# 7

# Switchgear and Motor Control Centres

## 7.1 TERMINOLOGY IN COMMON USE

The terms ‘switchgear’ and ‘motor control centres’ are used in general to describe combinations of enclosures, busbars, circuit breakers, power contactors, power fuses, protective relays, controls and indicating devices. The standards used in Europe often refer to IEC60050 for definitions of general terms. Particular IEC standards tend to give additional definitions that relate to the equipment being described, e.g. IEC60439 and IEC60947 for low voltage equipment, IEC60056, IEC60298 and IEC60694 for high voltage equipment. An earlier standard IEC60277 has been withdrawn. These standards tend to prefer the general terms ‘switchgear’ and ‘controlgear’. Controlgear may be used in the same context as ‘motor control centres’ which is a more popular and specific term used in the oil industry.

In general switchgear may be more closely associated with switchboards that contain circuit breaker or contactor cubicles for power distribution to other switchboards and motor control centres, and which receive their power from generators or incoming lines or cables. Motor control centres tend to be assemblies that contain outgoing cubicles specifically for supplying and controlling power to motors. However, motor control centres may contain outgoing cubicles for interconnection to other switchboards or motor control centres, and circuit breakers for their incomers and busbar sectioning. Switchboards may be a combination of switchgear and motor control centres. For example a main high voltage switchboard for an offshore platform will have switchgear for the generators, busbar sectioning and outgoing transformer feeders. It will have motor control centre cubicles for the high voltage motors. IEC60439 applies to low voltage equipment that is described as ‘factory built assemblies’, or FBAs, of switchgear and controlgear.

Switchgear tends to be operated infrequently, whereas motor control centres operate frequently as required by the process that uses the motor. Apart from the incomers and busbar section circuit breakers, the motor control centres are designed with contactors and fuses (or some types of moulded case circuit breakers in low voltage equipment) that will interrupt fault currents within a fraction of a cycle of AC current. Circuit breakers need several cycles of fault current to flow before interruption is complete. Consequently the components within a circuit breaker must withstand the higher forces and heat produced when several complete cycles of fault current flow.

Switchgear is available up to at least 400 kV, whereas motor control centres are only designed for voltages up to approximately 15 kV because this is the normal limit for high voltage motors.

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## 7.2 CONSTRUCTION

The switchgear (SWGR) and motor control centres (MCC) considered in this section are those found in the onshore and offshore oil industry for supplying power to processes and utilities. Extra high voltage (EHV) transmission and distribution equipment used by electricity authorities is not considered herein. Hence most of the equipment used onshore and offshore is limited to an upper service voltage of between 11 kV and 15 kV. Occasionally voltages in the range of 30 kV to 40 kV are used when the incoming line or generating capacity exceeds approximately 120 MW. Voltages as high as 69 kV are used for long submarine cable systems.

The SWGR and MCC equipment are invariably housed in a building or enclosed module, or at least effectively protected against bad weather and aggressive environmental conditions. The construction is therefore of the metal clad type, in which all the live parts are housed in a mild-steel sheet metal enclosure. The enclosure is sub-divided so that personnel may work safely on some compartments without danger or the risk of electric shock.

Various degrees of personnel and ingress protection are commonly available. The degree of protection is defined in various international standards e.g. NEMA and NEC in USA, IEC in UK and Europe. For use inside buildings where manual operation and interference is infrequent and where the atmosphere is cool, dry and clean an enclosure of the IEC60529 type IP40, 41 or 42 or NEMA type 1 or 2 is usually adequate. If equipment is to be located in a poor atmosphere e.g. dust laden, damp, hot and where hose-pipes may be used to wash down adjacent plant, then a more demanding enclosure type is required e.g. IP54 or NEMA type 4, but this would normally only apply to low voltage equipment.

The main electrical components are:-

- Main busbars.
- Earthing busbar.
- Incoming and busbar section circuit breakers.
- Outgoing switching devices, contactors or circuit breakers.
- Fuses for MCC outgoing circuits.
- Safety interlocking devices.
- Electrical protective relays and devices for all power circuits.
- Control and indication devices.
- Communication or network interfacing system.
- Main connections and terminal compartments.

### 7.2.1 Main Busbars

The main busbars should be made of high-grade copper. Aluminium is not recommended because it suffers from mechanical problems associated with the soft nature of the metal, which makes the physical jointing and connection of auxiliary devices difficult. For voltages up to 600 V it is often required to use four busbars, one being for the neutral. This is because unbalanced loads need to be supplied as a 4-wire system. In this case a 4-wire feeder from the source is necessary, e.g. a HV/LV transformer, LV generator. Care needs to be taken when specifying the number of horizontal and

**Table 7.1.** Busbar normal current ratings in amps

| HV MCCs and SWBDs | LV MCCs and SWBDs |
|---|---|
| 400 | |
| 630 | 800 |
| 800 | 1600 |
| 1200 | 2400 |
| 1600 | 3000 |
| 2000 | 3150 |
| 2400 | 3500 |
| 3000 | 4000 |
| 3150 | |

vertical busbars in low voltage motor control centres. Often in oil industry motor control centres there is a mixture of motor controllers and static load feeder units. Motors seldom need a 4-wire supply but static loads are often unbalanced and require the fourth or neutral wire. The motor and static load units need not necessarily be segregated into different complete vertical assemblies, although this is good engineering practice, and so it is advisable to specify a fourth vertical busbar in each vertical assembly. When a 4-wire system is required the incoming and busbar section circuit breakers may be 3-pole with a linked neutral or be 4-pole. If the SWBD or MCC feeds equipment located in a hazardous area then the 4-pole circuit breakers should be used, as recommended in the international standards, see Chapter 10.

For balanced loads and for voltages above 1000 V a 3-wire source is used and hence only three busbars are needed. Unbalanced loads are seldom encountered at high voltages. Typical busbar normal current ratings used in the oil industry are shown in Table 7.1.

The maximum value of 4000 A for low voltage busbars roughly corresponds to the secondary current of a fully loaded 2500 kVA transformer. 2500 kVA is often chosen as the limit for transformers that feed motor control centres because the fault current that they allow through is typically near to the limit that the manufacturers can normally supply, e.g. 80 kA symmetrical rms current. A 2500 kVA transformer with a 6% leakage impedance and a 400 V secondary winding will pass approximately 60 kA of fault current. If the MCC feeds mostly motors then they will collectively contribute some fault current in addition to that from the transformer, see IEC60363 clause 4 and IEC60909 clause 13. In the above simple example some of the margin between 60 kA and 80 kA will be taken up by the sub-transient contributions from the motors. It can be noted at this point that if the transformer is subsequently increased in rating by the addition of forced air fans, then the fault current passed by the transformer will be unchanged. It is advisable to specify the rating of the transformer in its forced air-cooled mode of operation, if such cooling is considered likely to be needed in the future. This would ensure that the incoming circuit breakers and busbar normal rated currents would be correctly matched to the transformers.

High voltage switchboards are available with busbar ratings up to 5000 A. Consider for example an 11 kV switchboard that is fed by four 25 MVA generators, two connected to the left-hand side busbar section and two on the right-hand side section. The total rated current from a pair of generators is 2624 A, which is the maximum current that can flow across the busbar section circuit breaker. Hence the busbars can be adequately rated at 3000 A or 3150 A for this plant.

Busbars are mounted on insulated bushes that are strong enough to withstand the peak short-circuit currents and forces. The busbars may be air insulated or enclosed in an insulating sleeve.

The sleeve is used where the atmosphere may be damp or corrosive. Neutral busbars are usually rated at half the phase busbar current ratings. If the neutral is likely to carry harmonic currents then it is good practice to use a fully rated neutral busbar i.e. the same as the individual phase busbars.

## 7.2.2 Earthing Busbars

The earthing (grounding) busbar is separate from the neutral busbar, and is used to earth all conductors that need to be earthed as well as the metallic frame and casing of the switchboard or motor control centre. The earthing busbar is made of high-grade copper and is usually located at the front or rear of the enclosure at ground level.

## 7.2.3 Incoming and Busbar Section Switching Device

### *7.2.3.1 Low voltage systems up to 600 V*

The incoming and busbar section switching devices are usually air-break circuit breakers, which can be fixed or withdrawable from the main frame or enclosure. They can be 3 or 4-pole depending upon whether a 3 or 4-wire supply is required. Some low power switchboards may use load-break switches for these functions.

### *7.2.3.2 High voltage systems up to 15 kV*

Several types of circuit breakers are available for high voltage operation. The main types are:-

- Air-break.
- Sulphur hexafloride gas.
- Vacuum.

The use of oil in switchgear has become unnecessary and discontinued. The choice of circuit breaker type for a particular power system depends upon several main factors:-

- Ambient and environmental conditions, derating may be required for high ambient temperatures.
- Rated normal rms current.
- Fault peak making current with the appropriate DC offset.
- Fault rms breaking current with the appropriate DC offset if it is still present.
- Fault withstand duty.
- Cost and economics.
- Variety of choice in the market so that a technical and economic comparison can be made.
- Physical size and suitability for the intended location.
- Manufacturing time and delivery time.
- Obsolescence and the availability of spare parts.
- Post purchase follow up services.

- History of operation in similar plants and locations.
- Single or duplicate busbar system requirements.

Air-break circuit breakers are almost the same in design as the low voltage air-break devices described above except that they are more robust and insulated for the high voltage. They are only available in the 3-pole form, and up to about 24 kV is possible. They tend to be the most expensive and require more frequent maintenance due to their exposed construction and relatively more complicated mechanisms. Vacuum and sulphur hexafloride equipment is less expensive and tend to be preferred to air-break equipment.

Sulphur hexafloride (usually referred to as SF6) gas is also used as the arc extinguishing medium. SF6 circuit breakers are very robust, economical, small in size, and extremely reliable. They require almost no major maintenance for at least 10 years of operation. The gas is contained under a pressure slightly above atmospheric pressure and sealed in hermetically. There is no contact with the outside air. Metalclad equipment is available up to 36 kV and SF6 has to a large extent replaced all the air-blast equipment for distribution voltages up to 400 kV. At 11 kV the typical ratings are 400 A to 2500 A with fault making duties up to about 25 kA.

Vacuum and SF6 devices were developed at about the same time as competitors. There is little to choose between them since they are both simple mechanisms. Some engineers in the past considered the possibility that the vacuum could be lost while the circuit breaker was in its ‘on’ state was a serious disadvantage. However, the technology has greatly improved and thousands of vacuum circuit breakers are in service. Vacuum circuit breakers are limited to about 13.8 kV due to insulation difficulties across the open contacts. Current ratings at 13.8 kV are limited to about 3000 A, with corresponding fault making duties up to 100 kA peak. SF6 equipment tends to be preferred to vacuum equipment.

### 7.2.4 Forms of Separation

Cubicle type switchgear can be constructed in many different arrangements depending upon a variety of requirements. For example the following aspects may be important for a particular plant, environmental protection, ease of access to internal parts, ease of terminating cables, fixed or withdrawable switching devices, maintainability and level of personnel skill, cost and economics, expected life duration of the product, fitness for its purpose. The switchgear industry is very competitive and so it is essential to clearly specify what is required in the form of assembly and its construction. Otherwise a false or unsatisfactory decision may be made mainly based on a cost comparison.

The steel clading and compartments are necessary for support of the electrical and mechanical components, and for providing a safety barrier for the personnel who operate and maintain the switchgear. Safety risk has two main features. Firstly, electric shock and secondly, injury from explosive faults and fires. A well-designed enclosure should ensure that these features are minimised. The following discussion refers to IEC standards for low voltage switchgear in particular. However, the basic concepts also apply to high voltage switchgear.

The main IEC standard for low voltage switchgear assemblies is IEC60439 which has seven parts. Part 1 covers the basic requirements for internal separation, compartments, barriers and partitions. It uses the IPXY notation of IEC60529 as a basis for the ingress protection, mainly concentrating on ‘X’ for access by tools, fingers, hands, small particles and dust. The minimum value of ‘X’ used in the standard is 2 for protection against live parts, and for ingress between adjacent units of an assembly, in particular by the fingers of a person. The standard defines four basic 'forms' of separation:-

- Form 1. No separation is provided.
- Form 2. Separation is only provided between the busbars and other functional units.
- Form 3a. Separation of the busbars from the functional units. Separation of one functional unit from another. However, the terminals for the external cables need not be separated from the functional units, nor from each other.
- Form 3b. As for Form 3a except that the terminals as a group are separated from the functional units. The terminals need not be separated from each other in the group.
- Form 4. As for Form 3a except that the terminals are an integral part of a separated functional unit. The terminals need to be separated from each other in the group.

Also defined in the standard are many terms and expressions that are used to describe individual parts and components as well as combinations of them, e.g. assembly, functional unit, barrier. The standard states what is to be achieved but not how and with what materials. An annex has been issued in the UK that expands the general principles. In June 1996 The Electrical Installation Equipment Manufacturer's Association (EIEMA) published Reference 1. The four 'forms' were sub-divided as follows:-

- Form 1. No sub-divisions.
- Form 2. Sub-divisions as:-
  Form 2a
  Form 2b, Type 1
  Form 2b, Type 2
- Form 3. Sub-divisions as:-
  Form 3a
  Form 3b, Type 1
  Form 3b, Type 2
- Form 4. Sub-divisions as:-
  Form 4a, Type 1
  Form 4a, Type 2
  Form 4a, Type 3

These various 'forms' and 'types' differ in detail regarding:-

- Separation of busbars and terminations.
- Separation provided between the busbars and cable terminals.
- Use of rigid barriers.
- Location of cable glands.
- Whether each functional unit has its own integral glanding arrangement.

Reference 1 has an excellent diagram in the form of a 'decision tree' to fully illustrate the above details. Another good summary which includes a table showing the relationship between busbars, functional units and terminations is Reference 2.

Oil industry users tend to prefer the various types of Form 4, with an ingress code of IP31, 32, 41 or 42 for use indoors.

### 7.2.5 Ambient Temperature Derating Factor

Switchboards and motor control centres are generally required to operate continuously at temperatures above 15°C, for example when the switchroom air conditioning fails or the ambient temperature is exceptionally high. However, switchboards are usually manufactured to meet the requirements of an ambient temperature of 40°C, see for example, IEC60439 clause 6.1.1 'ambient air temperature'.

### 7.2.6 Rated Normal Current

When choosing the root mean square ratings of switchboards due regard should be made for possible extra consumption of power in the future. The amount of extra power depends upon the particular situation, for example:-

- Updating an existing plant.
- New plant with detailed data.
- New plant with estimated data.
- Future plans for growth.

A good 'rule-of-thumb' guide is to assume that between 15% and 25% extra capacity will be required. Hence the chosen rating will be 115% to 125% of the best-known estimate at the early design stage. This requirement also applies to power transformers and their main cables or overhead power lines, and to outgoing feeder cables to auxiliary switchboards and motor control centres. It does not usually apply to individual motor consumers, see Chapter 1.

### 7.2.7 Fault Making Peak Current

The circuit breakers and busbars in the switchgear must be capable of withstanding the worst-case fault making situation, which should include the appropriate DC off-set. This is taken to be due to a zero impedance short circuit occurring within the switchboard, e.g. on the busbars, and is also assumed to exist or have been applied before the incoming feeder circuit breaker is closed. Hence the equipment must be capable of closing on to the worst possible fault, and clearing the fault within the breaking duty time period. Switchboards that are fed by generators usually have the most onerous fault conditions to clear, due to the high off-set of the current that can occur. High voltage induction motors can also contribute fault current that has a significant DC off-set, see Reference 3. The equation (7.1) below gives the transient phase current in Phase A for a three-phase worst-case fault on a generator.

$$I_a = V_{pk}\left[\left[\frac{1}{X''_d} - \frac{1}{X'_d}\right]\exp\frac{-t}{T''d} + \left[\frac{1}{X'_d} - \frac{1}{X_d}\right]\exp\frac{-t}{T'd} + \frac{1}{X_d}\right]\cos[\omega t + \phi_o]$$

$$+ V_{pk}\exp\frac{-t}{Ta}\left[\frac{1}{2}\left[\frac{1}{X''_d} + \frac{1}{X''_q}\right]\cos\phi_o + \frac{1}{2}\left[\frac{1}{X''_d} + \frac{1}{X''_q}\right]\cos[2\ \omega t + \phi_o]\right] \quad (7.1)$$

$I_a =$ Fundamental AC part + DC part + Double frequency AC part

Where $\phi_o$ is the angle in the sine wave of the Phase A current when the short circuit is applied. It is also the angle between the axis of Phase A and the d-axis as the rotor rotates.

Suppose the generator is connected to a nearby switchboard. The generator and busbar section circuit breakers will need to at least withstand the fault current given in (7.1). The equation consists of three essential parts:-

- Fundamental AC part.
- DC part.
- Double frequency AC part.

### 7.2.8 Fundamental AC Part

This starts with high values of sinusoidal current that are determined by $X''_d$. After about 20 cycles the current will have decayed to a value determined by $X_d$. This part is symmetrically distributed above and below the zero axis. During the sub-transient and transient early period the automatic voltage regulator (AVR) action in the generator may be ignored since it will not have had time to respond. However, during the later period in the steady state the AVR will have caused the field current to reach and stay at its ceiling (maximum) value. This means that $V_{pk}$ in (7.1) will have effectively risen by up to 170% of its prefault value. This aspect is more significant for the breaking duty of the circuit breakers. Reference 4 gives a method of calculating the decrement of short circuit for a generator, which includes a modification to the basic equations so that the effect of the AVR and exciter can be included. Figure 12.3 implements this method and shows the effect of AVR response in terms of the rms fault current. The method is well suited for programming in a small desktop computer.

### 7.2.9 DC Part

It is a particular characteristic in the solution of differential equations involving resistances and inductances that a DC component accompanies the symmetrical AC component. The magnitude of the DC component can equal that of the peak AC component since both are determined by $X''_d$. The decay of the DC component can be reasonably slow and is determined by $T_a$ which is a function of $X''_d$ and the armature winding resistance $R_a$. With machines that have significant values of $X''_d$ and particularly low values of $R_a$, the value of $T_a$ can become relatively high. When $T_a$ is high in relation to $T''_d$ and $T'_d$ it is possible that the initial AC decay is faster than the DC decay. When this happens the AC instantaneous current does not reach zero until several cycles have passed. This puts an extra strain on the circuit breaker and can cause problems at the point when it starts to open to clear the fault current.

Hence the circuit breakers and the busbars in the switchboard may have to be derated for the breaking duty. The amount of DC component, or 'off-set' as it is often called, depends upon the point in time set by $\phi_o$ when the fault is applied. The occurrence of 100% off-set is seldom but cannot be ignored. The design and selection of the switchboard should be based on 100% off-set, especially if it is fed by generators and feeds a group of high voltage motors.

### 7.2.10 Double Frequency AC Part

A small double frequency part occurs due to sub-transient saliency of the rotor pole surfaces. Often the data from the manufacturer are not good enough to distinguish between $X''_d$ and $X''_q$. The quadrature axis parameters are difficult to obtain from the normal factory tests. It is usually adequate to assume that $X''_q$ equals $X''_d$ and so the double frequency component becomes zero and can therefore be ignored.

The worst-case condition of (7.1) is when $\phi_o$ is zero, and if $X''_q$ equals $X''_d$ then the equation becomes:-

$$I_a = V_{pk}\left[\left[\frac{1}{X''_d} - \frac{1}{X'_d}\right]\exp^{\frac{-t}{T''_d}} + \left[\frac{1}{X'_d} - \frac{1}{X_d}\right]\exp^{\frac{-t}{T'_d}} + \frac{1}{X_d}\right]\cos(\omega t) + V_{pk}\exp^{\frac{-t}{Ta}}\left[\frac{1}{X''_d}\right] \tag{7.2}$$

In some cases it is also necessary to consider the fault current contributed by motor consumers, particularly if large synchronous motors are fed from the same busbars as the main generators or main transformer infeeds, see Chapter 11. Induction motors contribute fault current during the sub-transient period and so extra allowance must be made when calculating the making duty.

If generators are physically remote from the switchboard, e.g. interconnected by long cables or overhead lines, then the impedance between the generators and the switchboard may be large enough to swamp the sub-transient and transient current contributions, as well as reducing the DC component effects.

It has become the established practice to specify circuit breaker and switchboard making and breaking duty in kilo-amperes (kA) rather than mega-volt-amperes (MVA) which was earlier the case. This is partly due to the variety of nominal voltages used by equipment purchasers. For example a manufacturer may specify his equipment for a maximum continuous service voltage of 15 kV and yet the user will operate it at 11 kV for a particular plant. The limiting factor in all cases is the current and its associated mechanical forces. It is therefore more logical and practical to use current when specifying fault duties. Since making duty is determined by the value of the fault current at the peak of the first cycle it is customary to specify the 'fault making capacity' in terms of peak asymmetrical current ($kA_{peak}$). It is necessary for the engineer to assess the amount of DC off-set appropriate at the time the peak of the first cycle occurs. Table H.1b shows the properties of the fault current for different X-to-R ratios (see also Chapter 11) shows how the decay of the DC component determines the 'doubling factor' of the first cycle peak, and how the circuit X-to-R ratio determines the magnitude of the doubling effect. High voltage switchgear suffers far more from DC off-set currents than low voltage switchgear. This is due to the high X-to-R ratios that tend to occur at high voltages. At low voltages the X-to-R ratio typically ranges between 1 and 4, and so the DC off-set can often be ignored in low voltage networks.

Figure 7.1 shows the worst-case current decrement waveform for a generator that has the following data,

| | |
|---|---|
| Rated MVA | = 30.0 |
| Rated power factor | = 0.8 lagging |
| Rated line voltage | = 11,000 volts |
| Synchronous reactance $X_d$ | = 2.5 pu |
| Transient reactance $X'_d$ | = 0.3 pu |
| Sub-transient reactance $X''_d$ | = 0.25 pu |
| Sub-transient reactance $X''_q$ | = 0.32 pu |
| Transient time constant $T'_d$ | = 1.08 sec |
| Sub-transient time constant $T''_d$ | = 0.042 sec |
| Armature time constant $T_a$ | = 0.375 sec |

(Note, $T_a$ was made 50% higher to show the effect more clearly in the graph).

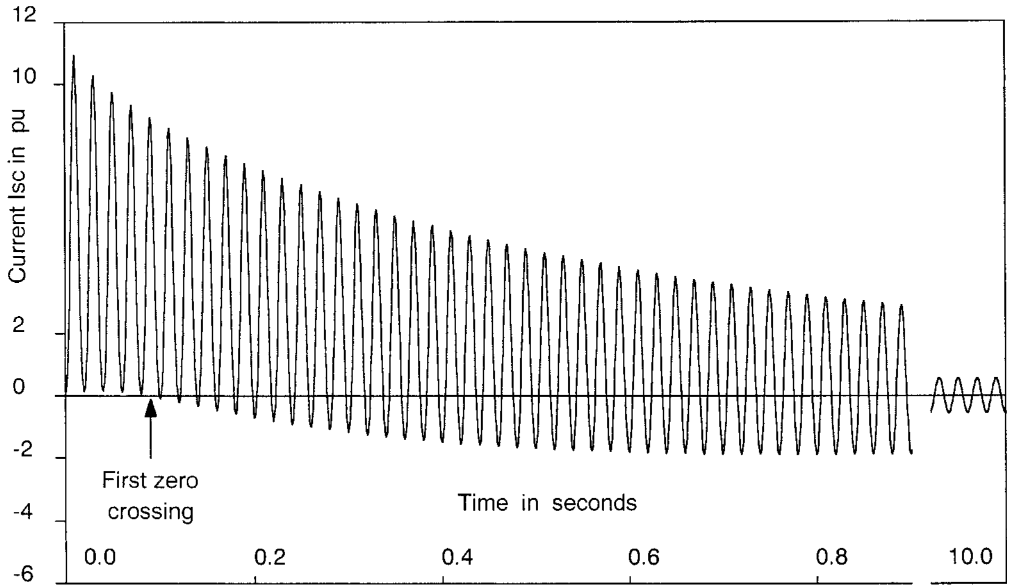


**Figure 7.1** Short-circuit current decrement for a salient pole generator that has a high armature time constant $T_a$.

### 7.2.11 Fault Breaking Current

The fault current effects have been described above for the making duty. However, some further points are appropriate for the breaking duty. The breaking duty root-mean-square duty is usually specified to take place after a number of cycles of fault current have passed. (It may also be expressed as a peak value of current, although this is less common.) This is usually taken to be the time given by the manufacturer for the circuit breaker to open and clear the fault. This is typically 5 to 8 cycles of the fundamental current. The engineer should specify the requirements for the particular power system and the manufacturer should then confirm whether the equipment offered could meet the requirement. Each power system should be considered on its own merits in this regard.

Equation (7.2) can be used to calculate the situation at the time given for the breaking duty. Usually the sub-transient time decay term has fallen to zero, and the solution is in the transient period. When an 'external' impedance is present its resistance can be included in the $T_a$ time constant and its reactance added to the appropriate machine reactances. References 5 and 6 explain how the 'derived' reactances and time constants are calculated and affected by the addition of the external impedance.

If the lower envelop of the transient AC part and the DC part of (7.2) are separated out then two functions can be presented as follows. At current zero the critical time $t_c$ in seconds occurs when, $t = t_c$,

$$\frac{I_a}{V_{pk}} = -\left[\left[\frac{1}{X'_d} - \frac{1}{X_d}\right] \exp\frac{-t}{T'd} + \left[\frac{1}{X_d}\right] + \left[\frac{1}{X''_d}\right]\right] \exp\frac{-t}{Ta} \tag{7.3}$$

Let,

$$y_{lhs} = \left[\frac{1}{X'_d} - \frac{1}{X_d}\right] \exp\frac{-t}{T'd} + \left[\frac{1}{X_d}\right] \quad (7.4)$$

and

$$y_{rhs} = \left[\frac{1}{X''_d}\right] \exp\frac{-t}{Ta} \quad (7.5)$$

If these two functions are plotted on a graph which has a common base of time, then they will cross each other at the critical time. Figures 7.2 and 7.3 show critical times for several ranges of values for $T'_d$, $T_a$, $X''_d$ and $X'_d$. The parameter that has the greatest sensitivity is the armature time constants $T_a$ since it moves the crossing point from the left to the right very noticeably. Changes in the value of the sub-transient reactance $X''_d$ move the curves 4 and 8 in (7.5) vertically. The higher the value of $X''_d$ the lower is the critical time. It can be seen that in order to achieve low values of the critical time, or to keep the number of cycles to the first current zero to a low number, it is necessary to have a low value of $T_a$ and a high value of $X''_d$.

## 7.2.12 Fault Withstand Duty

So far particular conditions have been considered, initial reaction to the severest fault and what happens at the time of clearing the fault. What happens during the fault is also of importance since

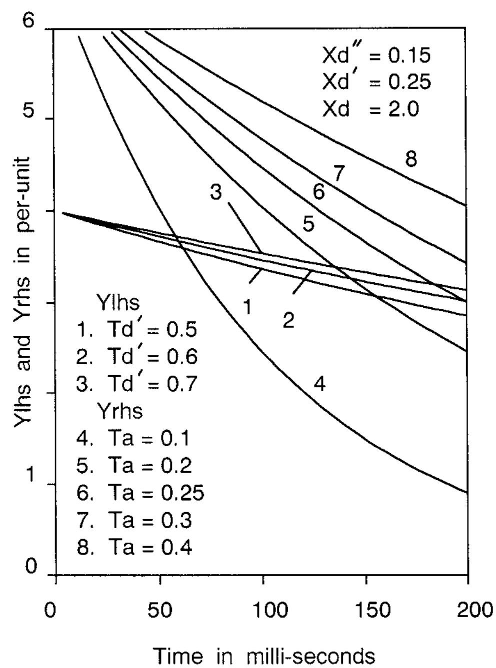


**Figure 7.2** Functions pertaining to the calculation of the critical switching time of circuit breaker that disconnects a generator from a switchboard. The generator has low values of sub-transient and transient reactances. The sensitivity of the time constant $T_a$ is shown.

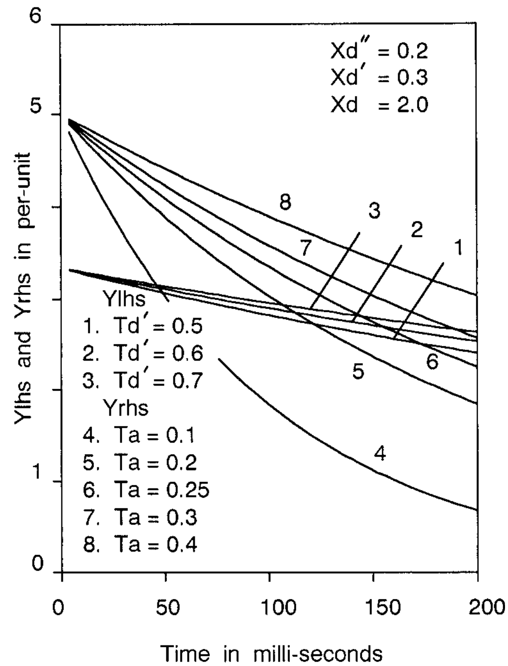


**Figure 7.3** Functions pertaining to the calculation of the critical switching time of circuit breaker that disconnects a generator from a switchboard. The generator has high values of sub-transient and transient reactances. The sensitivity of the time constant $T_a$ is shown.

extra heat is generated and the copper conductors are under considerable mechanical stress. In order to account for any cumulative effects it is necessary to rate the equipment for the long duration of a fault. The time duration usually adopted in European practice is one second, but occasional up to three seconds are applied for particularly severe service conditions. IEC60439 part 1, clause 4.3, and IEC60964 clause 4.7 give more details for the root-mean-square and peak values and duty. The withstand current duty is usually proportional to the making duty for a given voltage rating.

## 7.3 SWITCHING DEVICES

Switching devices for the power circuits that need to be operated frequently are usually circuit breakers and contactors. Manually operated load break switches, fuse-switch combinations and molded case circuit breakers are used for feeder circuits that are infrequently operated.

### 7.3.1 Outgoing Switching Device for Switchgear

The outgoing switching device in a high current, high fault level, switchboard will usually be a power circuit breaker if it feeds more that about 400 amps to the load. Below 400 amps the circuit could have a fuse-contactor combination, see sub-section 7.3.2 for comments on contactors and Chapter 8 on fuses. Therefore if the outgoing device must be a circuit breaker then the comments and discussion in sub-section 7.2.3 above apply. Low voltage switchboards often use moulded case circuit breakers for incoming and outgoing circuits, and these can be fitted with a variety of auxiliary devices such as motor operators for remote control, padlocks for safe isolation and shunt trip coils for rapid opening under some fault conditions.

### 7.3.2 Outgoing Switching Device for Motor Control Centres

Motor control centres and some switchboards use contactors as the frequently operated switching device for individual outgoing loads up to about 400 amps. The figure of 400 amps is about the limit of fuse and contactor design capability. See Chapter 8 for a discussion on fuses. Contactors and their accompanying fuses should be used where ever possible because:-

- Much less expensive than a circuit breaker.
- Much smaller and simpler in the construction.
- Heavy faults are cleared faster due to the fast action of the fuses.
- Enables the outgoing cable sizes to be significantly smaller due to the reduced fault clearing time provided by the fuses. Cables are sized for rated running current and fault current withstand when a major fault occurs at the load terminals. See Chapter 9.

Contactors differ from circuit breakers in that they are designed to handle rated running current and very short-term low fault level situations. Contactors cannot withstand the high fault currents. A fuse must be placed in series to interrupt fault currents and sustained overcurrents. This means that the device is physically much more compact than a circuit breaker and hence much less expensive. The fuses and the contactor must be carefully coordinated for fault current let-through capability. European practice often refers to IEC60158 part 1, 60292 part 1, 60947 part 2 and 60632 part 1. IEC60947 part 4, clause 7.2.5.1, applies to low voltage equipment and the coordination should be at least 'Type 2'. IEC60632 applies similarly to high voltage equipment where the coordination is referred to as 'Type C', in clause B4.1 therein. The concept of this coordination is that the contactor may suffer permanent damage if it passes the fault current for too long a period. The less stringent Type 1 for low voltage switchgear requires the contactor or starter to be repaired or replaced after a short circuit has been cleared. Type 2 on the other hand, and Type C for high voltage switchgear, is more stringent and requires these devices to be suitable for further service after passing the short-circuit current. The more stringent situation has the risk of the contacts in the contactor becoming welded together by the heat produced by the short circuit, but this is recognised and deemed acceptable.

Low voltage contactors are simple air-break electromagnetic devices. High voltage contactors are air-break, vacuum or SF6 devices, although air-break is becoming obsolete. Most contactors are closed and held closed by the action of a powerful fast acting electromagnet. Occasionally a mechanically held arrangement is required to safeguard against a loss of supply and the need to maintain power to the load once the supply is restored. This practice often applies to feeders for distribution transformers, where restoration of the secondary supply must not be delayed by manual intervention. In all cases the opening of the contactor is carried out by a powerful spring. With a mechanically held arrangement an auxiliary solenoid is fitted to unlatch the holding mechanism.

Low voltage contactors are usually fitted with purpose-made protection devices for guarding against overloading and single-phase operation. These devices are used individually or in combination and operate on magnetic, thermal or electronic principles. Electronic static devices offer the widest range of time-current characteristics.

High voltage contactors use similar protection devices to those used with high voltage circuit breakers, except that high voltage fast-acting fuses are also connected in series with the contactor. The protection devices tend to be more sophisticated and are usually mounted away from the contactor and fuse assembly, in a relay compartment. Single-phase protection is usually required for high voltage motors. Earth fault protection also tends to be more sophisticated and special current transformers and relays are necessary. See Chapter 12 for details of protection relays and their coordination with each other and with their associated equipment.

## 7.4 FUSES FOR MOTOR CONTROL CENTRE OUTGOING CIRCUITS

Fuses are chosen to match the normal current of the load. The fuse current rating is always chosen to be higher than the load current by an amount called the 'fusing factor', which is given by:-

$$\text{Fusing factor} = \frac{\text{Fuse rating, in amps}}{\text{Normal load current, in amps}}$$

For low voltage motors the fusing factor is larger for the small motors (less than 15 kW) than it is for the large motors (up to 250 kW). Figure 7.4 shows how the typical fusing factor varies for low voltage motors. The slope and bias of the lines in the figure will be different for each type or 'model' of fuse. For high voltage motors the fusing factor tends to be between 1.5 and 2.5. The characteristics of the fuses vary according to the type of load, e.g. continuous motor load, very intermittent motor load, feeder transformers, static heaters, thyristor controlled loads, power rectifier loads.

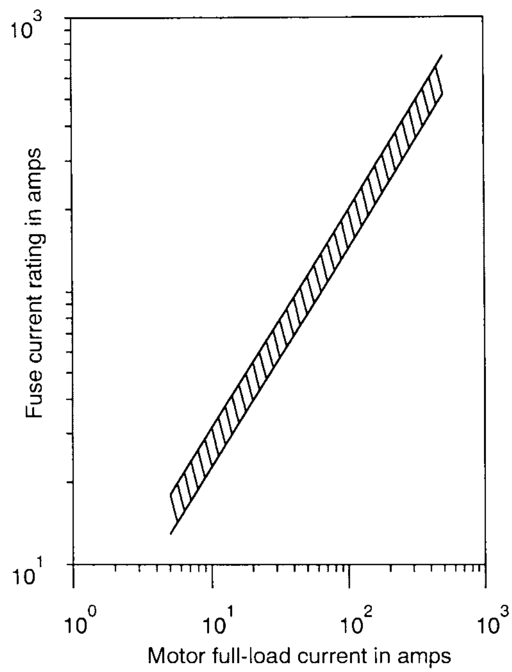


**Figure 7.4** Low voltage fusing factor for induction motor circuits.

Fuse manufacturers will usually offer advice on the most appropriate fuses to be used in a particular installation.

## 7.5 SAFETY INTERLOCKING DEVICES

Most switchboards and motor control centres are fitted with a variety of electrical and mechanical safety interlocking devices. Their purposes are to protect against for example:-

- Withdrawing the switching device while it is carrying load or fault current.
- Prevent the switching mechanism from being inserted when it is in its ‘on’ state.
- Opening of access doors or panels before setting the switching device in its ‘off’ state.
- Gaining physical access by human operators while the main conductors and contacts are energised.
- Gaining access to the busbars when the switching devices have been withdrawn.
- To prevent earthing switches from being closed on to live circuits or busbars.
- Incorrect electrical operation of a complex process system in which various external devices, motors, pumps, etc. are intimately related. For example a lubrication oil pump must be running before the main drive motor is started on a pump or compressor.

Most of the above interlocks are mechanical latches, bolts and shutters. The last category is electrical functions using wired relays or electronic logic. Electrical interlocking is also used to ensure that certain closing and tripping functions take place in a particular sequence. The following examples are typical interlocking sequences:-

- Energising a downstream switchboard through a transformer or plain interconnector. The upstream switching device is closed first. The downstream device is then closed. If either trips on fault then the other may be caused to trip by auxiliary circuits and relays.
- ‘Two-out-of-three paralleling’ is a term used when a switchboard has two parallel feeders. It is the term given to a particular closing scheme applied to the two incoming and the busbar section circuit breaker. The feeders are usually transformers. The purpose of the scheme is to enable a no-break transfer of the feeders to take place, and to minimise the duration of a prospectively high fault level that may exist during the transfer. Auxiliary switches are fitted within the three circuit breakers to determine when all three are closed. As soon as the third circuit breaker is closed the fault level at the busbars will in most cases be too high, and a signal is then given to one of the circuit breakers to trip. A selector switch is sometimes used to choose which of the three will trip. Some installations use a timer relay to delay the automatic tripping action, and the time delay setting is typically 0.5 to 2.0 seconds. This scheme is not used for all dual feeder switchboards, but is common practice with low voltage switchboards.
- Where a situation can arise that two supplies could be switched in parallel, then it is necessary to check that they are in synchronism and come from the same source, e.g. either side of an upstream switchboard. Checking can be arranged in one of two methods, or a combination of both methods. The first method uses auxiliary switches on the upstream circuit breakers, usually the busbar section circuit breakers. These auxiliary switches give a signal that its circuit breaker is open, thereby signalling that an unsynchronised supply will exist at the downstream location. The signal is used to prevent the three downstream circuit breakers being closed all at the same time, i.e. the ‘two-out-of-three paralleling’ scheme is inhibited from closing its third circuit breaker. The

second method is popular and uses a 'synchronising check' relay (25) to sense the voltage on both sides of a circuit breaker. For the above mentioned dual incomer switchboard all three circuit breakers would be equipped with the synchronising check relays.

## 7.6 CONTROL AND INDICATION DEVICES

The requirements for control and indication vary considerably depending upon the type of circuit, e.g. incoming, busbar section or outgoing circuit, whether the equipment is a switchboard or a motor control centre, high or low voltage, process duty, the need for remote indication and control, and owner preferences. Table 7.2 gives typical minimum requirements for switchboard and motor control centre incoming, busbar section and outgoing circuits, but at the equipment and not including remote devices or recording instruments.

Some of these devices may be mounted on a local panel in the switchroom so as to avoid a human operator having to stand in front of a live cubicle to operate the open and close controls.

A modern plant requires more information, events and alarms to be made available at the main control room than was generally the case in the past. This has been made much easier to achieve by the use of computer networking and fibre optical technology. Most of the information that is available at the switchboard can be transferred to the main control room; so that, for example, a one-line diagram presentation can be made on a computer desk-top monitor (man-machine interface, MMI).

### 7.6.1 Restarting and Reaccelerating of Motors

During the normal operation of a power system there are occasions when the voltage profile of the whole system or just a part of it is lowered for a short period of time. This drop in voltage may be due to:-

**Table 7.2.** Control and indication devices

| Device | Generator incoming | Transformer incoming | Busbar section | Motor outgoing | Transformer outgoing |
|---|---|---|---|---|---|
| Stop (open) button | Yes | Yes | Yes | Yes | Yes |
| Start (close) button Note 2 | Yes | Yes | Yes | Yes | Yes |
| One ammeter | No | Yes | Yes | Yes | Yes |
| Three ammeter or a selector switch | Yes | Note 1 | Note 1 | No | Note 1 |
| One voltmeter with or without a selector switch | Yes | Yes | Note 3 | No | No |
| One wattmeter | Yes | Yes | No | Note 4 | Note 1 |
| One varmeter | Yes | Note 1 | No | No | No |
| One power factor meter | Yes | Note 1 | No | No | Note 1 |
| One frequency meter | Note 1 | Note 1 | No | No | No |
| Synchronising devices | Yes | Note 1 | Note 1 | No | Note 1 |

Note 1: Optional, may be necessary.
Note 2: Some oil companies are not in favor of having a human operator standing in front of a high voltage switchboard to manually close the switching device.
Note 3: One voltmeter for each side of the switchboard busbars.
Note 4: Occasionally used for high voltage motors and variable speed drives.

- Starting a large motor.
- Occurrence and clearance of a fault.
- Malfunction of an automatic voltage regulator of a generator.
- Lightning surge from an overhead line.

In general motors are specified to be able to reaccelerate or restart their loads from a constant voltage that is 80% of its nominal value, assuming that it does not recover during these operations. This voltage should be that appearing at the terminals of the motor. For motors that are located at the end of short cables, the volt-drop in the cables may be neglected. Volt-drop in long cables may be high enough to aggravate the reacceleration or starting process, even to the extent that these operations cannot be completed.

If high voltage motors and transformers are switched by contactors that derive their coil voltage from the switchboard busbars, then the contactor coil may not hold in when the busbar voltage drops below a particular value. It is better practice to derive the coil voltage from a reliable source such as an uninterruptible power supply (UPS) or a battery. Switchboards are often provided with undervoltage (27) relays to trip predetermined loads when the busbar voltage falls below a certain limit for a preset length of time. The loads may be tripped individually or in groups. If group tripping is used then the motors in the group should be related to a particular process rather than being chosen by their kW rating or some other criterion.

The scheduling of the restarting of individual motors or groups of motors should be progressive so that a large surge of reactive power is avoided. Each oil company tends to have its own philosophy for restarting and reaccelerating motors, and schemes can become complicated to understand. The introduction of micro-computers has enabled almost any philosophy to be implemented.

If a severe disturbance occurs that causes the voltage to drop well below 80% then the duration should be relatively short, e.g. 0.15 second, otherwise recovery may be difficult. If a complete loss of voltage occurs then even progressive restarting in an automatic manner may prove difficult if the loss exceeds about 3 seconds.

### 7.6.2 Micro-computer Based Systems

Modern switchgear is available with micro-computer based intelligence and network communication facilities. These facilities enable much more information to be managed, manipulated and displayed than was possible in the past, when only analog devices were available. Modern practice for most major projects is to ensure that the network communication precisely matches that of other facilities within the plant. System control and data acquisition (SCADA) systems and distributed control systems (DCS) were developed in the industrial process control industries long before micro-computers became available for switchgear. In recent years there has been some convergence of approach between the more traditional SCADA and DCS network languages and protocols and those of the electrical power industries. Consequently it is now much easier to specify fully compatible process and electrical network systems.

Within switchgear the approach to control, indication and protection has changed. These functions are no longer separate entities. They are combined into micro-computer based electronic relay modules. A module is used for each incoming, busbar section and outgoing unit, that is capable of measuring currents, voltages, status of switching devices, interfacing with external interlocks. They are also capable of carrying out relatively simple calculations such as active power, reactive power and power factor of the circuit, number of attempted starts for a motor.

Transmission of information between switchboards and to other locations such as a control room can be achieved by either optical fibre or 'hard wire' cables. Suitable interfaces are placed at each end of the cables. As with many aspects of computing the speed of data transmission, method of porting, the protocols available, memory capacity and speed of calculation are upgraded, improved and superseded almost on a yearly basis. It is therefore necessary to be well aware of 'the state of the art' in these subjects so that a system that is about to be superseded is not purchased.

The following description of integrated motor control systems (IMCS) is based upon Reference 7, for which permission to use the material therein was kindly given by Switchgear and Instrumentation Ltd. The principles described can be used for low and high voltage switchgear that contain plain feeders, interconnectors, incomers and busbar section circuit breakers, in addition to motor feeders.

Four main units are used in the IMCS, which are the motor control unit (MCU), the feeder control unit (FCU), the circuit breaker control unit (CBCU) and the central control unit (CCU). A MCU is a microprocessor (micro-computer) based module which has integrated control, monitoring, protection functions, and a communication interface for the motor starter. An FCU is very similar to a MCU and interfaces communication for the plain feeder contactor or circuit breaker. A CBCU is also similar to a MCU but is used for incomers, interconnectors and busbar section circuit breakers. A CCU provides the facility to communicate simultaneously with MCUs, FCUs, CBCU, a distributed control system (DCS), system control and data acquisition (SCADA) and other digital information systems. Other discrete devices such as special protective relays can also be addressed by the CCU provided the software and porting systems are compatible.

Serial communication network equipment is used to couple all the microprocessor based units. Figure 7.5 shows the basic arrangement of a typical system. The number of switchboards and motor

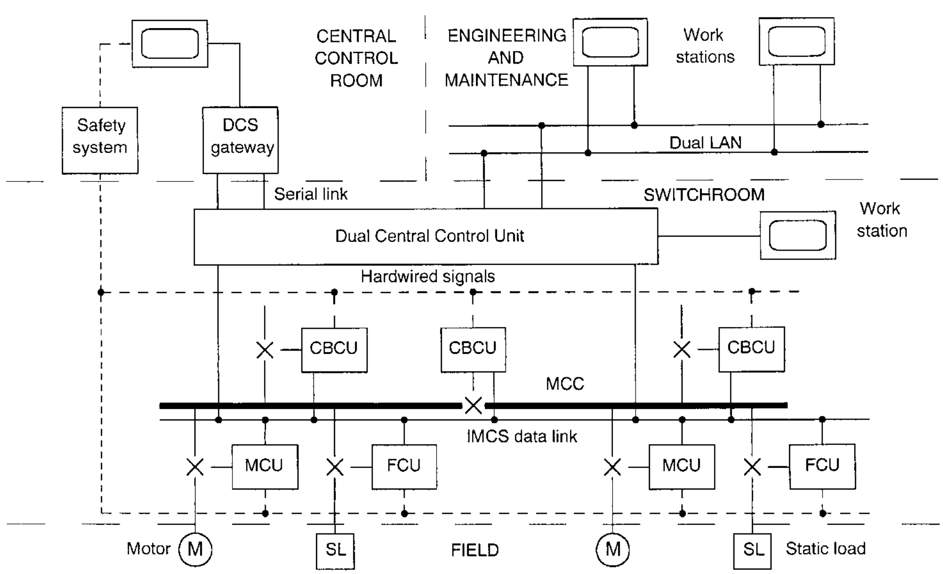


**Figure 7.5** Intelligent motor control centre.

control centres can be increased to cater for a large plant. A typical IMCS should include at least the following components:-

- Each outgoing motor or plain feeder unit requires a MCU or a FCU.
- Each incoming interconnector and busbar circuit breaker also requires a FCU.
- A CCU should be provided for either, a complete switchboard, a group of switchboards, or all switchboards located in a switchroom. A dual redundant system may be chosen so as to raise the system reliability and availability.
- Interfacing equipment and software to communicate with a DCS and a SCADA system, if they exist.
- A local area network (LAN) to couple all the units within the IMCS, which should not be a shared system such as the DCS.
- Various sources of uninterruptible power will be required, if the plant is spread over a large site. These will provide the essential power to the IMCS processing units when other less reliable power supplies interrupt or fail.
- Protection circuits and devices to render the system immune from electromagnetic interference.

In switchboards that supply motors the protection, control and measurement functions will be the most varied for the motor circuits. Generator incomers would be the next lower in complexity. The following functions are typical of all but the lowest ratings of motors:-

- Motor current.
- Motor overload protection, settings, status, pre-alarms and time to trip.
- Unbalanced loading, settings, status and pre-alarms.
- Earth fault protection, settings, status, alarms.
- Thermal status information including inhibition of starting.
- Stalling protection, settings and status.
- Acceleration time.
- Automatic restarting information due to voltage drop at the busbars.
- Total operating time of the motor.
- Operating time since the last start command.
- Non-operating time since the last stop command.
- Number of operations of the contactor.
- Local stop command function, i.e. a push button or key.
- Manual resetting of all trips and alarms.
- Remote resetting of certain trip and alarm functions by using a password.
- Facilities to allow external hard-wired circuits, such as interlocks, to be monitored and used by the IMCS.
- Underpower protection of the motor and its driven equipment.
- Undervoltage tripping facilities for mechanically latched contactors.
- Historical event logging for all alarms, trips, commands and inhibiting of starting.
- Trend records should be stored for a predetermined period such as six weeks.

A similar set of functions are typical for plain feeder, incomer, interconnector and busbar circuit breakers:-

- Circuit current.
- Circuit voltage.
- Circuit power factor (optional).
- Circuit active power (optional).
- Circuit reactive power (optional).
- Open-close status of the switching device.
- Unbalanced loading, settings, status and pre-alarms (optional).
- Protective device performance information, settings and status.
- Manual resetting of all trips and alarms.
- Remote resetting of certain trip and alarm functions by using a password.
- Facilities to allow external hard-wired circuits, such as interlocks, to be monitored and used by the IMCS.
- Undervoltage tripping facilities for mechanically latched contactors.
- Historical event logging for all alarms, trips, commands and inhibiting of starting.
- Trend records should be stored for a predetermined period such as six weeks.

Indicative information such as running current should be displayed at the unit or starter itself, as well as being accessible at a console or visual display unit in a remote location.

Process control systems traditionally use an analog signal of 4 to 20 mA DC and so it is recommended that such signals should be interfaced with the MCUs by use of compatible high-speed analog-to-digital converters.

The IMCS will scan all the MCUs, FCUs and CBCUs on a continuous basis with a complete cycle time in the order of 0.5 second, regardless of the number of units in the system. Priority interrupting functions should be used for protective relaying functions, interlocking and safety related signals, where rapid action is necessary.

## 7.7 MOULDED CASE CIRCUIT BREAKERS

### 7.7.1 Comparison with Fuses

Low voltage switchgear incorporate circuit breakers and contactors as its main power switching and control devices, particularly for the outgoing plain and motor feeder circuits. The international standards that are often used for moulded case circuit breakers are, IEC60157 part 1 and IEC60292 part 1 which have been incorporated into IEC60947. IEC60947 parts 1, 2, 3 and 4 are for power circuit breakers, switches and contactors. In addition the international standards ANSI-C37.13, NEMA-SG3, NEMA-AB1 and VDE 0660 are regularly applied.

Circuit breakers are invariably used for the incomer, busbar section and switchboard interconnector switching devices, because the currents that they need to switch are too high for contactors to handle properly. Outgoing circuits can be static loads or motor loads, and these are usually limited to about 300 A to 400 A of line current. Such currents can be easily handled by a fuse-contactor combination or a moulded case circuit breaker. The lowest three-phase ratings are about 16 A. Historically systems that were designed on UK practice tended to favour fuse-contactor technology, whereas those based on European and American practices favoured a combination of a moulded case circuit breaker and a contactor. Both technologies have their own advantages and disadvantages. Reference 7 compares fuses and moulded case circuit breakers, as well as miniature circuit breakers for final sub-circuit applications. Fuses are simple, fast acting, economical and almost completely free of maintenance. They tend to enable smaller conductor sizes of cables to be used. On the other hand circuit breakers can be immediately reset after a fault has been investigated and removed, they require less spare units to be stored in a storeroom. Some types of moulded case circuit breakers have adjustable characteristics and one frame size can house many different ratings. Historically moulded case circuit breakers were placed downstream of current limiting fuses because they could not withstand high prospective fault currents that began to develop in power systems. Nowadays this problem seldom exists because of the advances made in the technology.

### 7.7.2 Operating Characteristics

Moulded case circuit breakers are available in two basic modes of operation, current limiting and non-current limiting. It is difficult to design a moulded case circuit breaker to have a cut-off characteristic that is less than 0.01 second when a fully asymmetrical short-circuit current flows. However, there are such circuit breakers available, and care is needed when selecting these devices for a circuit that has a high prospective fault current. Some manufacturers are able to provide a cut-off in the order of 0.006 second.

The protection characteristic of moulded case circuit breakers is divided into two main parts, a long time $(<t)$ part and a short time $(\ll t)$ part. The long time part provides overload protection and is created by a thermal bi-metal strip mechanism and a mechanical latch. This part functions when the current is in the range of 105% and 1000% of the rated current. In some designs, and those with ratings above about 250 A, the upper limit is adjustable between 500% and 1000%. These adjustments are made to the second part of the protection characteristic. This part $(\ll t)$ is created by a magnetic repulsion mechanism or an electromagnet that is very fast acting once the fault current exceeds the set value. The fast action does, however, have a limit to the time that is taken, and is usually in the range of 0.003 second and 0.01 second. The lower value occurs at very high currents, e.g. 200 times the rated current.

Moulded case circuit breakers are also available for incoming and busbar section purposes, with ratings up to 6000 A and service voltages between 220 V and 660 V. (At 415 V a 4000 A circuit breaker would satisfy the duty of a 2500 kVA feeder transformer with about 15% spare capacity.) These are also available as 4-pole units. Circuit breakers having ratings of 800 A and above are often provided with several adjustments that widely modify the shape of the complete protection curve, as described in Chapter 12. This enables the curve to coordinate with almost any other protective device or equipment that is immediately upstream or downstream of the circuit breaker. Some circuit breakers with the higher rated currents are also provided with integral earth fault protection facilities.

Various external attachments can be fitted to moulded case circuit breakers, e.g. pad-locking tabs, shunt trip coils, hazardous area enclosure with an 'on' and 'off' operating handle, withdrawable rack mountings, undervoltage tripping units, auxiliary switches of the normally open and normally closed types, interlocking devices, ambient temperature compensation for the protection curves. Some models are provided with a comprehensive solid-state module for creating the protection functions such as, long time delay, short time delay, instantaneous tripping, earth fault detection and alarm messages. The solid-state module may be self-powered or will require an external voltage source from a UPS.

### 7.7.3 Cut-off Current versus Prospective Current

Fuses and moulded case circuit breakers that have cut-off characteristics have similar shaped curves for cut-off current plotted against the prospective current. For a fuse the cut-off current is the value of current at the end of the melting process of the fuse element, and at the beginning of the arc that is then created. For a moulded case circuit breaker it is the current that exists when enough energy has developed to force apart the power contacts, and again the value at the beginning of the arc. The cut-off current is the highest value of instantaneous current that passes through the fuse or circuit breaker. It is also called the 'peak let-through' current. This current is shown on the y-axis of the graph. The x-axis is the root-mean-square value of the fault current that is available in the actual circuit, and is usually taken to be the symmetrical value before any 'doubling' factor is included.

The graphs are plotted in two parts. The first part is a straight line that occupies all of the graphical area available, and is the line for the peak value of the asymmetrical current available against the symmetrical fault current available. The relationship between these variables is simply the appropriate 'doubling' factor, which can be found from the manufacturer's curves to be typically in the range of 2.1 and 2.4 per unit. The second part is a set of curves or lines of lower slope that apply to all the fuses or circuit breakers in the manufacturer's range of products. Each one of these lines intersects the single prospective line, at a point which represents the current that corresponds to melting a fuse or parting the contacts of a circuit breaker when the instantaneous current is at its peak value in the first half-cycle. This point is called the 'threshold current' in some of the literature, see Reference 8. At this point no cut-off occurs. Thereafter for higher symmetrical fault currents the particular rated device will experience an amount of cut-off, the higher the fault current the more the cut-off will occur. Theoretically the set of lines for the devices will be curved when plotted on a log-log scale, but in practice manufacturers may approximate these by straight lines. Figure 7.6 shows the characteristic for one fuse and one moulded case circuit breaker, each rated at 40 A for protecting an induction motor. The location of the device lines or curves in the vertical plane will vary considerably with different manufacturers and functions, such as motor feeders, heavy duty or light duty. In general they will be parallel lines or curves for a particular type of device, i.e. one type with many different ratings in the range of product.

### 7.7.4 *I*-squared-*t* Characteristic

When fuses or moulded case circuit breakers are applied to a circuit it is necessary to ensure that their *I*-squared-*t* characteristics coordinate properly with the thermal capabilities of the downstream equipment, especially the cables. In order to determine the *I*-squared-*t* characteristics of a protective device it is assumed that the current in the device suddenly changes from a normal load value to the fault value in a very short period of time, i.e. similar to a step change in a control system. Hence for each value of current along the x-axis of the device's time-current characteristic the value of the current squared multiplied by the corresponding time can be plotted. For cables and busbars the *I*-squared-*t* function equals a constant (k) for each cross-sectional area of conductor, as explained

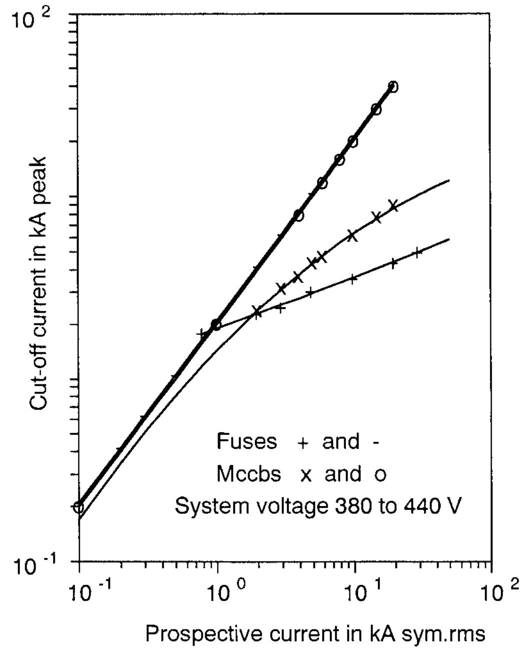


**Figure 7.6** Cut-off and prospective current curves for a 40 A fuse and a 40 A moulded case circuit breaker.

in Chapter 9. For EPR and XLPE insulated cables with copper conductors the value of k is usually taken as 143 or 144.

Fuses or moulded case circuit breakers have known current-time functions and for practical purposes these functions can be simply converted into their $I$-squared-$t$ characteristics by using the above method on as many sample points as can be conveniently transcribed. Figures 7.7 and 7.8 show the I-t and the corresponding derived $I$-squared-$t$ characteristics for 32 A and 125 A fuses, 32 A and 125 A moulded case circuit breakers, and appropriate cables for the circuit.

## 7.7.5 Complete and Partial Coordination of Cascaded Circuit Breakers

Where moulded case circuit breakers are chosen for a plant in favour of fuses the coordination of cascaded units becomes a little more difficult than with fuses. This difficulty arises from the fact that these circuit breakers have a definite or 'near definite' minimum time limit to their time-current characteristic. This causes the lower part of the circuit breaker protection curve to be almost horizontal at a low value of time, typically in the range of 0.003 and 0.01 second.

If a particular type or model is chosen from a manufacturer it can be seen that this low horizontal part may be similar or the same for all ratings of circuit breakers within the range. Supposing a 2:1 or 3:1 ratio of upstream rating to downstream rating is chosen for a particular circuit. Selective tripping of the downstream unit can only be relied upon for fault currents beyond the magnetic vertical part of the curve for the downstream unit, but less than the vertical part of the upstream unit. For faults beyond the vertical part of the upstream unit there will be a race between both units and the upstream unit may trip before the downstream unit. This is not a satisfactory

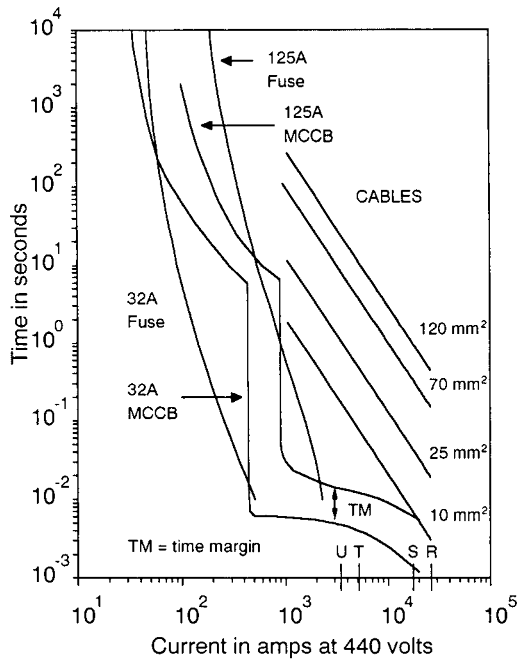


**Figure 7.7** Clearing time versus fault current for fuses and moulded case circuit breaker curves.

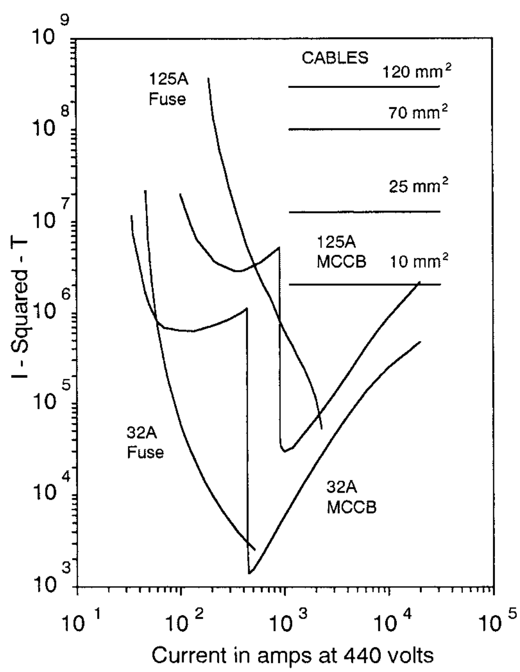


**Figure 7.8** *I*-squared-*t* versus fault current for fuses and moulded case circuit breaker curves.

situation and is called 'partial coordination'. What is called 'complete coordination' is obtained by ensuring that the horizontal part of the upstream curve is located above that of the downstream unit by a suitable time margin. This may not be easily obtained and it may be necessary to use different types or even models from different manufacturers to create a sufficient time margin. If the ratio of upstream to downstream rating is greater than about 3:1 and the upstream unit has an adjustable short-time delay then the difficulty can be overcome by suitable adjustments. This can be seen in Figure 7.7 by comparing the curves of the 32 A and 125 A circuit breakers.

### 7.7.6 Worked Example for Coordination of Cascaded Circuit Breakers

A 440 V 60 Hz switchboard feeds a 4-wire distribution board for small loads such as socket outlets. The switchboard has a fault making capacity of 100 kA rms. After applying diversity factors to the loads the total load current is 90 A. Moulded case circuit breakers (MCCBs) rated at 16 A and 32 A are to be used for the loads. The installation will use cables having copper conductors and XLPE insulation. The cable from the switchboard to the distribution board is 20 metres in length. A typical load cable is 15 metres in length and will carry a current of 29 A at a power factor of 0.85 lagging. Ignore the presence of induction motors at the switchboard. Find the following:-

- Rating of the incoming circuit breaker.
- Size of the incoming cable.
- Size of the load cable.
- Check that the MCCB coordination is complete.

The following sequence will be used to calculate the results:-

- Choose the upstream MCCB at the switchboard and its settings.
- Choose the incoming feeder cable.
- Choose the downstream load MCCB and its settings.
- Find the upstream fault source impedance.
- Find the cut-off, or let-through, current from the switchboard.
- Find the impedance of the incoming cable.
- Find the impedance of the load cable.
- Find the fault current at the distribution board, point B.
- Find the fault current at the beginning of the load cable, point C.
- Find the fault current at the end of the load cable, point D.
- Check the peak making capacity and peak let-through capacity of the MCCBs chosen above.
- Find the highest $I$-squared-$t$ value for the upstream MCCB.
- Calculate a suitable size for the load cable to satisfy the $I$-squared-$t$ duty.
- Calculate the volt-drop in the load cable.
- Select the largest conductor size from the above calculations.
- Plot the results.

Solution:

a) Choose the upstream MCCB at the switchboard and its settings.

From a manufacturer's data sheet a 125 A MCCB with an adjustable 100 A thermal release is chosen. The thermal release is set to 90 A to match the total load.

b) Choose the incoming feeder cable.

From a manufacturer's data sheet several cables can be compared for the same ambient conditions and laying arrangements. Their details are:-

50 $mm^2$cable, maximum current 124 $A$, $R = 0.492$, $X = 0.110$ ohms/km.

70 $mm^2$cable, maximum current 159 $A$, $R = 0.340$, $X = 0.106$ ohms/km.

95 $mm^2$cable, maximum current 193 $A$, $R = 0.247$, $X = 0.093$ ohms/km.

The 70 $mm^2$ cable is chosen since the rating of the 50 $mm^2$ cable is just too low.

c) Choose the downstream load MCCB and its settings.

From a manufacturer's data sheet a 32 A MCCB with an adjustable 32 A thermal release is chosen. The thermal release is set to 29 A to match its load.

d) Find the upstream fault source impedance.

For a prospective symmetrical fault current of 100 kA rms the upstream fault source impedance $Z_{up}$ is:-

$$Z_{up} = \frac{440.0}{1.732 \times 100000.0} = 0.0 + j\ 0.00254 \text{ ohms}$$

e) Find the cut-off, or let-through, current from the switchboard.

From a manufacturer's data sheet a 125 A MCCB has a let-through current $I_p$ of 25 $kA_{peak}$ for a prospective fault current $I_s$ of 100 $kA_{rms}$.

f) Find the impedance of the incoming cable.

The impedance $Z_{c1}$ of the incoming cable is:-

$$Z_{c1} = \frac{25.0(0.340 + j\ 0.106)}{1000.0} = 0.0085 + j\ 0.00265 \text{ ohms}$$

g) Find the impedance of the load cable.

The impedance $Z_{c2}$ of the incoming cable is:-

From a manufacturer's data sheet several cables can be compared for the same ambient conditions and laying arrangements. Their details are:-

6 $mm^2$ cable, maximum current 33.8 $A$, $R = 3.91$, $X = 0.130$ ohms/km.

10 $mm^2$ cable, maximum current 46.7 $A$, $R = 2.31$, $X = 0.126$ ohms/km.

The 6 $mm^2$ cable is chosen provisionally, since its rating is above the 32 A rating of the MCCB that feeds it. The impedance $Z_{c2}$ of the load cable is:-

$$Z_{c2} = \frac{15.0(3.91 + j\ 0.13)}{1000.0} = 0.0587 + j\ 0.00195 \text{ ohms}$$

h) Find the fault current at the distribution board, point B.

From a manufacturer's data sheet the contact impedance data for low voltage MCCBs are:-

| MCCB Rating in amps | Resistance in ohms | Reactance in ohms at 60 Hz |
|---|---|---|
| 16 | 0.01 | neglect |
| 20 | 0.008 | neglect |
| 25 | 0.0065 | neglect |
| 32 | 0.005 | 0.000009 |
| 50 | 0.0027 | 0.000016 |
| 63 | 0.002 | 0.000025 |
| 80 | 0.0014 | 0.000042 |
| 100 | 0.0011 | 0.00007 |
| 125 | 0.0008 | 0.0001 |
| 160 | 0.00055 | 0.00015 |
| 200 | 0.0004 | 0.0002 |
| 250 | 0.00029 | 0.00027 |
| 320 | 0.0002 | 0.0004 |

Hence the upstream MCCB impedance $Z_{m1}$ is 0.0008 + j 0.0001 ohms.

Therefore the fault impedance $Z_{fb}$ is:-

$$Z_{fb} = Z_{c1} + Z_{m1} = 0.00093 + j\ 0.00275 \text{ ohms}$$

The fault making current $I_{fb}$ is:-

$$I_{fb} = \frac{V_p}{Z_{fb}} = \frac{440.0}{1.732(0.0093 + j\ 0.00275)} = 26{,}195 A_{\text{rms}}$$

Where $V_p$ is the line-to-neutral voltage. Locate the point R for 26,195 A on the prospective curve in Figure 7.9.

i) Find the fault current at the beginning of the load cable, point C.

Hence the downstream MCCB impedance $Z_{m2}$ is $0.005 + j0.000009$ ohms. Add this to $Z_{fb}$ to give the fault impedance $Z_{fc}$ as:-

$$Z_{fc} = Z_{fb} + Z_{m2} = 0.00093 + j\ 0.00275 + 0.005 + j\ 0.000009$$
$$= 0.0143 + j\ 0.002759 \text{ ohms}$$

The fault making current $I_{fc}$ is:-

$$I_{fc} = \frac{V_p}{Z_{fc}} = \frac{440.0}{1.732(0.0143 + j\ 0.02759)} = 17{,}443 A_{\text{rms}}$$

Locate the point S for 17,443 A on the prospective curve in Figure 7.9.

j) Find the fault current at the end of the load cable, point D.

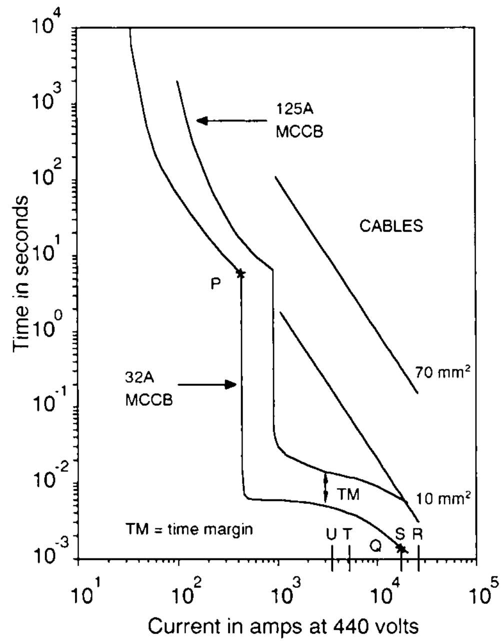


**Figure 7.9** Coordination of MCCBs at a distribution board.

Add $Z_{c2}$ to $Z_{fc}$ to give the fault impedance $Z_{fd}$ as:-

$$Z_{fd} = Z_{fc} + Z_{c2} = 0.0143 + j\ 0.002759 + 0.0587 + j\ 0.00195$$
$$= 0.073 + j\ 0.00471 \text{ ohms}$$

The fault making current $I_{fd}$ is:-

$$I_{fd} = \frac{V_p}{Z_{fd}} = \frac{440.0}{1.732(0.073 + j\ 0.00471)} = 3473 A_{\text{rms}}$$

Locate the point U for 3473 A on the prospective curve in Figure 7.9.

k) Check the peak making capacity and peak let-through capacity of the MCCBs chosen above. The following manufacturer's data are typical for 125 A and 32 A MCCBs:-

| MCCB rating | Making capacity | | Let-through capacity $kA_{peak}$ (cut-off) |
|---|---|---|---|
| | $kA_{rms}$ | $kA_{peak}$ | |
| | | Note 1 | |
| 32 A | 95 | 209 | 6.0 |
| 125 A | 132 | 290 | 25.0 |

Note 1: Approximate values of the doubling factor taken to be 2.2.

Hence the peak making capacity of the 32 A MCCB is well in excess of the let-through peak current of the 125 A MCCB.

l) Find the highest $I$-squared-$t$ value for the upstream MCCB.

Locate two points P and Q on the curve of the upstream MCCB as follows,

| Point | Current in p.u. | Current in amps | Time in Seconds | $I^2t$ |
|---|---|---|---|---|
| P | 14 | 406 | 6 | 989016.0 |
| Q | 602 | 17,450 | 0.0016 | 487204.0 |

Hence $I^2t$ at P exceeds that at Q.

m) Calculate a suitable size for the load cable to satisfy the $I$-squared-$t$ duty.

For XLPE cables the 'k factor' for the $I$-squared-$t$ is 143. The cross-sectional area A is:-

$$A = \frac{(I^2t)^{0.5}}{K} = \frac{(9{,}89{,}016)^{0.5}}{143} = 7.42\ \text{mm}^2$$

The next standard cross-sectional area is 10 mm$^2$.

n) Calculate the volt-drop in the load cable.

The usual limit to volt-drop in three-phase cables feeding static loads is 2.5% at full load.

$$\text{Volt-drop} = \frac{1.732 \times I_{\text{flc}} \times L(R\cos\phi + X\sin\phi)}{1000}$$

Where, $I_{flc} = 29$ A, L = 15 m and $\phi = 54.5495$ degrees.

For a 6 mm$^2$ cable the volt-drop is found to be:-

$$\text{Volt-drop} = \frac{1.732 \times 29.0 \times 15.0(3.91 \times \cos 54.5495 + 0.13 \times \sin 54.5495)}{1000}$$
$$= 2.504 + 0.0516 = 2.6 \text{ volts or } 0.58\% \text{ of } 440 \text{ V}$$

which is well within the limit of 2.5%.

o) Select the largest conductor size from the above calculations.

Comparing the conductor sizes found in m) and n) gives the larger as 10 mm$^2$, and this size should be used.

p) Revise the calculation of the fault current $I_{fd}$

The impedance $Z_{c2}$ of the load cable is:-

$$Z_{c2} = \frac{15.0(2.31 + j\ 0.128)}{1000.0} = 0.0347 + j\ 0.00192 \text{ ohms}$$

Add $Z_{c2}$ to $Z_{fc}$ to give the fault impedance $Z_{fd}$ as:-

$$Z_{fd} = Z_{fc} + Z_{c2} = 0.0143 + j\ 0.002759 + 0.0347 + j\ 0.00192$$
$$= 0.049 + j\ 0.00468 \text{ ohms}$$

The fault making current $I_{fd}$ is:-

$$I_{fd} = \frac{V_p}{Z_{fd}} = \frac{440.0}{1.732(0.049 + j\ 0.00468)} = 5161 A_{\text{rms}}$$

Locate the point T for 5161 A on the prospective curve in Figure 7.9.

q) Plot the results.

The results are plotted in Figure 7.9.

### 7.7.7 Cost and Economics

A proper cost and economic analysis can only be made after all the invited manufacturers have fully complied with the details of the enquiry specification. The engineer must satisfy himself that this requirement has been properly met, otherwise a low bid price may indicate non-compliance or poor understanding of the enquiry specification. Apart from the important technical requirements there are often other engineering considerations that should be taken into account, e.g. vendor documentation, spare parts, delivery schedule, obsolescence, testing and inspection. Some of these aspects have a definite cost impact whereas some are somewhat intangible, e.g. history of performance, delivery schedule, obsolescence.

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