7. SELECTION

In selecting MCCBs for a particular application, in addition to purely electrical aspects of load and distribution conductor systems, physical factors such as panelboard configuration, installation environment, ambient-temperature variations, vibration, etc. must also be considered.

MCCBs are rated for an ambient of 40°C, and where panelboard internal temperatures may exceed this, the MCCBs installed should be derated in accordance with Table 7.1.

1. Actual load currents may exceed the nominal-values.
2. Load currents may increase with time, due to deterioration of load devices (i.e., friction in motors).
3. Source voltage and frequency may vary.

Table 7.1 MCCB Deratings Due to Installation Factors

Panelboard max. internal temp. (°C)	Load allowable, due to panelboard temp. (%)
50	90
55	80
60	70

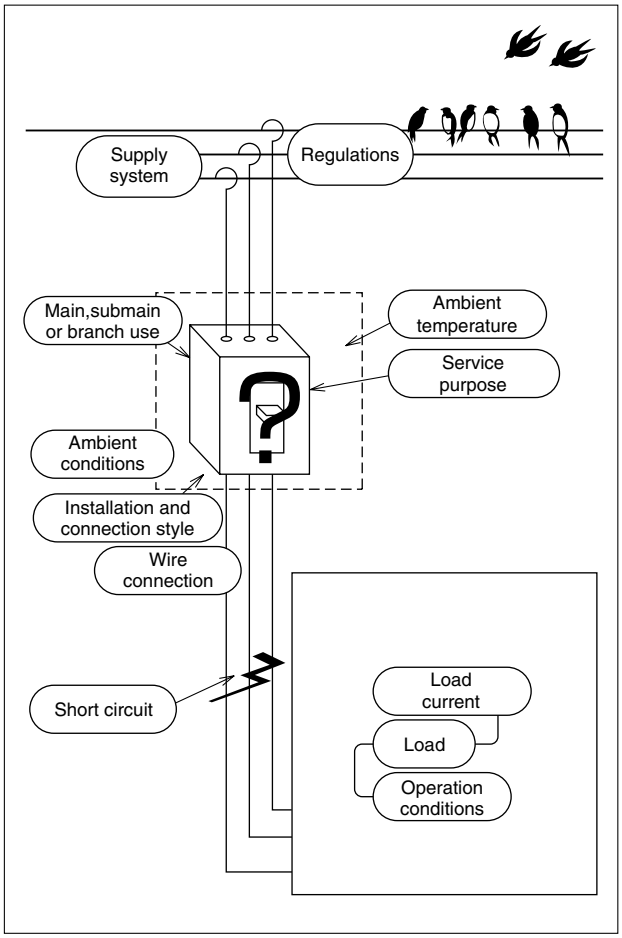


Fig. 7.1 MCCB Selection Consideration

7.1 Motor Branch Circuits

The following discussion assumes single motors and cold-start operation.

7.1.1 General Considerations

The starting current (I_{MS}) and time (T_{MS}) for the motor, and its full-load current, dictate the rated current, long-delay trip and instantaneous-trip curves for the MCCB as shown in Fig. 7.2. A safety-margin of up to 50% should be considered for the starting time, to allow for voltage variations and increase in load friction.

The instantaneous-trip curve should be at least 1.4 x normal starting current to allow for the effect of the DC component attendant to the low power factor (about 0.3) of the starting current. For Y-delta starting the unphased-switching allowance increases the 1.4 margin to 1.9. For running restarting the unphased-switching allowance increases the factor to 2.4.

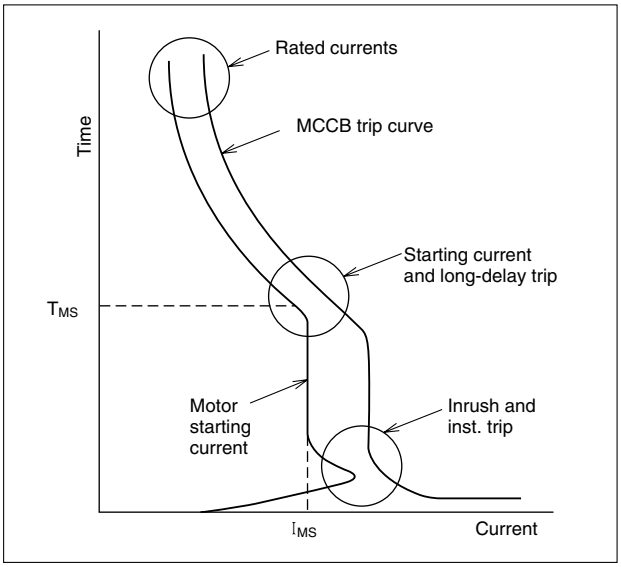


Fig. 7.2 MCCB and Motor Starting

7.1.2 Motor Breaker

Where starting times are relatively short and currents are small, the Mitsubishi M Line motor breakers can be used without the need for a motor starter.

7.2 For Lighting and Heating Branch Circuits

In such circuits, switching-surge magnitudes and times are normally not sufficient to cause spurious tripping problems; however, in some cases, such as mercury-arc lamps or other large starting-current equipment, the methods presented in §7.1 above should be considered.

In general, branch MCCBs should be selected so that the total of ratings of the connected loads is not more than 80% of the MCCB rating.

7.3 For Main Circuits

7.3.1 For Motor Loads

The method of "synthesized motors" is recommended – that is, the branch-circuit loads to be connected are divided into groups of motors to be started simultaneously (assumed), and then each group is regarded as a single motor having a full-load current of the total of the individual motors in the group. The groups are regarded as being sequentially started.

The rating of the branch MCCB for the largest synthesized motor is designated I_B max., those of the subsequent synthesized motors as I_1, I_2, ...I_{n-1}. The rating of the main MCCB becomes:

$$I_{MAIN} = I_B \text{ max} + (I_1 + I_2 + ... I_{n-1}) \times D$$

where D is the demand factor (assumed as 1 if indeterminate).

7.3.2 For Lighting and Heating, and Mixed Loads

For lighting and heating loads the rating of the main MCCB is given as the total of the branch MCCB ratings times the demand factor. For cases where both motor-load branches and lighting and heating branches are served by a common main MCCB, the summation procedures are handled separately, as described in the foregoing, then grand-totalized to give the main MCCB rating.

7.4 For Welding Circuits

7.4.1 Spot Welders

A spot welder is characterized by a short, heavy intermittent load, switched on the transformer primary side. The following points must be considered in MCCB selection:

1. The intermittent load must be calculated in terms of an equivalent continuous current.
2. The excitation transient surge due to the breaker being on the transformer primary side must be allowed for.

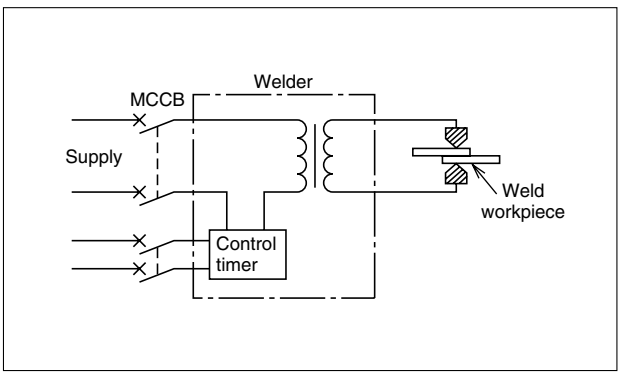


Fig. 7.3 Spot-Welder Circuit

The temperature rise of the MCCB and wiring depends on the thermal-equivalent continuous current. To convert the welder intermittent current into a thermal-equivalent continuous value (I_e), consider the current waveform (Fig. 7.4); load resistance (R) gives power dissipation:

$$W = I_1^2 Rt_1$$

and average heat produced:

$$\frac{W}{t_1 + t_2} = \frac{I_1^2 Rt_1}{t_1 + t_2} = I_1^2 R\beta = R(I_1\sqrt{\beta})^2$$

where β is the duty factor, defined as

$$\frac{\text{total conduction time}}{\text{total time}}$$

This is equivalent to heating by a continuous current of $I_1\sqrt{\beta}$.

In the example of Fig. 7.4:

$$I_e = I_1\sqrt{\beta} = 1200 \times 0.0625 = 300 \text{ (A)}$$

i.e., a continuous current of 300A will produce the average temperature. In practice, however, the instantaneous temperature will fluctuate as shown in Fig. 7.5 and the maximum value (T_m) will be greater than the average (T_e) that would be produced by a continuous current of 300A. The operation of an MCCB thermal element depends on the maximum rather than the average temperature, so it must be selected not to trip at T_m; in other words, it is necessary to ensure that its hot-start trip delay is at least as great as the interval of current flow in the circuit. The rated current of a "mag-only" MCCB (which does not incorporate a thermal trip function) can be selected based on the thermal equivalent current of the load, allowing a margin of approximately 15% to the calculated value to accommodate supply-voltage fluctuations, equipment tolerance, etc. Thus:

$$I_{MCCB} = I_e \times 1.15 = 300 \times 1.15 = 345 \text{ (A)}$$

The MCCB selected becomes the nearest standard value above 345A.

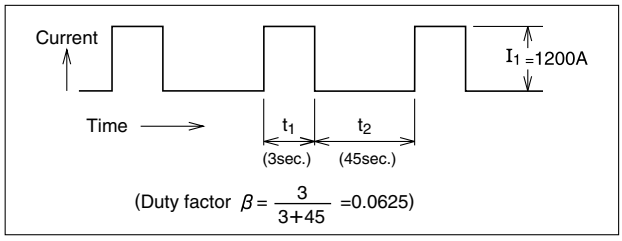


Fig. 7.4 Welder Intermittent Current

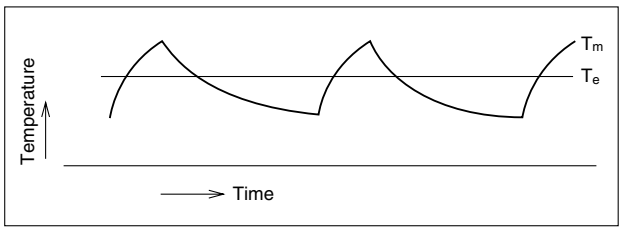


Fig. 7.5 Temperature Due to Intermittent Current

For practical considerations, rather than basing selection on welding conditions, the MCCB should be selected to accommodate the maximum possible duty, based on the capacity and specifications of the welder.

If the welder rated capacity, voltage and duty factor in Fig. 7.3 are 85kVA, 200V and 50% respectively, the thermal-equivalent continuous current (I_e) be-

comes:

$$I_e = \frac{\text{rated capacity}}{\text{rated voltage}} \times \sqrt{\text{duty factor}}$$

$$= \frac{85 \times 10^3}{200} \times \sqrt{0.5} = 300\text{A}$$

Hence, the MCCB rated current becomes:

$$I_{MCCB} = I_e \times 1.15 = 300 \times 1.15 = 345\text{A}$$

(i.e., the next higher standard value).

The relationship between the duty factor, which does not exceed the working limitations, and the maximum permissible input I_β at the above duty factor is:

$$I_\beta = \frac{I_e}{\sqrt{\beta}} = \frac{300}{\sqrt{\beta}}$$

If the total period is taken as 60 seconds and the duty factor is converted into the actual period during which current flows, the above relationship can be expressed graphically as in Fig. 7.6. Thus, although the thermal equivalent current is 300A, the maximum permissible input current for a duty factor of 50% (30 seconds current flow) is 425A. For a duty factor of 6.25% (3.75 sec current flow) it is 1200A. Even if the secondary circuit of the welder were short circuited, however, the resultant primary current would only increase by about 30% over the standard maximum welding current. If this is 400kVA, the maximum primary current $I_{\beta max}$ is:

$$I_{\beta max} = \frac{\text{standard maximum input}}{\text{primary voltage}} \times 1.3$$

$$= \frac{400 \times 10^3}{200} \times 1.3 = 2600\text{A}$$

Hence the maximum input current I_β should be restricted to 2600A.

The 75% hot-start characteristic of the 350A Type NF400-SW breaker is shown by the broken line in Fig. 7.6, and the temperature-rise characteristics up to the upper limit of the welder, by the solid line. To ensure protection of the welder from burnout, the delay-trip characteristic is selected at higher than the solid line; however, to establish MCCB protection criteria, it is necessary to look at each welder individually.

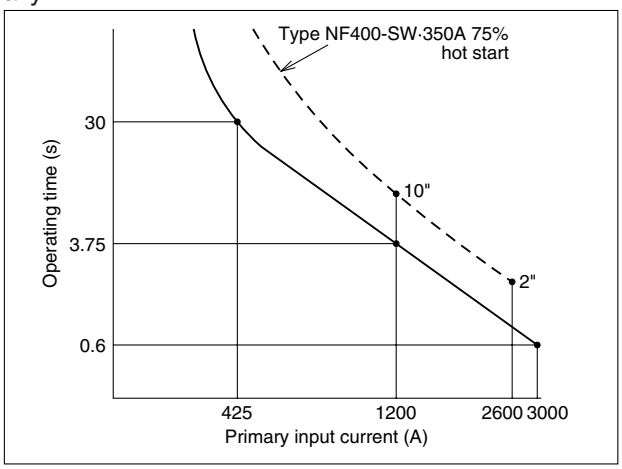


Fig. 7.6 Welder Temperature Rise and MCCB Trip Curve

7.4.2 MCCB Instantaneous Trip and Transformer Excitation Surge

When a welding-transformer primary circuit is closed, depending upon the phase angle at the instant of closure, a transient surge current will flow, due to the super-imposed DC component and the saturation of the transformer core.

In order to prevent spurious tripping of protective devices resulting from such surges, and also to maintain constant welding conditions, almost all welders currently available are provided with a synchronized switch-on function, with or without wave-peak control.

With synchronized switch-on, the measured ratio between the RMS value of the primary current under normal conditions and the maximum peak transient current ranges from $\sqrt{2} \sim 2$.

For nonsynchronized soft-starting-type welders the measured ratio is a maximum of 4.

Maximum instantaneous transient surge excitation currents for various starting methods are as follows:

Synchronized switch-on welders with wave peak control:

$$I_{max} = \sqrt{2} \times I_{\beta max}$$

Synchronized switch-on welders without wave peak control:

$$I_{max} = 2 \times I_{\beta max}$$

Nonsynchronized switch-on welders with soft start:

$$I_{max} = 4 \times I_{\beta max}$$

Nonsynchronized switch-on welders without soft start:

$$I_{max} = 20 \times I_{\beta max}$$

If synchronized switch-on is employed, the transient surge excitation currents are relatively consistent, so that the relationship $I_{max} = 2\ I_{\beta max}$ is sufficient.

For a synchronized switch-on type welder of maximum primary input ($I_{\beta max}$) = 2600A

$$I_{max} = 2 \times I_{\beta max} = 2 \times 2600 = 5200\text{A}$$

Since MCCB instantaneous trip currents are specified in terms of RMS value, I_{inst} is as follows:

$$I_{inst} = \frac{I_{max}}{\sqrt{2}} = \frac{5200}{\sqrt{2}} = 3680\text{A}$$

The MCCB should be selected so that I_{inst} is smaller than the lower tolerance limit, of the instantaneous trip current.

7.4.3 Arc Welders

An arc welder is an intermittent load specified. The MCCB rating can by selected by converting the load current into thermal-equivalent continuous current. If this is taken as the rated current, however, the current duration per cycle will become relatively long, with the attendant danger of thermal tripping of the MCCB. In the total period of 10 minutes, if the duty factor is 50%, a 141% overload exists for 5 minutes; if the duty factor is 40%, a 158% overload exists for 4 minutes; and if the duty factor is 20%, a 224% overload exists

for 2 minutes. Thus:

$$I_{MCCB} \geq \frac{1.2 \times P \times 10^3}{E}$$

where 1.2: Allowance for random variations in arc-welder current, and supply-voltage fluctuations

P: Welder rated capacity (kVA)

E: Supply voltage (V)

The switching transient in the arc welder is measured as 8~9 times the primary current. Consequently, using 1.2 allowance, it is necessary to select instantaneous-trip characteristics such that the MCCB does not trip with a current of 11 times the primary current.

7.5 MCCBs for Transformer-Primary Use

Transformer excitation surge current may possibly exceed 10 times rated current, with a danger of nuisance tripping of the MCCB. The excitation surge current will vary depending upon the supply phase angle at the time of switching, and also on the level of core residual magnetism. The maximum is as shown for switching-point P in Fig. 7.7. During the half cycle following switch-on the core flux will reach the sum of the residual flux ϕ_r, plus the switching-surge flux $2\phi_m$. The total, $2\phi_m + \phi_r$, represents an excitation current in excess of the saturation value. The decay-time constant of this tends to be larger for larger transformer capacities. Table 7.2 shows typical values of excitation surge current, but as these do not take circuit impedance into account, the actual values will be larger. If both the primary leakage impedance and circuit impedance are known, the surge current may be derived by considering the transformer as an air core reactor; otherwise the values in Table 7.2 should be used. This table gives maximum values, however, that are based on the application of rated voltages to rated taps; it should be noted that supply overvoltage will result in even larger surges.

Since it is the instantaneous-trip function of the MCCB that responds to the transient current, thermal-magnetic MCCBs, which can more easily be manufactured to handle high instantaneous-trip currents, are advantageous over completely electromagnetic types, where the instantaneous-trip current is a relatively small multiple of the rated current.

Table 7.2 Transformer Excitation Surge Currents

Capacity (kVA)	1ph transformer		3ph transformer	
	First 1/2-cycle peak (multiple)[1]	Decay time constant (Hz)	First 1/2-cycle peak (multiple)[1]	Decay time constant (Hz)
5	37	4	26	4
10	37	4	26	4
15	35	5	26	4
20	35	5	26	4
30	34	6	26	4
50	34	6	23	5
75	29	6	18	5
100	28	6	17	5
150	24	8	14	6
200	22	8	13	6
300	18	9	13	8
500	17	12	11	9

Note: 1 "Multiple" means the first 1/2-cycle peak as a multiple of the rated-current peak.

Table 7.3 Transformer Capacities and Primary-Side MCCBs

Tran. kVA	MCCB Type (rated current (A))			
	1 phase 230V	1 phase 400V	3 phase 230V	3 phase 400V
5	NF125-SW (80)	NF125-SW (40)	NF63-HW (50)	NF32-SW (32)
7.5	NF125-SW (100)	NF125-SW (63)	NF125-SW (40)	NF63-HW (40)
10	NF250-SW (150)	NF125-SW (80)	NF125-SW (63)	NF63-HW (50)
15	NF250-SW (200)	NF250-SW (125)	NF125-SW (100)	NF125-SW (50)
20	NF400-SW (300)	NF250-SW (150)	NF250-SW (125)	NF125-SW (63)
30	NF400-SW (400)	NF250-SW (225)	NF250-SW (175)	NF125-SW (100)
50	NF630-SEW (600)	NF400-SW (400)	NF400-SW (250)	NF250-SW (150)
75	NF1000-SEW (500)	NF630-SW (500)	NF400-SW (300)	NF250-SW (175)
100	NF1000-SEW (500)	NF630-SW (630)	NF400-SW (400)	NF250-SW (225)
150	NF1000-SEW (800)	NF1000-SEW (500)	NF630-SW (500)	NF400-SW (300)
200	NFE2000-S (1200)	NF1000-SEW (600)	NF630-SW (600)	NF400-SW (350)
300	NFE2000-S (1500)	NF1000-SEW (900)	NF1000-SEW (900)	NF630-SW (600)
500	—	NFE2000-S (1400)	NF1600-SEW (1400)	NF1000-SEW (900)

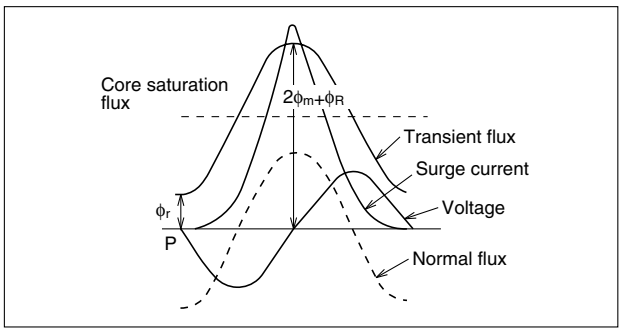


Fig. 7.7 Excitation Surge Effects

In MC CB selection for 400V, 50kVA transformer-primary used, rated RMS current is:

$$I = \frac{\text{Capacity (kVA) x } 10^3}{\sqrt{3} \text{ x Voltage (V)}} = \frac{50 \text{ x } 10^3}{\sqrt{3} \text{ x } 400} = 72.2\text{A}$$

From Table 7.2, the peak value of the excitation surge current $I\phi$ is 23 times that of the rated current, hence:

$$I\phi = 23 \text{ x } \sqrt{2}\ I = 23 \text{ x } \sqrt{2} \text{ x } 72.2\text{A} = 2348\text{A}$$

Thus the MCCB selected should have instantaneous trip current of no less than 2348A. The Type NF250-SW 150A MCCB, with:

$$I_{inst} = \sqrt{2} \text{ x } 150 \text{ x } 11.2 = 2376\text{A}$$

satisfies the above condition. Thus the 3-pole version of this type is suitable for this application.

Examples of MCCBs selected in this way are shown in Table 7.3; it is necessary to confirm that the short-circuit capacities of the breakers given are adequate for the possible primary-side short-circuit current in each case.

7.6 MCCBs for Use in Capacitor (PF Correction) Circuits

The major surge tendency results from circuit opening due to the leading current. If the capacitor circuit of Fig. 7.8 is opened at time t_1 in Fig. 7.8, arc extinction will occur at time t_2, the zero-point of the leading current (i). Subsequently the supply-side voltage (V_t) will vary normally, but the load-side voltage (V_c) will be maintained at the capacitor charge value. The potential difference (V_c-V_t) will appear across the MCCB contacts and at time t_3, approximately 1/2-cycle after t_2, will become about twice the peak value of the supply voltage (E_m). If the MCCB contacts are not sufficiently open, an arc will reappear across the gap, resulting in an oscillatory capacitor discharge (at a frequency determined by the circuit reactance, including the capacitor) to an initial peak-to-peak amplitude of $4E_m$. When the arc extinguishes, V_c will once again be maintained at a potential of $-E_m$ and the potential difference across the MCCB contacts will increase again. This cycle will repeat until the gap between the contacts becomes too great, and the interruption will be completed.

Since Mitsubishi MCCBs exhibit extremely rapid contact separation, repetitive arcing is virtually non-existent; however, some MCCBs do not make and break so rapidly, and in such cases, if the load capacitance is large enough, they will not discharge quickly, and if the arc extinguishes near the peak of the reverse-going oscillation voltage, the capacitor voltage will be maintained in the region of $-3E_m$ by the first restriking of the arc; at the second restrike it will become $5E_m$, on the third $-7E_m$, etc., ultimately leading to breakdown of the capacitor. Thus, rapid switching is essential in leading power-factor circuits.

In selecting an MCCB, first consider the surge current. If the supply voltage is V volts, the capacitor C farads, the frequency f Hertz and the current I amp, the kVA rating (P) becomes:

For a three-phase system:

$$1000\ P = \sqrt{3}\ VI = 2\pi fCV^2$$

For a single-phase system:

$$1000\ P = VI = 2\pi fCV^2$$

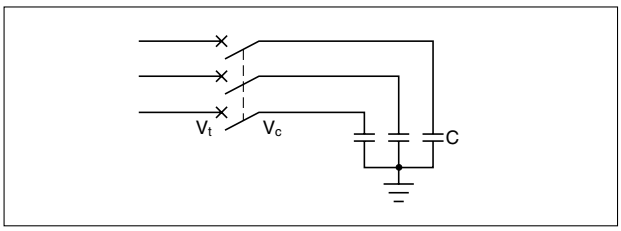


Fig. 7.8 Capacitor Circuit

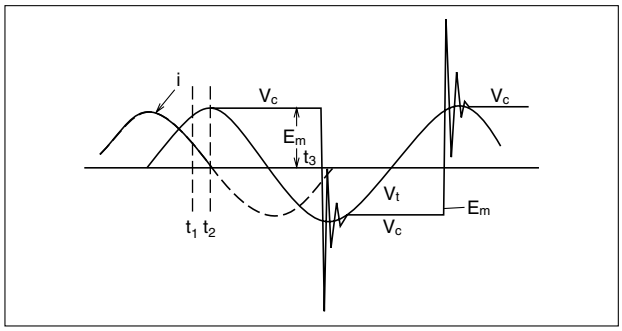


Fig. 7.9 Circuit-Opening Conditions

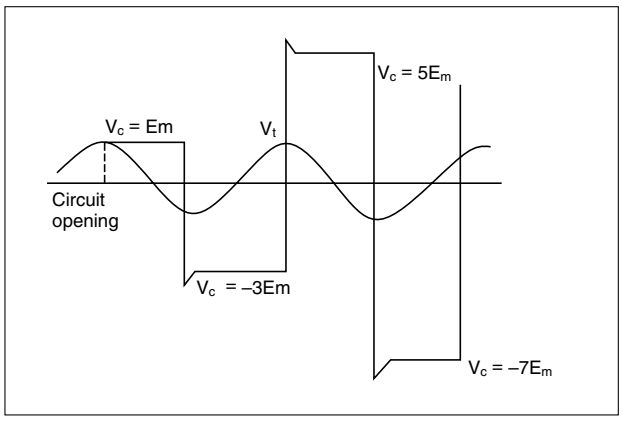


Fig. 7.10 Accumulative Capacitor Charge

When the switch (Fig. 7.11) is closed, a charge (q=CV) must be instantaneously supplied to equal the

instantaneous supply voltage (V), according to the phase angle at the instant of circuit closure. This charge results in a large surge current. If the circuit is closed at the peak (E_m) of the supply voltage (V), the surge current (i), according to transient phenomena theory, is:

$$i = \frac{2\,E_m}{\sqrt{\frac{4L}{C} - R^2}}\,\varepsilon^{-\frac{R}{2L}t}\,\sin\frac{\sqrt{\frac{4L}{C} - R^2}}{2L}\,t$$

From Fig. 7.12, the maximum value (i_m) is:

$$i_m = \frac{E_m}{\sqrt{\frac{L}{C}}}\,\varepsilon^{-\frac{R}{\sqrt{\frac{4L}{C} - R^2}}\arctan\frac{\sqrt{\frac{4L}{C} - R^2}}{R}}$$

and appears at time t = τ_0 where:

$$\tau_0 = \frac{2L}{\sqrt{\frac{4L}{C} - R^2}}\,\arctan\frac{\sqrt{\frac{4L}{C} - R^2}}{R}$$

Although V is not constant, τ_0 is extremely small, so that V = E_m can be assumed for the transient duration; similarly, the conduction time can be assumed as $2\tau_0$. Thus, an MCCB for use in a capacitive circuit must have an instantaneous-trip current of greater than i_m x $2\tau_0$.

Example: MCCB selection for a 3-phase 230V 50Hz 150 kVA capacitor circuit.

From Table 7.4, C = 0.9026 x 10^{-2} (F) and I = 377(A).

The values of R and L in the circuit must be estimated, and for this purpose it is assumed that the short-circuit current is approximately 100 times the circuit capacity – i.e., 50,000A.

$$Z = \sqrt{R^2 + (2\pi fL)^2} \quad \therefore\ 50{,}000 = \frac{V}{\sqrt{3}\ Z}$$

thus: $Z = \frac{230}{\sqrt{3}\ \text{x}\ 50{,}000} = 2.66 \text{ x } 10^{-3}$

and assuming: $\frac{2\pi fL}{R} = 5$

then: $2\pi fL = 2.60 \text{ x } 10^{-3}\ \Omega$

thus: $R = 5.21 \text{ x } 10^{-4}\ \Omega \quad L = 8.29 \text{ x } 10^{-6}$ (H)

since: $E_m = \frac{\sqrt{2}}{\sqrt{3}}\,V = 188$, i_m and τ_0 can be obtained from their respective formulas as,

i_m =6200A

$\tau_0 = 4.27 \text{ x } 10^{-4}$ (s).

Since current-flow duration is approximately $2\tau_0$, an MCCB is selected with a latching time of 0.001 seconds at 6200A. The Type NF630-SW is suitable, having a latching time of 0.0029 seconds at 10,000A. Even with a shorter latching time, tripping is unlikely under the application of the above current, but selection of an MCCB with an instantaneous-trip current of greater than $\frac{6200}{\sqrt{2}}$ = 4400A is recommended for an adequate safety margin. Such an MCCB will be rated at 600A. Accordingly, in this example the Type NF630-SW, rated at 600A, is selected. Table 7.4 is a basis for selection, but since, in cases where the short-circuit capacity of the circuit is considerably higher than that of the MCCB, spurious tripping due to the switching surge may occur, it is also necessary to make calculations along the lines of the above example.

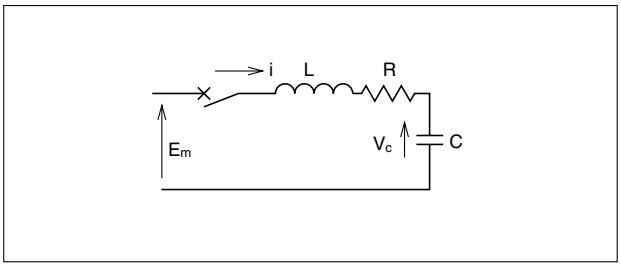


Fig. 7.11 PF Correction Capacitor

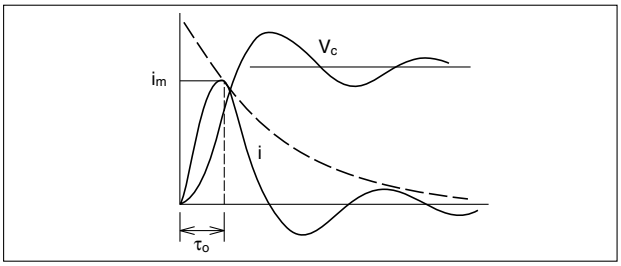


FIg. 7.12 Currents and Voltages

7.7 MCCBs for Thyristor Circuits

Both overcurrent and overvoltage protection must be provided for these elements. MCCBs can be used effectively for overcurrent, although application demands vary widely, and selection must be made carefully in each case. Overvoltage protection must be provided separately; devices currently in use include lightning arresters, dischargers, RC filters and others.

1. MCCB Rated Currents

A primary factor determining the rated current of the MCCB to be used is the question of AC-side or DC-side installation. AC-side installation permits a lower rating, which is a considerable advantage. Fig. 7.13 shows both AC and DC installation (MCCBs 1 and 2); Table 7.5 gives a selection of circuit formats and current configurations; using this table it is possible to determine the MCCB rating for either MCCB 1 or 2, as required. The current curve of the thyristor (average current is usually given) and the tripping curve of the MCCB should be rechecked to ensure that there is no possibility of overlap.

When an overcurrent is due to a fault in the load, causing a danger of thermal destruction of the circuit elements, either AC or DC protection is adequate, provided the parameters are properly chosen. When the fault is in one of the thyristor elements, resulting

Table 7.4 MCCB Selection for Circuits with PF-Correction

a) 230V, 50Hz Circuit

Capacitor rating		Single-phase circuit		Three-phase circuit	
kvar	μF	Capacitor rated current (A)	MCCB rated current (A)	Capacitor rated current (A)	MCCB rated current (A)
5	301	21.7	40	12.6	20
10	602	43.5	75	25.1	40
15	903	65.2	100	37.7	63
20	1203	87.0	125	50.2	80
25	1504	108.7	175	62.8	100
30	1805	130.4	200	75.3	125
40	2407	173.9	250	100.4	150
50	3009	217.4	350	125.5	200
75	4513	326.1	500	188.3	300
100	6017	434.8	700	251.0	400
150	9026	652.2	1000	376.5	600
200	12034	869.6	1400	502.0	800
300	18052	1304.3	2000	753.1	1200
400	24069	1739.1	2500	1004.1	1500

c) 400V, 50Hz Circuit

Capacitor rating		Single-phase circuit		Three-phase circuit	
kvar	μF	Capacitor rated current (A)	MCCB rated current (A)	Capacitor rated current (A)	MCCB rated current (A)
5	99	12.5	20	7.2	15
10	199	25.0	40	14.4	32
15	298	37.5	63	21.7	40
20	398	50.0	80	28.9	50
25	497	62.5	100	36.1	63
30	597	75.0	125	43.3	80
40	796	100.0	150	57.7	100
50	995	125.0	200	72.2	125
75	1492	187.5	300	108.3	175
100	1989	250.0	400	144.3	225
150	2984	375.0	600	216.5	350
200	3979	500.0	800	288.7	500
300	5968	750.0	1200	433.0	700
400	7958	1000.0	1500	577.4	900

b) 230V, 60Hz Circuit

Capacitor rating		Single-phase circuit		Three-phase circuit	
kvar	μF	Capacitor rated current (A)	MCCB rated current (A)	Capacitor rated current (A)	MCCB rated current (A)
5	251	21.7	40	12.6	20
10	501	43.5	80	25.1	40
15	752	65.2	100	37.7	63
20	1003	87.0	125	50.2	80
25	1254	108.7	175	62.8	100
30	1504	130.4	200	75.3	125
40	2006	173.9	250	100.4	150
50	2507	217.4	350	125.5	200
75	3761	326.1	500	188.3	300
100	5014	434.8	700	251.0	400
150	7522	652.2	1000	376.5	600
200	10029	869.6	1400	502.0	800
300	15043	1304.3	2000	753.1	1200
400	20057	1739.1	2500	1004.1	1500

d) 400V, 60Hz Circuit

Capacitor rating		Single-phase circuit		Three-phase circuit	
kvar	μF	Capacitor rated current (A)	MCCB rated current (A)	Capacitor rated current (A)	MCCB rated current (A)
5	83	12.5	20	7.2	15
10	166	25.0	40	14.4	32
15	249	37.5	63	21.7	40
20	332	50.0	80	28.9	50
25	414	62.5	100	36.1	63
30	497	75.0	125	43.3	80
40	663	100.0	150	57.7	100
50	829	125.0	200	72.2	125
75	1243	187.5	300	108.3	175
100	1658	250.0	400	144.3	225
150	2487	375.0	600	216.5	350
200	3316	500.0	800	288.7	500
300	4974	750.0	1200	433.0	700
400	6631	1000.0	1500	577.4	900

Notes: 1. The MCCB rated current should be approx. 150% of the capacitor rated current.
2. The MCCB short-circuit capacity should be adequate for the circuit short-circuit capacity.

in reverse current, the result is often that other circuit elements will be destroyed (see Fig. 7.14) if the circuit is not interrupted immediately. In this case AC-side protection or protection in series with each element is necessary.

2. Tyristor Overcurrent Protection

Total protection of each element is possible in theory, but in practice overall coordination and the best compromise for economy are usually demanded. Where elements are critical, complex combinations of protective devices can be employed, at proportionally higher cost.

Basically, overcurrent leads to excessive temperature rise of the thyristor junction, resulting in loss of the control function, and thermal destruction. A fault, therefore, must be interrupted as quickly as possible, before the junction temperature rises above its specified limit. In the overcurrent region, designated on the current-surge withstand curves of the circuit element, the element can usually withstand the surge for at least one cycle. The current-surge withstand, generally specified as a peak value, must be converted to RMS, to select a suitable MCCB.

An overload of short-circuit proportion, either external or in a bridge-circuit thyristor element, necessitates rapid interruption of the circuit. Normally, such

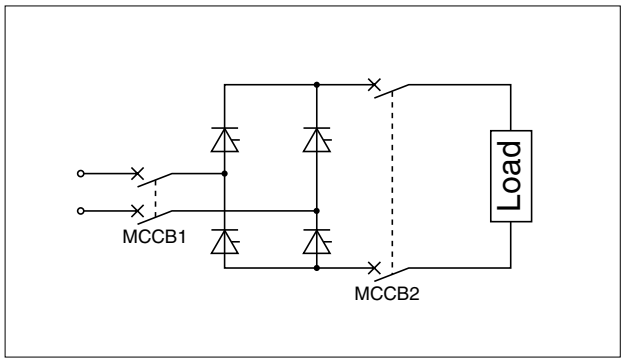


Fig. 7.13 AC- and DC-side Protectors for Thyristors

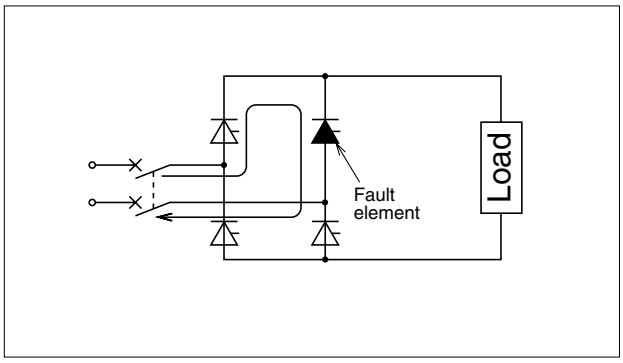
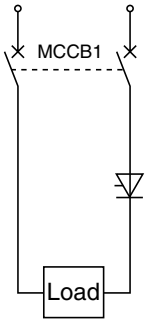
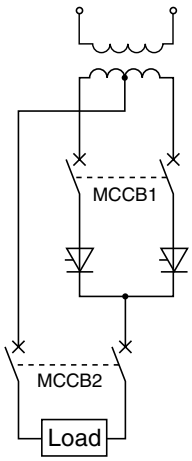
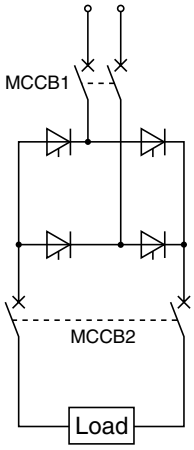
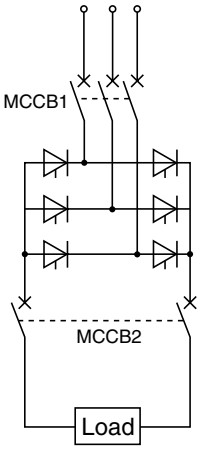
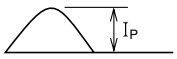
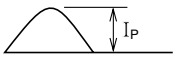
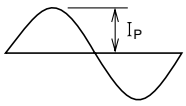
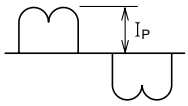
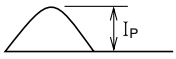
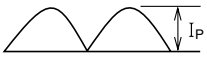


Fig. 7.14 Fault-Current Flow

Table 7.5 Thyristor Circuits and Current Formats

			Circuit No. I	Circuit No. II	Circuit No. III	Circuit No. IV
Circuit diagram						
Element average current I_F (A)			$\frac{I_P}{\pi}$	$\frac{I_P}{\pi}$	$\frac{I_P}{\pi}$	$\frac{I_P}{\pi}$
Element RMS current I_e (A)			$\frac{I_P}{2}$	$\frac{I_P}{2}$	$\frac{I_P}{2}$	$\sqrt{\frac{1}{6}+\frac{\sqrt{3}}{4\pi}}\,I_P$ ($\fallingdotseq 0.552\ I_P$)
Average DC current I_D (A)			I_F	$2I_F$	$2I_F$	$3I_F$
Current flow	MCCB1	RMS current I_B (A)	$\frac{\pi}{2}I_F$ or $\frac{\pi}{2}I_D$	$\frac{\pi}{2}I_F$ or $\frac{\pi}{4}I_D$	$\frac{\pi}{\sqrt{2}}I_F$ ($\fallingdotseq 2.22\ I_F$) or $\frac{\pi}{2\sqrt{2}}I_D$ ($\fallingdotseq 1.11\ I_D$)	$\pi\sqrt{\frac{1}{3}+\frac{\sqrt{3}}{2\pi}}\,I_F$ ($\fallingdotseq 2.45\ I_F$) or $\frac{\pi}{3}\sqrt{\frac{1}{3}+\frac{\sqrt{3}}{2\pi}}\,I_D$ ($\fallingdotseq 0.817\ I_D$)
		Current waveform				
	MCCB2	RMS current I_B (A)	I_e or $\frac{\pi}{2}I_D$	$\frac{\pi}{\sqrt{2}}I_F$ or $\frac{\pi}{2\sqrt{2}}I_D$	$\frac{\pi}{\sqrt{2}}I_F$ or $\frac{\pi}{2\sqrt{2}}I_D$	$\pi\sqrt{\frac{1}{2}+\frac{3\sqrt{3}}{4\pi}}\,I_F \fallingdotseq 3I_F$ or $\frac{\pi}{3}\sqrt{\frac{1}{2}+\frac{3\sqrt{3}}{4\pi}}\,I_D \fallingdotseq I_D$
		Current waveform				

Note: Load is assumed resistive, with elements conductive through 180°.

interruption takes place within one cycle; thus, from the point of view of element thermal destruction, the time integral of the current squared must be considered. Quantitatively, the permissible $\int i^2dt$ of the element must be greater than the $\int i^2dt$ of the MCCB current through interruption, converted to apply to the element. The latter is influenced by the short-circuit current magnitude, the interruption time, and the current-limiting capability of the MCCB.

It is important to note that the MCCB interruption time will be considerably influenced by the short-circuit current rise rate, di/dt, on the load side. In the short circuit of Figs. 7.15 and 7.16, the current is:

$$i = \frac{E}{R}\left(1 - \varepsilon^{-\frac{R}{L}t}\right)$$

and the current rise rate di/dt is:

$$\left(\frac{di}{dt}\right)_{t=0} = \frac{E}{L}$$

Thus, the inductance of the line, and the smoothing inductance significantly affect di/dt. Where the potential short-circuit current is very large, the inductance should be increased, to inhibit the rise rate and assist the MCCB to interrupt the circuit in safe time. This is illustrated in Fig. 7.17, for MCCB2 of Fig. 7.15.

The MCCB current during total time (t_T) is $\int i^2\,dt$, which, converted to the $\int i^2\,dt$ applied to the circuit element, must be within the limit specified. Having determined the circuit constants, testing is preferable to calculation for confirmation of this relationship.

Assuming a large current-rise rate, with an AC-side short-circuit current $i = I_{ps}\sin\omega t$, and an MCCB interruption time of one cycle, the $\int i^2\,dt$ applied to the thyristor is as follows:

1. For circuits I, II and III of Table 7.10:

$$\int i^2dt = \int_0^{\frac{1}{2f}} I_p^2 \sin^2\omega t dt = \frac{1}{4f} I_p^2 \quad (A^2s)$$

2. For circuit IV:

$$\int i^2dt = 2\int_{\frac{1}{6f}}^{\frac{1}{3f}} I_p^2 \sin^2\omega t dt = \frac{I_p^2}{f}\left(\frac{1}{6} + \frac{\sqrt{3}}{4\pi}\right) \quad (A^2s)$$

where I_p is the peak value of the element current and f is the supply frequency.

If the $\int i^2\,dt$ of the circuit element is known, the permissible $\int i^2dt$ for the MCCB can be determined, using the last two equations given above. Provided that the interruption time is not greater than one cycle, the MCCB current will be the same as the element current for circuits I and II, and twice that for circuits III and IV. This means that the MCCB $\int i^2dt$ through the interruption time should be within twice the permissible $\int i^2dt$ of the element.

Diodes are generally stronger against overcurrent than thyristors, and since diodes can handle larger $I^2{\cdot}t$, protection is easier.

Fig. 7.17 shows the protection coordination situation of a selection of devices, plotted together with the thyristor current-surge withstand curve. AC-side protection (MCCB1, Fig. 7.15) is presented, but the DC-protection case (MCCB2) can be plotted in the same way.

Region 2 in Fig. 7.17 is the area of overcurrent for which protection is effected by the MCCB. For protection of region 1, an overload relay is effective, and for region 2, inductance L must be relied on to limit the fault-current rise rate, or a high-speed current-limiting fuse must be used. Practical considerations, including economy and the actual likelihood of faults in the regions concerned, may dictate the omission of the protective devices for regions 1 and 3, in many cases. The lower the instantaneous-trip setting of the MCCB, the wider the region 2 coverage becomes.

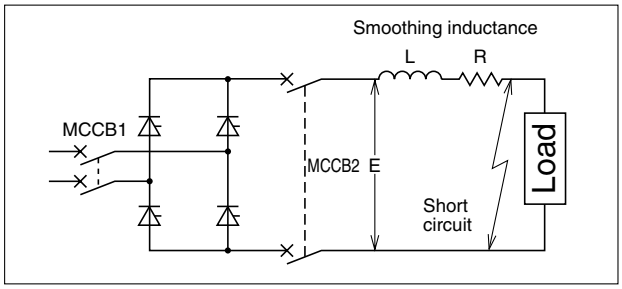


Fig. 7.15 Thyristor Short Circuit

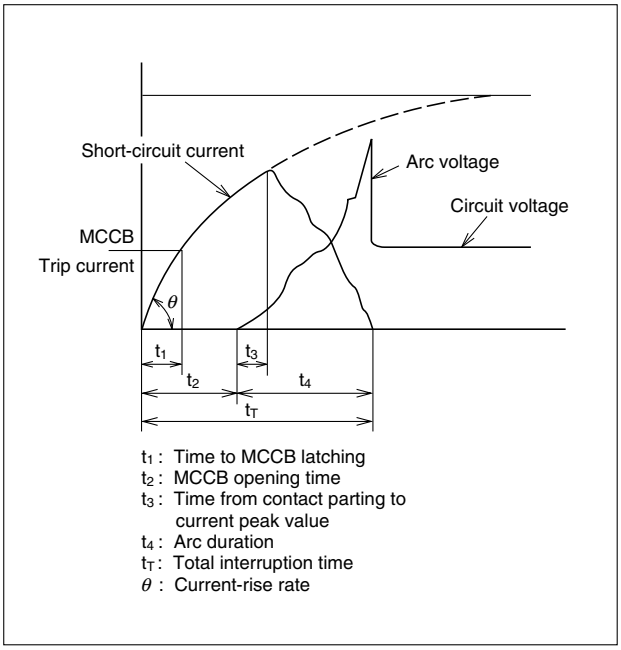


Fig. 7.16 Thyristor Short-Circuit Interruption

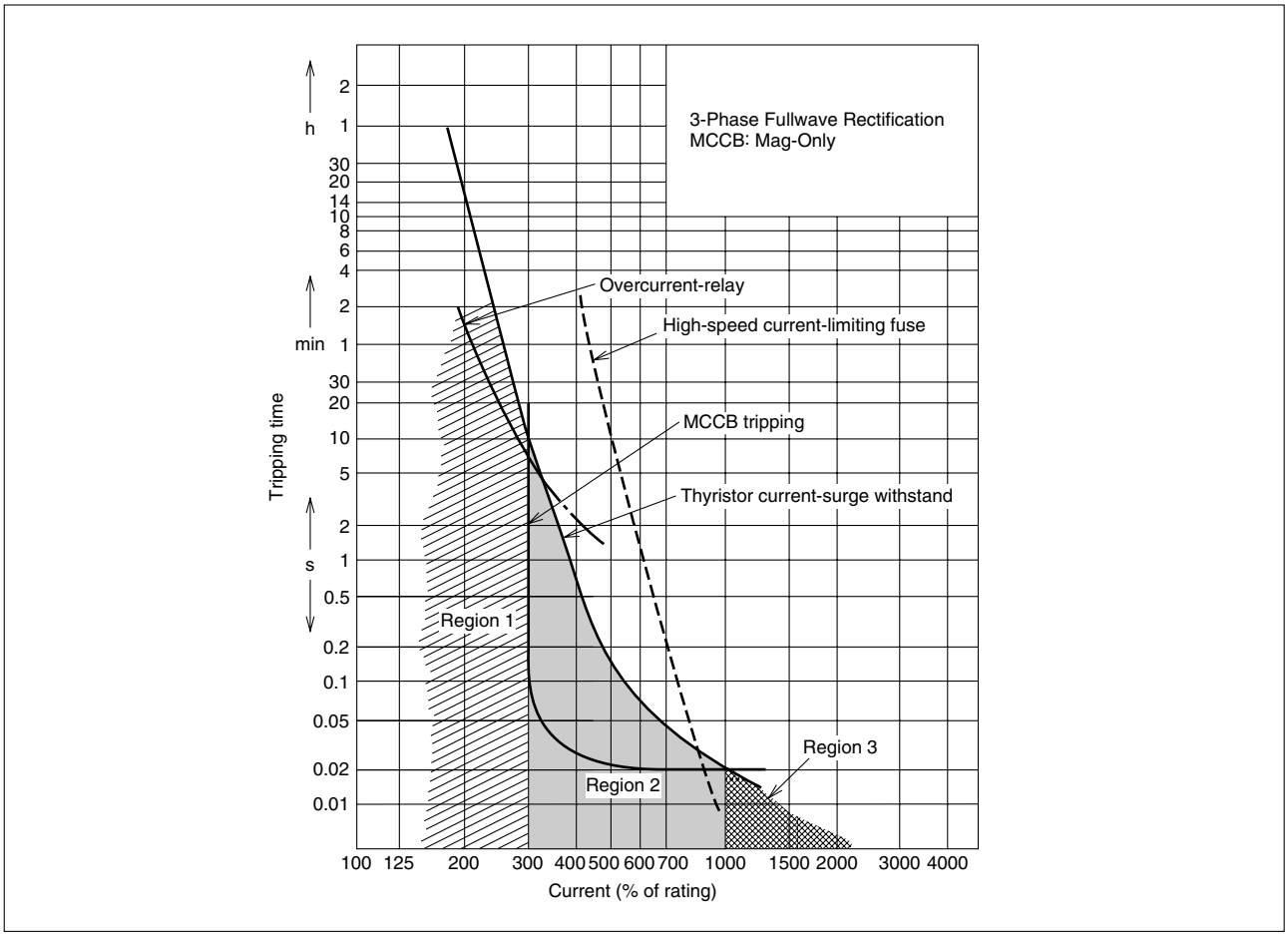


Fig. 7.17 Thyristor and Protector Operating Curves

3. Element Breakdown in Thyristor-Leonard Systems

In this system of DC motor control, if power outage or commutation failure due to a thyristor control-circuit fault occurs during inversion (while motor regenerative power is being returned to the AC supply), the DC motor, acting as a generator while coasting, will be connected to a short-circuit path, as in Fig. 7.18. For thyristor protection, MCCBs must be placed in the DC side, as shown.

A Mag-Only MCCB with a tripping current of about 3 times the rated current is employed, either 3- or 4-pole, series-connected as shown in Fig. 7.20. Since the element short-circuit current is the same as the MCCB current, circuit protection is effected provided that the $\int i^2 dt$ limit for the element is larger than that for the MCCB interruption duration. This must be established by test.

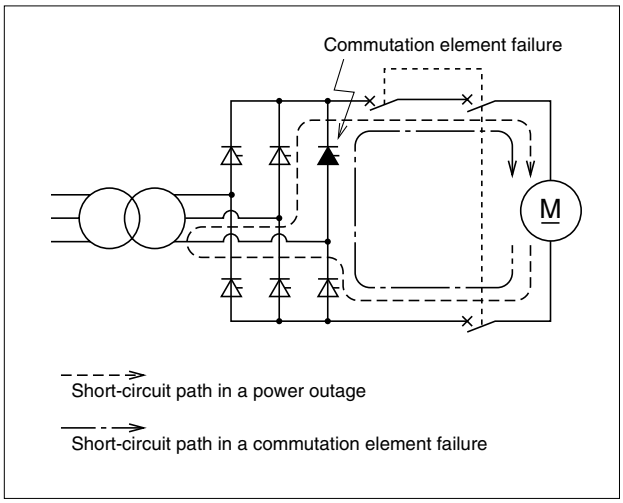


Fig. 7.18 Ward-Leonard Thyristor Protection

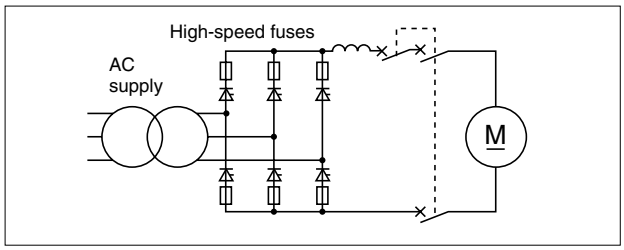


Fig. 7.19 High-Speed Fuses for Thyristor-Circuit Protection

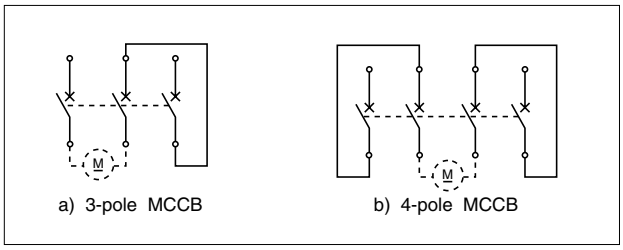


Fig. 7.20 Series Connection of MCCB Poles

Fig. 7.19 shows connection of high-speed fuses for protection against thyristor breakdown that would otherwise result in short-circuit flow from the AC supply side.

4. MCCBs for Lamp Mercury-Lamp Circuits

The ballasts (stabilizers) used in this type of lamp cover a variety of types and characteristics. For 200V applications (typical), choke-coil ballasts are used. For 100V applications a leakage-transformer ballast is employed. Normal ballasts come in low power-factor versions and high power-factor versions, with correction capacitors. More sophisticated types include the constant-power (or constant-output) type, which maintains constant lamp current both in starting and normal running, and flickerless types, which minimize the flicker attendant on the supply frequency.

In selecting an MCCB where normal (high or low PF) ballasts are to be used, the determining factor is the starting current, which is about 170% of the stable running current. In the cases of constant-power or flickerless types, the determining factor is the normal running current, which is higher than the starting current. For MCCB selection, the latter types can be regarded as lighting and heating general loads, as previously discussed.

For selection of MCCBs for regular ballasts, the 170% starting current is assumed to endure for a maximum of 5 minutes. MCCBs of 100A or less frame size have a tripping value very close to rating for overloads of duration of this order, so that the MCCB rating should be the nearest standard value above 170% of the stable running current. MCCBs of above 100A frame size can handle a current of around 120% of the rating for 5 minutes without tripping; thus the nearest standard MCCB rating above $\frac{1.7}{1.2}$ = 1.4 times the stable-running current of the lamp load is the suitable protector.

As an example, consider MCCB selection for 10 units of 100W, 100V, 50Hz general-purpose high power-factor mercury lamps. The stable-running current per lamp is 1.35A. Thus:

1.35 x 10 x 1.7 = 23A, and the selection becomes NF32-SW, 32A rated.

7.8 Selection of MCCBs in inverter circuit

7.8.1 Cause of distorted-wave current

Distorted-wave current is caused by factors such as the CVCF device of a computer power unit, various rectifiers, induction motor control VVVF device corresponding to more recent energy-saving techniques, etc, wherein thyristor and transistor are used. Any of these devices generates DC power utilizing the switching function of a semiconductor and, in addition, transforms the generated DC power into intended AC power. Generally, a large capacity capacitor is connected on its downstream side from the rectification circuit for smoothing the rectification, so that the charged current for the capacitor flows in pulse form into the power circuit. Because voltage is chopped at high frequency in AC to DC transforming process, load current to which high frequency current was superimposed by chopping basic frequency flows into the load line. This paragraph describes the VVVF inverter, of these devices, which will develop further as main control methods for induction motors currently in broad use in various fields . Fig. 7.27 illustrates an example of MCCBs application to inverter circuit. Two control methods of PAM (Pulse Amplitude Modulation) and PWM (Pulse Wide Modulation) are available for the VVVF inverter and generating higher harmonic wave components differs depending on the difference between the control methods. As seen from Tables 7.9 and 7.10, this harmonic wave component of input current can be made smaller (improved) by inputting DC reactor (DCL) or AC reactor (ACL). Further, in the case of the output current waveform in Fig. 7.29, the PWM generates higher harmonic wave components than that of the PAM.

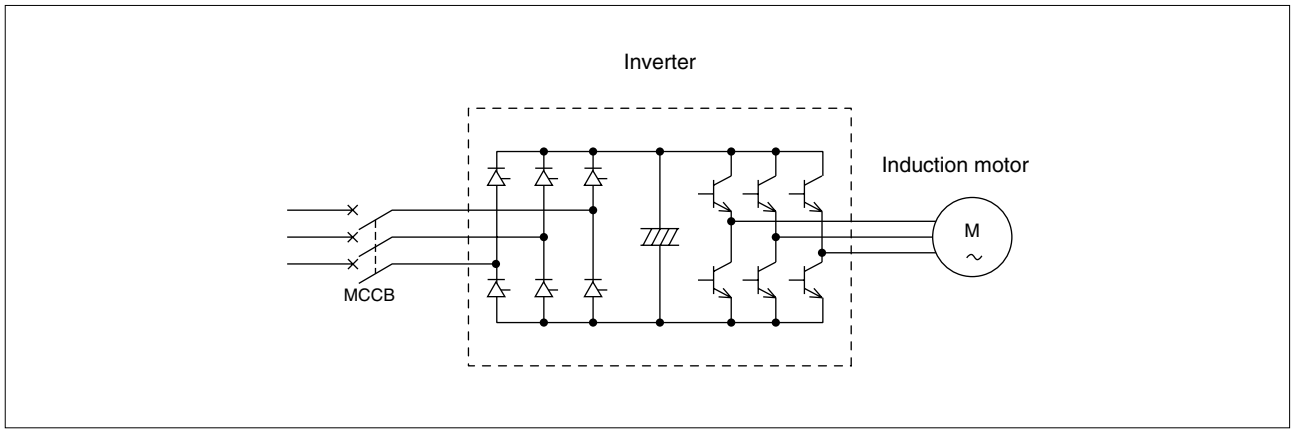


Fig.7.27 Example of MCCBs Application to Inverter Circuit

7.8.2 Selection of MCCBs

MCCBs characteristic variations and temperature rises dependent on distortion of the current wave must be considered when selecting MCCBs for application to an inverter circuit (power circuit). The relation of rated current I_{MCCB} to load current I of MCCBs is selected as follows from the MCCBs tripping system.

$$I_{MCCB} \geqq K \times I$$

Thermal-magnetic type (bimetal system) and electronic type (RMS value detection) are both RMS current detection systems which enable exact overload protection even under distorted-wave current. Due to the above explanation, it is advantageous to select RMS current detection type MCCBs.

Table 7.8 Reduction Rate

MCCBs tripping system	Reduction rate K
Thermal-magnetic (bimetal system)	1.4
(Note 1) Hydraulic-magnetic	1.4
Electronic (RMS value detection)	1.4

This table is subject to the current which meets the following requirements.

① Distortion factor = $\dfrac{\text{RMS value of total harmonic wave component}}{\text{RMS value of basic frequency}} \times 100 \leqq 100\%$ or less

② Peak factor = $\dfrac{\text{Peak value}}{\text{RMS value}} \leqq 3$ or less

③ Higher harmonic wave components are mainly No.7 or a lower harmonic wave.

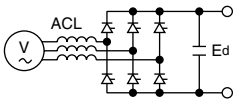
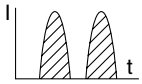
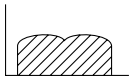
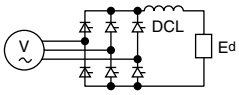
Notes: 1. The characteristics of hydraulic-magnetic type MCCBs vary significantly depending on wave distortion. Therefore, use of thermal-magnetic type MCCBs is recommended.

Table 7.9 Data of High Harmonic Wave Current Content in Inverter Power Circuit (Example)

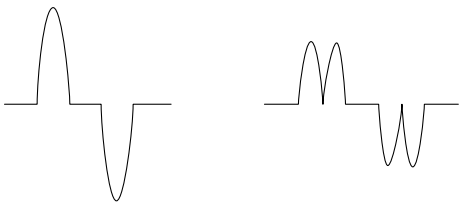
High harmonic wave degree	High harmonic wave current content (%)			
	P W M		P A M	
	No ACL (Standard)	With power factor modifying ACL	With standard ACL	With power factor modifying ACL
Basic	81.6	97.0	83.6	97.2
2	–	–	–	–
3	3.7	–	2.5	–
4	–	–	–	–
5	49.6	21.9	48.3	21.7
6	–	–	–	–
7	27.4	7.1	23.7	7.0
8	–	–	–	–
9	–	–	–	–
10	–	–	–	–
11	7.6	3.9	6.2	3.7
12	–	–	–	–
13	6.7	2.8	4.7	2.6

Note: No DCL Output frequency 60Hz , subject to 100% load

Table 7.10 Peak Factor of Inverter Input Current

Circuit			Input current			
			Power factor	Waveform factor	Peak factor	Waveform (half wave portion)
with ACL	Large ←ACL→ Small		Below 58.7	Above 1.99	Above 2.16	
			58.7%	1.99	2.16	
			58.7–83.5%	1.99–1.27	2.16–1.71	
			83.5%	1.27	1.71	
			83.5–95.3%	1.27–1.23	1.71–1.28	
With DCL			95.3%	1.23	1.28	

Power factor = (DC voltage x DC) /($\sqrt{3}$ x AC RMS voltage x AC RMS current)
Waveform factor = (RMS value) /(Mean value)
Peak factor = (Max value) /(RMS value)



(a) PAM system (b) PWM system

Fig.7.28 Inverter Input Current

(a) PAM system (b) Equal-value PWM system

Fig.7.29 Inverter Output Current