Lecture 8: Transmission II

8.1 Power system faults

Causes: Lightning, weather (gales, snow/ice), insulation failure, people.

Typically 400 - 500 faults per annum in UK.

Types of fault:

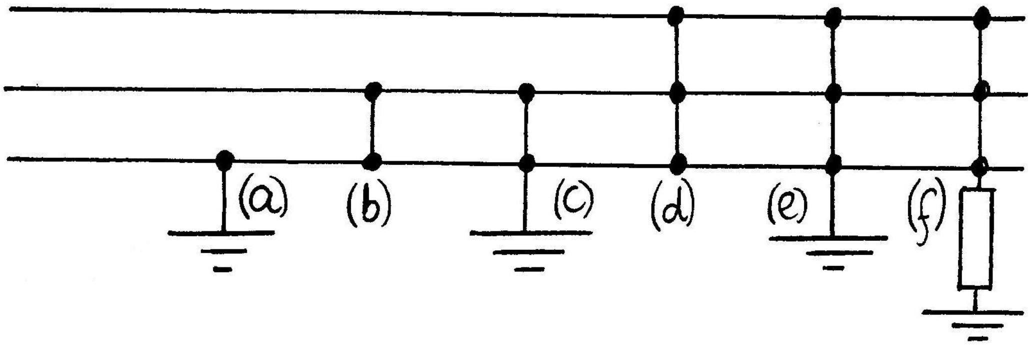


Fig. 8.1

Only concerned with three-phase symmetrical fault to earth - type (e) in fig. 8.1.

8.2 Protection

Circuit breaker: Opens on-load.

Isolator: Only opens off load.

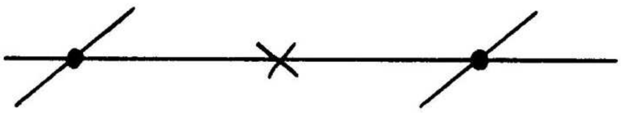


Fig. 8.2

In this lecture, we will see how the pu method can be applied to the analysis of faults in power systems. The majority of faults occur in the transmission of electrical power i.e. in overhead lines, which is why this topic comes under the heading of transmission. Faults will occur on the best-designed and best-run power systems, and the amount of energy that can flow into a fault is massive. The potential damage to a power system is therefore huge, and it is vitally important that the system is protected in a way which enables the fault to be isolated (and then fixed) before damage occurs. On a smaller scale, the idea of protection in power systems is the same as fuses for domestic electrical appliances - if an appliance develops a fault which causes it to take excessive current, the fuse in the plug (or the appliance) blows, thus saving the device and your domestic wiring. In power systems, faults are often caused by weather - lightning strikes, and gales or snow causing lines to touch. Other causes include insulation failure, and people (workmen digging into underground cables, for example). As shown in fig. 8.1, a wide variety of types of fault exist: a) is a single line-ground fault, b) is a pair of lines shorting together etc. The only type which we will study is e) i.e. a symmetrical three-phase to earth fault. This is because this type of fault is a 'worst-case scenario' in terms of the fault current which flows, and also because the system remains balanced, and is amenable to single-phase analysis.

The protection of power systems is achieved using circuit breakers and isolators, illustrated in fig. 8.2. Circuit breakers are designed to interrupt the circuit when the current flowing exceeds a

Sequence of events following a fault:

Fault occurs → sensors detect → circuit-breaker opens → re-closes → reopens if fault not cleared → isolators open.

Breaker operates by moving metal contacts apart → causes arc → current falls to zero naturally (a.c.) → remove ionisation products by a blast of fluid (air, oil, SF_6) to prevent arc re-striking.
Isolator in series with circuit-breaker opens when current has been interrupted.

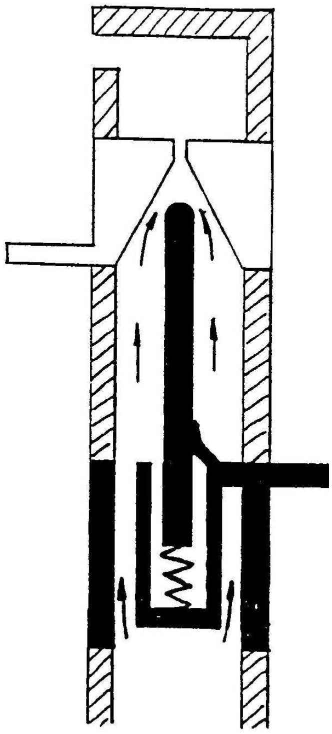


Fig. 8.3

Qualities required from protection system:

Discrimination: Only isolates faulty part of system.

Stability: Breaker stays closed when fault is outside the protected zone.

Sensitivity: Ability to set current level at which beaker opens.

threshold value due to a fault- a large-scale version of a fuse ! Isolators in series with the circuit breaker then open to cut off the faulted part of the system from the rest of the system, enabling the problem to be sorted out. The sequence of events following a fault is:
Sensors (usually relays) detect the fault; all such sensors are connected to a supervising computer which identifies the part of the system where the fault occurred, and instructs the relevant breaker to open. This typically takes 5 - 7 mains cycles. Because many faults are self-clearing e.g. lightning, temporarily shorted lines due to high winds etc. the breaker re-closes to see whether the fault has cleared. If the current starts to build up again, it reopens. Isolators in series with the breaker then open.
Fig. 8.3 illustrates a typical circuit breaker. The terminals are normally connected together via the spring-loaded moving contact. In operation, the moving contact moves downwards, thus causing an open-circuit between the contacts. However, because of the large amount of inductance in typical power systems, the current continues to flow in the form of an arc. When the arc current falls to zero, which occurs naturally in an a.c. system, fluid is blasted as shown in fig. 8.3, with the aim of removing ionisation products, and preventing the arc from re-striking as the voltage rises again.

A list of the qualities required of a protection scheme is given opposite. Because the act of opening circuit breakers can ultimately cause consumers to lose their supply, it is vital that the protection scheme only operates where necessary - **discrimination**. A circuit breaker opening usually causes power to be re-routed via a different feeder. In badly-designed protection schemes this can cause the breaker

Speed: Breaker opens quickly enough to prevent damage to generators, transformers etc.

Reliability: Breakers should not open when there is no fault (15 % of faults are spurious).

Back-up: Separate system in case primary protection fails.

8.3 Fault analysis

Aim: To determine fault current levels, and hence specify breaker VA ratings, defined as $\sqrt{3}V_{nominal} \times I_{fault}$.

Assumptions:

i) All generators can be modelled as $1.0 \angle 0^0$ pu emf in series with synchronous reactance.

ii) Transmission lines and transformers can be modelled as series inductive reactances.

iii) The effect of loads connected to the network can be ignored.

Method: Reduce network to Thevenin equivalent, and find $X_{F(pu)}$ and hence $I_{F(pu)}$.

protecting that feeder to open, and so on - **stability**. Rather like a house of cards, breakers keep opening until much of the network is down. This is avoided by the supervising computer instantly changing the **sensitivity** of the breakers to reflect the system following the opening of the original breaker. The large currents which build up following a fault can do serious damage to generators, transformers, bus-bars and other cables. Also, generators can lose synchronism. The damage caused largely relates to the **speed** of operation of the protection, which should be as fast as possible. On the other hand, it is important that breakers do not open when they should not e.g. during switching transients - **reliability**. Finally, a **back-up** system is required should the primary protection fail, owing to the severe consequences of such failure.

Circuit breakers are given VA ratings - they must withstand the nominal system voltage under normal operation, and the fault current under fault conditions; the rating is defined as the product of these quantities. Therefore, in order to determine the VA rating of a circuit breaker to be used at a given point in a power system, the worst-case fault current at that point must be determined. This is the subject of fault analysis. To simplify the analysis, it is usual to assume (i) that all generators are generating 1 pu voltage, and that they are in phase with each other (ii) all network components can be modelled as series inductive reactance, since this dominates resistive and capacitive effects (iii) the effect of electrical loads connected to the system can be ignored, since these draw negligible current when compared to the fault current.

$$I_{F(pu)} = V_{pu} / X_{F(pu)} = 1 / X_{F(pu)} \tag{8.1}$$

$$VA_{F(pu)} = V_{pu} I_{F(pu)} = 1 / X_{F(pu)} \tag{8.2}$$

$$VA_F = VA_{F(pu)} VA_b = VA_b / X_{F(pu)} \tag{8.3}$$

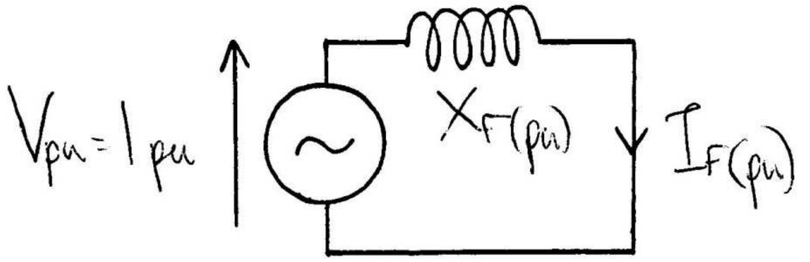


Fig. 8.4

To find the total fault VA level, the network is reduced to its Thevenin equivalent, with the fault point regarded as the load, fig. 8.4. The pu fault current, $I_{F(pu)}$ is then given by equation 8.1, where $X_{F(pu)}$ is the total pu reactance 'seen' by the fault. Since the generated voltages are all 1 pu, V_{pu} in equation 8.1 is 1. The pu VA supplied to the fault is then given by equation 8.2, again with V_{pu}=1. The actual fault level, VA_F is then found by multiplying $VA_{F(pu)}$ by the base VA, giving equation 8.3.

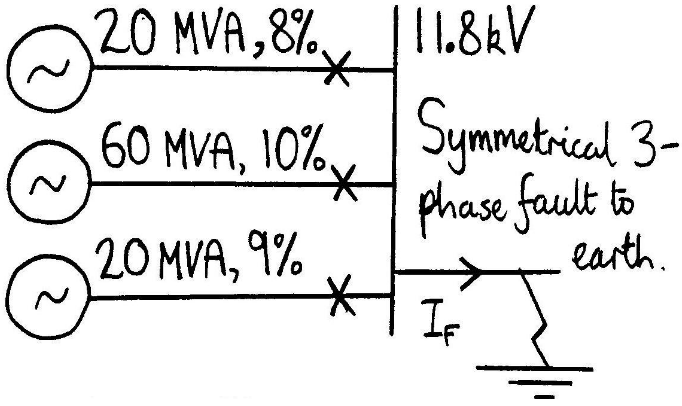
Example 8.1

Find fault current and fault VA and VA rating of generator circuit breakers.

Generator 1

Generator 2

Generator 3



Here we illustrate these ideas with an example, in which three generators supply an 11.8 kV bus-bar. The generators are rated as follows:

Generator 1: 20 MVA, X_s=8%
Generator 2: 60 MVA, X_s=10%
Generator 3: 20 MVA, X_s=9%

and all have a rated voltage of 11.8 kV. A symmetrical three-phase fault to earth occurs at the 11.8 kV bus-bar, as shown opposite, and the aim is to find the current which flows into the fault, the total fault VA and the VA ratings of the three generator circuit breakers. Notice that the pu reactances are specified as percentages e.g. 8 % means a pu reactance of 0.08.

<u>Step 1</u> Choose VA_b and V_b

VA_b = 60 MVA (base changes), V_b=11.8 kV.

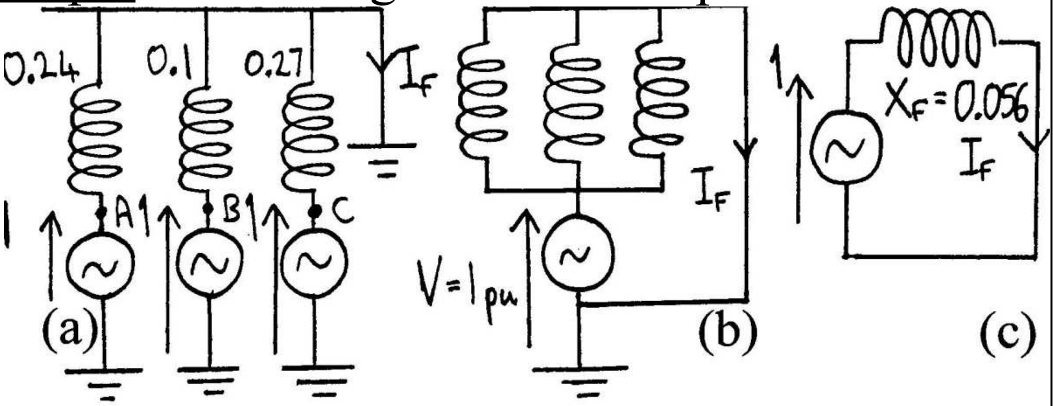
<u>Step 2</u> Perform changes of base

Generator 1: $X_{pu(60\,MVA)} = 0.08 \times 60/20 = 0.24$

Generator 3: $X_{pu(60\,MVA)} = 0.09 \times 60/20 = 0.27$

As always, the first step is to specify an overall system base VA, and also system base voltages. The obvious choice for voltage base is 11.8 kV, since all generator reactances are quoted to this base. The VA base is a choice between 20 MVA and 60 MVA. If 20 MVA is chosen, only one change of base is required, but the factor involved is 1/3, giving nastier numbers. Choosing 60 MVA means performing two base changes, but these are trivial operations, amounting to multiplying by 3, as shown in step 2.

Step 3 Combine generators and pu reactances



The single-line diagram for the problem is shown in fig. (a) opposite. As all generators are assumed to be operating in phase and at 1 pu excitation voltage, the voltages at the points marked A, B and C in fig. (a) are all 1 pu. Therefore, these points can all be connected together, and so now the generator reactances all appear in parallel, fig. (b). They can therefore be combined using:
$1/X_F=1/X_1+1/X_2+1/X_3$
This gives the total impedance seen by the fault as 0.056 pu, and the circuit, as far as the fault point is concerned, becomes that shown in fig. (c).

Step 4 Find fault current and VA

$$I_{F(pu)} = 1/X_{F(pu)} = 1/.0560 = 17.9$$

The fault current can be found by obtaining the pu fault current, and then multiplying by the base current.

$$I_b = \frac{VA_b}{\sqrt{3}V_b} = \frac{60\times10^6}{\sqrt{3}\times11.8\times10^3} = 2.94\ \text{kA}$$

$$I_F = I_b I_{F(pu)} = 2.94\times17.9 = 52.5\ \text{kA}$$

The total fault VA is obtained using equation 8.3.

$$VA_F = VA_b/X_{F(pu)} = 60/0.056 = 1.07\ \text{GVA}$$

Step 5 Find VA rating for each circuit breaker

To find the required VA ratings for the separate generator circuit breakers, the generator pu fault currents which flow must first be established. In this case, they are given by $1/X_{G(pu)}$, where $X_{G(pu)}$ is the individual generator pu reactance. The pu VA rating is then found by multiplying by the pu voltage i.e. 1. The actual VA rating is then found by multiplying by the VA base, giving equation 8.4. It is now a matter of inserting the numbers for each generator into equation 8.4. Intuitively, we would expect the 60 MVA generator to require the largest circuit breaker rating, which it does.

$$VA_{G(pu)} = V_{pu} I_{G(pu)} = 1/X_{G(pu)} \quad VA_G = VA_b/X_{G(pu)} \tag{8.4}$$

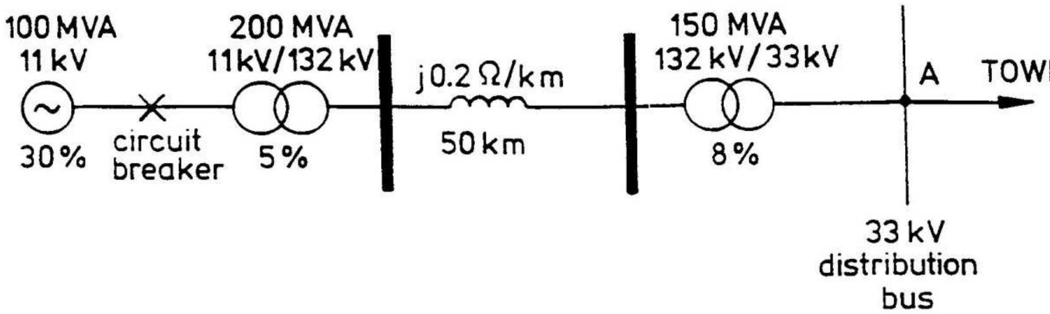
Generator 1: $VA_G = 60/0.24 = 250$ MVA

Generator 2: $VA_G = 60/0.1 = 600$ MVA

Generator 3: $VA_G = 60/0.27 = 222$ MVA

Example 8.2

Find the fault current in the 33 kV bus and the 132 kV line, and the VA rating of the circuit breaker. Find the additional reactance added at A to reduce fault current at A to 3500 A.



Step 1 Choose system VA and voltage base

VA_b = 600 MVA (simplifies changes of base)
V_b = 11 kV, 132 kV and 33 kV (turns ratios)

Step 2 Perform changes of base

1. Generator

$$X_{pu(600\,MVA)} = X_{pu(100\,MVA)} \cdot \frac{600}{100} = 0.3 \times 6 = 1.8$$

2. 11/132 kV transformer

$$X_{pu(600\,MVA)} = X_{pu(200\,MVA)} \cdot \frac{600}{200} = 0.05 \times 3 = 0.15$$

3. 132/33 kV transformer

$$X_{pu(600\,MVA)} = X_{pu(150\,MVA)} \cdot \frac{600}{150} = 0.08 \times 4 = 0.32$$

Finally, to finish off this subject, we consider a Tripos question (Q4, paper 5, 1997).

The figure opposite illustrates the problem. A 100 MVA, 11 kV generator, supplies a town connected to a 33 kV distribution bus via an 11/132 kV step-up transformer, a 50 km transmission line and a 132/33 kV step-down transformer. The problem is to i) determine the fault currents which flow at the 33 kV bus, and in the transmission line when a three-phase symmetrical fault to earth occurs at the 33 kV bus ii) find the VA rating of the circuit breaker placed at the generator terminals iii) determine the extra series-connected reactance (in Ohms) which, when inserted at A, limits the distribution bus fault current to 3500 A.

Firstly, an overall system base VA is chosen; there is no outstandingly obvious choice, since all components in the system have different VA ratings. However, 600 MVA will make base changes easy, since all the device VA ratings divide into 600 giving integers. It is obvious that 11 kV, 132 kV and 33 kV should be used as our base voltages, otherwise unnecessary changes of base w.r.t. voltage will have to be carried out.

The next step is to carry out all the base changes, by multiplying the given pu values by the 'new base' i.e. 600 MVA divided by the 'old base', as shown opposite.

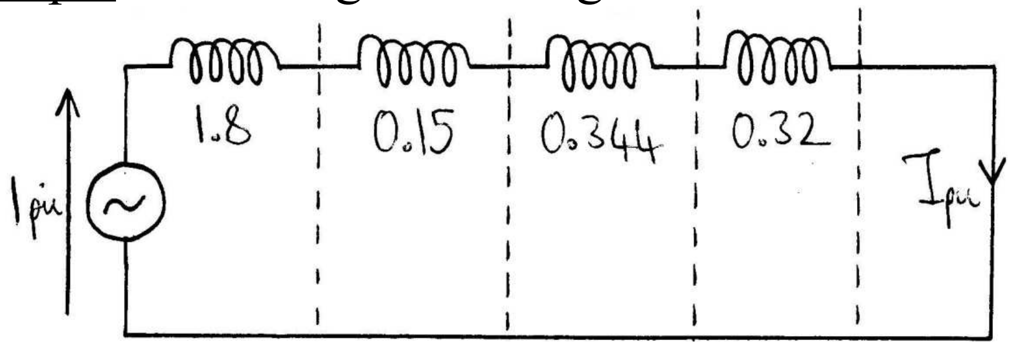
Step 3 Find pu feeder impedance

$$Z_b = \frac{V_b^2}{VA_b} = \frac{\left(132 \times 10^3\right)^2}{600 \times 10^6} = 29.0\ \Omega$$

$$Z_{pu} = \overline{Z}(\Omega)/Z_b = 50 \times 0.2/29.0 = 0.344$$

The pu feeder impedance is found by firstly determining the base impedance for the feeder, and then dividing the actual impedance by that base value. Notice that the base voltage at the feeder is 132 kV. Also, the feeder impedance is given as an impedance per-unit length, in Ohms/km. It is therefore necessary to multiply by the feeder length, 50 km, to obtain the feeder impedance in Ohms.

Step 4 Draw single-line diagram



A single-line diagram can now be drawn, since all pu reactances are known, and it is assumed that the generator is generating with 1 pu excitation.

Step 5 Find total pu series reactance

$$X_{F(pu)} = 1.8 + 0.15 + 0.344 + 0.32 = 2.614$$

The total pu series reactance is found by adding all individual pu reactances together.

Step 6 Find pu fault current

$$I_{pu} = V_{pu}/X_{F(pu)} = 1./2.614 = 0.383$$

The pu current flowing into the fault is found by Ohms law.

Step 7 Find 33 kV bus fault current

$$I_b = \frac{VA_b}{\sqrt{3}V_b} = \frac{600 \times 10^6}{\sqrt{3} \times 33 \times 10^3} = 10.5\ \text{kA}$$

$$I_F = I_{F(pu)} I_b = 0.383 \times 10.5 = 4.02\ \text{kA}$$

The 33 kV bus and the 132 kV transmission line fault currents can now be found, by determining the base currents in each case, and then multiplying by the pu fault current just found. Clearly, the base current at the 33 kV bus is found using V_b = 33 kV, whereas that of the transmission line is found using V_b = 132 kV.

Step 8 Find transmission line fault current

$$I_b = \frac{VA_b}{\sqrt{3}V_b} = \frac{600 \times 10^6}{\sqrt{3} \times 132 \times 10^3} = 2.62 \text{ kA}$$

$$I_F = I_{F(pu)} I_b = 0.383 \times 2.62 = 1.00 \text{ kA}$$

Step 9 Find circuit-breaker rating

$$VA_{F(pu)} = V_{pu} I_{F(pu)} = 1.0 \times 0.383 = 0.383$$

$$\text{Rating} = VA_{F(pu)} VA_b = 0.383 \times 600 = 230 \text{ MVA}$$

Step 10 Find fault-limiting reactance

Fault current of 3500 A at 33 kV bus $\Rightarrow$

$$I_{F(pu)} = I(A)/I_b = 3.5/10.5 = 0.333$$

$$I_{F(pu)} = V_{pu} \Big/ \left(X_{F(pu)} + X_{A(pu)} \right)$$

$$\therefore \; 2.614 + X_{A(pu)} = 1.0/0.333 = 3 \quad X_{A(pu)} = 0.386$$

$$Z_b = \frac{V_b^2}{VA_b} = \frac{\left(33 \times 10^3\right)^2}{600 \times 10^6} = 1.82 \ \Omega$$

$$\therefore \quad X_A(\Omega) = X_{A(pu)} Z_b = 0.386 \times 1.82 = 0.71 \ \Omega$$

The pu fault VA is now found by multiplying the nominal pu system voltage i.e. 1 with the pu fault current. Since the circuit breaker placed at A experiences the full fault current, this value is also the pu circuit-breaker rating. The actual rating is then found by multiplying by the base VA.

One technique for limiting fault currents in power systems is to insert extra reactances at suitable places. In this question, the extra reactance is to be connected in series at the 33 kV bus, and chosen so that the fault current is limited to 3500 A. Since the base current at the 33 kV bus is 10.5 kA, this equates to a pu fault current of 3.5/10.5, as shown opposite. Denoting the addition pu reactance as $X_{A(pu)}$, the total pu reactance now seen by the fault is $X_{F(pu)}+X_{A(pu)}$, and so the new pu fault current is given as shown opposite. Using the fact that $V_{pu} = 1$ and $I_{pu} = 0.333$ shows that the total pu reactance must be 3, from which the additional pu reactance is found. The actual reactance may then be determined by multiplying this pu value by the base impedance at the 33 kV bus. This is found in the normal way, remembering to use 33 kV as the base voltage.

You can now finish off Examples Sheet 5/4.