short-circuit interrupting capability. Theoretically, this is not so for contact-parting times of four cycles and higher, but the small error is considered to be negligible.

When the circuit *X*/*R* ratio exceeds 15, the dc component of the short-circuit current may increase the breaker short-circuit duty.

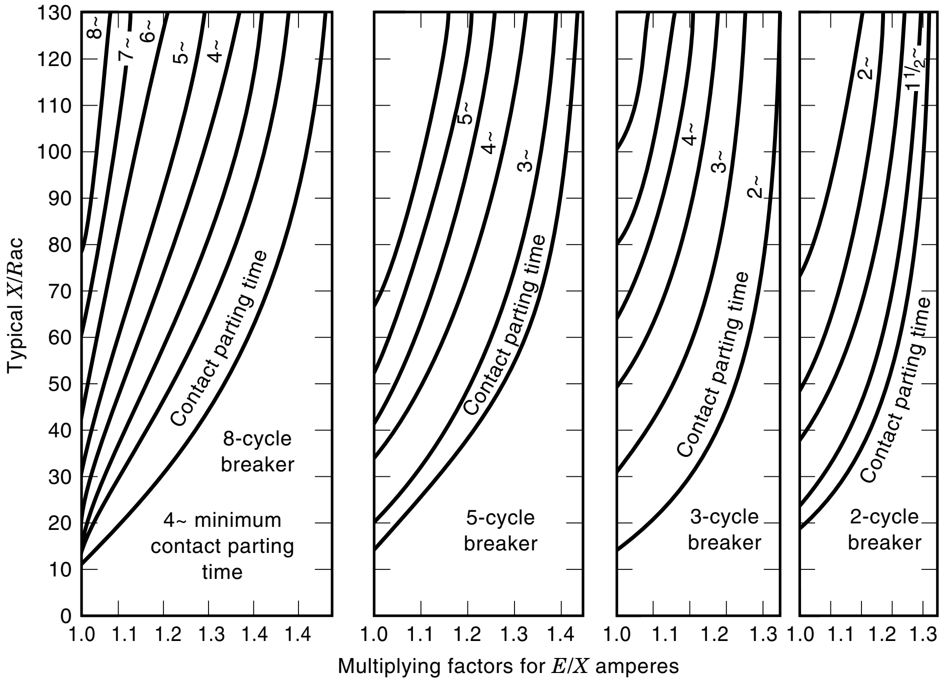

Figure 15. Multiplying factors (symmetrical rating basis) for three-phase and line-to-ground-faults fed predominantly through two or more transformations (remote) (10). (© 1969 IEEE)

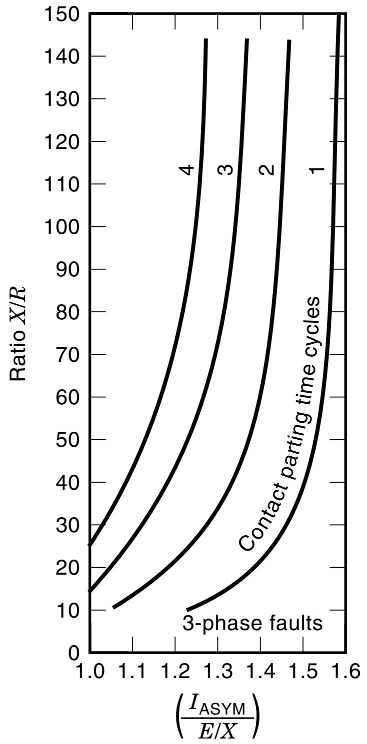

Figure 16. Multiplying factors (total current rating basis) for three-phase faults fed predominantly from generators through not more than one transformation (local) (9). (© 1979 IEEE)

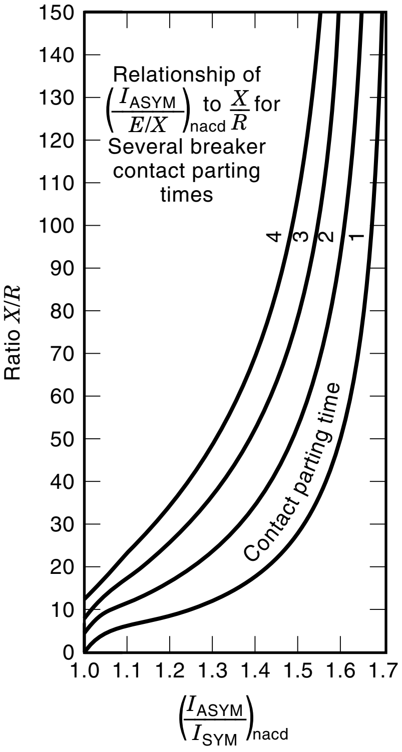

Figure 17. Multiplying factors (total current rating basis) for three-phase and line-to-ground faults fed predominantly through two or more transformations (remote) (9). (© 1979 IEEE)

Step 2. Determine X/R Ratio. A resistance network is constructed with a resistance corresponding to each reactance element in the reactance network, and this is reduced to a fault point. The short-circuit X/R ratio is taken to be the ratio of the X and R values obtained by reducing the reactance and resistance networks. The resistance value for each element of the network should be obtained for major elements from the manufacturer whenever possible. In the absence of information from the manufacturer, the approximate values of resistance from the Table 11 are suggested. In both bases, measured values on rotating machine should be converted to normal operating temperature. In setting up the R network for the calculation of the equivalent X/R ratio of any system, rotating machine resistance values obtained from the manufacturer or through use of values in Table 11 should be adjusted by the applicable rotating machine reactance multipliers from Table 10.

The ranges and typical values of the X/R ratios of system components may be obtained from Table 11. An estimate of the total system equivalent X/R ratio to the point of fault may be obtained from Table 12.

System Components	Approximate Resistance
Turbine generators and condensers	Effective resistance[a]
Salient pole generators and motors	Effective resistance[a]
Induction motors	1.2 times the dc armature resistance
Power transformers	Alternating-current load loss resistance (not including no-load losses or auxiliary losses)
Reactors	Alternating-current resistance
Lines and cables	Alternating-current resistance

[a] Effective resistance = $X_{2v}/2\pi f T_{a3}$, where X_{2v} is the rated voltage negative-sequence reactance and T_{a3} is the rated voltage generator armature time constant in seconds. It is usually about 1.2 times the dc resistance.

Step 3. Determine Multiplying Factors. A short-circuit duty value which may be compared with the circuit-breaker symmetrical interrupting capability is then obtained by multiplying the E/X current by a multiplying factor obtained from curves as a function of the short-circuit X/R ratio. There are two sets of curves for three-phase faults in Standard C37.010 shown in Figs. 14 and 15. The multiplying factor from Fig. 15 is to be used when the major contribution to the short-circuit current is from remote sources such as from utility generators seen through two or more transformations. The multiplying factor from Fig. 14 is to be used when the major contribution to the short-circuit current is from local sources such as in-plant generators. The multipliers of Fig. 14 include the effects of ac decay from local generators; those of Fig. 15 include no ac-decay effects.

As shown in Figs. 14 and 15, intentionally delayed tripping which increases contact parting time reduces the multiplying factor and thus reduces the calculated interrupting duty. Note that multiplying factors below 1.0 are not recognized.

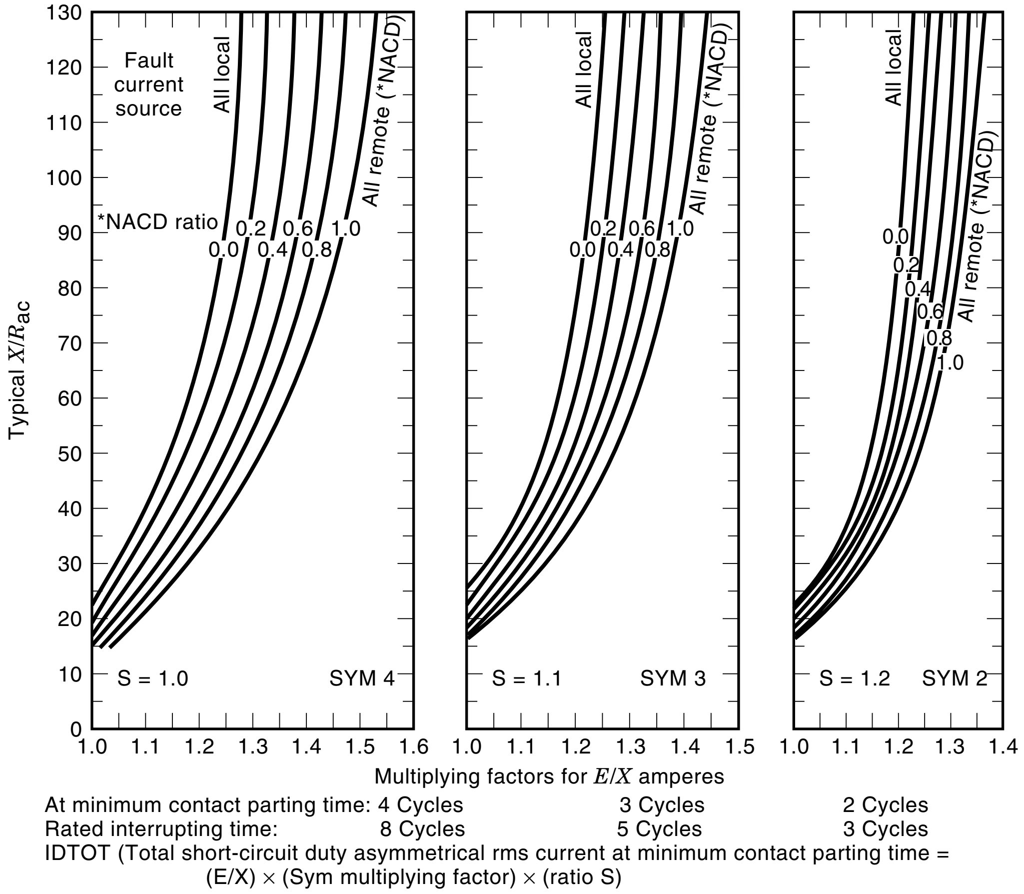

Figure 18. Multiplying factors (symmetrical current rating basis) for three-phase faults fed from both local and remote generators (10). *NACD = no ac decrement. Example: Utility generators separate from an industrial power system by two transformations are remote (NACD) sources. (© 1969 IEEE)

$$\text{NACD ratio} = \frac{\text{Remote source contributions}}{E/X\ \text{current}}$$

Momentary duties should always be checked for industrial power systems when motor loading is heavy since motors influence momentary duty more than interrupting duty. This *E*/*X* value is multiplied by 1.6 for comparison with the total current closing and latching capability of the symmetrical current-rated circuit breaker.

Total-Current-Rated Circuit-Breaker Short-Circuit Current Calculation Procedures. For application of total-current-rated circuit breakers including checking the applications of existing circuit breakers whose MVA ratings can be converted to a total current, the recommended procedure according to the proposed Standard C37.5 has the same basis as that for symmetrical-current-rated circuit breakers. The momentary and interrupting reactance network are identical. Usually it is necessary to find the fault point *X*/*R* ratio (even if less than 15) and then a multiplying factor using the curves of Figs. 16 and 17. The product of the interrupting reactance network *E*/*X* current and the multiplying factor is a total (asymmetrical) rms current to be compared with the total current interrupting capability of the circuit breaker. Only if the fault point $X/R \leq 15$ and the circuit-breaker-rated interrupting time is eight cycles, then the unmodified *E*/*X* current can be compared directly with the current interrupting capability of a total-current-rated circuit breaker. The momentary duty calculation according to Standard C37.5 is the same as the momentary duty calculation of Standard C37.010.

Multiplying Factor Interrupting Using the NACD Ratio

Finding the proper multiplying factor for a calculated *E*/*X* current depends on knowing the contact parting time for the Figcircuit breaker, the fault-point *X*/*R* ratio, and the electrical proximity of the major sources of short circuit current. The curves of Fig. 14 (for symmetrical-current-rated circuit breakers) and Fig. 16 (for total-current-rated circuit breakers) are used when major sources of short-circuit current are local such as at in plant generators. The multiplying factors from these curves account both for dc component decay and for an ac component decay that presumably covers only the generator contribution. The decay of motor ac short-circuit current contributions is covered by reactance multipliers.

The curves of Fig. 15 (for symmetrical current rated circuit breakers) and Fig. 17 (for total current rated circuit breakers)

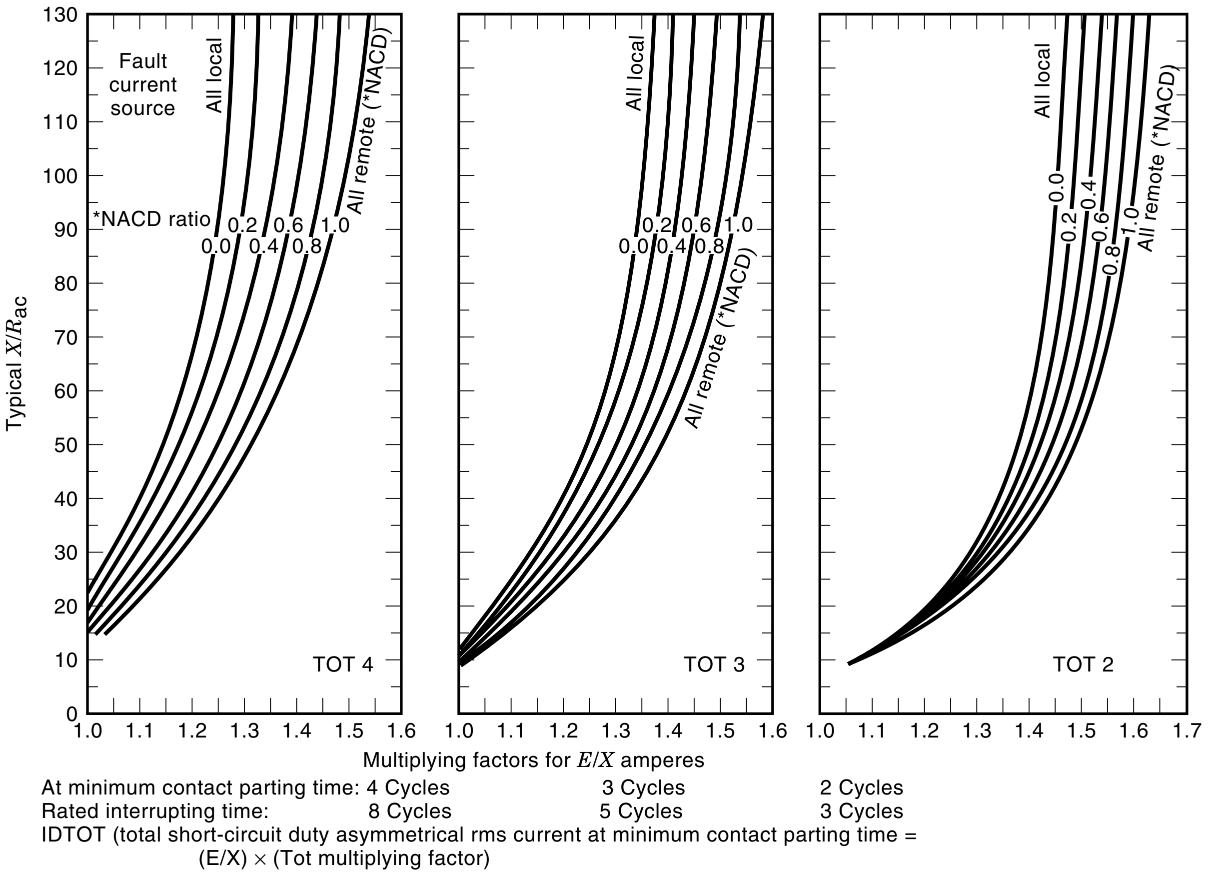

Figure 19. Multiplying factors (total current rating basis) for three-phase faults fed from both local and remote generators (10). *NACD = no ac decrement. Example: Utility generators separate from an industrial power system by two transformations are remote (NACD) sources. (© 1969 IEEE)

$$\text{NACD ratio} = \frac{\text{Remote source contributions}}{E/X\ \text{current}}$$

and Fig. 17 (for total current rated circuit breakers) are used for power systems where the major sources of short-circuit currents are remote. These multiplying factors account only for dc component decay because the ac component is assumed to remain constant. Remote sources are identified as NACD sources. Since the effect of only dc decay is included, these multiplying factors are larger.

Many industrial power systems have both local and remote sources, neither one predominant. Presumably the situation can be covered adequately by a multiplying factor part way between those obtained from the two separate curves above. The interpolation uses the curves of Figs. 18 and 19. It is based on the fraction of the interrupting network E/X current that is contributed by NACD (remote) sources. This fraction is identified by the NACD ratio:

$$\text{NACD ratio} = \frac{\text{Sum of NACD source currents}}{E/X\ \text{for interrupting network}}$$

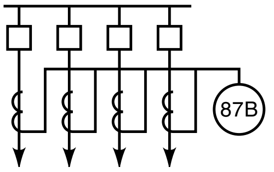

Figure 20. Single-bus differential protection (11). (© 1979 IEEE)

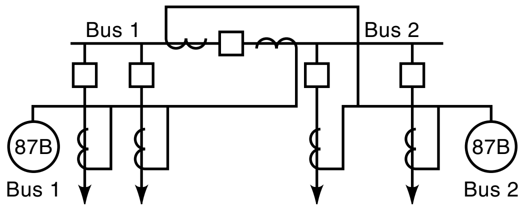

Figure 21. Multiple-bus differential protection (11). (© 1979 IEEE)

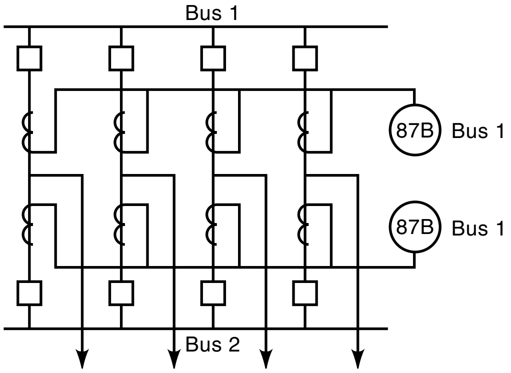

Figure 22. Double-bus-double-breaker differential protection (11). (© 1979 IEEE)

In Fig. 18 the curves for an NACD ratio equal to 0.0 are taken from the minimum contact parting time curves of Fig. 14 and for an NACD ratio equal to 1.0 from Fig. 15. In Fig. 19 the curves for an NACD ratio equal to 0.0 are taken from the minimum contact parting time curves of Fig. 16 and for an NACD ratio equal to 1.0 from Fig. 17. Between these limiting curves the interpolation at any X/R ratio is linear with the NACD ratio.

The curves of Figs. 18 and 19 have been marked with abbreviations SYM and TOT to indicate that the first is used when applying symmetrical-current-rated circuit breakers and that the second is used when applying total-current-rated circuit breakers. Accompanying each abbreviation is the contact parting time in cycles which applies for that particular curve.

SWITCHGEAR AND BUS PROTECTION

Switchgear, a critical element of a power distribution system, is normally used to tie many circuits—transmission line, generation, motors and load feeders—together to a bus or multiple buses for transferring electrical energy from one circuit to the other. A fault in the switchgear or bus should be isolated promptly to minimize equipment damages to limit process interruption and, furthermore, to maintain system stability. For these reasons, fast-acting protection is essential. Inadequate switchgear protection can result in catastrophic failures and present serious personnel hazards. Factors such as bus configuration, current transformer accuracy, and protection relaying sensitivity are all important elements in switchgear and bus protection.

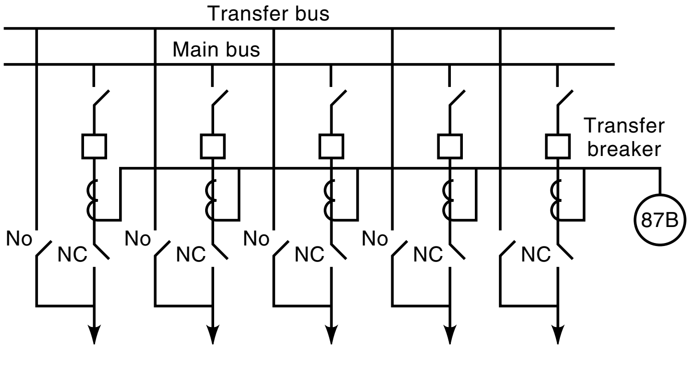

Figure 23. Main and transfer bus differential protection (11). (© 1979 IEEE)

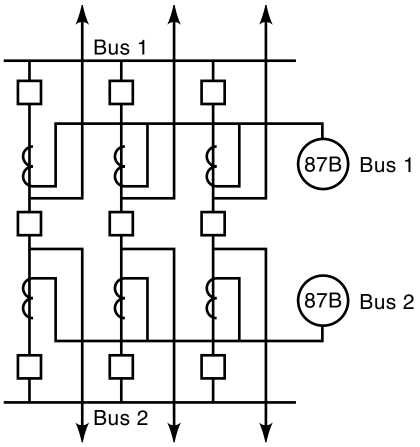

Figure 24. Breaker and one-half bus differential protection (11). (© 1979 IEEE)

Several methods of switchgear and bus protection are available. Probably the most sensitive method employs the bus differential principle, in which the phasor summation of all the measured current entering and leaving the bus must be zero unless there is a fault within the protected zone. For a fault not in the protected zone the instantaneous direction of at least one current is opposite to the others.

Various Bus Differential Protections Based on Bus Arrangements

Single-Bus Arrangement. This arrangement as shown in Fig. 20, consists of a single main bus, with a relay input source for each connected line, generator, or transformer.

Multiple Bus Sections with Bus Ties. This arrangement, as shown in Fig. 21, consists of single buses connected by means of bus tie breakers. Differential relay zones can be established with each overlapping the bus tie breakers. Only the faulted bus section is removed for a bus fault.

Double-Bus–Double-Breaker Configuration. The double-bus–double-breaker configuration is shown in Fig. 22. Each bus and its breakers are protected by a separate differential relay system. A fault on either bus clears that bus only; the other bus and all circuits remain in service.

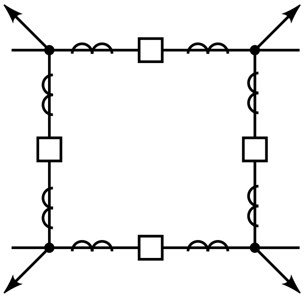

Figure 25. Ring bus arrangement (11). (© 1979 IEEE)

Main and Transfer Bus Arrangement. The main and transfer bus arrangement, as shown in Fig. 23, is a modification of the single-bus scheme, with the addition of a transfer breaker, transfer bus, and disconnects. The transfer bus may be rated less than the main bus. The purpose of the transfer system is to provide a means for bypassing a breaker during maintenance without circuit interruption.

The transfer breaker is included in the main bus differential scheme. The transfer bus becomes a part of the incoming line with the bypassed breaker and is not included in the bus differential zone.

Breaker and One-Half Bus Arrangements. The breaker and one-half bus arrangement, as shown in Fig. 24, is similar in operating advantages and bus relaying to the double-bus–double-breaker arrangement. Its advantage is economic, in that three breakers instead of four are required for each two circuits. Bus relaying is required for each main bus section only.

Directional-type bus protection systems are not recommended for use on the breaker and one-half bus arrangement since the direction of flow of fault current in component parts of the extremely low impedance bus network may not be predictable during bus faults.

Ring Bus. The ring bus, as shown in Fig. 25, does not require bus differential protection. The bus section between each pair of circuit breakers is relayed as a part of the connected circuit.

Single Bus with Connected Load (Partial Differential Protection). The single bus with a transformer connected load, as shown in Fig. 26, may be protected by instantaneous relays or units of overcurrent relays which are set above low-side fault magnitude to provide proper coordination. The time overcurrent elements are set to sense low-side faults, to provide transformer protection, and to provide backup protection for low-side faults. If the primary of the transformer is fused, instantaneous protection cannot be coordinated.

Single Bus with Connected Load (Combined Differential Zones). The bus arrangement with connected load, as shown in Fig. 27, illustrates the application of the combined differential zones protection.

The differential zone extends from the current transformer on the bus breaker(s) to the current transformer on the other side of the transformer. Both the bus and transformer are included in the differential zone.

Generally, transformer differential relays, rather than bus differential relays, are used in this application to accommodate transformation ratio and other problems associated with transformer differential protection. Hence, the bus is included in the transformer zone.

Other Considerations Associated with Bus Protection

Current Transformer Location. Bushing current transformers are not used in some extra-high-voltage breakers. Each phase has a separate device containing a multicore multiratio current transformer. These current transformers are located on one side of the breaker.

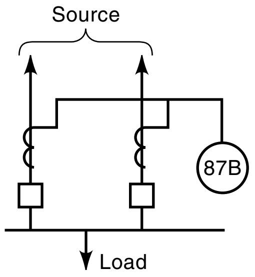

Figure 26. Partial differential protection (11). (© 1979 IEEE)

Hence, the breaker may not be within the bus protection zone. Additional relaying is usually provided in this case for breaker failure and current transformer failure.

Wiring and Grounding. The coupling of extraneous currents or voltages into bus differential circuits should be adequately considered. The principles of single-point grounding of each metallically connected part of the current transformer system is particularly important in minimizing these effects.

Location of Bus on the System. The location of the bus on the system has a bearing on the selection of the type of bus protection scheme. Where system stability is a consideration, as at most generating station buses and bulk power substations, high-speed bus protection schemes must be used. At other locations, high-speed schemes minimize fault damage and duration of outage to loads tapped to the connecting lines, but slower speed schemes may be tolerable.

Bus Construction. Buses are built using several types of construction (such as strain bus, rigid bus, or isolated or segregated phase bus), or they are a part of metal-clad switchgear. A bus may be located indoors or outdoors or partially in both. Enclosed buses may be gas-insulated. Factors related to bus construction, such as electrical clearances and insulation levels, shielding against lightning, environmental conditions, and so on, are of concern because of their effect on system reliability and the protection required. However, few aspects of bus construction bear directly on the type of bus protection applied. An exception is the fault-bus scheme.

Problems Associated with Switching and Bypassing. Most special application problems involved in bus protection relaying

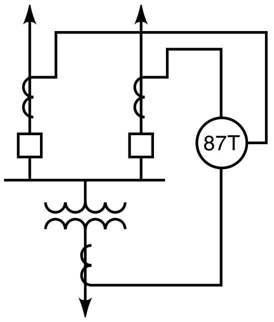

Figure 27. Combined differential zones protection (11). (© 1979 IEEE)

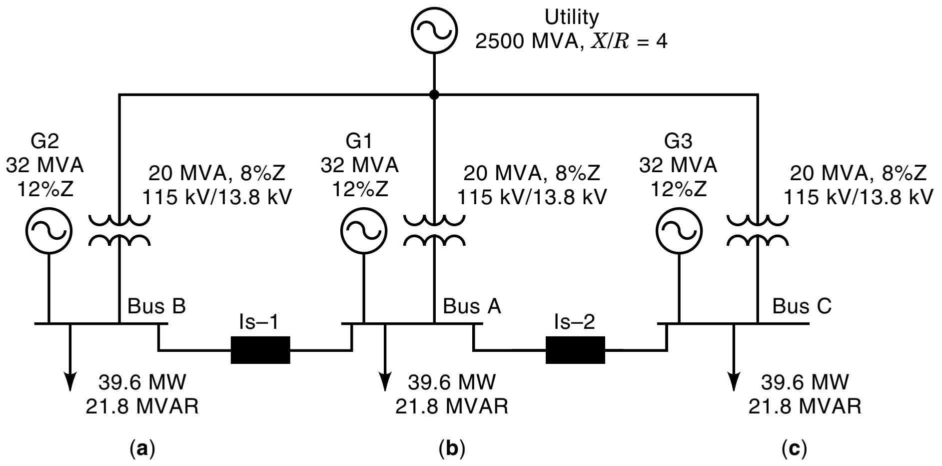

Figure 28. A typical distribution system applying current limiters. (a) System 2. (b) System 1. (c) System 3 (12). (© 1998 IEEE)

are the result of the adaptability of the bus design to the required line switching and bypass procedures for the breakers connected to the bus. Usually, these problems occur at older stations that have been enlarged or at new stations based on lower cost design. These schemes may introduce limitations and undesirable features.

Lockout Relays. Bus protection relays usually energize a multicontact auxilliary relay which has individual tripping contacts for each breaker connected to the bus. A common practice is to use a lockout type tripping relay to prevent reenergizing the bus until an inspection is made. It may also be desirable to interrupt the breaker closing circuits by separate lockout relay contacts connected in the closing circuit of each breaker to prevent breaker closing, even though the breaker would be immediately tripped by the unrest lockout relay tripping contacts.

One type of lockout tripping relay is spring actuated, with a latch released by a tripping solenoid. In one version of this relay a manually operated handle is used to reset the relay. In another version, a motor performs this reset function so that the relay can be reset remotely. A second type of lockout relay uses an electrical seal-in coil to lock itself in the operated position. The seal-in coil is energized by one of the tripping contacts on the relay. A third type of lockout relay has a mechanical latch that is reset electricity.

Fault-Current Limiter Application

The power distribution system of a modern industrial plant is expanding continuously. At some point, the available short-circuit current may exceed the short-circuit ratings of the switchgear. To alleviate the cost of switchgear replacement, electronically triggered fault-current limiters (hereafter referred to as current limiters) have been used to limit the available short-circuit current, so that the underrated switchgear can be operated safely. A description of the presently available current limiters has been presented by Chao. It basically consists of two parallel elements, namely, the main conductor and the current-limiting fuse. The main conductor provides normal load current up to 3000 A, and the current-limiting fuse "chops" the fault current within a quarter to half-cycle when a fault occurs.

However, to ensure a safe and proper usage of this device, two major operational parameters—namely, trigger level and *di*/*dt*—need to set properly.

Trigger Level. The trigger level is a value defined as the maximum short-circuit contribution permitted from a major

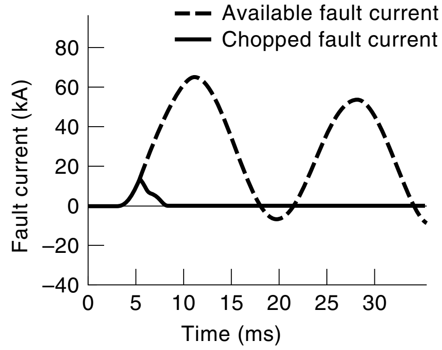

Figure 29. Fault current from Bus B to Bus A (12). (© 1998 IEEE)

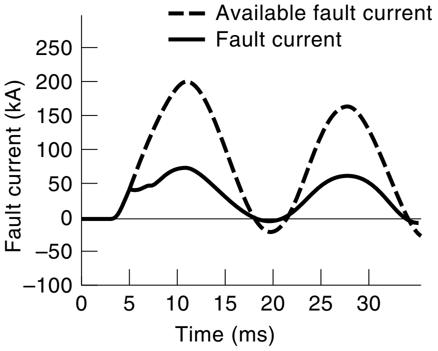

Figure 30. Fault current on faulted breaker on Bus A (12). (© 1998 IEEE)

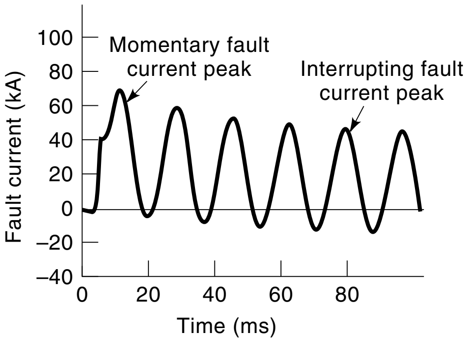

Figure 31. Faulted breaker current on Bus A with both momentary and interrupting currents (12). (© 1998 IEEE)

power source, so that the total overall fault current superimposed from all short-circuit contribution will not exceed the momentary and interrupting ratings of the switchgear.

The trigger level in kiloampere peak is a value preprogrammed in the current limiter. When the instantaneous fault current reaches this value, an automatic fault transfer process will occur in the current limiter. The entire process will take 0.4 ms to 0.72 ms to complete, depending on the manufacturer. The fault peak value may reach more than twice that of the trigger level before it is reduced, due to the current-limiting effect of the fuses. The maximum fault peak value may also vary depending on the initial fault voltage angle.

The selection of the trigging value is on a “trial-and-error” basis. However, this value should not be below 10 kA, to avoid a nuisance trip.

di/dt. The *di/dt* in kiloamperes per millisecond is a value defined as the minimum fault-current change rate limit to prevent nuisance current-limiter operation. It is also used in combination with the triggering value to determine when the fault transfer process will occur. The general formula of short-circuit current is described by

$$i_{\mathrm{SC}} = I_{\mathrm{M}} \sin(wt + \phi - \theta) - I_{\mathrm{M}} \sin(\phi - \theta) e^{(-w/X/R)t} \tag{1}$$

The following is a mechanism to determine the current change rate limit *di/dt*. According to Eq. (1), the *di/dt* in peak can be approximated as

$$\frac{di_{\mathrm{peak}}}{dt} \approx W I_{\mathrm{M}} \tag{2}$$

where *w* is the system angular frequency in radians per second. The approximation is based on the assumption that the derivative of the dc offset is considered to be zero. According to Eq. (2), the *di/dt* can be determined by the system angular frequency and symmetrical fault current, which is nothing but the system voltage divided by the equivalent short-circuit impedance.

Furthermore, *di/dt* may be correlated to the trigger level for a specific system. Note that the symmetrical short-circuit current is related to the asymmetrical short-circuit current, as shown in Eq. (1). The peak of the asymmetrical current is a factor of the symmetrical current, depending on the *X/R* ratio. The factor normally ranges from 1.70 to 1.96, in which the *X/R* ranges from 9.0 to 40.0. Conservatively, the factor of 1.70 is applied, which covers most *X/R* ratios in industry. Thus, the *di/dt* can be derived from Eq. (2) as

$$\begin{aligned} \frac{di_{\mathrm{peak}}}{dt} &= \frac{w}{1.7} \times \text{Trigger level} \\ &= 221.76 \times \text{Trigger level} \end{aligned} \tag{3}$$

based on 60 Hz frequency.

Application Example. In Fig. 28, three buses-A, B, and C-are connected through two current limiters, Is-1 and Is-2, respectively. For simplicity, three systems are assumed to have the same capacity.

Originally, system 1 is 750 MVA and the switchgear has a 58 kA (ms) momentary rating and a 30.4 kA (rms) interrupting rating. Prior to the tie connection, the downstream fault on system 1 has a short-circuit current of 41.0 and 28.9 kA (rms) for momentary and interrupting currents, respectively.

When system 1 is connected to systems 2 and 3, the current limiters Is-1 and Is-2 will limit the fault currents to the level in which the total fault current does not exceed the switchgear ratings. Initially 13 kA (peak) cutoff current and 2.9 kA/ms of *di/dt* were chosen.

A set of computer simulation results are provided in Fig. 29 and 31. Figure 29 shows the available fault current and chopped fault current on Is-1, if the fault occurs at the downstream Bus A breaker. With the current limiter, the fault current is chopped at 13 kA and gradually decays to zero. The characteristic is similar to a low-voltage fuse, in which the rising and decaying correspond to melting time and arcing time. However, in current limiters, arcing happens twice, with one from the main conductor and the other from the fuse. Fuse arcing follows the main contacts arcing.

Table 13. Fault Current on Bus A (12)

	Fault Current				
	Momentary (1/2 cycle)		Interrupting (5 cycles)		
Stations Out of Service	Ratings (kA)	Duties (kA)	Ratings (kA)	Duties (kA)	Current Limiters Fired
None	58	41.0	30.4	28.9	ls-1 and ls-2
G2	58	41.9	30.4	25.3	ls-2
Xfm2	58	40.9	30.4	24.9	ls-1 and ls-2
G2 and G3	58	39.9	30.4	31.3	None
Xfm2 and Xfm3	58	40.3	30.4	24.7	ls-1 and ls-2

Figure 30 shows the faulted breaker current waveform in which the current contributed from systems 2 and 3 are chopped by current limiters Is-1 and Is-2, respectively. In order to examine the interrupting current, the fault current is expanded beyond five cycles to see the interrupting current, as shown in Fig. 31. According to the simulation, the momentary and interrupting duties are 69.7 kA and 49.1 kA in peak. They are equivalent to 41.0 kA and 28.9 kA in rms, respectively, which are based on a factor of 1.7 between peak and rms value. Both duties are within the switchgear ratings, which are 58 kA and 30.4 kA in rms.

Table 13 represents various fault duties under various operating conditions, in which the current limiter settings are kept the same. According to Table 13 the fault duties are below the ratings, except the case that has both generators G2 and G3 out of service. In this case, the interrupting duty exceeds the ratings, even though the momentary duty is adequate. Therefore, the current-limiter settings have to be lower, so that the fault current is chopped at a lower value. In this case, the 12 kA cutoff current, instead of 13 kA, will force one of the currents limiters to fire. As a result, the momentary and interrupting currents will be reduced to 37.2 kA and 26.4 kA, respectively, and they are all within the switchgear ratings.

Capacitance Effect on Current-Limiter Operations. The current limiter is operated according to the preprogrammed instantaneous value and current change rate. There are many situations in which the current limiters may be operated in nuisance, due to the existence of system capacitance. Nuisance tripping is essentially caused by high-frequency transients, such as switching transients. Lightning strikes on exposed (bare) overhead lines can also cause nuisance tripping. System capacitance exists in two major forms. One is the capacitor banks for power factor correction purposes or filtering. The other is the stray capacitance, which exists almost everywhere. One of the significant stray capacitances is cable capacitance. These system capacitances have a significant effect on the operation of the current limiters, due to the excessive current magnitude and rate of current change during transients caused by capacitive switchgear.

In addition to the capacitor bank, the same phenomenon may occur with stray capacitance. It is not uncommon for the current limiter to be fired in a system which does not have a capacitor bank, but contains hidden capacitance, such as overhead line capacitance.

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