Session Eight:

Short Circuit Requirements and Selection of HV Switchgear and Power Cables

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1 Executive Summary

The objective of this paper is to discuss the short circuit requirements of HV switchgear such as generator circuit breakers and other distribution circuit breakers, both indoors and outdoors. This paper identifies the various short circuit withstand capabilities, their significance and importance in relation to short circuit and other transient conditions that exist in a power system under fault conditions. Many electrical engineers often confuse the real meanings of these requirements and generally depend on manufacturers in selecting the right switchgear for the intended application. The influence of environmental conditions is also briefly discussed for outdoor switchgear. In addition, this paper briefly explains the short circuit requirements and selection of power cables for MV & HV applications.

2 Short-circuit Requirements and Selection of Circuit Breakers

2.1 Understanding Short Circuits in a Power System

2.1.1 The Usual Causes and Nature of Faults

Short circuits (S.C) are generally caused by insulation failure, flashovers, short circuits, broken conductors, physical damage or human error. Short circuits involving all three phases simultaneously are of symmetrical nature, whilst those involving only one or two phases are asymmetrical faults. The balanced three phase faults are normally analysed using equivalent single phase circuits. Use of symmetrical components helps to resolve the asymmetrical system faults.

Short circuits do occur even in well-designed power systems, which result in disruptive electro-dynamic and thermal stresses that are potentially damaging. Fire risks and explosions are often inherent. It is essential to isolate the power source to the faulty section, and away from the healthy section as quick as possible in order to protect both equipment and personnel. It is essential that the short circuit withstand ratings of the protected equipment such as transformers, reactors, cables and conductors are not exceeded and thus the consequential damages are either eliminated or limited. Fast isolation/interruption reduces the transient instabilities and the power system will remain in synchronism. The fault current interrupting device is the *'switchgear'* or the *'circuit breaker'* and it should withstand the dynamic effects of short circuits (Although there are some conceptual differences between these two terms, this paper carries the same meaning for both).

2.1.2 Properties of Short Circuit Currents

In a power system, asymmetrical single or two phase faults are more common as compared to three-phase faults. Consider a sinusoidal time-invariant single phase source of power $E = E_m \sin \omega t$ connected to a single phase distribution line with impedance $Z = (R + j\omega L)$ as shown in Fig.1 below.

For simplification of short circuit calculations, we assume that the circuit impedance Z does not vary with flow of high short circuit current. This means, all static components such as transformers, cables, transmission lines and reactors connected to the power system have constant impedance (time-invariant). The short circuit current then is limited by the constant impedance Z and its steady state value is given by E_m/Z.

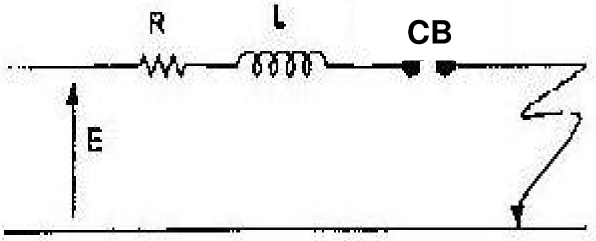


Fig.1 A Single Phase Short Circuit

However, the truth is different in practice. The flux densities and saturation characteristics of the transformer core may entirely change with its leakage reactance. The core will be driven to saturation under the influence of high short circuit currents. This will result in distorted waveforms and harmonics within. Ignoring these effects, we could write the following differential equation.

$$L(di/dt) + Ri = E_m \sin(\omega t + \theta) \qquad (1)$$

Where:

θ is the angle on the voltage wave, at which the fault occurs

i is the S.C current at a given time

The solution of this differential equation is given by

$$i = I_m \sin(\omega t + \theta - \varnothing) - I_m \sin(\theta - \varnothing)e^{-Rt/L} \qquad (2)$$

Where:

I_m is the maximum steady state current = E_m/Z

$\varnothing$ = power factor angle = $\tan^{-1}(\omega L)/R$

Equation (2) is used in the following discussion for identifying the nature of the short circuit current when the fault occurs while the voltage wave is at zero or at peak amplitude value.

Non-decaying and Decaying Components of SC Current

In power systems, generally the inductive reactance would be far greater than the circuit resistance.

i.e., $X = \omega L = 2\pi f L \gg R$.

For example, a 100MVA 0.85 pf synchronous generator may have an X/R ratio of 110 and a transformer of the same rating, an X/R ratio of 45.

Assuming a high X/R ratio, $\varnothing \approx 90° \approx \pi/2$

If a short circuit occurs at time $t = 0$ and $\theta = 0$ (i.e., when the voltage wave crosses the zero amplitude on the X-axis), the instantaneous value of the short circuit current from equation (2) is given by:

$$'i' = 2I_m = \text{Double the steady state maximum S.C current}$$

This is called the doubling effect of the transient phenomenon. If the short circuit occurs at an instant when the voltage wave peaks, $t = 0$ and $\theta = \pi/2$, the second part of equation (2) becomes zero and then there is no transient component. This means, $'i' = I_m$. These two scenarios are clearly shown in Fig. 2, (a) and (b) below.

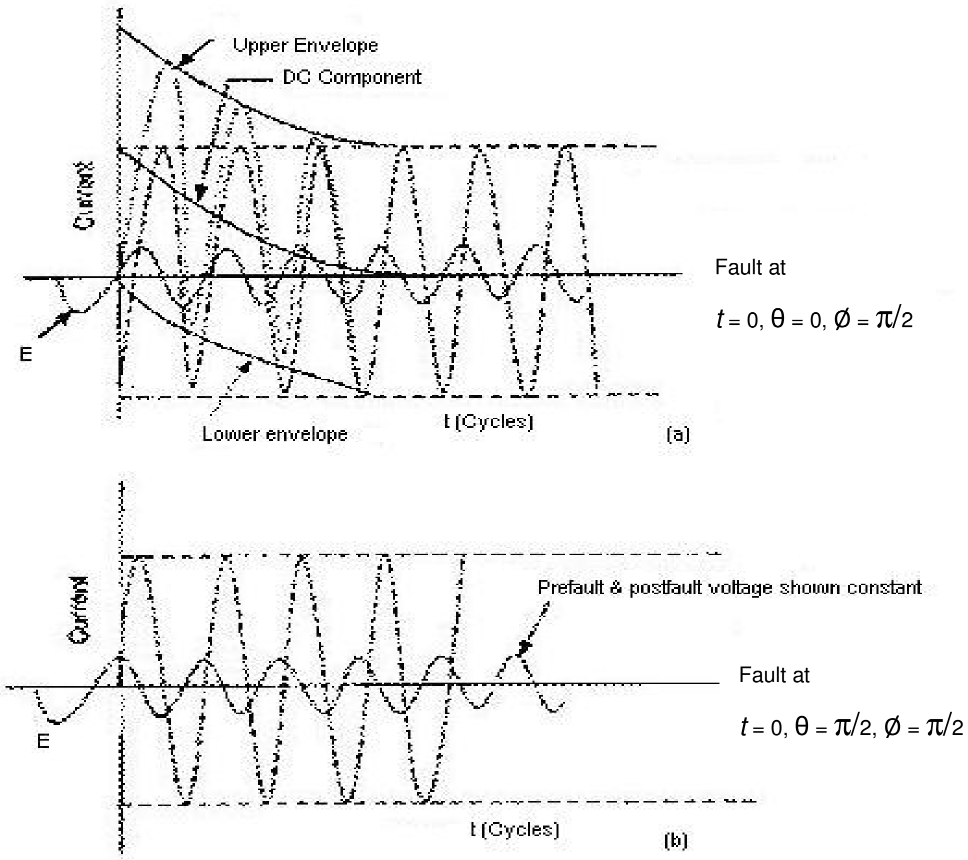


Fig.2 (a) Short circuit current waveform with maximum asymmetry;
(b) Short circuit waveform with no dc component

Therefore, the S.C. transient current component is produced by second term of equation (2) at the time of the S.C. This is called the dc component of the S.C. current. As seen from the equation it decays at an exponential rate $I_{dc}e^{-Rt/L}$. Hence, the presence of this dc component makes the fault current wave-shape envelope asymmetrical with respect to the zero axis, but symmetrical with respect to the axis of dc component (See Fig.2a). It may be noted that the higher the X/R ratio, the slower is the decay. The factor L/R in the exponential expression is termed as the *time constant* of the power system.

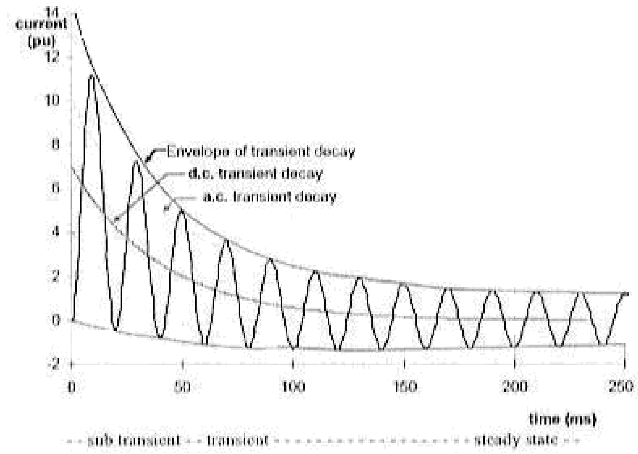
Assuming the fault impedance remains invariant throughout the short circuit, but before the full decay of the dc component, we may write:

"Total SC current in a faulted phase at a particular instant is the sum of non-decaying symmetrical AC component and the decaying DC component at that instant"

Transient Decay of AC & DC Components of SC Current

We have considered above a time-invariant impedance Z. However, this assumption is not valid for synchronous generators, synchronous and induction motors. These machines are the major sources of short circuit currents. The effective fault impedance of these machines is very low at the instant of S.C because the flux in these rotating machines cannot change suddenly. As a result, the machine will produce very high S.C currents initially, several times the steady state fault current. Later, the flux increases rapidly in the armature until its saturation. This variation of flux in the machine will vary the inductance L and hence the machine reactance X. The effect of this variation in machine reactance is a decaying AC component of the S.C current in addition to the decaying DC component.

Three regions of reactance are identified in rotating machines. They are – the initial low reactance or the sub-transient reactance Xd”, the intermediate reactance or the transient reactance Xd’, and the steady state reactance or the synchronous reactance Xd of the machine. As the circuit breakers are stressed with the initial high currents, the sub-transient reactance Xd” is usually used for fault analysis. Fig.3 below portrays this transient decay of both AC and DC components of the short circuit current in a synchronous generator.



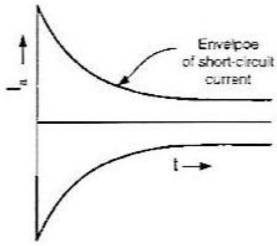
Transient decay of current in synchronous generator

Fig.3 The transient decay of AC and DC components of short circuit current in a synchronous generator.

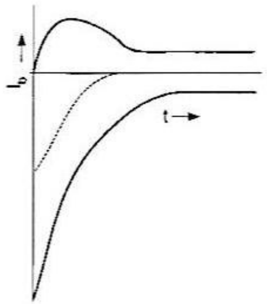
Asymmetries in Short Circuit Phase Currents

Another interesting property to be noted in the nature of short circuit is the 120° electrical time displacement in the three-phase system. Even if the short circuit happens at the voltage peak of one phase, the other two phases will produce dc offset and asymmetry because of this time displacement. Therefore, all the three poles of the same circuit breaker will experience different short circuit stresses. Such asymmetries in phase currents are characterised in Fig.4 below.

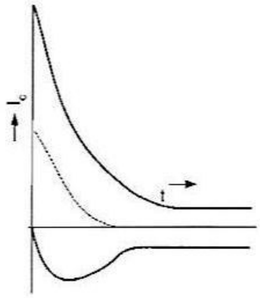
Again, if the fault is symmetrical, the sum of the above currents would be zero at any instant.



Phase ‘A’ S.C envelope



Phase ‘B’ S.C



Phase ‘C’ S.C envelope

Fig.4 Asymmetries in phase currents in a three phase short circuit

2.2 Short Circuit Requirements for a Circuit Breaker

2.2.1 Principle of Current Zero Interruption

All high voltage circuit breakers, whatever may be the arc quenching medium (oil, air or gas), use current zero interruption. Modern circuit breakers have short arc duration and low arc voltage. Fig.5 below depicts a typical short circuit current interruption in a current-zero breaker.

The short circuit happens at time $t = 0$. At t = t1 the contacts start parting and the arc is drawn across the breaker contacts. As the arc is mostly resistive, the arc current is in phase with the arc voltage as seen from Fig.5(b). The arc is then intensely cooled by the quenching medium (Air, SF6 or Oil). The rapidly rising dielectric strength across the breaker contacts extinguishes the arc at a particular current zero amplitude. The fast movement of the contacts prevents the continuation of arc.

The arc interruption happens at time t = t2 as seen from Fig.5(c). The duration of current interruption depends mainly on the interrupting time of the circuit breaker and the speed of operation of the protective relay. In modern circuit breakers this interruption time is as low as two cycles (40ms) or even less. The faster the breaker, the greater is the asymmetry and the interrupted current. The different breaker timings such as (i) Min tripping delay, (ii) CB Contact parting time, (iii) CB Arcing time and (iv) Rated interrupting time of the breaker are also shown in Fig.5(b).

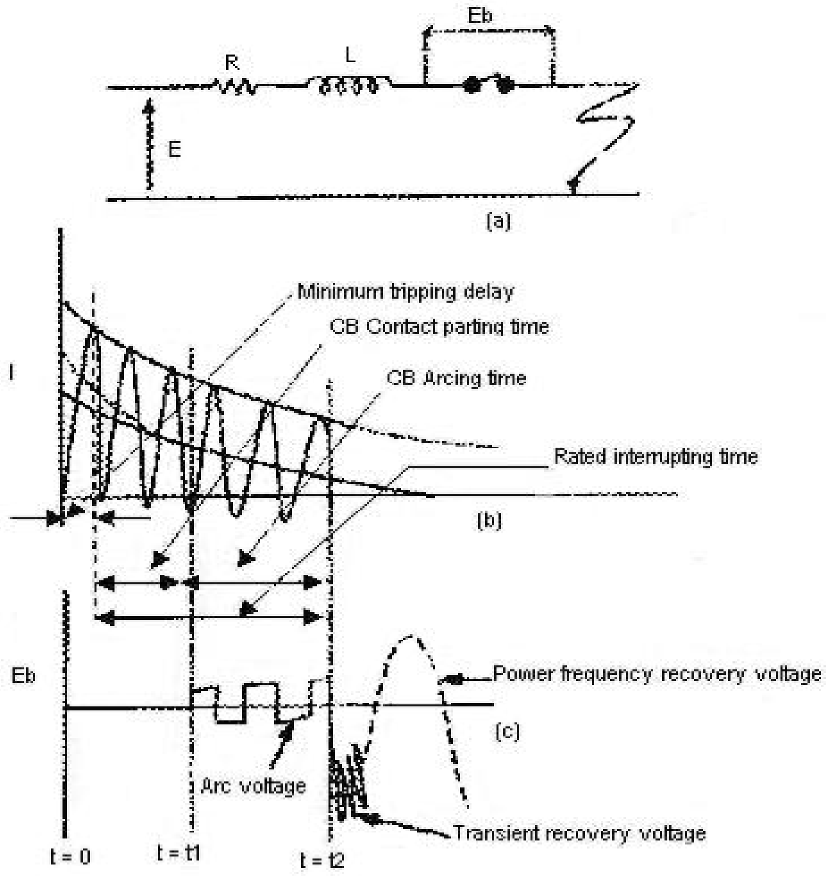


Fig.5 Current interruption in a current zero breaker: (a) Short circuit in an inductive circuit; (b) Short circuit current waveform; (c) Arc voltage during interruption and TRV after fault clearance

2.2.2 Transient Recovery Voltage (TRV)

Once the arc has been interrupted in the circuit breaker, a high frequency oscillation superimposed on the power frequency appears across the breaker contacts. The power frequency voltage has its peak at current zero because of the more inductive nature of the power system impedance. These high frequency oscillations are called the TRV as outlined in Fig.5(c) above. The amplitudes of these oscillations are sometimes as high as to breakdown the hot dielectric medium and reignite the arc. Therefore, fast rate of recovery of the dielectric strength is important in a circuit breaker design which varies with:

i) The quenching medium used (Oil, gas, air or vacuum)
ii) The interaction pressure of the medium
iii) The arc velocity
iv) The arc control devices
v) The contact shape and
vi) Number of breaks per phase etc.

Controlling TRV will help to improve the breaking capacity of the circuit breakers by eliminating restrikes. This is achieved in practice by several means. One of them is by the use of shunt capacitors at both terminals of the breaker contacts. It delays the occurrence of TRV which helps in rapid recovery of the dielectric medium. Another way of improving the breaking capacity is by influencing the rate of rise of recovery voltage (RRRV) by resistors (As these methods are beyond the scope of this paper, they are not discussed here).

2.2.3 Rated Short Circuit Duty Cycle

For circuit breakers intended for rapid re-closing, three standard duty cycles are specified by IEEE Std C37.04-1999 when operated under fault within 85-100% of the asymmetrical breaking capacity and other standard operating conditions. They are:

O-15s-CO-3min-CO OR O-0.3s-CO-3min-CO

Definite purpose circuit breakers such as GCBs are not intended for re-closing.

2.2.4 Short Circuit Ratings of the Circuit Breaker

This refers to the symmetrical component of short circuit current in r.m.s. amperes to which all required short circuit capabilities are related (IEEE Std C37.04-1999). The rated breaking current, withstand current, making current and the peak withstand current are the significant ratings of the circuit breaker.

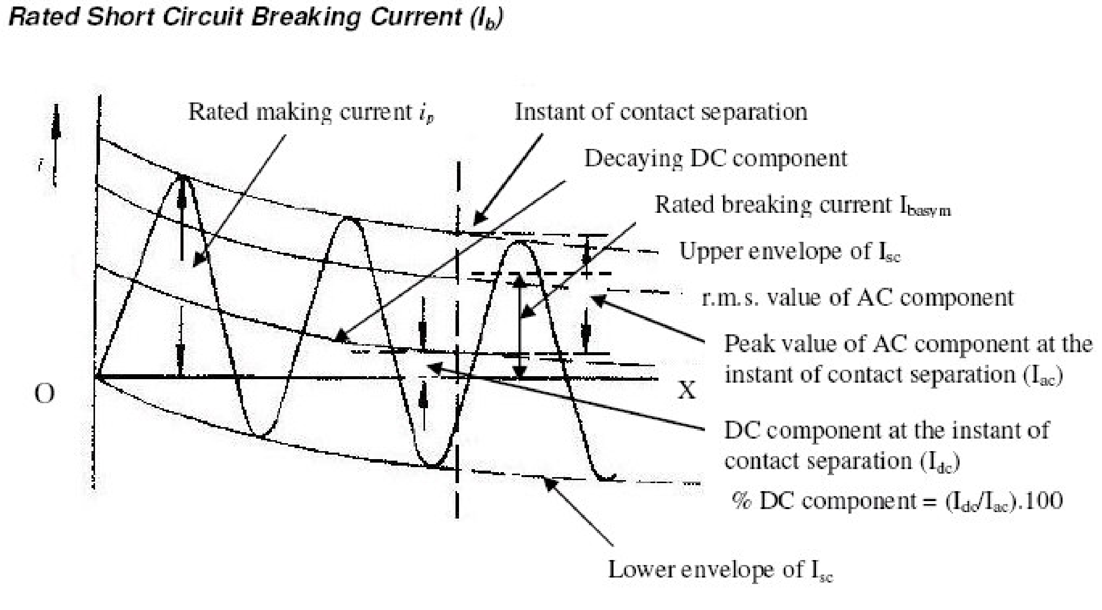


Fig.6 Short circuit breaking and making currents of a circuit breaker

As per AS 3851-1991, the rated short circuit breaking current, I_{basym}, is the highest rms asymmetrical short circuit current that the circuit breaker shall be capable of breaking (at the instant of contact parting). This becomes I_{bsym} when the breaker is used in a system where the DC offset decays very fast even before the breaker contacts start parting. For example, a short circuit far from a generator.

The value of SC breaking current is generally expressed in kA. The standard values of breaking current as per IEC are 6.3, 8, 10, 12.5, 16, 25, 31.5, 40, 50, 63, and 100kA. The breaking current is characterised by an AC component and a DC component as depicted in Fig.6 above.

Rated Short Circuit Withstand Current (I_k)

As per AS 62271.100-2008 or IEC 60694, the rated short circuit withstand current is the rated short circuit breaking current.

Rated Short Circuit Making Current (i_p)

According to IEC and AS standards, the rated S.C making current, i_p, is the highest value of current reached in a phase immediately after the short circuit (making operation). See i_p in Fig.6.

Rated Peak Withstand Current (I_p)

As per AS 62271.100-2008 or IEC 60694, the rated peak withstand current (I_p) is the rated short circuit making current (i_p).

2.3 Selection of Circuit Breakers

While selecting circuit breakers it is important to make sure that none of the capabilities are exceeded in their application. These capabilities are basically obtained from the short circuit current calculations available at the equipment location. Therefore, the starting point is the careful fault analysis of the power system. This is usually carried out in per unit quantities although there are other methods such as percentage and MVA methods available.

2.3.1 Fault Analysis of Power System

If the power system is connected to the Utility, the supply authority shall supply the necessary available fault levels at the point of network connection - both three-phase and single-phase, or the source impedance and the corresponding X/R ratios. This will help in analysing the fault contributions to/from the Utility. Any approved software packages such as ETAP, SKM Tools, PSS(E) may be used or manual computations if the system is simple. AS3851-1991 provides necessary guidance for manual computations.

As the power system constantly undergoes changes due to additions of generators and/or distribution networks, fault studies need to be performed routinely. It would be prudent to consider the short term expansion programmes of the network while selecting switchgear capabilities so that the expected increase in SC level could well be accommodated.

Determining the Short Circuit Duties of Breakers

Considering an industrial scenario where there is no in-plant power generation, the total three phase fault current at the faulted point includes both currents from the power source (electric utility) and the fault contribution from electric motors (both synchronous and induction) present in the system. If in-plant generation is involved, then the total fault current would be the sum of fault contributions from in-plant generator(s), electric utility and from in-plant electrical motors irrespective of whether they are on the same faulted bus or on the downstream buses.

Fig-7 depicts the simple open cycle power plant SLD showing connection to a 132kV external network. For a fault at location F1, the generator CB (52G) will carry the fault contributions from the network and from the plant distribution system. The external network fault contribution is commonly known as *'system source fault'*. Whereas, 52G only carries the *'generator source fault'* current if the fault occurs at location F2. The highest value shall be selected as the short circuit duty of the GCB. The short circuit duties of other CBs in the system could be analysed and determined in a similar way (Faults at locations F4 to F9 are not discussed).

It may be noted from Fig.7 that the worst fault would be at location F3 (On the IPBs or at the 15kV bushing terminals or on the HV windings of UAT) because of fault contributions from generator, 132kV network and from the in-plant distribution system.

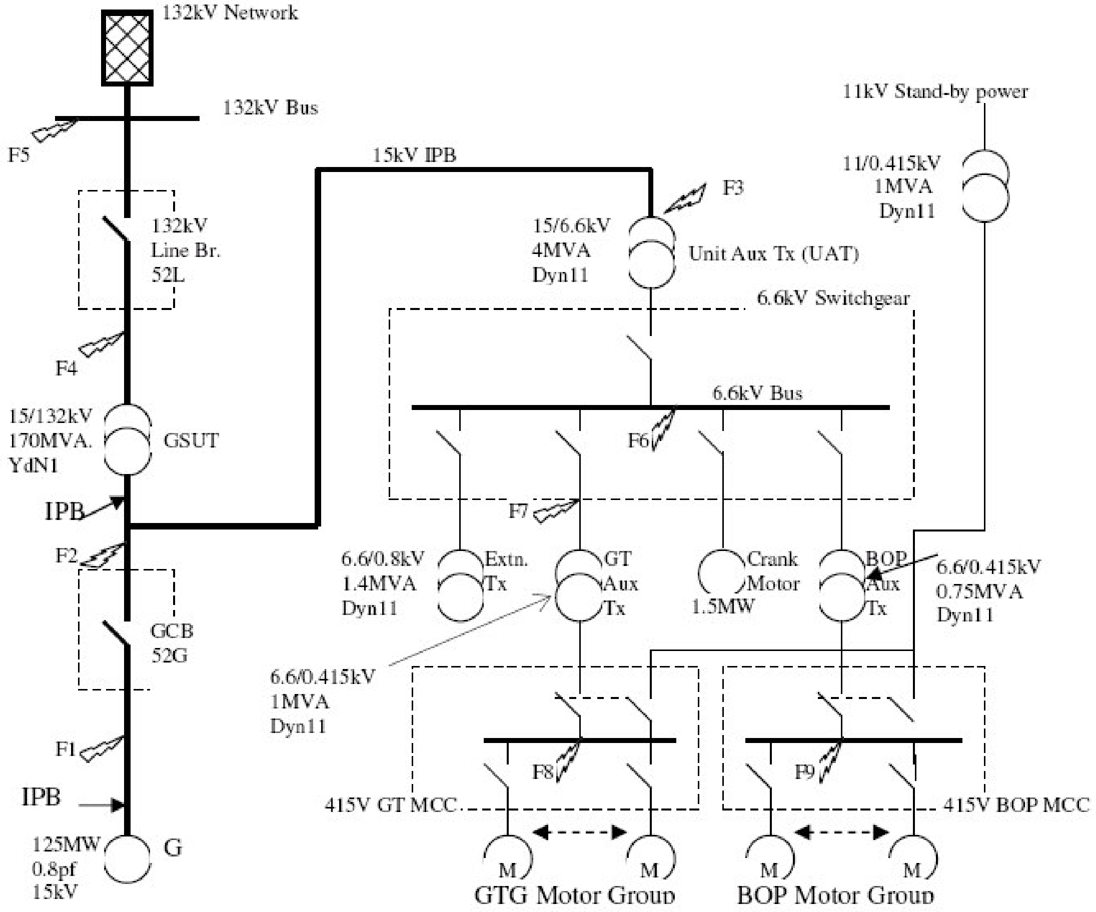


Fig.7 A simple open cycle power plant single line diagram showing potential fault locations

2.3.2 Other Relevant Factors in Switchgear Selection

Identifying the short circuit duties is not the only criteria to be considered in the switchgear selection process. It is important to check what type of switchgear available in the market satisfies these requirements and is best suited for the intended application(s). In brief, the other relevant factors to be carefully considered are:

i) Rated voltage (U_r)
ii) Rated duration of short circuit (1'/3')
iii) Rated frequency (f_r)
iv) Rated normal current (I_r) and temperature rise
v) Dielectric medium (Air, oil, gas, vacuum)
vi) Pollution class and creepage distance (20/25/30mm/kV)
vii) Power frequency withstand voltage (kV)
viii) Lightning impulse withstand voltage (kVpeak for wave 1.2/50μs)
ix) Out-of-phase making and breaking currents (90el/180el)
x) Application (Definite applications - GCB, Cable charging, Line charging, Capacitance switching, Reactor switching or general purpose distribution)

xi) Duty cycle or rated operating sequence (e.g. O-0.3s-CO-3min-CO)
xii) Gang operated or independent pole operation
xiii) First-pole-to-clear factor
xiv) Mechanical endurance class (M1/M2)

(The above points are not discussed in detail as they are beyond the scope of this paper.)

2.3.3 Use of Consultants/Specialists

The protection design of the power system involves a good understanding of the system components, their short circuit requirements, primary and back-up protection requirements and the overall system stability under fault conditions. Hence, more users employ consultants / specialist companies to undertake power system protection related studies due to the limitations of in-house expertise or resources. Such studies involve:

i) Short circuit study
ii) Load flow study
iii) Insulation coordination study
iv) Lightning protection study
v) Earthing study
vi) CT/VT selection study
vii) Protection coordination study
viii) Transient stability study
ix) Motor starting /dynamic system stability study

2.3.4 Use of Suppliers

Some suppliers help the buyer in the selection of equipment. This process works out well when the system requirements are simple. However, a number of inter-related studies as mentioned above are necessary before selecting the right equipment. In such situations, trusting the suppliers alone could lead to over/under-sizing the equipment.

2.3.5 Risk Factors

A certain degree of risk is involved in all the selection methods discussed above, unless the system is properly studied. Underrated switchgear can cause frequent failures and excessive maintenance costs. Overrated switchgear will result in high initial investment and project cost escalation. Care must be taken in fault analysis to find out actual fault levels regardless whether the study has been performed by the user, supplier or a consultant. Assumptions must be eliminated in the study process. The user and the network authority shall provide all necessary information to the designer. This will eliminate over-rating of the interrupting duties of the switchgear and results in borderline equipment selection with consequent savings in the equipment cost.

2.3.6 Influence of Environmental Conditions

The following sections briefly describe the influence of environmental conditions and their influence on outdoor switchgear design, selection and their installation.

Seismic Conditions

The seismic conditions do affect the design of structures for outdoor switchgears. These structures are to be designed to minimise the likelihood of collapse in the event of an earthquake. AS1170.4-1993, minimum design loads on structures, provides guidelines on structural designs to withstand earthquake loads. As an example, this standard provides the seismic acceleration coefficient map of NT (please refer p.21). The acceleration coefficient is an index related to the expected severity of earthquake ground motion; the higher the coefficient the greater the severity. For example, the seismic acceleration coefficient of Darwin is 0.09 and that of Tennant Creek is 0.13.

Other site factors such as soil conditions are to be considered in conjunction with the seismic acceleration coefficient for the proper design of switchgear structures to withstand earthquake loads.

Wind Velocity (Normal & Cyclonic Conditions)

The regional wind pressure shall be considered while designing structures of outdoor switchgears. AS/NZS 1170.2:2002, Structural design actions – Part 2: Wind actions, provides guidelines on non-cyclonic and cyclonic regional wind speeds. As per this standard, regions C & D are classified as the tropical cyclone regions in Australia included throughout the northern coast. For example, Darwin hence falls under wind region C. Wind speed also varies with the height, surrounding terrain roughness and topographic features. The above standard provides the necessary multipliers for accommodating their influence in the design of structures to withstand the wind loads.

Ambient Temperature & Humidity

When a circuit breaker is selected for a particular short circuit duty, it is equally important to consider its suitability for continuous operation under maximum ambient conditions. Circuit breakers are generally rated for operation at an ambient temperature of 40°C. Any ambient conditions below -30°C or above 40°C are considered as unusual service conditions.

In Australia, during summer, some areas experience a maximum ambient temperature of up to 46.5°C (Source: Australian Govt – Bureau of Meteorology). This will definitely influence the normal continuous current rating of the switchgear. Hence, an ambient compensation needs to be applied unless a forced cooling system is installed.

High humidity can cause corrosion of structural components. It can also cause insulation failures. Further, humidity in coastal regions contains traces of salt which accelerate the corrosion process. Use of high quality galvanised structures and proper painting of equipment will mitigate the severity of corrosion. Use of anti-condensation heaters in mechanism control cabinets and indoor switchgear will help to maintain the insulation levels.

Site Altitude

Site altitude usually influences the ambient conditions such as temperature, pressure and wind velocity. In addition, chances of lightning strikes are more. Switchgear is generally designed for installation and operation at altitudes up to 1000m above sea level. No de-rating is applicable as at higher elevations the ambient temperature is less than the maximum of 40°C. However, the need for de-rating is based on the use of surge arresters on both sides of the circuit breaker at higher altitudes above 1000m. If such surge arresters have a minimum of 20% protective level greater than the equipment BIL, no de-rating should be necessary as per IEEE Std C37.010-1999. Further, AS2067-1984, switchgear assemblies and ancillary equipment for alternating voltages above 1kV, specifies an increase of 1% clearance distance in air (phase-to-phase and phase-to-earth) for each 100m in excess of 1000m above sea level.

Pollution Level

Outdoor circuit breakers are affected by the environmental contamination. The user needs to assess the level of pollution in a location where the switchgear is intended to be used. The equipment must have additional creepage distance on the insulator surface (mm/kV – phase-to-earth) in order to maintain the designed withstand voltages to avoid any flashovers. Four levels of pollution are defined by IEEE Std C37.010-1999 from light to very heavy pollution. Accordingly, the recommended minimum creepage distance by pollution level is given in Table.1 below.

Pollution level	Min nominal specific creepage distance (mm/kV Line-to-earth)
Light	28
Medium	35
Heavy	44
Very heavy	54

Table.1 Minimum creepage distance for outdoor circuit breakers

3 Short Circuit Requirements and Selection of Power Cables

3.1 Causes of cable failure and need of protection

Cables are the mortar that holds the bricks of equipment in an electric system. They are not unlimited in their power capability and hence need to be protected to prevent being exposed to operation beyond their capability. Cable protection is required to protect the cable, personnel and the equipment. High temperature and thermal stresses are the main causes of cable failure.

3.2 Influence of fault currents on power cables

Cable conductor temperature rises rapidly due to the high I^2R losses in the cable under the short circuit conditions and could result in permanent damage of the cable insulation, shield and the possibility of a fire. A standard cable insulation structure is given in Fig.8 below.

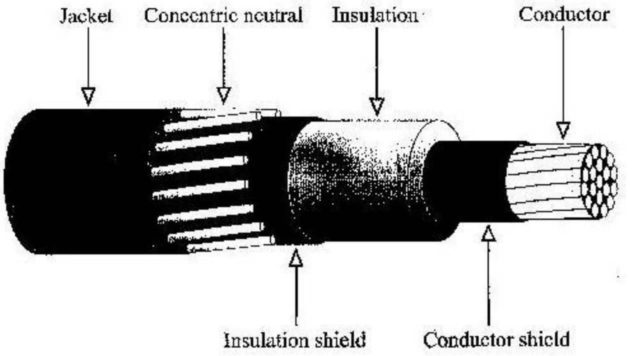


Fig.8 A standard power cable insulation structure

The temperature of the cable, while in service, depends on the load current, the ambient temperature and the installation conditions. The installation conditions include confined space, metallic or non-metallic ducts, bunched or flat configuration, spaced or touching, underground or overground, soil types, spacing between nearby cables etc. The designers shall take special care in assessing these conditions so that the cables are properly sized and rated against overheating while in normal service, overload and under fault conditions. The cable manufacturers specify these maximum permissible temperature limits based on the type of insulation used. Table.2 depicts these limits for typical insulating materials.

Insulation Type	Max Voltage Class kV	Max Operating Temperature °C	Max Overload Temperature °C	Max S.C Temperature °C
PE	35	75	90	150
XLPE	35	90/110	130	250
PVC	2	90	105	150
Silicon Rubber	5	125	150	250

Table.2 Maximum temperature ratings of cable insulation

3.3 Short circuit requirements of power cables

It is important to identify the short circuit requirements of cables for maintaining their temperature under all operating and fault conditions within the maximum permissible limits. These requirements and the recommended necessary steps to be followed in the cable sizing and selection process are listed in Table.3 below.

Short circuit requirements	**Recommendations**
Maximum available short circuit current	- Conduct SC study / fault analysis of the power system before cable selection
Maximum conductor temperature that will not damage the insulation	- Select cable operating temperature (75/90/110°C) - Consider high temperature cables if necessary - Consider all other de-rating factors of installation conditions as per AS3008
Cable conductor size that has the capability to contain the heat produced by I^2R losses.	- Sizing of conductor to withstand the calculated short circuit current without exceeding the maximum SC temperature limits of insulation for the expected fault time
Longest time that the fault current can flow.	- Estimate the fault tolerance time - Select the tripping time of protective devices - Relays, Fuses (Instantaneous, time delayed) - Set relay coordination, if necessary

Table.3 Cable selection based on short circuit criteria

3.4 Factors affecting cable selection and ratings

The above discussion briefly recognised the short circuit fault current influence on cable sizing and selection based on their ampere ratings. Proper selection and ratings ensures their suitability in the power system. Therefore, it may be concluded that the selection of power cables generally depends on the following factors.

i) Operating voltage
ii) Load current
iii) Emergency loading requirements and duration
iv) Fault current
v) Fault clearing time (Protection relays & Fuses)
vi) Allowable voltage drop
vii) Ambient temperature for the particular installation configuration (Environmental conditions)
viii) Cable route length
ix) Method of cable installation (derating factors)

4 Conclusion

In preparing this paper, it has been the author's intent to describe the short circuit dynamics of a HV power system in which the circuit breakers are being operated to protect the equipment, cabling and personnel. In the absence of a full understanding, anyone who performs the fault analysis by manual computations or using software tools and attempting to size and select switchgear and/or power cables can lead to design errors, cost inefficiencies, under rated equipment and operational problems.

Although this paper doesn't cover all types of circuit breakers using Oil, Air, SF6 or Vacuum as the dielectric medium for arc quenching, it presents a brief analysis of the nature of short circuit as a simultaneous interaction between time, voltage and current. The need for fault analysis and thereby identifying the actual short circuit capabilities required for switchgear and/or power cables is also emphasised. In addition, the influence of environmental conditions on the design and selection of switchgear and power cables is discussed.

In summary, this paper intends to develop an awareness and understanding of the short circuits in a power system and their influence on selection of switchgear and power cables. This awareness/knowledge will not only minimise the cost of the project during the design phase, but will also significantly reduce the cost during installation, testing, commissioning, defect liability period and during operation throughout the equipment life.

5 References

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