

FAULTS IN SUGAR MILL POWER SYSTEMS

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Abstract

An established method of calculating three-phase symmetrical fault currents in alternating current power circuits is presented. General information is given on the methods used to limit and control fault currents. The practical approach adopted makes the method useful to engineers who are not specialists in electrical technology.

Introduction

Under fault conditions the magnitudes of currents flowing in power circuits increase greatly, and the switches must be capable of safely interrupting these fault currents. It is therefore important that the highest possible fault currents be calculated.

In this paper some simplifications have been applied. However, the resulting relatively small inaccuracies cause the calculated fault levels to be conservative, i.e. on the high side.

With switchgear the worst condition possible is a symmetrical three-phase fault, and this is the type of fault that occurs most under plant conditions. When a single or two-phase fault occurs, it usually rapidly burns through into a three-phase fault.

In this paper, only symmetrical three-phase faults have been considered. Remember that in the design of protective relay systems for major plant items such as large alternators, single and two-phase faults should be rigorously taken into account.

With overhead distribution lines, single and two-phase faults are less likely to develop into three-phase faults.

The calculation method presented is only one of a number of possible approaches. The author believes it to be the most practical approach for the plant engineer who is not a specialist in electrical technology and who requires quick, conservative answers. For formal, accurate analyses, other methods may be superior.

Discussion

Switchgear ratings

Figure 1 shows a simple AC circuit comprising a transformer feeding a heater bank, and controlled by a switch.

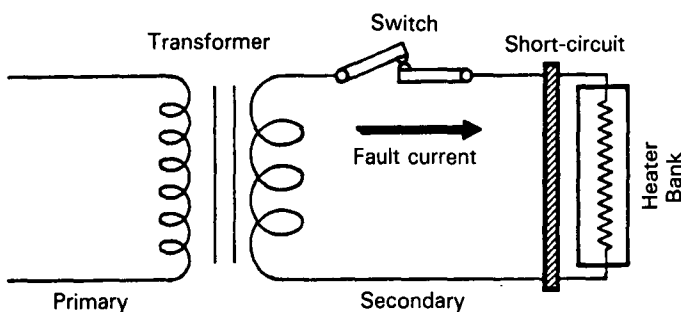


FIGURE 1 Basic circuit under short-circuit conditions.

Under normal conditions the switch has to handle the 'making' current, i.e. the current which appears at the instant of closing the switch, and has to conduct the normal current on a continuous basis without overheating. It must be able to 'make' and 'break' these initial and continuous currents as often as required, and remain reliable.

The switch also has to be able to close onto, withstand and interrupt the maximum current which can occur in the circuit under fault conditions. This prospective fault current may be a thousand times more than the normal continuous current.

Introduction to fault currents

Were a short circuit to occur across the heater bank shown in Figure 1, the fault current would be a function of the voltage available from the transformer, the internal impedance of the transformer and the impedance of any cables or other conductors in the circuit.

If the fault occurred close to the transformer, the fault current would be determined only by the impedance of the transformer.

The transformer as source of fault currents

Every power transformer has its characteristic 'impedance voltage' stated on the nameplate. This is defined as the voltage which has to be applied to the primary winding to allow the full-load current to flow in the primary, when the secondary winding is short circuited. This is expressed as a percentage of the rated phase-to-phase voltage (see Figure 2).

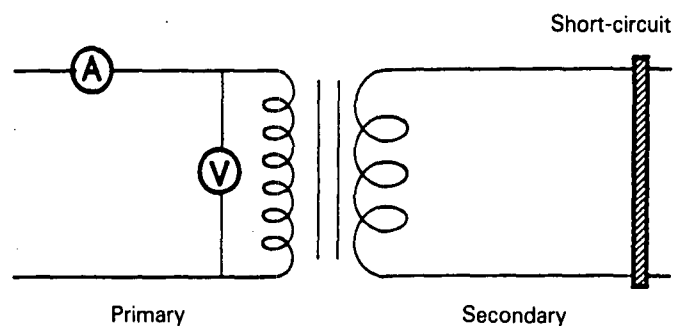


FIGURE 2 Transformer 'impedance voltage' test circuit.

Taking a typical impedance voltage value of 5% means that if 5%, or one twentieth, of the normal voltage was applied to the transformer primary winding, the rated full-load current would flow in the primary winding when the secondary winding was short-circuited.

It can be assumed that under these conditions the current in the short-circuited secondary winding would also be close to its rated full-load value. Therefore if the full rated primary voltage was applied, the current in the short-circuited secondary would be twenty times the rated full-load secondary current of the transformer.

The prospective fault current that can be expected from a transformer therefore depends on the transformer full-load rating (expressed in secondary amps or in kVA), and on transformer impedance. This assumes that the power supply to the transformer would be able to maintain full primary voltage for the duration of the fault. Transformer fault current (secondary amps) = rated secondary current (amps) * 100/impedance voltage (%).

or

Fault level (MVA)
= rating (MVA) * 100/impedance voltage (%) ... (1)

This is a simplification which gives slightly conservative (high) values and is applicable to faults located close to the transformer secondary terminals.

Table 1 shows typical impedance voltages of transformers manufactured to SABS 780.

Table 1
Impedance voltages of SABS 780 transformers

Transformer rating (kVA)	Impedance voltage (%)
< 500	4,0 to 5,0
501 to 1 250	4,5 to 5,5
> 1 250	5,0 to 6,5

Where more than one transformer is connected in parallel, the total prospective fault current is equal to the sum of the prospective fault currents of the individual transformers.

The alternator as source of fault currents

The prospective fault currents of alternators can be calculated in a similar manner to transformers. The resistance of an alternator is low in comparison with its reactance and so the resistance is usually ignored. Instead of the impedance, the reactance then becomes the important quantity in fault calculations.

Instead of the impedance voltage considered in transformers, the relevant characteristic for alternators is the 'sub-transient reactance'. Table 2 shows typical sub-transient reactance values for sugar mill alternators.

Table 2
Sub-transient reactance values for typical four-pole 6,6 kV sugar mill alternators

Mill	Alternator rating (MVA)	Sub-transient reactance (%)
FX	13 125	21
AK	5 000	20
DL	8 130	25
MS	9 060	17,5

Effect of cables on prospective fault currents

Unlike transformers and alternators, cables have substantial resistance as well as reactance. In calculating the reduction in prospective fault current caused by a particular cable run, the impedance per conductor, being the vector sum of the resistance and reactance, must be used. Table 3 provides reactance values for cable types frequently found in sugar mills.

Table 3
Typical cable impedance values (ohms/km at 50 Hz) from a manufacturer's catalogue

Cond cross-section	Cable type and insulation					
	600/1 000 V PVC		600/1 100 V Paper		6,6 kV XLPE	
mm ²	Cu	Al	Cu	Al	Cu	Al
25	0,807	1,325	0,807	1,326	0,923	
35	0,578	0,947	0,578	0,947	0,663	
50	0,410	0,666	0,410	0,666	0,470	
70	0,297	0,480	0,297	0,481	0,343	0,548
95	0,226	0,358	0,225	0,358	0,260	0,409
120	0,185	0,291	0,185	0,291	0,213	0,328
150	0,154	0,239	0,155	0,239	0,179	0,267
185	0,134	0,202	0,134	0,201	0,153	0,223
240	0,113	0,153	0,115	0,167	0,129	0,179

Relative impedances

The percentage impedance of each item of equipment is based on the apparent power rating (MVA) of that item. The percentage impedances of items with different MVA ratings cannot be directly combined. For example, the combined percentage impedance of a 10 MVA transformer with 5% impedance, in parallel with a 1 MVA transformer with 5% impedance, is not 2,5%, which would be the case if the transformers were identical. If the equipment items all had the same MVA rating then the percentage impedances could be directly combined. In the method of relative impedances, the MVA ratings of the different items of equipment are all referred to a common base, usually 100 MVA, and the calculated relative percentage impedances can then be directly combined.

Consider a 10 MVA transformer with 5% impedance. From (1) the fault level is 10 * 100/5 = 200 MVA. If a 100 MVA transformer is substituted, what must its percentage impedance be to give the same fault level?

From (1), 200 MVA fault level = 100 MVA rating * 100/X

therefore X = 50%, or 10 times the original impedance.

The relative percentage impedance when referred to 100 MVA base, is equal to the original percentage impedance multiplied by the ratio of 100 MVA to the original MVA rating. ... (2)

Formulae

The following formulae apply to the manipulation of relative reactances. The common base has been taken as 100 MVA.

- Xp = Percentage reactance at nameplate MVA rating.
- Xpr = Relative percentage reactance at 100 MVA base.
- Xo = Reactance in ohms.
- E = System voltage (kV) (phase-to-phase).
- N = Actual equipment rating in MVA. ... (3)
- FL = Actual fault level in MVA. ... (4)

From (1), FL = N * 100/Xp

From (2), Xpr = Xp * 100/N

For cables:

Apparent fault power per conductor
 = phase current (I) * phase voltage (Ep)
 but from Ohm's law, $I = E_p/X_o$

therefore apparent fault power for three conductors
 = FL = $3 * E_p^2/X_o$
 but $E_p = E/\sqrt{3}$
 therefore FL = E^2/X_o ... (5)

from (5) and (3), $X_p = 100 * N * X_o/E^2$
 hence, from (4), X_{pr} for cables = $100 * 100 * X_o/E^2$... (6)

From 3-phase power circuit basics:
 Fault current (kA) = $FL/(\sqrt{3} * E)$... (7)

Reactances in series are combined by addition, and in parallel by the usual formula: $1/X = 1/X_1 + 1/X_2 + \dots + \dots$ (8)

In AC circuits, impedance is the vector sum of resistance and reactance.

Example

A typical distribution circuit is shown in Figure 3.

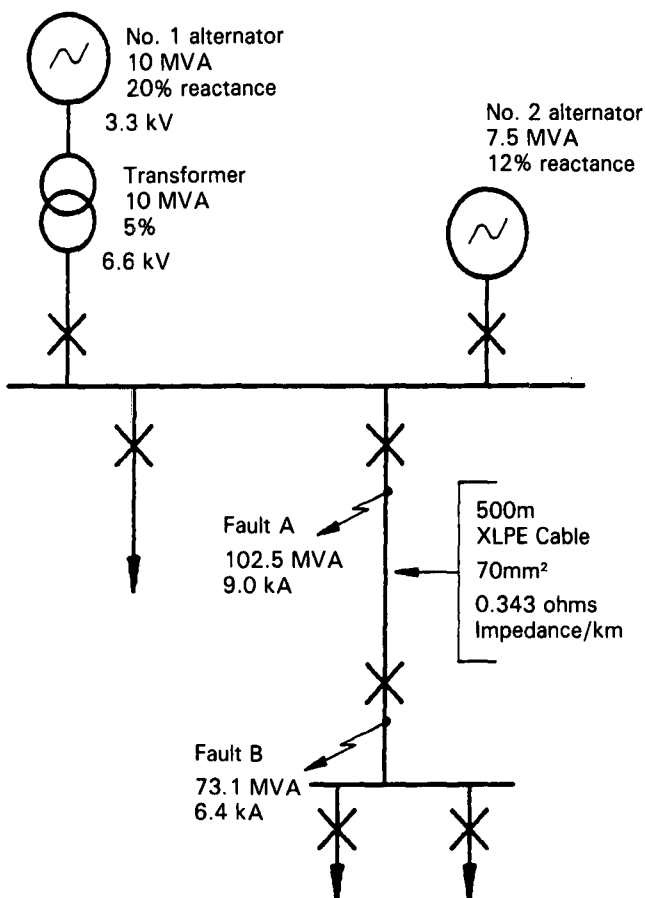


FIGURE 3 Typical power system

From (3), X_{pr} of Alternator 1 = $20 * 100/10 = 200\%$
 X_{pr} of Alternator 2 = $12 * 100/7.5 = 160\%$
 X_{pr} of transformer = $5 * 100/10 = 50\%$

The impedances of Alternator 1 and the transformer are in series. The combined relative impedance of these items is $200\% + 50\%$.

The above combined relative impedance is in parallel with that of Alternator 2.

Let the combined X_{pr} at point A be X_{prA} ;
 $1/X_{prA} = 1/(200 + 50) + 1/(160)$
 $X_{prA} = 97,6\%$

From (3), with 100 MVA substituted for N,
 FL at A = $100 * 100/97,6 = 102,5$ MVA

From (7), the prospective fault current at point A is
 $102,5/(1,73 * 6,6) = 9,0$ kA

The impedance of the cable is 0,327 ohms/km, or 0,171 ohms for the 500 m run.

From (6), X_{pr} for the cable is $100 * 100 * 0,171/6,6^2 = 39,3\%$

$X_{prB} = X_{prA} + X_{pr}$ for the cable,
 = $97,6 + 39,3 = 136,9\%$

From (3), FL at B = $100 * 100/136,9 = 73,1$ MVA

From (7), the prospective fault current at B is
 $73,1/(1,73 * 6,6) = 6,4$ kA.

The cable brings about a substantial reduction in prospective fault current.

HRC fuses and current-limiting circuit breakers

If there is not a convenient cable run or transformer to reduce the prospective fault current, current-limiting high-rupturing-capacity (HRC) fuses or circuit breakers can be used to perform this duty.

One HRC fuse design (GEC 1990) comprises a copper strip inside the fuse, surrounded by silica granules. The copper strip has a number of sections of reduced cross-section along its length. If the fuse is suddenly subjected to greatly increased current, heat builds up rapidly at the sites of reduced cross-section which melt simultaneously. Multiple arcs form in series, increasing the resistance to current flow and generating high temperatures. The heat fuses the silica, forming glass which is an excellent insulator, and the high current is interrupted. This interruption takes place very rapidly (less than one quarter of a cycle) and the fault current is interrupted while it is still building up, and before it attains its maximum (prospective) value.

Circuit breakers with very short operating times are now also available to limit prospective fault currents. These circuit breakers are more expensive than fuses, but are quicker and easier to reset, thus reducing the time necessary to restore the supply after tripping. The ease of resetting can lead to abuse by plant operators who may repeatedly reset a circuit breaker which has tripped because they believe the tripping to have been caused by a relatively innocuous overload, rather than by a potentially catastrophic short circuit.

Sizing HRC fuses

Once the appropriate fuse type has been chosen from the manufacturer's catalogue, the fuse size can be determined from graphs provided by the manufacturer (see Figure 4).

Alternating currents are usually expressed as 'root mean square' (RMS) values. In the case of a sine wave, the peak value is $\sqrt{2}$ (i.e. 1,41) times the RMS value. However under fault conditions the reactance of the circuit can impose a direct-current component on the alternating fault current, increasing the ratio of RMS to peak value of typically 2,26. The 'cut-off' line in Figure 4 provides a ratio of 2,26 between the X-axis values ('prospective current - RMS symmetrical') and the Y-axis ('cut-off current - peak'). This line therefore provides a direct relationship between the prospective RMS

current and its corresponding peak value. The 'fuse characteristic' line in Figure 4 shows how the peak current varies with the RMS fault current.

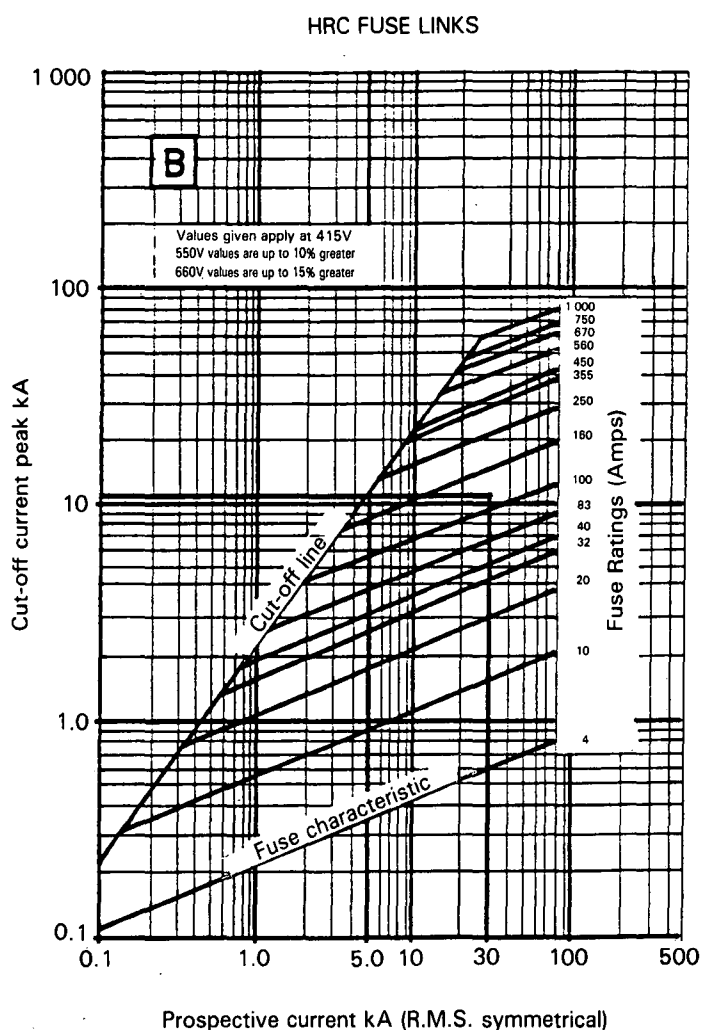


FIGURE 4 Fuse sizing diagram

To determine what fuse rating must be used to reduce the RMS prospective fault current from, say 30 kA to 5 kA, determine the peak current equivalent of 5 kA by drawing a vertical line from 5 kA on the X-axis to the cut-off line. This peak current is 11,3 kA.

A fuse must be chosen which will not permit more than this peak fault current to pass when a prospective fault current of 30 kA is applied. Draw a horizontal line at 11,3 kA peak current, and a vertical line from 30 kA prospective RMS symmetrical current. The fuse line below the intersection of these two lines (100 A) is the largest fuse that should be used, but any smaller fuse of the same type will also be suitable.

Typical application of HRC fuses

Figure 5 shows a typical sub-station layout with a 1 MVA 380 V transformer and main distribution board. Two utility services sub-boards are tapped off the main board, to provide lighting and small power in the sub-station building.

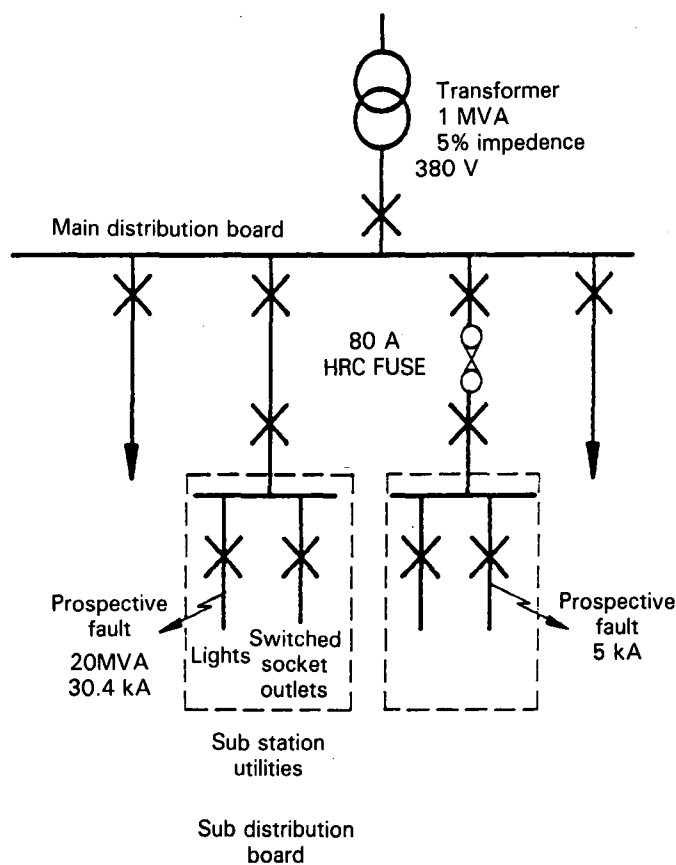


FIGURE 5 Reduction of fault levels by means of HRC fuses.

One sub-board is tapped directly off the main board while the other is supplied via a fuse.

The prospective fault level on the main board busbars is 20 MVA or 30,4 kA. In the direct connection the prospective fault level is not reduced between the main bars and the sub-board, (ignoring the reactance of the very short cables to the sub-board). All the circuit breakers on the sub-board will therefore have to be able to clear 30,4 kA. This means that in practice the five and 20 amp miniature circuit breakers (MCBS) controlling the room lights and socket outlets would be required to clear fault currents of almost 30,4 kA.

As the rupturing capacity of these MCBS is usually between two and five kA, they would probably not clear the fault current resulting from a short in the lighting circuit. The MCBS would probably explode causing an even larger fault, which would be transferred to the main board. Serious plant damage and danger to personnel could result. The second sub-distribution board is supplied via a HRC fuse which is a simple and cost-effective way of reducing the prospective fault level.

Conclusions

Sugar mills are usually expanded in capacity during their lives, with the addition of alternators, transformers and larger cables. These items all increase the prospective fault currents, possibly to levels greater than the original switchgear can handle.

It is necessary for plant engineers to check the effects of proposed modifications to the electrical distribution system, to ensure that the prospective fault currents can be adequately controlled by existing or new switchgear.