1 Distribution and reticulation system Part (1)

CHAPTER II

TRANSMISSION OF ELECTRICAL ENERGY

Transmission by Low Voltage Direct Current. The Radial System. The early supply of electrical energy was by means of low voltage direct current, and a number of such systems still exist. A populated area is served by one power station, and the system is as shown in Fig. 16. *Feeder mains, F*, which are cables of large current-carrying capacity, carry the current in bulk to *feeding points*, where *distributors, D*, tap off the current to the *service mains, S*; the latter are small cables which lead the current to the consumers' premises. Such a system is called a *radial system*, as the feeders, distributors, and service mains radiate outwards from the generator. The size of the feeders is determined mainly by the current to be transmitted, as the volt-drop along them can be allowed for by regulation or compounding. The size of the distributors, however, is determined by the fact that the voltage fluctuation at the consumers' terminals must not exceed the Regulation limit of ± 6 per cent. The disadvantage of the radial system is that the consumer is dependent on a single feeder, so that a fault on any feeder or distributor cuts off the supply from all consumers who are on the side of the fault away from the station.

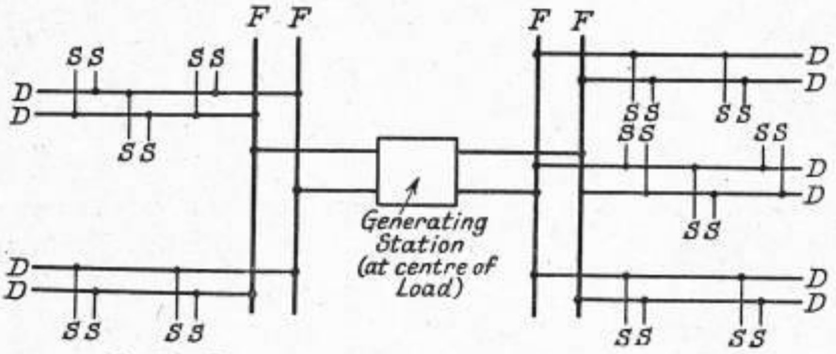

FIG. 16. EARLY DISTRIBUTION SCHEME, RADIAL SYSTEM

The Ring System. This disadvantage is removed by the *ring system*, in which each consumer is supplied via two feeders. A simple example of the ring system is shown in Fig. 17; for simplicity the two (or three) wires of the supply lines are represented by a single line. If there is a fault on a feeder at a point *A*, the section between *B* and *C* can be switched out without interrupting the supply to any consumers.

When the ring main is employed, the electrical energy can be supplied by two or more generators at the same or different points

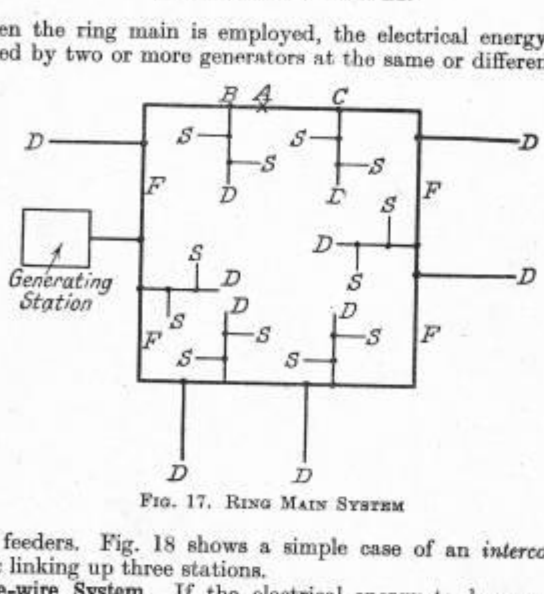

FIG. 17. RING MAIN SYSTEM

of the feeders. Fig. 18 shows a simple case of an *interconnected network* linking up three stations.

Three-wire System. If the electrical energy to be supplied is great, the current must be large and the feeders and distributors

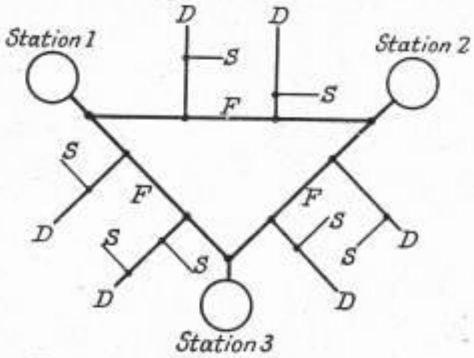

FIG. 18. SIMPLE INTERCONNECTED SYSTEM

must have a large cross-section. A considerable economy is effected by the use of a 3-wire system, which is shown in Fig. 19. One generator supplies current via the wires *1* and *N*, and the other via *N* and *2*; *N* is the neutral and is earthed. If the generators

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supply equal loads, the currents I_1 and I_2 are equ
carries no current. In practice, I_1 and I_2 are no
the neutral carries a current which is small com
The neutral wire cannot be made of very small c
unbalance current $I_1 - I_2$ will cause a large vol
different points and vary the potential from the
usual for the neutral to have a cross-section equ
the outer wires. The saving in copper is found in
Let V be the voltage between the wires in th
between the outers and the neutral in the 3-wire
to be transmitted, R_1 the resistance per cm. per

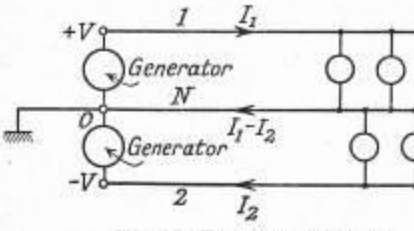

FIG. 19. THREE-WIRE SYSTEM

case, and R_2 the resistance per cm. per outer wire
resistance of the neutral is $2R_2$ per cm., as it h
section of the outers. We have to find the rel
and R_2 so that there are the same I^2R losses in b
2-wire case the current per wire is P/V, and the
the two wires are

$$2(P/V)^2R_1.$$

In the 3-wire case, if we assume balanced loa
the outers is $(P/2V)$ and zero in the neutral. The

$$2(P/2V)^2R_2.$$

We get therefore

$$2(P/V)^2R_1 = 2(P/2V)^2R_2,$$

or

$$R_2 = 4R_1.$$

The cross-section of the outer is thus one-four
2-wire case, so that the copper ratio is

$$\frac{\text{3-wire}}{\text{2-wire}} = \frac{(2 \times \frac{1}{4}) + (\frac{1}{2} \times \frac{1}{4})}{2 \times 1} = \frac{5}{16} = 31{\cdot}2$$

If the neutral has the same cross-section as the

$$\frac{\text{3-wire}}{\text{2-wire}} = \frac{(2 \times \frac{1}{4}) + (1 \times \frac{1}{4})}{2 \times 1} = \frac{3}{8} = 37{\cdot}5$$

If the currents in the outers are not equal, the main consideration is that there shall not be an excessive voltage drop along the neutral due to the unbalance. In this case the 3-wire system must be made of larger gauge cable and the saving is much reduced. It is therefore essential that the loads be balanced as far as possible.

Balancers. The 3-wire system shown in Fig. 19 has two generators which can be regulated independently, so that unbalanced loads can be allowed for. It is more usual to connect a single generator across the outers with a great saving in cost. In this case a *balancer* must be used to deal with the unbalance in the loads. The balancer consists of two shunt-wound dynamos coupled mechanically, the fields and armatures of which are connected in series across the outers, whilst the middle wire is connected to the junction of the armatures, as shown in Fig. 20. If the loads are balanced the balancer dynamos run as unloaded motors and take merely their no-load currents. Suppose now the load on the upper half is greater than that on the lower, so that I_1 is greater than I_2. The voltage across dynamo 1 drops and that across dynamo 2 rises, with the result that the latter acts as a motor and drives the former which then generates and tends to equalize the voltages between the outers and the neutral.

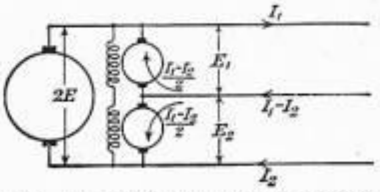

FIG. 20. BALANCER FOR THREE-WIRE SYSTEM

If the armature resistances were zero and the windage and friction losses negligible, the balancing action would be perfect. For then the voltages across the machines would be equal to their e.m.f.'s, which are the same since the fields are the same and the machines run at the same speed (as they are coupled mechanically). Moreover, one-half of the unbalance current, $\frac{1}{2}(I_1 - I_2)$, goes up through one machine and down through the other as shown in Fig. 20; this follows from the fact that the dynamo 1 acts as a generator with an output equal to its e.m.f. times its current, whilst the dynamo 2 acts as a motor to drive it and must therefore *receive* this same value of current.

If the armature resistance and losses are not negligible, the balancing action is not perfect and may be calculated as follows. Let us consider the case when I_1 is greater than I_2, suppose that dynamo 1 gives a current i_1 upwards and dynamo 2 i_2 downwards as in Fig. 21. Then

$$i_1 + i_2 = I_1 - I_2 \quad . \quad . \quad . \quad . \quad . \quad . \qquad \text{(i)}$$

Let the e.m.f.'s of the dynamos be e (equal,
same field and speed). The voltages across the
the voltages between the outers and neutral, are

$$E_1 = e - ri_1 \text{ and } E_2 = e + ri_2$$

where r is the resistance of each armature. Le
and friction losses. Then

$$w = ei_2 - ei_1 = e(i_2 - i_1) \quad .$$

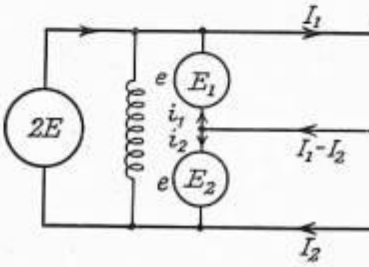

FIG. 21. BALANCER FOR THREE-WIRE S

Equations (i), (ii), and (iii) are sufficient to
i_1 and i_2. Eliminating e from equations (ii) w
unbalance as

$$E_2 - E_1 = r(i_2 + i_1) = r(I_1 -$$

To find i_1 and i_2 we proceed as follows. Adding

$$E_1 + E_2 = 2E = 2e + r(i_2 - i$$

Substituting from this equation in (iii) for e w

$$w = (i_2 - i_1)\,[E - \tfrac{1}{2}r(i_2$$

which is a quadratic equation for $i_2 - i_1$, the sol

$$\begin{aligned} i_2 - i_1 &= \frac{E}{r} - \sqrt{\frac{E^2}{r^2} - \frac{2w}{r}} \\ &\simeq \frac{E}{r} - \frac{E}{r}\left(1 - \frac{wr}{E^2}\right) \\ &= \frac{w}{E}. \end{aligned}$$

With the help of equation (i) we get

$$i_1 = \tfrac{1}{2}(I_1 - I_2) - \frac{w}{2E},$$

$$i_2 = \tfrac{1}{2}(I_1 - I_2) + \frac{w}{2E}.$$

It is clear that the terms $\frac{w}{2E}$ represent the current drawn from the mains of voltage $2E$ to provide the friction and windage losses w.

The voltage unbalance $E_2 - E_1$ can be reduced by using cross-connected field windings for the balance dynamos, as shown in Fig. 22. It can be shown in the same way as used above, that if the dynamo fields have a linear characteristic the voltage unbalance with this system is

$$\tfrac{1}{2}r(I_1 - I_2)$$

instead of $r(I_1 - I_2)$ for the straight through fields. Since E_2 is greater than E_1, the field of dynamo 1 is increased and that of dynamo 2 is decreased, so that the e.m.f. of dynamo 1 is increased and that of dynamo 2 is decreased.

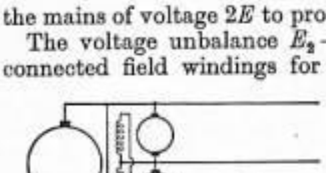

FIG. 22. CROSS-CONNECTED FIELDS FOR BALANCERS

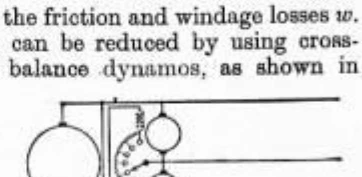

FIG. 23. RHEOSTATIC CONTROL AND CROSS-CONNECTED FIELDS

Hand regulation of the balancer may be employed in addition to the cross-connecting of the fields, as shown in Fig. 23. If the rheostat is set to give equal voltages E_1 and E_2 on half the maximum unbalance current, the unbalance voltage from zero to maximum unbalance current is then about $\pm \tfrac{1}{4}r(I_1 - I_2)$.

Boosters. These are generators inserted into a circuit to compensate for a variable voltage drop. For instance, if the current in a feeder varies, the voltage supplied to the distributors may vary more than the legal amount. This difficulty may be overcome by using very large gauge feeders, but this is costly. A more economical method is to insert a *feeder booster* in the feeder. This booster is a series generator in which the e.m.f. is proportional to the field current, which is here the feeder current. By proper choice of the constants of the booster, the e.m.f. can exactly neutralize the voltage drop in the feeder. Fig. 24 shows the method adopted in practice. The booster is clearly a low-voltage, heavy current machine.

The effect of voltage drop in the feeders can be overcome by

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using compound d.c. generators, but the
convenient when there are feeders of diffe

In a tramway system it may be desira
the line at a distant point. This can b
feeder from the generator to the point and inserting a booster in series with the feeder.

NEGATIVE BOOSTERS subtract from the voltage, and are used in earth return systems in order to keep the potential of all points of the return rail within the Board of Trade regulation limit of 4·2 volts (to avoid the troubles
of electrolysis). Fig. 25 shows how the ne
this case a known fraction of the feeder cu
R, is used for the field winding.

If a d.c. system is subjected to violent
traction system, it is usual to "float" a bat
as shown in Fig. 26. If the resistance of

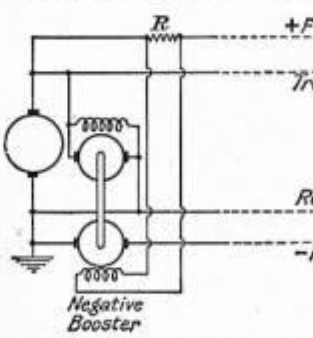


FIG. 25. NEGATIVE BOOSTER C

potential difference would be constant an
would then be the voltage between the b
load the generator will send charge into t
the line; but when the load is heavy the v
terminals will drop, the battery will cea
will send it out on to the line. But the b
resistance, r; if its e.m.f. is E, its voltag
on discharge it is $E - rI$. The voltage flu
may be neutralized by means of a *battery*
There is an additional voltage fluctuatio
varies on charge and discharge. There ar
Entz booster, which attempt to allow for

Advantage of High Voltage. It was shown in the last section that the use of a 3-wire system causes a saving in the amount of copper required, the reason being that the voltage of transmission is effectively doubled.

It can be seen that if the voltage of transmission is multiplied m times, the copper in the conductors can be reduced $1/m^2$ times to transmit the same power with the same ohmic loss. For if the voltage is increased m times, the current is $1/m$ times the previous value for the same transmitted power. The ohmic loss is equal to the resistance multiplied by the square of the current, so that for the same loss the resistance can be m^2 times the previous value and thus the copper in the conductors need be only $1/m^2$ as much as before.

It can be seen that if the criterion is that the voltage drop be the same percentage in both cases, the conductors can be made $1/m^2$ of the previous section as above. For the voltage drop is equal to the product of resistance and current; if the voltage is increased m times and the power is the same, the current is reduced to $1/m$, and the voltage drop can be m times the previous value. The resistance can therefore be increased m^2 times.

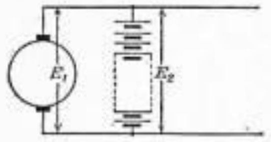


FIG. 26
FLOATING BATTERY

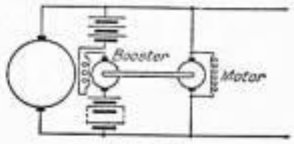


FIG. 27
FLOATING BATTERY AND BOOSTER

Transmission by Alternating Current. It has been shown that it is economical to transmit large blocks of electrical energy at high voltage. The maximum voltage in d.c. transmission was limited by the voltage that was considered safe for the consumer, about 200 volts; the 3-wire system was a method of doubling the effective voltage of transmission. As there were no convenient means of transforming d.c. from one voltage to another, the main trend in the last forty years has been in the direction of high voltage, alternating current transmission.

For transmission and primary distribution the three-phase, 3-wire system of high voltage has been universally adopted. For secondary distribution the three-phase, 4-wire system has been standardized, as it gives 400 volts three-phase for large motors and 230 volts single-phase (between one line and the neutral) for small consumers. Radial and ring mains are used. There is still a fair amount of d.c. 3-wire distribution, and a main obstacle to the conversion to the three-phase, 4-wire system is that new 4-core cables would be required. A single-phase 3-wire system 46
be supplied, but is not welcome because of
working of single-phase motors.

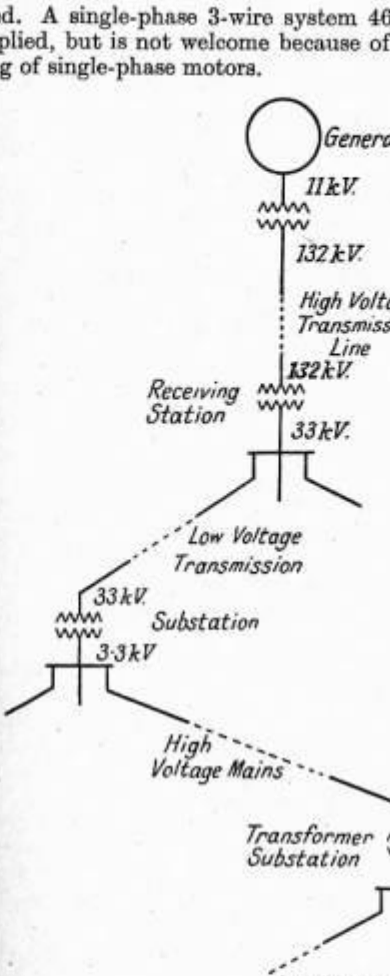


FIG. 28. TYPICAL A.C. SYS

A typical alternating current system of tra
tion is shown in Fig. 28. The generator pr
at 6·6 or 11 kV., in some cases as high as
steps the voltage up to 132 or 110 kV. at
transmission takes place. The receiving st

down to 33 kV. and feeds the substations, which step the voltage down to 3·3 kV. (3 300 volts) and radiate out in a system of high voltage distribution mains. There are transformer stations at various populated places, where the voltage is stepped down to 400/230 volts (400 volts between phases and 230 volts between phase and earth), at which voltage the consumers draw their loads. A large consumer will have his own transformer station, so that he is fed at 3 300 volts.

There is now, however, an important swing towards very high voltage d.c. transmission, which will be described later.

Alternating Current Systems. There are various ways in which alternating currents can be transmitted.

SINGLE-PHASE, TWO- AND THREE-WIRE SYSTEMS. The generator may produce an alternating e.m.f., which is called a *single-phase*

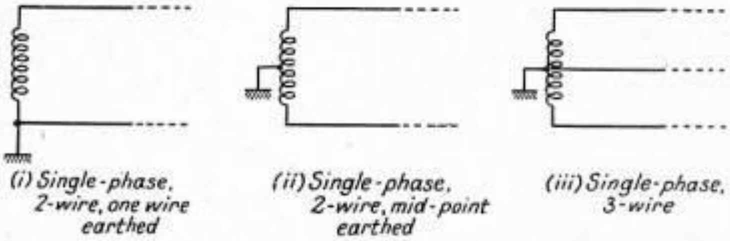

(i) Single-phase, 2-wire, one wire earthed
(ii) Single-phase, 2-wire, mid-point earthed
(iii) Single-phase, 3-wire

FIG. 29. SINGLE-PHASE SYSTEMS

voltage. The transmission may take place along two wires one of which is earthed; or the wires may possess equal and opposite voltages to earth, in which case the mid-point is earthed. These cases are shown in Fig. 29; the earthing may be done on the secondary of a transformer, as shown in the figure, or it may be done on the generator winding itself. There may, however, be three wires, as in the case of d.c. transmission, the mid-wire being the neutral and earthed; this method also is shown in the figure. Single-phase 3-wire transmission has the same advantage over single-phase 2-wire with one wire earthed, as 3-wire d.c. has over 2-wire d.c.

TWO-PHASE, THREE- AND FOUR-WIRE SYSTEMS. The generator may have two windings spaced 90° apart electrically, so that their e.m.f.'s are in quadrature. There are then said to be *two phases.* There are two important types of transmission using two phases; and these are shown in Fig. 30 and are called *two-phase 3-wire* and *two-phase 4-wire* systems. The generator windings are placed at right angles to indicate that their e.m.f.'s are in quadrature.

In the case of the two-phase 4-wire system, the mid-points of the phases are joined.

THREE-PHASE, THREE- AND FOUR-WIRE SYSTEMS. The most

common method of alternating current
three-phase system. In this case the gener
spaced 120° apart electrically, so that th
magnitude but 120° apart in phase.

Fig. 31 shows the three-phase 3-wire sy
practice. They are called the *star* or ⅄ an

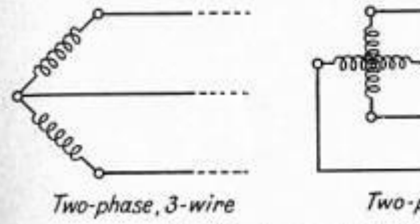

Two-phase, 3-wire
Two-

FIG. 30. TWO-PHASE SYST

tions. The common point in the star co
point O and is generally earthed, either dir
tance or an inductance coil (Petersen coil).

In the star system the line currents are equ
but the voltages between lines are $\sqrt{3}$ time
lag behind them by 90°. In the delta syst

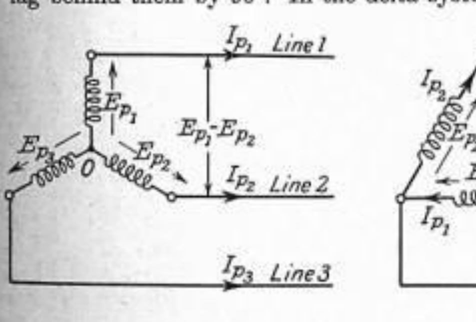


FIG. 31. THREE-PHASE SYS

equal to the phase voltages, but the line cu
phase currents and lag behind them by 90°.

In both the star and delta arrangement
given by $E_p'I_p'$ cos ϕ per phase, where
voltage, I_p' the r.m.s. phase current, and
between them; the total power is $3E_p'I_p'$ co
It is seen that in both cases the power is eq
where E_l' and I_l' are the r.m.s. values o

currents. For in the star system $I_p' = I_l'$ and $(\sqrt{3})E_p' = E_l'$, whilst in the delta system $(\sqrt{3})I_p' = I_l'$ and $E_p' = E_l'$. Thus the power is

$$P = 3E_p'I_p' \cos \phi = (\sqrt{3})E_l'I_l' \cos \phi$$

In low-voltage distribution a neutral wire is used, so that household loads can be taken between one line and neutral. We have thus a three-phase, 4-wire system.

Copper Efficiencies. The cost of the copper is one of the most important charges in a system, and it is interesting to compare the cost in the various systems described in the previous section. The method adopted is to compare the quantity of copper in any system with that in a simple d.c. 2-wire system, it being assumed that the same total power is transmitted with the same loss and with the same maximum voltage to earth or the same maximum voltage between conductors.

Both of the last conditions are important, the maximum voltage to earth being the quantity of importance in overhead lines and in single core cables, the maximum voltage between conductors being important in multi-core cables.

Table VII gives the ratio of copper in any system compared with that in the corresponding d.c. 2-wire system; cos ϕ is the power factor in an a.c. system.

TABLE VII

COPPER EFFICIENCIES

System	Same Maximum Voltage to Earth	Same Maximum Voltage between Conductors
D.C. 2-wire . . .	1	1
D.C. 2-wire Mid-point earthed . .	0·25	1
D.C. 3-wire Neutral = $\frac{1}{2}$ × outer .	0·3125	1·25
D.C. 3-wire Neutral = outer . .	0·375	1·5
Single-phase, 2-wire .	$2/\cos^2\phi$	$2/\cos^2\phi$
Single-phase, 2-wire Mid-point earthed . .	$0·5/\cos^2\phi$	$2/\cos^2\phi$
Single-phase, 3-wire Neutral = $\frac{1}{2}$ × outer .	$0·625/\cos^2\phi$	$2·5/\cos^2\phi$
Two-phase, 4-wire .	$0·5/\cos^2\phi$	$2·0/\cos^2\phi$
Two-phase, 3-wire .	$1·46/\cos^2\phi$	$2·91/\cos^2\phi$
Three-phase, 3-wire .	$0·5/\cos^2\phi$	$1·5/\cos^2\phi$
Three-phase, 4-wire Neutral = outer . .	$0·67/\cos^2\phi$	$2/\cos^2\phi$

Two of the cases of the d.c. 3-wire system have been worked out on page 33, and two cases of three-phase systems will be discussed to show the method.

To compare the copper required in a d.c.
three-phase, 3-wire system having the same maxi
Let E be the voltage between conductors
I the current. The power is EI and the los
resistance of each wire per unit length.
We shall consider a star-connected, thre
maximum phase voltage is E and the r.m.s.
is the r.m.s. value of the line currents, the po
and the loss is $3R'I'^2$, where R' is the resista
therefore

$$EI = (3/\sqrt{2})EI' \cos \phi$$

and $$2RI^2 = 3R'I'^2,$$

so that $$R = R'/3 \cos^2 \phi.$$

Each wire in the three-phase system ha
$1/3 \cos^2 \phi$ of that in the d.c. system. As the
in the d.c. system and three in the a.c., the d

$$(3/2) \times (1/3 \cos^2 \phi) = 0·5/c$$

as much copper. The delta system will req
of copper as the star system, since the power
in both systems.

To compare the copper required in the d.c
three-phase, 4-wire system having the same ma
lines and a neutral equal to the outers.
We consider again a star-connected system
voltage between lines, the maximum phase
the r.m.s. is $E/\sqrt{6}$. If the line current is I',
cos ϕ and the loss is $3R'I'^2$. Therefore

$$EI = (3/\sqrt{6})EI' \cos \phi$$

and $$2RI^2 = 3R'I'^2,$$

so that $$R = R'/\cos^2 \phi.$$

The cross-section in the a.c. system is 1/c
d.c. system, and as there are two conductors
in the former, the copper ratio is $(4/\cos^2 \phi) \div$
The effect of raising the voltage has al
Multiplying the voltage m times reduces the
previous value.

High Voltage, Direct Current. There ar
advantages to be gained by the use of high
transmission. If we consider overhead lines
which alone are used with extra high voltage
voltage to earth is the criterion, the ratio
2-wire system with earthed mid-point and t
system is $(0·25) \div (0·5/\cos^2 \phi) = 0·5 \cos^2 \phi$

factor is 0·85, the d.c. system requires only 0·36 as much copper as the a.c. system. Furthermore in a.c. systems the charging currents contribute to a continuous loss even when there is no load, whilst the d.c. system will have losses only when the load is on. It is held that the losses due to the charging current are a determining factor in the economics of long distance transmission.

Furthermore the transmission of a.c. for great distances is attended with instability, i.e. a synchronous machine will not be pulled back into phase if it departs from its correct position; and it is necessary to inject reactive power at intervals of about 100 miles to limit the reactive drop which is the cause of instability. D.C. transmission is not affected by instability and the lines may have any length.

Insulation difficulties are much greater with a.c. than with d.c., and the adoption of d.c. will raise the permissible transmission voltage without extra cost or trouble. Thus the current-carrying capacity of buried cables used for very high voltages (100 kV. and above) is determined partly by thermal instability due to the rise of the power factor of the dielectric with temperature. As there are no appreciable dielectric losses with d.c. the current-carrying capacity can be increased considerably.

Until recently there was no adequate method of transforming electrical energy from low voltage a.c. or d.c. to high voltage d.c., and from the latter to the former. The only method of utilizing high voltage d.c. was the Thury method. In this system series-wound generators are connected in series, the current is kept constant and the power is varied by varying the voltage of transmission. This is done by varying the speed of the generators or by inserting more generators into the circuit. The Thury system between Moutiers and Lyons, 112 miles apart, has a constant line current of 75 amperes and a maximum voltage of 60 000 volts, so that the maximum output is 4 500 kW. The generators have to be insulated from earth for the maximum voltage.

Power is taken from the circuit by motor-generators, the motors being series-wound and connected in series with the main circuit. The generators driven by them can give d.c. or a.c. at any desired voltage. The motors have to be insulated from earth for the maximum voltage, and are short-circuited when they are not required.

The main disadvantages of the Thury system are the facts that the line losses are constant at all loads so that the efficiency at low loads is very poor, and an increase of power of the system necessitates fresh insulation of the line for higher voltage since the current is constant.

There are now available various rectifiers, of the mercury vapour and atmospheric arc types, which can handle 30 000 kW. at 400 kV. Energy can be transformed from a.c. to d.c. and from d.c. to a.c. with a very high efficiency and at reasonable cost.

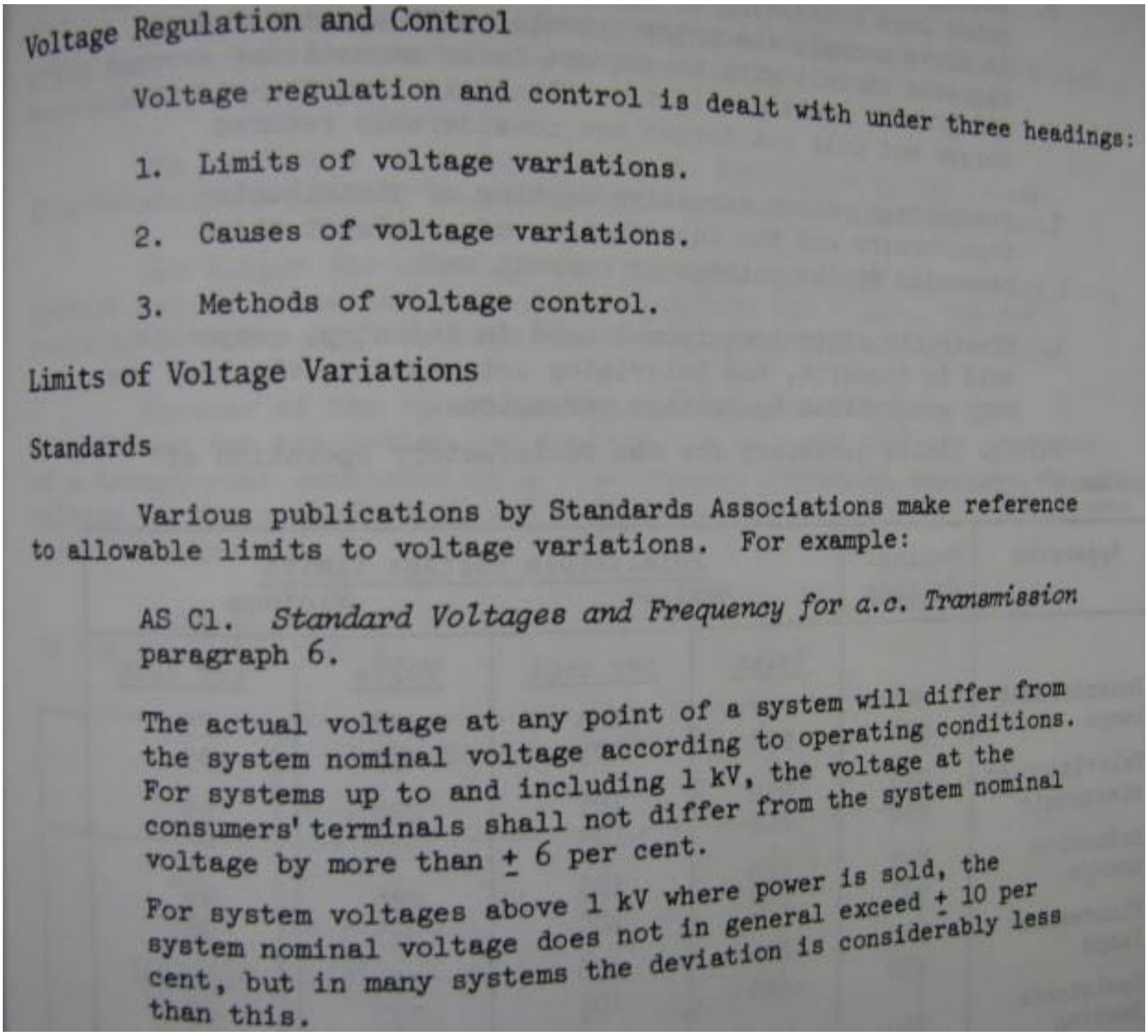
EXAMPLES II

1. Discuss the advantages, possibilities and diff
large amounts of power over long distances by mea
current as compared with the usual three-phase syste

2. Discuss the advantages of a 3-wire system as
system for a d.c. distribution network and explain
maintain approximately equal voltages across the
system at the end of a long radial feeder with a heav

3. A power of 150 000 kW. is to be transmitted
miles. Discuss the relative advantages of (*a*) three-
rent, transmission. Explain why, at the present tim
systems are three-phase.

1 Distribution and reticulation system Part (2)



Voltage Regulation and Control

Voltage regulation and control is dealt with under three headings:

1. Limits of voltage variations.
2. Causes of voltage variations.
3. Methods of voltage control.

Limits of Voltage Variations

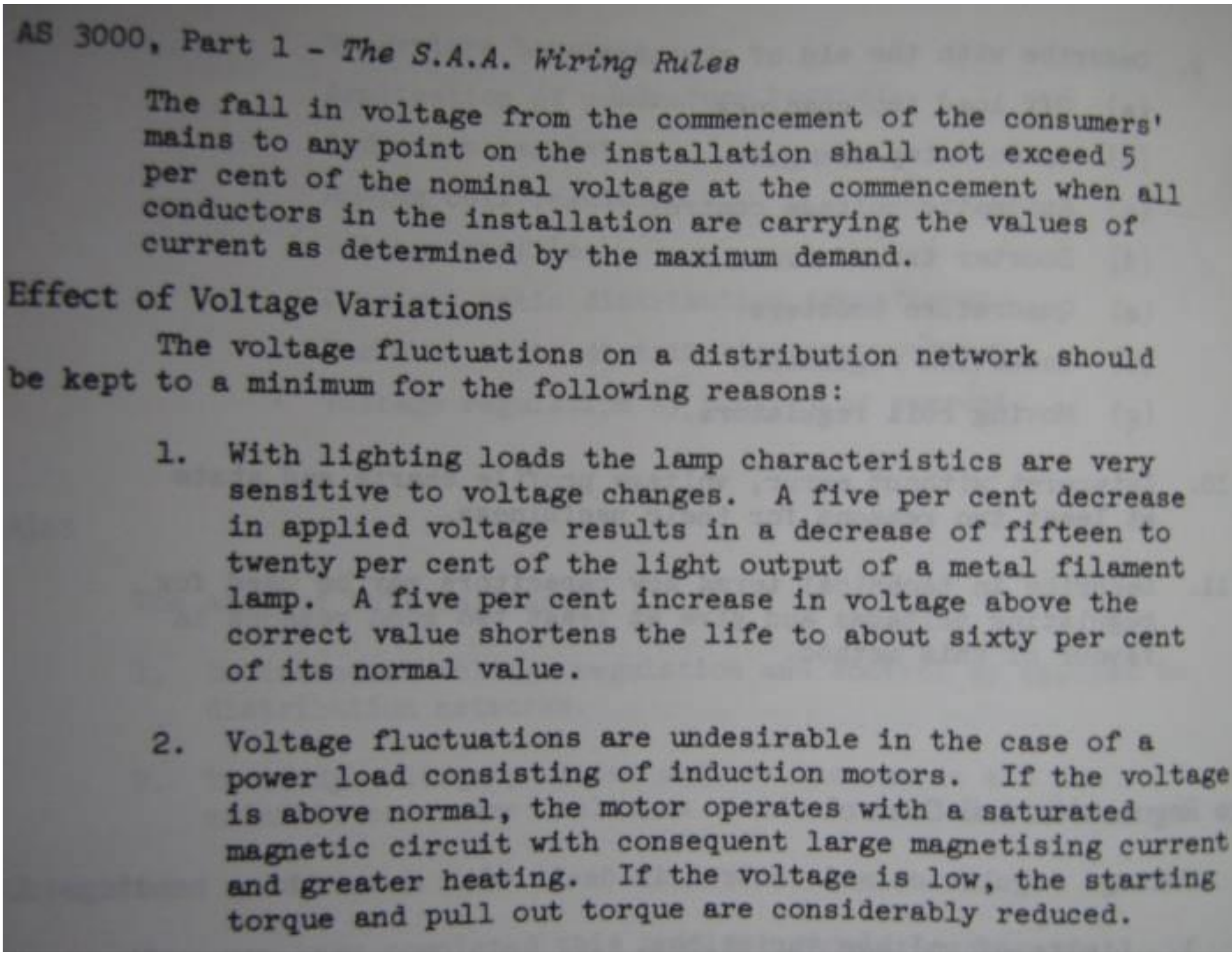
Standards

Various publications by Standards Associations make reference to allowable limits to voltage variations. For example:

AS C1. *Standard Voltages and Frequency for a.c. Transmission* paragraph 6.

The actual voltage at any point of a system will differ from the system nominal voltage according to operating conditions. For systems up to and including 1 kV, the voltage at the consumers' terminals shall not differ from the system nominal voltage by more than ± 6 per cent.

For system voltages above 1 kV where power is sold, the system nominal voltage does not in general exceed ± 10 per cent, but in many systems the deviation is considerably less than this.



AS 3000, Part 1 - *The S.A.A. Wiring Rules*

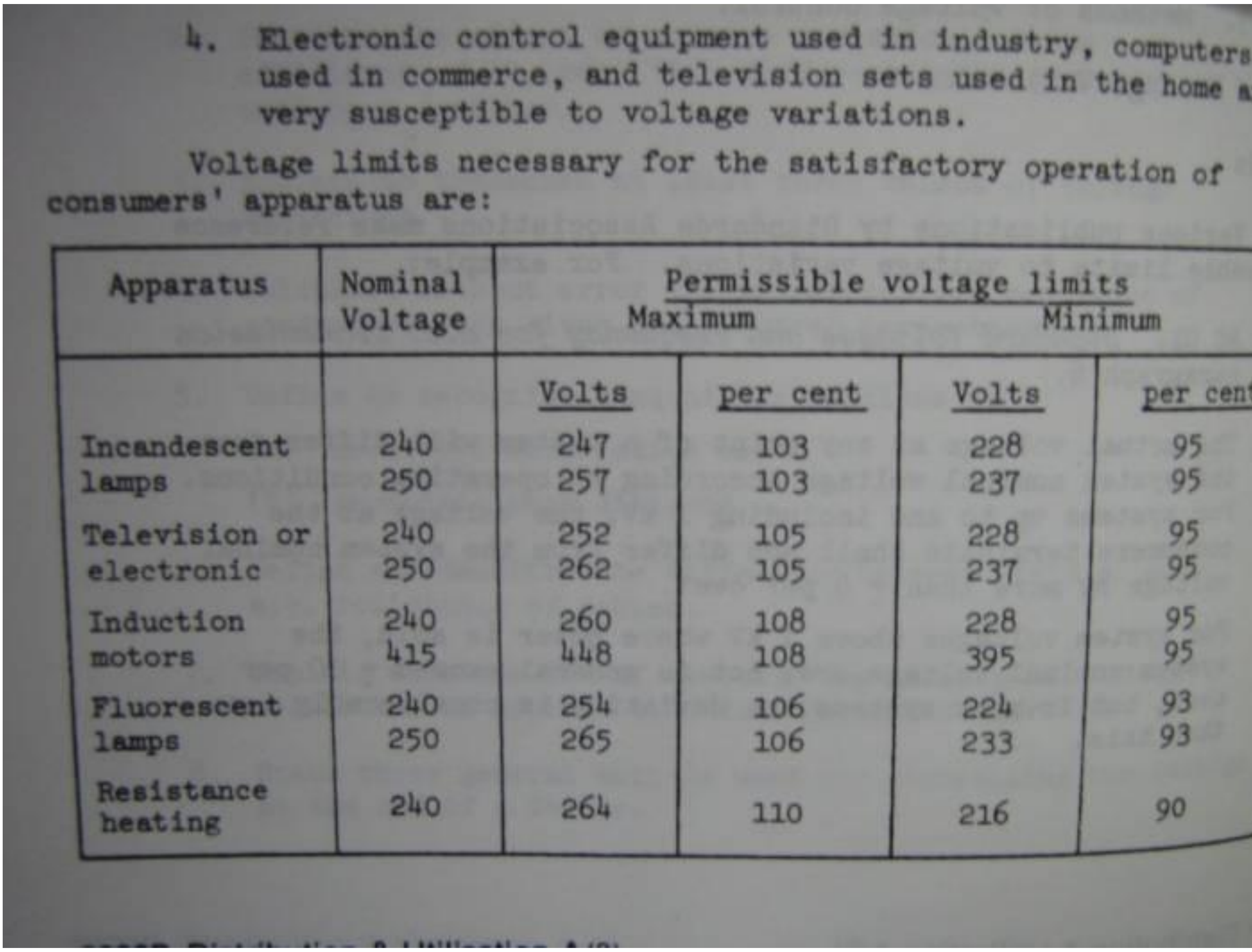
> The fall in voltage from the commencement of the consumers' mains to any point on the installation shall not exceed 5 per cent of the nominal voltage at the commencement when all conductors in the installation are carrying the values of current as determined by the maximum demand.

Effect of Voltage Variations

The voltage fluctuations on a distribution network should be kept to a minimum for the following reasons:

1. With lighting loads the lamp characteristics are very sensitive to voltage changes. A five per cent decrease in applied voltage results in a decrease of fifteen to twenty per cent of the light output of a metal filament lamp. A five per cent increase in voltage above the correct value shortens the life to about sixty per cent of its normal value.

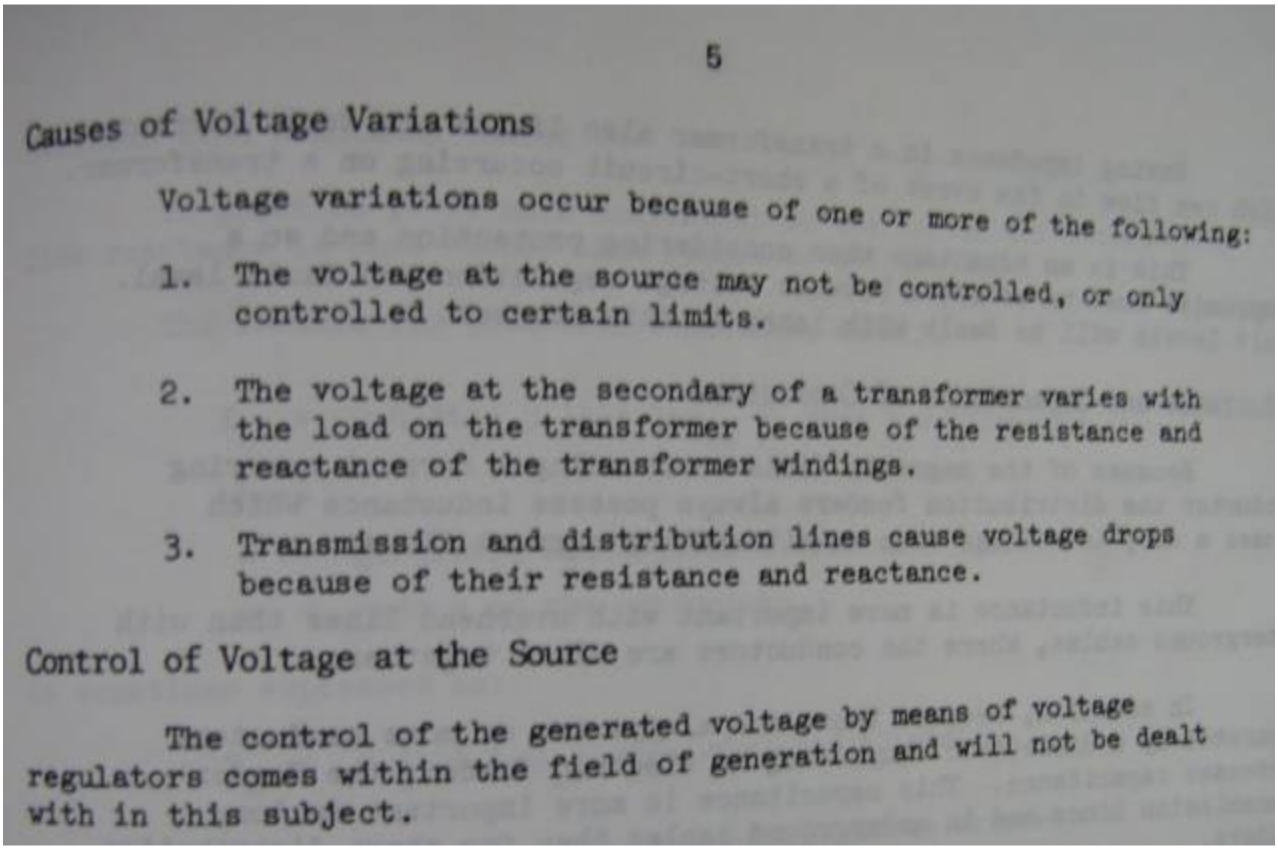
2. Voltage fluctuations are undesirable in the case of a power load consisting of induction motors. If the voltage is above normal, the motor operates with a saturated magnetic circuit with consequent large magnetising current and greater heating. If the voltage is low, the starting torque and pull out torque are considerably reduced.



4. Electronic control equipment used in industry, computers used in commerce, and television sets used in the home a very susceptible to voltage variations.

Voltage limits necessary for the satisfactory operation of consumers' apparatus are:

Apparatus	Nominal Voltage	Permissible voltage limits Maximum		Minimum	
		Volts	per cent	Volts	per cen
Incandescent lamps	240 250	247 257	103 103	228 237	95 95
Television or electronic	240 250	252 262	105 105	228 237	95 95
Induction motors	240 415	260 448	108 108	228 395	95 95
Fluorescent lamps	240 250	254 265	106 106	224 233	93 93
Resistance heating	240	264	110	216	90



Causes of Voltage Variations

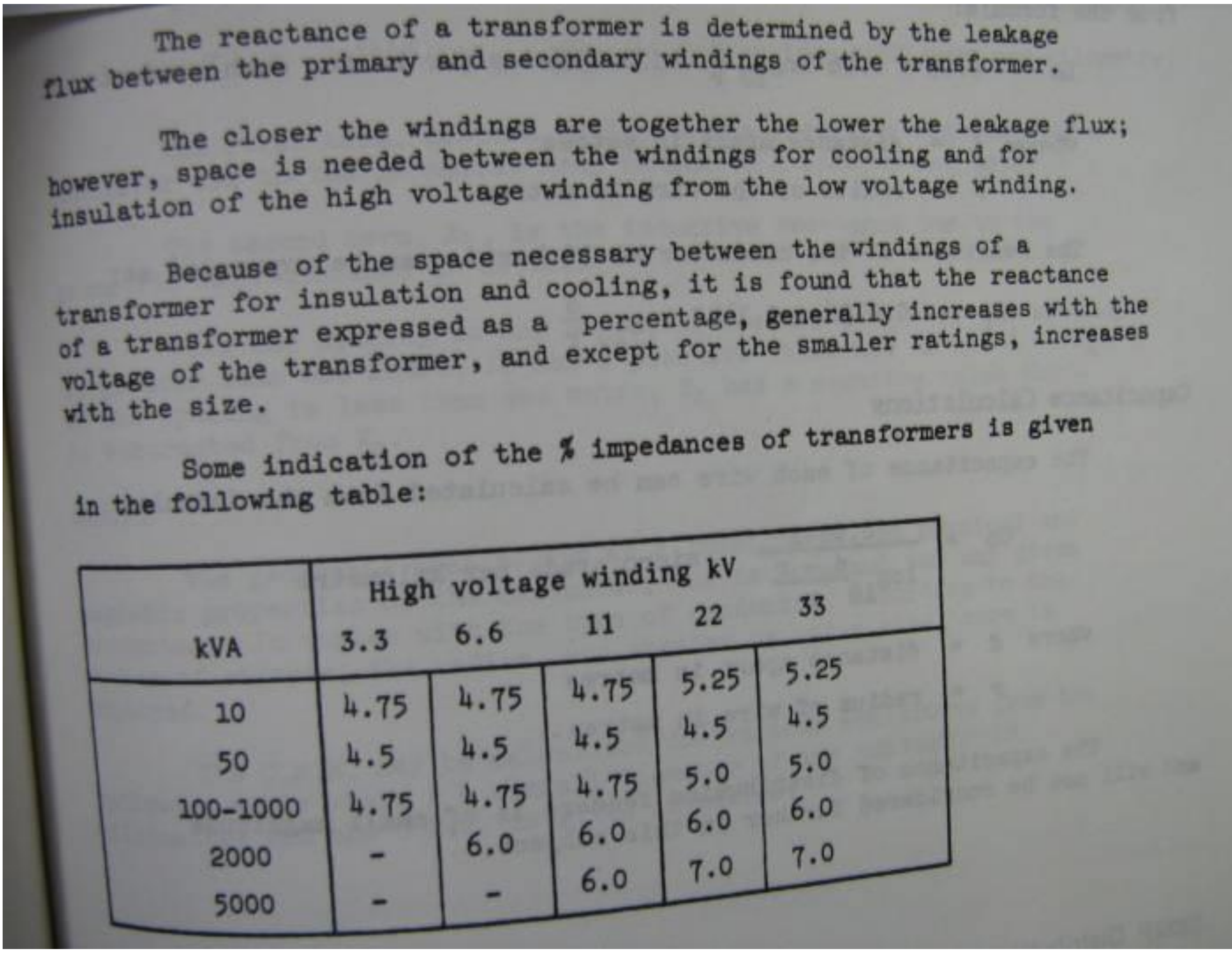
Voltage variations occur because of one or more of the following:

1. The voltage at the source may not be controlled, or only controlled to certain limits.
2. The voltage at the secondary of a transformer varies with the load on the transformer because of the resistance and reactance of the transformer windings.
3. Transmission and distribution lines cause voltage drops because of their resistance and reactance.

Control of Voltage at the Source

The control of the generated voltage by means of voltage regulators comes within the field of generation and will not be dealt with in this subject.

TRANSFORMER



The reactance of a transformer is determined by the leakage flux between the primary and secondary windings of the transformer.

The closer the windings are together the lower the leakage flux; however, space is needed between the windings for cooling and for insulation of the high voltage winding from the low voltage winding.

Because of the space necessary between the windings of a transformer for insulation and cooling, it is found that the reactance of a transformer expressed as a percentage, generally increases with the voltage of the transformer, and except for the smaller ratings, increases with the size.

Some indication of the % impedances of transformers is given in the following table:

kVA	High voltage winding kV 3.3	6.6	11	22	33
10	4.75	4.75	4.75	5.25	5.25
50	4.5	4.5	4.5	4.5	4.5
100-1000	4.75	4.75	4.75	5.0	5.0
2000	-	6.0	6.0	6.0	6.0
5000	-	-	6.0	7.0	7.0

1 Distribution and reticulation system Part (3)

INTRODUCTION

The major electrical items encountered in most types of industrial and commercial plants are listed below.

1. Power generation equipment, or purchased power switching, or sub-station.

2. Primary and secondary distribution systems, including feeders, transformers, switchgear, protective equipment and standby generating plant.

3. Motor drives, heaters, ovens, and the associated wiring and control equipment.

4. Lighting equipment and lighting wiring circuits.

5. Electrical and electronic control and instrumentation systems.

6. Auxiliary systems (fire alarms, electric clocks, burglar alarms).

7. Communication equipment (paging, intercommunication).

8. Special items peculiar to processes such as welding, batteries, rectifiers, electroplating apparatus, elevators and lifts,

8. Special items peculiar to processes such as welding, batteries, rectifiers, electroplating apparatus, elevators and lifts, industrial trucks, cranes and hoists, ventilation and air-conditioning.

9. Yard, roadway, and protective lighting.

While it is necessary to realise that, for industrial plants, all of the above are important, this elective subject deals only with the items listed in numbers 2, 3, 4 and 9. The remaining sections are covered by other electives or are of a highly specialised nature.

Administration

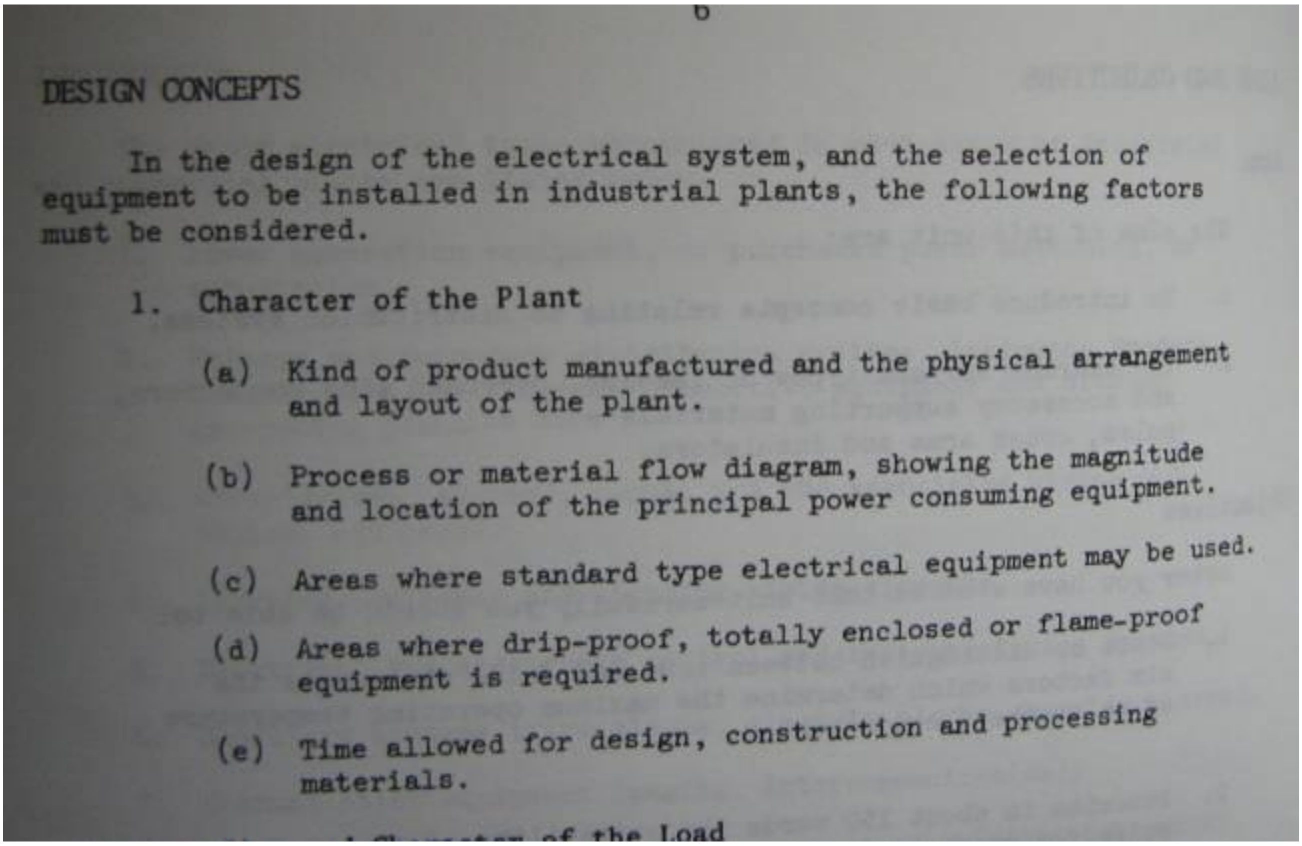
As well as the above electrical items, electrical supervisors must be concerned with the following:

1. Basic industrial costs.

2. Management (supervision, work simplification).

3. Legal responsibilities (acts, ordinances, patents, copyrights).

Of this group, mention will be made throughout the subject to relative equipment costs, but specific costing is not possible without adequate catalogues and price lists. Some aspects of the legal responsibilities of personnel engaged in the electrical field will also be dealt with.



6

DESIGN CONCEPTS

In the design of the electrical system, and the selection of equipment to be installed in industrial plants, the following factors must be considered.

1. Character of the Plant

   (a) Kind of product manufactured and the physical arrangement and layout of the plant.

   (b) Process or material flow diagram, showing the magnitude and location of the principal power consuming equipment.

   (c) Areas where standard type electrical equipment may be used.

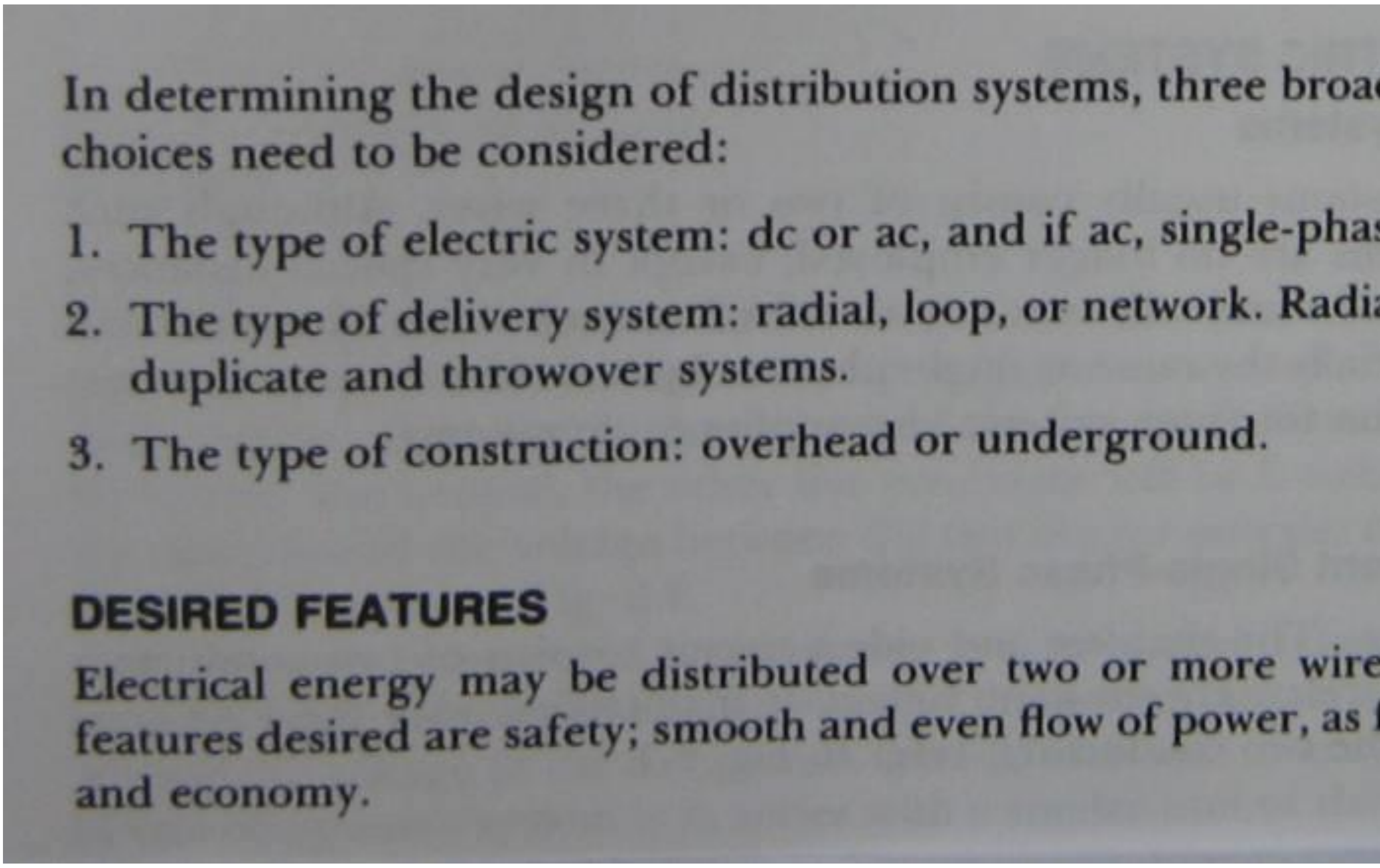
   (d) Areas where drip-proof, totally enclosed or flame-proof equipment is required.

   (e) Time allowed for design, construction and processing materials.

Character of the Load

1 Distribution and reticulation system Part (4)

Distribution System Consideration



In determining the design of distribution systems, three broa
choices need to be considered:

1. The type of electric system: dc or ac, and if ac, single-pha
2. The type of delivery system: radial, loop, or network. Radi
   duplicate and throwover systems.
3. The type of construction: overhead or underground.

DESIRED FEATURES

Electrical energy may be distributed over two or more wire
features desired are safety; smooth and even flow of power, as
and economy.

TYPES OF ELECTRIC SYSTEMS

Direct Current Systems

Direct current systems usually consist of two or three wires. Alth
distribution systems are no longer employed, except in very specia
older ones now exist and will continue to exist for some time. Dir
systems are essentially the same as single-phase ac systems of two or t
the same discussion for those systems also applies to dc systems.

Alternating Current Single-Phase Systems

Two-Wire Systems The simplest and oldest circuit consists of two c
between which a relatively constant voltage is maintained, with the
nected between the two conductors; refer to Fig. 2-1.

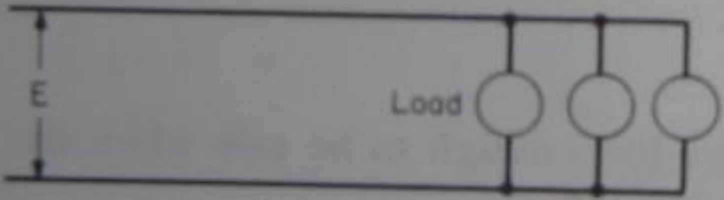
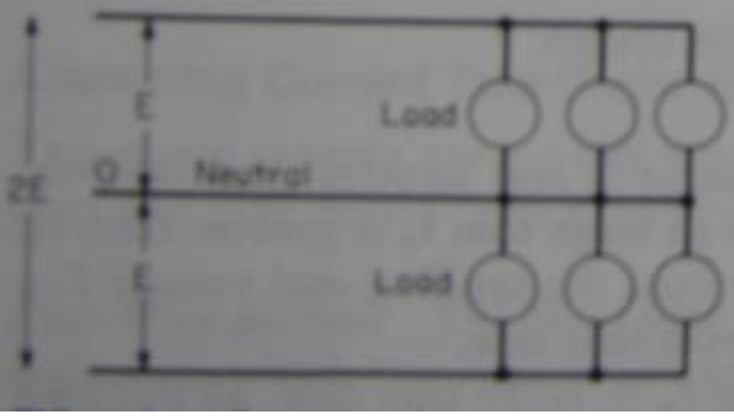


FIG. 2-1 AC single-phase two-wire system.

In almost all cases, one conductor is grounded. The grounding of
ductor, usually called the *neutral*, is basically a safety measure. Shoul
conductor come in contact accidentally with the neutral conductor, th
of the live conductor will be dissipated throughout a relatively large
earth and thereby rendered harmless.

In calculating power (I^2R) losses in the conductors, the re
conductors must be considered. In the case of the neutral con
the ground, in parallel with the conductor, reduces the effectiv
"return" current will divide between the conductor and ground
portion to their resistances. Thus the I^2R loss in the neutral co
lower than that in the live conductor; the I^2R loss in the earth m
purposes, be disregarded.

In calculating voltage drop in the circuits, both the resistanc
of the two conductors must be considered. (In dc circuits, rea
exist during normal flow of current.) This combination of reac
tance, known as impedance, is measured in ohms (Ω). Becaus
the grounded neutral conductor may be less than the current
ductor, the voltage drop in the neutral conductor may also be l



Three-Wire Systems Essentially the three-wire system is a combination
two-wire systems with a single wire serving as the neutral of each of th
wire systems. At a given instant, if one of the live conductors is E volts (s
V) "above" the neutral, the other live conductor will be E volts (120 V) "
the neutral, and the voltage between the two live (or outside) conductors
$2E$ (240 V). Refer to Fig. 2-2.

If the load is balanced between the two (two-wire) systems, the co
neutral conductor carries no current and the system acts as a two-wire s
at twice the voltage of the component system; each unit of load (such as a
of one component system is in series with a similar unit of the other syst
the load is not balanced, the neutral conductor carries a current equal
difference between the currents in the outside conductors. Here agai
neutral conductor is usually connected to ground.

For a balanced system, power loss and voltage drop are determined
same way as for a two-wire circuit consisting of the outside conductor
neutral is neglected.

Where the loads on the two portions of the three-wire circuit are unbala
voltages at the utilization or receiving ends may be different. These are s
schematically in Fig. 2-3. Let the distance between the dashed lines repr
the voltage. There will be a voltage drop, with reference to the neutral, in
of the conductors 1 and 2. The neutral conductor will carry the differen
currents, that is, $I_2 - I_1$, or I_n. This current in the neutral conductor will pro
a voltage drop in that conductor, as indicated in Fig. 2-3. The result will

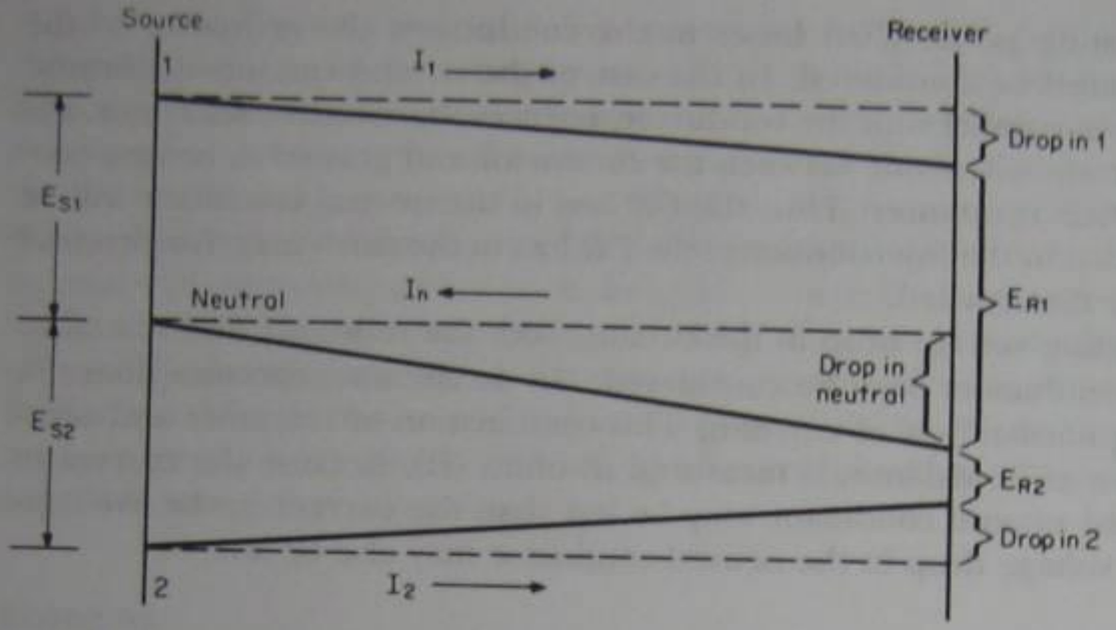


FIG. 2-3 Unbalanced load—single-phase three-wire system.

much larger drop in voltage between conductor 2 and neutral than betwe conductor 1 and neutral. If the unbalance is so large that I_n is greater than the receiving end voltage E_{R1} will be greater than the sending end voltage E and there will be an actual rise in voltage across that side.

The limiting case occurs when $I_1 = 0$ and $I_n = I_2$. In that case, all the loa is carried on side 2; the rise in voltage on side 1 will be half as much as the dro in voltage on the loaded side 2. However, if an equal load is now added to sic 1, the loads in both parts of the circuit will be balanced and I_n will equal 0. Th drop in voltage between conductor 2 and the neutral will be reduced to ha that obtained with the load on side 2 only, although the load now supplied doubled.

Voltage drops in the conductors will depend on the currents flowing in ther and their impedances. The power loss in each conductor (I^2R) will depend o the current flowing in it and its resistance.

In all of this discussion, the size of the neutral has been assumed to be th same as the live or outside conductors.

Alternating Current Two-Phase Systems

Two-phase systems are rapidly becoming obsolete, but a good number of them exist and may continue to exist for some time.

Four-Wire Systems The four-wire system consists of two single-phase two-wire systems in which the voltage in one system is 90° out of phase with the voltage in the other system, both usually supplied from the same generator. Refer to Fig. 2-5.

In determining the power, power loss, and voltage drops in such a system, the values are calculated as for two separate single-phase two-wire systems.

Three-Wire Systems The three-wire system is equivalent to a fo
phase system, with one wire (the neutral) made common to both
to Fig. 2-6. The current in the outside or phase wires is the same a
wire system; the current in the common wire is the vector sum of th
but opposite in phase. When the load is exactly balanced in the two
currents are equal and 90° out of phase with each other and the resu
current is equal to $\sqrt{2}$ or 1.41 times the phase current.

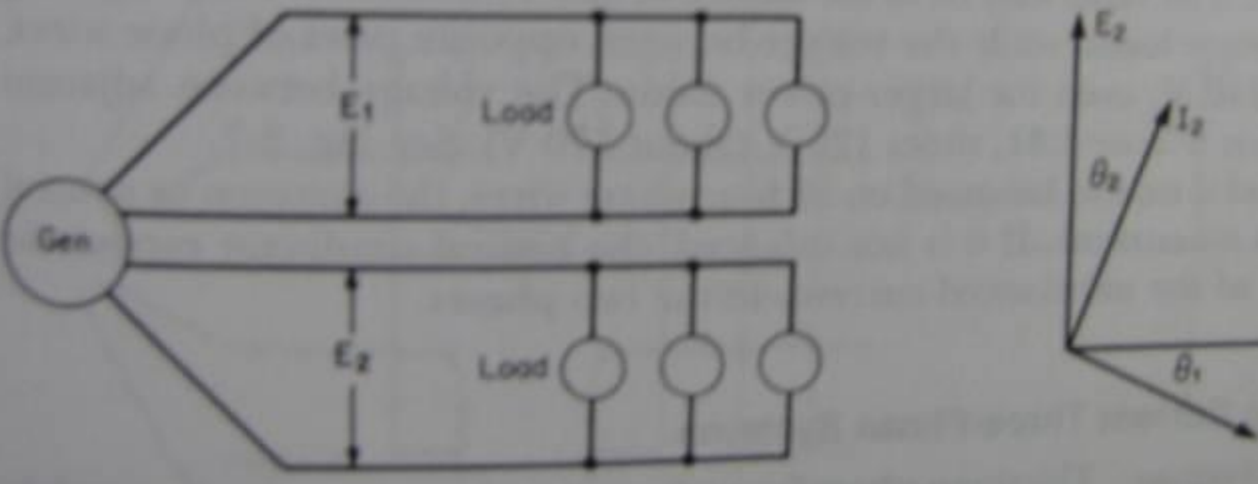


FIG. 2-5 AC two-phase four-wire system and vector diagram.

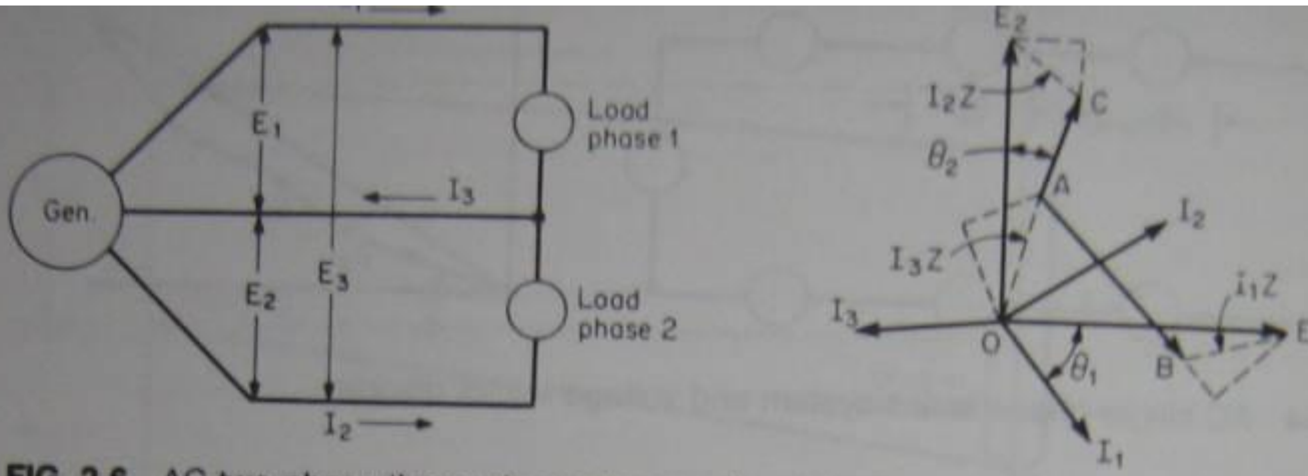
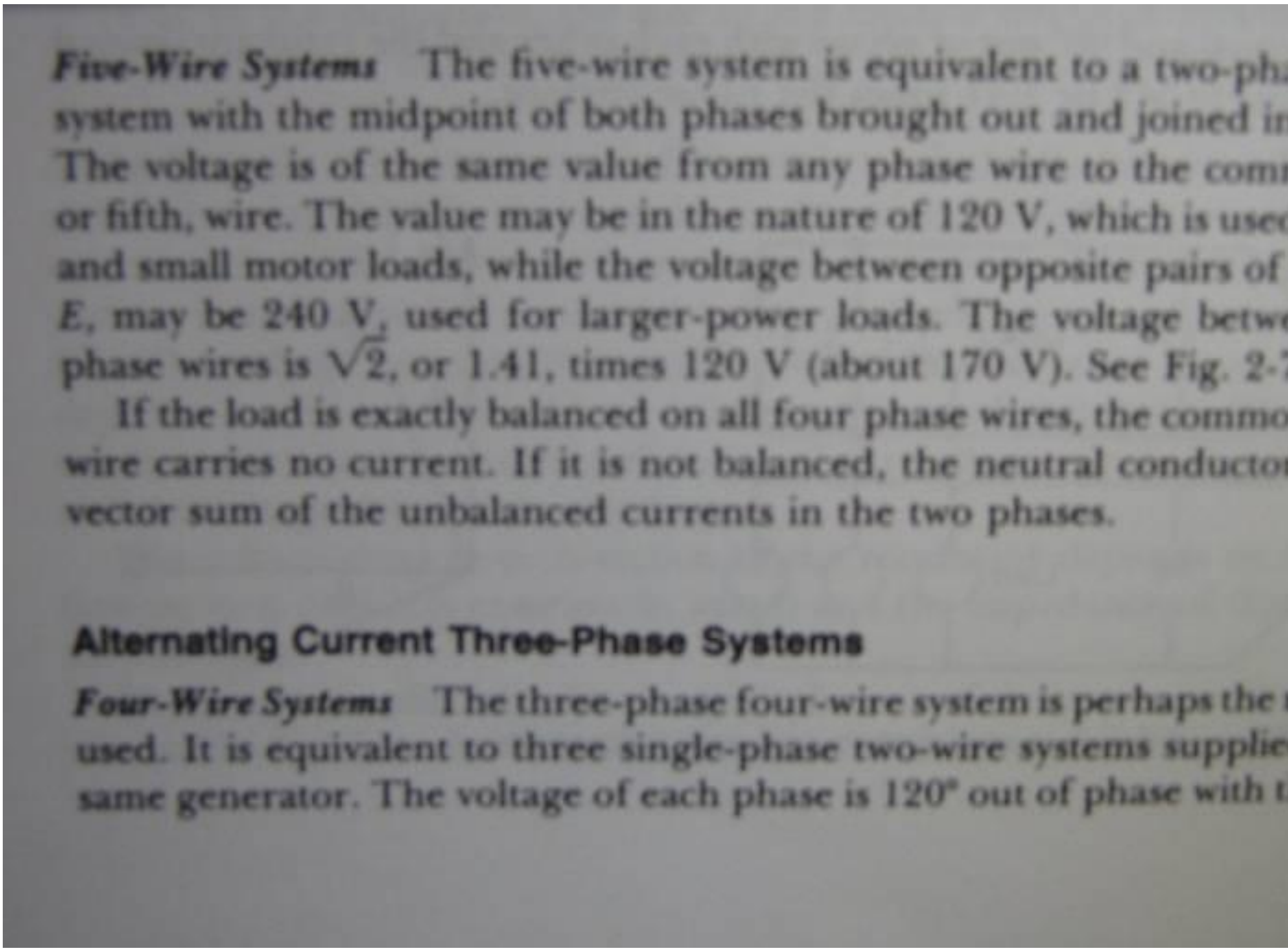


FIG. 2-6 AC two-phase three-wire system and vector diagram.

The voltage between phase wires and common wire is the normal p voltage, and, neglecting the difference in neutral *IR* drop, the same as in four-wire system. The voltage between phase wires is equal to $\sqrt{2}$ or 1.41 t that voltage.

The power delivered is equal to the sum of the powers delivered by the phases. The power loss is equal to the sum of the power losses in each of three wires.

The voltage drop is affected by the distortion of the phase relation cau by the larger current in the third or common wire. In Fig. 2-6, if E_1 and E_2 the phase voltages at the source and I_1 and I_2 the corresponding phase curre (assuming balanced loading), I_3 is the current in the common wire. The volt *(IZ)* drops in the two conductors, subtracted vectorially from the source volta E_1 and E_2, give the resultant voltages at the receiver of *AB* for phase 1 and for phase 2. The voltage drop numerically is equal to $E_1 - AB$ for phase 1, a $E_2 - AC$ for phase 2. It is apparent that these voltage drops are unequal a that the action of the current in the common wire is to distort the relatio between the voltages and currents—the effect shown in Fig. 2-6 is exaggerat for illustration.



Five-Wire Systems The five-wire system is equivalent to a two-ph
system with the midpoint of both phases brought out and joined in
The voltage is of the same value from any phase wire to the comm
or fifth, wire. The value may be in the nature of 120 V, which is use
and small motor loads, while the voltage between opposite pairs of
E, may be 240 V, used for larger-power loads. The voltage betw
phase wires is $\sqrt{2}$, or 1.41, times 120 V (about 170 V). See Fig. 2-

If the load is exactly balanced on all four phase wires, the commo
wire carries no current. If it is not balanced, the neutral conducto
vector sum of the unbalanced currents in the two phases.

Alternating Current Three-Phase Systems

Four-Wire Systems The three-phase four-wire system is perhaps the
used. It is equivalent to three single-phase two-wire systems supplie
same generator. The voltage of each phase is 120° out of phase with t

Three-Wire Systems If the load is equally balanced on the three four-wire system, the neutral carries no current and hence could l making a three-wire system. It is not necessary, however, that the loa balanced on a three-wire system.

Considering balanced loads, on a three-phase three-wire system, a load may be connected with each phase connected between two ph

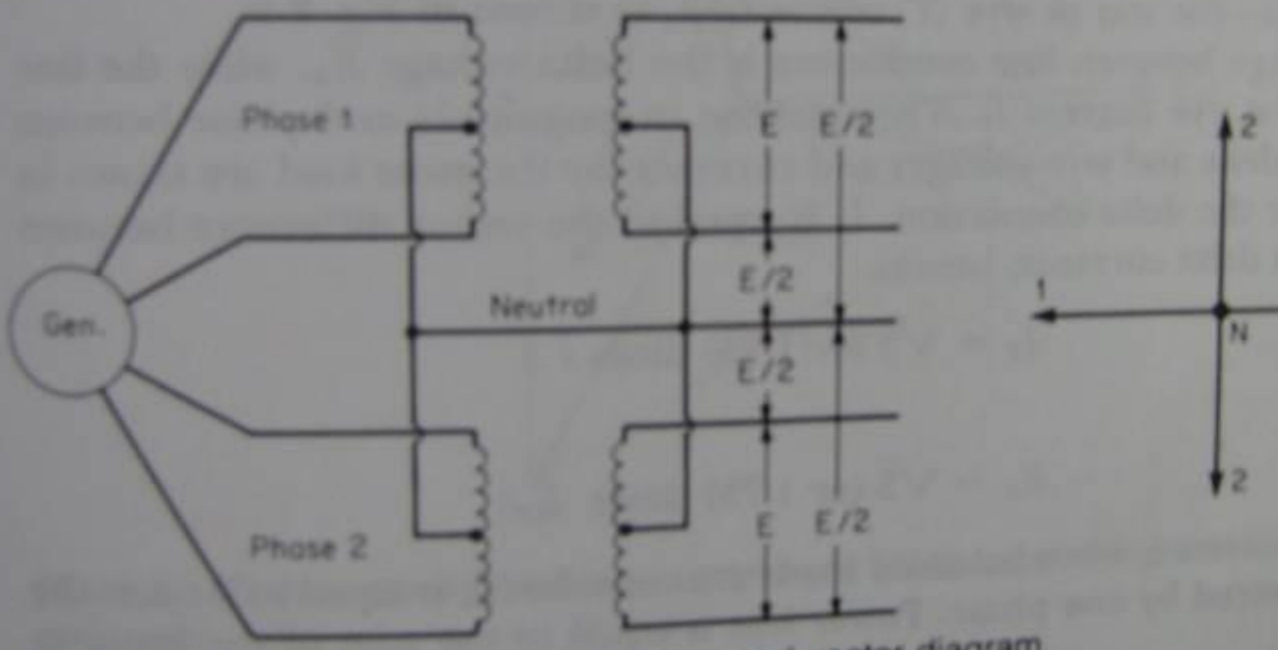


FIG. 2-7 AC two-phase five-wire system and vector diagram.

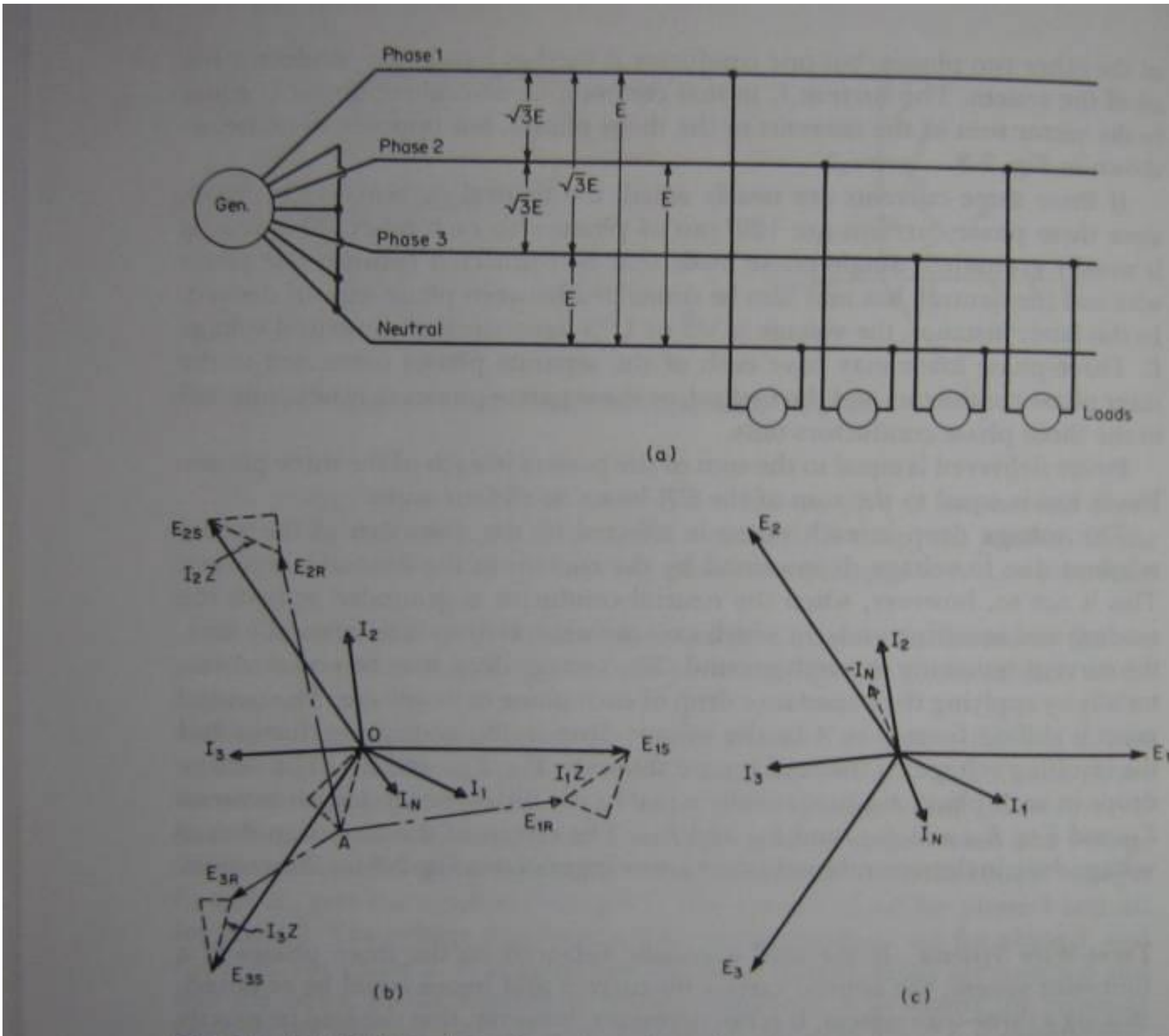
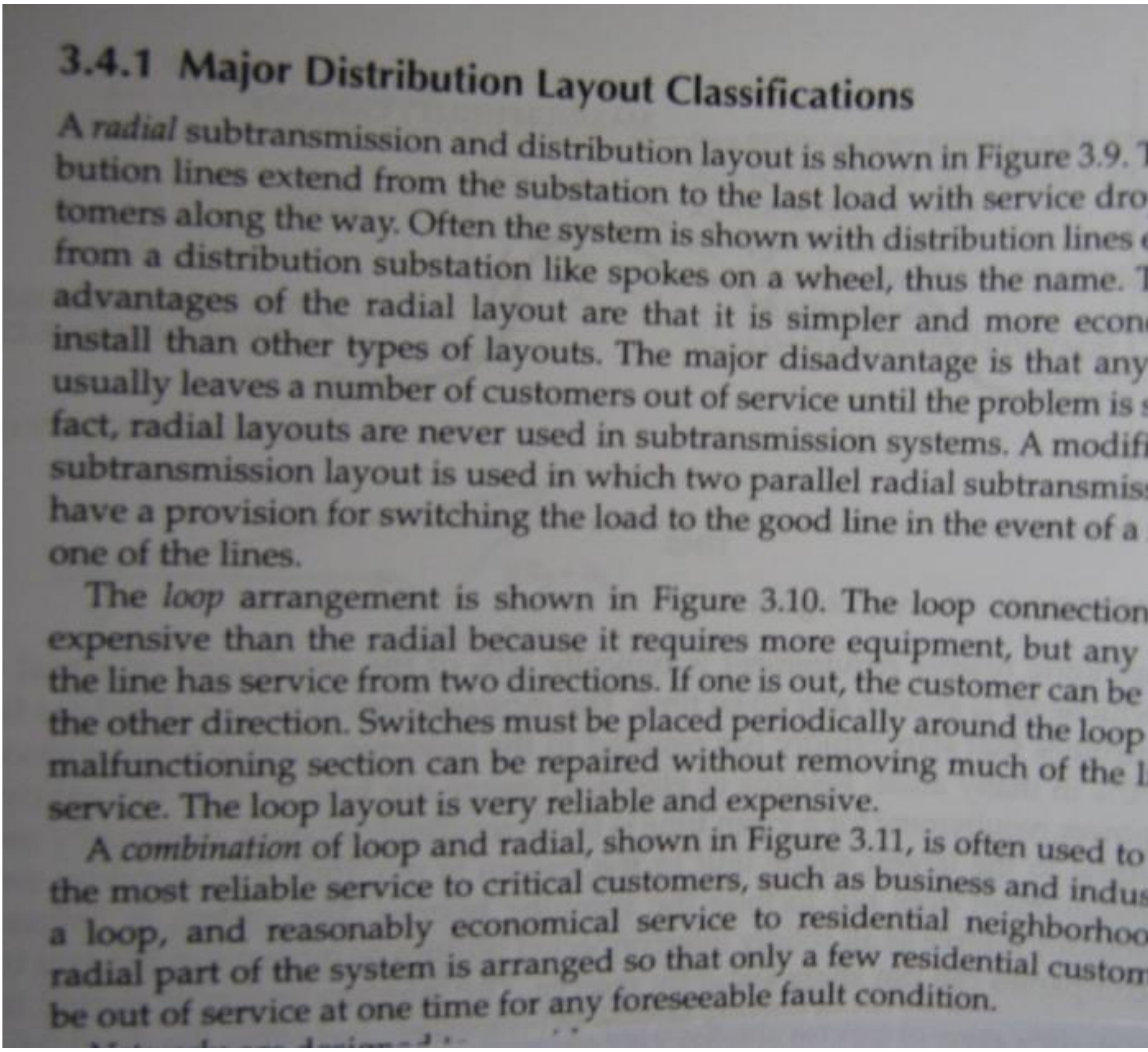


FIG. 2-8 (*a*) AC three-phase four-wire system; (*b*) voltage and current vector diagram; (c
current vector diagram.

2. LOAD CONNECTION AND SYSTEM COMPONENTS (Part 1)

LOAD CONNECTIONS

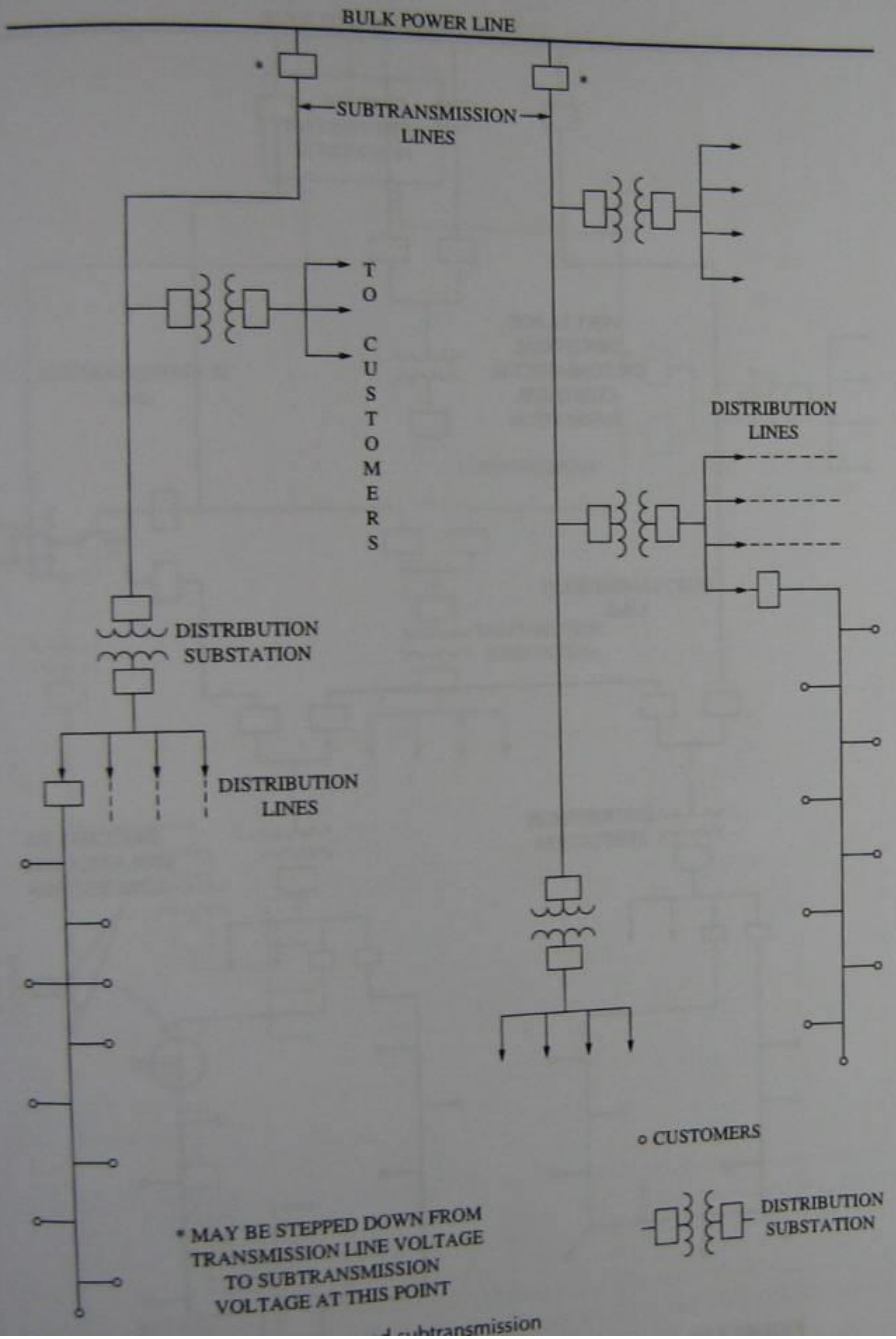


3.4.1 Major Distribution Layout Classifications

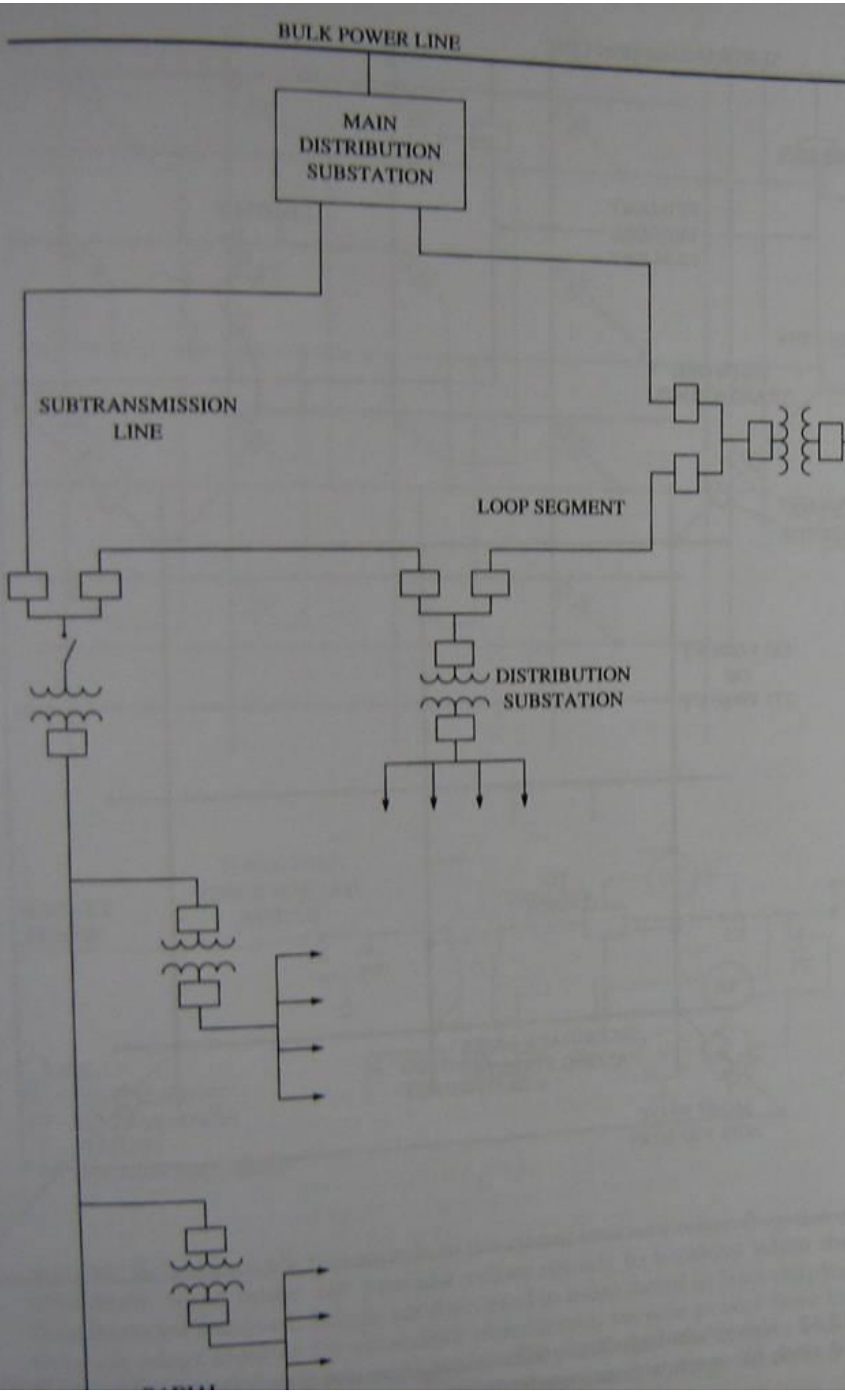
A *radial* subtransmission and distribution layout is shown in Figure 3.9. T
bution lines extend from the substation to the last load with service dro
tomers along the way. Often the system is shown with distribution lines
from a distribution substation like spokes on a wheel, thus the name. T
advantages of the radial layout are that it is simpler and more econ
install than other types of layouts. The major disadvantage is that any
usually leaves a number of customers out of service until the problem is
fact, radial layouts are never used in subtransmission systems. A modifi
subtransmission layout is used in which two parallel radial subtransmis
have a provision for switching the load to the good line in the event of a
one of the lines.

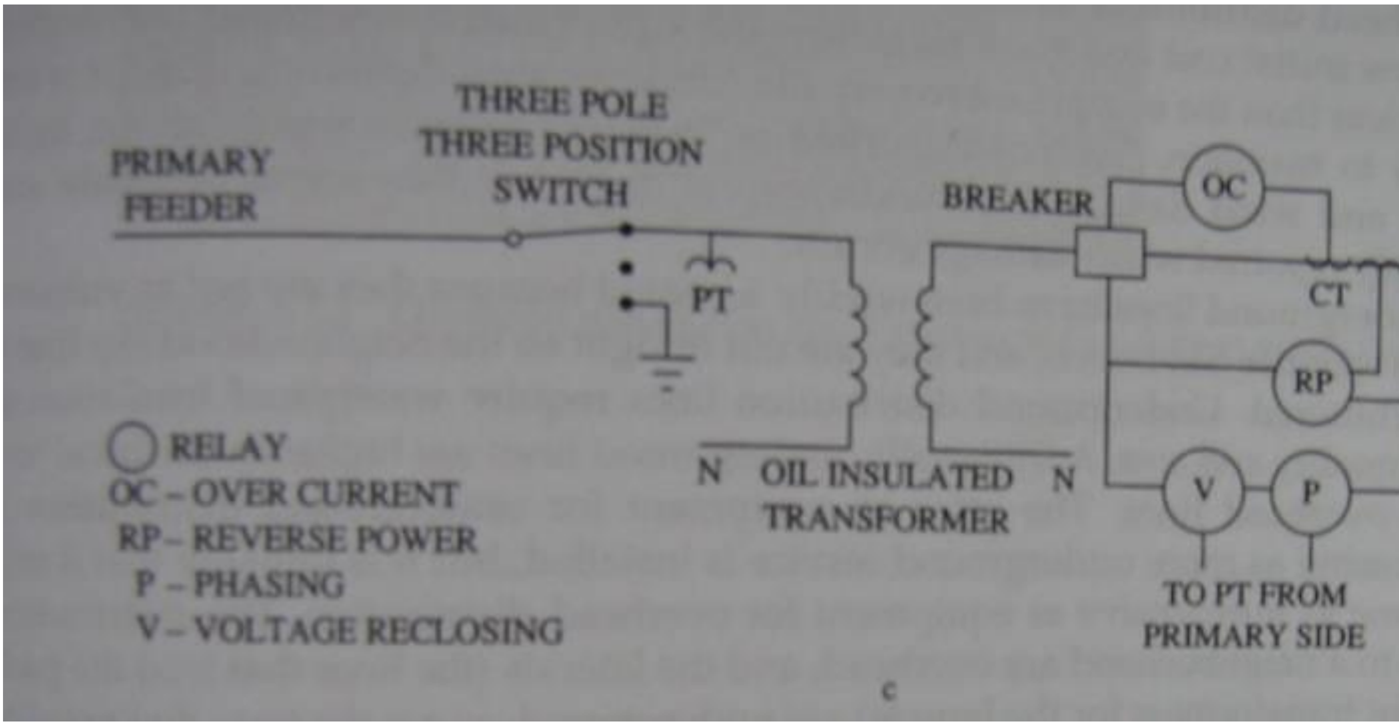
The *loop* arrangement is shown in Figure 3.10. The loop connection
expensive than the radial because it requires more equipment, but any
the line has service from two directions. If one is out, the customer can be
the other direction. Switches must be placed periodically around the loop
malfunctioning section can be repaired without removing much of the l
service. The loop layout is very reliable and expensive.

A *combination* of loop and radial, shown in Figure 3.11, is often used to
the most reliable service to critical customers, such as business and indus
a loop, and reasonably economical service to residential neighborhoo
radial part of the system is arranged so that only a few residential custom
be out of service at one time for any foreseeable fault condition.



d subtransmission


BULK POWER LINE
MAIN DISTRIBUTION SUBSTATION
SUBTRANSMISSION LINE
LOOP SEGMENT
DISTRIBUTION SUBSTATION



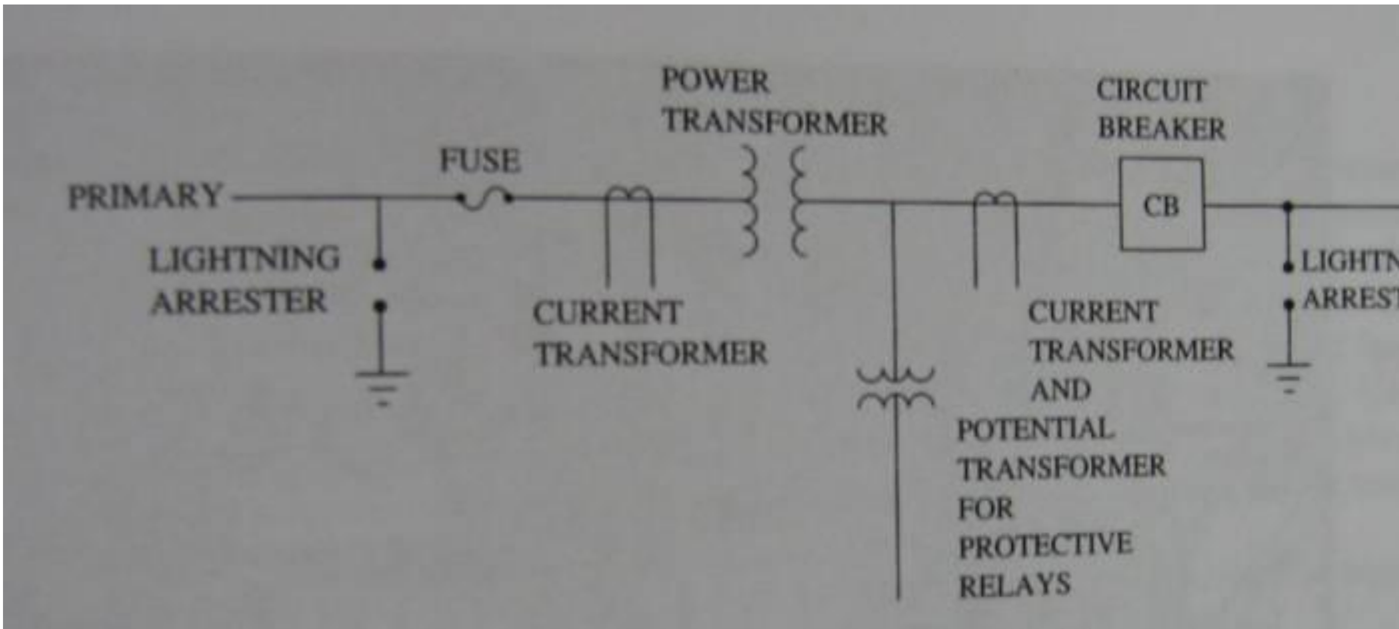


FIGURE 4.18 Power transformer one-line drawing with protection

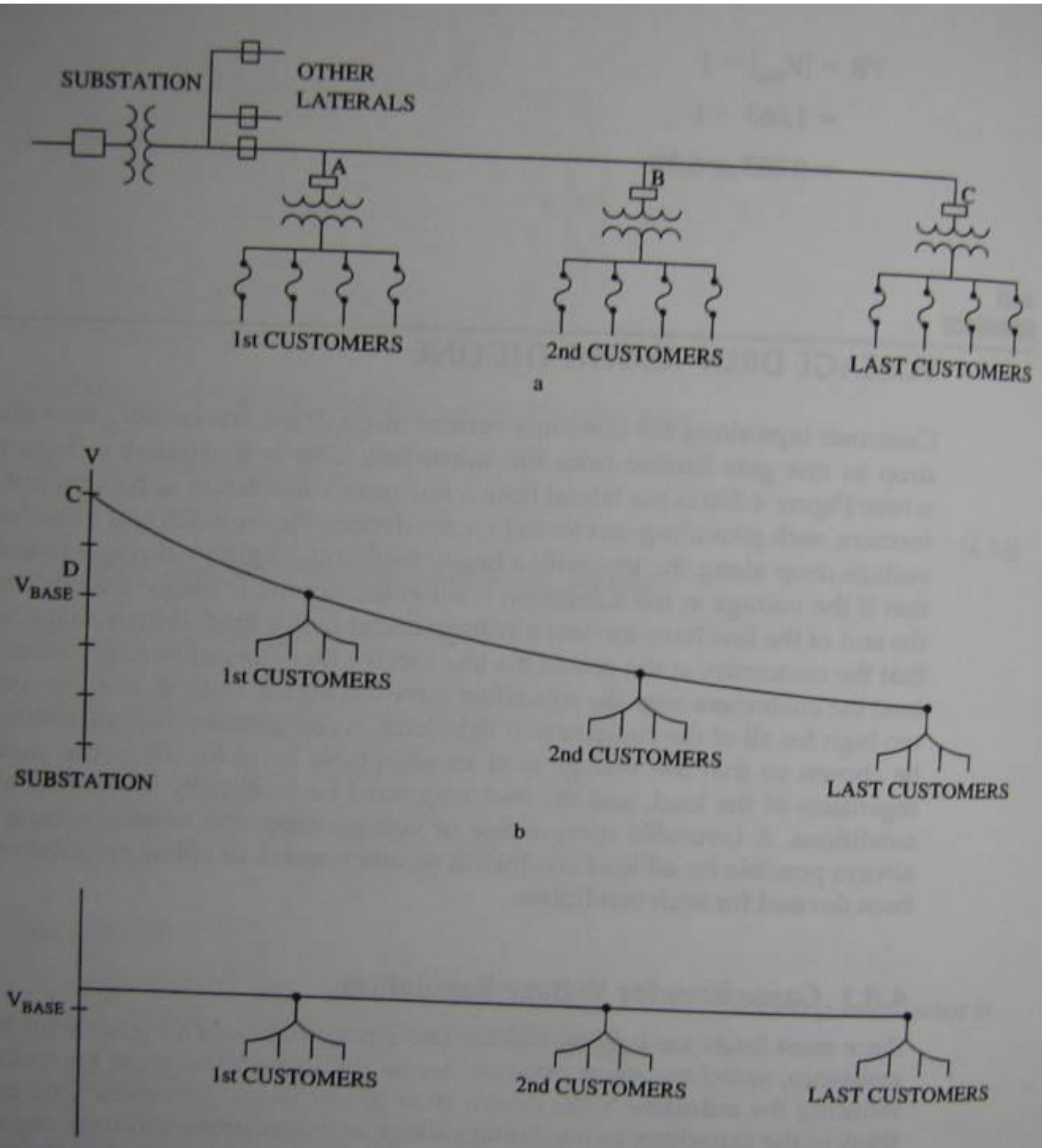
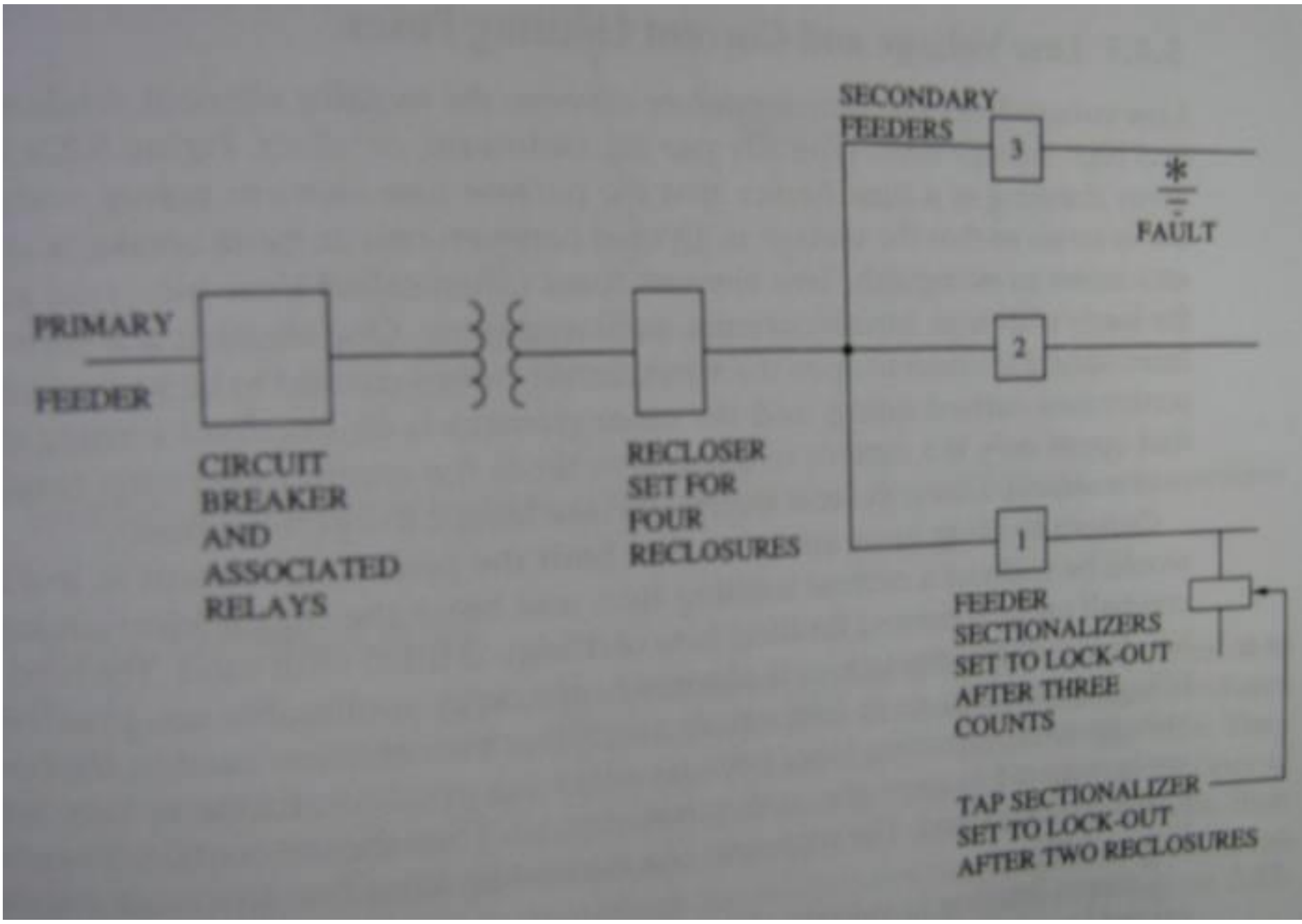


FIGURE 4.32 Voltage drop along line (a) Representation of distribution circuit (b) line voltage drop with heavy load and (c) line voltage drop with light load.



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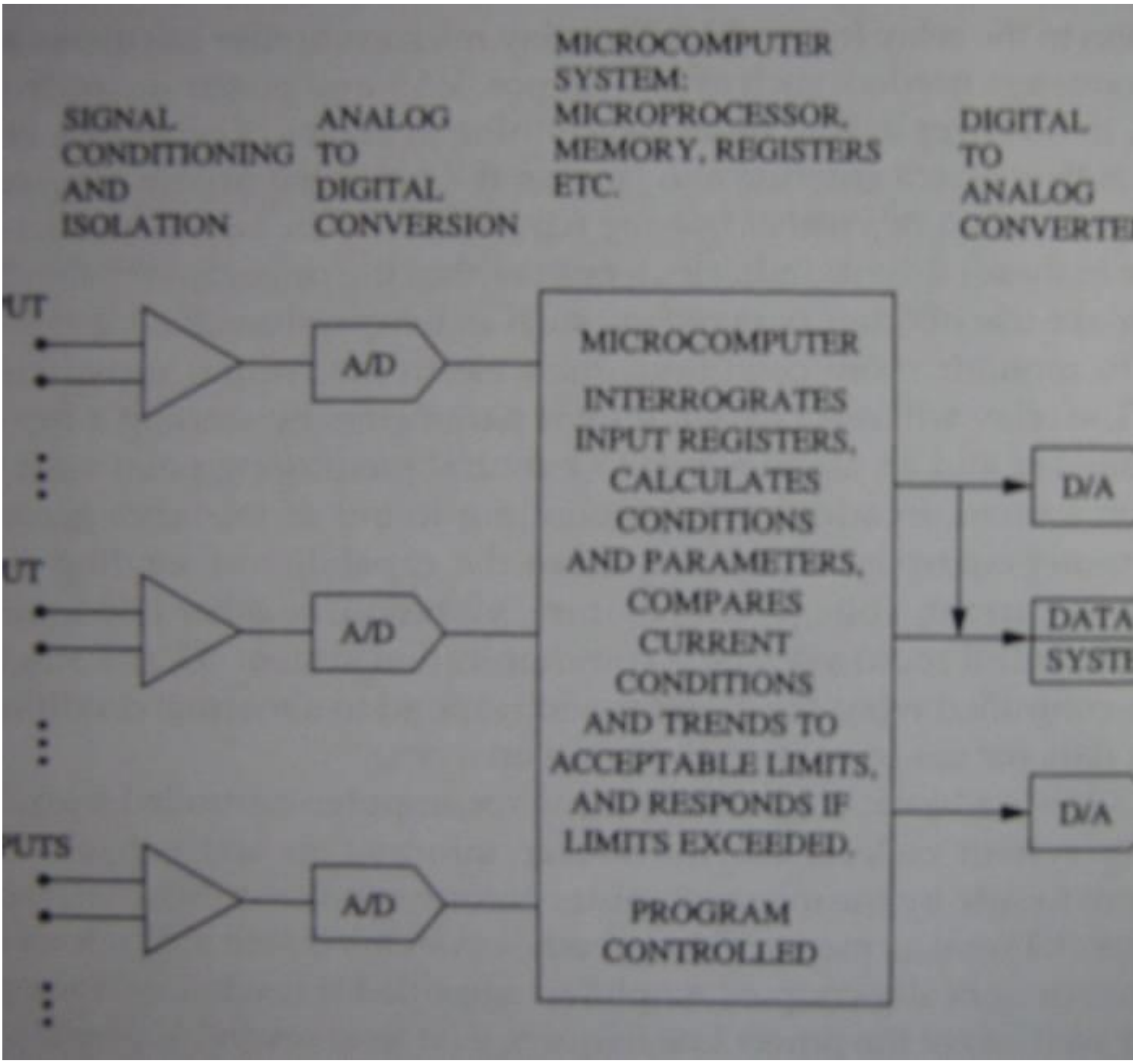
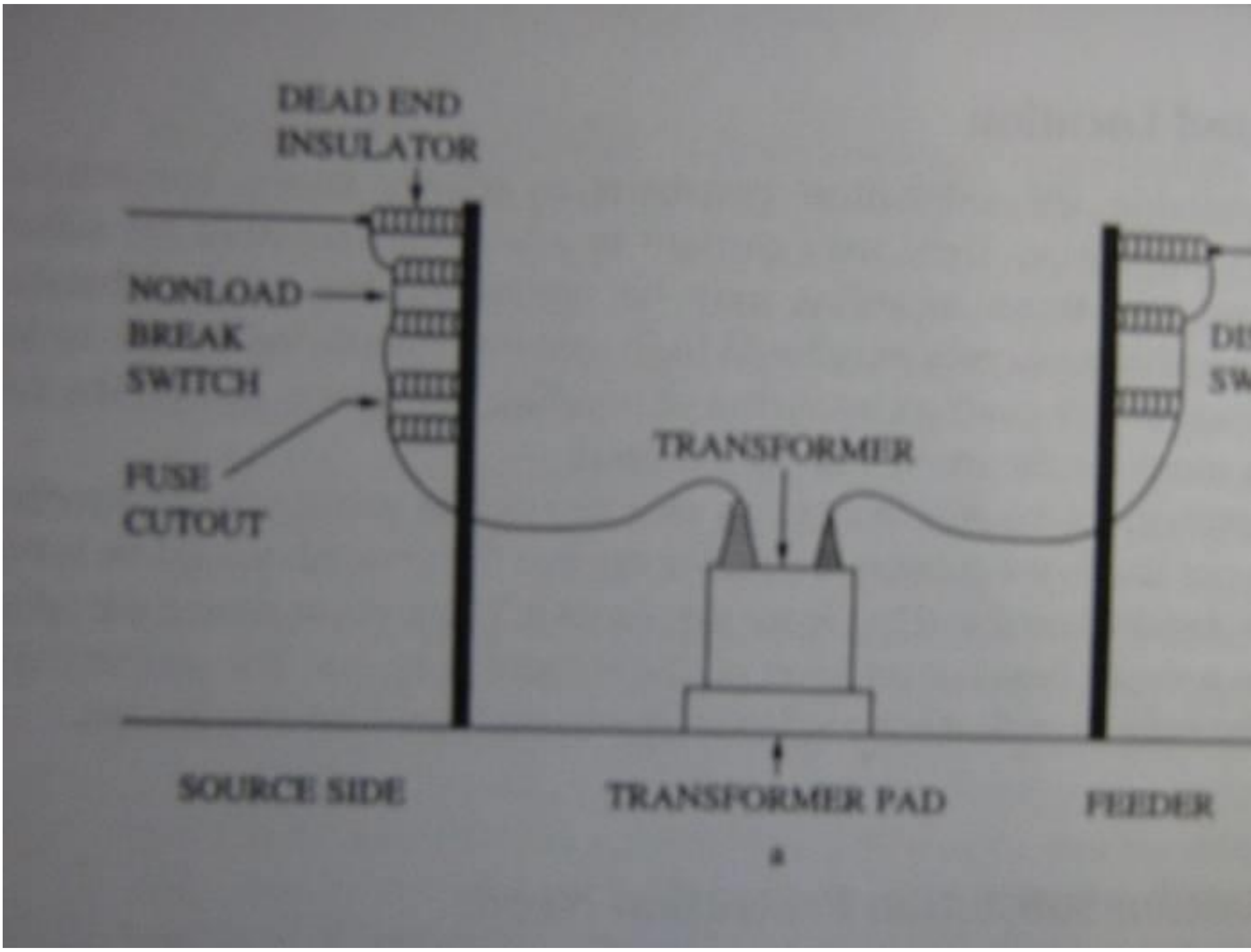
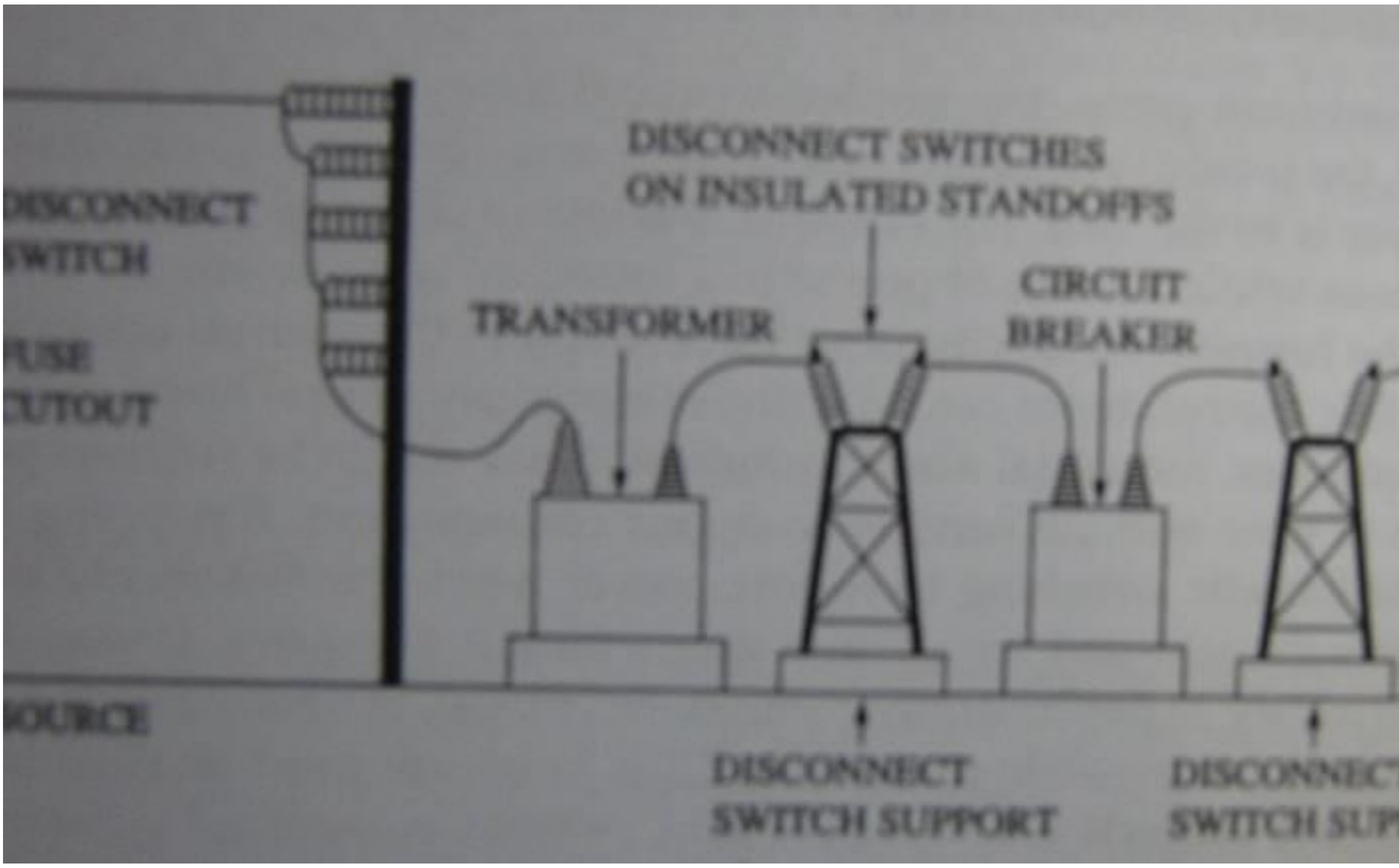
2. LOAD CONNECTION AND SYSTEM COMPONENTS (Part 2)

System Component (Computerised System)



Transformer Connection


DEAD END
INSULATOR
NONLOAD
BREAK
SWITCH
FUSE
CUTOUT
TRANSFORMER
DI
SW
SOURCE SIDE
TRANSFORMER PAD
FEEDER
a



System Component

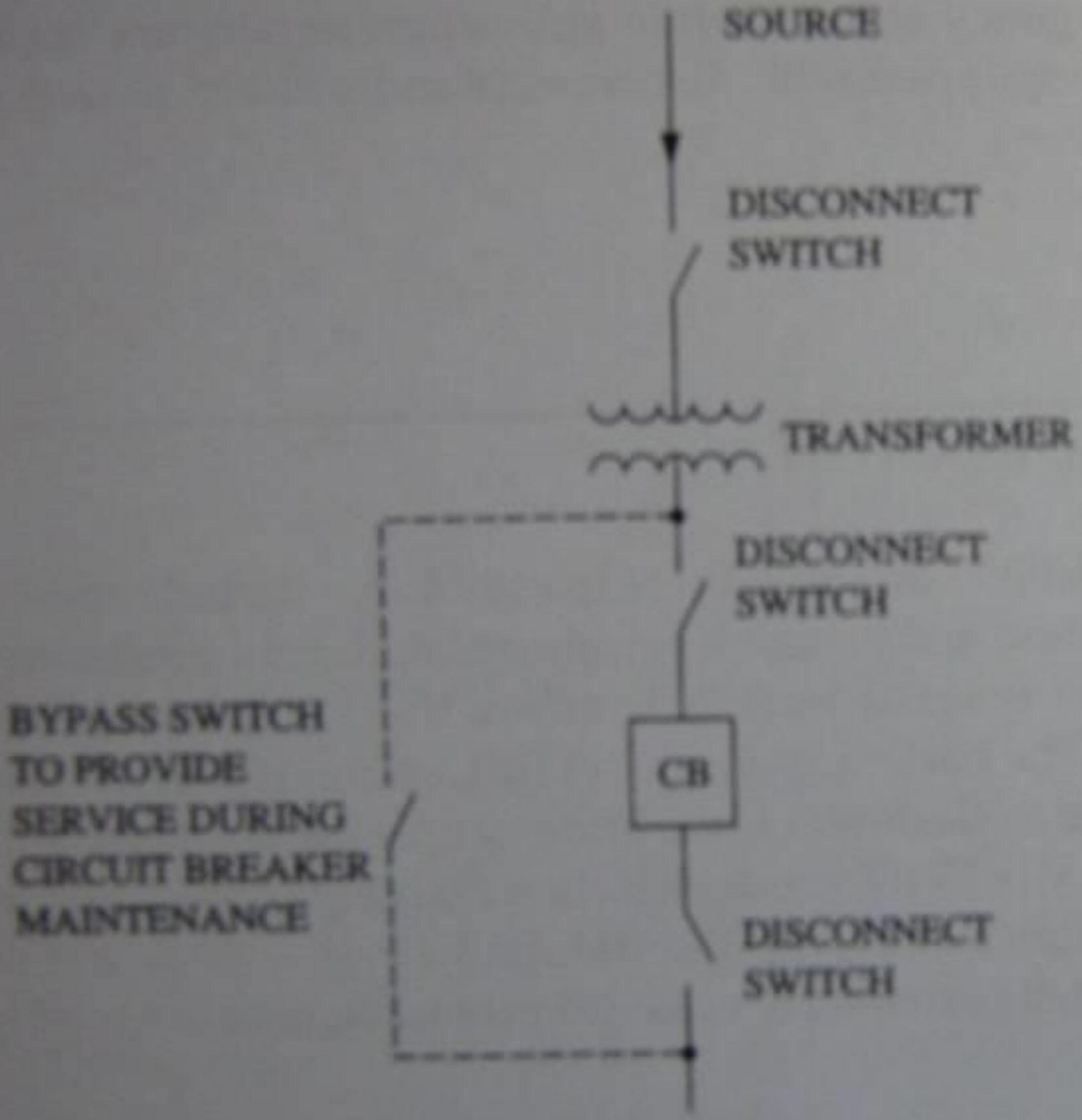
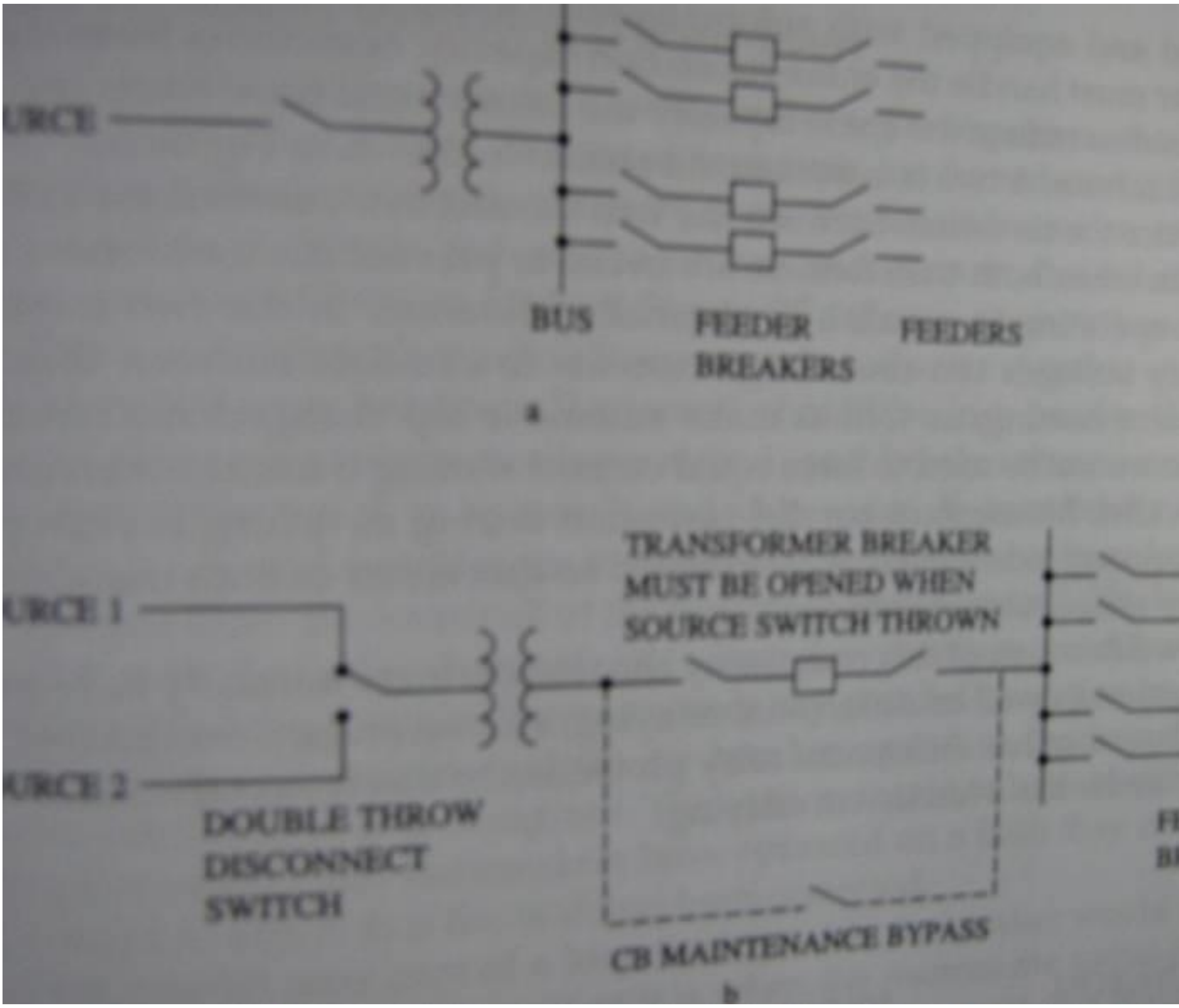
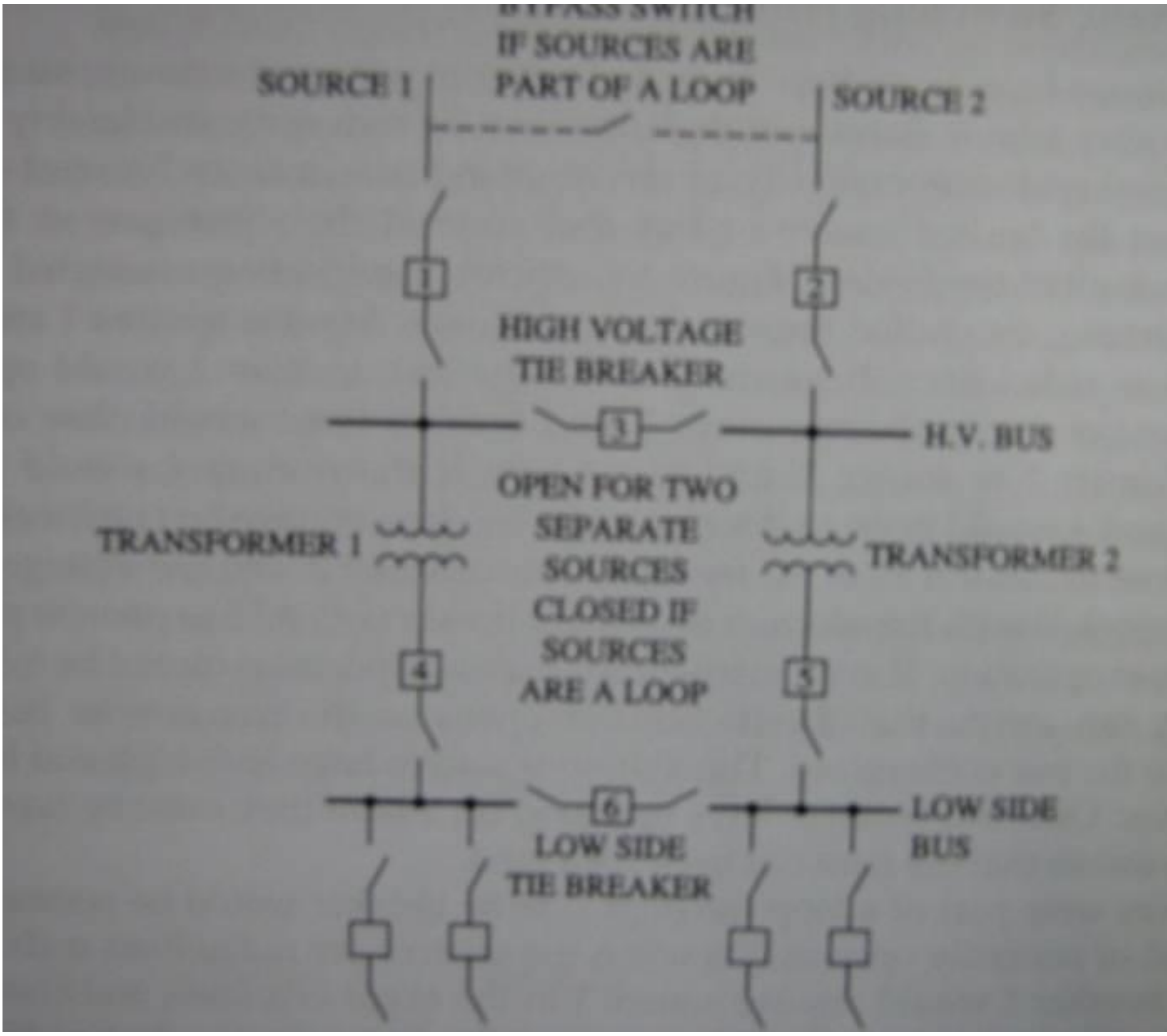


FIGURE 6.4 One-line diagram of single source, single feeder substa


URCE
BUS
FEEDER
BREAKERS
FEEDERS
a
URCE 1
URCE 2
DOUBLE THROW
DISCONNECT
SWITCH
TRANSFORMER BREAKER
MUST BE OPENED WHEN
SOURCE SWITCH THROWN
CB MAINTENANCE BYPASS
FE
BR
b


BYPASS SWITCH
IF SOURCES ARE
PART OF A LOOP
SOURCE 1
SOURCE 2
1
2
HIGH VOLTAGE
TIE BREAKER
3
H.V. BUS
OPEN FOR TWO
SEPARATE
SOURCES
CLOSED IF
SOURCES
ARE A LOOP
TRANSFORMER 1
TRANSFORMER 2
4
5
6
LOW SIDE
TIE BREAKER
LOW SIDE
BUS

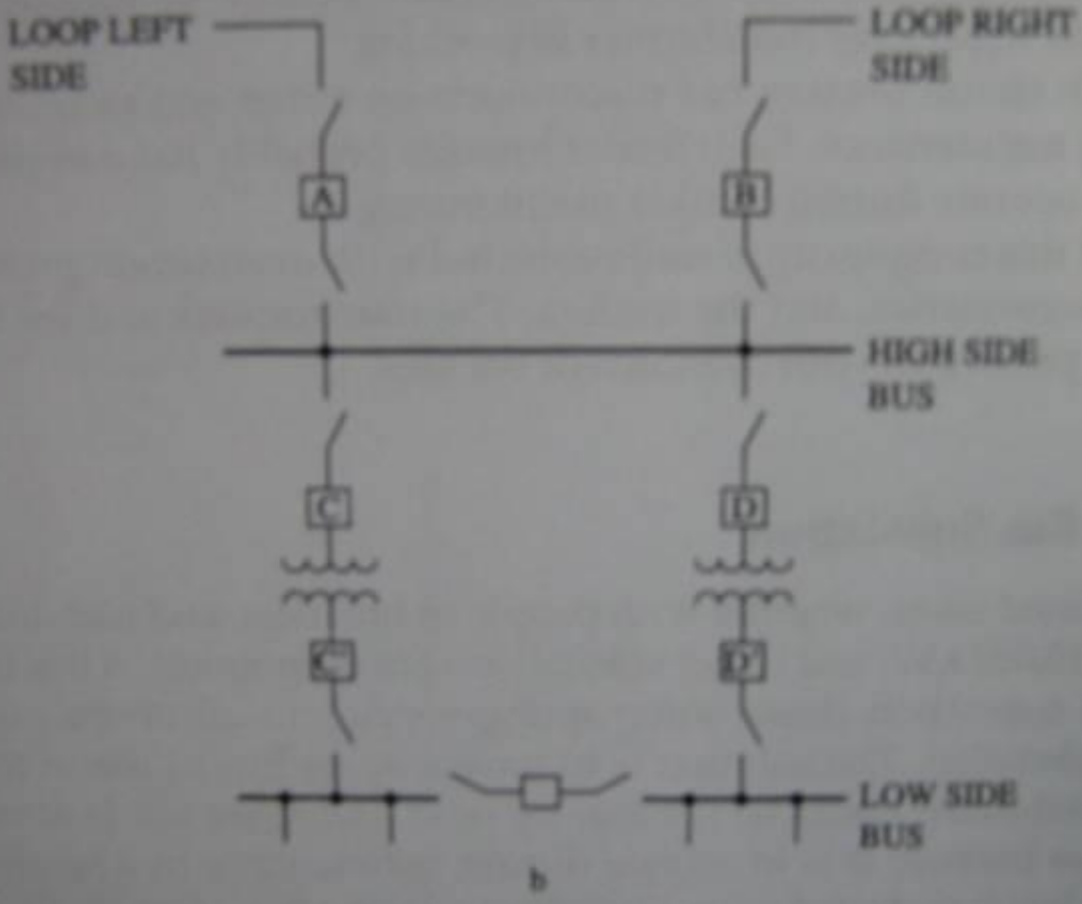
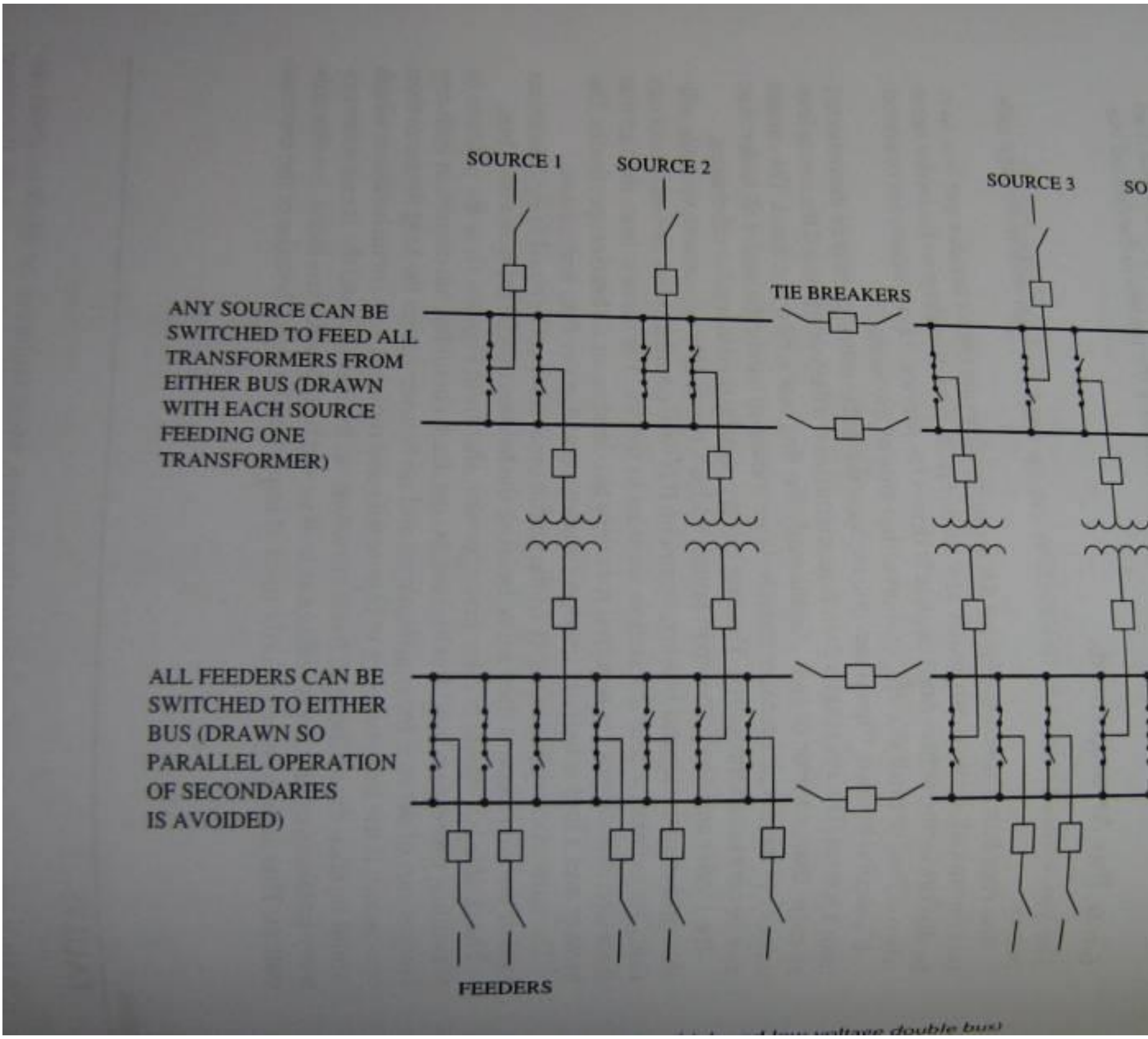
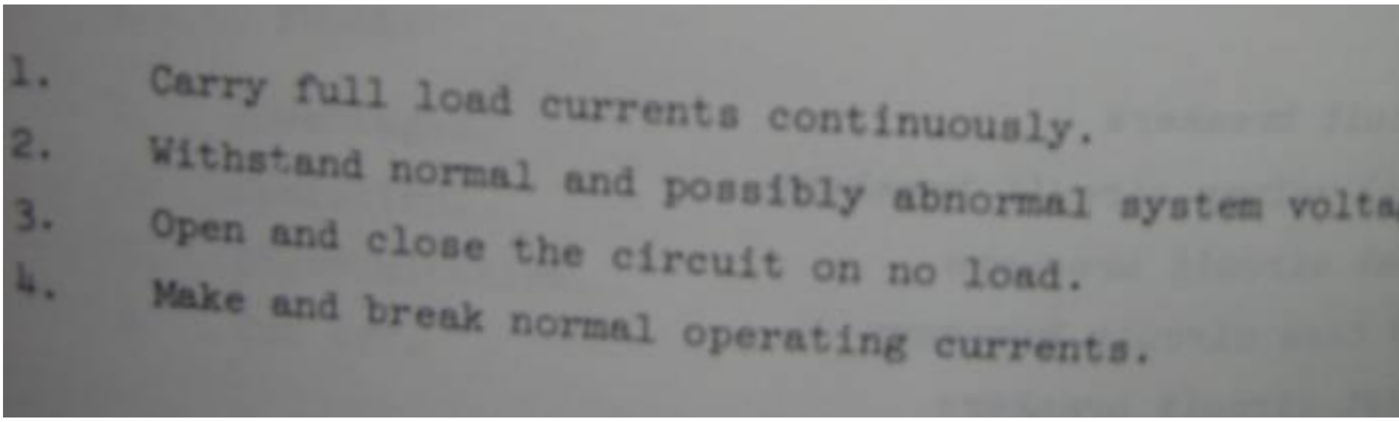


FIGURE 6.7 Automatic switching two source, two transformer substation (a) Two source, radial or loop and (b) better high side loop arrangement



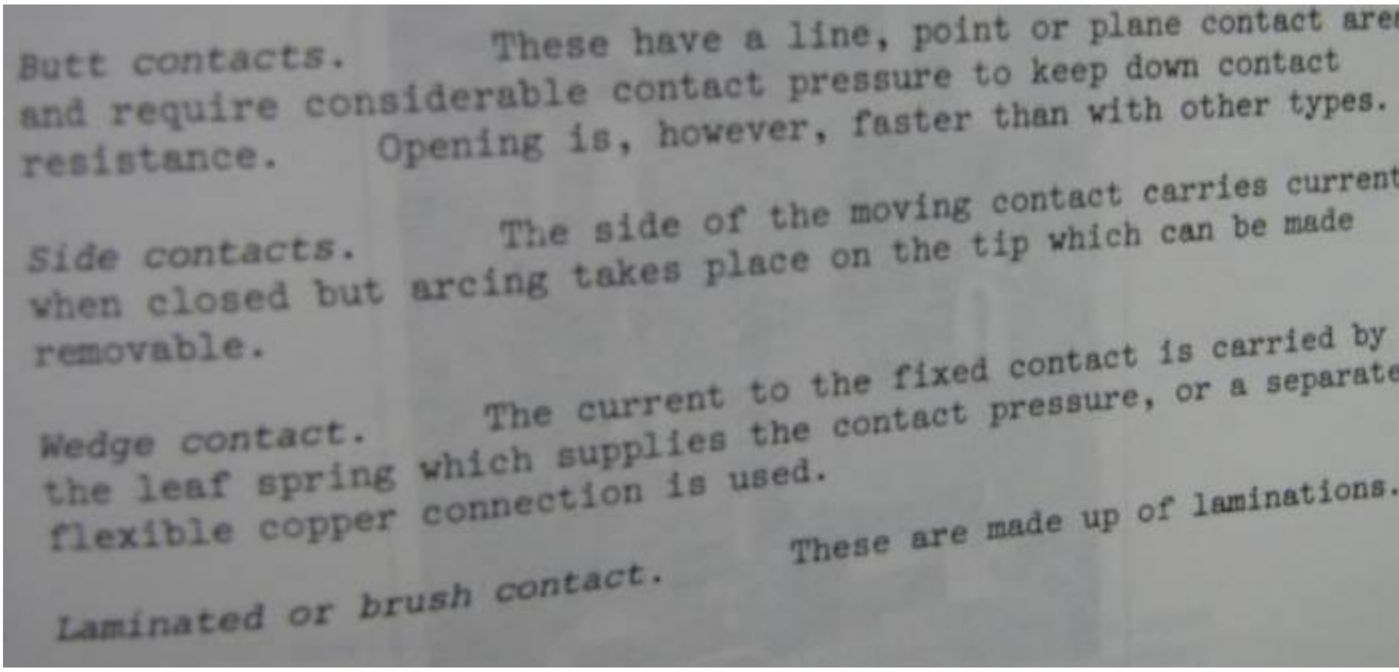
3 CIRCUIT BREAKERS (PART 1)

Switch Gear Principle



1. Carry full load currents continuously.
2. Withstand normal and possibly abnormal system volta
3. Open and close the circuit on no load.
4. Make and break normal operating currents.

Contacts



Butt contacts. These have a line, point or plane contact are and require considerable contact pressure to keep down contact resistance. Opening is, however, faster than with other types.

Side contacts. The side of the moving contact carries current when closed but arcing takes place on the tip which can be made removable.

Wedge contact. The current to the fixed contact is carried by the leaf spring which supplies the contact pressure, or a separate flexible copper connection is used.

Laminated or brush contact. These are made up of laminations.

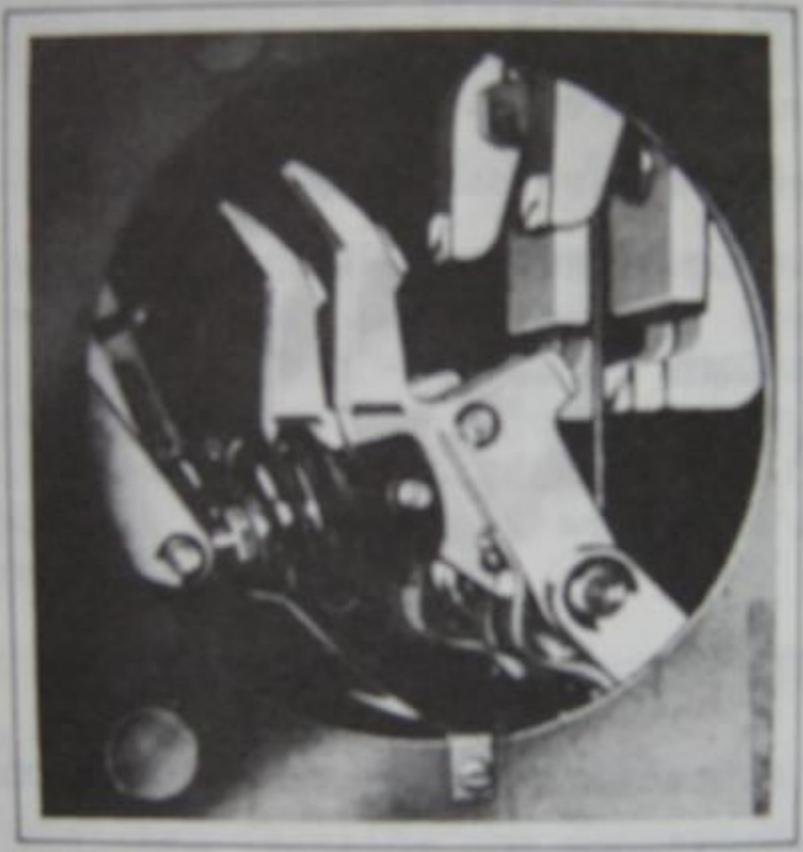
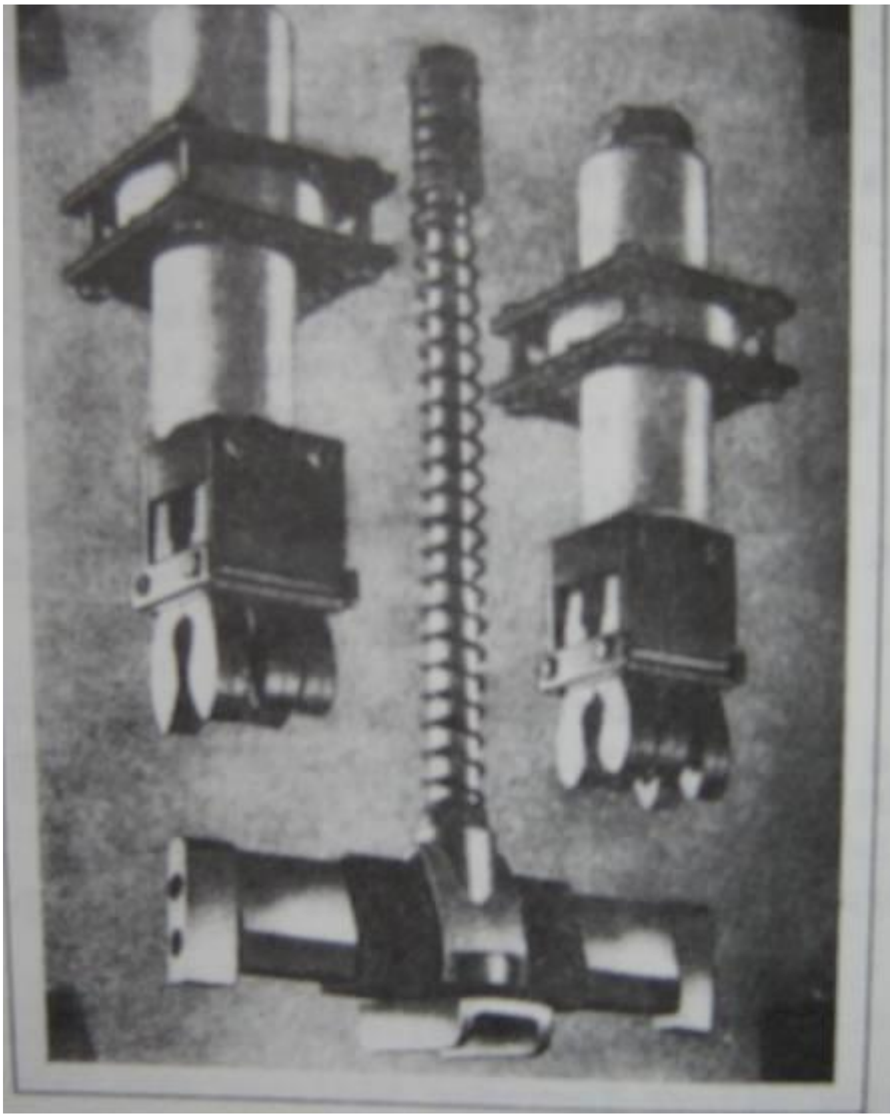
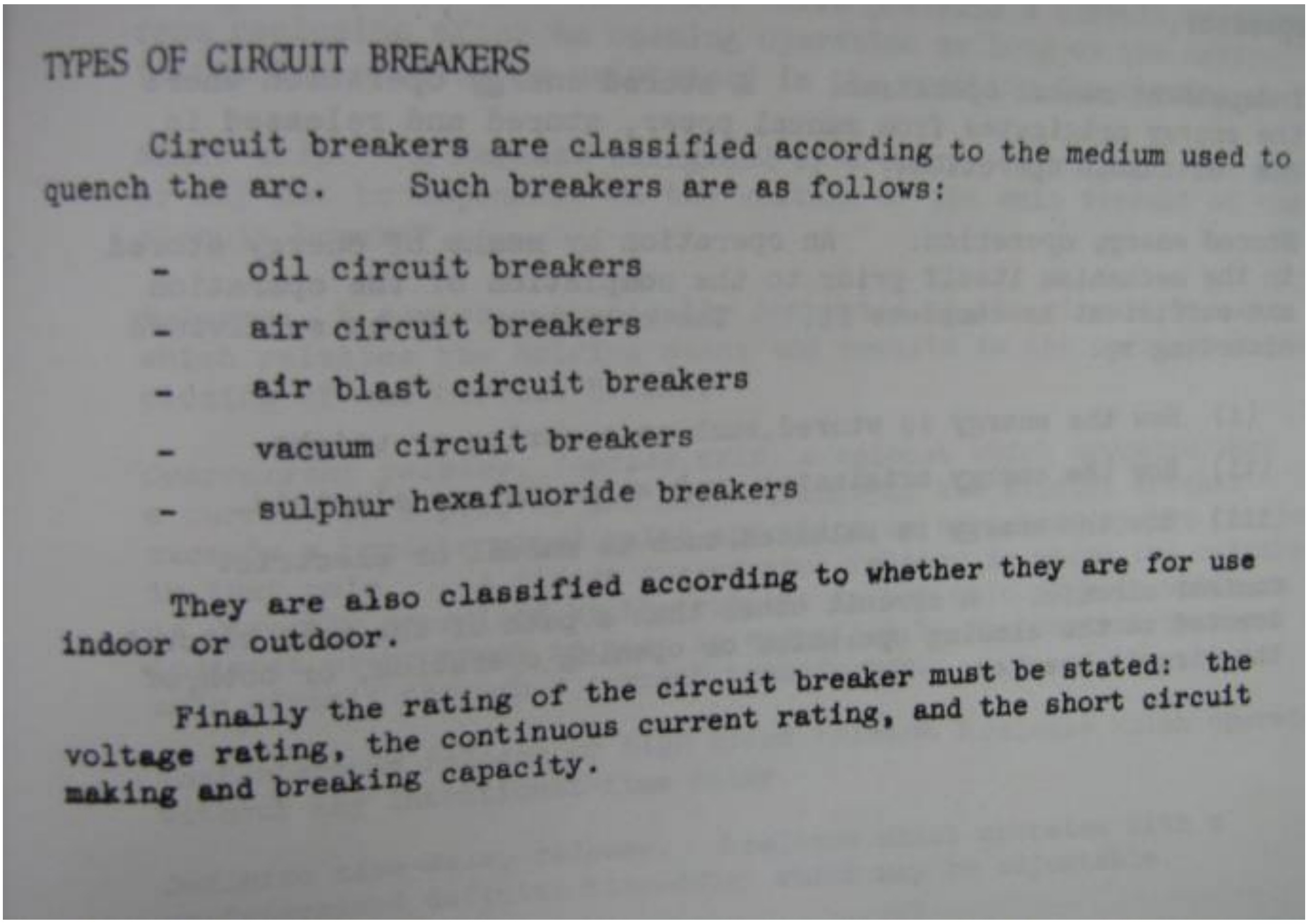


Figure 1

Butt Contact





TYPES OF CIRCUIT BREAKERS

Circuit breakers are classified according to the medium used to quench the arc. Such breakers are as follows:

- oil circuit breakers
- air circuit breakers
- air blast circuit breakers
- vacuum circuit breakers
- sulphur hexafluoride breakers

They are also classified according to whether they are for use indoor or outdoor.

Finally the rating of the circuit breaker must be stated: the voltage rating, the continuous current rating, and the short circuit making and breaking capacity.

Definitions Relating to Circuit Breakers

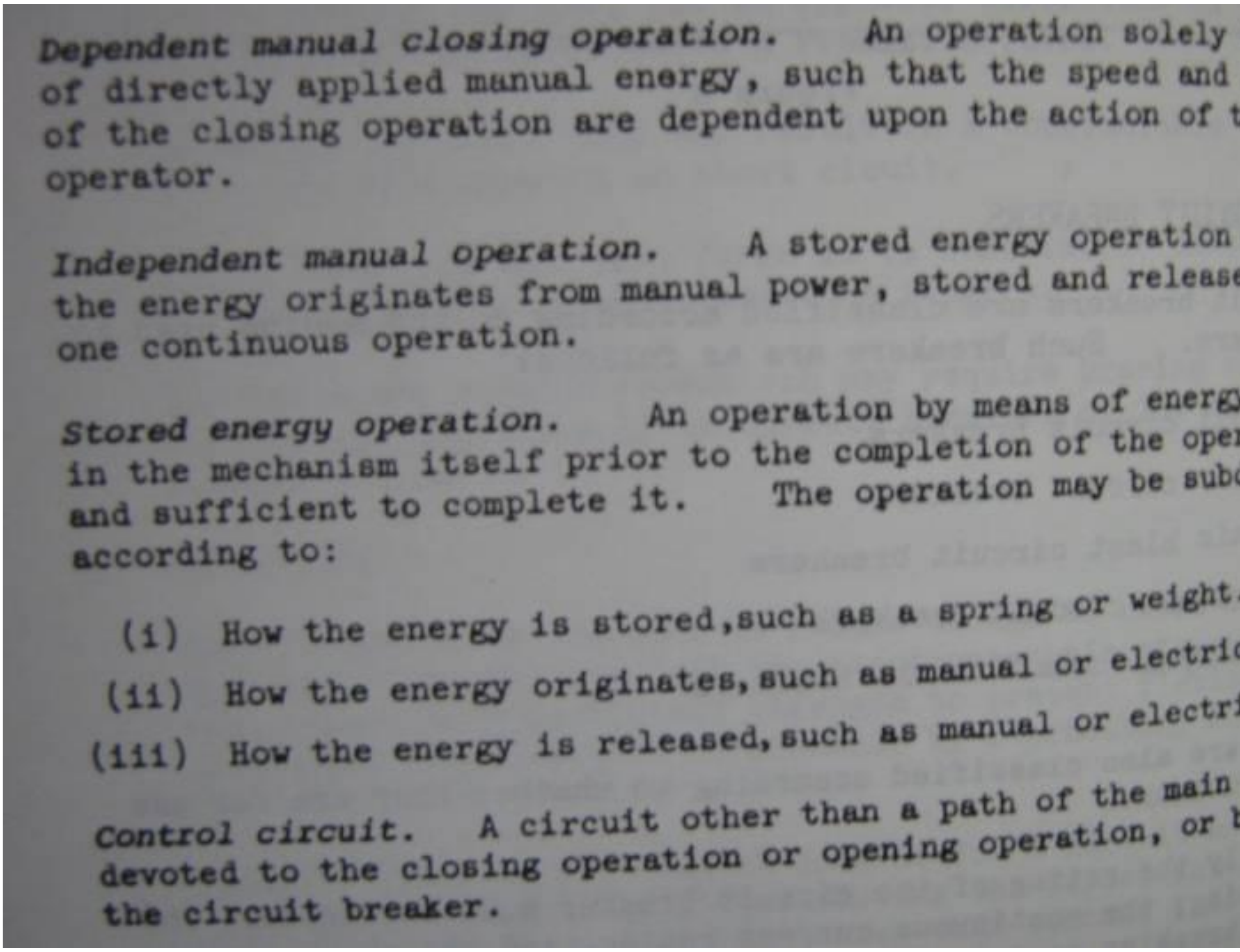
The following definitions cover most of the terms asso
circuit breakers. These definitions should be referred to
are used in the notes.

Switchgear. A general term covering the combination
devices and their associated, control, measuring, prot
regulating equipment.

Circuit breaker. A mechanical switching device capa
carrying and breaking currents under normal circuit co
also under predetermined conditions, making, carrying
time and breaking currents under abnormal conditions s
of short circuits.

Prospective current of a circuit. The current that
if each pole of the circuit breakers were replaced by a
negligible impedance without any other change of the c
of the supply.

Breaking capacity. A value of breaking current that t
breaker is capable of breaking at a stated voltage and
prescribed conditions.



Dependent manual closing operation. An operation solely of directly applied manual energy, such that the speed and of the closing operation are dependent upon the action of t operator.

Independent manual operation. A stored energy operation the energy originates from manual power, stored and release one continuous operation.

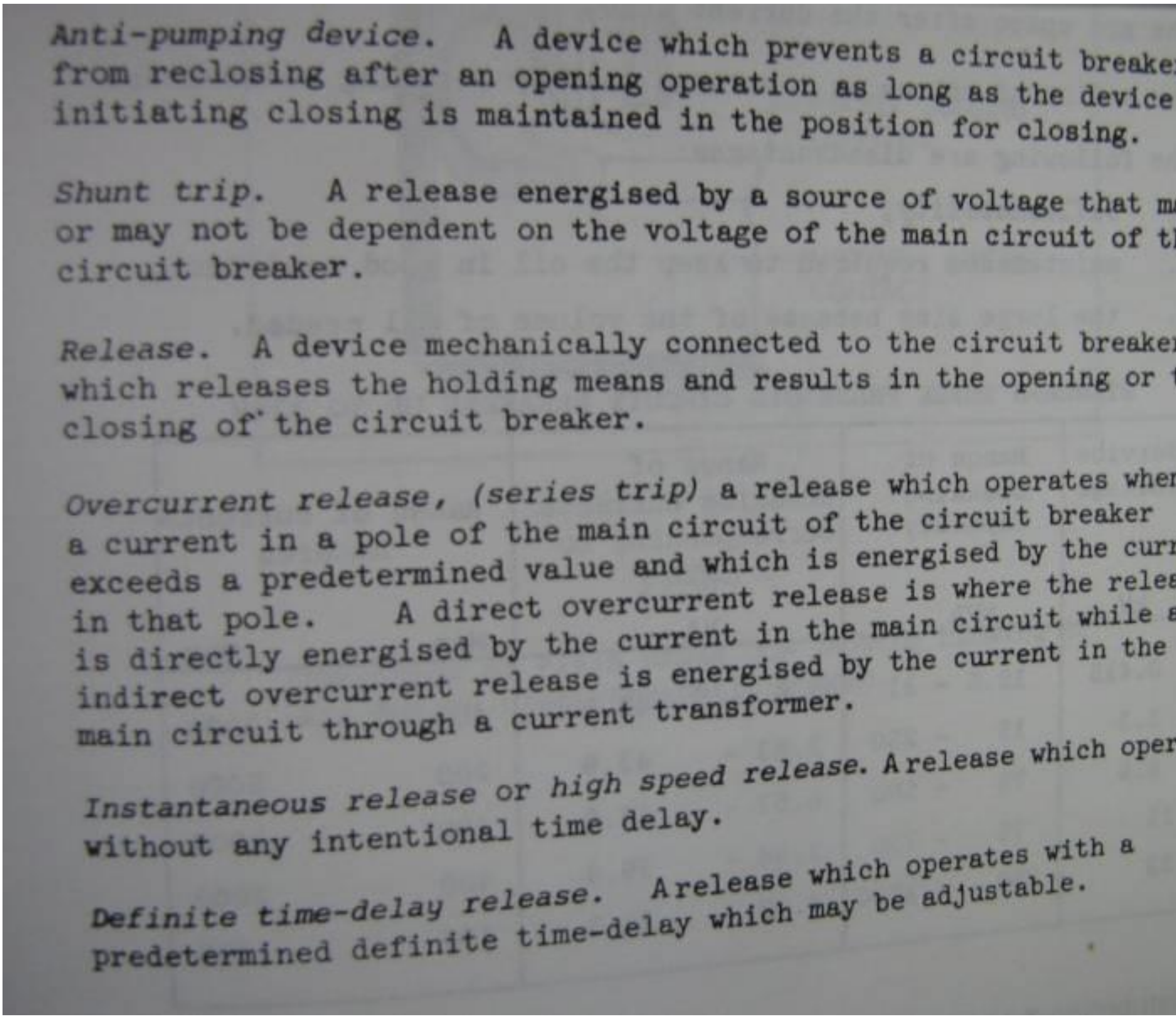
Stored energy operation. An operation by means of energ in the mechanism itself prior to the completion of the oper and sufficient to complete it. The operation may be subd according to:

(i) How the energy is stored, such as a spring or weight.
(ii) How the energy originates, such as manual or electric
(iii) How the energy is released, such as manual or electr

Control circuit. A circuit other than a path of the main devoted to the closing operation or opening operation, or b the circuit breaker.

3 CIRCUIT BREAKERS (PART 2)

Components of Oil Circuit Breaker



Anti-pumping device. A device which prevents a circuit breake
from reclosing after an opening operation as long as the device
initiating closing is maintained in the position for closing.

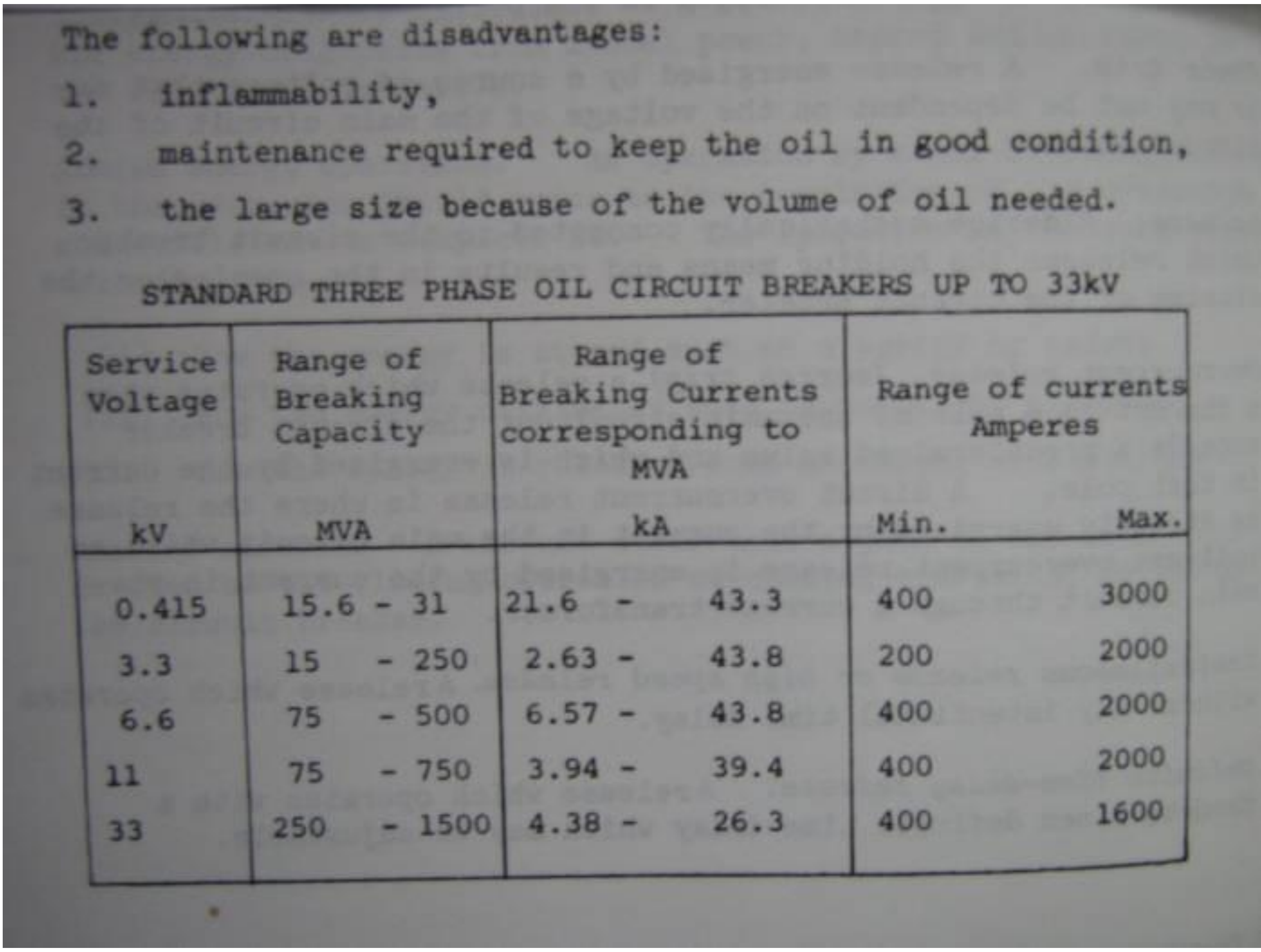
Shunt trip. A release energised by a source of voltage that m
or may not be dependent on the voltage of the main circuit of t
circuit breaker.

Release. A device mechanically connected to the circuit breake
which releases the holding means and results in the opening or t
closing of the circuit breaker.

Overcurrent release, (series trip) a release which operates whe
a current in a pole of the main circuit of the circuit breaker
exceeds a predetermined value and which is energised by the cur
in that pole. A direct overcurrent release is where the rele
is directly energised by the current in the main circuit while a
indirect overcurrent release is energised by the current in the
main circuit through a current transformer.

Instantaneous release or *high speed release.* A release which oper
without any intentional time delay.

Definite time-delay release. A release which operates with a
predetermined definite time-delay which may be adjustable.



The following are disadvantages:

1. inflammability,
2. maintenance required to keep the oil in good condition,
3. the large size because of the volume of oil needed.

STANDARD THREE PHASE OIL CIRCUIT BREAKERS UP TO 33kV

Service Voltage kV	Range of Breaking Capacity MVA	Range of Breaking Currents corresponding to MVA kA	Range of currents Amperes Min.	Max.
0.415	15.6 - 31	21.6 - 43.3	400	3000
3.3	15 - 250	2.63 - 43.8	200	2000
6.6	75 - 500	6.57 - 43.8	400	2000
11	75 - 750	3.94 - 39.4	400	2000
33	250 - 1500	4.38 - 26.3	400	1600

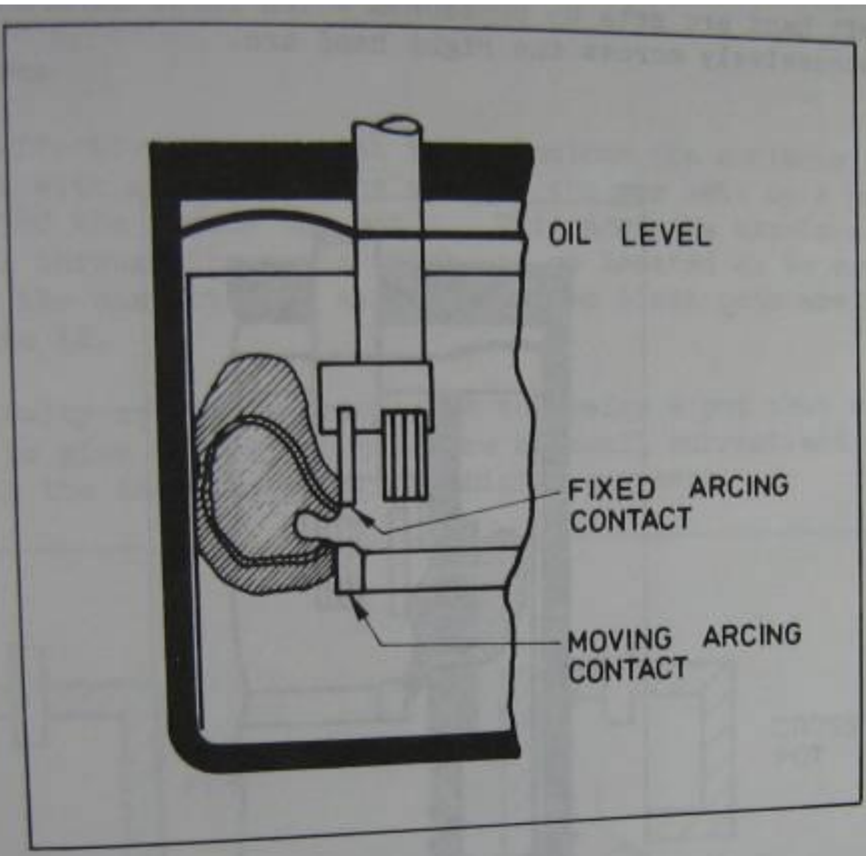


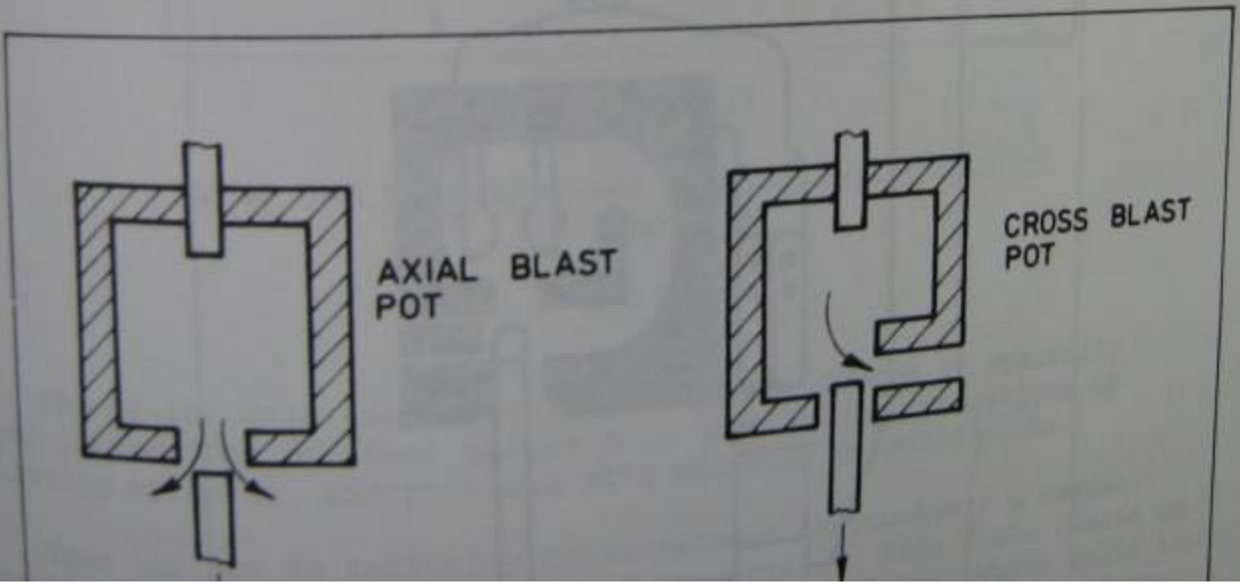
Figure 9

Operation of Plain Break OCB showing blowing of arc due to electromagnetic forces.

Arc control pots

A more effective arrangement is to enclose the contacts in an insulating pot with suitable vents so that the arc sets up a pressure of 1030 kPa to 1380 kPa inside the pot. This pressure expels a stream of gas and oil through the vents which are so located as to cross the arc space between the contacts. Axial and cross blast pots are used as shown in Figure 12.

A difficulty exists in being able to design a pot that will be small enough to give sufficient pressure at small currents and yet will not burst with the larger pressure at higher currents.



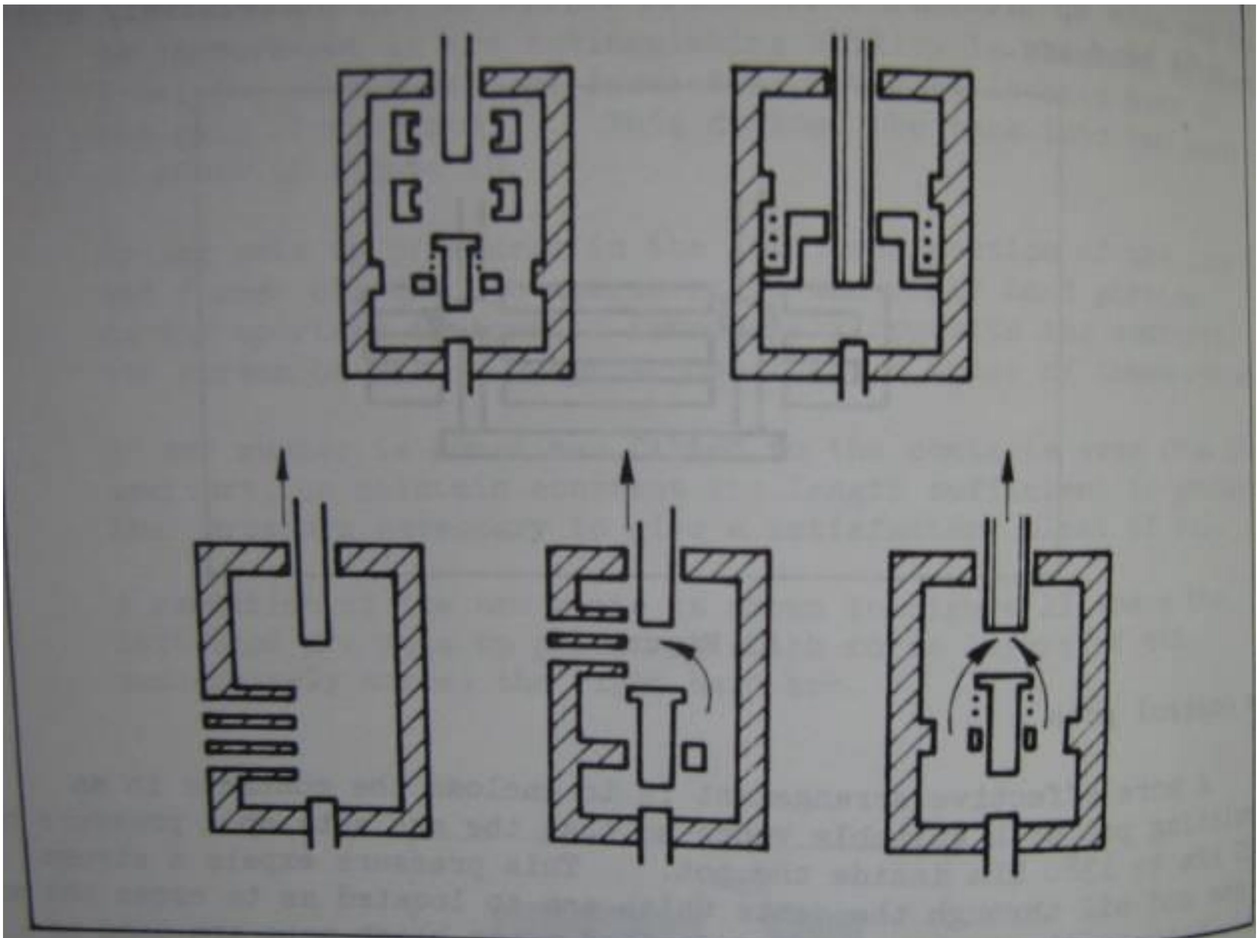
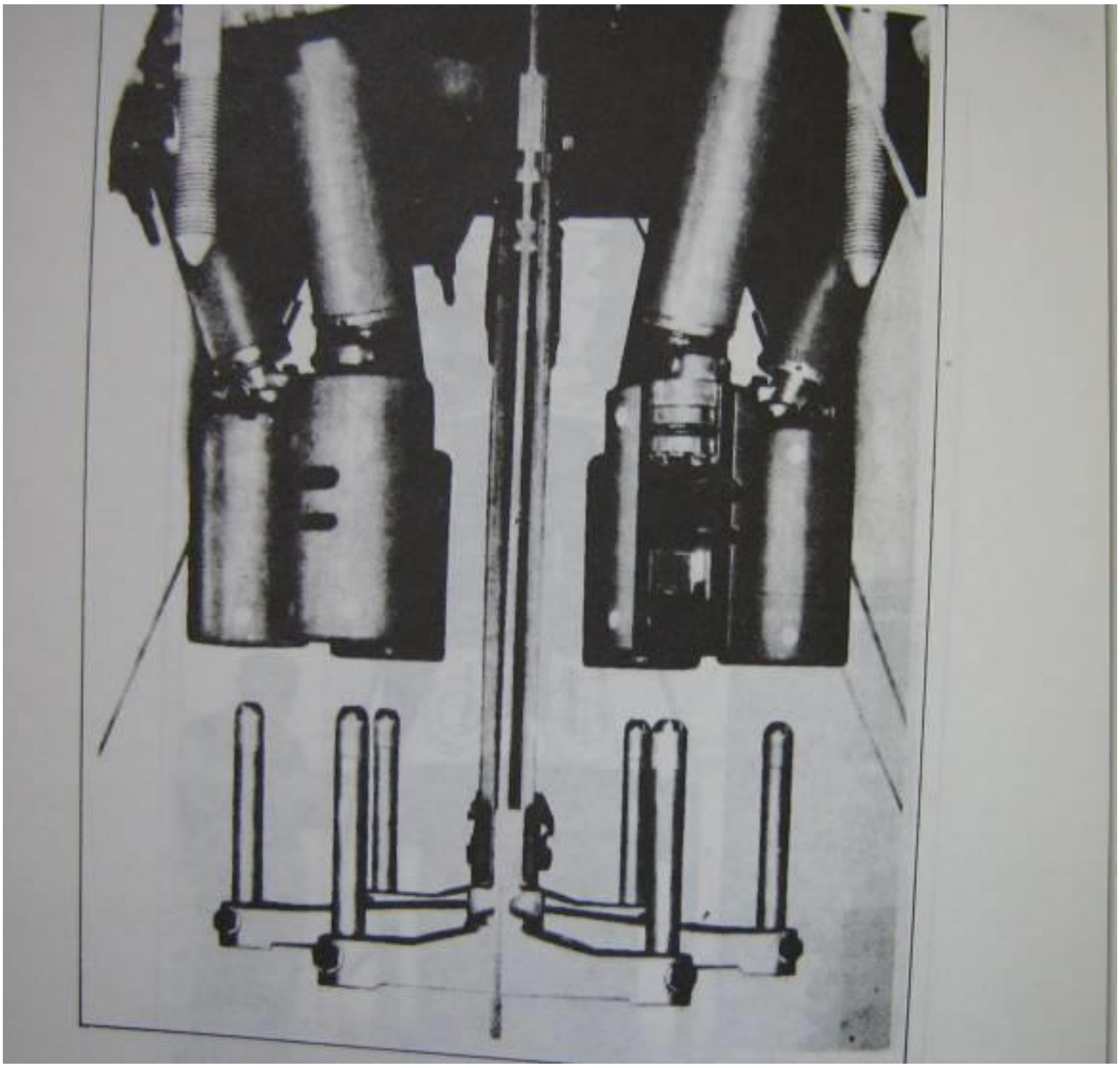
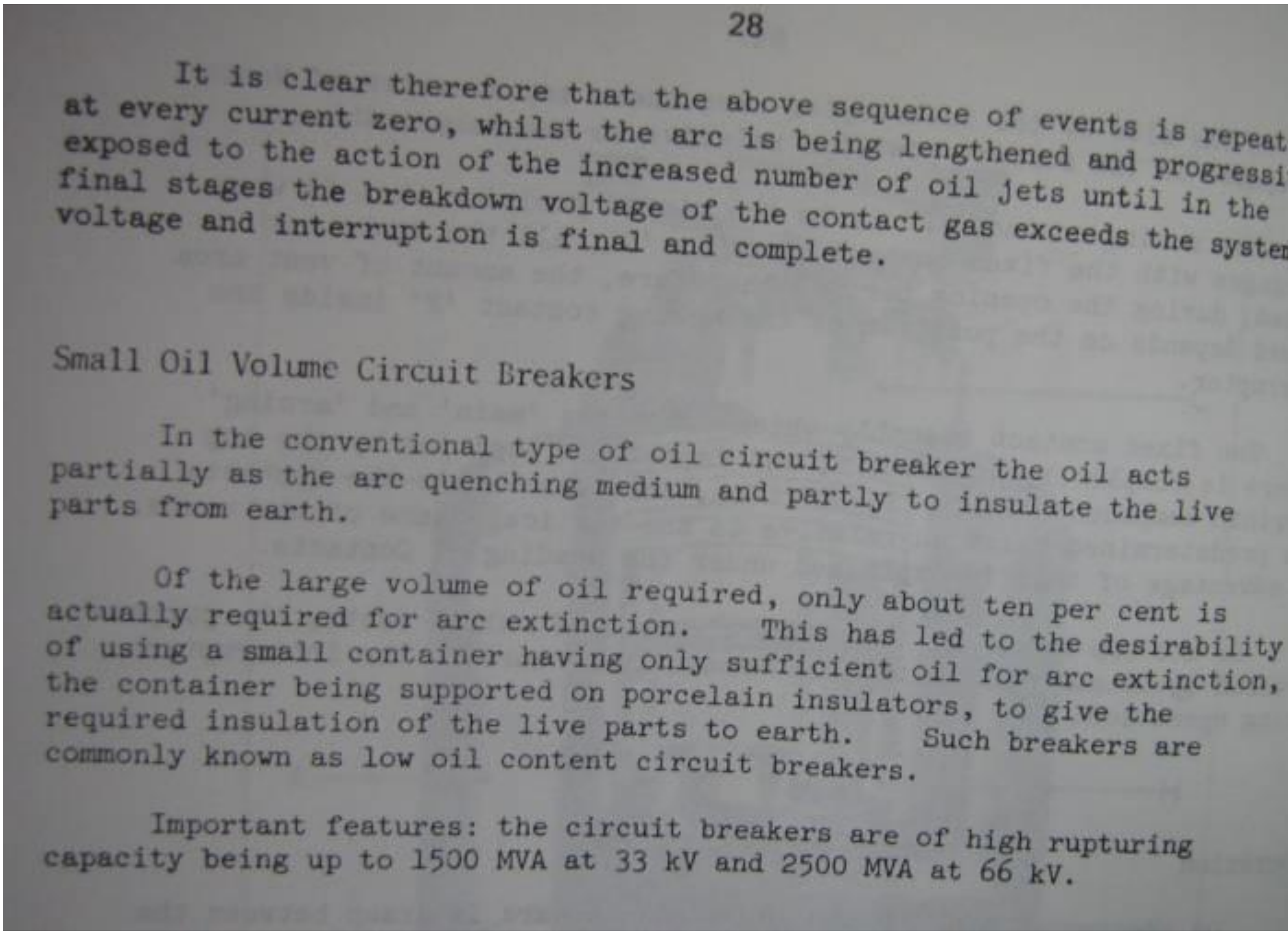


Figure 13

Modified forms of Arc Control Pots





28

It is clear therefore that the above sequence of events is repeat
at every current zero, whilst the arc is being lengthened and progressi
exposed to the action of the increased number of oil jets until in the
final stages the breakdown voltage of the contact gas exceeds the syste
voltage and interruption is final and complete.

Small Oil Volume Circuit Breakers

In the conventional type of oil circuit breaker the oil acts partially as the arc quenching medium and partly to insulate the live parts from earth.

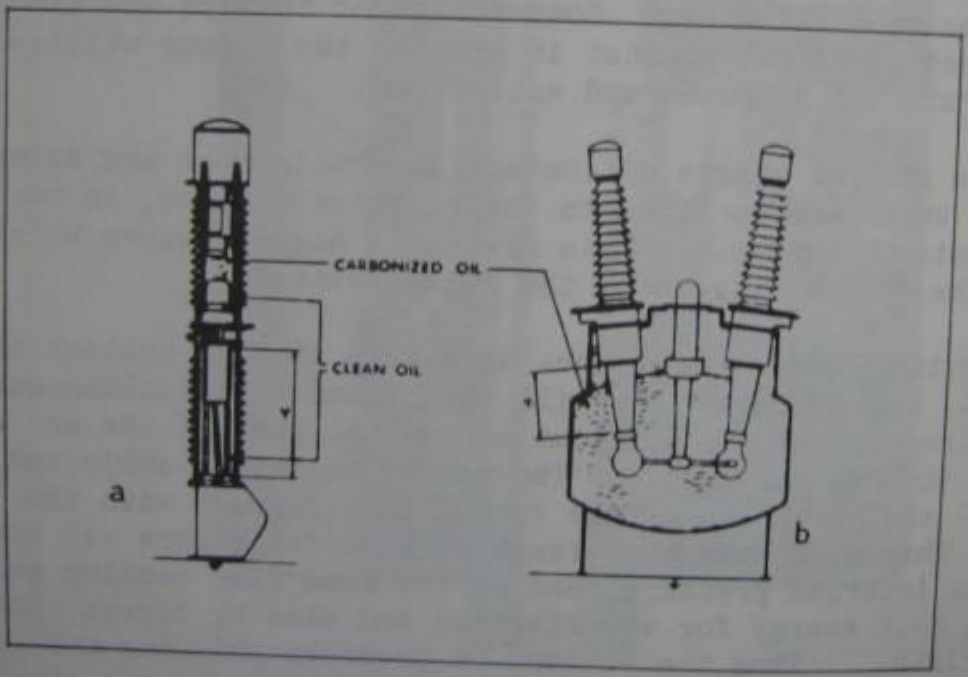
Of the large volume of oil required, only about ten per cent is actually required for arc extinction. This has led to the desirability of using a small container having only sufficient oil for arc extinction, the container being supported on porcelain insulators, to give the required insulation of the live parts to earth. Such breakers are commonly known as low oil content circuit breakers.

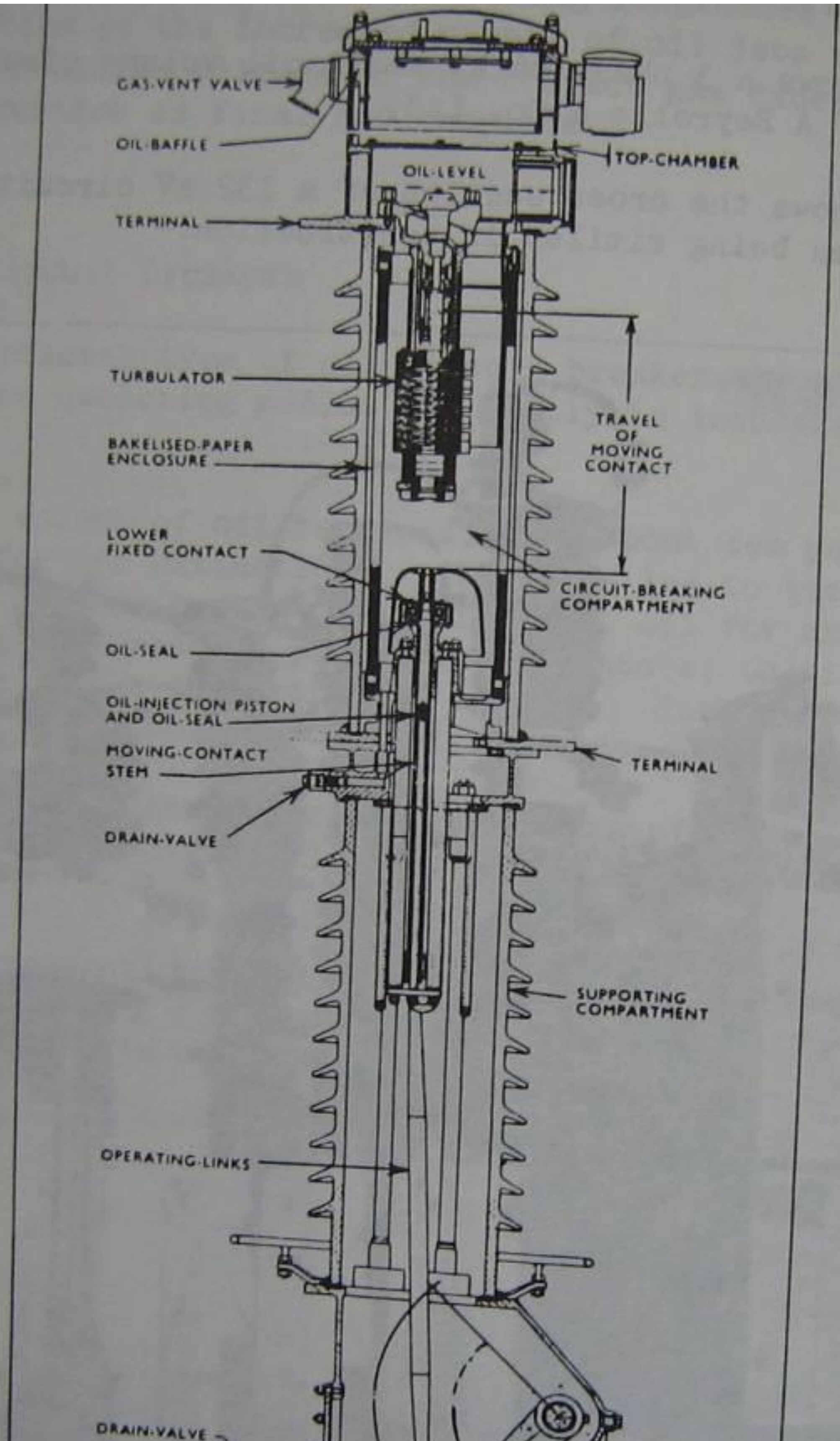
Important features: the circuit breakers are of high rupturing capacity being up to 1500 MVA at 33 kV and 2500 MVA at 66 kV.

3 CIRCUIT BREAKERS (PART 3)

Important features: the circuit breakers are of high rupturing capacity being up to 1500 MVA at 33 kV and 2500 MVA at 66 kV.

The physical separation of the arc quenching oil from the main insulating oil ensures that insulation under permanent electrical stress to earth is not immersed in carbonized oil. (See Figure 21.)

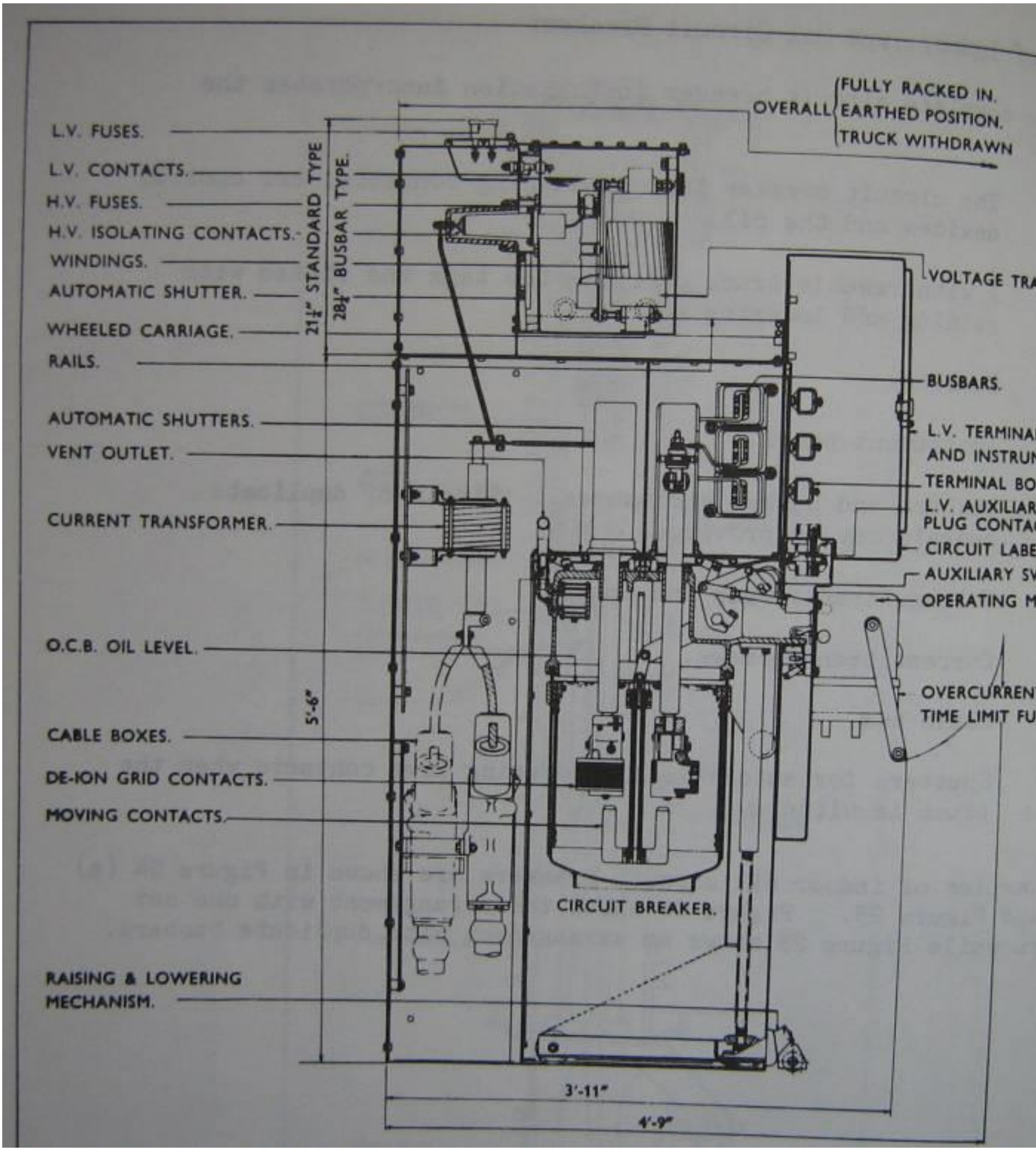



GAS-VENT VALVE
OIL-BAFFLE
TOP-CHAMBER
OIL-LEVEL
TERMINAL
TURBULATOR
TRAVEL OF MOVING CONTACT
BAKELISED-PAPER ENCLOSURE
LOWER FIXED CONTACT
CIRCUIT-BREAKING COMPARTMENT
OIL-SEAL
OIL-INJECTION PISTON AND OIL-SEAL
MOVING-CONTACT STEM
TERMINAL
DRAIN-VALVE
SUPPORTING COMPARTMENT
OPERATING-LINKS
DRAIN-VALVE

Assembly of Indoor Type Oil Circuit Breakers

The complete circuit breaker installation incorporates the following:

1. The circuit breaker tank containing contacts, arc control devices and the oil.
2. A withdrawable truck carrying the tank and fitted with raising and lowering screws.
3. Housing.
4. Instrument panel.
5. Busbars and busbar enclosures. Single or duplicate busbars may be provided.
6. Voltage transformer and fuses.
7. Current transformers.
8. Cable box.
9. Shutters for automatically covering live contacts when the truck is withdrawn.


OVERALL
FULLY RACKED IN.
EARTHED POSITION.
TRUCK WITHDRAWN
L.V. FUSES.
L.V. CONTACTS.
H.V. FUSES.
H.V. ISOLATING CONTACTS.
WINDINGS.
AUTOMATIC SHUTTER.
WHEELED CARRIAGE.
RAILS.
21½" STANDARD TYPE
28¼" BUSBAR TYPE.
VOLTAGE TRA
BUSBARS.
AUTOMATIC SHUTTERS.
VENT OUTLET.
CURRENT TRANSFORMER.
L.V. TERMINAL
AND INSTRUM
TERMINAL BO
L.V. AUXILIAR
PLUG CONTAC
CIRCUIT LABE
AUXILIARY SV
OPERATING M
O.C.B. OIL LEVEL.
OVERCURRENT
TIME LIMIT FU
5'-6"
CABLE BOXES.
DE-ION GRID CONTACTS.
MOVING CONTACTS.
CIRCUIT BREAKER.
RAISING & LOWERING
MECHANISM.
3'-11"
4'-9"

Co-ordination of Protection

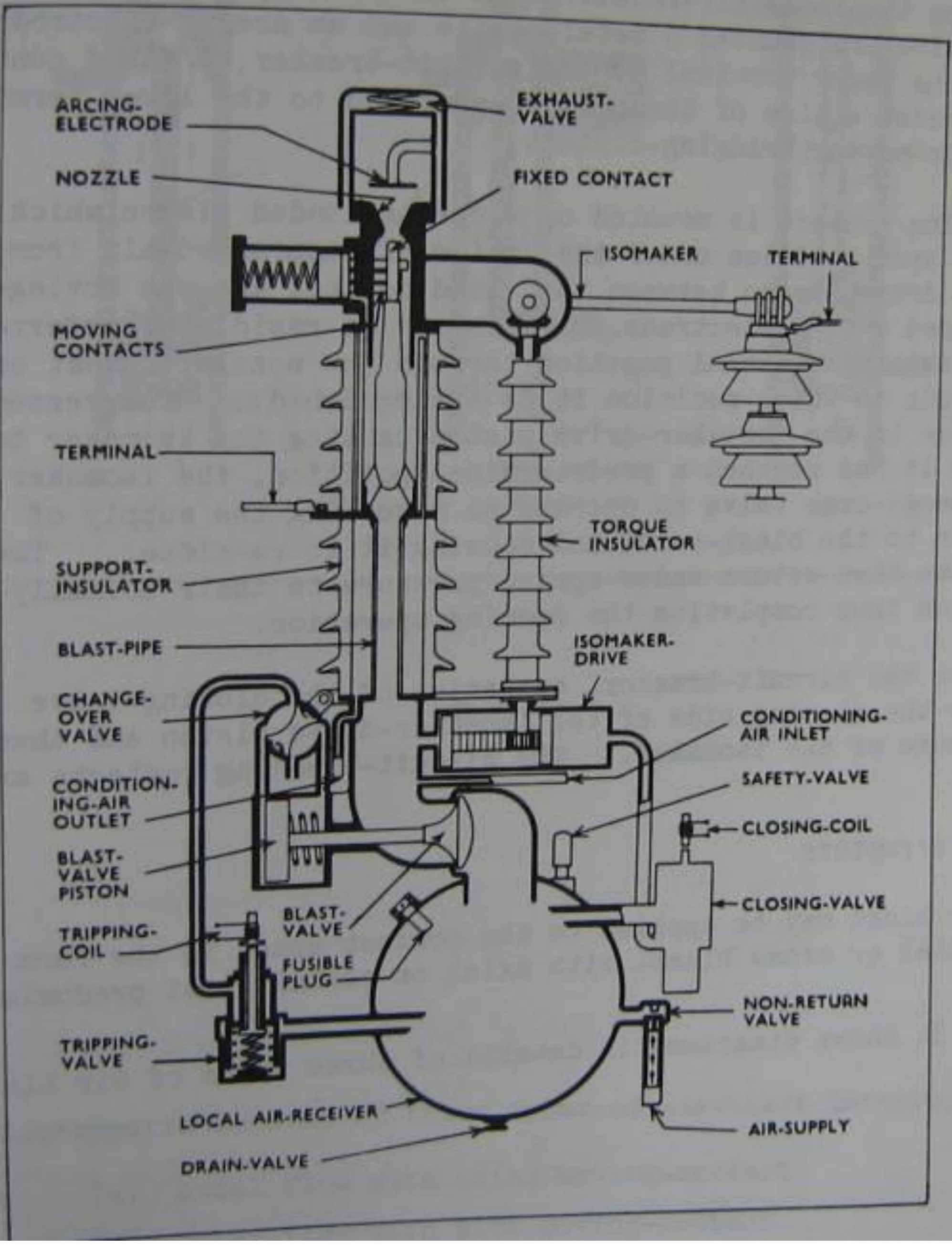
The co-ordination of the three protection units in a moulded c circuit breaker namely time delay thermal trip, instantaneous magneti trip and current limiting protection, is arranged so that overcurrent and low magnitude faults are cleared by the thermal action, normal short-circuits are cleared by the magnetic action, and high fault-cur above a predetermined value, are cleared by the current limiting devic This ensures that unless a severe short circuit occurs the current limiter is unaffected and the frequency of replacement is kept to a minimum.

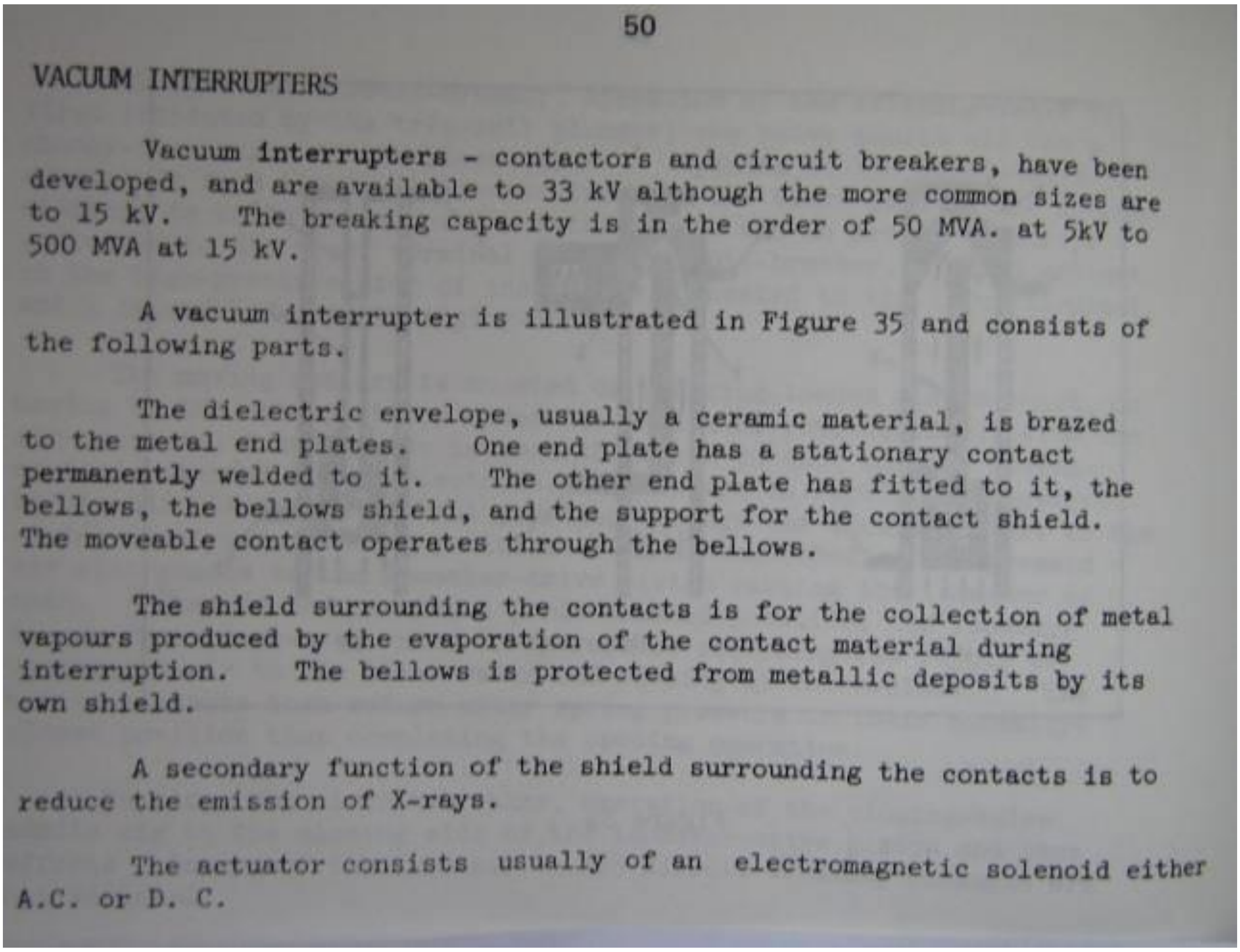
AIR BLAST CIRCUIT BREAKERS

Air blast circuit breakers have been developed to meet the deman for a circuit breaker without the fire risk and other disadvantages of oil circuit-breakers.

They are particularly suitable for very high voltage systems, an are mainly used for transmission systems rather than distribution. The range of circuit breakers available is suitable for voltages of 11 and above depending on the manufacturer and the breaking capacities are 750 MVA for 11 kV breakers, 1500 MVA for 66 kV breakers to 15 000 MVA at 380 kV.

A simplified diagram of an air blast circuit breaker as manufactured by A Reyrolle & Co. Ltd. is shown in Figure 33 and a description of the operation of the circuit-breaker is as follows.





VACUUM INTERRUPTERS

Vacuum interrupters - contactors and circuit breakers, have been developed, and are available to 33 kV although the more common sizes are to 15 kV. The breaking capacity is in the order of 50 MVA. at 5kV to 500 MVA at 15 kV.

A vacuum interrupter is illustrated in Figure 35 and consists of the following parts.

The dielectric envelope, usually a ceramic material, is brazed to the metal end plates. One end plate has a stationary contact permanently welded to it. The other end plate has fitted to it, the bellows, the bellows shield, and the support for the contact shield. The moveable contact operates through the bellows.

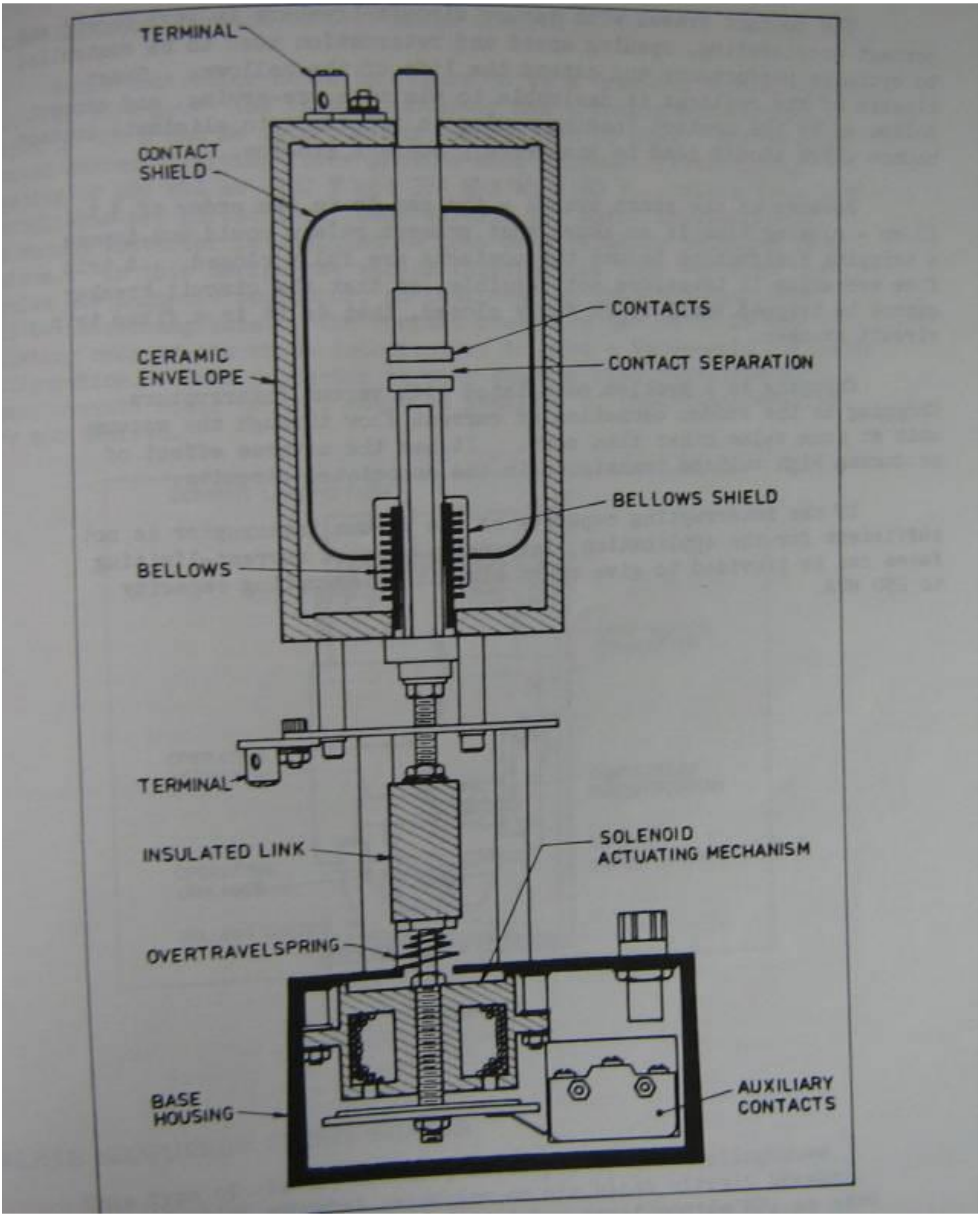
The shield surrounding the contacts is for the collection of metal vapours produced by the evaporation of the contact material during interruption. The bellows is protected from metallic deposits by its own shield.

A secondary function of the shield surrounding the contacts is to reduce the emission of X-rays.

The actuator consists usually of an electromagnetic solenoid either A.C. or D. C.

3 CIRCUIT BREAKERS (PART 4)

Vacuum Circuit Breaker


TERMINAL
CONTACT SHIELD
CONTACTS
CERAMIC ENVELOPE
CONTACT SEPARATION
BELLOWS SHIELD
BELLOWS
TERMINAL
SOLENOID ACTUATING MECHANISM
INSULATED LINK
OVERTRAVELSPRING
BASE HOUSING
AUXILIARY CONTACTS

SULPHUR HEXAFLUORIDE CIRCUIT BREAKERS

This type of circuit breaker, developed by the Westinghouse Electric Corporation somewhat resembles an air blast circuit breaker, in that a non combustible heavy gas, sulphur hexafluoride SF_6,is use under pressure as the arc extinguishing medium. The gas, however, sealed within the circuit breaker and is recycled for all circuit bre functions.

Sulphur hexafluoride has the important property of having a st affinity for electrons. Because of this it readily acquires free electrons produced in the arc, and at a current zero enables the arc to be converted to a good dielectric.

Ratings

Typical power ratings for these circuit breakers are 500 MVA a 33 kV, 5000 MVA at 132 kV, and 25000 MVA at 345 kV, with continuous current ratings from 1200 to 3000 amperes.

Advantages

The advantages claimed for this type of circuit breaker are:

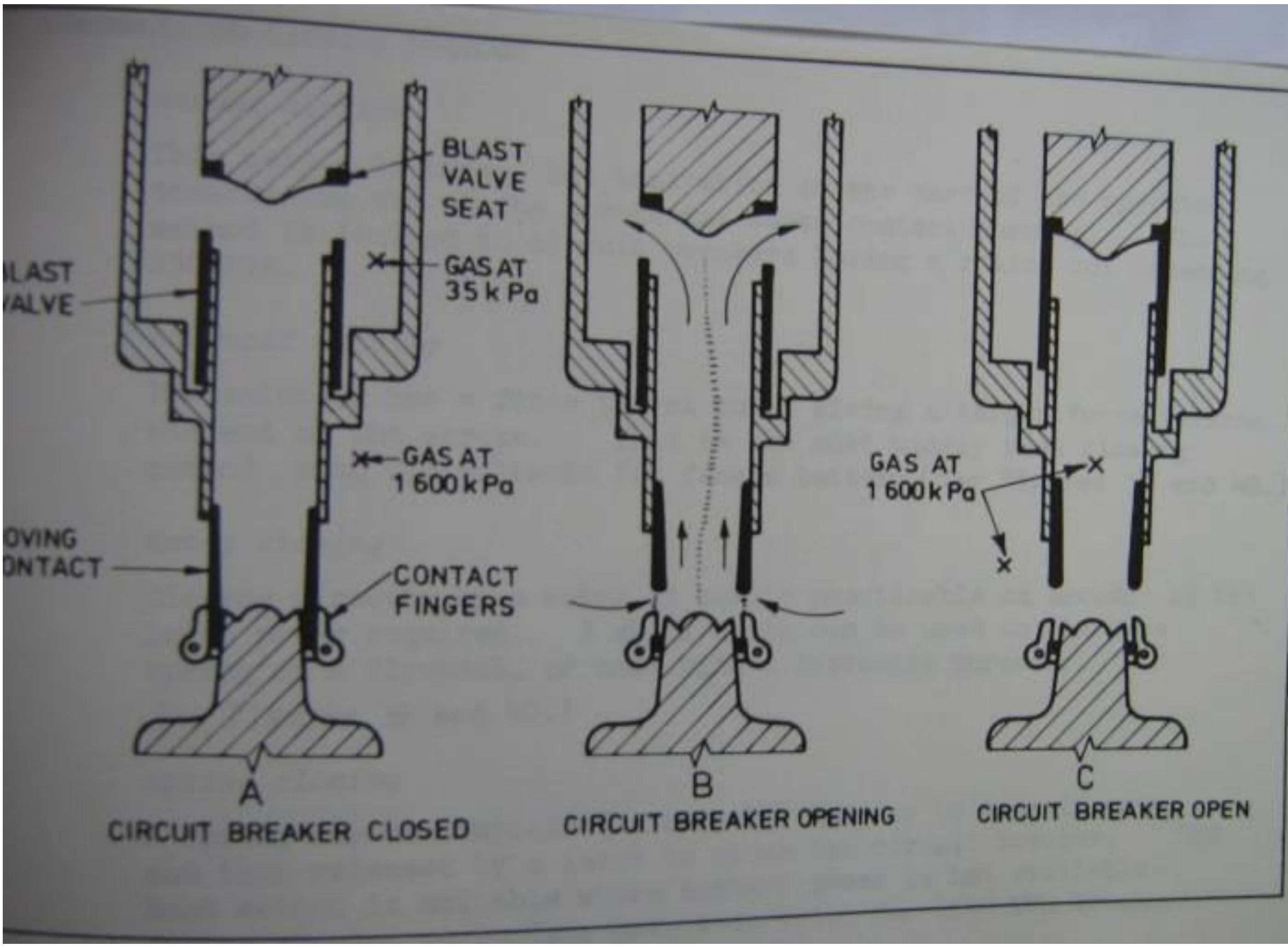
Very quiet in operation, because there is no external exhaust the operating medium.

No fire hazard,SF_6 being chemically inert, non toxic, and non flammable.

The moving parts are relatively small and require little energ

Arc interruption is very fast; breakers can interrupt faults u to 63kA within two cycles.

The circuit breaker is less bulky than a similar size air blas circuit breaker.



A CIRCUIT BREAKER CLOSED

B CIRCUIT BREAKER OPENING

C CIRCUIT BREAKER OPEN

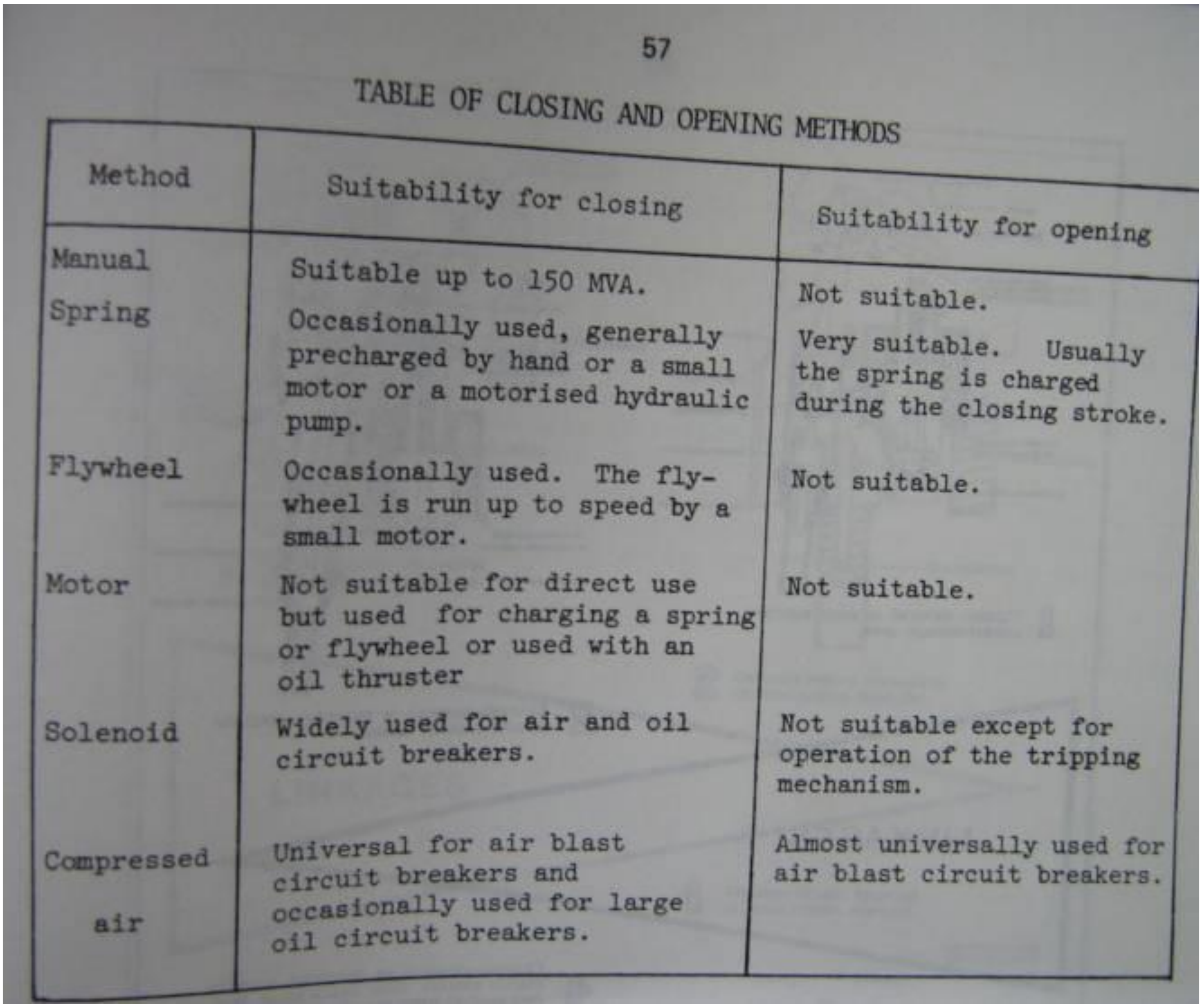
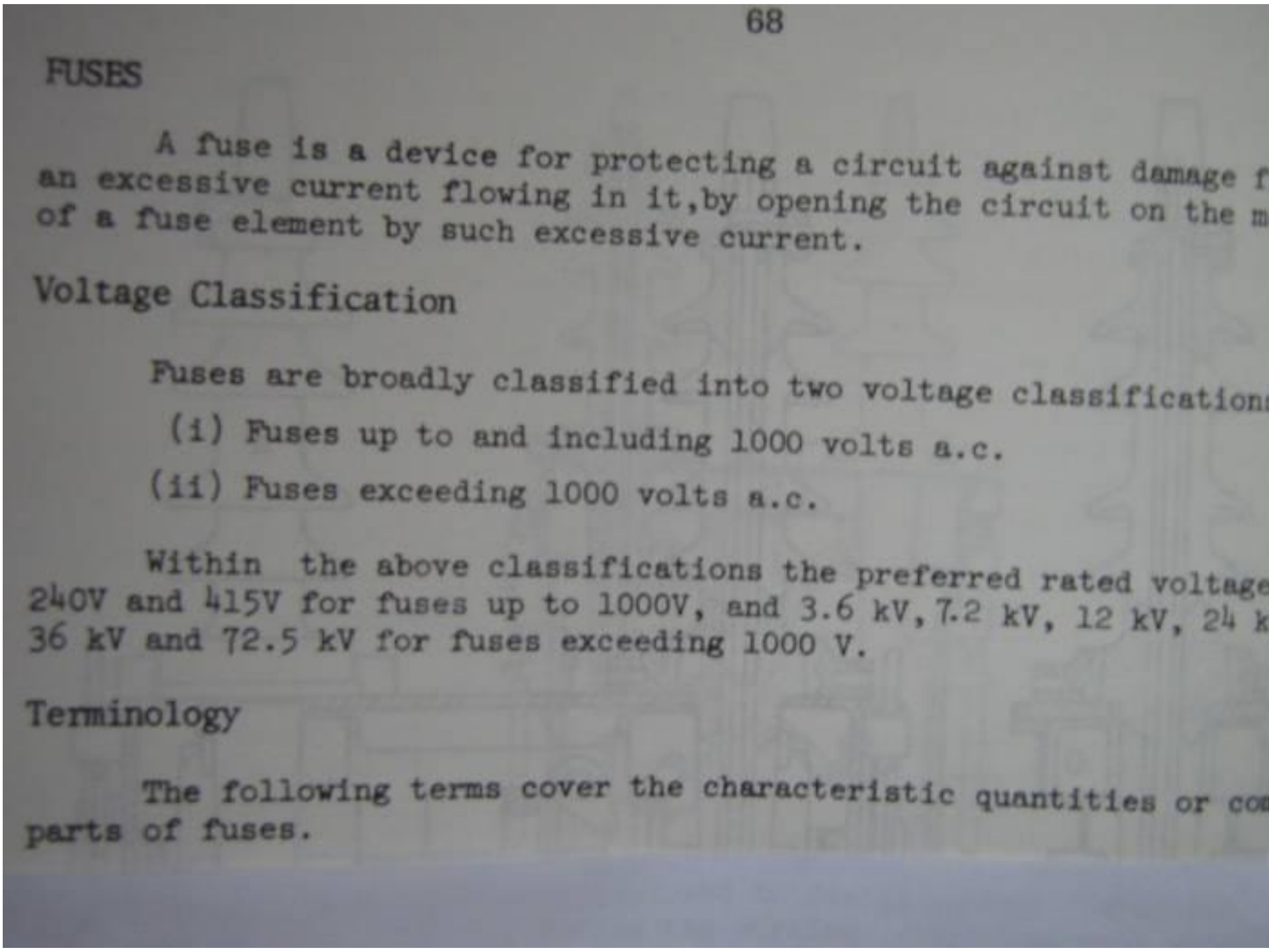


TABLE OF CLOSING AND OPENING METHODS

Method	Suitability for closing	Suitability for opening
Manual	Suitable up to 150 MVA.	Not suitable.
Spring	Occasionally used, generally precharged by hand or a small motor or a motorised hydraulic pump.	Very suitable. Usually the spring is charged during the closing stroke.
Flywheel	Occasionally used. The flywheel is run up to speed by a small motor.	Not suitable.
Motor	Not suitable for direct use but used for charging a spring or flywheel or used with an oil thruster	Not suitable.
Solenoid	Widely used for air and oil circuit breakers.	Not suitable except for operation of the tripping mechanism.
Compressed air	Universal for air blast circuit breakers and occasionally used for large oil circuit breakers.	Almost universally used for air blast circuit breakers.



FUSES

A fuse is a device for protecting a circuit against damage f an excessive current flowing in it,by opening the circuit on the m of a fuse element by such excessive current.

Voltage Classification

Fuses are broadly classified into two voltage classification

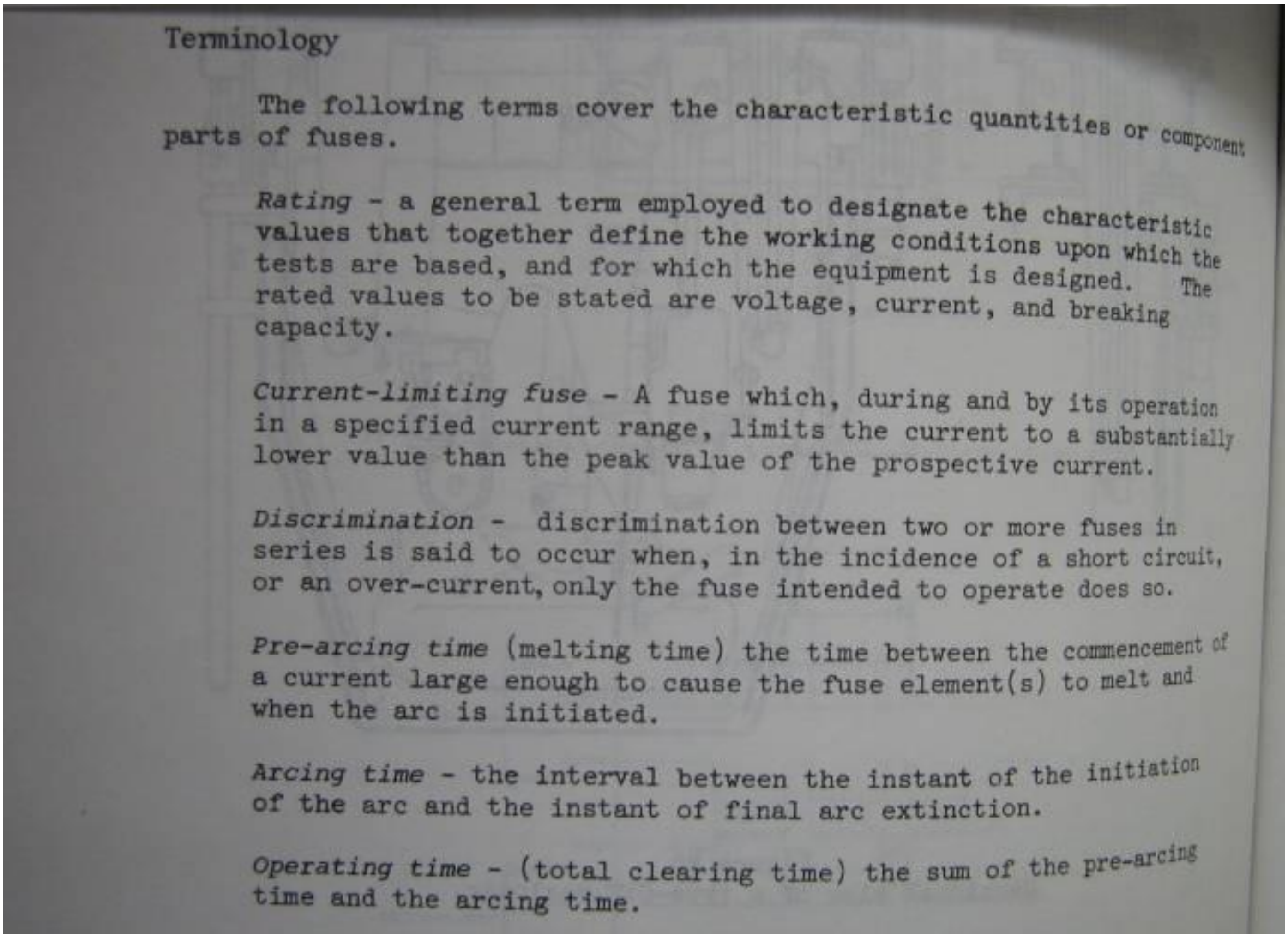
(i) Fuses up to and including 1000 volts a.c.

(ii) Fuses exceeding 1000 volts a.c.

Within the above classifications the preferred rated voltage 240V and 415V for fuses up to 1000V, and 3.6 kV, 7.2 kV, 12 kV, 24 k 36 kV and 72.5 kV for fuses exceeding 1000 V.

Terminology

The following terms cover the characteristic quantities or co parts of fuses.



Terminology

The following terms cover the characteristic quantities or component parts of fuses.

Rating - a general term employed to designate the characteristic values that together define the working conditions upon which the tests are based, and for which the equipment is designed. The rated values to be stated are voltage, current, and breaking capacity.

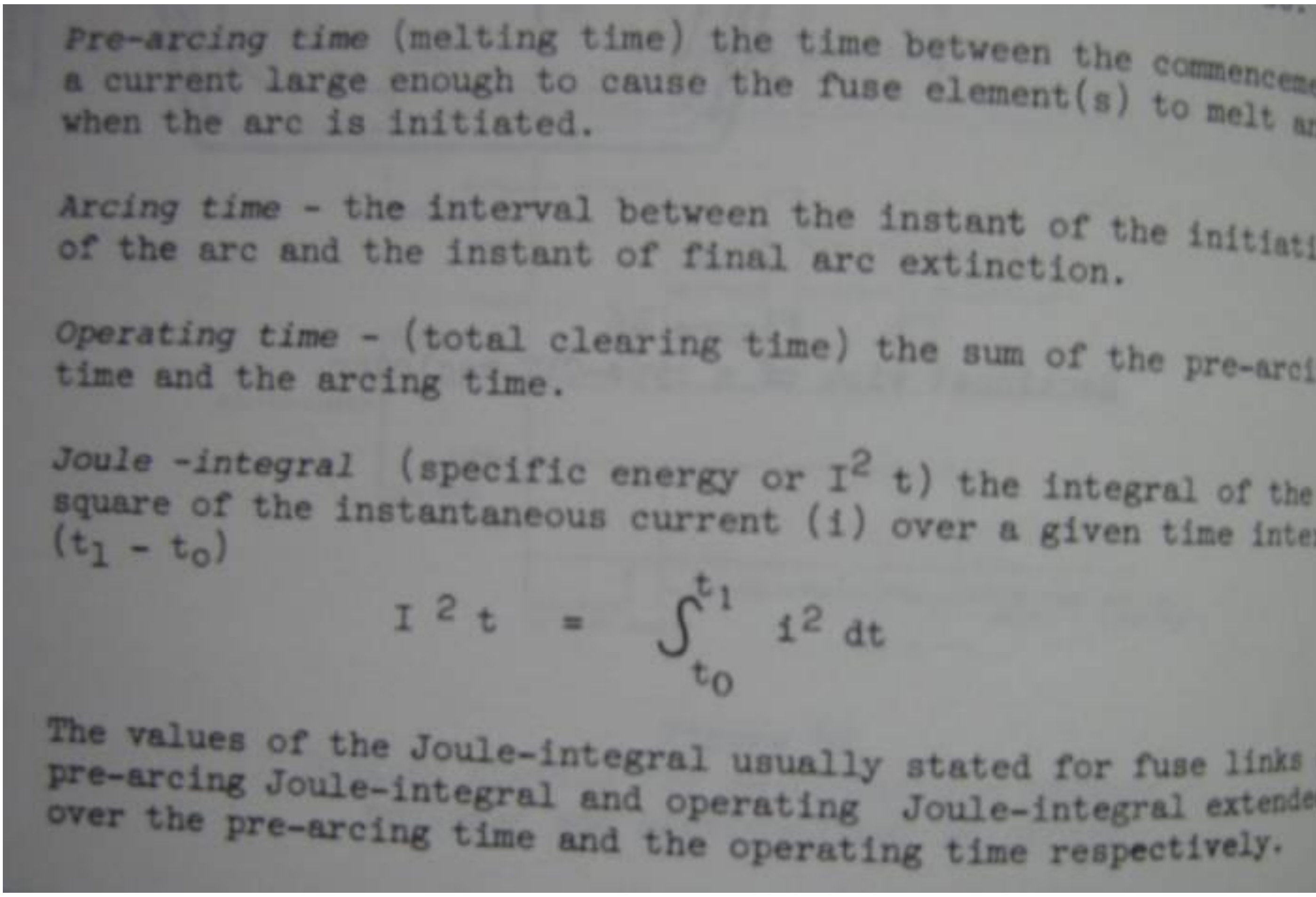
Current-limiting fuse - A fuse which, during and by its operation in a specified current range, limits the current to a substantially lower value than the peak value of the prospective current.

Discrimination - discrimination between two or more fuses in series is said to occur when, in the incidence of a short circuit, or an over-current, only the fuse intended to operate does so.

Pre-arcing time (melting time) the time between the commencement of a current large enough to cause the fuse element(s) to melt and when the arc is initiated.

Arcing time - the interval between the instant of the initiation of the arc and the instant of final arc extinction.

Operating time - (total clearing time) the sum of the pre-arcing time and the arcing time.



Pre-arcing time (melting time) the time between the commenceme a current large enough to cause the fuse element(s) to melt ar when the arc is initiated.

Arcing time - the interval between the instant of the initiati of the arc and the instant of final arc extinction.

Operating time - (total clearing time) the sum of the pre-arci time and the arcing time.

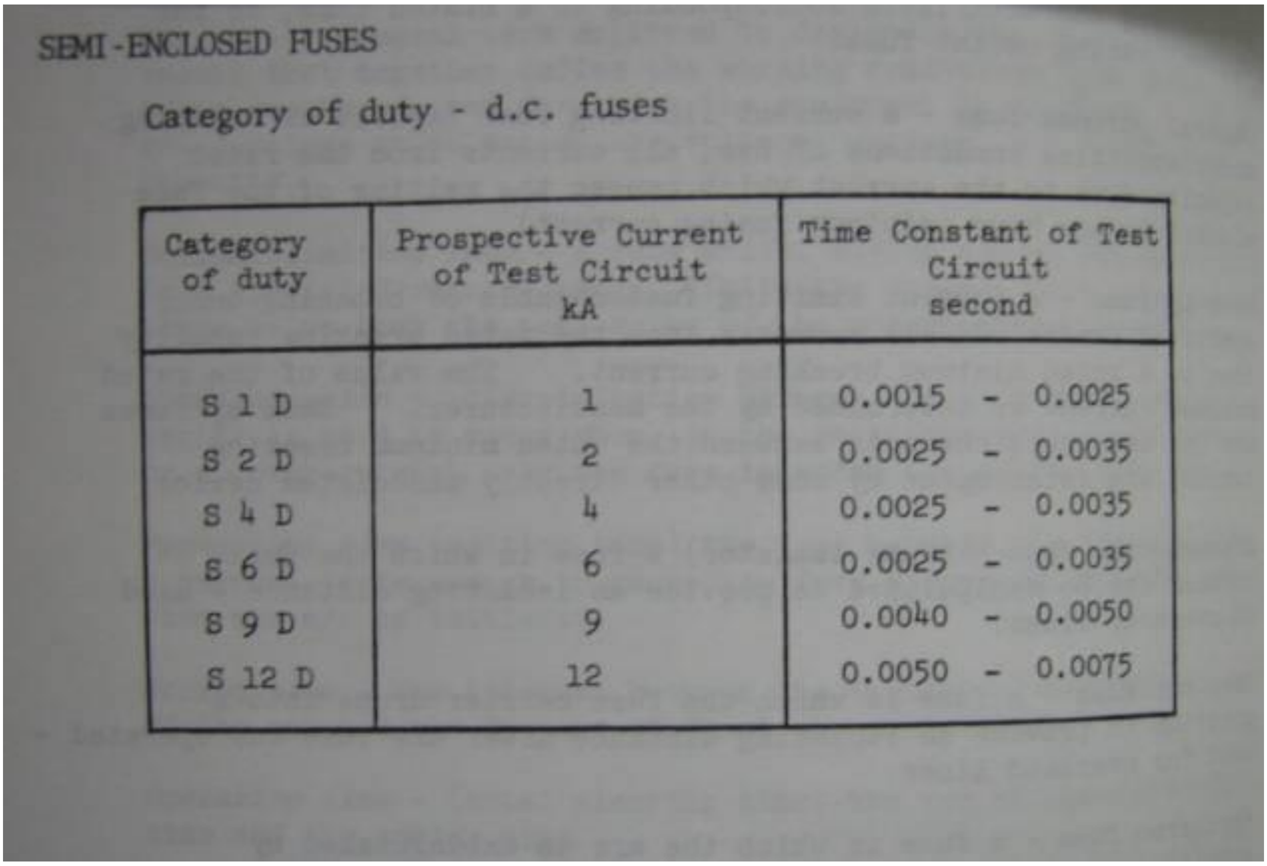
Joule -integral (specific energy or I^2 t) the integral of the square of the instantaneous current (i) over a given time inte $(t_1 - t_0)$

$$I^2 t = \int_{t_0}^{t_1} i^2 \, dt$$

The values of the Joule-integral usually stated for fuse links pre-arcing Joule-integral and operating Joule-integral extende over the pre-arcing time and the operating time respectively.

3 CIRCUIT BREAKERS (PART 5)

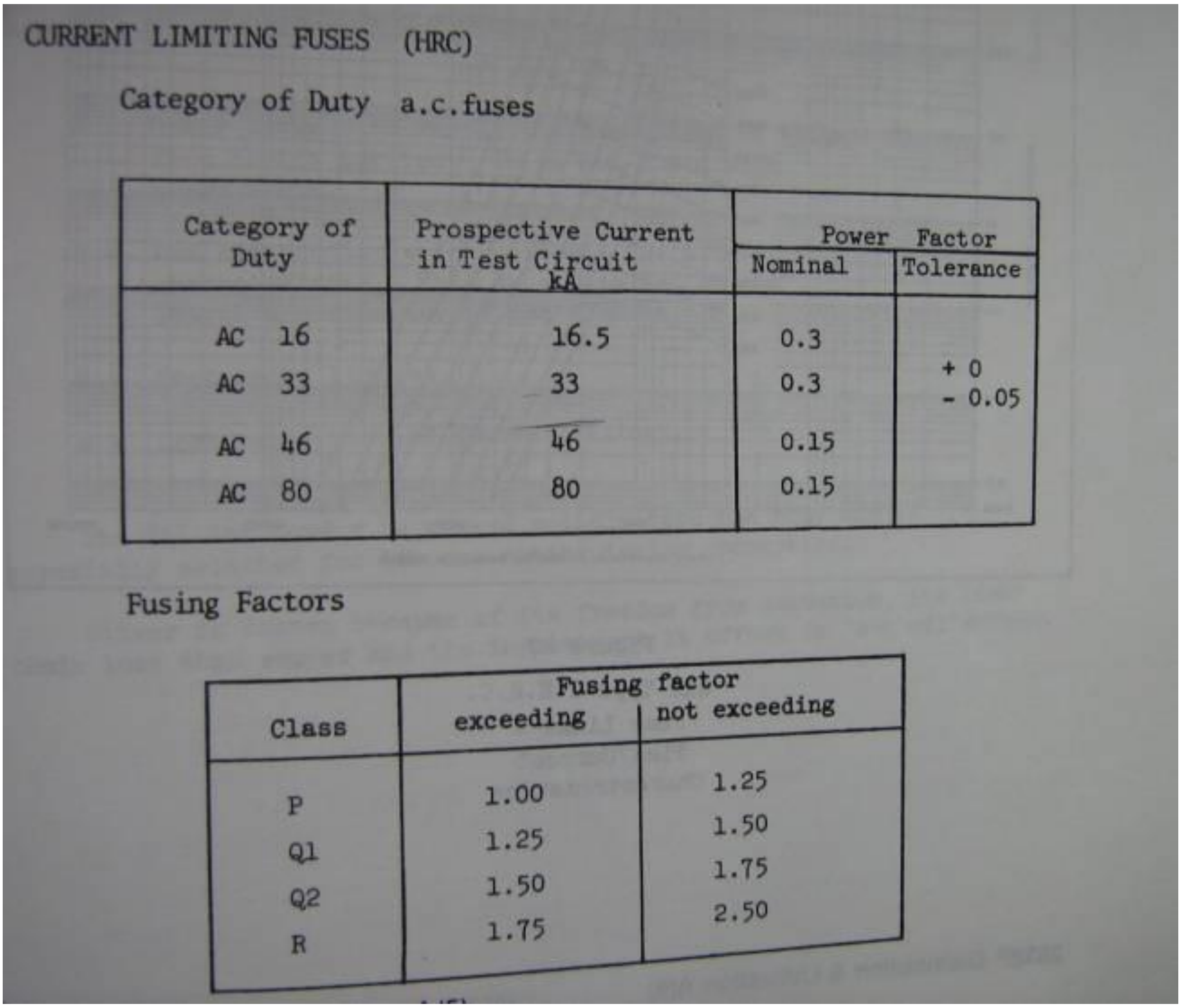
Semi Enclosed Fuse



SEMI-ENCLOSED FUSES

Category of duty - d.c. fuses

Category of duty	Prospective Current of Test Circuit kA	Time Constant of Test Circuit second
S 1 D	1	0.0015 - 0.0025
S 2 D	2	0.0025 - 0.0035
S 4 D	4	0.0025 - 0.0035
S 6 D	6	0.0025 - 0.0035
S 9 D	9	0.0040 - 0.0050
S 12 D	12	0.0050 - 0.0075



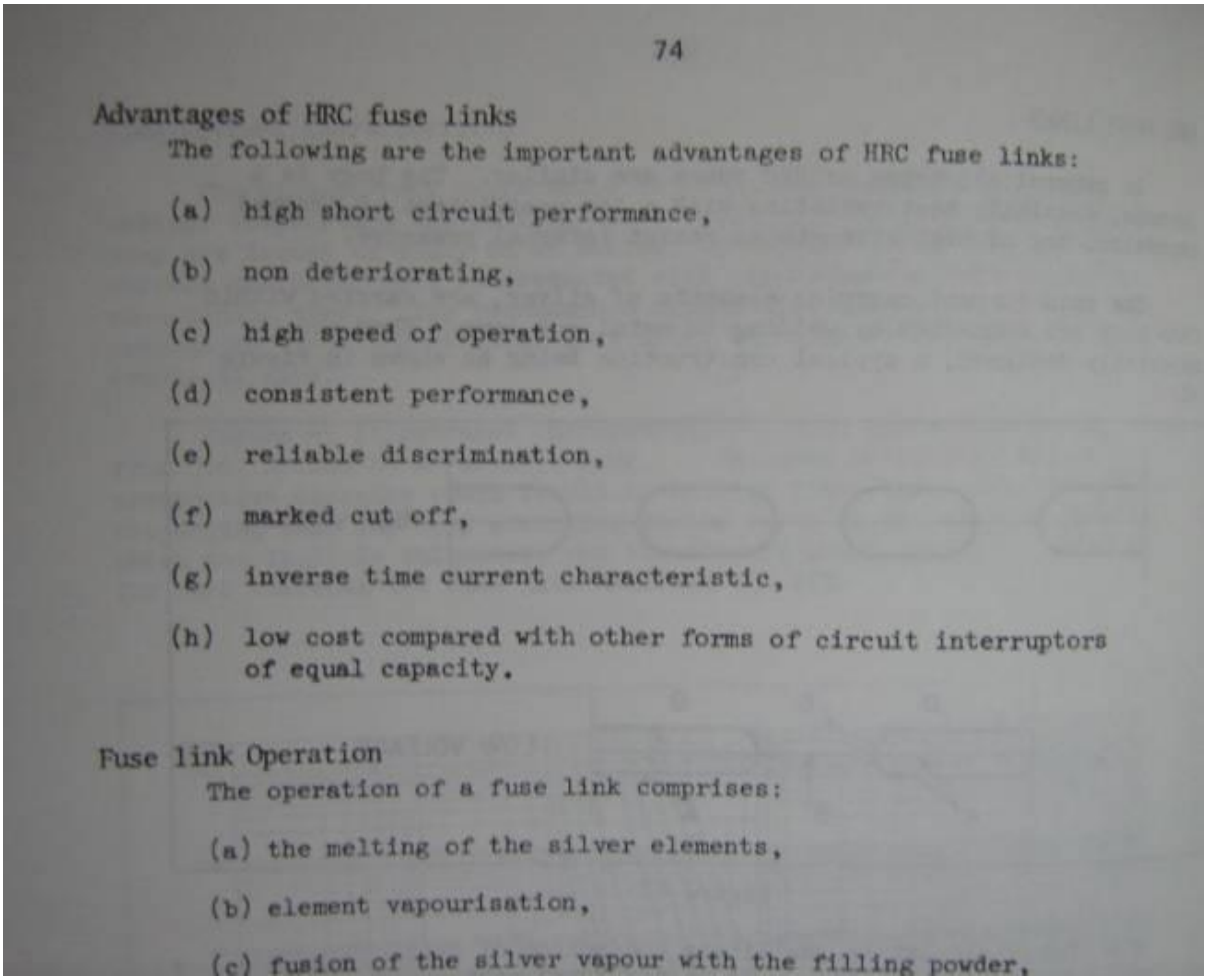
CURRENT LIMITING FUSES (HRC)

Category of Duty a.c.fuses

Category of Duty	Prospective Current in Test Circuit kA	Power Factor	
		Nominal	Tolerance
AC 16	16.5	0.3	+ 0 - 0.05
AC 33	33	0.3	
AC 46	46	0.15	
AC 80	80	0.15	

Fusing Factors

Class	Fusing factor	
	exceeding	not exceeding
P	1.00	1.25
Q1	1.25	1.50
Q2	1.50	1.75
R	1.75	2.50



Advantages of HRC fuse links

The following are the important advantages of HRC fuse links:

(a) high short circuit performance,

(b) non deteriorating,

(c) high speed of operation,

(d) consistent performance,

(e) reliable discrimination,

(f) marked cut off,

(g) inverse time current characteristic,

(h) low cost compared with other forms of circuit interruptors of equal capacity.

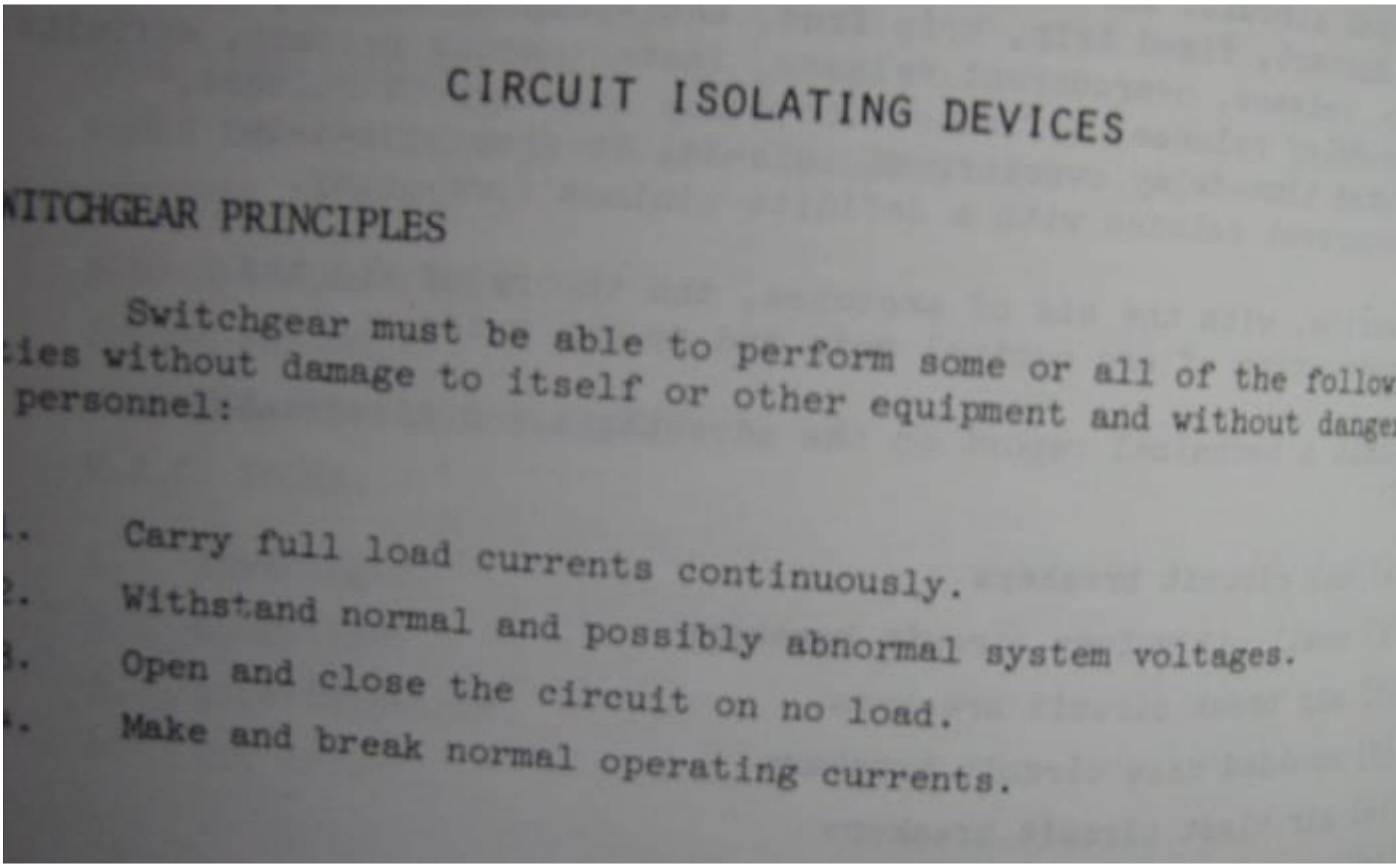
Fuse link Operation

The operation of a fuse link comprises:

(a) the melting of the silver elements,

(b) element vapourisation,

(c) fusion of the silver vapour with the filling powder,

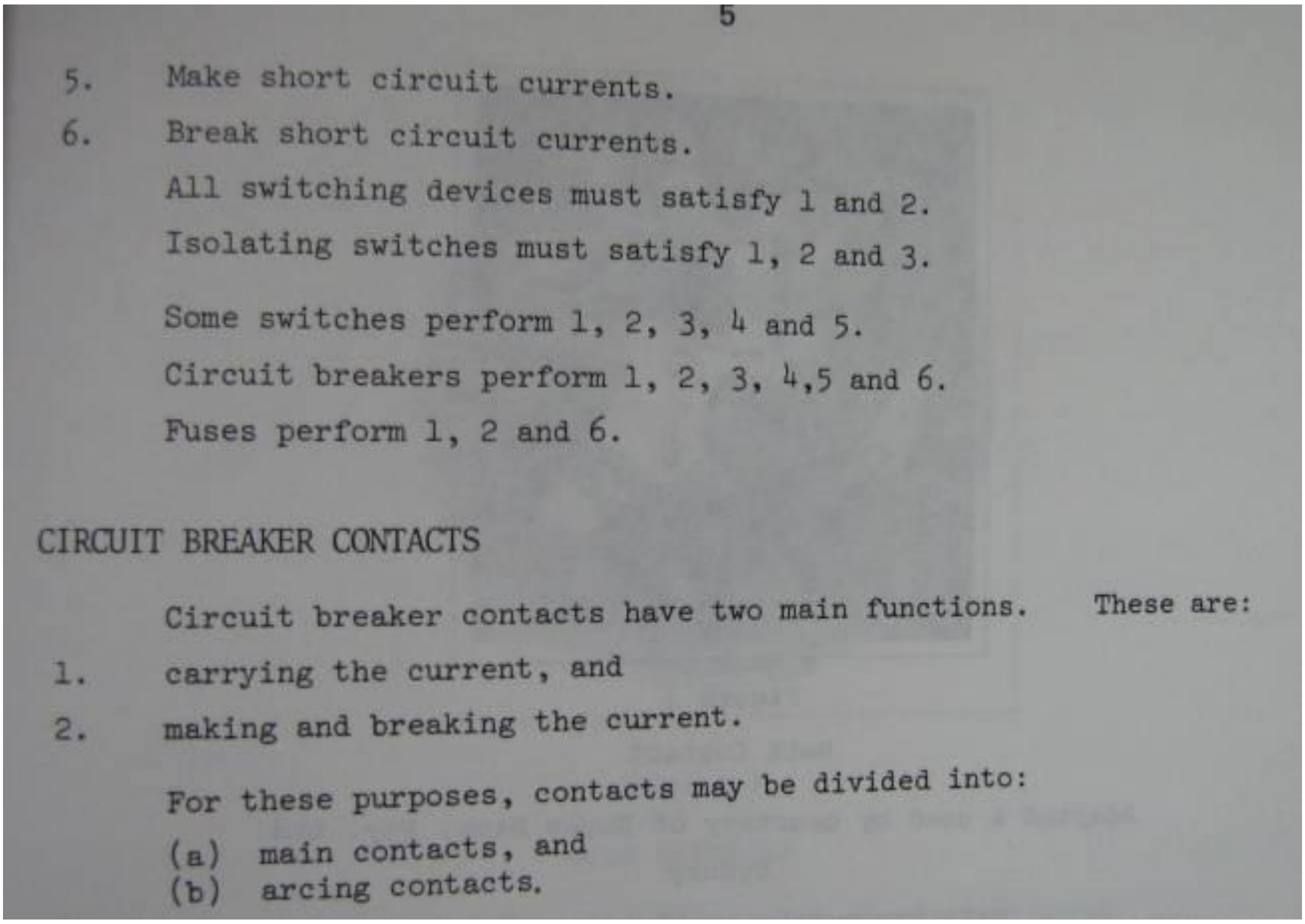


CIRCUIT ISOLATING DEVICES

ITCHGEAR PRINCIPLES

Switchgear must be able to perform some or all of the follow
ies without damage to itself or other equipment and without dange
personnel:

- Carry full load currents continuously.
- Withstand normal and possibly abnormal system voltages.
- Open and close the circuit on no load.
- Make and break normal operating currents.



5. Make short circuit currents.
6. Break short circuit currents.

All switching devices must satisfy 1 and 2.

Isolating switches must satisfy 1, 2 and 3.

Some switches perform 1, 2, 3, 4 and 5.

Circuit breakers perform 1, 2, 3, 4,5 and 6.

Fuses perform 1, 2 and 6.

CIRCUIT BREAKER CONTACTS

Circuit breaker contacts have two main functions. These are:

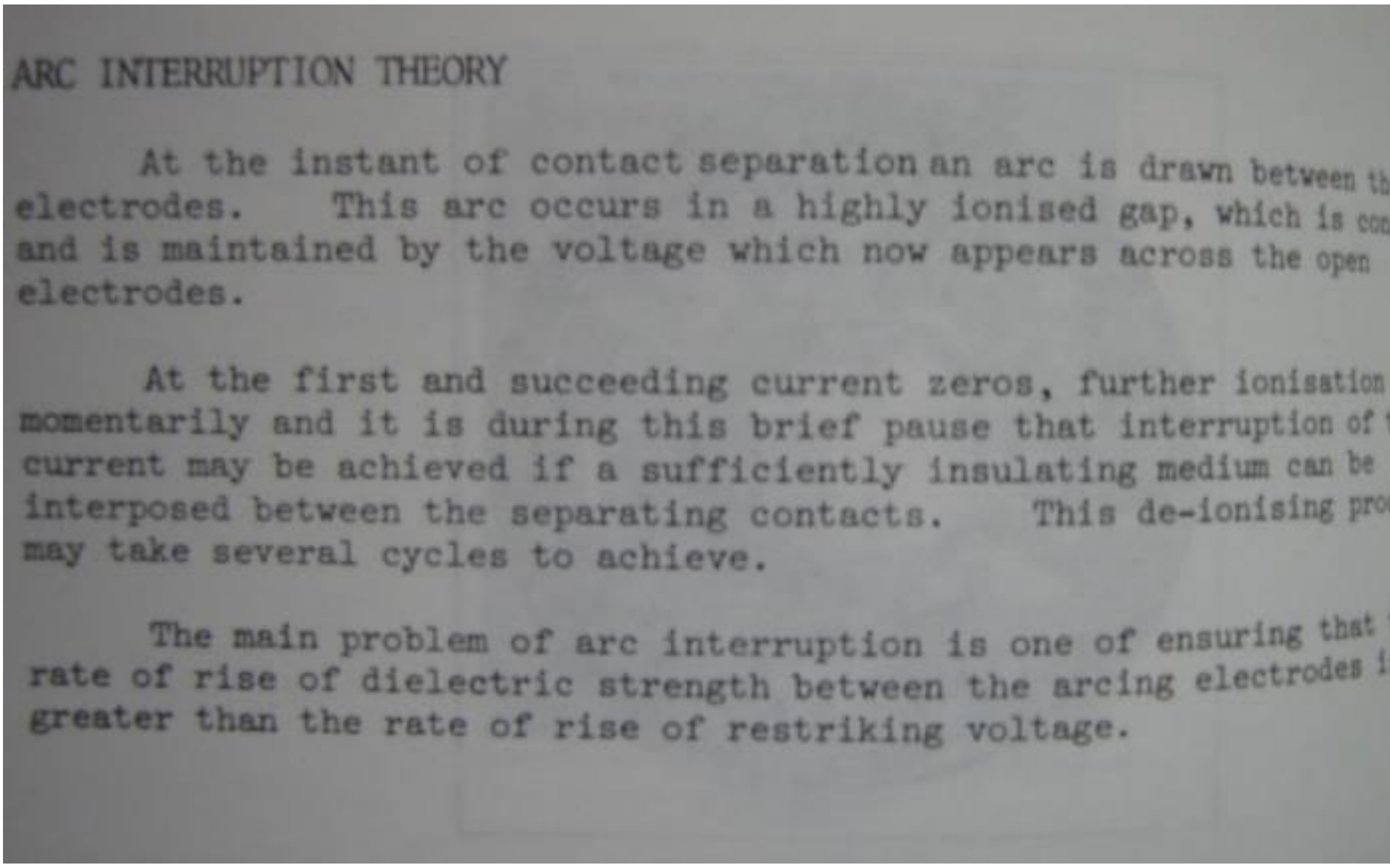
1. carrying the current, and
2. making and breaking the current.

For these purposes, contacts may be divided into:

(a) main contacts, and
(b) arcing contacts.

3 CIRCUIT BREAKERS (PART 6)

Arc Interruption

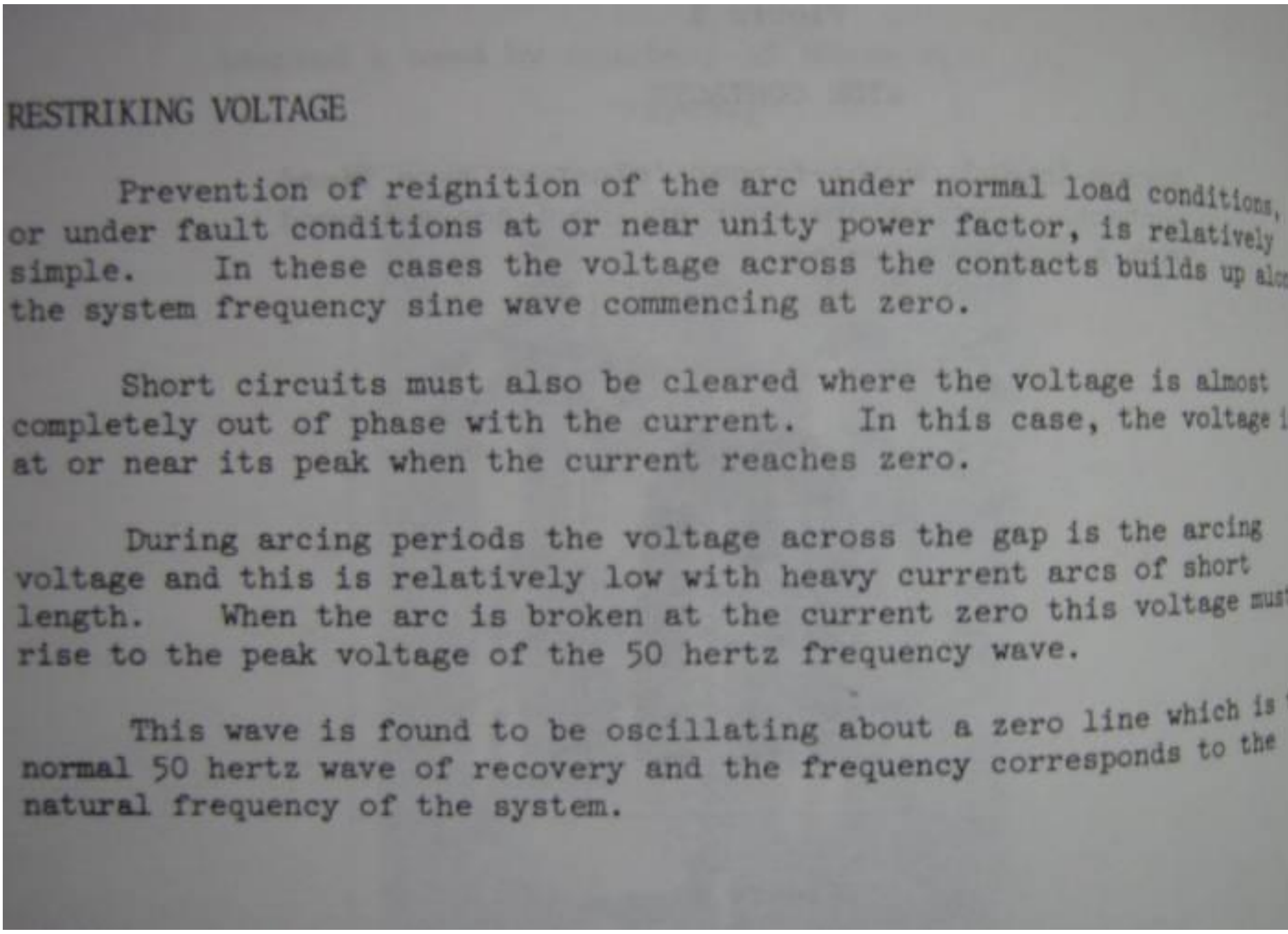


ARC INTERRUPTION THEORY

At the instant of contact separation an arc is drawn between th
electrodes. This arc occurs in a highly ionised gap, which is con
and is maintained by the voltage which now appears across the open
electrodes.

At the first and succeeding current zeros, further ionisation
momentarily and it is during this brief pause that interruption of t
current may be achieved if a sufficiently insulating medium can be
interposed between the separating contacts. This de-ionising pro
may take several cycles to achieve.

The main problem of arc interruption is one of ensuring that t
rate of rise of dielectric strength between the arcing electrodes i
greater than the rate of rise of restriking voltage.



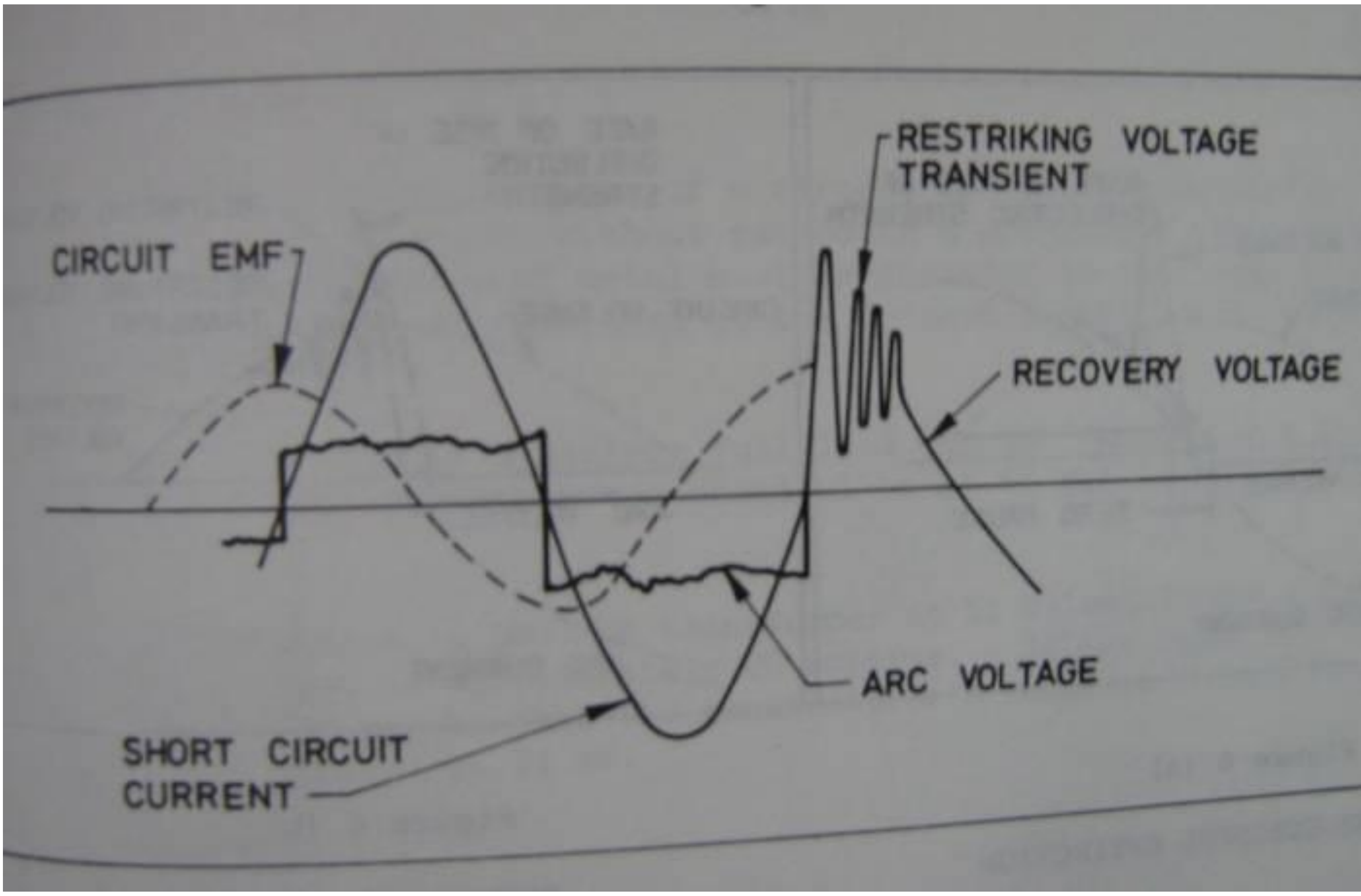
RESTRIKING VOLTAGE

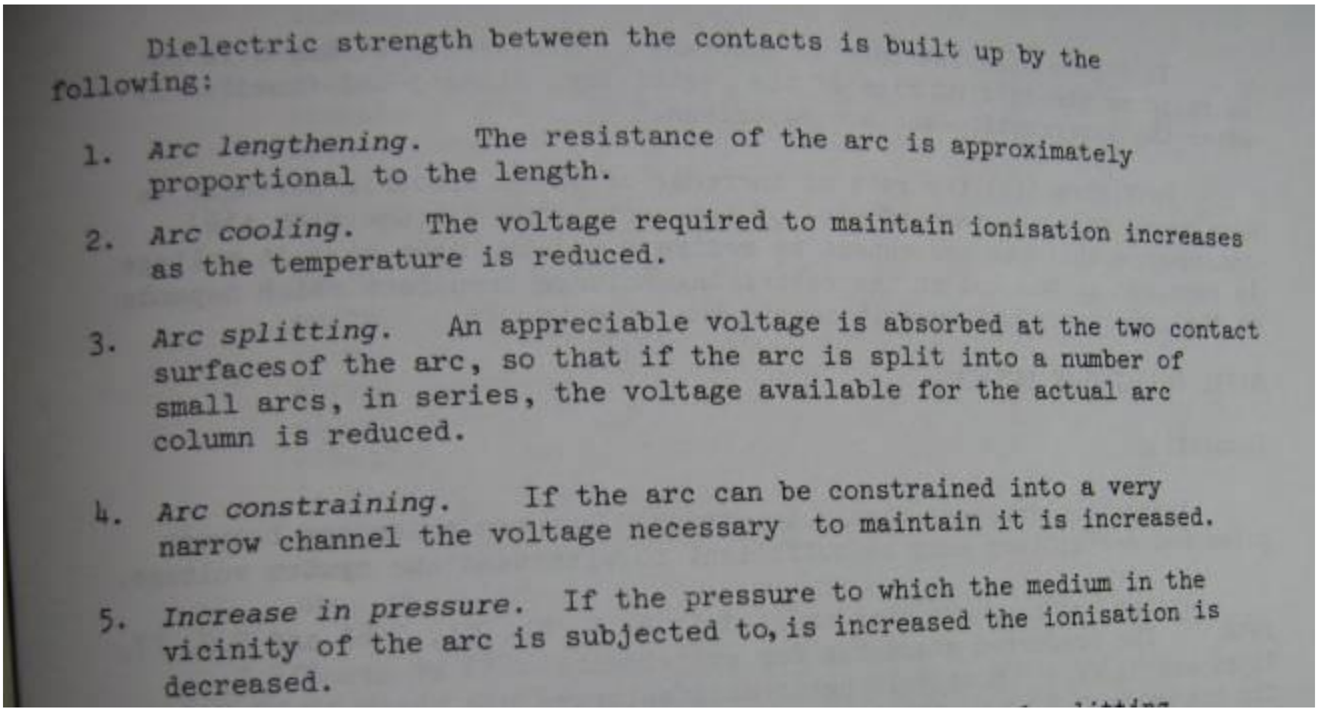
Prevention of reignition of the arc under normal load conditions, or under fault conditions at or near unity power factor, is relatively simple. In these cases the voltage across the contacts builds up alo the system frequency sine wave commencing at zero.

Short circuits must also be cleared where the voltage is almost completely out of phase with the current. In this case, the voltage i at or near its peak when the current reaches zero.

During arcing periods the voltage across the gap is the arcing voltage and this is relatively low with heavy current arcs of short length. When the arc is broken at the current zero this voltage mus rise to the peak voltage of the 50 hertz frequency wave.

This wave is found to be oscillating about a zero line which is normal 50 hertz wave of recovery and the frequency corresponds to the natural frequency of the system.





Dielectric strength between the contacts is built up by the following:

1. *Arc lengthening.* The resistance of the arc is approximately proportional to the length.
2. *Arc cooling.* The voltage required to maintain ionisation increases as the temperature is reduced.
3. *Arc splitting.* An appreciable voltage is absorbed at the two contact surfacesof the arc, so that if the arc is split into a number of small arcs, in series, the voltage available for the actual arc column is reduced.
4. *Arc constraining.* If the arc can be constrained into a very narrow channel the voltage necessary to maintain it is increased.
5. *Increase in pressure.* If the pressure to which the medium in the vicinity of the arc is subjected to,is increased the ionisation is decreased.

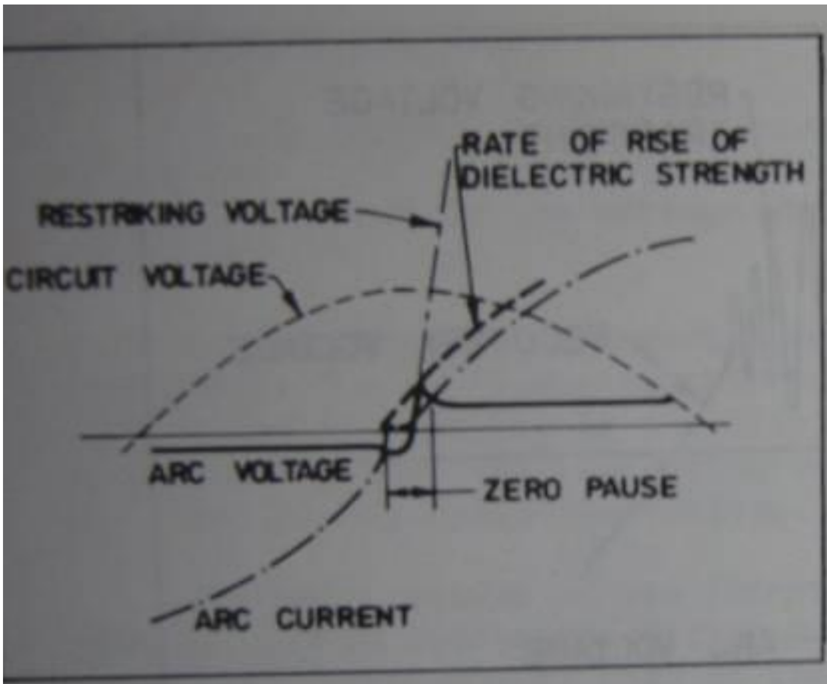


Figure 6 (a)

UNSUCCESSFUL EXTINCTION

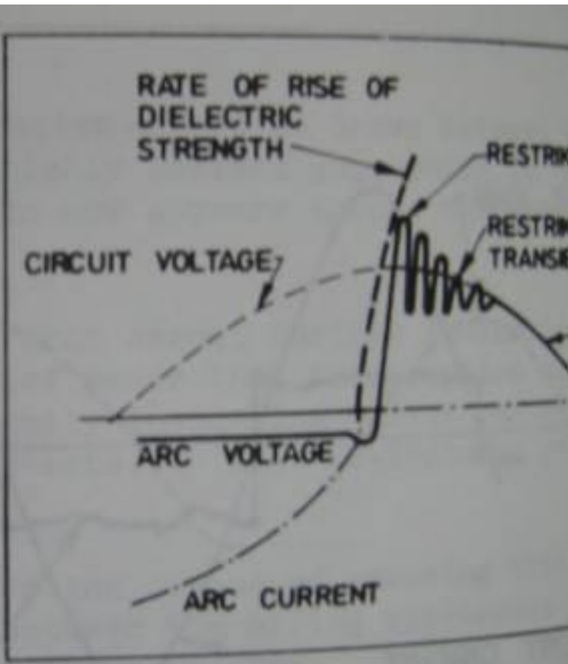


Figure 6 (b)

SUCCESSFUL EXTINCT

BASIC SWITCHGEAR DESIGNS

Insulation

Adequate clearances should be arranged between poles and between poles and earth; they must be sufficient to withstand the system voltage.

System voltages are standardised in A. S. No. C1, 1961 and B.S. 77, 1958. The preferred standards for switchgear to 33 kV are 415 V, 11 kV and 33 kV. Most switchgear manufacturers use their 11 kV designs for the range 3.3 kV to 11 kV and their 33 kV designs for 22 kV and 33 kV.

The switchgear may have to withstand impulse surges if connected to overhead distribution systems. Impulse voltage tests are recommended with the object of determining the effect of voltage surges of short duration on the circuit breaker, the surges being such as are caused by lightning discharges.

AIR BREAK CIRCUIT BREAKERS 415 volts

Heavy duty air break circuit breakers for medium voltages were designed to meet the need for a circuit breaker of about 25 MVA breaking capacity and usually 35 MVA.

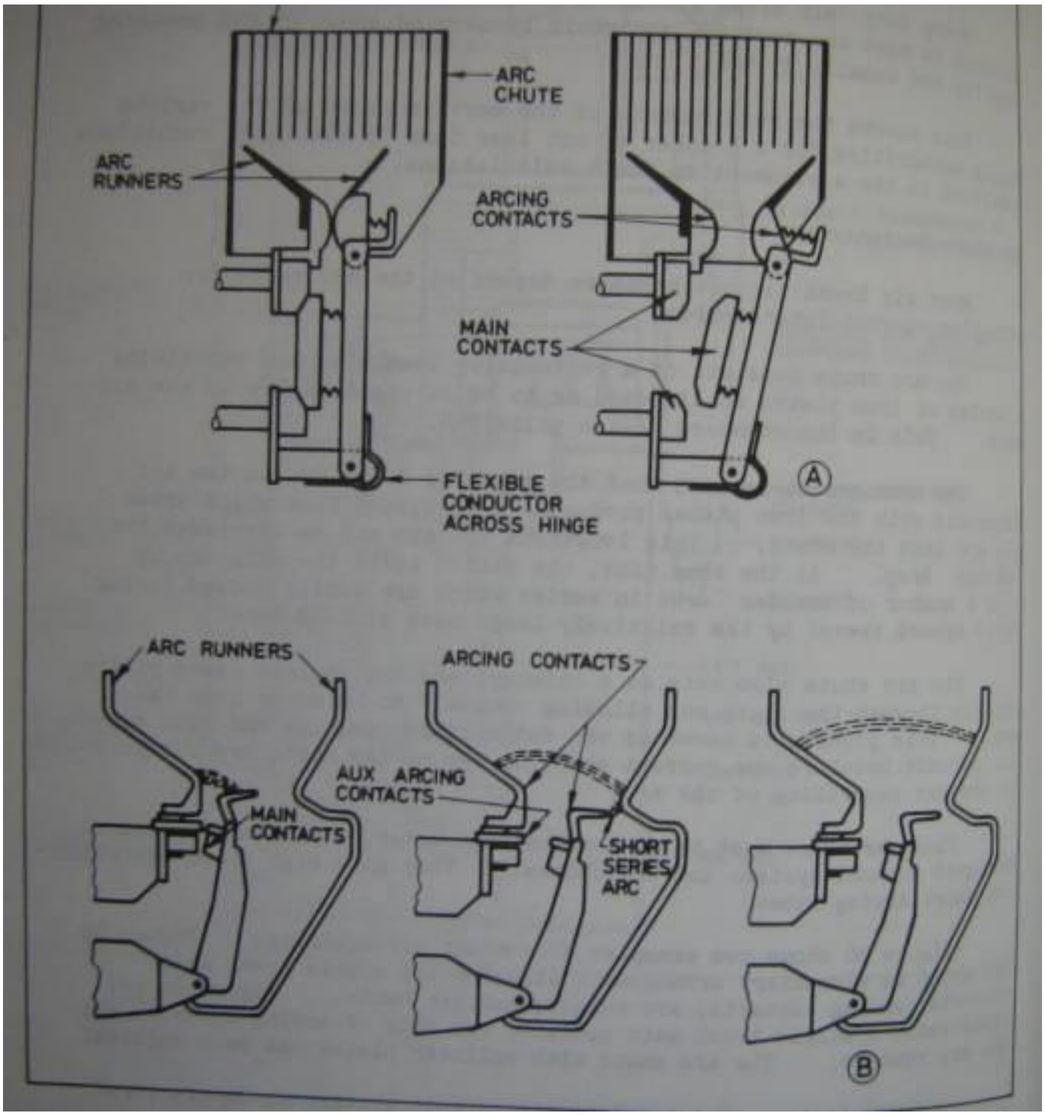
This covers the requirements of the service rules of the various Supply Authorities for a breaker of not less than 25 MVA under conditions mentioned in the assignment on fault calculations.

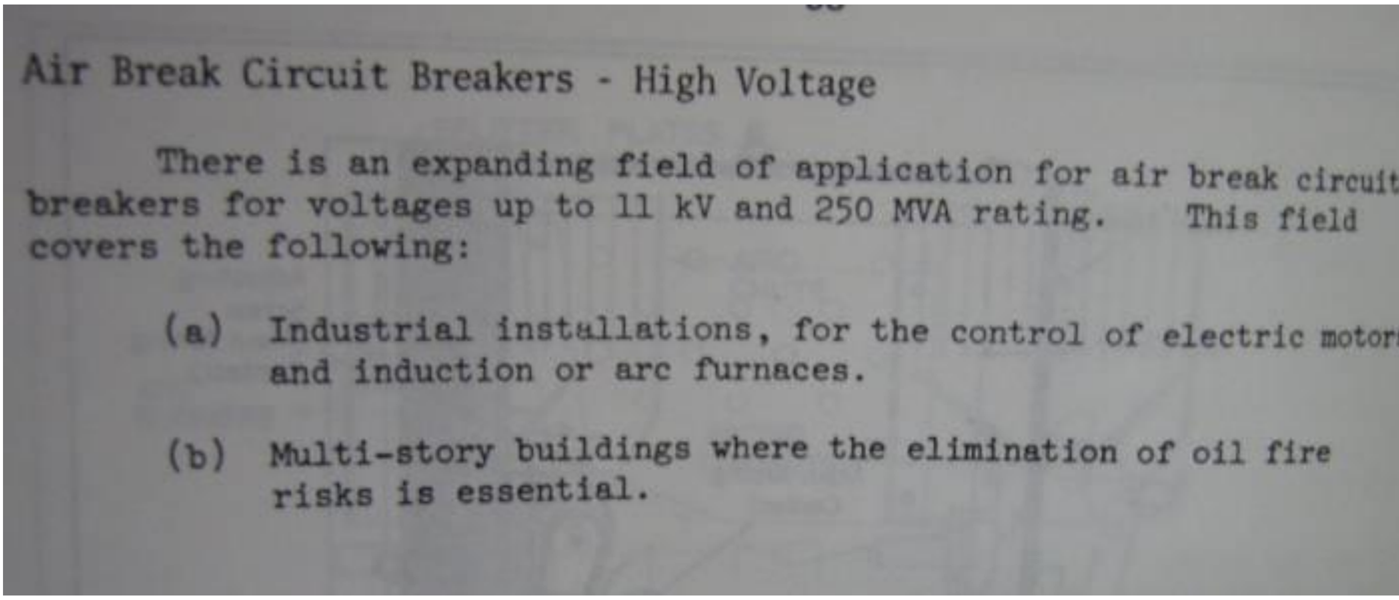
Arc Chute Design

Most air break circuit breakers depend on the arc chute for effective current interruption.

The arc chute consists of a rectangular insulated box containing a series of iron plates so disposed as to be at right angles to the arc path. This is the standard de-ion principle.

The arrangement is such that the magnetic field due to the arc interacts with the iron plates producing a resultant flux which draws the arc into the chute. This lengthens the arc and so increases the voltage drop. At the same time, the plates split the main arc up into a number of smaller arcs in series which are easily cooled during their upward travel by the relatively large mass of cold metal.



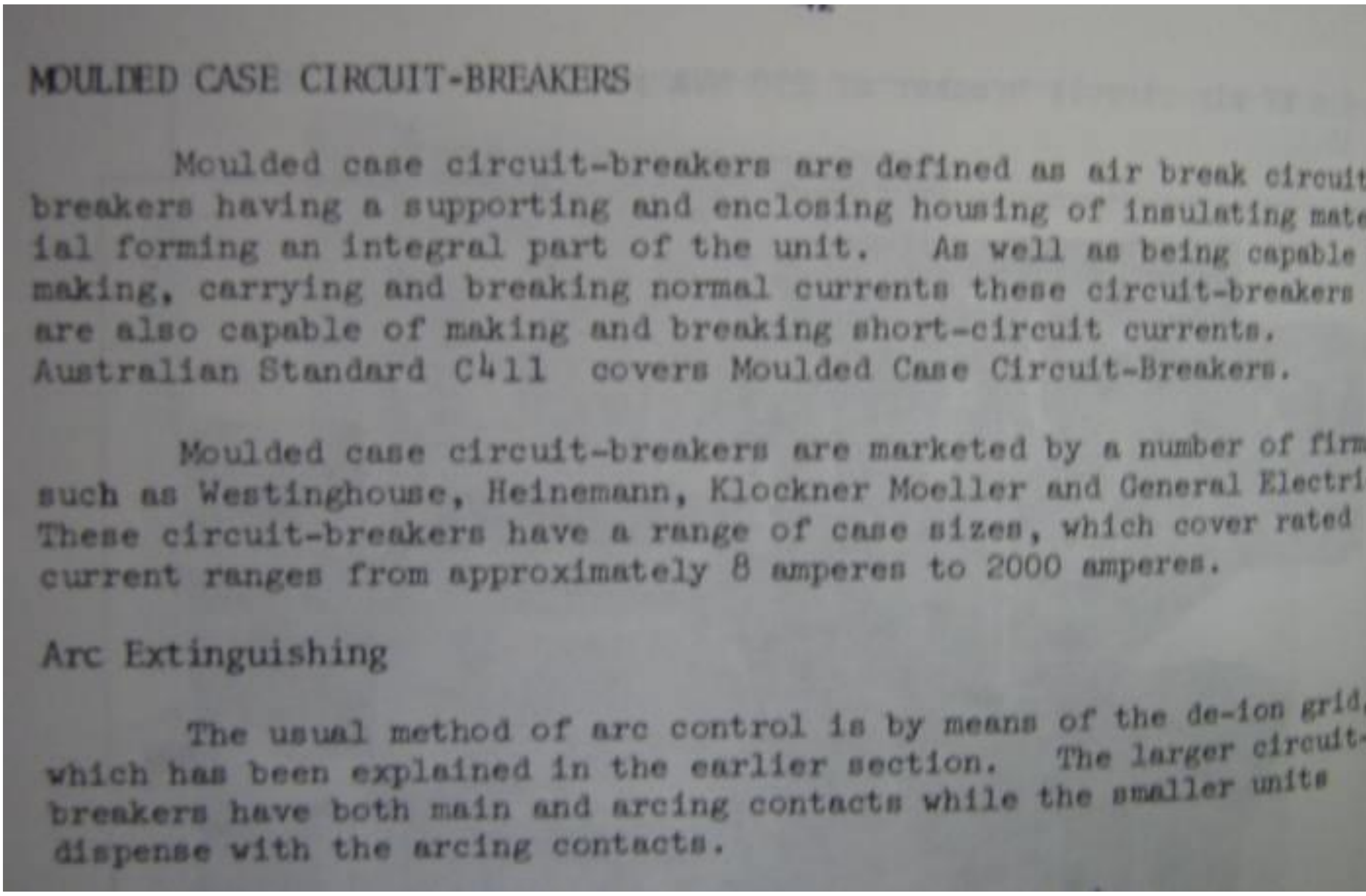


Air Break Circuit Breakers - High Voltage

There is an expanding field of application for air break circuit breakers for voltages up to 11 kV and 250 MVA rating. This field covers the following:

(a) Industrial installations, for the control of electric motors and induction or arc furnaces.

(b) Multi-story buildings where the elimination of oil fire risks is essential.



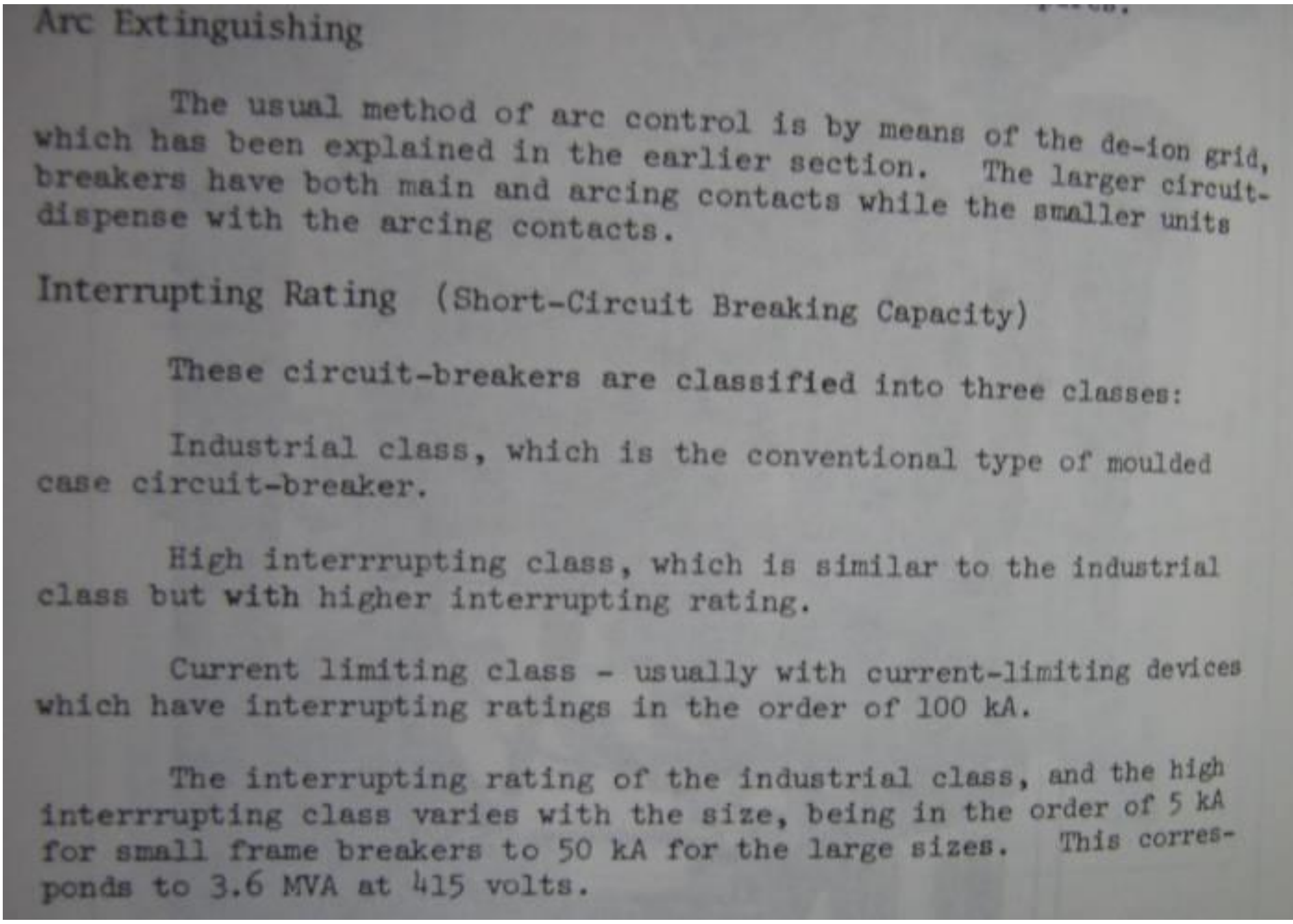
MOULDED CASE CIRCUIT-BREAKERS

Moulded case circuit-breakers are defined as air break circuit breakers having a supporting and enclosing housing of insulating mate ial forming an integral part of the unit. As well as being capable making, carrying and breaking normal currents these circuit-breakers are also capable of making and breaking short-circuit currents. Australian Standard C411 covers Moulded Case Circuit-Breakers.

Moulded case circuit-breakers are marketed by a number of firm such as Westinghouse, Heinemann, Klockner Moeller and General Electri These circuit-breakers have a range of case sizes, which cover rated current ranges from approximately 8 amperes to 2000 amperes.

Arc Extinguishing

The usual method of arc control is by means of the de-ion grid, which has been explained in the earlier section. The larger circuit-breakers have both main and arcing contacts while the smaller units dispense with the arcing contacts.



Arc Extinguishing

The usual method of arc control is by means of the de-ion grid, which has been explained in the earlier section. The larger circuit-breakers have both main and arcing contacts while the smaller units dispense with the arcing contacts.

Interrupting Rating (Short-Circuit Breaking Capacity)

These circuit-breakers are classified into three classes:

Industrial class, which is the conventional type of moulded case circuit-breaker.

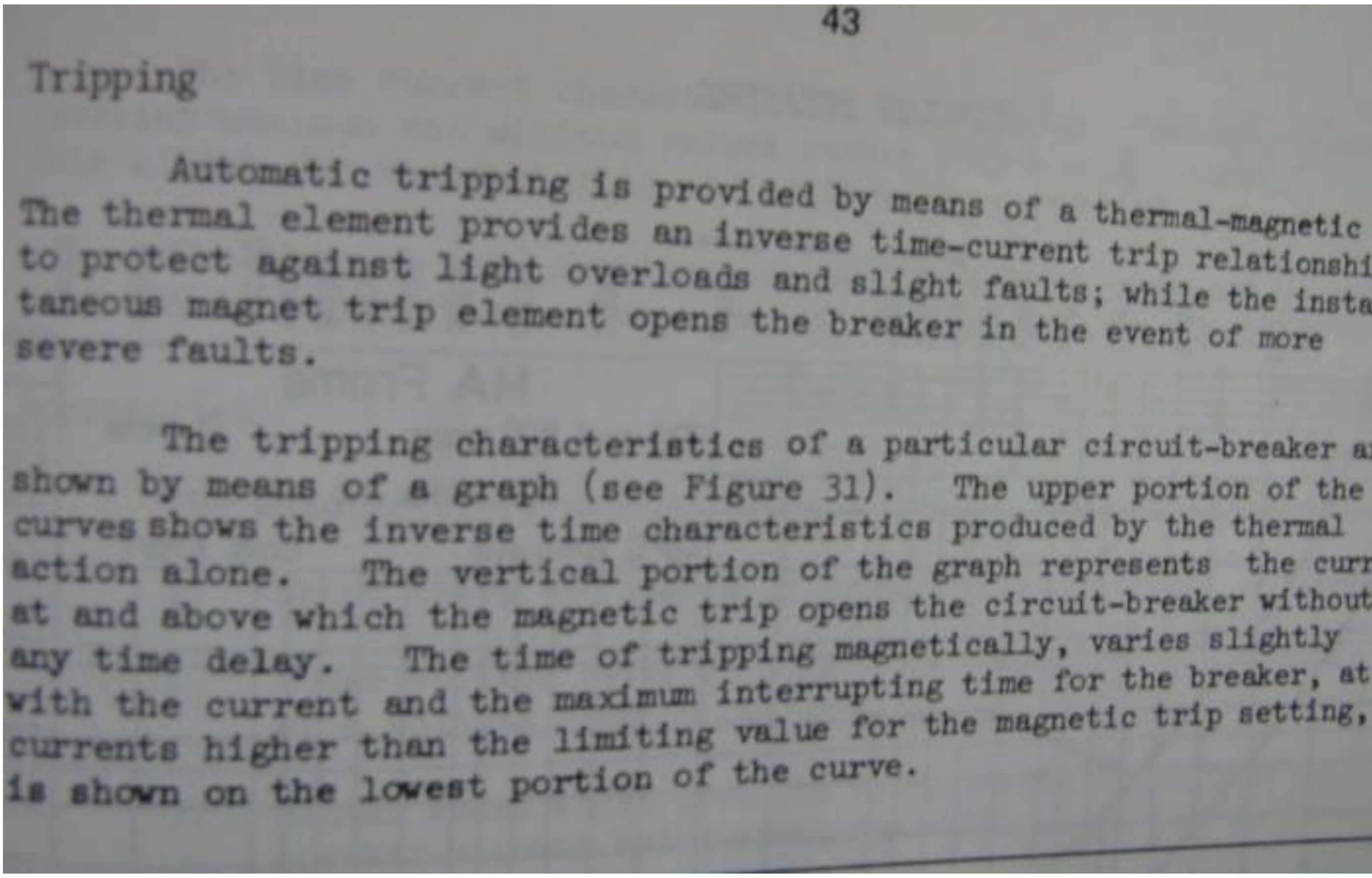
High interrrupting class, which is similar to the industrial class but with higher interrupting rating.

Current limiting class - usually with current-limiting devices which have interrupting ratings in the order of 100 kA.

The interrupting rating of the industrial class, and the high interrrupting class varies with the size, being in the order of 5 kA for small frame breakers to 50 kA for the large sizes. This corresponds to 3.6 MVA at 415 volts.

3 CIRCUIT BREAKERS (PART 7)

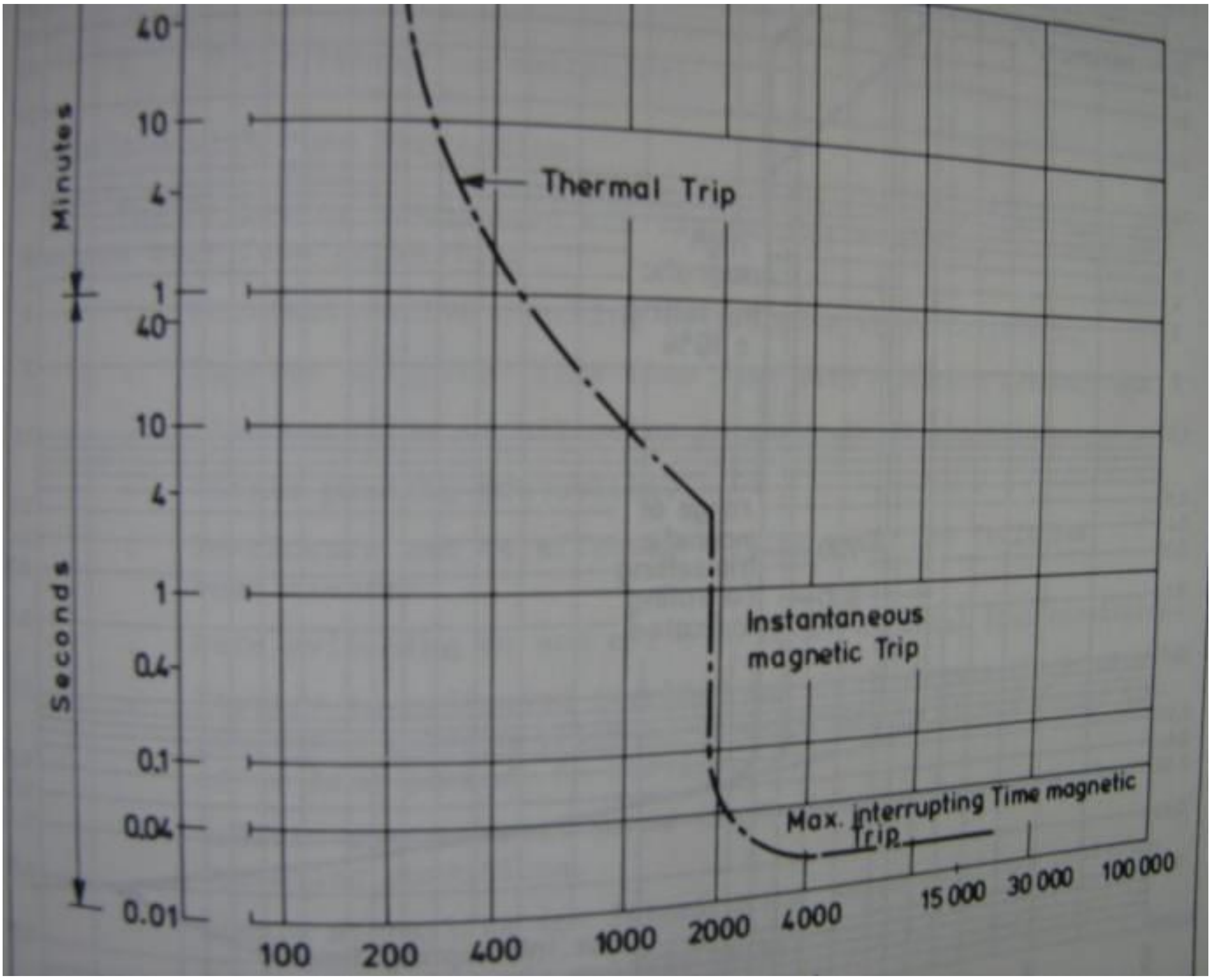
Tripping of circuit breaker



Tripping

Automatic tripping is provided by means of a thermal-magnetic The thermal element provides an inverse time-current trip relationshi to protect against light overloads and slight faults; while the insta taneous magnet trip element opens the breaker in the event of more severe faults.

The tripping characteristics of a particular circuit-breaker a shown by means of a graph (see Figure 31). The upper portion of the curves shows the inverse time characteristics produced by the thermal action alone. The vertical portion of the graph represents the curr at and above which the magnetic trip opens the circuit-breaker without any time delay. The time of tripping magnetically, varies slightly with the current and the maximum interrupting time for the breaker, at currents higher than the limiting value for the magnetic trip setting, is shown on the lowest portion of the curve.


40
10
4
1
Minutes
40
10
4
1
0.4
0.1
0.04
0.01
Seconds
Thermal Trip
Instantaneous magnetic Trip
Max. interrupting Time magnetic Trip
100
200
400
1000
2000
4000
15 000
30 000
100 000

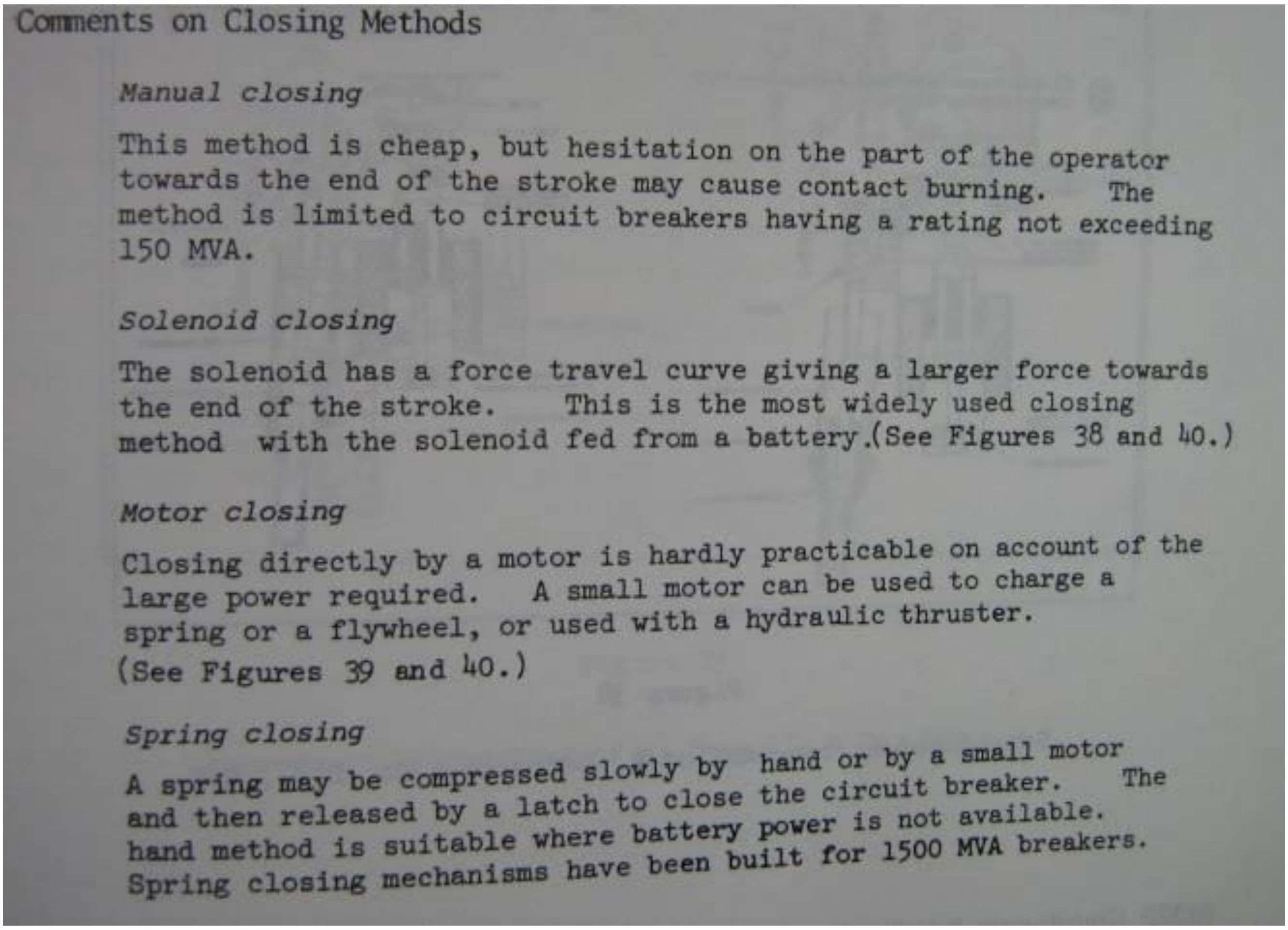
The time current characteristics are usually given as a band covering maximum and minimum values rather than a single curve. This allows for manufacturing and calibrating variations.

The thermal trip settings are usually sealed, while the magnetic trip may be adjustable. These variations are shown in Figure 32.

Accessories

The manufacturers usually provide for the following accessories:

1. Shunt trips for remote tripping and interlocking functions.
2. Under voltage trips to disconnect the switch in the event of a voltage drop or collapse.
3. Manual reset which prevents re-operation of the circuit-breaker without being reset manually.
4. Auxiliary contacts.
5. Locking facilities.
6. Motor operating mechanism.



Comments on Closing Methods

Manual closing

This method is cheap, but hesitation on the part of the operator towards the end of the stroke may cause contact burning. The method is limited to circuit breakers having a rating not exceeding 150 MVA.

Solenoid closing

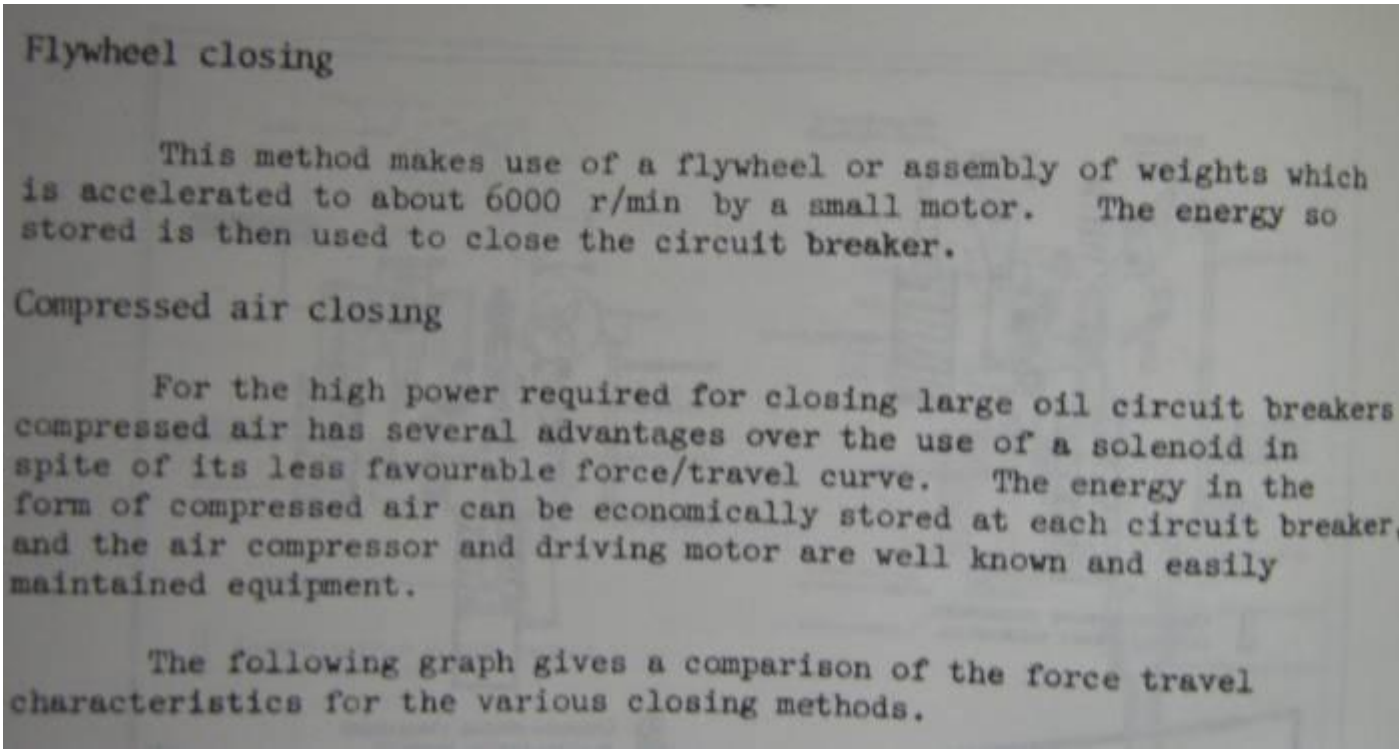
The solenoid has a force travel curve giving a larger force towards the end of the stroke. This is the most widely used closing method with the solenoid fed from a battery.(See Figures 38 and 40.)

Motor closing

Closing directly by a motor is hardly practicable on account of the large power required. A small motor can be used to charge a spring or a flywheel, or used with a hydraulic thruster. (See Figures 39 and 40.)

Spring closing

A spring may be compressed slowly by hand or by a small motor and then released by a latch to close the circuit breaker. The hand method is suitable where battery power is not available. Spring closing mechanisms have been built for 1500 MVA breakers.



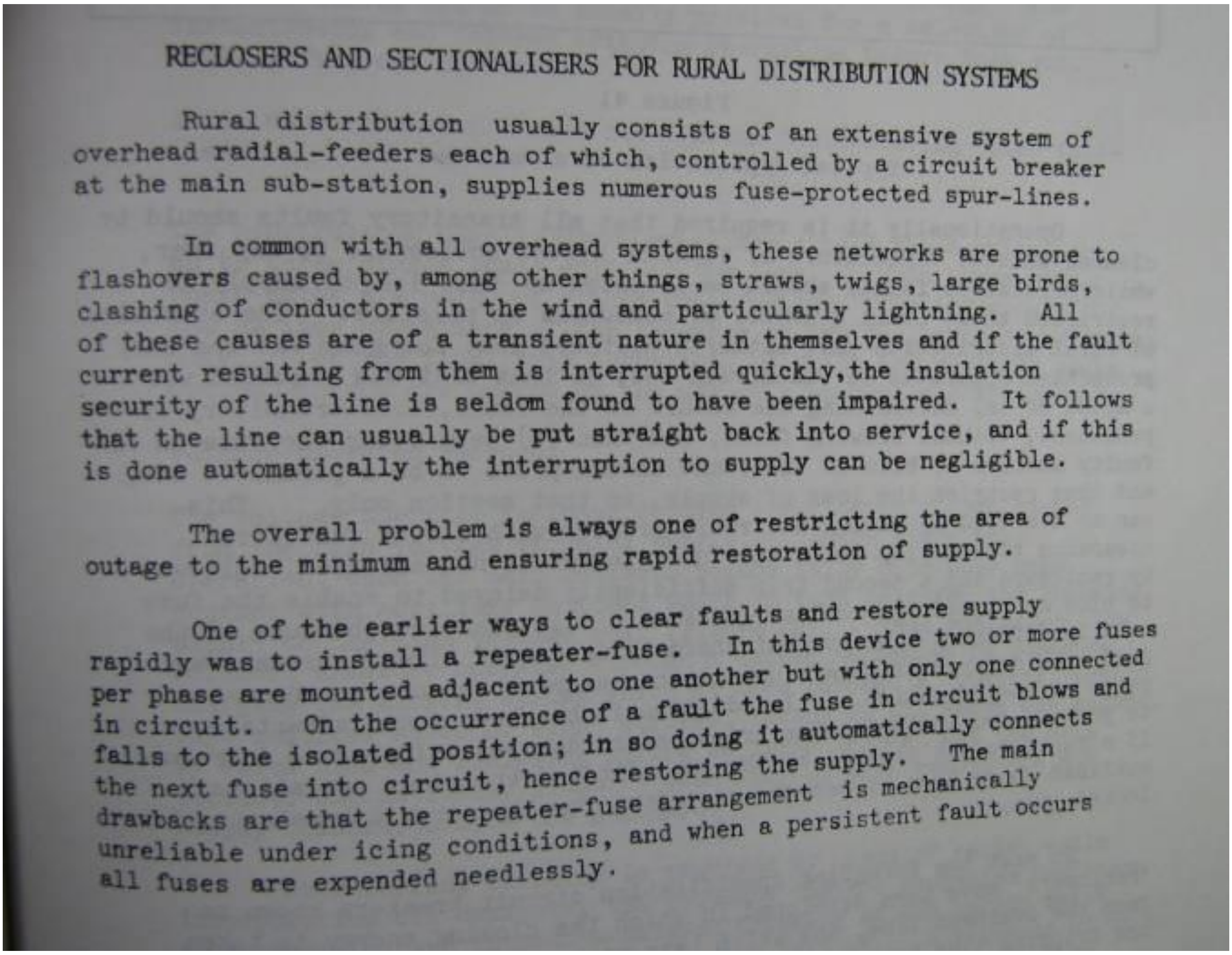
Flywheel closing

This method makes use of a flywheel or assembly of weights which is accelerated to about 6000 r/min by a small motor. The energy so stored is then used to close the circuit breaker.

Compressed air closing

For the high power required for closing large oil circuit breakers compressed air has several advantages over the use of a solenoid in spite of its less favourable force/travel curve. The energy in the form of compressed air can be economically stored at each circuit breaker, and the air compressor and driving motor are well known and easily maintained equipment.

The following graph gives a comparison of the force travel characteristics for the various closing methods.



RECLOSERS AND SECTIONALISERS FOR RURAL DISTRIBUTION SYSTEMS

Rural distribution usually consists of an extensive system of overhead radial-feeders each of which, controlled by a circuit breaker at the main sub-station, supplies numerous fuse-protected spur-lines.

In common with all overhead systems, these networks are prone to flashovers caused by, among other things, straws, twigs, large birds, clashing of conductors in the wind and particularly lightning. All of these causes are of a transient nature in themselves and if the fault current resulting from them is interrupted quickly, the insulation security of the line is seldom found to have been impaired. It follows that the line can usually be put straight back into service, and if this is done automatically the interruption to supply can be negligible.

The overall problem is always one of restricting the area of outage to the minimum and ensuring rapid restoration of supply.

One of the earlier ways to clear faults and restore supply rapidly was to install a repeater-fuse. In this device two or more fuses per phase are mounted adjacent to one another but with only one connected in circuit. On the occurrence of a fault the fuse in circuit blows and falls to the isolated position; in so doing it automatically connects the next fuse into circuit, hence restoring the supply. The main drawbacks are that the repeater-fuse arrangement is mechanically unreliable under icing conditions, and when a persistent fault occurs all fuses are expended needlessly.

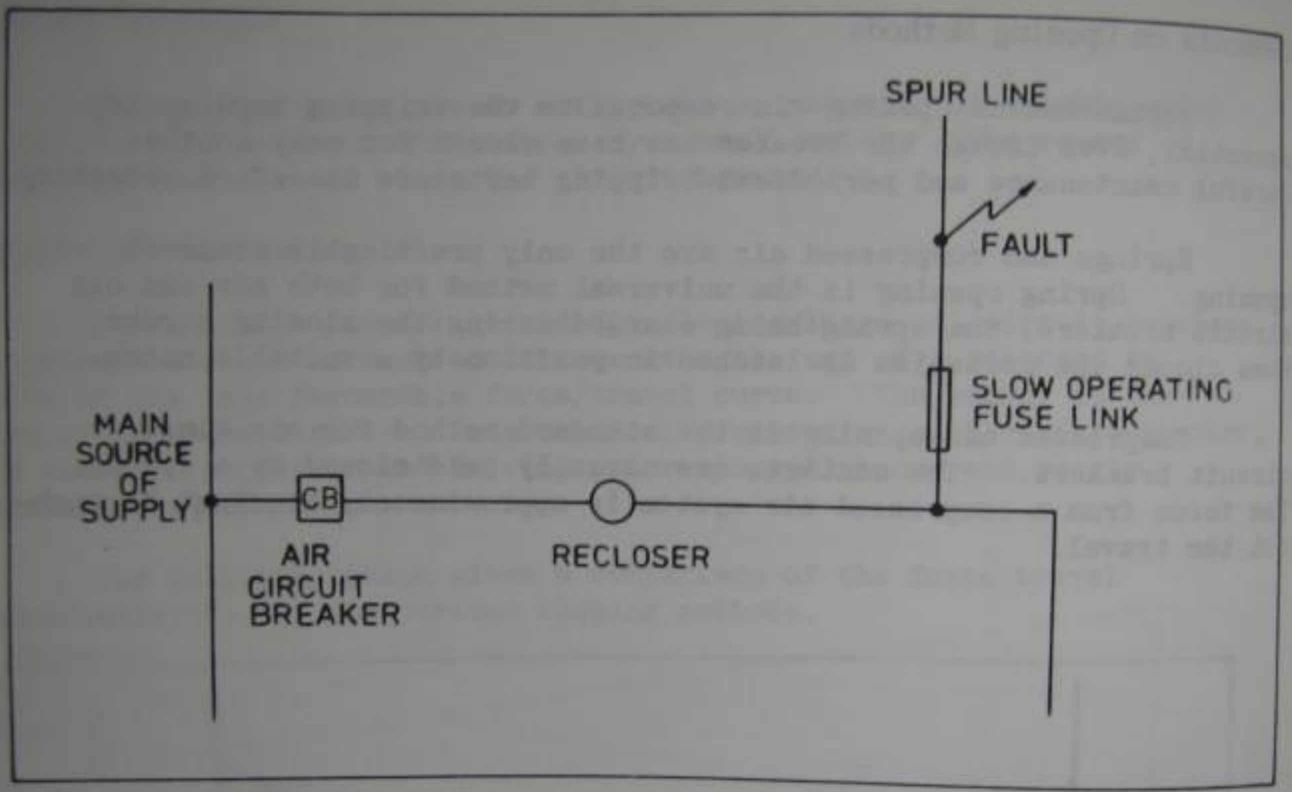
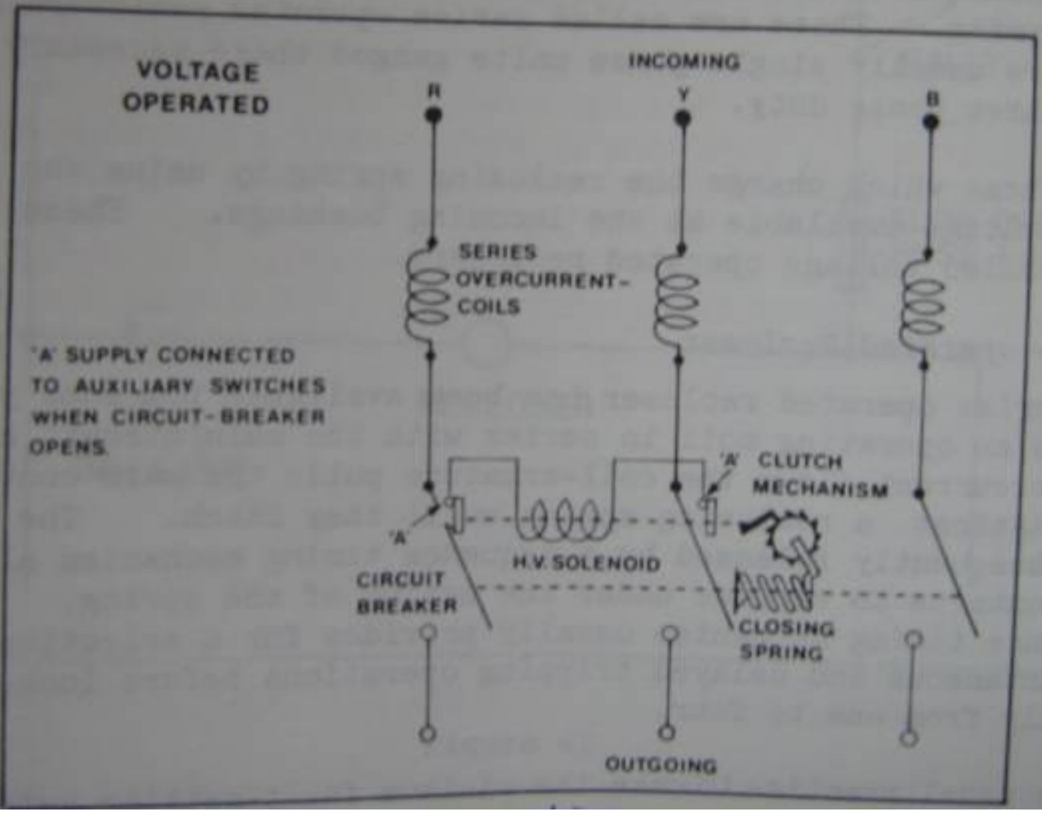
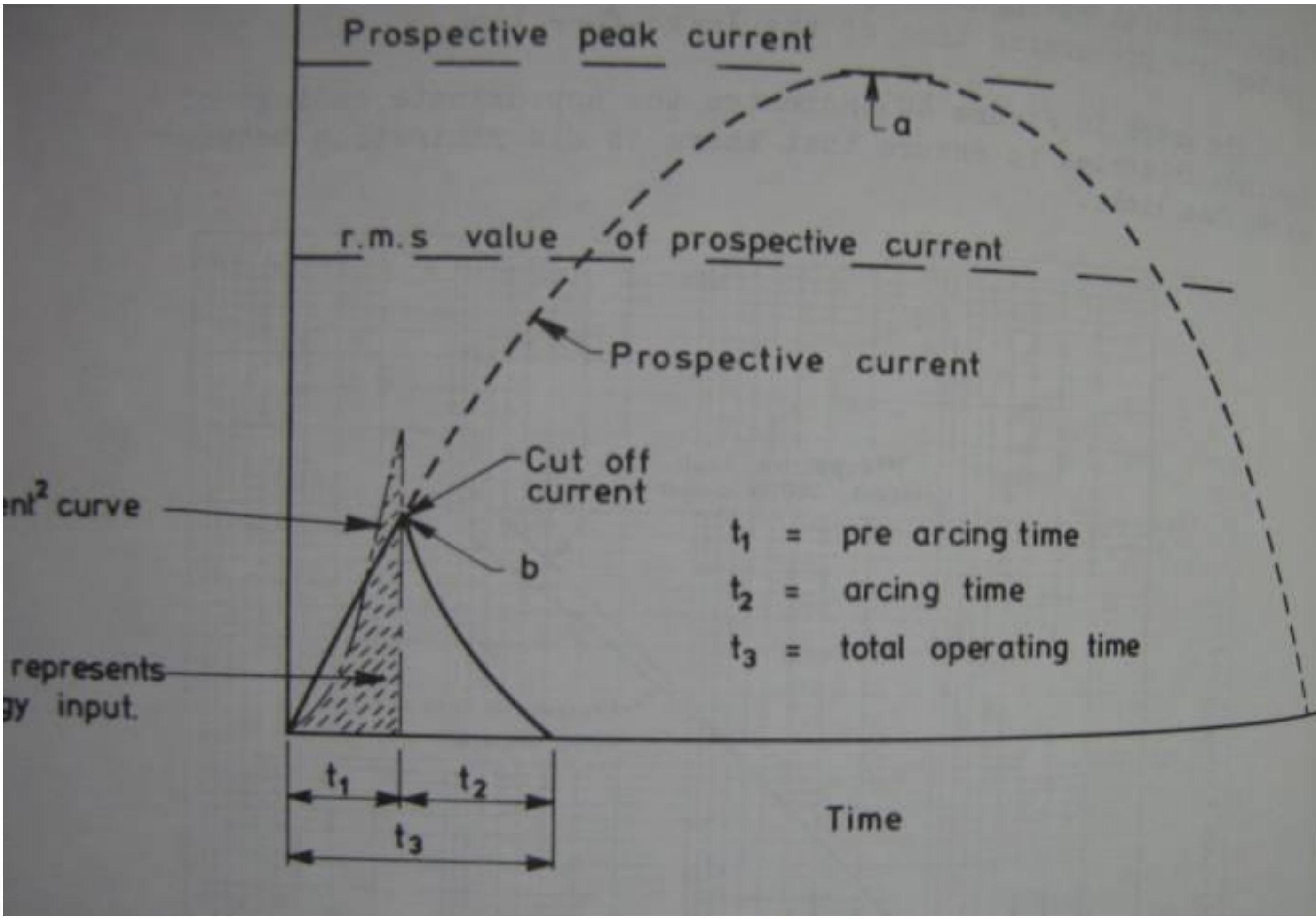


Figure 41

Typical Application of a Recloser

Figure 43 shows a typical operation sequence comprising two instantaneous trips, followed by two delayed trips, and terminated by lock-out. If the prearranged sequence is not completed because the fault is cleared, the sequence control mechanism will reset ready for the next fault.





Basic d.c. Tripping Circuit

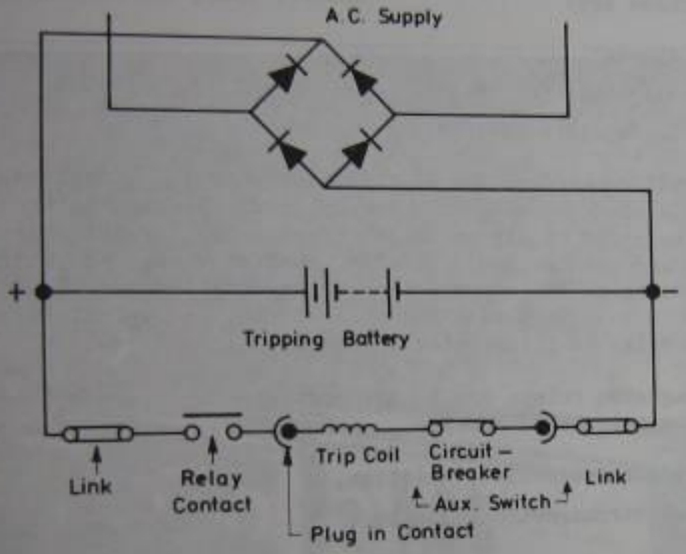


Figure 6

The usual design features are as follows:

1. The trip coil should be so designed that the relay contact is not subjected to a making current greater than five amperes.

tripping the

(4) More Detailed Faults

In the same way it is found that the reactance of the other generator is 1·31 Ω. It is assumed that the rated voltage in this case also is 6·6 kV., although the generated voltage is 6·5 kV.

Similarly the transformer reactances referred to the low voltage sides are 0·292 and 0·525 Ω. The line reactance transferred to the low voltage side is 20 ÷ (33/6·6)² = 0·8 Ω. The system is then as shown in Fig. 168. We then apply Thévénin's theorem to the system to the left of A. The voltage when the line is disconnected is

$$3\,820 - \frac{(3\,820 - 3\,750)\,(0{\cdot}727 + 0{\cdot}292)}{0{\cdot}727 + 0{\cdot}292 + 1{\cdot}31 + 0{\cdot}525}$$
$$= 3\,795 \text{ V.}$$

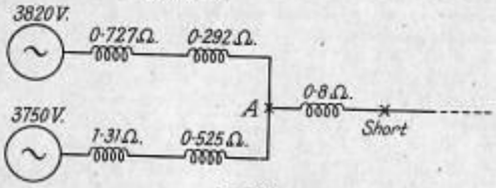


Fig. 168

The impedance is

$$\frac{(0{\cdot}727 + 0{\cdot}292)\,(1{\cdot}31 + 0{\cdot}525)}{0{\cdot}727 + 0{\cdot}292 + 1{\cdot}31 + 0{\cdot}525} = 0{\cdot}654\ \Omega$$

The short-circuit current is thus

$$\frac{3\,795}{0{\cdot}654 + 0{\cdot}8} = \underline{2\,600} \text{ A.}$$

The *actual* short-circuit current is

$$2\,600 \times (6{\cdot}6/33) = 520 \text{ A.}$$

520 A. is the r.m.s. of the steady short-circuit current, whilst the peak value is 520 × $\sqrt{2}$ = 735 A. There may be an increased peak value due to a "doubling effect," which, in circuits of normal value of reactance to resistance, is 1·8 times the steady peak. Thus a maximum peak value of 1·8 × 735 = 1 320 A. may occur.

Short-circuit Current of Alternators. When an alternator is shorted, across all three phases, say, the current rises rapidly to a high value, about 18 times full-load current in turbo-alternators which have cylindrical rotors, and about 12 times in generators with salient poles. The value of the peak current is limited only by the *transient or leakage reactance* of the armature. Moreover if the short circuit occurs at an instant at which the voltage is zero there is a doubling effect, and the current wave is offset from the zero. Fig. 169 shows the kind of current wave obtained. If the short circuit persists, the wave becomes symmetrical; then armature reaction reduces the excitation and the current falls to a steady value, which is 4 to 6 times the full-load value. Another way of considering the effect of armature reaction is to consider it as increasing the transient impedance to the synchronous impedance.

Armature reaction

The doubling effect may be demonstrated as follows. Let the generator be considered as an e.m.f. $E \sin(\omega t + \theta)$ in series with an impedance (R, L) which is the *transient* or *true impedance*. If a short occurs at $t = 0$, the equation for the short-circuit current is

$$L(di/dt) + Ri = E \sin(\omega t + \theta).$$

The complementary function is given by

$$L(di/dt) + Ri = 0,$$

i.e.

$$i = A\varepsilon^{-(R/L)t} \quad . \quad . \quad . \quad . \quad (101)$$

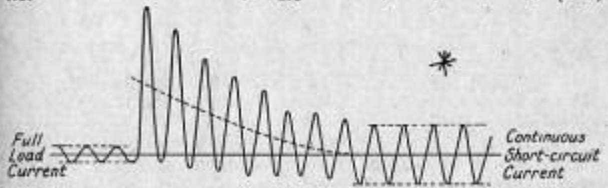


Fig. 169. Doubling Effect in Short-circuit Current

The particular integral is

$$i = \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right) \quad . \quad . \quad (102)$$

which is the steady current under these conditions. The actual current is the sum of the currents given in equations (101) and (102). At $t = 0$ the current is zero. This gives

$$0 = A + \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\theta - \tan^{-1}\frac{\omega L}{R}\right).$$

The current is thus

$$i = -\frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\theta - \tan^{-1}\frac{\omega L}{R}\right)\varepsilon^{-(R/L)t}$$
$$+ \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right) \quad . \quad (103)$$

We may consider ωL as much greater than R. Then the first term, which is considered as a d.c. component which decays exponentially, has magnitude

$$-\frac{E}{\omega L} \sin\left(\theta - \frac{\pi}{2}\right)\varepsilon^{-(R/L)t}$$
$$= \frac{E}{\omega L} \cos\theta \,.\, \varepsilon^{-(R/L)t}.$$

If $\theta = 0$, i.e. the voltage is zero and the current is a maximum at $t = 0$, the d.c. component has the initial value of $E/\omega L$. As the alternating part of the current has a magnitude of nearly $E/\omega L$, the d.c. component doubles the current at the instant when the former has its peak value, and reduces it to zero when the former reaches its negative maximum. The current is thus on one side of the zero to begin with. If, however, $\theta = \pi/2$, i.e. the voltage is a maximum and the current is zero at the instant of short circuit, the d.c. term is zero. The short-circuit current has then the form shown in Fig. 170.

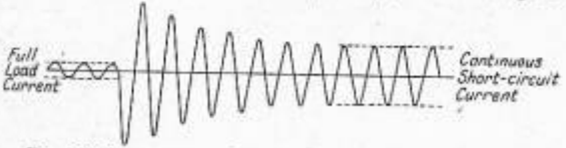


FIG. 170. SHORT-CIRCUIT CURRENT WITHOUT DOUBLING EFFECT

The change from the large current at the instant of short circuit to the comparatively small current after armature reaction has asserted itself is of importance in the design of switchgear operation. The behaviour of an alternator is most easily expressed in terms of *decrement factors*, which are found by extensive tests in the following way. The generator excitation is adjusted to the value for full load at 0·8 power factor lagging, and external reactance is put in series with the alternator to bring the value up to some definite amount, 5, 10, 20 . . . per cent. This value includes the transient reactance. A short circuit is applied and an oscillogram of the current taken. In order that the test results should be as severe as possible, it is arranged that the short circuit should take place at an instant when the full doubling effect is incurred, viz. at an instant of zero voltage. The oscillogram is analysed so that the r.m.s. current is found as a function of time. To do this the current wave of Fig. 169 is resolved into the d.c. and a.c. components shown in Fig. 171. The r.m.s. of the a.c. component is shown by the dotted line. and has a value $I_{A.C.}$ at time t; the d.c. component, which decays exponentially, has a value $I_{D.C.}$ at the same instant, and the total current has an r.m.s. value of $\sqrt{[I_{D.C.}{}^2 + I_{A.C.}{}^2]}$. Curves are then drawn giving the r.m.s. of the current (as a multiple of full-load current) against time for different values of the total percentage reactance. Fig. 172 shows a set of such curves for a short circuit across all three phases.

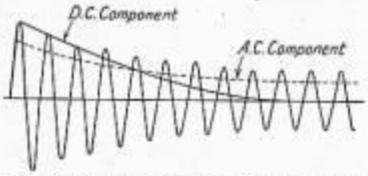


FIG. 171. D.C. AND A.C. COMPONENTS OF SHORT-CIRCUIT CURRENT

When looking up the decrement factor, the transient reactance of the alternator is added to the external reactance to give the appropriate percentage reactance.

EXAMPLE. A 20 000 kVA. generator, whose decrement curves are shown in Fig. 172, has 15% reactance and feeds a line through a step-up transformer of 6% reactance. Find the breaking capacity of the circuit-breakers, which operate in 0·25 sec. and are on the high voltage side of the transformer.

The total reactance is 21%, and from Fig. 172 it is seen that the decrement factor at 0·25 sec. is 3·4. The current to be interrupted is thus 3·4 times the full-load current. If we assume that the recovery voltage in the breaker is equal to the normal voltage (the matter will be investigated in detail in Chapter IX), the kVA. to be broken is

$$3{\cdot}4 \times 20\,000 = \underline{68\,000} \text{ kVA.}$$

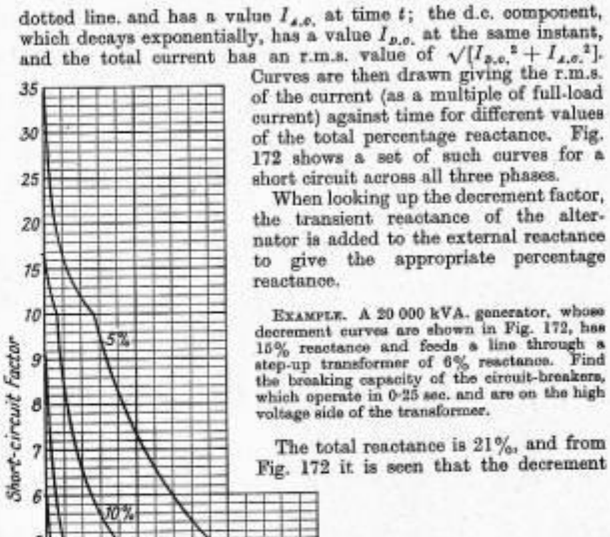


FIG. 172. DECREMENT CURVES FOR ALTERNATOR

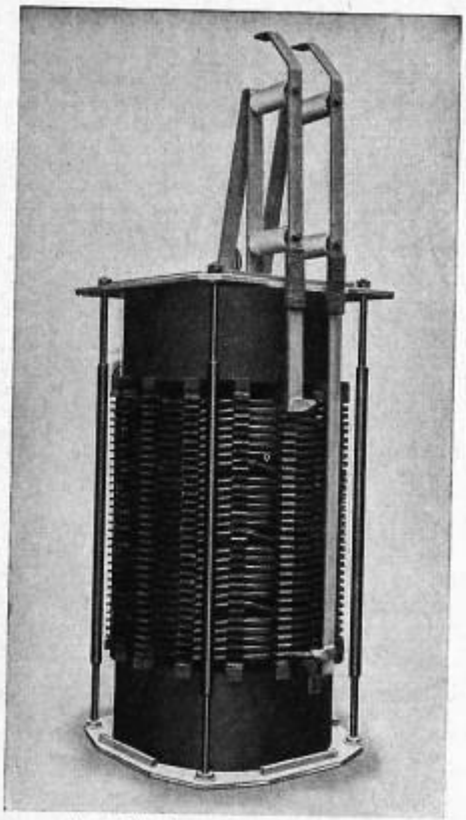


Fig. 173. Current Limiting Reactor
(English Electric Co.)

Current-limiting Reactors: Sectionalization of Networks. It is clear that the short-circuit currents are decreased by an increase of the percentage reactance in the system. In large interconnected systems the total rating of the generators is very high, and unless precautions are taken, the current fed into a fault will be enormous. The short-circuit current at a fault can be considerably reduced by the judicious placing of protective reactors in the system. It is possible to arrange the reactors so that they do not cause a large voltage drop during normal operation, but prevent a large short-circuit current being fed by most of the generators into the fault. The methods of placing reactors in a system will be considered later.

Reactors are moreover of considerable importance in limiting the currents so that the various circuit-breakers are not called upon to break currents above their rated value. If extensions are made in a system, it is essential that the additional kVA. be virtually segregated from the existing circuit-breakers when a short-circuit occurs. This is done by means of current-limiting reactors.

Fig. 174. Generator Reactors

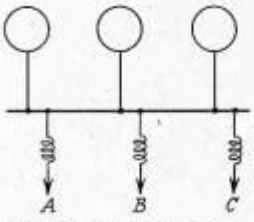


Fig. 175. Feeder Reactors

Fig. 173 shows a reactor. The turns, which are of copper bar or strip, experience large attractive forces under the influence of the short-circuit currents, and they are placed in concrete separators to prevent their being buckled.

Methods of Locating Reactors. Reactors may be inserted in series with each generator, as shown in Fig. 174. The main disadvantage of this method is that if a short occurs on one feeder, the voltage at the common bus-bar drops to a low value and the synchronous machines attached to the other feeders may fall out of step. The whole system is interrupted, and the synchronous machines must be re-synchronized when the faulty feeder is cut out. Moreover in modern alternators the transient reactance is sufficiently large to protect the machine itself against short-circuit currents, and separate reactors are used only with old alternators.

The main disadvantage of the last method is avoided by putting reactances in series with each feeder, as shown in Fig. 175. When a short-circuit occurs on feeder A, the main voltage drop is in its reactor and the bus-bar voltage does not drop unduly. The remaining load and plant are therefore able to continue running. It is true that when a short circuit occurs across the bus-bars, the reactors do not protect the generators. This is, however, of no importance, as bus-bar short circuits seldom occur and the generators are protected by their internal reactances.

A disadvantage from which both the previous methods suffer is that the reactors take the full-load currents under normal operation, so that there is a constant loss and a voltage drop. The voltage drop is eliminated in a new type of reactor in which part of the windings are shunted by a carbon tetrachloride fuse. Under normal conditions the windings are such that they neutralize each other's magnetic field and the reactor has a very small reactance; but when a short circuit occurs and the fuse blows, a large reactance is inserted into the circuit. The constant loss, however, is not eliminated.

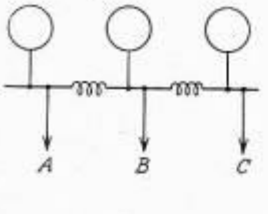


FIG. 176. BUS-BAR REACTORS, RING SYSTEM

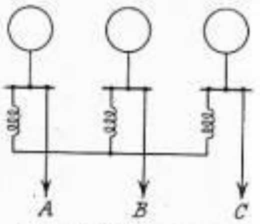


FIG. 177. BUS-BAR REACTORS, TIE-BAR SYSTEM

The constant loss in reactors can be avoided by inserting the reactors in the bus-bars in the ways shown in Figs. 176 and 177. The former is the *ring* system, and the latter is the *tie-bar* system. In the ring system each feeder is normally fed by one generator, only a small amount of power flowing across the reactances. The reactors can therefore be made with a fairly high ohmic resistance and there is not much voltage drop across it. When a short circuit occurs in one feeder, the current is fed mainly by one generator, the other generators having to feed through the reactances. The tie-bar system acts in the same way, but has the following advantage. If the number of sections in the tie-bar system is increased, the current that flows into the fault will not exceed a certain value which is fixed by the size of the individual reactors. If the switchgear is designed to operate successfully on this limiting value of current, the system can be extended to any number of sections without modification of the switchgear.

EXAMPLE. Find the ratio of the percentage reactance of the reactors to that of the generators in a tie-bar system, if the short-circuit current is not to exceed three times the current of a single section.

Let the percentage reactance of a generator be G and of a reactor X, and suppose there are n sections. When there is a short circuit on a feeder, the remaining reactors and generators are in parallel, so that their percentage reactance is $(G + X)/(n - 1)$. This reactance is in series with the reactor of the faulty feeder, giving a reactance

$$X + (G + X)/(n - 1) = (G + nX)/(n - 1).$$

This reactance is in parallel with the reactance of the generator which is connected to the faulty feeder, so that the total reactance is

$$\frac{G \times \dfrac{G + nX}{(n - 1)}}{G + \dfrac{G + nX}{(n - 1)}} = G\frac{G + nX}{nG + nX}.$$

The short-circuit current is thus

$$I \times \frac{100}{G} \times \frac{nG + nX}{G + nX}$$

where I is the normal full-load current.

When $n = 1$, the current is

$$I \times (100/G).$$

The last factor gives the effect of the remaining sections, and increases from unity when $n = 1$ to $(G + X)/X$ when n is infinitely large. Thus if the current is not to exceed three times the short-circuit current due to a single section

$$(G + X)/X = 3$$

i.e. $$X = \tfrac{1}{2}G.$$

If it is certain that the number of sections will not exceed a known number n we have

$$(nG + nX)/(G + nX) = 3$$

i.e. $$X = [(n - 3)/2n]G.$$

Thus if n will not exceed 6, X need not be greater than $\tfrac{1}{4}G$.

Choice of Interconnection to Limit Currents. The cost of reactors is large and their installation is avoided if possible. It is sometimes practicable to make use of the reactance of feeders and transformers so that reactors are unnecessary.

CHAPTER X

VOLTAGE TRANSIENTS AND LINE SURGES

Introduction. There are various ways in which a transmission line may experience voltages greater than the working value, and it is necessary to provide protective apparatus to prevent or minimize the destruction of the plant. Internal causes producing a voltage rise are (1) resonance, (2) switching operations, (3) insulation failure, and (4) arcing earths: a very important external cause is lightning.

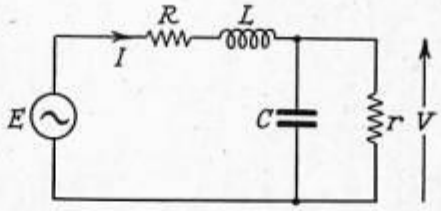


FIG. 237. RESONANCE

Resonance. The effect of resonance is most easily understood by considering the voltage at the end of a lightly loaded cable of short length. The alternator and transformers may be represented by their leakage inductance L, and the cable by a capacitance C. The system is then as shown in Fig. 237, where R represents the resistance of the alternator winding, transformers and cable, and r the resistive load. The total impedance of the circuit is

$$Z = R + j\omega L + \frac{(1/j\omega C)r}{1/j\omega C + r} = R + j\omega L + \frac{r}{1 + j\omega Cr},$$

the current is

$$I = E/Z,$$

and the voltage on the cable is

$$V = I \times r/(1 + j\omega Cr),$$

since the latter expression represents the impedance of the parallel combination of C and r. Substituting for I in terms of E we get

$$\begin{aligned} V/E &= \left(\frac{r}{1 + j\omega Cr}\right) \div \left(R + j\omega L + \frac{r}{1 + j\omega Cr}\right) \\ &= \frac{1}{1 + (R + j\omega L)(1/r + j\omega C)} \\ &= \frac{1}{(1 - \omega^2 LC + R/r) + j\omega(L/r + CR)} \end{aligned}$$

The magnitude of (V/E) is

$$|V/E| = [(1 - \omega^2 LC + R/r)^2 + \omega^2(L/r + CR)^2]^{-\frac{1}{2}} \quad . \quad (112)$$

Let us consider the case of an unloaded line first. In this case $r = \infty$, so that

$$|V/E| = [(1 - \omega^2 LC)^2 + \omega^2 C^2 R^2]^{-\frac{1}{2}} \quad . \quad . \quad (112a)$$

If we consider that C can vary, by the insertion of different lengths of cable, $|V/E|$ varies in the manner shown in Fig. 238. The maximum value occurs when

$$C = \frac{1}{\omega^2 L + R^2/L} = \frac{1}{\omega^2 L(1 + R^2/\omega^2 L^2)} \simeq \frac{1}{\omega^2 L},$$

when $$|V/E| = \frac{1}{\omega CR\sqrt{(1 + R^2/\omega^2 L^2)}} \simeq \frac{1}{\omega CR} \simeq \frac{\omega L}{R}.$$

A reasonable value of L in a 33 kV. system is 0·05 henry, and the resonating capacitance is then

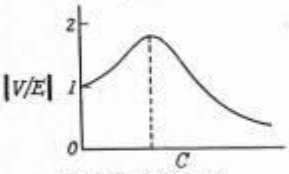


FIG. 238. RESONANCE

$$C \simeq \frac{1}{(2\pi \,.\, 50)^2 \times 0{\cdot}05} = 202\ \mu\text{F.},$$

which is the capacitance of some hundreds of miles of cable. Resonance in short lines will thus never occur at the fundamental frequency. If we consider the fifth harmonic, which is often present to the extent of 2 or 3 per cent, we see that resonance can occur. The capacitance required is

$$C = \frac{1}{(2\pi \,.\, 250)^2 \times 0{\cdot}05} = 8{\cdot}1\ \mu\text{F.},$$

which is provided by a cable of length about 28 miles. If we assume a 10 per cent harmonic, the value of V_5 is

$$|V_5| = |E_5| \times 2\pi \,.\, 250L/R = 0{\cdot}10\,|E_1| \times 2\pi \,.\, 250L/R,$$

where E_1 is the fundamental, and E_5 the fifth harmonic. If we take $R = 5$, we find that

$$|V_5| = 1{\cdot}57\,|E_1|,$$

so that the fundamental voltage of $E_1 = 33$ kV. has a fifth harmonic of magnitude 52 kV. (r.m.s.). The peak value between phases may then be $\sqrt{2} \times 85$ kV. in place of the normal value of $\sqrt{2} \times 33$ kV.

The effect of a load is seen by comparing equations (112a) and (112). It is seen that the term (R/r) is an additive constant in the first term on the right-hand side of the equations and alters the condition for the neutralization of reactance, whilst the term (L/r) causes a considerable damping of the resonance. Let us take $r = 200$ ohms, which corresponds to a load of 5 000 kW. Then with the values of L, C, and E_5 taken above, we find that

$$1 - \omega^2 LC + R/r \simeq 5/200 = 0{\cdot}025$$

and $$\omega(L/r + CR) = \omega CR(1 + L/CRr) = 7{\cdot}2\omega CR = 0{\cdot}46.$$

The first term is thus negligible compared with the second, so that we may take

$$|V_5/E_5| \simeq \frac{1}{\omega(L/r + CR)} = \frac{1}{7{\cdot}2\omega CR} \simeq \frac{\omega L}{7{\cdot}2R},$$

so that V_5 is reduced by the factor 7·2 and has a magnitude of $52 \div 7{\cdot}2 = 7{\cdot}2$ kV. The resonance voltage has been therefore effectively damped by the load.

Switching. A switching operation produces a sudden change in the circuit conditions, and is accompanied by a *transient state* which leads from the earlier to the later steady (a.c.) states. The behaviour of the system can be explained with exactness only by means of *travelling waves*, which will be explained later; but in short systems the behaviour is sufficiently well explained if we consider the circuit to be composed of lumped resistances, inductances, and capacitances. The method used is that given on pages 214–16, where we showed that a current of twice the normal peak value can be obtained when an alternator is short-circuited.

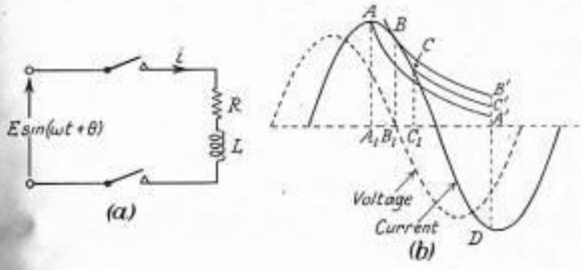


FIG. 239. SWITCHING-IN AN INDUCTIVE RESISTANCE

Transients in Circuits with Lumped Constants. There are two interesting cases which we will solve, the switching-in of an inductive load and the switching-in of an open-circuited line.

Fig. 239 (a) represents the switching-in of a load of inductance L and resistance R. The equation for the circuit is

$$L(di/dt) + Ri = E \sin(\omega t + \theta),$$

of which the solution is (see page 215)

$$i = Ae^{-(R/L)t} + \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right).$$

The constant A is determined by the fact that $i = 0$ at the time $t = 0$, so that we find that

$$i = -\frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\theta - \tan^{-1}\frac{\omega L}{R}\right)\varepsilon^{-(R/L)t}$$
$$+ \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right) \quad . \quad (103)$$

The first term represents the *transient current* which decays exponentially. It has an initial value equal and opposite to that of the a.c. component at the time of switching (so that the initial current is zero).

If the circuit is very inductive $\omega L \gg R$, and we may put

$$\sqrt{[R^2 + (\omega L)^2]} \simeq \omega L$$

and

$$\tan^{-1}(\omega L/R) = \pi/2.$$

The current then becomes

$$i = (E/\omega L)\,[\sin(\omega t + \theta - \pi/2) - \varepsilon^{-(R/L)t}\sin(\theta - \pi/2)]$$
$$= (E/\omega L)\,[\varepsilon^{-(R/L)t}\cos\theta - \cos(\omega t + \theta)].$$

During the early period after switching $\varepsilon^{-(R/L)t}$ does not decay rapidly from the value of unity, and the current is therefore approximately

$$i = (E/\omega L)\,[\cos\theta - \cos(\omega t + \theta)], \qquad (113)$$

and varies between the values of $(E/\omega L)\,[\cos\theta - 1]$ and $(E/\omega L)\,[\cos\theta + 1]$. The peak value is thus

$$(E/\omega L)\,(1 + |\cos\theta|),$$

i.e. $(1 + |\cos\theta|)$ times the normal peak value. The maximum peak is thus obtained when $\theta = 0$ and is twice the normal peak. This condition occurs when the circuit is closed at zero voltage and the current is

$$i = (E/\omega L)\,[1 - \cos\omega t], \quad . \quad . \quad . \quad (114)$$

which varies between zero (at $t = 0$) and $(2E/\omega L)$ (at $t = \pi/\omega$).

It can be shown that, whatever the power factor of the circuit may be, the maximum "doubling" effect is obtained when the circuit is closed at zero voltage. Fig. 239 (*b*) shows the normal sinusoidal current. If the circuit is switched in at A the transient has initial amplitude AA_1, if at B the amplitude BB_1, and if at C the amplitude CC_1. The transients corresponding to these switching points are represented by the curves AA', BB', CC' and must be subtracted from the sine wave. The total current at any instant is thus the vertical distance between the sine wave and the appropriate transient curve. It is clear that if the circuit is switched in at position B the current is greater than if switched at any other position, since the transient curves have the same time factor $\varepsilon^{-Rt/L}$ and have the same decay rate. The topmost curve is clearly seen to be that whose slope at the point of contact with the sine wave is equal to the slope of the sine wave. Let us consider this as the time $t = 0$. Equating slopes we get

$$\left[-\frac{R}{L}\sin\left(\theta - \tan^{-1}\frac{\omega L}{R}\right)\varepsilon^{-(R/L)t}\right]_{t=0}$$
$$= \left[\omega\cos\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right)\right]_{t=0}$$

i.e.

$$-(\omega L/R) = \tan\,[\theta - \tan^{-1}(\omega L/R)],$$

which gives $\theta = 0$ or π. If $\theta = 0$ or π the voltage is zero at $t = 0$, i.e. the maximum doubling occurs if the circuit is closed at the instant of zero voltage.

Suppose the load has a power factor of 0·8 lagging,

$$\omega L/R = 0{\cdot}6/0{\cdot}8 = 0{\cdot}75.$$

If the circuit is closed at zero voltage the current is

$$i = \frac{E}{\sqrt{[R^2 + (\omega L)^2]}}\left[\sin\left(\omega t - \tan^{-1}\frac{\omega L}{R}\right)\right.$$
$$\left. + \sin\left(\tan^{-1}\frac{\omega L}{R}\right)\varepsilon^{-(R/L)t}\right]$$
$$= \frac{E}{\sqrt{[R^2 + (\omega L)^2]}}\,[\sin(\omega t - 36^\circ\,52') + 0{\cdot}6\varepsilon^{-1{\cdot}33\omega t}].$$

For this case the voltage and currents in Fig. 239 (*b*) must be reversed. The maximum current occurs when $di/dt = 0$, i.e. when

$$\cos(\omega t - 36^\circ\,52') = 0{\cdot}6 \times 1{\cdot}33\varepsilon^{-1{\cdot}33\omega t} = 0{\cdot}8\varepsilon^{-1{\cdot}33\omega t}.$$

Let $\omega t - 36^\circ\,52' = \phi$, so that

$$\omega t = \phi + 36^\circ\,52' = \phi + 0{\cdot}64 \text{ radians}.$$

The equation becomes

$$\varepsilon^{1{\cdot}33\phi}\cos\phi = 0{\cdot}8\varepsilon^{-0{\cdot}853} = 0{\cdot}34.$$

ϕ	1	1·5	1·54
$\varepsilon^{1{\cdot}33\phi}$ . .	3·78	7·39	7·76
$\cos\phi$ . .	0·540	0·0707	0·0308
$\varepsilon^{1{\cdot}33\phi}\cos\phi$.	2·04	0·52	0·24

We may take $\phi = 1{\cdot}53$ radians $= 87° \, 40'$, so that

$$i_{max} = \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} [\sin 87° \, 40' + 0{\cdot}6\varepsilon^{-1{\cdot}33\omega t}]$$
$$= \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} [1 + 0{\cdot}34\varepsilon^{-1{\cdot}33 \times 1{\cdot}533}]$$
$$= \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} [1{\cdot}044],$$

and the peak does not exceed the normal value by more than 4·5 per cent.

Fig. 240 represents the switching-in of an open-circuited line; we assume for simplicity that the e.m.f. is constant and equal to E, but the same method is applicable for an a.c. case. The equation for the current is

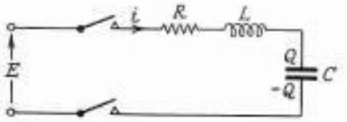


FIG. 240. SWITCHING-IN AN OPEN-CIRCUITED LINE

$$L(di/dt) + Ri + Q/C = E$$

where $i = dQ/dt$.

The voltage at the end of the line is $V = Q/C$. Substituting for i in terms of Q we get

$$L(d^2Q/dt^2) + R(dQ/dt) + Q/C = E,$$

the solution of which is

$$Q = CE + \varepsilon^{-(R/2L)t} (A \cos \alpha t + B \sin \alpha t),$$

where $\alpha = \sqrt{[(1/LC) - (R^2/4L^2)]}$, and A and B are constants which are determined by the initial conditions. At the instant, $t = 0$, of switching-in Q and i are zero. These conditions give

$$A = -CE \text{ and } B = AR/2L\alpha,$$

$$\left.\begin{aligned} \text{so that} \quad V &= Q/C = E - E\varepsilon^{-(R/2L)t} [\cos \alpha t + (R/2L\alpha) \sin \alpha t] \\ &= E - E[1/\alpha\sqrt{(LC)}]\varepsilon^{-(R/2L)t} \cos [\alpha t - \cos^{-1} (\alpha\sqrt{(LC)})], \\ \text{and } i &= dQ/dt = (E/\alpha L)\, \varepsilon^{-(R/2L)t} \sin \alpha t. \end{aligned}\right\} \quad (115)$$

If the resistance is negligible the voltage and current reduce to

$$\left.\begin{aligned} V &= E - E \cos [t/\sqrt{(LC)}] \\ \text{and} \quad i &= [E\sqrt{(C/L)}] \sin [t/\sqrt{(LC)}], \end{aligned}\right\} \quad . \quad . \quad (115a)$$

since $\alpha = 1/\sqrt{(LC)}$ in this case.

The voltage in this case oscillates sinusoidally between 0 and $2E$, whilst the current is a sine wave of peak value $E\sqrt{(C/L)}$. Fig. 241 shows the voltage and current for the case of no resistance (curves A) and for some resistance (curves B).

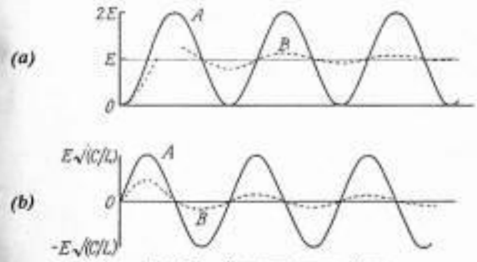


FIG. 241. OPEN-CIRCUITED LINE
(a) Voltage. (b) Current.

Switching Surges. We have found that when an e.m.f. E is switched on to a line, which we replaced by an inductance L and a capacitance C, the voltage oscillates sinusoidally between 0 and $2E$ whilst the current varies similarly between $-E\sqrt{(C/L)}$ and $+E\sqrt{(C/L)}$. It is clear that this does not represent the state of affairs with exactness, for any transfer of energy must travel with a velocity less than that of light, so that the far end of a line is unaffected for the finite time that it takes the energy wave to reach it. It therefore follows that part of the line may be passing current and maintaining a voltage whilst a further part has neither current

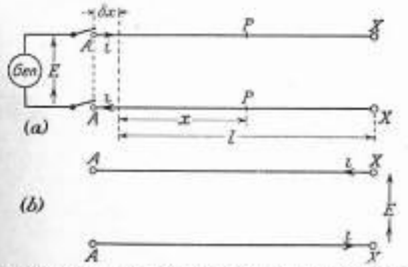


FIG. 242. SWITCHING SURGE ON OPEN-CIRCUITED LINE

nor voltage. We will consider the case of the switching-in of an unloaded line from this point of view, and will make the simplifying assumption that resistance and leakage are negligible. Fig. 242 (*a*) shows the arrangement; the line has inductance L and capacitance C per unit length and is open at the far end XX.

At the instant of switching an e.m.f. E is placed on the line at AA, and a current i passes to the right in the upper conductor and to the left in the lower conductor. Suppose that in a very small time δt the conditions of a current i and a voltage E are established along a length δx of the line. The e.m.f. E is balanced by the back e.m.f. generated by the magnetic flux which is produced by the current in this length of the line. The inductance of the length δx is $L\delta x$, so that the flux built up is $iL\delta x$ and the back e.m.f. is the rate of build-up, viz. $iL(\delta x/\delta t)$. We have therefore

$$\begin{aligned} E &= iL(\delta x/\delta t) \\ &= iLv, \qquad . \quad . \quad . \quad . \quad . \quad (116) \end{aligned}$$

where v is the velocity of the wave.

The current i carries a charge $i\delta t$ in the time δt, and this charge remains on the line to charge it up to the potential E. Since the capacitance of the length δx of the line is $C\delta x$, its charge is $EC\delta x$. We have therefore

$$\begin{aligned} i\delta t &= EC\delta x, \\ \text{or} \qquad i &= EC(\delta x/\delta t) \\ &= ECv. \qquad . \quad . \quad . \quad . \quad . \quad (117) \end{aligned}$$

The switching of an e.m.f. E on to the line results therefore in a wave of current i and velocity v where i and v are given by equations (116) and (117). Multiplying these equations we get

$$\begin{aligned} Ei &= iLvECv = EiLCv^2, \\ \text{so that} \qquad v &= 1/\sqrt{(LC)}. \qquad . \quad . \quad . \quad . \quad (118) \end{aligned}$$

Substituting for v in equation (118) we find that

$$\left.\begin{aligned} i &= E\sqrt{(C/L)} = E/Z \\ \text{where} \qquad Z &= \sqrt{(L/C)}. \end{aligned}\right\} \quad . \quad . \quad . \quad (119)$$

Z is called the *surge impedance* or *natural impedance* of the line; it is a pure resistance for a line without resistance or leakage, and has a value of 400 to 600 ohms for an overhead line and 40 to 60 ohms for a cable. The velocity of the wave on an overhead line is approximately equal to the velocity of light, for

$$\begin{aligned} L &= [1 + 4\,\text{logh}\,(D/r)] \times 10^{-9}\ \text{H. per cm.} \\ &\simeq 4\,\text{logh}\,(D/r) \times 10^{-9}\ \text{H. per cm.} \end{aligned}$$

$$\begin{aligned} \text{and} \qquad C &\simeq \frac{1}{4\,\text{logh}\,(D/r)}\ \text{cm. per cm.} \\ &= \frac{1}{9 \times 10^{11}}\,\frac{1}{4\,\text{logh}\,(D/r)}\ \text{F. per cm.} \\ \text{so that} \qquad v &= \frac{1}{\sqrt{(LC)}} = \sqrt{(10^9 \times 9 \times 10^{11})}\ \text{cm. per sec.} \\ &= 3 \times 10^{10}\ \text{cm. per sec.} \\ &= c, \end{aligned}$$

the velocity of light.

The velocity in a cable is $c/\sqrt{\varepsilon}$, where ε is the dielectric constant. v is thus about 186 000 miles per sec. on an overhead line, and $186\,000 \div \sqrt{3{\cdot}6} = 98\,000$ miles per sec. in a cable.

We have shown that a wave of voltage E and current $i = E/Z$, travels towards the right along the line with a velocity v. Such a wave is called a *pure travelling wave*. At any part PP of the line nothing happens until the wave reaches it (at time $t = x/v$), and then the current jumps from zero to i and the voltage from zero to E. This goes on until the wave reaches the open end of the line (XX) at time $t = l/v$. When the wave reaches XX, the current there is i; but this current has no capacitance to charge up, so that it must cease immediately.

The open end of the line has thus a disturbing influence which neutralizes the current completely; this disturbing influence then travels back along the line towards AA, and can therefore be represented by a pure travelling wave moving towards the left and carrying a current $-i$. A travelling wave must possess a voltage and a current whose ratio is Z, the surge impedance of the line. If the current is to the left in the upper conductor and to the right in the lower from the end XX, it is seen from Fig. 242 (*b*) that the voltage is E, i.e. the upper conductor is E volts above the lower. For if an e.m.f. E were switched in at XX the current would be in the direction required and as shown. The disturbing effect of the open end of the line is thus to introduce another pure travelling wave, which moves to the left with velocity v, has a voltage E, and a current i in the opposite direction to that previously flowing. It is convenient to consider a current to the right in the upper conductor as positive, and a current to the left in the upper conductor as negative. The new travelling wave, which moves to the left, has therefore a voltage E and a current $-E/Z$. In general, a wave (E_1, i_1) moving to the right satisfies the relation

$$i_1 = E_1/Z, \qquad . \quad . \quad . \quad . \quad (120)$$

while a wave (E_2, i_2) moving to the left satisfies the relation

$$i_2 = -E_2/Z. \qquad . \quad . \quad . \quad . \quad (121)$$

The result of the new travelling wave is to establish an extra voltage E at any point of the line that it passes so that a resulting voltage of $2E$ is produced, whilst the current is neutralized. Thus the conditions at the point PP of the line are such that its voltage and current values are $(0, 0)$ from $t = 0$ until $t = x/v$, (E, i) from $t = x/v$ until $t = (2l - x)/v$, and $(2E, 0)$ from $t = (2l - x)/v$ onwards. This goes on until the disturbing wave reaches the generator at AA at time $t = 2l/v$; by this time the line has voltage $2E$ and zero current at every point. When this instant occurs, the voltage at the generator terminals is $2E$. But the generator is supposed to maintain a voltage E at AA, so that another wave is called into play to reduce $2E$ to E. This wave must therefore have potential $-E$, and as it moves to the right it must have a current $-E/Z = -i$ by equation (120). As this wave travels from AA to XX it reduces the voltage to E and produces a current $-i$. Thus the voltage drops from $2E$ to E at the point PP at time $t = (2l + x)/v$ and the current jumps from zero to $-i$. When this third wave reaches XX it establishes a current $-i$ there, which must be neutralized by a fourth wave travelling to the left with current $+i$, and voltage $-iZ = -E$ by equation (121). As this fourth wave travels from XX to AA, the current vanishes at any point it passes, and the voltage becomes $E - E = 0$ at every point. The line is thus completely discharged and has no current, and a complete cycle of travelling waves has been finished. If the line were completely without resistance and leakage, this cycle would be repeated indefinitely. The current at AA, the current and voltage at the mid-point of the line, and the voltage at XX are shown in Fig. 243.

It is interesting and instructive to compare the exact description of the switching phenomenon with the approximate description derived by considering the line as composed of a lumped inductance and capacitance. In both descriptions the potential at any point varies between 0 and $2E$; but in the exact description the time-variation of the potential depends greatly upon the point considered (see Fig. 243, last two curves) and changes in jumps, whilst in the approximate method the time-variation is sinusoidal. The current varies between $+i$ and $-i$ in both cases, where $i = E/Z$ and $Z = \sqrt{(L/C)}$; but again the time-variations are radically different. There is one further difference, viz. the periodicity of the two descriptions. In the approximate method the frequency is $1/2\pi\sqrt{(LC)}$; whilst in the exact method a complete cycle is of duration $4l/v$, so that the frequency is

$$v/4l = 1/4l\sqrt{(LC)} = 1/4\sqrt{(L_0C_0)},$$

where L_0 and C_0 are the total inductance and capacitance. The difference is therefore in replacing the 2π by 4.

Before entering on a somewhat more general description of travelling waves, it is worth while considering the energy properties of the simple waves we have described.

Energy Considerations. A wave of voltage E and current i carries a power of Ei. A simple travelling wave therefore transmits a power Ei with a velocity v. As this wave travels it establishes a magnetic field with energy $\frac{1}{2}Li^2$ per cm. length of the line and an electrostatic field with energy $\frac{1}{2}CE^2$ per cm. length. From equations (116) and (117) it is seen that the magnetic and electrostatic energies delivered by a simple wave are equal, for

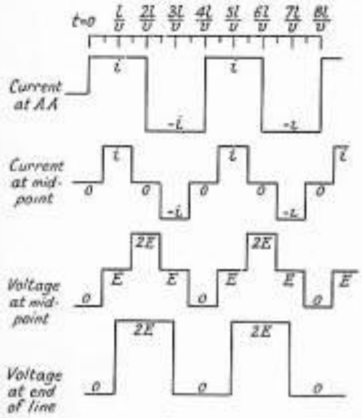


FIG. 243. CURRENT AND VOLTAGE IN SWITCHING SURGE

$$\begin{aligned}\tfrac{1}{2}Li^2 &= \tfrac{1}{2}(iLv)(i/v) = \tfrac{1}{2}(Ei/v)\\ &= \tfrac{1}{2}(E/v)(ECv) = \tfrac{1}{2}CE^2.\end{aligned}$$

Each of these is equal to $\frac{1}{2}Ei/v$, which is half the total energy delivered by the wave in the time it passes along the part of the line. The energy of the wave is thus half absorbed as magnetic and half as electrostatic energy.

When a pure travelling wave of voltage E and current i moves to the right and meets an open-circuited line, we said that the disturbing effect of the open end is to bring into action a reflected wave of voltage E and current $-i$ (travelling to the left). It will be seen that this is consistent with the conservation of energy, and is in fact demanded by this principle. For suppose that the disturbance engenders a wave with a current $-i$, the latter being required in order to neutralize the current at the open end of the line. Suppose that the voltage attached to this wave is E'. When the wave has travelled a distance XY (Fig. 244), the voltage over XY is $E + E'$ whilst the current is zero. The energy associated with this part of the line is now

$$\tfrac{1}{2}C \,.\, XY \,.\, (E + E')^2,$$

whereas previously it was

$$\tfrac{1}{2}C \,.\, XY \,.\, E^2 + \tfrac{1}{2}L \,.\, XY \,.\, i^2 = C \,.\, XY \,.\, E^2,$$

since $\tfrac{1}{2}Li^2 = \tfrac{1}{2}CE^2$. The gain in energy has been derived from the first (incident) wave, which feeds energy into the section XY at a rate Ei; the gain is thus Ei multiplied by the time that the reflected wave takes to travel from X to Y, viz. $Ei \times (XY/v)$. If the principle of conservation of energy is to hold, then

$$\tfrac{1}{2}C \,.\, XY \,.\, (E + E')^2 = C \,.\, XY \,.\, E^2 + Ei(XY/v),$$

or

$$\tfrac{1}{2}(E + E')^2 = E^2 + Ei/Cv = E^2 + E^2$$

(by equation (117)),

so that

$$(E + E')^2 = 4E^2,$$

i.e.

$$E' = E.$$

The principle of the conservation of energy thus demands that the reflected wave at an open end shall have a voltage equal to that of the incident wave; the current is equal and opposite to that of the incident wave since no current can leave the open end.

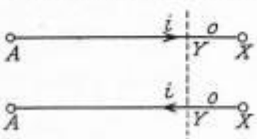


FIG. 244. ENERGY CONSIDERATIONS IN SURGES

Sudden Interruption of a Circuit. We have described in full the surge that takes place when a generator is suddenly switched on to a line that is open at the far end. The phenomenon that takes place when the far end is terminated by a finite impedance will be considered in the section on the reflection and transmission of travelling waves. The method employed above serves to describe the events that occur when a current in a circuit is suddenly interrupted, by the action of a circuit-breaker, say.

Suppose that a circuit has a current i, which is suddenly interrupted by the breakers S, S (Fig. 245). The disturbance produces two travelling waves moving from S, S to the right and to the left. The wave travelling to the right has a current $-\, i$, and must therefore have a voltage $-\, E$, where $E = iZ$; line A is therefore $-\, E$ volts above line B. The wave travelling to the left has a current $-\, i$, and must therefore have a voltage $+\, E$, where $E = iZ$; C is therefore $+\, E$ volts above D. These waves progress in a normal manner until they meet abrupt changes in the line, when they are reflected and transmitted in the ways described later. It should be noted that if only one break is made, so that B and D are always commoned, the voltage between A and C is $2E$.

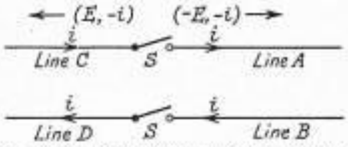


FIG. 245. SUDDEN INTERRUPTION OF A CIRCUIT

The surge voltage E is superposed on the normal voltage in that part of the line which remains connected to the generator.

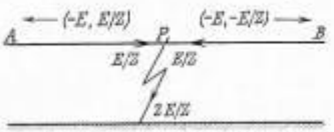


FIG. 246. SURGES DUE TO A FAILURE OF INSULATION

Insulation Failure or Earthing of a Line. Suppose that a line AB, at potential E, is earthed at a point P. The effect of earthing is to introduce a voltage $-\, E$ at P, and two equal waves of voltage $-\, E$ travel along PA and PB. The wave travelling to the right has a current of $-\, E/Z$, and that to the left $+\, E/Z$. Both these currents pass through P to earth, so that the current to earth is $2E/Z$. Fig. 246 shows the waves and currents in the system.

As these waves travel to the ends of the line they reduce the voltage to zero; and when they reach the open ends, reflected waves are set up which reduce the voltage to $E - E - E$, i.e. $-\, E$, and the current is neutralized. When the reflected waves reach P, the portions of the line along which they have travelled will be charged to $-\, E$. The current at P can be reversed by a flashover in the opposite direction, and the result is a periodic flashover with reversals of potential on the line and currents at P until the stored energy is dissipated by damping.

Reflection and Transmission of Travelling Waves. Suppose that a travelling wave (E, i) moves along a line of surge impedance Z and meets a termination of resistance R (Fig. 247). If R is not equal to Z, the end of the line cannot have the voltage E and current i since $E/i = Z$. There is therefore a disturbance which

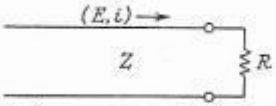


FIG. 247. REFLECTION OF A TRAVELLING WAVE

produces a reflected wave (E', i') moving towards the left. The following relations exist.

$$E = iZ,$$
$$E' = -i'Z.$$

The total voltage at the end is $E + E'$ and the total current is $i + i'$, so that

$$E + E' = R(i + i').$$

These equations give

$$Z(i - i') = R(i + i')$$

so that
$$\left.\begin{aligned} i' &= [(Z - R)/(Z + R)]i \\ \text{and} \qquad E' &= -i'Z = [(R - Z)/(Z + R)]E. \end{aligned}\right\} \quad (122)$$

The total current and voltage are

$$\left.\begin{aligned} i + i' &= [2Z/(Z + R)]i \\ \text{and} \qquad E + E' &= [2R/(Z + R)]E. \end{aligned}\right\} \quad . \quad . \quad . \quad (123)$$

If the line is open at the end, $R = \infty$ so that the total current is zero and the total voltage is $2E$, as found before.

If the line is shorted at the end, $R = 0$ so that the current is doubled and the voltage drops to zero.

The case for a finite resistance termination is given by equations (122) and (123). When the termination is not a pure resistance, the result is still given by these equations but they must be evaluated by the operational calculus.

Junction of Two Lines. Fig. 248 shows the case of two lines of surge impedances Z_A and Z_B. A wave (E, i) travels along the left-hand line and meets the junction. So far as a travelling wave is concerned the right-hand line can be considered to have an impedance Z_B, so that the case is the same as that shown in Fig. 247,

provided Z is replaced by Z_A and R by Z_B. The reflected wave is thus (E', i') where

$$\left.\begin{aligned} i' &= [(Z_A - Z_B)/(Z_A + Z_B)]i \\ \text{and} \qquad E' &= [(Z_B - Z_A)/(Z_A + Z_B)]i. \end{aligned}\right\} \quad . \quad (122a)$$

The transmitted wave must clearly have a voltage equal to the total voltage at the junction and a current equal to the total. Thus the transmitted wave is (E'', i'') where

$$\left.\begin{aligned} i'' &= i + i' = (2Z_A/(Z_A + Z_B)]i \\ \text{and} \qquad E'' &= E + E' = (2Z_B/(Z_A + Z_B)]E. \end{aligned}\right\} \quad . \quad (123a)$$

EXAMPLE. Deduce a simple expression for the natural impedance of a transmission line. A transmission line has a capacitance of 0·0125 μF. per mile and an inductance of 1·5 mH. per mile. This overhead line is continued by an underground cable with a capacitance of 0·3 μF. per mile and an inductance of 0·25 mH. per mile. Calculate the rise of voltage produced at the junction of the line and cable by a wave with a crest value of 50 kV. travelling along the cable. (*Lond. Univ.*, 1931.)

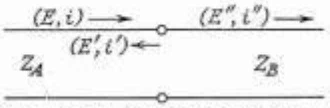


FIG. 248. EFFECT OF A SUDDEN CHANGE IN THE LINE ON TRAVELLING WAVES

The natural impedance is $\sqrt{(L/C)}$. The value for the cable is

$$Z_A = \sqrt{\left[\frac{0{\cdot}25 \times 10^{-3}}{0{\cdot}3 \times 10^{-6}}\right]} = \sqrt{833} = 28{\cdot}9\ \Omega.,$$

whilst the value for the overhead line is

$$Z_B = \sqrt{\left[\frac{1{\cdot}5 \times 10^{-3}}{0{\cdot}0125 \times 10^{-6}}\right]} = \sqrt{120\,000} = 346{\cdot}4\ \Omega.$$

The reflected wave has a crest voltage

$$\begin{aligned} E' &= [(Z_B - Z_A)/(Z_B + Z_A)] \times 50 \text{ kV.} \\ &= (317{\cdot}5/375{\cdot}3) \times 50 \text{ kV.} = \underline{42{\cdot}3 \text{ kV.}}, \end{aligned}$$

so that the maximum voltage at the junction is 92·3 kV.

The next example shows the calculation of the reflected and transmitted waves at a point where a line forks.

EXAMPLE. Obtain the law for the behaviour of a voltage surge with vertical wave-front which, after travelling in a transmission line of inductance L and capacitance C per unit length, reaches a fork where the line splits into two sections having line constants L_1C_1 and L_2C_2 respectively. Neglect resistance and attenuation and obtain the distribution of voltage and current immediately after the wave-front has reached the fork.

An overhead transmission line has a surge impedance of 700 Ω., and a voltage wave of 10 000 V. travelling along it. The wave is assumed to be of infinite length and the wave-front is vertical. At a certain point the overhead line terminates and the circuit is continued by two cables in parallel. The surge impedance of one cable is 100 Ω., and that of the other is 200 Ω. Calculate the voltage and current in the overhead line and in the two cables immediately after the travelling wave has reached the fork.

(*Lond. Univ.*, 1927.)

Fig. 249 represents the arrangement schematically. The surge impedances are

$$Z = \sqrt{(L/C)},\ Z_1 = \sqrt{(L_1/C_1)},\ \text{and}\ Z_2 = \sqrt{(L_2/C_2)}.$$

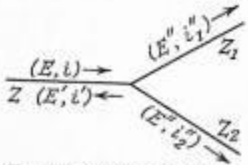


FIG. 249. TRAVELLING WAVES AT JUNCTION OF LINES

Let the incident wave be (E, i) travelling to the right, the reflected wave (E', i') travelling to the left, and the transmitted waves (E'', i_1'') and (E'', i_2'') travelling towards the right. The transmitted waves clearly have the same voltage as they are in parallel. Equations (120) and (121) give the relations

$$E = iZ,$$
$$E' = -i'Z,$$
$$E'' = i_1''Z_1,$$
and
$$E'' = i_2''Z_2.$$

The current entering the fork must be equal to the current leaving, so that

$$i + i' = i_1'' + i_2'' \quad . \quad . \quad . \quad . \quad (124)$$

The voltage at the junction is

$$E + E' = E'' \quad . \quad . \quad . \quad . \quad . \quad (125)$$

These six equations are sufficient to find E', E'', i, i', i_1'', and i_2'' for an incident wave of given magnitude E. Substituting for the currents in terms of the voltages we see that equation (124) becomes

$$E - E' = E''Z\left(\frac{1}{Z_1} + \frac{1}{Z_2}\right).$$

Adding this to equation (125) we get

$$2E = E''(1 + Z/Z_1 + Z/Z_2),$$

so that the voltage at the fork is

$$E'' = \frac{2E}{1 + Z/Z_1 + Z/Z_2} = 2E\frac{1/Z}{1/Z + 1/Z_1 + 1/Z_2}.$$

The transmitted currents are

$$i_1'' = E''/Z_1 \text{ and } i_2'' = E''/Z_2,$$

whilst the incident current is $i = E/Z$.

The reflected voltage is

$$E' = E'' - E = E\frac{1/Z - 1/Z_1 - 1/Z_2}{1/Z + 1/Z_1 + 1/Z_2}$$

and the current is $i' = -E'/Z$. It is seen that the reflected wave is zero when

$$1/Z = 1/Z_1 + 1/Z_2,$$

i.e. when the parallel combination of the surge impedances of the outgoing lines at the fork is equal to the surge impedance of the line along which the incident wave travels.

In the example $Z = 700$, $Z_1 = 100$, $Z_2 = 200$, and $E = 10\ 000$. We then have

$$i = 10\ 000/700 = \underline{14{\cdot}3}\text{ A.},$$

$$E' = 10\ 000\,\frac{\dfrac{1}{700} - \dfrac{1}{100} - \dfrac{1}{200}}{\dfrac{1}{700} + \dfrac{1}{100} + \dfrac{1}{200}} = -\ \underline{8\ 260}\text{ V.}$$

$$i' = -E'/Z = 8\ 260/700 = \underline{11{\cdot}8}\text{ A.},$$

$$E'' = E + E' = 10\ 000 - 8\ 260 = \underline{1\ 740}\text{ V.},$$

$$i_1'' = E''/Z_1 = \underline{17{\cdot}4}\text{ A. and } i_2'' = E''/Z_2 = \underline{8{\cdot}7}\text{ A.}$$

The cables thus have the beneficial effect of reducing the surge voltage from 10 kV. to 1·74 kV.

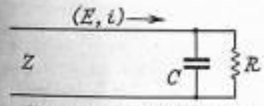


FIG. 250. EFFECT OF SHUNT CAPACITANCE ON TRAVELLING WAVE

Effect of a Capacitance. Suppose that a wave (E, i) meets a termination composed of the parallel combination of a capacitance C and resistance R, as shown in Fig. 250. The problem is the same as that shown in Fig. 247, except that R in equations (123) must be replaced by

$$\frac{(1/pC)R}{1/pC + R} = \frac{R}{1 + pCR},$$

where $p = d/dt$.

jects and reaches earth in a random manner. A direct stroke may use a potential of 10 million volts, and shatter insulators and wers in its vicinity. The most that can be hoped from protective vices is that they will limit the damage and prevent the resulting avelling waves from affecting the plant. Fortunately direct rokes are rare.

The majority of surges in a transmission system are due to htning, and are caused by electrostatic induction in the manner

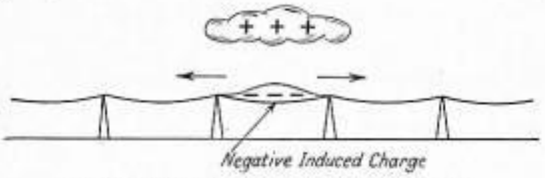


FIG. 253. SURGE DUE TO ELECTROSTATIC INDUCTION

dicated in Fig. 253. A positively charged cloud is above the line d induces a negative charge on the line by electrostatic induction. e induced positive charge leaks slowly to earth via the insulators. hen the cloud discharges to earth or to another cloud, the negative arge on the line is isolated as it cannot flow quickly to earth over e insulators. The line thus acquires a high negative potential, hich is a maximum at the place nearest the cloud and falls slowly

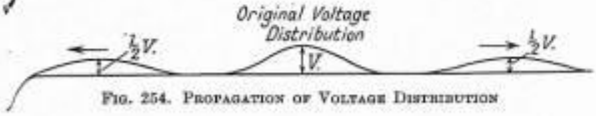


FIG. 254. PROPAGATION OF VOLTAGE DISTRIBUTION

a small value at a distance. The charge will flow from a higher a lower potential and the result is travelling waves in both rections. The two waves will be equal and thus each will have lf the potential of the charge at the time of the discharge of the oud; they will also have the space-voltage distribution of the iginal charge, as shown in Fig. 254. The waves travel in exactly e same way as the waves due to switching, so that the current any point of the line is the voltage divided by the surge impedance. a line without resistance or leakage the waves travel without ange of shape, but the effect of resistance and leakage is to tenuate the wave and to flatten the wave-front.

The steepness of the wave-front depends upon the space-voltage stribution. If the wave reaches its maximum in 1 000 ft., the time

that it takes for the wave to reach the maximum when it passes a point is

$$\frac{1\ 000}{186\ 000 \times 5\ 280}\text{ sec.} = 1{\cdot}02\ \mu\text{sec.}$$

Waves have been recorded with wave-fronts of 1 to 80 μsec. and wave-tails of 3 to 200 μsec. A very steep wave-front may be obtained when a thundercloud is near a building which the line enters. The building screens the line inside from the cloud, so that the induced charge stops abruptly at the building. Extra precautions are therefore necessary where an overhead line enters a building.

Arcing Earths. In the early days of transmission it was the practice to insulate the neutral point of three-phase lines, for then

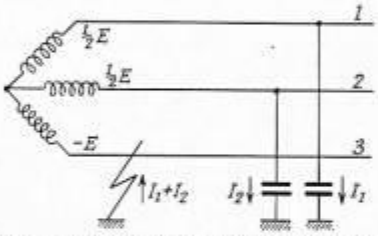


FIG. 255. ARCING GROUND IN THREE-PHASE LINE

an earth on one phase would not put the line out of action; this also eliminated the longitudinal (or zero phase-sequence) current and resulted in a decrease of interference with communication lines. Insulated neutrals gave no trouble with short lines and comparatively low voltages, but it was found that when the lines became long and the voltages high a serious trouble was caused by *arcing earths*, which produced severe voltage oscillations of three to four times the normal voltage. These oscillations were cumulative, and hence very destructive. Arcing earths are eliminated in this country and in America by solid earthing of the neutral, whilst in Germany the neutral is earthed through an inductance (a *Petersen coil*).

There are two accepted theories of arcing earths, in one of which the arc is extinguished at the normal frequency, and in the other at the frequency of oscillation of the line. Let us consider the *normal-frequency arc-extinction theory* for a three-phase line.

Fig. 255 shows a three-phase line. Suppose that line 3 arcs to earth when its voltage to neutral is a maximum $-E$. At this instant lines 1 and 2 have voltage $+\frac{1}{2}E$. Before the arcing earth occurs the capacitances of the lines cause the neutral to be at or near the earth potential, so that the earthing of line 3 causes a sudden voltage of $+E$ to be applied to lines 1 and 2. The ultimate steady state would then be for the lines 1 and 2 to be at potential $\frac{3}{2}E$. But we have shown that when an e.m.f. E is suddenly switched into a circuit of low resistance, the voltage in the circuit oscillates between 0 and $2E$ with a frequency $1/2\pi\sqrt{(LC)}$ (see equations (115*a*) *et seq.*), where L and C are the inductance and capacitance in the circuit. The voltage of lines 1 and 2 will therefore oscillate rapidly between the original value of $\frac{1}{2}E$ and $\frac{1}{2}E + 2E = \frac{5}{2}E$. The high frequency oscillation dies out rapidly. The arc is fed through the capacitances of the lines, as shown in Fig. 255, and will go out when the sum of the capacitance currents passes through zero. The capacitance currents lead the voltages by 90°, so that when their sum $I_1 + I_2$ is zero the line voltages are $E_1 = -\frac{3}{2}E$, $E_2 = -\frac{3}{2}E$, and $E_3 = 0$. If the arc were to remain extinct, the voltages would have to be these values plus E, viz. $E_1 = -\frac{1}{2}E$, $E_2 = -\frac{1}{2}E$, and $E_3 = +E$. Thus the faulty line 3 would have a maximum voltage again, and so arc to earth again. In other words, when line 3 arcs to earth the capacitance currents of lines 1 and 2 maintain the arc until the voltage of line 3 attains its opposite maximum voltage with respect to the neutral; then at the instant when the capacitance currents would allow the arc to go out, line 3 arcs again to ground. We saw that at the instant that the arc is extinct the lines are at potentials $-\frac{3}{2}E$, $-\frac{3}{2}E$, and 0. The charges due to these potentials diffuse rapidly through the system in an oscillatory manner, with the average voltage $\frac{1}{3}(-\frac{3}{2}E - \frac{3}{2}E + 0) = -E$ as the mean position. This is equivalent to an insertion of an e.m.f. of $\frac{1}{2}E$ in lines 1 and 2, so that an added voltage E is applied to these lines. When the arc restrikes, lines 1 and 2 acquire potentials of $-\frac{5}{2}E$ plus this new value $-E$, so that the maximum voltage is $\frac{7}{2}E$. We see therefore that the healthy lines are subjected to a voltage of 3½ times the normal value. As this state can be maintained for a considerable length of time, in a known case 30 min., by the continued arcing, it is very dangerous.

Petersen Coil. We have seen that the capacitance currents I_1 and I_2 maintain the arc even when the voltage of the faulty line 3 is too low to restrike it. In fact these currents have the particularly harmful effect of maintaining the arc until the very moment when the voltage of line 3 is sufficiently high to restrike it. If the neutral is earthed through an inductance L of such a value that the current it passes neutralizes $I_1 + I_2$, the normal frequency follow current through the arc is

$$I_L + I_1 + I_2 = 0.$$

The arc is then extinguished except for the brief moments when the voltage of line 3 passes through its maximum value and can restrike it.

It has been found that the Petersen coil is completely effective in preventing any damage by an arcing earth, and is therefore used extensively on the Continent. The coil is usually provided with tappings, so that its value can be adjusted to suit the capacitances of the system. It is found that effective operation is secured when the inductance is 90 to 110 per cent of the theoretical value for exact neutralization of the capacitance currents.

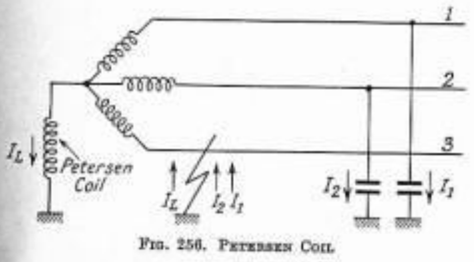


FIG. 256. PETERSEN COIL

Lightning and Over-voltage Protection. The insulation of a transmission system is always designed to withstand voltages of twice the normal value for a reasonable length of time, as switching surges often produce voltages of this magnitude. It is clearly uneconomical to design the system so that the insulation can withstand the very high voltages that may be encountered from extraneous or fault conditions, and recourse is had to protective devices which are adjusted to break down before the insulation, or otherwise prevent a dangerous voltage from damaging the insulation.

Dangerous voltage rises are found to be due to the following: (1) surges due to direct lightning strokes or induced voltages, (2) arcing earths, (3) comparatively low-voltage high-frequency oscillations, (4) static overvoltage. The protective apparatus for these classes are: (1) ground wire and lightning arrestors, (2) earthing of neutral solidly or through a Petersen coil, (3) surge absorber or capacitance, (4) water-jet earthing resistance, earthing inductance, or solid earthing of the neutral point.

It is true to say that with the advent of high-voltage overhead lines, such as the Grid, the main cause of damage is lightning. We have seen that most travelling waves due to lightning are caused by electrostatic induction. The latter can be reduced considerably by the use of earth wires running above the transmission line and earthed at every pole or tower. If C_1 is the capacitance of the cloud to the line and C_2 the capacitance of the line to ground, the induced voltage on the line is $C_1/(C_1 + C_2)$ times the cloud voltage. The presence of the earth wire *above* the line causes a considerable increase in C_2 and reduction of the line voltage. The induced voltage could be very much reduced by an array of earth wires above the line, but this is too expensive to install in practice.

The earth wire also provides considerable protection against direct strokes (of the A type), provided the earth resistance of the earth wire is kept low. If the current in the stroke is I and the earth resistance is R, the voltage of the earth wire is IR, and unless R is low this voltage may be sufficient to cause a flash-over from the earth wire to the lines. The earth resistance should be of the order of 10 to 20 ohms.

The earth wire affords an additional protective effect by causing an attenuation of any travelling waves that are set up, by acting as a short-circuited secondary. For this reason its resistance should not be too large. It is usually made of steel, which has a high permeability and thus possesses a resistance which increases with frequency.

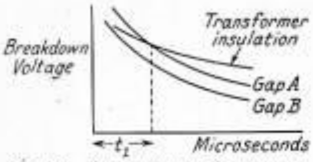


FIG. 257. VARIATIONS OF BREAKDOWN VOLTAGE WITH TIME OF APPLICATION

Having reduced the magnitude of induced voltages by means of an earth wire, we still find it necessary to install protective apparatus to prevent, or at least minimize, the damage due to the surges that do occur. It is, moreover, essential that the system shall be considered as a whole from the point of view of protection, so that the least essential and most accessible parts protect the more important apparatus; this involves the *co-ordination of system insulation*. The problem is rendered difficult by the fact that the breakdown voltages of the various parts of the system and of the protective apparatus behave differently with time; thus a horn gap which is set to flash-over at 100 kV. at 50 cycles may require 200 kV. in a wave lasting for 20 μsec., or 300 kV. in a wave lasting for 5 μsec. We define the *impulse ratio* of any piece of apparatus as the ratio of the breakdown voltage of a wave of specified duration to the breakdown voltage of a 50-cycle wave; thus the horn gap has an impulse ratio of 2 at 20 μsec., and 3 at 5 μsec. When a method of co-ordinated insulation is considered, the impulse ratio of the various parts must be known or the protection will not be adequate. Fig. 257 illustrates the point. Suppose that the insulation of a transformer to be protected has the breakdown voltage-time characteristic shown. Gap A may be set to break down at a lower voltage than, say, 80 per cent of the breakdown voltage of the insulation at 50 cycles. The gap, nevertheless, does not protect the transformer, as its characteristic rises more rapidly than that of the transformer insulation as the duration of the wave decreases. Then for waves of duration less than t_1 the transformer insulation breaks down before the gap. It is necessary to narrow the gap so that the characteristic is as shown for gap B before the transformer is completely protected. In practice it is not possible to narrow the gap so much that the insulation is protected for waves of the smallest duration, as then the gap would flash over at very low voltages at 50 cycles; a compromise is reached by protecting the insulation for voltages of waves down to a certain minimum time, which is found experimentally to be comparatively harmless.

Sphere Gap. A sphere gap in which the spacing is small compared with the diameter of the spheres has the useful advantage that the impulse ratio is unity. If then the apparatus is protected against 50-cycle waves, it is protected against a wave of any duration. Unfortunately, when the sphere gap flashes over, the power current maintains the arc, which requires only a very low voltage to maintain it, and the arc is not self-extinguishing. The circuit-breakers would have to intervene to break the arc current and the service is interrupted. For this reason the sphere gap is not of use.

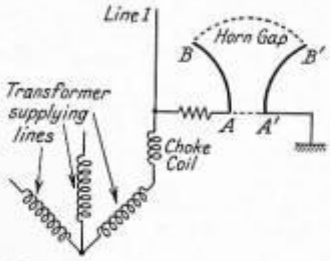


FIG. 258. HORN GAP WITH CHOKE COIL AND RESISTANCE

Horn Gap. Fig. 258 shows a simple sketch of the horn gap. The gap is set so that a flash-over occurs between A and A' at a voltage of 150 to 200 per cent of the normal voltage. The power current creates an arc, which may be considered to be a flexible conductor. A flexible electric circuit moves so as to embrace as many lines of magnetic force as possible, so that the arc is forced up to the position BB'. Another factor tending to blow the arc up to BB' exists when BB' is above AA', for then the arc heats the air and forms a vertical draught. The result is that the arc is forced up to BB', where the gap is wide and the normal voltage is insufficient to maintain it. The arc is thus extinguished, usually in about 3 sec.

The horn gap cannot rupture arc currents much in excess of

10 amperes, and as the arc is a dead short circuit it is necessary to limit the current to a small value. This is done by inserting a resistance, between the line and the horn on the line side, which reduces the current to about 5 amperes. The efficacy of the horn gap is seriously reduced by the resistance. The resistance is a water column, oil-immersed metal wire, carbon rod, or carborundum, and is made as non-inductive as possible.

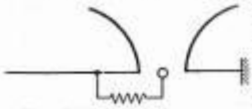


FIG. 259. HORN GAP WITH AUXILIARY ELECTRODE

It is found that high-frequency waves concentrate at the line-end turns of a transformer, so that although the magnitude of the wave on the line is not very great, the stress at the turns near the line is very high and may cause puncture between turns. This difficulty is overcome by the insertion of choke coils, as shown in Fig. 258.

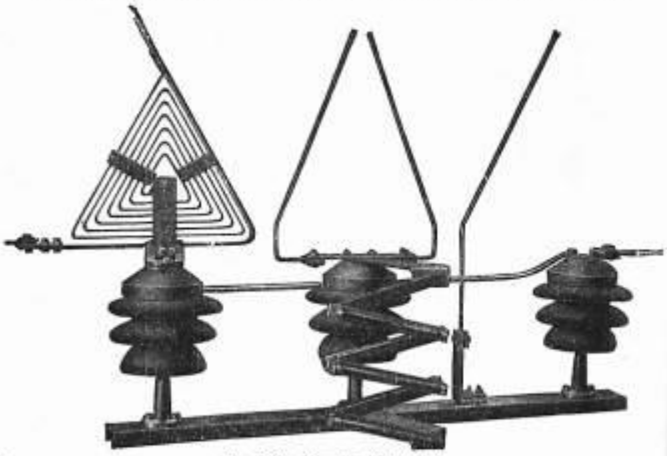


FIG. 260. BURKE ARRESTER
(*Metropolitan-Vickers*)

The high-frequency wave is then reflected back to the horn gap, where the doubled voltage causes a flash-over. The choke is without effect on the low-frequency power wave.

For small settings the horn gap is sensitive to corrosion or pitting of the horns, so that it does not maintain its setting. This difficulty is overcome in the arrester shown in Fig. 259. The main gap is set for a voltage well above that to be protected. The auxiliary gap has a platinum electrode, which possesses the character of permanence. When an over-voltage occurs the auxiliary gap flashes over and ionizes the air, and then the main gap flashes over.

Burke Arrester. Fig. 260 shows the Burke arrester. The line current passes through a triangular pancake choke coil, one side of which forms half of the main gap. Severe over-voltages flash across the main and auxiliary gap direct to earth. Less severe voltages flash over the main gap only, and the current is then limited by the resistance.

Multi-gap Arrester. This consists of a number of small gaps in series with a limiting resistance. Another resistance is placed across some of the gaps adjacent to the limiting resistance.

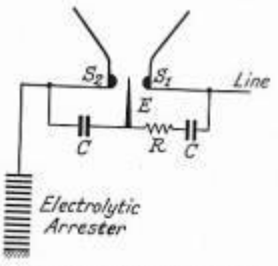


FIG. 261. IMPULSE GAP WITH ELECTROLYTIC ARRESTER

Impulse Protective Gap. It was pointed out that the sphere gap has an impulse ratio of unity, but suffers from the disadvantage that the arc between its electrodes is not self-extinguishing. The horn-gap, however, extinguishes the arc but has a high impulse ratio, 2 or 3. The impulse protective gap is designed to have a low impulse ratio, even less than unity, and to extinguish the arc. Fig. 261 shows a diagram of the impulse gap. S_1 and S_2 are sphere-horn electrodes, and are connected to the line and an electrolytic arrester, respectively. An auxiliary needle electrode E is placed mid-way between S_1 and S_2, and is connected to them via (R, C) and C. At the power frequency the impedance of the capacitances C is very much greater than that of R, so that the potential of E is mid-way between those of S_1 and S_2 and the electrode has no effect on the flash-over between them. At very high frequencies the impedance of C is small, so that E is at the potential of S_2 and the gap is effectively half the previous value. Flash-over takes place between S_1 and E at a voltage less than that required to flash-over between S_1 and S_2. An impulse ratio less than unity can thus be obtained. The electrolytic arrester on the earth side extinguishes the arc.

Electrolytic Arrester. This is the earliest type of arrester with a large discharge capacity. The action depends upon the fact that a thin film of aluminium hydroxide immersed in electrolyte presents a high resistance to a low voltage, but a low resistance to a voltage above a critical value. The critical breakdown voltage is about 400 volts, and voltages higher than this cause a puncture and a free flow of current. The insulating film of hydroxide is formed by applying a direct voltage up to the critical value to aluminium plates immersed in the electrolyte; during the formation of the film, current passes fairly readily, but when the film is formed the current ceases.

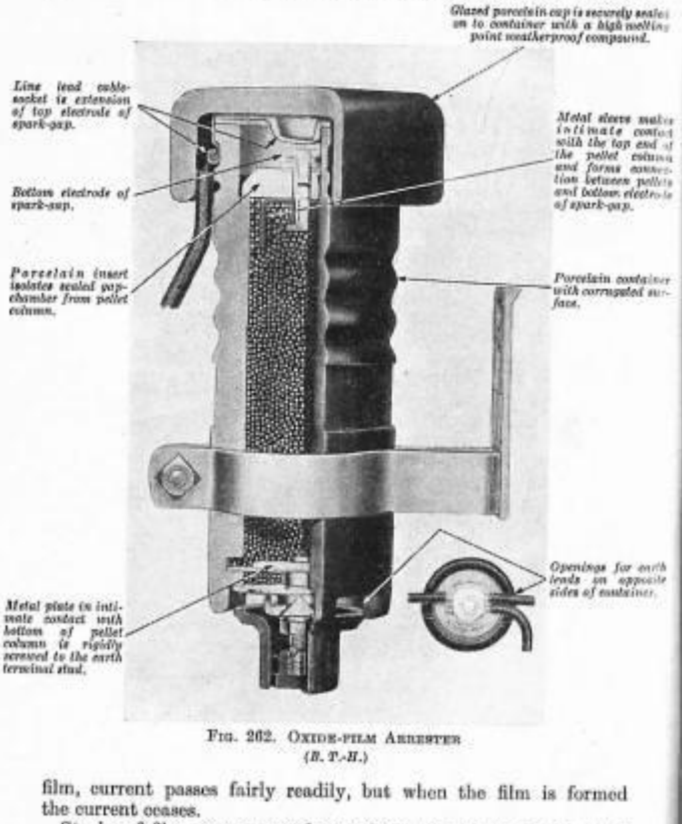


FIG. 262. OXIDE-FILM ARRESTER
(B. T.-H.)

Stacks of films are arranged one above the other and the total critical voltage is equal to the critical voltage of each film multiplied by the number of films.

Daily supervision and reforming of the films is essential, and for this reason the arrester is being replaced by the more robust oxide-film and auto-valve arresters. The electrolytic arrester is used in conjunction with an impulse gap, for the continual leakage and capacitance currents would damage the arrester.

Oxide-film Arrester. Fig. 262 shows the construction of the oxide-film arrester of the pellet type. The lead peroxide pellets are in a column of $2\frac{1}{4}$ in. diameter, the length of the column being 2 in. per kV. of rating. The tube contains a series spark-gap. A single tube system is available for voltages up to 25 kV. when the neutral is solidly earthed, and 18 kV. when the neutral is isolated or earthed through an inductance coil. For higher voltages several units are placed in series.

The pellets have a diameter of approximately $\frac{1}{32}$ in. and are made of lead peroxide with a thin porous coating of litharge.

Auto-valve Arrester. This consists of a number of flat discs of a porous material stacked one above the other and separated by thin mica rings. The material is made of specially prepared clay with a small admixture of powdered conducting substance. The discharge occurs in the capillaries of the material and is thus constrained to be a glow discharge, in which there is a voltage drop of about 350 volts per unit. The narrow gaps between the blocks are of sufficient total width to prevent flash-over due to the normal voltage, so that no current flows in the arrester under normal conditions. This arrester is very effective, robust and cheap, and is being rapidly introduced into modern high voltage systems.

Thyrite Arrester. Thyrite is a dense inorganic compound of a ceramic nature, which has a resistance that decreases rapidly from a high value at low currents to a low value at high currents. The current increases 12·6 times when the voltage is doubled; thus if the current-voltage relation for a given block of thyrite is

$$E = kI^n,$$

then $$2E = k(12{\cdot}6I)^n,$$

so that $$2 = 12{\cdot}6^n,$$

i.e. $$n = \log 2 \div \log 12{\cdot}6 = 0{\cdot}27.$$

Thus the voltage varies approximately as the fourth root of the current. Fig. 263 shows the current-voltage curve of the 11 kV. thyrite arrester of Fig. 264. There are eleven thyrite discs sprayed on both sides to provide a good surface contact; each disc has a diameter of 6 in. and thickness $\frac{3}{4}$ in., and will discharge several thousand amperes without the slightest tendency to flash over the outside edge. When passing 2 000 amperes each disc has a voltage of only 5 kV. At the normal voltage of 11 kV. to earth, the peak voltage is $(11\sqrt{2} \div \sqrt{3})$ kV. = 9 kV. and the current in the arrester is only 3·2 amperes. When one phase is earthed the peak voltage on the other phases is $11 \times \sqrt{2} = 15{\cdot}6$ kV. and the arrester passes

25 amperes. A series gap is provided to prevent current from flowing at the normal voltage. The value of k for the stack is 6 500, or 600 per disc.

When the gap and arrester flash over, a high current flows for the duration of the surge, which is discharged to earth rapidly as is shown by oscillographic records; there appears to be absolutely no time-lag in the thyrite itself. The normal frequency follow-current is very small, 3·2 amperes in a healthy system, and only 25 amperes in a system with an earthed phase. The gap is easily able to clear this small follow-current.

Some modern modifications of the thyrite arrester include a type in which resistance blocks of a ceramic nature are spaced at equal distances from one another. The total gap length is adjusted so that the gaps flash over at twice normal voltage; it is claimed that the distributed gaps behave better than a single gap. Round knobs are provided between the electrodes of the gaps so as to reduce the time-lag. The action of the resistance blocks is similar to that of thyrite.

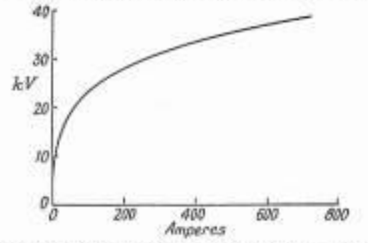


FIG. 263. VOLTAGE-CURRENT CURVE OF THYRITE ARRESTER

Condensers. We have shown on pages 290–22 that the effect of a condenser, placed between the line and earth, on a travelling wave is to reduce the steepness of the wave-front. This effect protects the windings of a transformer near the line, since a steep wave-front causes very high stresses in these turns.

The condenser, moreover, protects the transformer against comparatively low-voltage, high-frequency waves. The normal-frequency voltage produces only a very small current in the condenser, so that negligible loss is caused during normal operation.

The latest type of condenser used for protective purposes has a dielectric of acetyl cellulose, the electrodes being silver plating on the strips of the dielectric.

Surge Absorber. A pure condenser of the type described in the previous section cannot dissipate the energy in the wave-front of a travelling wave or in a high-frequency oscillation. It merely reflects the energy away from the apparatus to be protected, and the energy is dissipated in the resistance of the line conductors and the earthing resistances. If a resistance is placed in series with the condenser, the combination can dissipate part of the energy in addition to diverting it from the apparatus. Such a combination is called a *surge absorber*.

Another type of absorber consists of an inductance across which is placed a resistance. This combination is placed in series with the line. Steep wave-fronts or high-frequency waves find the inductance a high impedance path and are forced through the resistance, where they are dissipated. The normal-frequency currents find the inductance a low impedance path and pass through it without much loss.

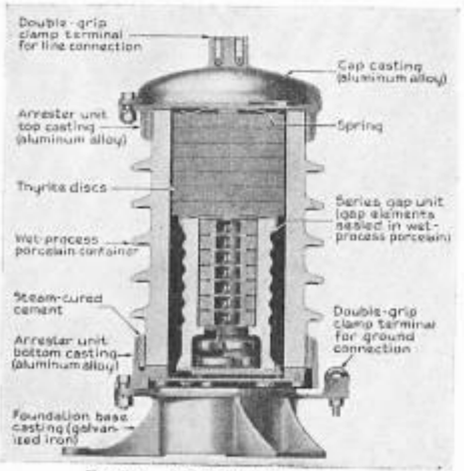


FIG. 264. 11 kV. THYRITE ARRESTER
(International General Electric Co. of New York, Ltd.)

The *Ferranti surge absorber* consists of an inductance coil, which is coupled magnetically, but not electrically, to a metal shield and/or the steel tank which contains it. The coil is of a cylindrical or pancake form, depending upon the voltage; for voltages above 33 kV. the coil is cylindrical and has inside it a metal shield in which currents are induced. The absorber is enclosed in a cylindrical boiler-plate tank, provided with porcelain-guarded terminals, and is vacuum-impregnated with a light transformer oil. Fig. 265 shows a 66 kV. surge absorber of this kind. The equivalent circuit of this absorber is shown in Fig. 266. There is a filter effect which prevents high frequency currents from passing freely through the absorber; also energy is transferred from the wave by the mutual induction between the coil and the shield and tank into the latter two, where the energy is dissipated as heat.

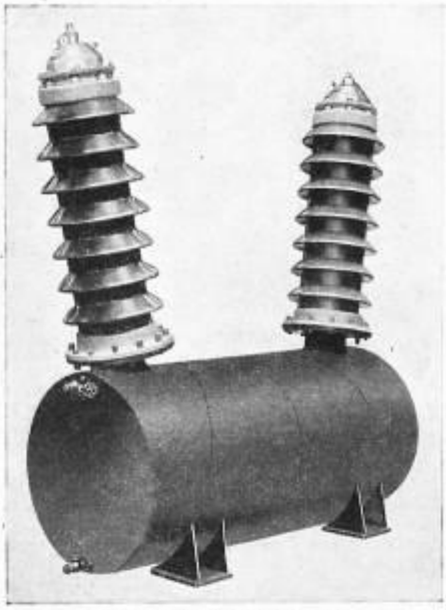


Fig. 265. Ferranti Surge Absorber
(I.E.E. Students' Journal)

Recording of Transmission Line Surges. There are three methods of recording transmission line surges, by the high-voltage cathode-ray oscillograph, the klydonograph, and the surge-crest ammeter. These will be described briefly.

High-voltage Cathode-ray Oscillograph. This is the only

instrument capable of delineating the voltage-time characteristic of a wave. Fig. 267 shows a high-speed cathode-ray oscillograph manufactured by Metropolitan-Vickers. The tube is continuously evacuated and the pressure in the deflection tube is 10^{-4} mm. of mercury or less. The cathode is cold and at a potential of 50 or 60 kV. above the anode, which is earthed.

The essential process is the following. A supply of electrons is obtained by the ionization of the residual gas in the discharge tube, and these are made to travel with an enormous velocity under the accelerative effect of the applied voltage. The electrons pass through a hole in the anode and proceed in a straight line, until they pass between the time deflection plates. The time deflection plates have applied between them a voltage which varies rapidly and uniformly from zero to a maximum value; the electron beam then undergoes a deflection, that is proportional to the time from a given instant. The beam then passes between the voltage deflection plates, between which the wave (or a fraction of it) is applied. The voltage deflection plates produce a deflection at right angles to the time deflection, so that the electron beam, which strikes the photographic plate at the end of the tube, traces out the voltage-time curve of the wave.

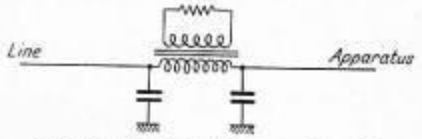


Fig. 266. Equivalent Circuit of Fig. 268

In order to photograph waves of only a few microseconds duration the utmost sensitivity is required. This sensitivity is achieved in the following way. The electron beam impinges directly on the sensitive plate, which must therefore be inside the evacuated tube. The velocity of the electrons must be very great, and a high voltage of 50 kV. or more is used to accelerate the electrons. It is quite clear that the electron beam must not impinge on the plate when there is no wave, otherwise the plate would be completely fogged. The beam is diverted from the photographic chamber by beam trap plates and a beam trap tube. When there is no wave, there is a voltage between the beam trap plates which deflects the beam from the straight path that leads through a small hole in a diaphragm at the bottom of the beam trap tube. It is seen that the axis of the discharge tube is inclined at an angle to the axis of the main tube. The reason for this is that although the electron beam is prevented from reaching the photographic plate by means of the beam trap plates during the absence of a surge or wave, there are retrograde

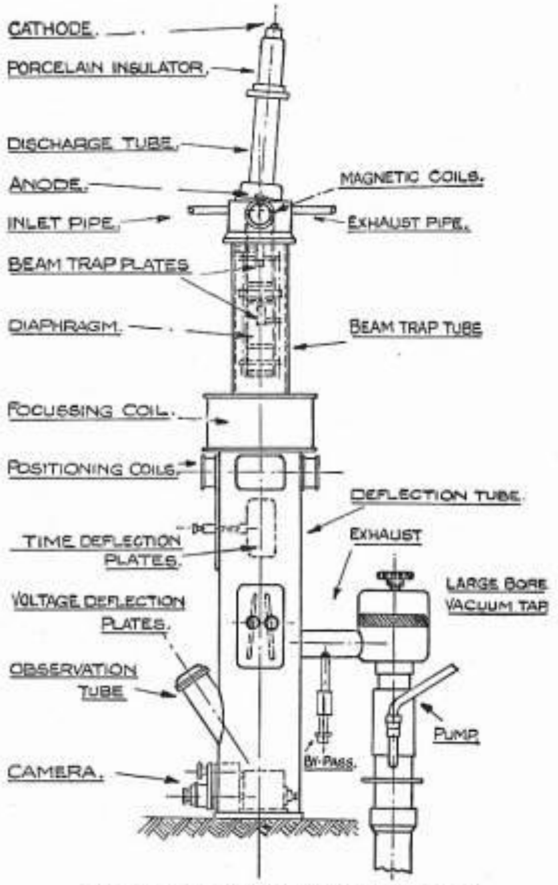


FIG. 267. HIGH-SPEED CATHODE-RAY OSCILLOGRAPH
(*Metropolitan-Vickers*)

rays consisting of atoms that are not much affected by the beam trap. These rays consist of relatively heavy particles and are thus not easily deflected, so that if they are moving along the axis towards the plate they will do so whether the beam trap is operating or not. Their very property of not being deflected easily is used to get rid of them by inclining the axis of the discharge tube. The retrograde rays and the electron beam travel along the axis of the discharge tube towards the anode. Magnetic coils then deflect the electron beam along the main axis, so that the beam can enter the beam trap tube; but the retrograde waves are not deflected from their inclined path and are prevented from entering the main tube.

FIG. 268. POTENTIAL DIVIDER AND DELAY CABLE

The electron beam is focused and positioned by magnetic coils.

When a surge arrives it is sent direct to a trigger device which removes the voltage between the beam trap plates, and the electron beam travels to the plate. Meanwhile the surge is put across a potential divider connected to a *delay cable*, which transmits a known fraction of the wave to the voltage deflection plates after a delay of a fraction of a microsecond. The delay cable is a concentric cable, with air or rubber dielectric. Fig. 268 shows the arrangement of the potential divider and the delay cable; R is equal to the surge impedance of the cable. If the capacitance C_1 is ten times the capacitance of the cable, no distortion is introduced and the ratio of step-down is $C_1/(C_1 + C_2)$.

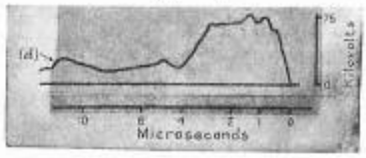


FIG. 269. VOLTAGE ACROSS LINE TURNS OF TRANSFORMER
(*I.E.E. Journal*)

Fig. 269 shows a cathode-ray oscillograph of the voltage appearing across 10 per cent of the line end turns of a transformer winding.* It is seen that in this case the time base is not quite linear.

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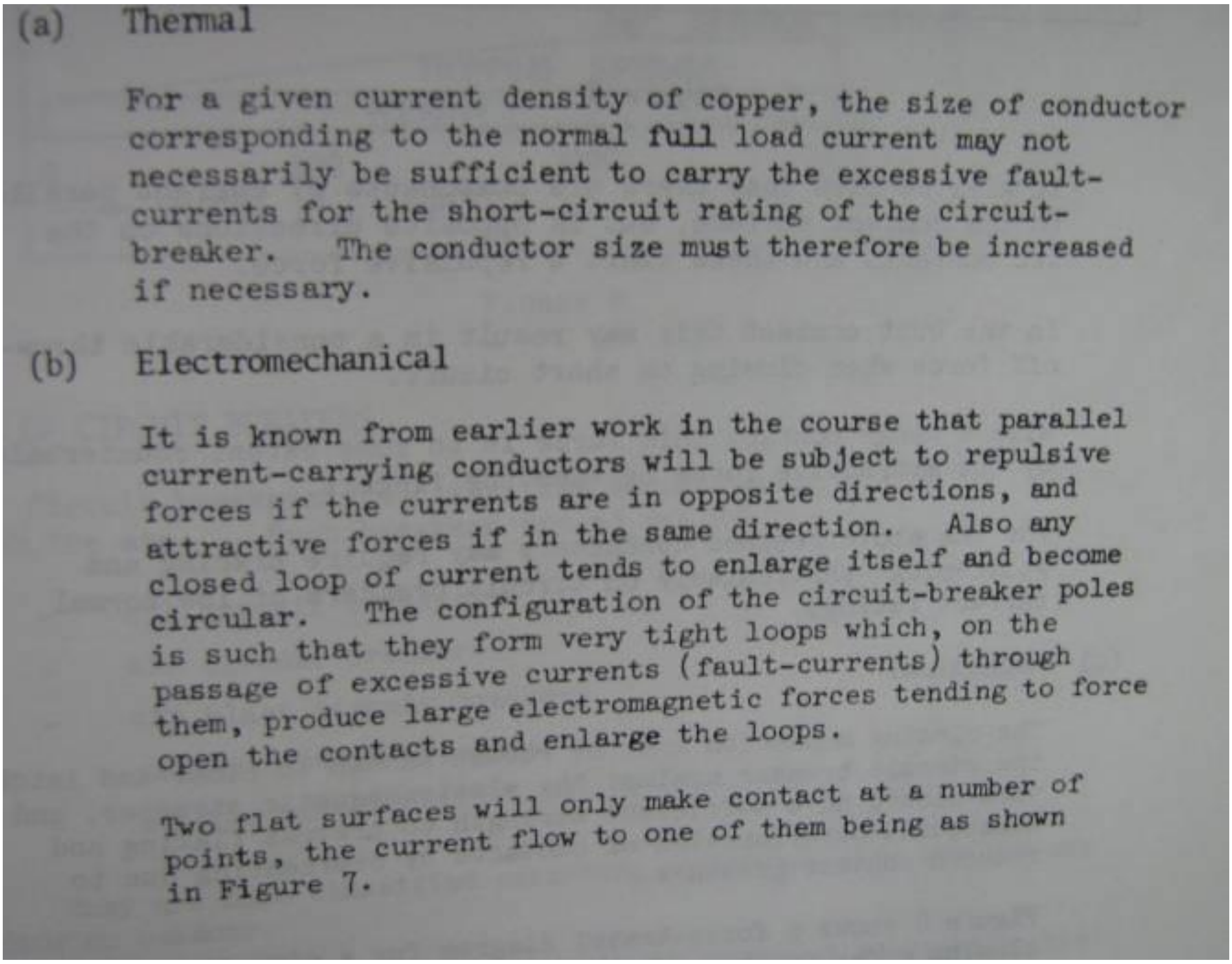
* Reproduced by kind permission of the Institution of Electrical Engineers from the paper by Miller and Robinson, *Journal of the I.E.E.*

KLYDONOGRAPH. It is found that if a potential difference is applied between the faces of a photographic plate, the emulsion is affected and on developing a figure is obtained. When the emulsion side is at a higher potential than the other side, the figure consists of fine lines radiating from the point of contact; when it is at a lower potential, the figure is a complete and fairly definite circle. The latter, or negative, figure is the more useful as its size is definite. The magnitude of the figure depends upon the magnitude of the potential and its frequency or steepness of wave-front. Thus 50-cycle potentials produce only a small figure, whilst high-frequency or steep-fronted waves produce a large figure. If the film is allowed to run past the electrodes (that on the emulsion side is usually pointed and the other flat), the developed film gives a long line with wide bands. The long narrow line corresponds to the normal operating voltage, and the wide bands to high-frequency discharges or steep-fronted surges. Useful qualitative information has been obtained by the use of the klydonograph, but because of the dependence of the size of the figure on frequency or steepness of wave-front the results are not quantitative.

SURGE CREST AMMETER. The principle of this instrument is the measurement of the residual magnetism in a piece of magnetic material, which has been magnetized by the surge current. From the residual magnetism the peak of the surge current is deduced.



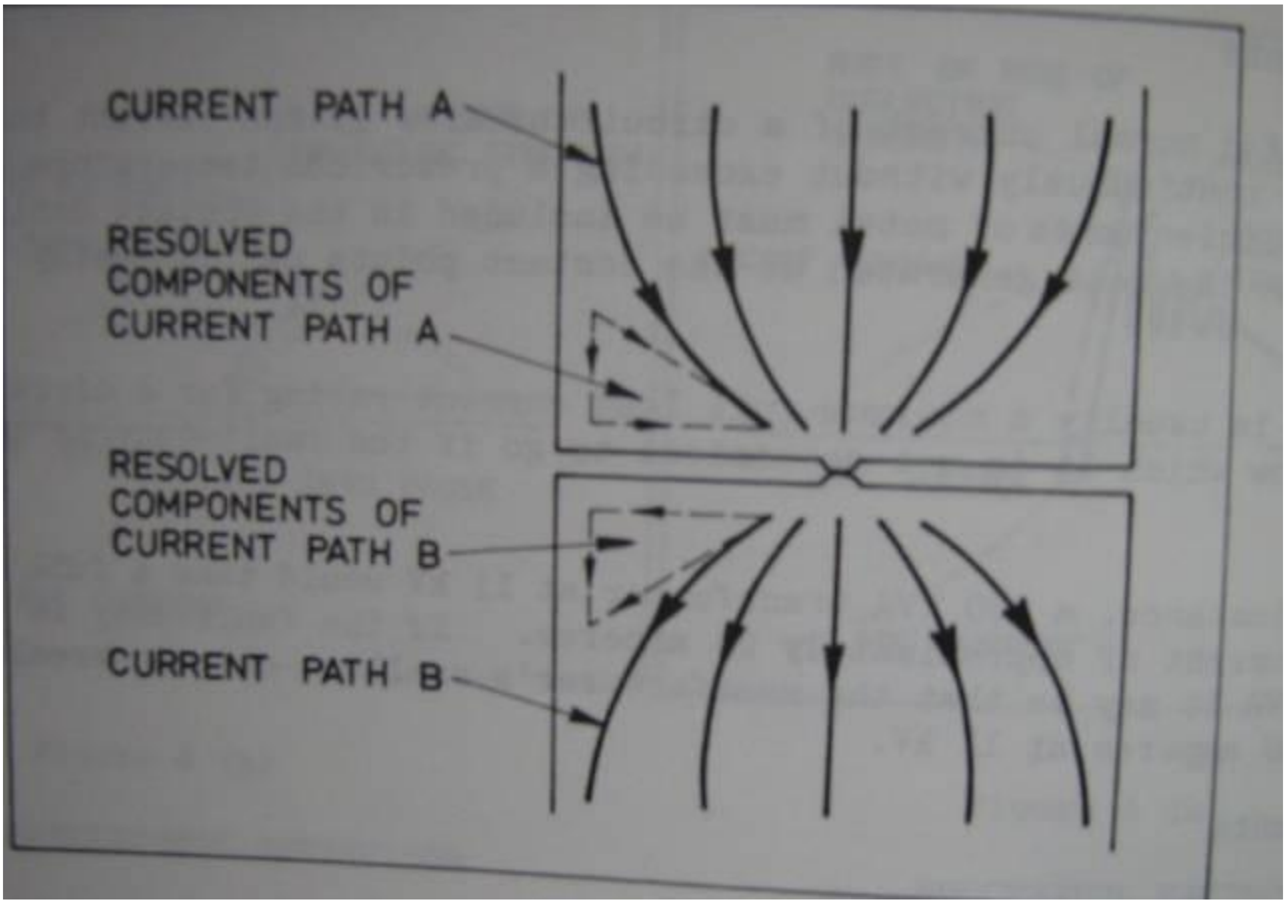
(a) Thermal

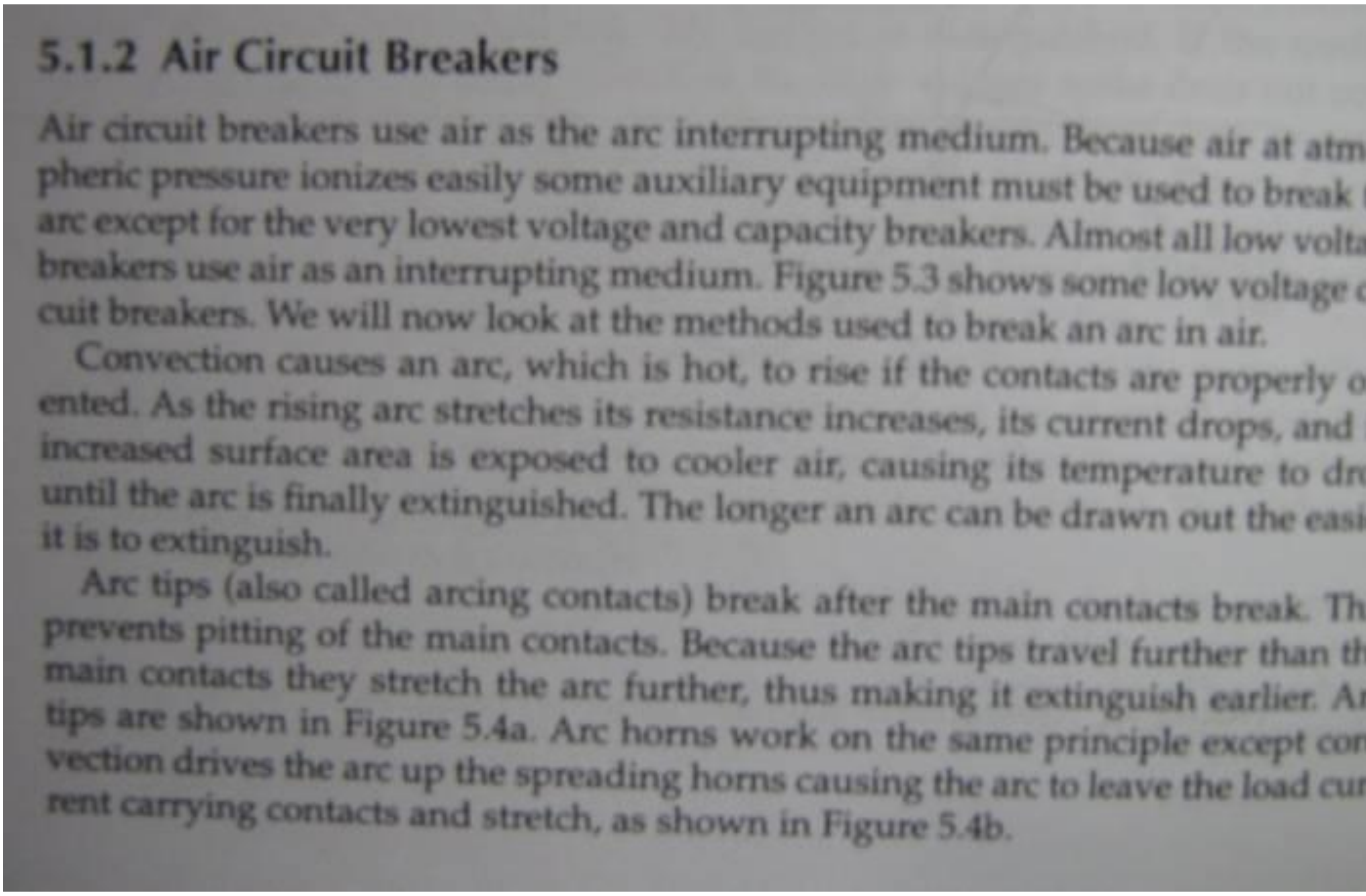
For a given current density of copper, the size of conductor corresponding to the normal full load current may not necessarily be sufficient to carry the excessive fault-currents for the short-circuit rating of the circuit-breaker. The conductor size must therefore be increased if necessary.

(b) Electromechanical

It is known from earlier work in the course that parallel current-carrying conductors will be subject to repulsive forces if the currents are in opposite directions, and attractive forces if in the same direction. Also any closed loop of current tends to enlarge itself and become circular. The configuration of the circuit-breaker poles is such that they form very tight loops which, on the passage of excessive currents (fault-currents) through them, produce large electromagnetic forces tending to force open the contacts and enlarge the loops.

Two flat surfaces will only make contact at a number of points, the current flow to one of them being as shown in Figure 7.





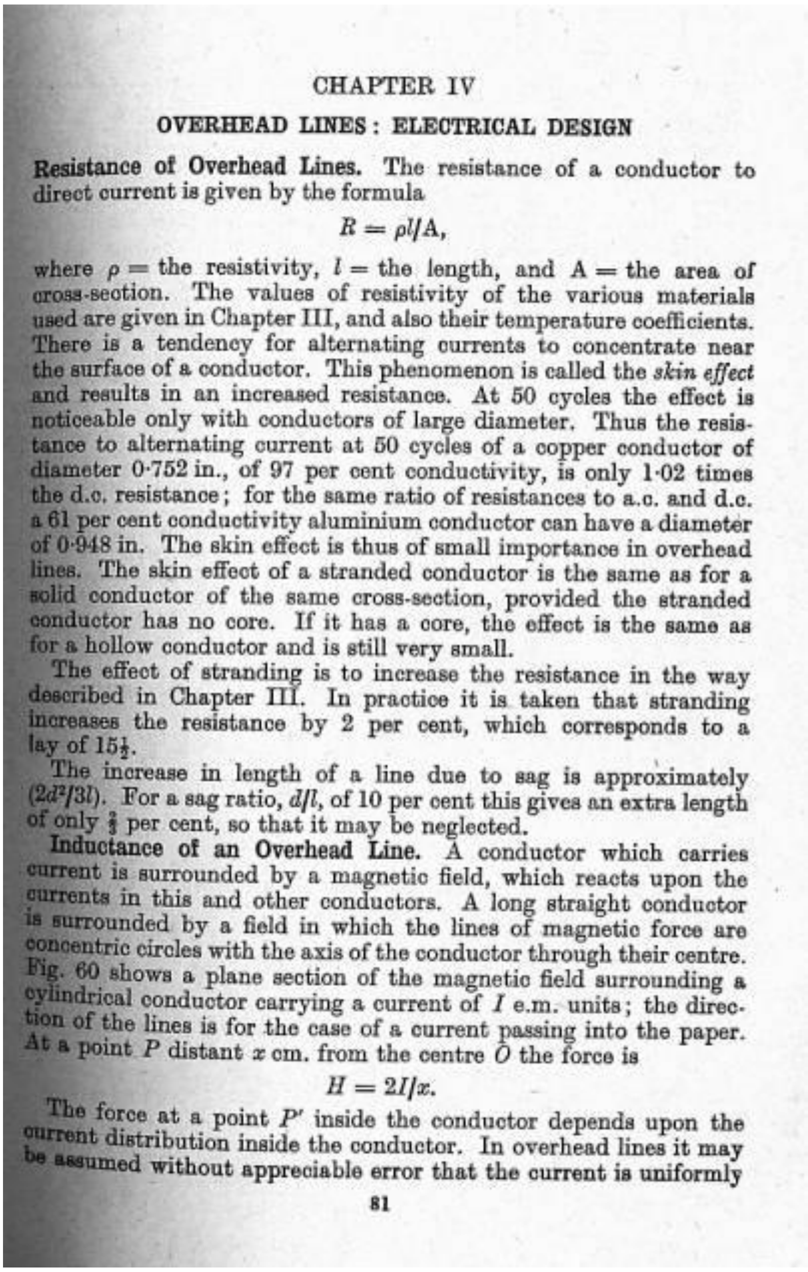
5.1.2 Air Circuit Breakers

Air circuit breakers use air as the arc interrupting medium. Because air at atm
pheric pressure ionizes easily some auxiliary equipment must be used to break
arc except for the very lowest voltage and capacity breakers. Almost all low volta
breakers use air as an interrupting medium. Figure 5.3 shows some low voltage c
cuit breakers. We will now look at the methods used to break an arc in air.

Convection causes an arc, which is hot, to rise if the contacts are properly o
ented. As the rising arc stretches its resistance increases, its current drops, and
increased surface area is exposed to cooler air, causing its temperature to dr
until the arc is finally extinguished. The longer an arc can be drawn out the easi
it is to extinguish.

Arc tips (also called arcing contacts) break after the main contacts break. Th
prevents pitting of the main contacts. Because the arc tips travel further than th
main contacts they stretch the arc further, thus making it extinguish earlier. Ar
tips are shown in Figure 5.4a. Arc horns work on the same principle except con
vection drives the arc up the spreading horns causing the arc to leave the load cur
rent carrying contacts and stretch, as shown in Figure 5.4b.

(5) Line Characteristics (Part 1)



CHAPTER IV

OVERHEAD LINES: ELECTRICAL DESIGN

Resistance of Overhead Lines. The resistance of a conductor to direct current is given by the formula

$$R = \rho l/A,$$

where ρ = the resistivity, l = the length, and A = the area of cross-section. The values of resistivity of the various materials used are given in Chapter III, and also their temperature coefficients. There is a tendency for alternating currents to concentrate near the surface of a conductor. This phenomenon is called the *skin effect* and results in an increased resistance. At 50 cycles the effect is noticeable only with conductors of large diameter. Thus the resistance to alternating current at 50 cycles of a copper conductor of diameter 0·752 in., of 97 per cent conductivity, is only 1·02 times the d.c. resistance; for the same ratio of resistances to a.c. and d.c. a 61 per cent conductivity aluminium conductor can have a diameter of 0·948 in. The skin effect is thus of small importance in overhead lines. The skin effect of a stranded conductor is the same as for a solid conductor of the same cross-section, provided the stranded conductor has no core. If it has a core, the effect is the same as for a hollow conductor and is still very small.

The effect of stranding is to increase the resistance in the way described in Chapter III. In practice it is taken that stranding increases the resistance by 2 per cent, which corresponds to a lay of 15½.

The increase in length of a line due to sag is approximately $(2d^2/3l)$. For a sag ratio, d/l, of 10 per cent this gives an extra length of only $\frac{2}{3}$ per cent, so that it may be neglected.

Inductance of an Overhead Line. A conductor which carries current is surrounded by a magnetic field, which reacts upon the currents in this and other conductors. A long straight conductor is surrounded by a field in which the lines of magnetic force are concentric circles with the axis of the conductor through their centre. Fig. 60 shows a plane section of the magnetic field surrounding a cylindrical conductor carrying a current of I e.m. units; the direction of the lines is for the case of a current passing into the paper. At a point P distant x cm. from the centre O the force is

$$H = 2I/x.$$

The force at a point P' inside the conductor depends upon the current distribution inside the conductor. In overhead lines it may be assumed without appreciable error that the current is uniformly distributed. Then the force at P' is due only to the currents inside a circle through P' with O as centre, so that at P' the magnetic force is

$$H' = (2I/x) \times (x^2/r^2) = 2Ix/r^2,$$

where $r =$ the radius of the conductor.

If the currents can be considered as flowing along geometrical lines (i.e. of no thickness) it is sufficient to calculate the total flux and divide it by the current in order to get the inductance. But when the currents flow along wires of finite thickness it is necessary to calculate the linkages and divide by the square of the current, a linkage being the product of a current element and a flux. The linkages inside the conductor are for unit length along the axis

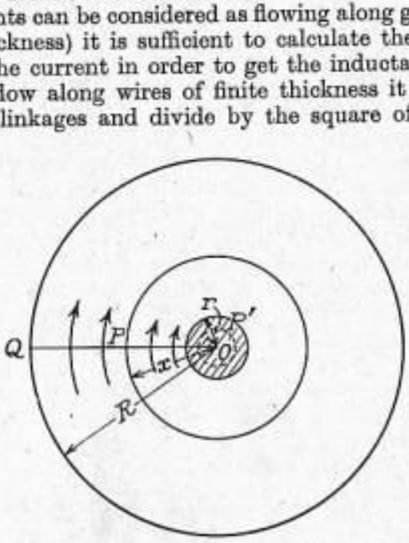


FIG. 60. MAGNETIC FIELD SURROUNDING A CONDUCTOR

$$\int_0^r H' \times I\frac{x^2}{r^2}dx = \frac{2I^2}{r^4}\int_0^r x^3dx = \tfrac{1}{2}I^2,$$

since the flux H' at P' links only a current $I \times (x^2/r^2)$.

The linkages outside up to a distance R (considered large) are

$$\int_r^{\mathrm{R}} H \times Idx = 2I^2\int_r^{\mathrm{R}}\frac{1}{x}dx = 2I^2 \text{ logh* } \frac{\mathrm{R}}{r}.$$

It is seen that the inductance *per unit length* of a long conductor is infinite, since R should be taken as infinite. In practice there is always a return conductor at a finite distance; at very great distances from both wires the flux due to this return wire neutralizes

---

* logh (R/r) = natural or hyperbolic or napierian logarithm of (R/r), viz. to the base $\varepsilon = 2{\cdot}71828$.

---

the flux due to the first wire, so that the lin
Fig. 61 shows the magnetic field due to the
conductor at a distance D from it. The linka
creates for itself between O and Q have been fo

$$\tfrac{1}{2}I^2 + 2I^2 \text{ logh } (\mathrm{R}/r).$$

The linkages created by conductor 2 round c

$$I\int_{\mathrm{D}}^{\mathrm{R}}\left(-\frac{2I}{x}\right)dx = -\,2\,I^2 \text{ lo}$$

so that the total linkages round conductor 1 ar

$$\tfrac{1}{2}I^2 + 2I^2 \text{ logh } (\mathrm{R}/r) - 2I^2 \text{ logh}$$
$$= \tfrac{1}{2}I^2 + 2I^2 \text{ logh } (\mathrm{D}/r)$$

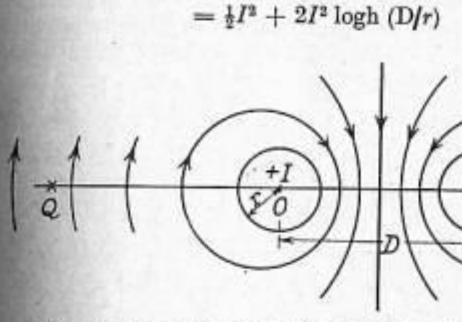


FIG. 61. MAGNETIC FIELD SURROUNDING T
CONDUCTORS

which we see is independent of R and is finite
inductance per unit length of conductor 1

$$L_1 = \tfrac{1}{2} + 2 \text{ logh } (\mathrm{D}/r).$$

The inductance of conductor 2 is the same.
the loop per unit length is

$$L_1 + L_2 = 1 + 4 \text{ logh } (\mathrm{D}/r)$$

If the wires are magnetic and have a permea
tance of the loop per cm. length is

$$L_1 + L_2 = \mu + 4 \text{ logh } (\mathrm{D}/r)$$

The unit of inductance in equations (17) and
magnetic unit, which is 10^{-9} henry. The indu
the loop is

$$L = L_1 + L_2 = [0{\cdot}161 + 1{\cdot}482 \text{ lo}$$

whilst $L_1 = L_2 = [0{\cdot}080 + 0{\cdot}741 \log (\mathrm{D}/r$

* Log (D/r) is the logarithm of (D/r) to th

Stranded conductors have a slightly higher inductance, the constant term being somewhat higher. Thus the constant for 3-strand is 0·125, 7-strand 0·103, 19-strand 0·089, 37-strand 0·085, 61-strand 0·083, solid conductor 0·080.

Example. Calculate the inductance per mile of a conductor 0·4 in. dia. at a spacing of 18 in.

$$\begin{aligned} L_1 &= [0{\cdot}080 + 0{\cdot}741 \log (18/0{\cdot}2)] \text{ mH.} \\ &= (0{\cdot}080 + 0{\cdot}741 \log 90) \\ &= 0{\cdot}080 + 1{\cdot}457 = 1{\cdot}537 \text{ mH.} \end{aligned}$$

Inductance of Three-phase Lines. Fig. 62 shows a cross-section of a three-phase system, consisting of three conductors A_1, A_2, and A_3 of radius r and spacings D_1, D_2, and D_3. The currents are I_1, I_2, and I_3, which must satisfy the relation $I_1 + I_2 + I_3 = 0$. If the loads and voltages are balanced, the currents can be represented by the three vectors shown in Fig. 63. The real components of I_2 and I_3 are $I \cos 120° = -\frac{1}{2}I_1$, whilst their imaginary components are $I_1 \sin(-120)$ and $I_1 \sin(+120°)$, viz. $-(\frac{1}{2}\sqrt{3})I_1$ and $+(\frac{1}{2}\sqrt{3})I_1$. Thus

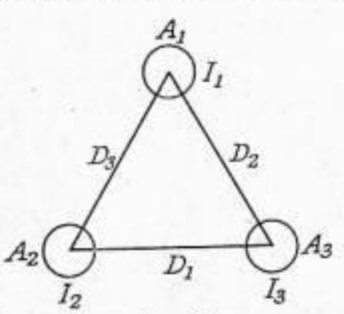


Fig. 62

Cross-section of Three-phase System

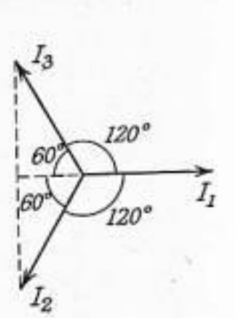


Fig. 63

Currents in Balanced, Three-phase System

$$\left.\begin{aligned} I_1 &= I_1 \\ I_2 &= [-\tfrac{1}{2} - j(\tfrac{1}{2}\sqrt{3})]I_1 = \lambda I_1, \text{ say} \\ \text{and} \quad I_3 &= [-\tfrac{1}{2} + j(\tfrac{1}{2}\sqrt{3})]I_1 = \lambda^2 I_1, \end{aligned}\right\} \quad . \quad . \quad (19)$$

$$\left.\begin{aligned} &\text{where} & j &= \sqrt{-1}, \text{ and} \\ &\text{where we have put} & \lambda &= -\tfrac{1}{2} - j(\tfrac{1}{2}\sqrt{3}). \\ &\text{It is easy to prove that} & \lambda^2 &= -\tfrac{1}{2} + j(\tfrac{1}{2}\sqrt{3}), \\ &\text{and} & 1 + \lambda &+ \lambda^2 = 0. \end{aligned}\right\} \quad . \quad . \quad (20)$$

1, λ, and λ^2 are the cube roots of unity, f

$$\sqrt[3]{1} = 1^{\frac{1}{3}} = (\cos 0 + j \sin 0)^{\frac{1}{3}} = \cos$$

$$\text{or} \qquad (\cos 360 + j \sin 360)^{\frac{1}{3}} = \cos$$

$$\text{or} \qquad (\cos 720 + j \sin 720)^{\frac{1}{3}} = \cos$$

This fact is also obvious from the vector d

The *flux* linking conductor 1 up to some l its own current is, as shown on page 82,

$$[\tfrac{1}{2} + 2 \text{ logh } (R/r)]I_1 \text{ per cm.}$$

The flux linking conductor 1 up to the current I_2 is, as shown on page 83,

$$[2 \text{ logh } (R/D_3)]I_2,$$

whilst the flux due to I_3 is

$$[2 \text{ logh } (R/D_2)]I_3.$$

The total flux linking conductor A_1 is thus

$$\begin{aligned} &[\tfrac{1}{2} + 2 \text{ logh } (R/r)]I_1 + [2 \text{ logh } (R/D_3)]I_2 + \\ &= [\tfrac{1}{2} + 2 \text{ logh } (1/r)]I_1 + [2 \text{ logh } (1/D_3)]I_2 + \\ &\qquad + (2 \text{ logh } R)(I_1 + I_2 + I_3) \\ &= [\tfrac{1}{2} + 2 \text{ logh } (1/r)]I_1 + [2 \text{ logh } (1/D_3)]I_2 + \end{aligned}$$

since $I_1 + I_2 + I_3 = 0$, even when the syste see that this flux is independent of R and is we take the flux up to infinity (at which inductance of conductor A_1 in the presence divide the preceding expression by I_1 and w

$$L_1 = \tfrac{1}{2} + 2 \text{ logh } (1/r) + [2 \text{ logh } (1/D_3)](I_2/I_1)$$

which depends upon the currents if they are

This means that we cannot represent the inductances for unbalanced currents. It i mutual inductances between pairs. If the so that equations (19) hold, we have

$$\begin{aligned} L_1 &= \tfrac{1}{2} + 2 \text{ logh } (1/r) + 2\lambda \text{ logh } (1/D_3) \\ &= \tfrac{1}{2} + 2 \text{ logh } \frac{\sqrt{(D_2 D_3)}}{r} + j\sqrt{3} \text{ logh } \end{aligned}$$

Similarly

$$L_2 = \tfrac{1}{2} + 2 \text{ logh } \frac{\sqrt{(D_3 D_1)}}{r} + j\sqrt{3} \text{ logh }$$

$$\text{and} \quad L_3 = \tfrac{1}{2} + 2 \text{ logh } \frac{\sqrt{(D_1 D_2)}}{r} + j\sqrt{3} \text{ logh }$$

The imaginary terms in L_1, L_2, and L_3 represent the transfer of power between phases due to mutual inductance, and it is seen that they add up to zero.

If the line is transposed along its length, i.e. the positions of the conductors are interchanged so that each occupies all three positions for an equal length, the inductance of each wire becomes the mean of the expressions in equations (22), so that

$$L_1 = L_2 = L_3 = \tfrac{1}{2} + \tfrac{1}{3}\left[2 \text{ logh } \frac{\sqrt{(D_2D_3)}}{r} + 2 \text{ logh } \frac{\sqrt{(D_3D_1)}}{r} \right.$$
$$\left. + 2 \text{ logh } \frac{\sqrt{(D_1D_2)}}{r}\right] = \tfrac{1}{2} + 2 \text{ logh } \frac{\sqrt[3]{(D_1D_2D_3)}}{r} \quad . \quad . \quad (23)$$

or $$0{\cdot}080 + 0{\cdot}741 \log \frac{\sqrt[3]{(D_1D_2D_3)}}{r} \text{ mH. per mile} \quad . \quad . \quad (23a)$$

If the spacings are equal to D, equations (21*a*) *et seq.* show that

$$\left.\begin{array}{ll} & L_1 = L_2 = L_3 = \tfrac{1}{2} + 2 \text{ logh } (D/r) \\ \text{or} & 0{\cdot}080 + 0{\cdot}741 \log (D/r) \text{ mH. per mile} \end{array}\right\} \quad . \quad . \quad (24)$$

even for unbalanced currents.

Skin effect decreases the inductance but only by a very small amount. The fact that the current follows spiral paths in a stranded conductor causes a small increase of inductance, but the increase is negligible at normal supply frequencies for non-magnetic wires.

Capacitance of Overhead Lines. When two cylindrical conductors have a potential difference V, they acquire charges $+ Q$ and $- Q$ per cm. length, and we say that they have a capacitance C per cm. to each other of

$$C = Q/V.$$

The charges are not spread uniformly over the surfaces but are concentrated at the inner parts of the cylinders. The exact calculation of the capacitance between two parallel, circular cylinders is known to give the value

$$\frac{1}{4 \text{ logh}\left[\dfrac{D + \sqrt{(D^2 - 4r^2)}}{2r}\right]} \text{ e.s.u. per cm. length} \quad . \quad (25)$$

The e.s.u. (electrostatic unit) of capacitance is the centimetre and is 10/9 $\mu\mu$F.

It is interesting and important to find the error caused by assuming that the charges are distributed uniformly over the cylinders. Fig. 64 shows a uniformly charged cylinder, $+ Q$ per cm. length. The electric force at every point P is radial and is the same at all points distant x from the axis. If a cylinder of radius x is drawn about the axis and has a length of 1 cm., the total electric flux crossing the cylinder is $F \times$ the area of the curved p

viz. $F \times 2\pi x$. But by Gauss's theorem this

$= 4\pi Q$.

$$\therefore \quad F \times 2\pi x = 4\pi Q,$$
$$\text{or} \qquad F = 2Q/x.$$

Fig. 65 shows two cylinders of radius r spac

having charges $+ Q$ and $- Q$. At the point P th

$$2Q/x + 2Q/(D - x).$$

The difference in potential between P_1 and

grating this force between P_1 and P_2: this sho

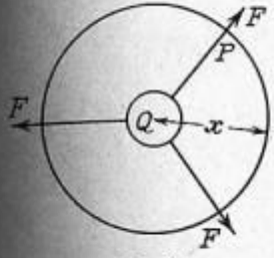


Fig. 64

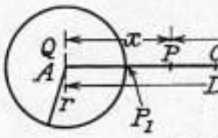


Fig.

difference between the cylinders, but actually

not be equipotentials for the two line charges.

integrate from P_1 to the centre of the other cylin

$2Q/x$, and from A to P_2 for the force $2Q/(D - x$

$$V = \int_r^{D} \frac{2Q}{x}dx + \int_0^{D-r} \frac{2Q}{D-x}$$
$$= 2Q \text{ logh } (D/r) + 2Q \text{ logh } ($$
$$= 4Q \text{ logh } (D/r).$$

This gives

$$C = \frac{Q}{V} = \frac{1}{4 \text{ logh } (D/r)} \text{ cm. per}$$

If $D = 8r$, the capacitance given by the

equation (25) is

$$1/4 \text{ logh } 7{\cdot}87 = 0{\cdot}1212 \text{ cm. per cm.}$$

whilst the approximate value given by equatio

$$1/4 \text{ logh } 8 = 0{\cdot}1203 \text{ cm. per cm.}$$

The error is thus only $\frac{3}{4}$ per cent. In overhe

mate method may thus be used without much e

The point O which is mid-way between the axes is at zero potential and is called the *neutral*. The potentials of the conductors are $\frac{1}{2}V$ and $-\frac{1}{2}V$ with respect to O, so that the capacitances C_0 to the neutral, are $2C$. Thus

$$\left.\begin{aligned} C_0 &= \frac{1}{2\ \mathrm{logh}\ (\mathrm{D}/r)}\ \text{cm. per cm. length} \\ \text{or}\qquad & \frac{0{\cdot}0388}{\log\ (\mathrm{D}/r)}\ \mu\text{F. per mile} \end{aligned}\right\} \quad . \quad . \quad . \ (27)$$

EXAMPLE. Find the capacitance to neutral of the conductors of the previous example.

Here $\mathrm{D} = 18$ in., $r = 0{\cdot}2$ in.

Therefore

$$C_0 = \frac{1}{2\ \mathrm{logh}\ 90}\ \text{cm. per cm.} = \frac{1}{2 \times 2{\cdot}303 \times \log 90}\ \text{cm. per cm.}$$
$$= \frac{10 \times 2{\cdot}54 \times 12 \times 5\,280}{2 \times 2{\cdot}303 \times \log 90 \times 9}\ \mu\text{F. per mile}$$
$$= \underline{0{\cdot}0198}\ \mu\text{F. per mile.}$$

It may be noted that

$$1/\sqrt{(LC)} = 1/\sqrt{(L_1C_0)} = 181\,000,$$

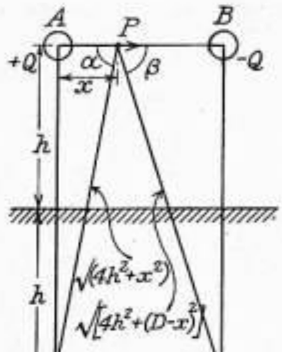


FIG. 66

which is the velocity of electro-magnetic waves along these conductors in miles per sec. The quantity

$$\sqrt{(L/C)} = \sqrt{(2L_1/\tfrac{1}{2}C_0)} = 2\sqrt{(L/C_0)}$$
$$= 556\ \Omega,$$

is the *surge impedance* of the line.

Effect of Earth. The effect of the earth may be allowed for by the method of images. Fig. 66 shows a single phase line, conductors A and B carrying charges $+Q$ and $-Q$ per cm. length, and an earth distance h below. Let A' and B' be the images of A and B in the earth. Then if conductor A' is considered to have a charge $-Q$ per cm. and B', $+Q$ per cm., the potential at any point on the earth is zero, as it should be. The electric field at any point above the earth may be considered as due to the conductors A, B, A', and B'; the field below the earth is, however, zero, since

---

the earth is considered to be a perfect cond
force at P, distance x from A, along AB is

$$\frac{2Q}{x} + \frac{2Q}{\mathrm{D}-x} - \frac{2Q\cos\alpha}{\sqrt{(4h^2+x^2)}} - \frac{2}{\sqrt{[4h^2}}$$
$$= \frac{2Q}{x} + \frac{2Q}{\mathrm{D}-x} - \frac{2Qx}{4h^2+x^2} - \frac{2Q+}{4h^2+}$$

The potential V is the integral of this force f

$$4Q\ \mathrm{logh}\ \frac{\mathrm{D}}{r} + 4Q\ \mathrm{logh}\ \frac{2h}{\sqrt{(4h^2+\mathrm{D}^2)}}\ {}^{*}$$
$$= 4Q\ \mathrm{logh}\ \frac{\mathrm{D}2h}{r\sqrt{(4h^2+\mathrm{D}^2)}} = 4Q\ \mathrm{logh}\ \frac{}{r\sqrt{}}$$

The capacitance to neutral is thus

$$C_0 = \frac{1}{2\ \mathrm{logh}\ \dfrac{\mathrm{D}}{r\sqrt{(1+\mathrm{D}^2/4h^2)}}}\ \text{cm. per cr}$$

$$\text{or}\qquad \frac{0{\cdot}0388}{\log\dfrac{\mathrm{D}}{r\sqrt{(1+\mathrm{D}^2/4h^2)}}}\ \mu\text{F. per mile}$$

EXAMPLE. Find the capacitance to neutral of the
vious example if they are 10 ft. above ground.

$$C_0 = \frac{0{\cdot}0388}{\log\dfrac{90}{\sqrt{\left(1+\dfrac{1{\cdot}5^2}{4\times 10^2}\right)}}} = \frac{0{\cdot}038}{\log 90{\cdot}}$$
$$= \underline{0{\cdot}0199}\ \mu\text{F. per mile.}$$

In the previous case $C_0 = \dfrac{0{\cdot}0388}{\log 90} = \dfrac{0{\cdot}0388}{1{\cdot}954}$,
which is only $\frac{1}{4}$ per cent less.

Generally the effect of the earth on overhead

Capacitance of Three-phase Line. Suppose
shown in Fig. 62, and that voltages V_1, V_2,
conductors with the result that the charges pe
Q_2, Q_3. The electric force due to a charged cy
Q is the charge per cm. length and x the distan
order to calculate the potential of A, we im
brought from infinity, which is assumed at zer

$$* \int \frac{2x}{4h^2+x^2}dx = \int \frac{d(x^2)}{4h^2+x^2} = \mathrm{logh}\ ($$

If the unit charge is brought from a large distance R to within a distance r of A_1, D_3 of A_2, and D_2 of A_3, the work done is

$$\int_r^R (2Q_1/x)\,dx + \int_{D_3}^R (2Q_2/x)dx + \int_{D_2}^R (2Q_3/x)dx$$

$$= 2Q_1 \text{ logh } (R/r) + 2Q_2 \text{ logh } (R/D_3) + 2Q_3 \text{ logh } (R/D_2)$$

$$= 2Q_1 \text{ logh } (1/r) + 2Q_2 \text{ logh } (1/D_3) + 2Q_3 \text{ logh } (1/D_2)$$

$$+ 2(Q_1 + Q_2 + Q_3) \text{ logh R}.$$

When R is infinite, this work is to be the potential V_1. It follows that a necessary condition is $Q_1 + Q_2 + Q_3 = 0$. Also then

$$\left.\begin{array}{l} V_1 = 2Q_1 \text{ logh } (1/r) + 2Q_2 \text{ logh } (1/D_3) + 2Q_3 \text{ logh } (1/D_2) \\ \text{Similarly} \\ V_2 = 2Q_1 \text{ logh } (1/D_3) + 2Q_2 \text{ logh } (1/r) + 2Q_3 \text{ logh } (1/D_1) \\ \text{and} \\ V_3 = 2Q_1 \text{ logh } (1/D_2) + 2Q_2 \text{ logh } (1/D_1) + 2Q_3 \text{ logh } (1/r) \end{array}\right\} \quad (28)$$

Q_1 can be found from the equations for V_1 and V_2 by replacing Q_3 by $-(Q_1 + Q_2)$ and solving. Then

$$Q_1 = \tfrac{1}{2}V_1 \frac{\text{logh } (D_1/r) - (V_2/V_1) \text{ logh } (D_2/D_3)}{\text{logh } (D_2/r) \text{ logh } (D_1/r) - \text{logh } (D_1/D_3) \text{ logh } (D_2/D_3)} \quad (28a)$$

There are similar expressions for Q_2 and Q_3. The charging currents are

$$I_1 = j\omega Q_1,\ I_2 = j\omega Q_2,\ I_3 = j\omega Q_3.$$

As the charge in equation (28a) contains a term (V_2/V_1), it is clear that the currents in a line are determined by all the line voltages.

The representation of the charging currents by capacitances is complicated except in certain cases.

EQUILATERAL SPACING. Here $D_1 = D_2 = D_3 = D$. Then $Q_1 = V_1/2 \text{ logh } (D/r)$, $Q_2 = V_2/2 \text{ logh } (D/r)$ and $Q_3 = V_3/2 \text{ logh } (D/r)$, independent of the values of the voltages. Then $Q_1/V_1 = Q_2/V_2 = Q_3/V_3 = 1/2 \text{ logh } (D/r)$, and this is called the capacitance of each line to neutral, i.e.

$$\left.\begin{array}{ll} & C_0 = 1/2 \text{ logh } (D/r) \text{ e.s.u. per cm. length} \\ \text{or} & 0{\cdot}0388/\log (D/r)\ \mu\text{F. per mile} \end{array}\right\} \quad . \quad . \quad (29)$$

TRANSPOSED LINE WITH BALANCED VOLTAGES. In this case

$$V_1 = V,\ V_2 = \lambda V,\ V_3 = \lambda^2 V, \text{ where } \lambda = -\tfrac{1}{2}(1 + j\sqrt{3}).$$

Also the conductors are transposed so as to occupy all three

positions for equal distances. It can then be show
$Q_2 = C_0V_2$ and $Q_3 = C_0V_3$, where

$$C_0 = \left[1/2 \text{ logh } \frac{\sqrt[3]{(D_1D_2D_3)}}{r}\right] \text{cm. per cr}$$

$$\text{or} \qquad \left[0{\cdot}0388/\log \frac{\sqrt[3]{(D_1D_2D_3)}}{r}\right] \mu\text{F. per}$$

Here again we call C_0 the capacitance to neutral
The effect of the earth can be found by the
described above, but the effect is generally neg
of an earth wire is found by assuming an induc
Then $Q_1 + Q_2 + Q_3 + Q_0 = 0$. Furthermore, by
tial of the earth wire to zero we obtain another e
to those obtained from the potentials of the line
are sufficient to solve the problem. The cha
increased by about 5 or 7 per cent in practical ca
of the earth wire.

Electric Stress. The electric force or stress
system is

$$2Q/x + 2Q/(D - x).$$

It is seen that this has a minimum value
maximum value for the smallest possible valu
maximum stress is thus

$$g = 2Q/r + 2Q/(D - r)$$

But $V = 4Q$ logh (D/r), so that

$$g = \frac{V}{2r \text{ logh } (D/r)}.$$

If E_0 is the voltage to neutral, $E_0 = \frac{1}{2}V$, so t

$$g = \frac{E_0}{r \text{ logh } (D/r)} \quad .$$

This formula holds for the symmetrically
system also.

In an actual case the gradient at the surface
maximum at the inner point, and varies round
Thus if $D/r = 20$ and we represent the true ma
1, the surface gradient at the outer point is 0·81 a
formula of equation (31) gives a value of 0·91. Th
formula gives a correct value for the average su
value of $D/r = 100$ or more, the various grad
than 2 per cent.

Stranding increases the maximum stress, bu
included in the formula for the corona voltage.

Corona Discharge. If the voltage is high the
reach a value at which the air breaks down, a
ductor. The conducting layer of air forms par

so that r increases and the maximum stress decreases. If the spacing is small enough, the *corona* may bridge the conductors and cause flash-over. Generally the spacing is large enough for the corona to cease spreading long before it bridges the conductors; values of r and g are reached such that the stress is insufficient to ionize any more air.

The phenomenon of corona is accompanied by a faint glow and a hissing noise. There is also an energy loss.

Disruptive Critical Voltage. The breakdown strength of air at 76 cm. pressure and 25° C. is 30 kV. per cm. or 21·1 kV. (r.m.s.) per cm. This value is called g_0. At a barometric pressure of b cm. of mercury and τ° C., the breakdown strength is δg_0, where

$$\delta = \frac{3{\cdot}92b}{273 + \tau} \quad . \quad . \quad . \quad . \quad (32)$$

If E_0 is the voltage to neutral that causes this breakdown equation (31) gives

$$E_0 = \delta g_0 r \operatorname{logh} (\mathrm{D}/r).$$

In practice it is necessary to allow for the condition of the surface of the wire, so that

$$\left.\begin{aligned} E_0 &= m\delta g_0 r \operatorname{logh} (\mathrm{D}/r) \\ &= 21{\cdot}1 m\delta r \operatorname{logh} (\mathrm{D}/r) \text{ kV. (r.m.s.) to neutral,} \end{aligned}\right\} \quad (33)$$

where $m = 1{\cdot}0$ for clean smooth wires;

$$\left.\begin{aligned} &0{\cdot}98 \text{ to } 0{\cdot}93 \text{ for roughened or weathered wires;} \\ &0{\cdot}87 \text{ to } 0{\cdot}80 \text{ for stranded wires.} \end{aligned}\right\} \quad (34)$$

The value of E_0 given by equations (33) and (34) is the *disruptive critical voltage*. Bad atmospheric conditions, such as fog, rain, or sleet, may reduce E_0 to 0·8 of the value given above.

Visual Critical Voltage. When the voltage of the line is the disruptive critical value, there is no visible corona. This is explained as being due to the fact that the charged ions in the air must be able to receive a finite energy before they can cause further ionization by collision, which is necessary for the corona discharge. Peek states that the disruptive critical voltage must be so exceeded that the stress is greater than the breakdown value up to a distance of $0{\cdot}3\sqrt{(\delta r)}$ cm. from the conductor. Thus visual corona will occur when the breakdown value is attained at the distance $r + 0{\cdot}3\sqrt{(\delta r)}$ from the axis, instead of at the distance r. This requires that the voltage to neutral be $(1 + 0{\cdot}3/\sqrt{(\delta r)})$ times the disruptive critical voltage. Thus the visual critical voltage is

$$E_v = 21{\cdot}1 m_v \delta r \left(1 + \frac{0{\cdot}3}{\sqrt{(\delta r)}}\right) \operatorname{logh} \frac{\mathrm{D}}{r} \text{ kV. (r.m.s.) to neutral} \quad (35)$$

---

m_v is a roughness factor, which is unity f
When the wire is stranded or rough, m_v is
states that m_v may be taken as 0·72 for stranc
is likely to occur in local places only; for de
length of the conductor he takes the value 0·

Corona Power Loss. If the visual corona v
power loss due to corona is given by

$$P = (390/\delta)\,(f + 25)\,[\sqrt{(r/\mathrm{D})}]\,(E - E_0)^2$$
$$\text{per phase,} \quad . \quad . \quad .$$

where f = the frequency in cycles per sec.,
and E = voltage to neutral.

High voltage lines are seldom designed tc
visual corona: what corona there is is loca
equation (36) will not hold accurately.

Example. Find the disruptive critical and vis
Grid line operating at 132 kV., the conductors b
steel-cored aluminium at a minimum spacing of
60° F., barometer 29·0 in.

Here $\mathrm{D} = 150$ in. and $r = 7 \times 0{\cdot}11$ in. $\div$

$$\tau = 60° \text{ F.} = 15{\cdot}6° \text{ C.}; \; b = 73{\cdot}7 \text{ cm.}$$

$$\delta = \frac{3{\cdot}92 \times 73{\cdot}7}{273 + 15{\cdot}6} = 1{\cdot}00.$$

$$E_0 = 21{\cdot}1m \times 0{\cdot}98 \operatorname{logh} \frac{150}{0{\cdot}385}$$

$$= m \times 21{\cdot}1 \times 0{\cdot}98 \times 2{\cdot}303 \times 2{\cdot}6$$

$$= 126m \text{ kV. (r.m.s.) to neutral.}$$

As the conductors are stranded, we take m =
and $m = 0{\cdot}83 \times 0{\cdot}8$ for rough weather. We

$$E_0 = \begin{cases} \underline{104} \text{ kV. in fine weat} \\ \underline{83} \text{ kV. in rough we} \end{cases}$$

$$1 + \frac{0{\cdot}3}{\sqrt{(\delta r)}} = 1 + \frac{0{\cdot}3}{\sqrt{0{\cdot}98}} =$$

$$E_v = 1{\cdot}30 \times 126m_v$$

$$= 164m_v.$$

For local visual corona $m_v = 0{\cdot}72$
so that

$$E_v = \underline{118} \text{ kV.,}$$

whilst for decided corona $m_v = 0{\cdot}82$
and

$$E_v = \underline{134} \text{ kV.}$$

The actual voltage to neutral is $132/\sqrt{3} = 76$ kV. Thus there is no corona under normal circumstances.

Avoidance of Corona. The critical voltage can be raised either by increasing the spacing or the diameter of the conductors. The spacing cannot be increased greatly or the cost of the supports will be very high. The diameter of the conductors can be increased by using hollow conductors with a hemp core. Steel-cored aluminium conductors have a large diameter for a given conductivity and weight, and are thus good from the point of view of corona.

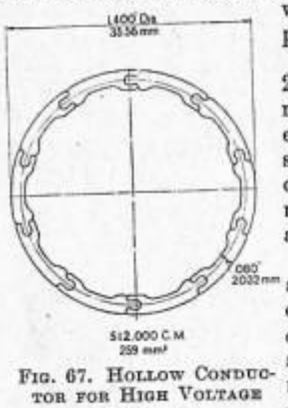


Fig. 67. Hollow Conductor for High Voltage
(*Electrician*)

For very high voltages, such as the 275 kV. of the Boulder Dam transmission scheme, it has been found economical to use the hollow conductor shown in section in Fig. 67. The conductor consists of tongued and grooved rectangular strips of copper, spiralled along the length of the conductor.

A line is usually designed to work at a voltage just below the disruptive critical voltage for fair weather (taking $\delta = 1$). It is economical to have a small corona loss in bad weather, rather than have larger conductors to avoid corona entirely. Moreover, corona acts as a safety valve for surges.

Current Effects of Corona. Corona forms when the voltage of a conductor passes the disruptive critical voltage, and disappears when the voltage descends through the same value. This occurs on each conductor every half-cycle and contributes a triple harmonic to the charging current, since the effective capacitance of the conductor increases when the corona is present. The triple harmonic currents pass through the neutral to earth in an earthed system; in a non-earthed system the neutral has a voltage to earth of triple frequency.

Insulators. Pin-type, suspension and strain insulators are shown in Figs. 48 and 49. Single-piece, pin-type insulators are used up to 26 kV., and multi-part types up to 80 kV. Above 50 kV. it is more economical to use suspension-type insulators, as they are cheaper and lighter. Moreover, the insulation of the line can be co-ordinated by using insulators with more units at some points of the line where breakdown or flash-over is to be avoided, and less units at other points where flash-over can do no costly damage. If it is desired to raise the working voltage at some later date, suspension insulators are very useful, as extra units can be added at small cost. The insulators on the Boulder Dam line are cap- and pin-type suspension insulators and have 24 units. The suspension type is preferable from the mechanical point of view, as it allows the conductor to

---

take up a position in which the insulator exper
only. Furthermore the earthed cross-arm is
and protects the line to some extent from light

If a flash-over creates an arc from the cond
cross-arm, the porcelain is liable to be shatt
arcing horns and ring, which draw the arc awa
lengthen the path and help to extinguish the a
the flash-over voltage of the insulator, but
outweighs this slight disadvantage.

Suspension-type Insulators. The voltage
cross-arm and conductor is not shared equally

Fig. 68.
of Sus

a suspension-type insulator because of the earth capacitances of the units. In consequence the flash-over voltage of a string of insulators is less than the flash-over voltage of a unit multiplied by the number of units. The *string efficiency* is defined as

$$(E/ne) \times 100 \text{ per cent} \quad . \quad (37)$$

where E is the flash-over voltage of the string, e that of a unit, and n is the number of units.

When the insulator is wet the direct capacitance between units is increased, whilst the earth capacitances are not increased (except for the unit ne
The result is a more uniform distribution of
when the unit is dry, and the string efficiency

The string efficiency can be increased in sever
is to design the units such that the direct capac
is much greater than the capacitance to earth:
be achieved. Another method is to increase the
the lower units: this is very inconvenient a
desirable that units be interchangeable. A thi
grading ring placed near the lower units and
as shown in Figs. 49 and 51. This ring screens
decreasing their earth capacitances; and it in
capacitances between the line and the insulat
tances being greater for the lower units an
voltages across them.

Example. Sketch the construction of a suspensio
how the voltage distribution over a string of insulator
explain what is meant by "string efficiency."

A string of suspension insulators consists of three
between each link pin and earth is one-sixth of the
unit. If the maximum peak voltage per unit is not to
the greatest working voltage and the string efficiency
(*B.Sc., Lo*

The voltage at the termination is thus

$$E_r = E + E' = \frac{2R/(1 + pCR)}{Z + R/(1 + pCR)} E$$
$$= \frac{2R}{Z(1 + pCR) + R.} E.$$

It must be remembered that $p = d/dt$ and E is a voltage which is zero until $t = 0$ and E after $t = 0$. E_r may be found in the following way.

$$E = \frac{Z(1 + pCR) + R}{2R} E_r$$
$$= \tfrac{1}{2}(pCZ + Z/R + 1)E_r$$
$$= \tfrac{1}{2}CZ(dE_r/dt) + \tfrac{1}{2}(Z/R + 1)E_r.$$

This is a linear differential equation for E_r of which the solution is

$$E_r = \frac{2E}{Z/R + 1} + A\varepsilon^{-[(Z + R)/CZR]t},$$

where A is an arbitrary constant and is determined by the fact that E_r can rise at a finite rate from its zero value. This gives

$$A = -\, 2E/(Z/R + 1)$$

so that
$$E_r = \frac{2E}{Z/R + 1} [1 - \varepsilon^{-[(Z + R)/CZR]t}]$$
$$= E_{r0} [1 - \varepsilon^{-[(Z + R)/CZR]t}],$$

where E_{r0} is the voltage at the end when there is no capacitance. Fig. 251 shows the graph of E_r. The effect of the capacitance is to cause the voltage at the end to rise to the full value gradually instead of abruptly, i.e. it flattens the wave front. It is usual to specify the condition of the wave-front by stating the time the wave takes to increase from 10 to 90 per cent of its value and multiplying by 1·25. If the wave reaches x of its value in time t

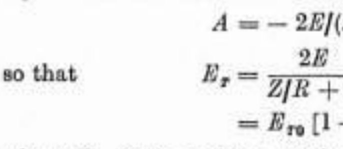


FIG. 251. FLATTENING OF WAVE DUE TO SHUNT CAPACITANCE

$$1 - \varepsilon^{-[(Z + R)/CZR]t} = x,$$

so that
$$t = \frac{CZR}{Z + R} \operatorname{logh}\left(\frac{1}{1 - x}\right).$$

The specifying time in this case is therefore

$$1{\cdot}25\,.\,[CZR/(Z + R)]\,[\operatorname{logh} 10 - \operatorname{logh} 1{\cdot}11] \text{ sec.}$$
$$= 2{\cdot}75\, CZR/(Z + R) \text{ sec.}$$

In the case of a capacitance at a point
in both directions away from it, $Z = R$ an

$$1{\cdot}37CZ \text{ sec.}$$

Thus a 10 000 $\mu\mu$F. capacitance in a
500 ohms flattens the wave so that the
becomes

$$1{\cdot}37 \times 10^{-8} \times 500 \text{ sec.} =$$

Flattening the wave-front has a very ben
the stress on the line-end windings of a
the line.

Lightning. With the increase of high-
problem of lightning is assuming greate

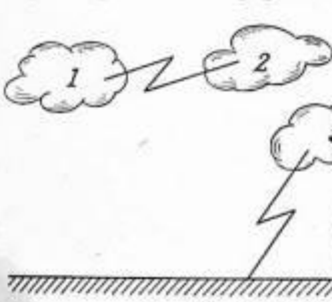


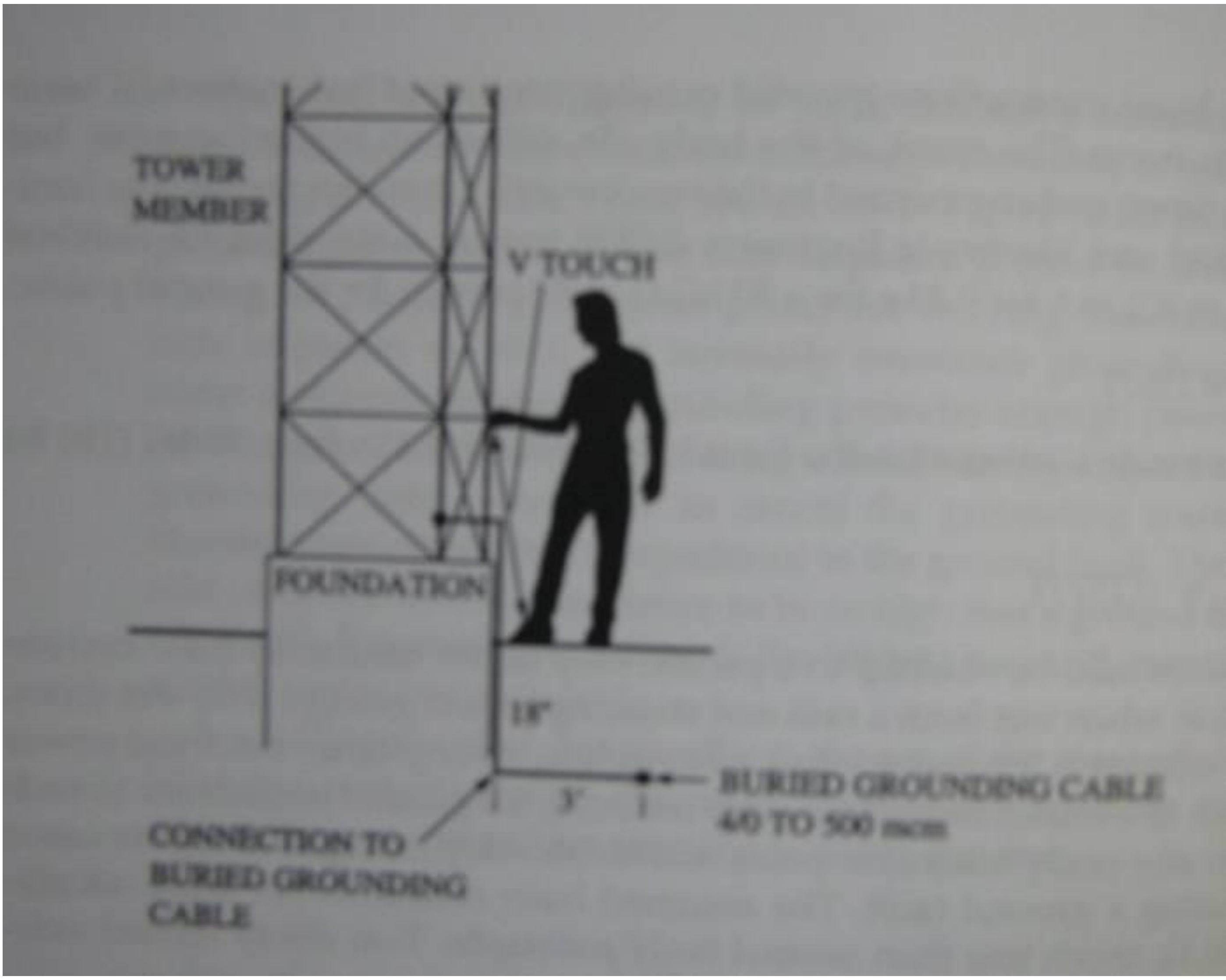
FIG. 252. B STROKE

damage is done yearly by lightning. The
which lightning affects a line: by a direct st
induction. The way in which thundercloud
high potentials is complicated and not kno
A direct stroke can take place in severa
charged cloud induces a charge of oppos
such as tall masts, church spires, etc. The
points of these objects causes ionization o
a direct stroke takes place between the clo
a stroke is known as the *A stroke*, and
comparatively long time taken to produc
strikes the highest point, usually a lightn
way results in a much more sudden strok
the manner shown in Fig. 252. Three clou
potential of cloud 3 is decreased by the
cloud 2. When cloud 1 flashes over to clo
are discharged rapidly; then cloud 3 a
potential and flashes to earth very rapidl
and is characterized by its rapidity and th

ages are defined, touch voltage and step voltage.

Touch voltage is the maximum voltage allowed on any structure from any point within reach from the ground, standing 3 feet from the structure, because of ground fault current. The maximum touch voltage is 653 V inside a substation, where only competent workers in proper clothing should be allowed, and 207 V on the substation fence. The magnitude of fault current that would produce the maximum touch voltage would be very large. Figure 10.33a illustrates the touch voltage. To minimize the touch voltage, which would be dropped along the structure, a ground conductor is buried 18 inches below the surface 3 feet from the structure as shown in Figures 10.33a and b. The buried copper cable is attached to the structure by conductor, and also connected to 58 inch copper clad rods driven 10 feet into the ground. The principle is to give the ground fault current a better path to ground than through a person hapless enough to be touching the structure at the instant of a ground fault. The buried cable also prevents a voltage from becoming too high because of fault current flowing through the soil near the structure. The 10 foot rod is needed to assure good connection of the grounding conductors to the low resistance subsoil. The resistance of topsoil is much higher than that of subsoil.

Step voltage is the maximum voltage that can flow from foot to foot as one is walking during a fault condition, as shown in Figure 10.34a. The maximum step voltage allowed is 2010 V in a substation, and 225 V at the substation fence. A high step voltage normally occurs only during a phase to ground fault. If a phase should fall to ground between two towers on a right of way, as shown in Figure 10.34b, the phase voltage will be distributed evenly along the Earth between the conductor ground point and the ground return points. If the line potential is 100 kV and the line is faulted 1000 feet from the tower on the left the ground potential


TOWER MEMBER
V TOUCH
FOUNDATION
18"
3'
BURIED GROUNDING CABLE 4/0 TO 500 mcm
CONNECTION TO BURIED GROUNDING CABLE

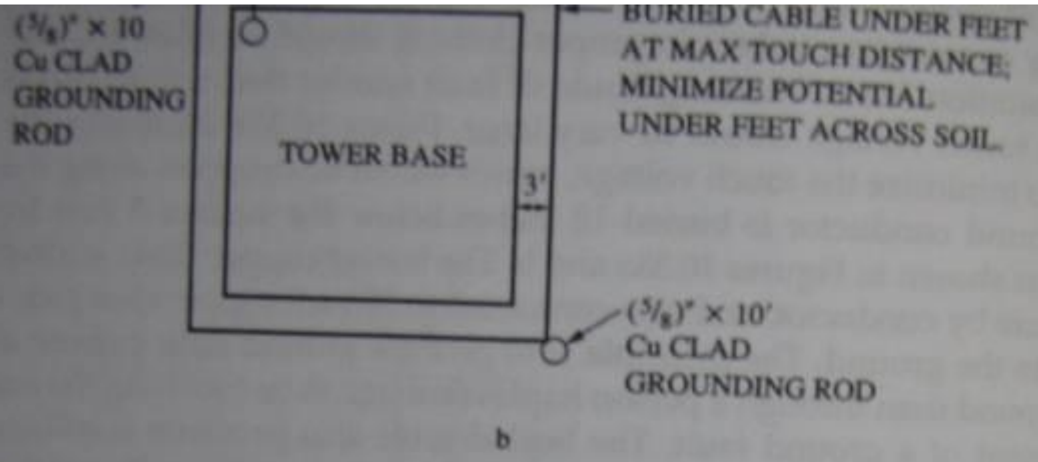


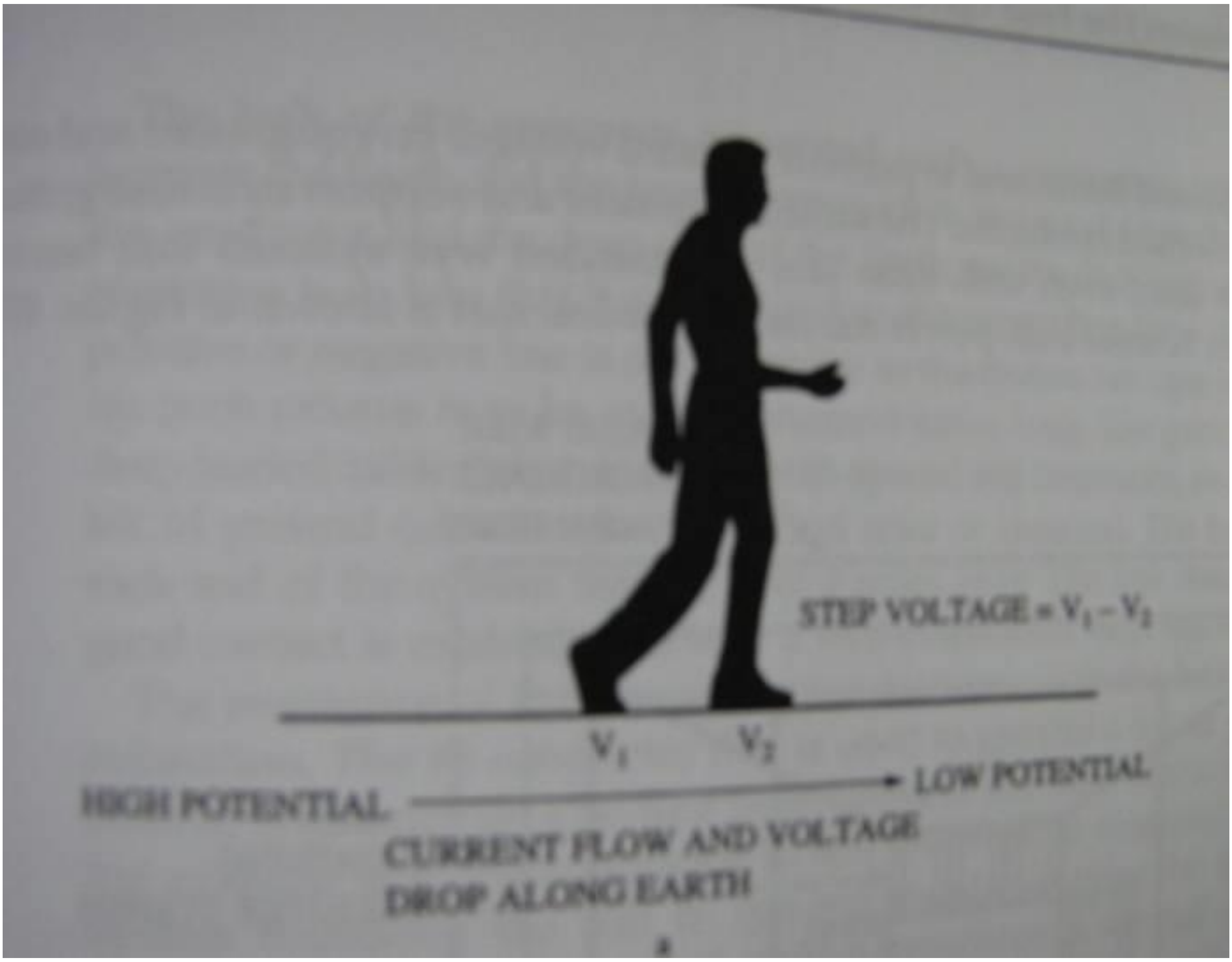
FIGURE 10.33 Touch voltage (a) Definition and (b) Minimized by grounding

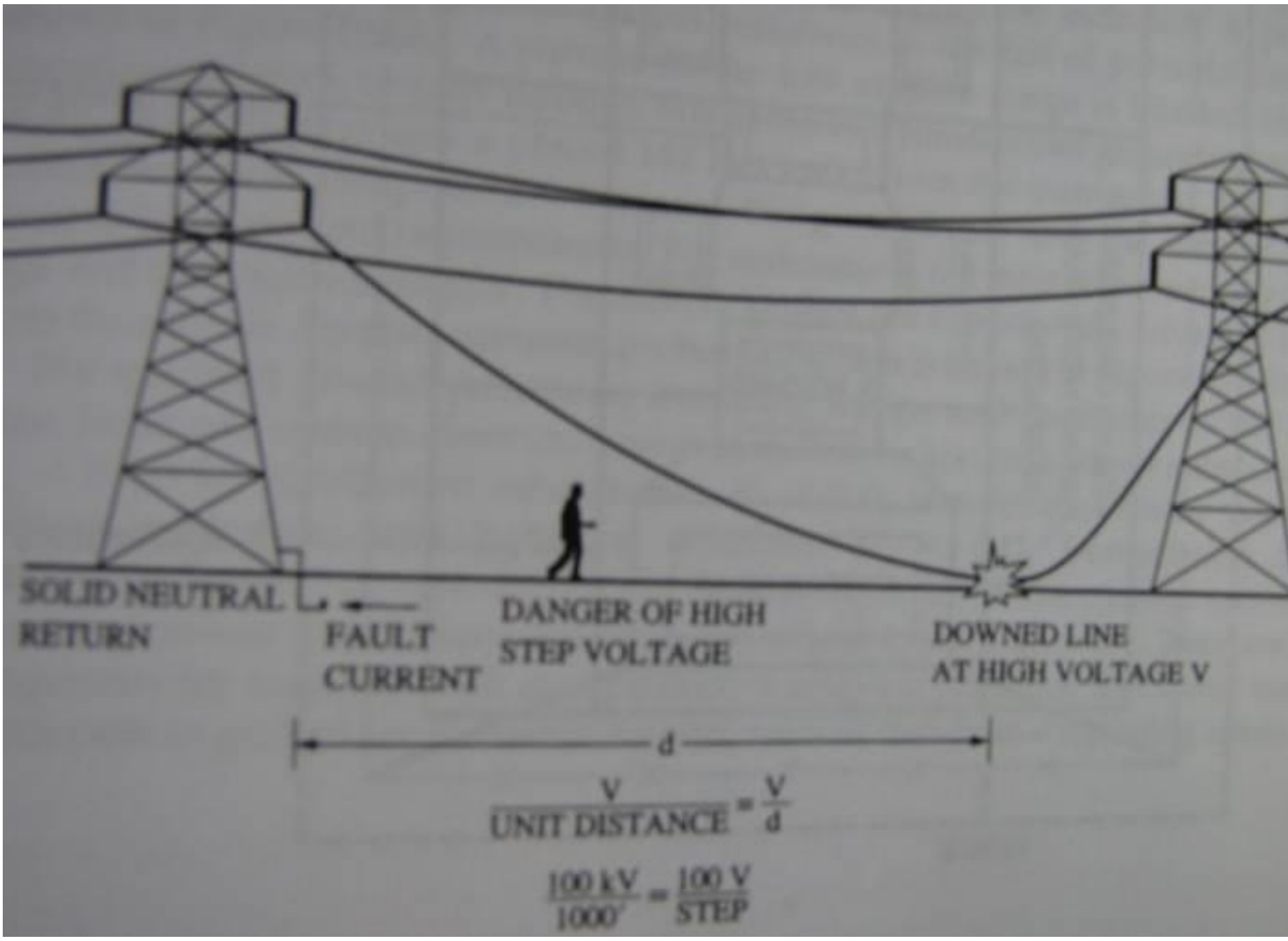
$$V_{ft} = \frac{V}{d} = \frac{100\ kV}{1000\ \text{ft}} = 100 \text{ volts per foot}$$

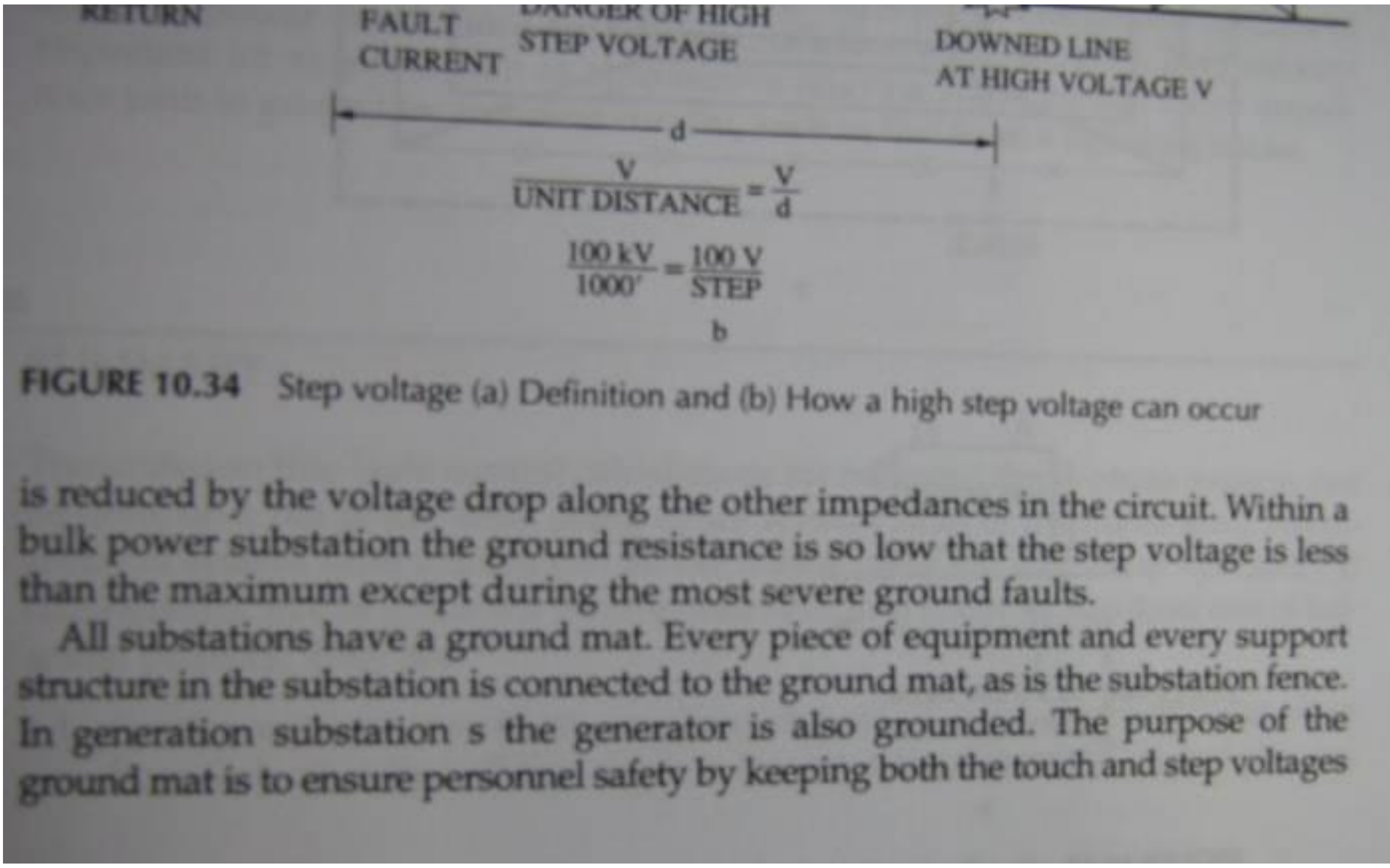
If the foot to foot body resistance of a person under the line walking with 3 feet strides is 1000 Ω, the step voltage is 300 V and the foot to foot current is

$$I_{\text{foot to foot}} = \frac{300V}{1000\Omega} = 0.3\ \text{A}$$

which is fatal. Of course foot to foot resistance is normally much higher because people normally wear shoes. Additionally the protective relays open the circuit breaker within five cycles, and the voltage at the ground point of the faulted phase


STEP VOLTAGE = $V_1 - V_2$
V_1
V_2
HIGH POTENTIAL
LOW POTENTIAL
CURRENT FLOW AND VOLTAGE DROP ALONG EARTH


SOLID NEUTRAL RETURN
FAULT CURRENT
DANGER OF HIGH STEP VOLTAGE
DOWNED LINE AT HIGH VOLTAGE V
d
$\frac{V}{\text{UNIT DISTANCE}} = \frac{V}{d}$
$\frac{100\ \text{kV}}{1000'} = \frac{100\ \text{V}}{\text{STEP}}$



$$\frac{V}{\text{UNIT DISTANCE}} = \frac{V}{d}$$

$$\frac{100\text{ kV}}{1000'} = \frac{100\text{ V}}{\text{STEP}}$$

FIGURE 10.34 Step voltage (a) Definition and (b) How a high step voltage can occur

is reduced by the voltage drop along the other impedances in the circuit. Within a bulk power substation the ground resistance is so low that the step voltage is less than the maximum except during the most severe ground faults.

All substations have a ground mat. Every piece of equipment and every support structure in the substation is connected to the ground mat, as is the substation fence. In generation substation s the generator is also grounded. The purpose of the ground mat is to ensure personnel safety by keeping both the touch and step voltages

(5) Line Characteristics (Part 2)

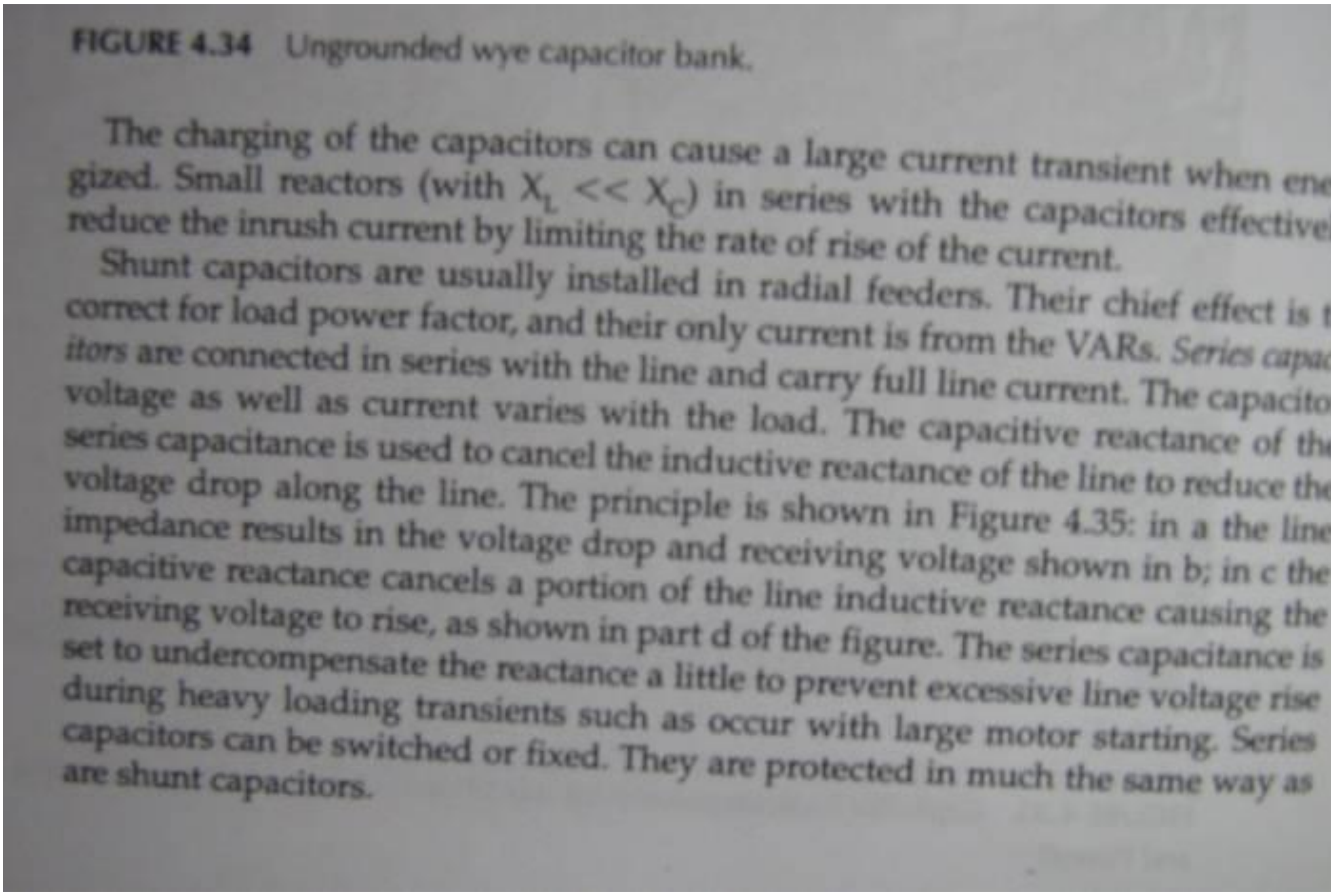
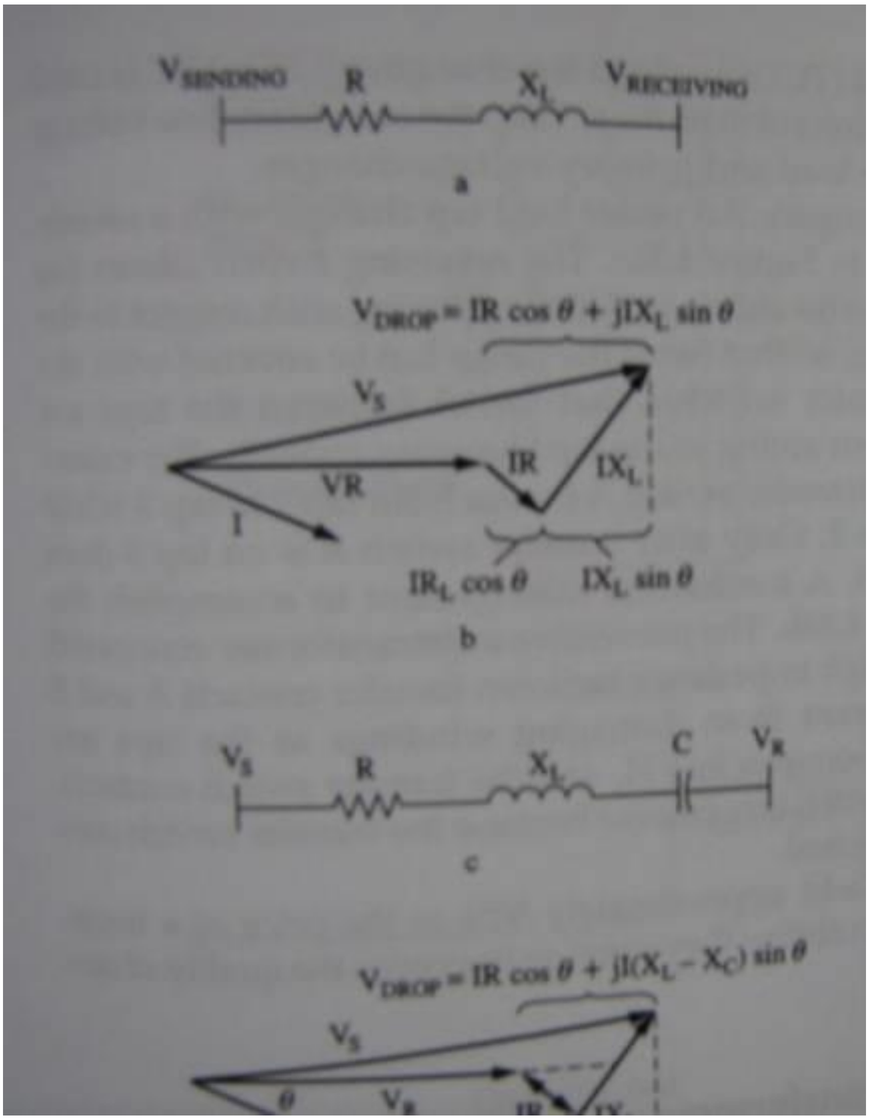
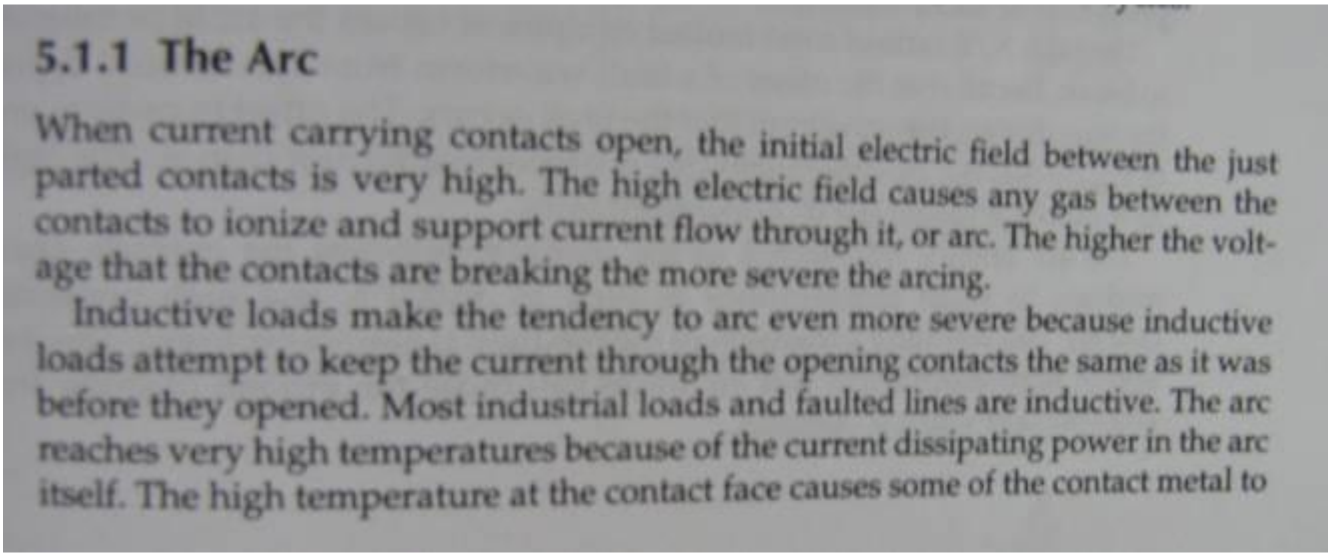


FIGURE 4.34 Ungrounded wye capacitor bank.

The charging of the capacitors can cause a large current transient when ene gized. Small reactors (with $X_L << X_C$) in series with the capacitors effective reduce the inrush current by limiting the rate of rise of the current.

Shunt capacitors are usually installed in radial feeders. Their chief effect is t correct for load power factor, and their only current is from the VARs. *Series capac itors* are connected in series with the line and carry full line current. The capacito voltage as well as current varies with the load. The capacitive reactance of th series capacitance is used to cancel the inductive reactance of the line to reduce th voltage drop along the line. The principle is shown in Figure 4.35: in a the line impedance results in the voltage drop and receiving voltage shown in b; in c the capacitive reactance cancels a portion of the line inductive reactance causing the receiving voltage to rise, as shown in part d of the figure. The series capacitance is set to undercompensate the reactance a little to prevent excessive line voltage rise during heavy loading transients such as occur with large motor starting. Series capacitors can be switched or fixed. They are protected in much the same way as are shunt capacitors.

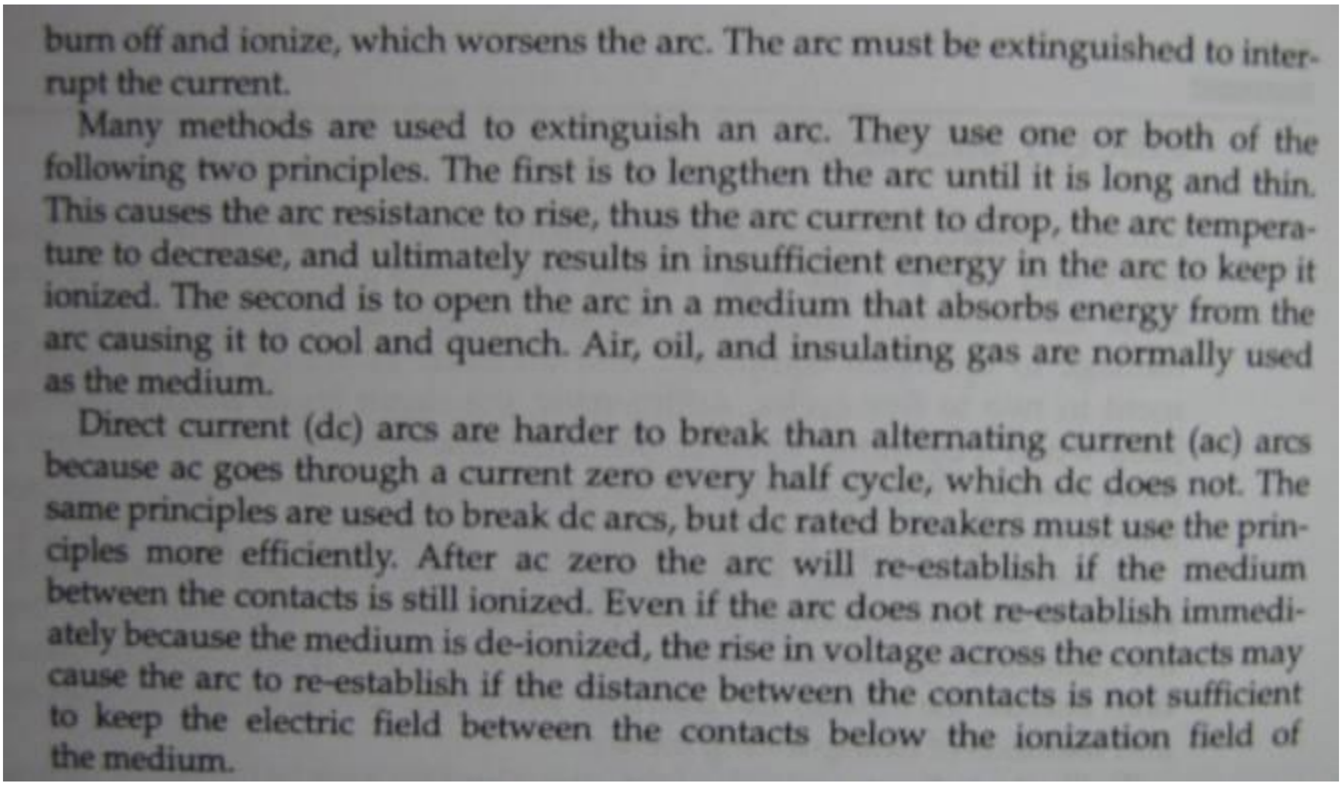




5.1.1 The Arc

When current carrying contacts open, the initial electric field between the just parted contacts is very high. The high electric field causes any gas between the contacts to ionize and support current flow through it, or arc. The higher the voltage that the contacts are breaking the more severe the arcing.

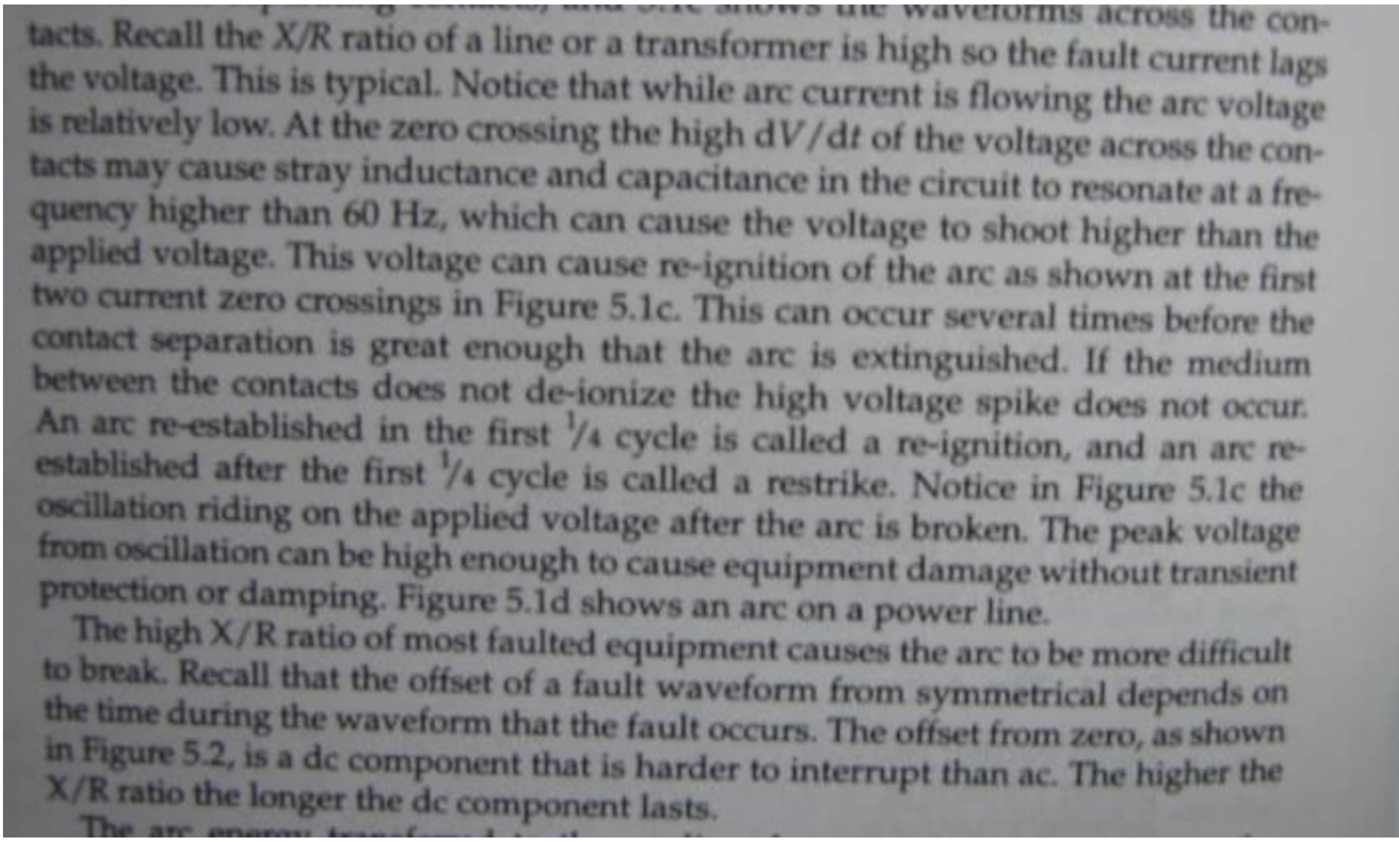
Inductive loads make the tendency to arc even more severe because inductive loads attempt to keep the current through the opening contacts the same as it was before they opened. Most industrial loads and faulted lines are inductive. The arc reaches very high temperatures because of the current dissipating power in the arc itself. The high temperature at the contact face causes some of the contact metal to



burn off and ionize, which worsens the arc. The arc must be extinguished to interrupt the current.

Many methods are used to extinguish an arc. They use one or both of the following two principles. The first is to lengthen the arc until it is long and thin. This causes the arc resistance to rise, thus the arc current to drop, the arc temperature to decrease, and ultimately results in insufficient energy in the arc to keep it ionized. The second is to open the arc in a medium that absorbs energy from the arc causing it to cool and quench. Air, oil, and insulating gas are normally used as the medium.

Direct current (dc) arcs are harder to break than alternating current (ac) arcs because ac goes through a current zero every half cycle, which dc does not. The same principles are used to break dc arcs, but dc rated breakers must use the principles more efficiently. After ac zero the arc will re-establish if the medium between the contacts is still ionized. Even if the arc does not re-establish immediately because the medium is de-ionized, the rise in voltage across the contacts may cause the arc to re-establish if the distance between the contacts is not sufficient to keep the electric field between the contacts below the ionization field of the medium.



waveforms across the contacts. Recall the X/R ratio of a line or a transformer is high so the fault current lags the voltage. This is typical. Notice that while arc current is flowing the arc voltage is relatively low. At the zero crossing the high dV/dt of the voltage across the contacts may cause stray inductance and capacitance in the circuit to resonate at a frequency higher than 60 Hz, which can cause the voltage to shoot higher than the applied voltage. This voltage can cause re-ignition of the arc as shown at the first two current zero crossings in Figure 5.1c. This can occur several times before the contact separation is great enough that the arc is extinguished. If the medium between the contacts does not de-ionize the high voltage spike does not occur. An arc re-established in the first $^1/_4$ cycle is called a re-ignition, and an arc re-established after the first $^1/_4$ cycle is called a restrike. Notice in Figure 5.1c the oscillation riding on the applied voltage after the arc is broken. The peak voltage from oscillation can be high enough to cause equipment damage without transient protection or damping. Figure 5.1d shows an arc on a power line.

The high X/R ratio of most faulted equipment causes the arc to be more difficult to break. Recall that the offset of a fault waveform from symmetrical depends on the time during the waveform that the fault occurs. The offset from zero, as shown in Figure 5.2, is a dc component that is harder to interrupt than ac. The higher the X/R ratio the longer the dc component lasts.

The arc

is relatively low. At the zero crossing the high dV/dt of the voltage across the contacts may cause stray inductance and capacitance in the circuit to resonate at a frequency higher than 60 Hz, which can cause the voltage to shoot higher than the applied voltage. This voltage can cause re-ignition of the arc as shown at the first two current zero crossings in Figure 5.1c. This can occur several times before the contact separation is great enough that the arc is extinguished. If the medium between the contacts does not de-ionize the high voltage spike does not occur. An arc re-established in the first $^1/_4$ cycle is called a re-ignition, and an arc re-established after the first $^1/_4$ cycle is called a restrike. Notice in Figure 5.1c the oscillation riding on the applied voltage after the arc is broken. The peak voltage from oscillation can be high enough to cause equipment damage without transient protection or damping. Figure 5.1d shows an arc on a power line.

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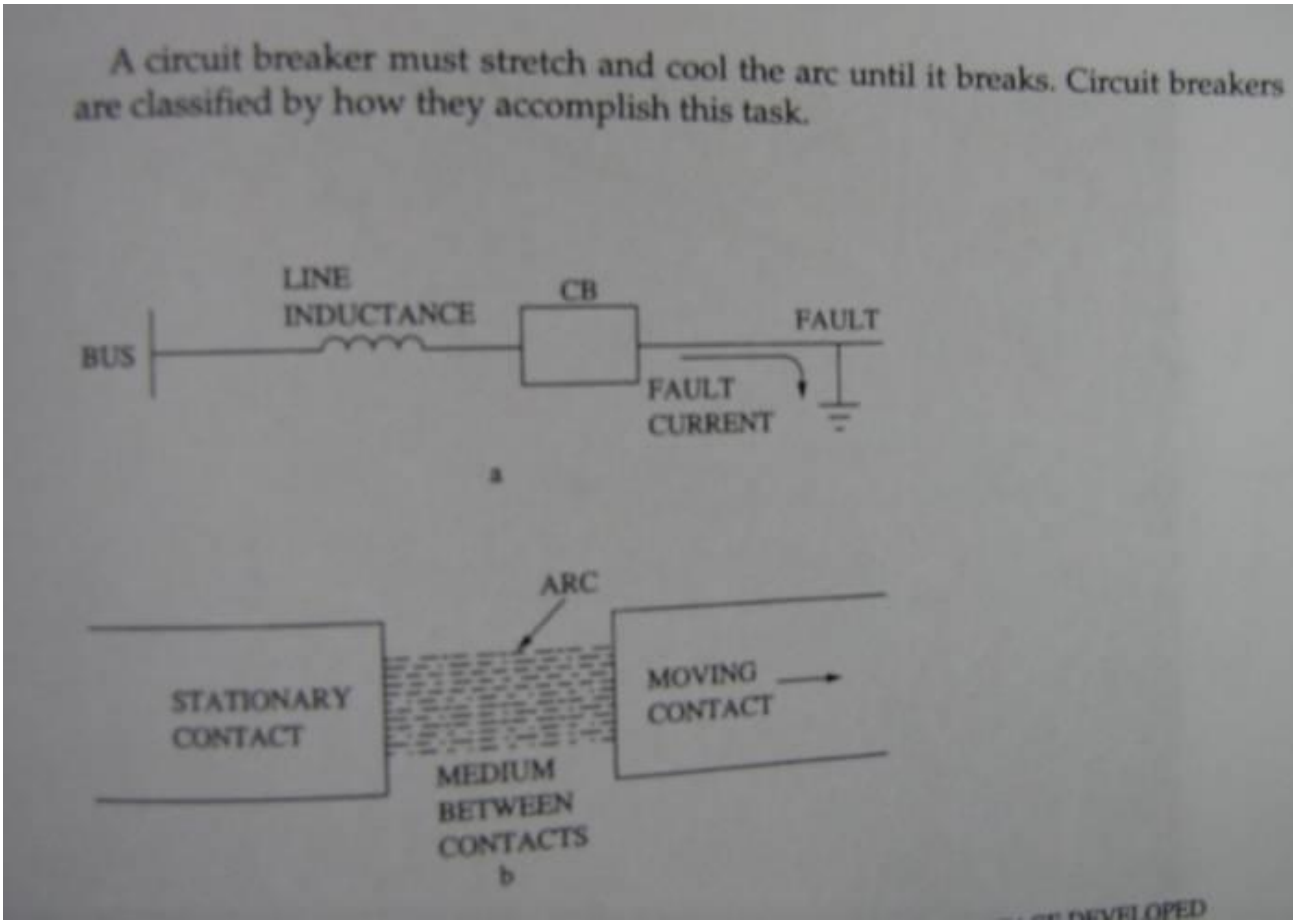
The arc energy transferred to the medium between the contacts causes the medium to reach temperatures as high as 30,000°K and high pressures very quickly. The resulting expansion of the medium is almost explosive. The combination of high mechanical and arc forces can cause the ground to shake around a large breaker when it operates.



A circuit breaker must stretch and cool the arc until it breaks. Circuit breakers are classified by how they accomplish this task.

(5) Line Characteristics (Part 3)

b

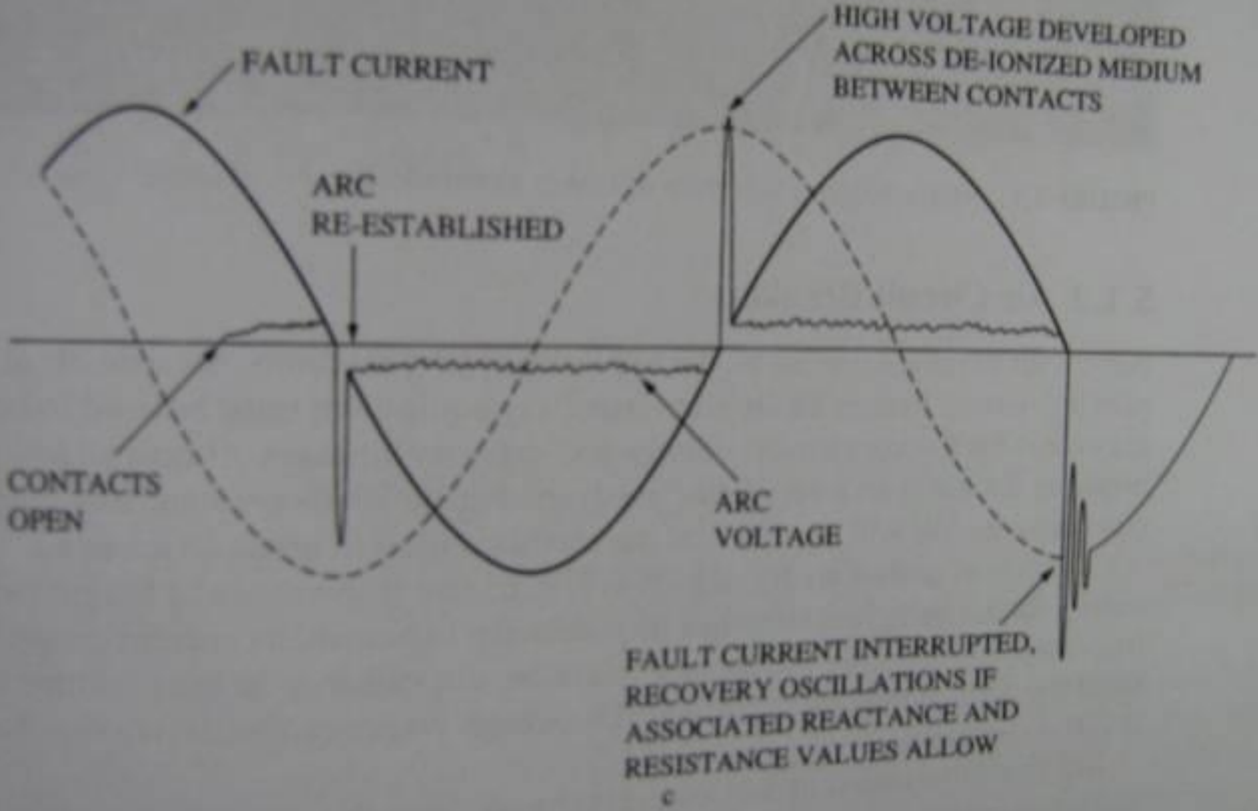
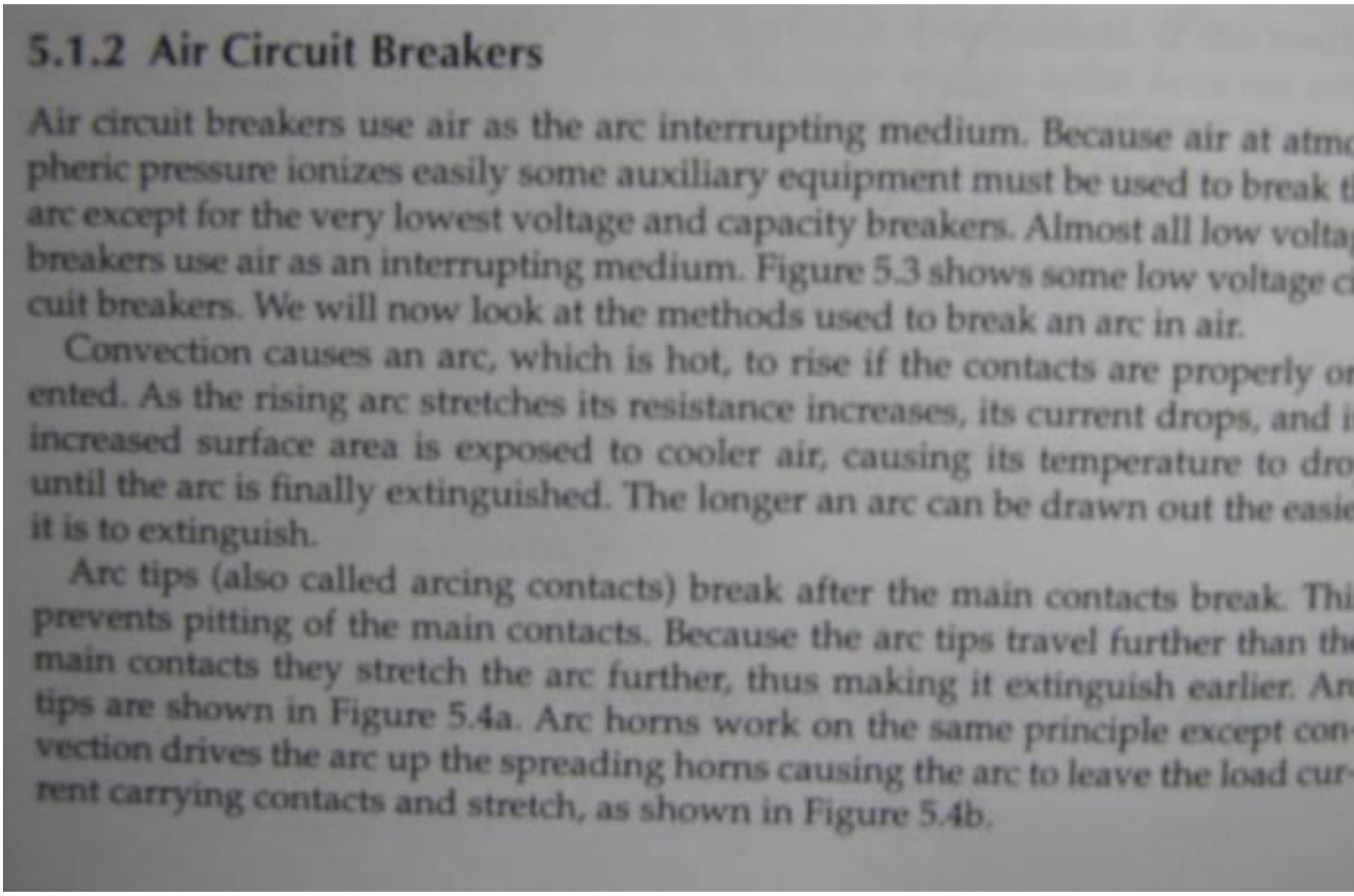


FIGURE 5.1 Contact arc (a) Equivalent circuit (b) Contacts and (c) Waveforms

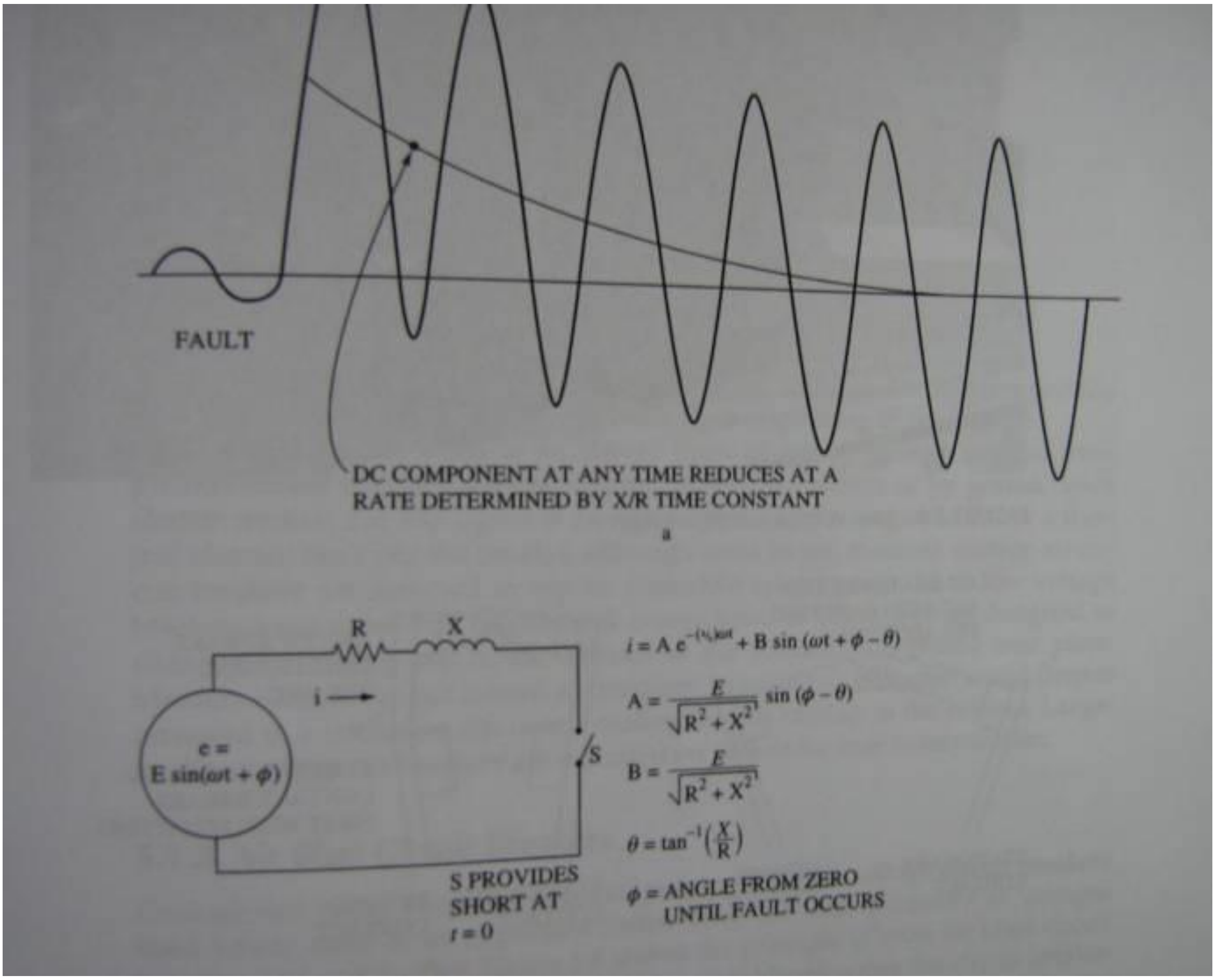


5.1.2 Air Circuit Breakers

Air circuit breakers use air as the arc interrupting medium. Because air at atmo
pheric pressure ionizes easily some auxiliary equipment must be used to break t
arc except for the very lowest voltage and capacity breakers. Almost all low volta
breakers use air as an interrupting medium. Figure 5.3 shows some low voltage c
cuit breakers. We will now look at the methods used to break an arc in air.

Convection causes an arc, which is hot, to rise if the contacts are properly or
ented. As the rising arc stretches its resistance increases, its current drops, and i
increased surface area is exposed to cooler air, causing its temperature to dro
until the arc is finally extinguished. The longer an arc can be drawn out the easie
it is to extinguish.

Arc tips (also called arcing contacts) break after the main contacts break. Thi
prevents pitting of the main contacts. Because the arc tips travel further than th
main contacts they stretch the arc further, thus making it extinguish earlier. Ar
tips are shown in Figure 5.4a. Arc horns work on the same principle except convection drives the arc up the spreading horns causing the arc to leave the load current carrying contacts and stretch, as shown in Figure 5.4b.



$$i = A\,e^{-({}^{R}\!/_{X})\omega t} + B \sin(\omega t + \phi - \theta)$$

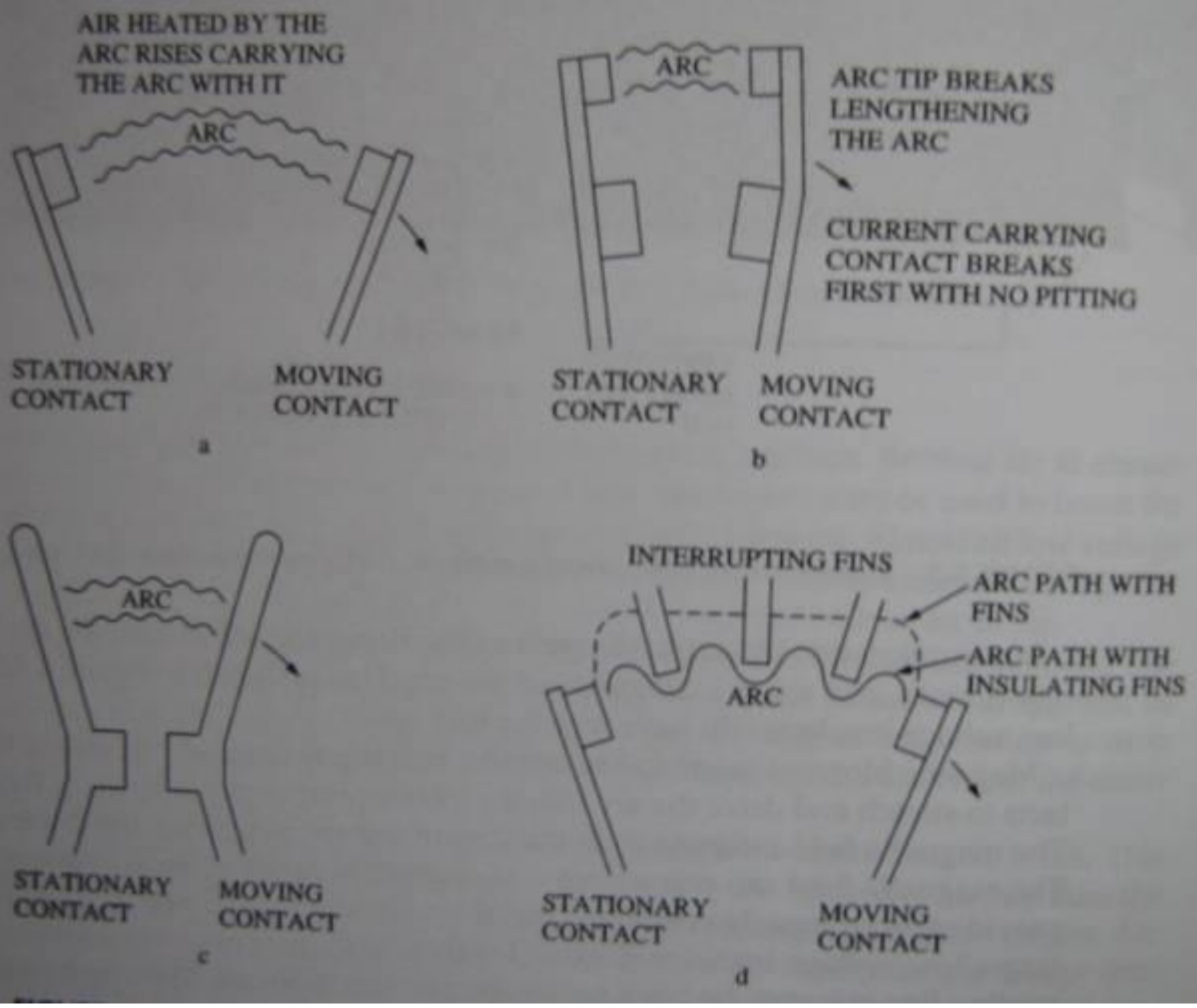
$$A = \frac{E}{\sqrt{R^2 + X^2}} \sin(\phi - \theta)$$

$$B = \frac{E}{\sqrt{R^2 + X^2}}$$

$$\theta = \tan^{-1}\left(\frac{X}{R}\right)$$

ϕ = ANGLE FROM ZERO
UNTIL FAULT OCCURS

FIGURE 5.3 Low voltage circuit breakers



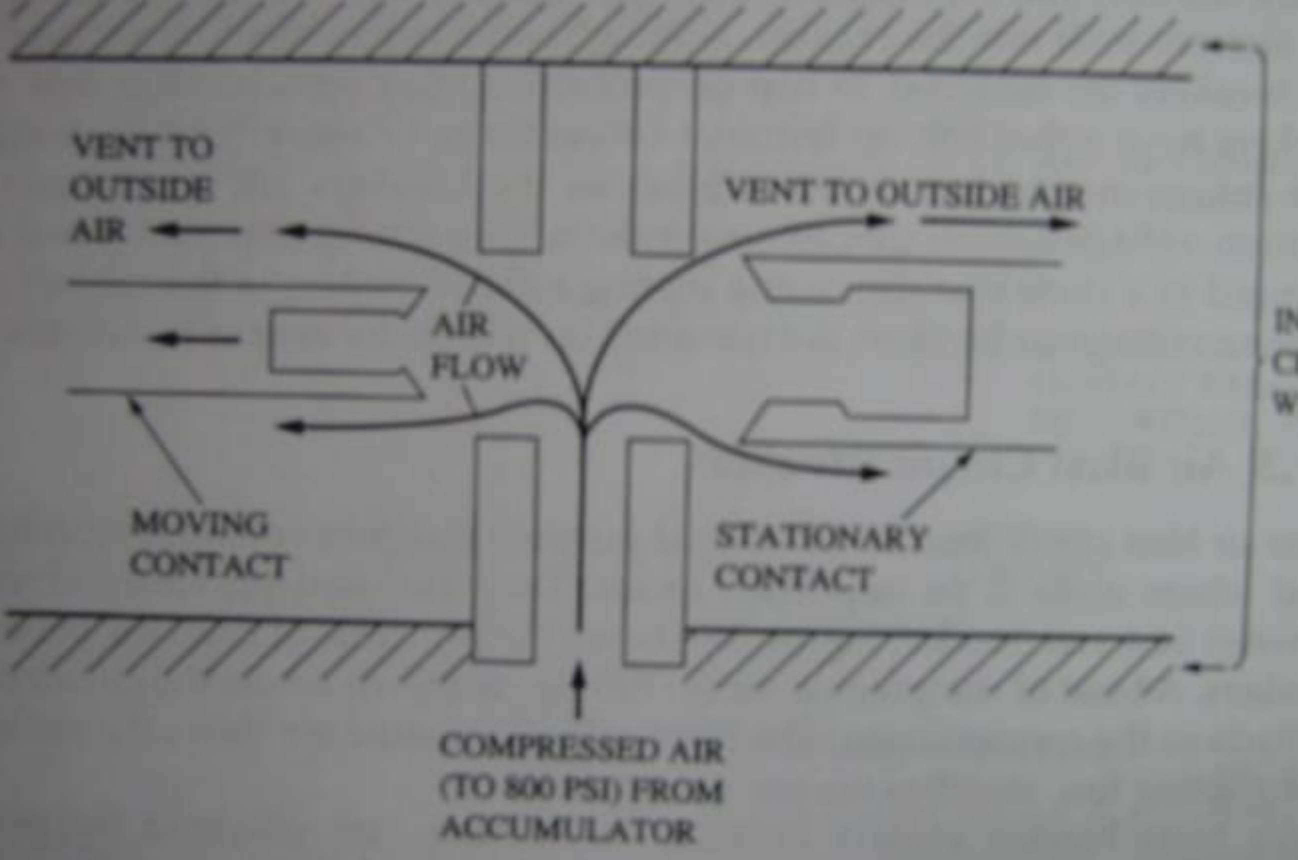
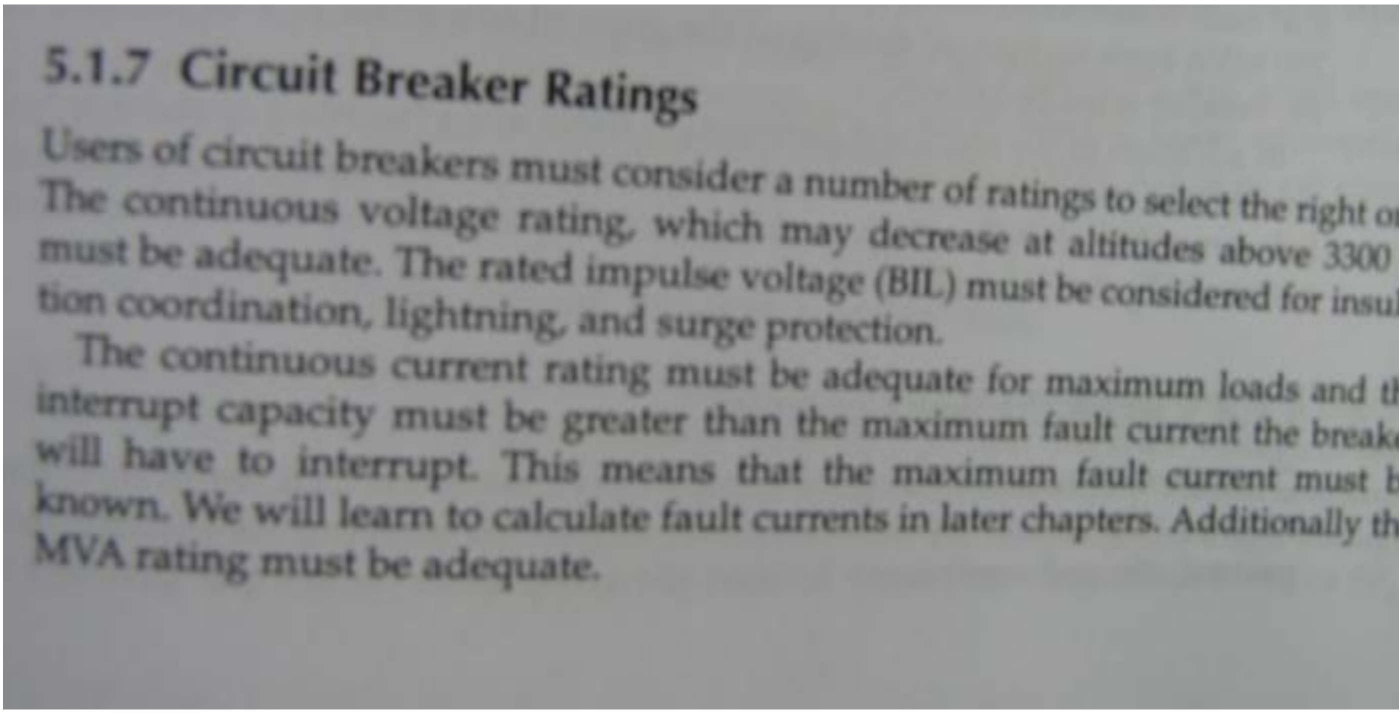


FIGURE 5.7 Axial air blast circuit breaker principle



5.1.7 Circuit Breaker Ratings

Users of circuit breakers must consider a number of ratings to select the right o
The continuous voltage rating, which may decrease at altitudes above 3300
must be adequate. The rated impulse voltage (BIL) must be considered for insul
tion coordination, lightning, and surge protection.

The continuous current rating must be adequate for maximum loads and th
interrupt capacity must be greater than the maximum fault current the break
will have to interrupt. This means that the maximum fault current must b
known. We will learn to calculate fault currents in later chapters. Additionally th
MVA rating must be adequate.

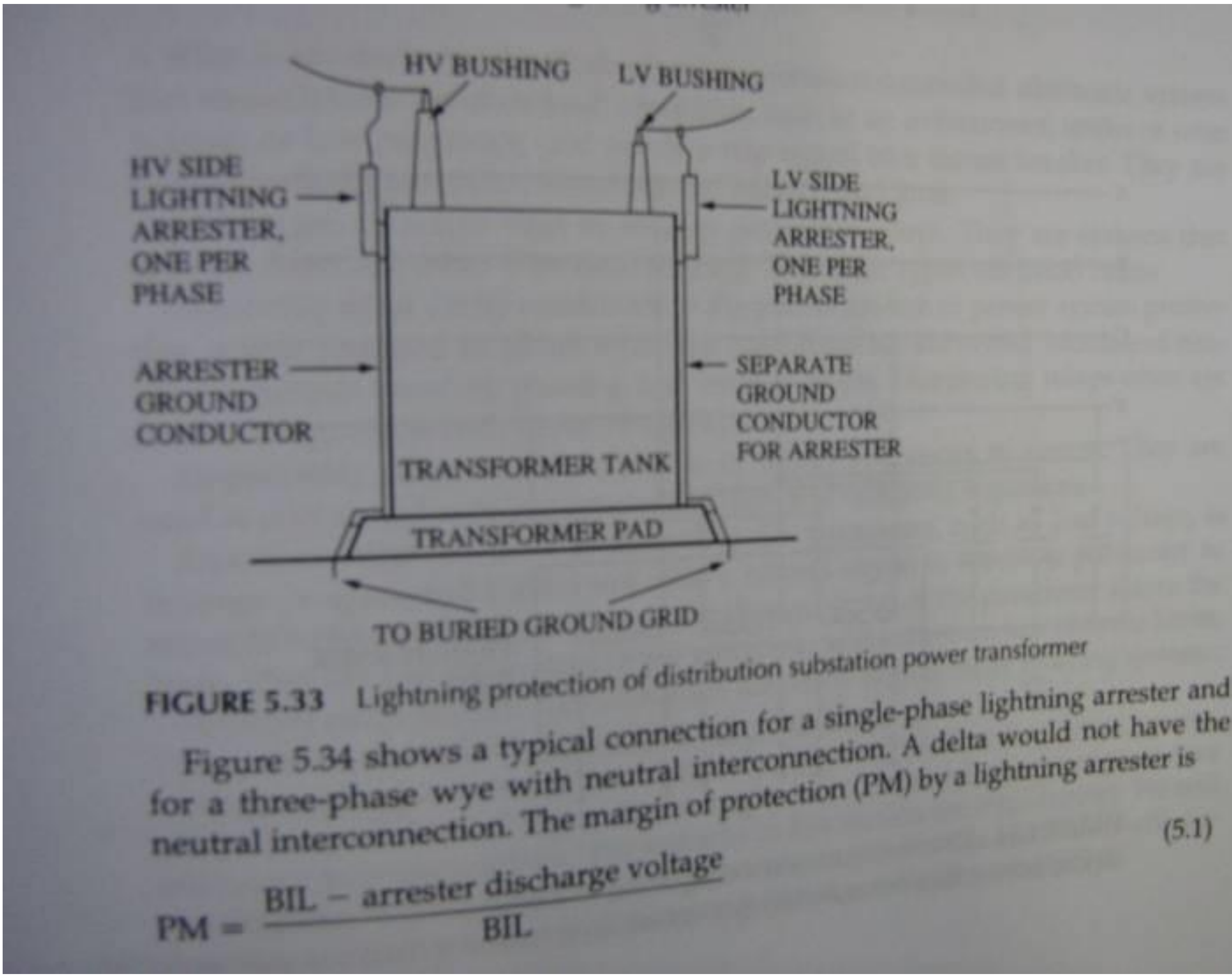


FIGURE 5.33 Lightning protection of distribution substation power transformer

Figure 5.34 shows a typical connection for a single-phase lightning arrester and for a three-phase wye with neutral interconnection. A delta would not have the neutral interconnection. The margin of protection (PM) by a lightning arrester is

$$PM = \frac{\text{BIL} - \text{arrester discharge voltage}}{\text{BIL}} \qquad (5.1)$$

(5) Line Characteristics (Part 4)

The voltage drop from A to C is now $0{\cdot}07 \times 22{\cdot}15 = 1{\cdot}55$ volts and the drop from A to D is $(0{\cdot}04 \times 32{\cdot}85) + (0{\cdot}03 \times 25) = 2{\cdot}06$ volts. When the feeder CD is replaced, the potential difference of 0·51 volts drives a circulating current from C to D via DE and EAC and EC in parallel. The resistance of EAC and EC in parallel is 0·0236, so that the circulating current has the value

$$\frac{0{\cdot}51}{0{\cdot}02 + 0{\cdot}03 + 0{\cdot}0236} = 6{\cdot}9 \text{ amperes.}$$

Of this the part that flows through EC is $0{\cdot}11/0{\cdot}14 \times 6{\cdot}9 = 5{\cdot}4$ amperes, and 1·5 amperes flows through EAC. The resulting system of currents is shown in Fig. 125 (a).

$$I_1 = I_2 = 23{\cdot}65,\ I_3 = -13{\cdot}25 = -I_6,\ I_4 = 6{\cdot}9,\ I_5 = 31{\cdot}35,$$
and $\mathrm{I}_7 = 18{\cdot}1$ amperes.

The results obtained by adding columns C and D of the method of superposition are

$$I_1 = I_2 = 23{\cdot}6,\ I_3 = -13{\cdot}4 = -I_6,\ I_4 = 7{\cdot}0,\ I_5 = 31{\cdot}4,$$
and $I_7 = 18{\cdot}0$ amperes,

which are in good agreement.

(5) **Use of Thévénin's Theorem.** Appendix IV states and proves Thévénin's theorem, and gives also some applications. The theorem is the following:

If a network has two terminals A and B between which there is placed an impedance Z, the current through Z is given by

$$I = E/(Z + Z_1),$$

where E is the potential difference between A and B when Z is removed, and Z_1 *is the impedance of the network between A and B calculated by assuming that generators are replaced by impedances equal to their internal impedances.*

By the internal impedance of a generator is meant that impedance which causes a drop in the terminal voltage when current flows. Thus if Z_i is the internal impedance of a generator, the voltage when a current I is taken is the open-circuit e.m.f. less IZ_i (which is called the *internal drop*). In an alternator it is called the *synchronous impedance*.

Example. Find the current I_1 in Fig. 122 by the use of Thévénin's theorem.

We assume that the feeder AB is removed and the network is then as shown in Fig. 126. The current along AE is 125 A.: let the current along ED be I. The remaining currents are then easily written down in terms of I, which is found by equating voltage drops along EFC and EDC. We get

$$0{\cdot}01(95 - I) + 0{\cdot}02(75 - I) = 0{\cdot}03I + 0{\cdot}02(I - 25),$$
giving
$$I = 36{\cdot}9 \text{ A.}$$

The potential difference between A and B is

$$\begin{aligned} E &= (0{\cdot}04 \times 125) + 0{\cdot}03I + 0{\cdot}02(I - 25) + (0{\cdot}03 \times 20) \\ &= 5{\cdot}10 + 0{\cdot}05I = 6{\cdot}94 \text{ V.} \end{aligned}$$

The resistance of the network between A and B is

$$Z_1 = 0{\cdot}04 + \frac{0{\cdot}03 \times 0{\cdot}05}{0{\cdot}03 + 0{\cdot}05} + 0{\cdot}03 = 0{\cdot}08875\ \Omega.$$

$$\text{giving } I_1 = \frac{\mathrm{E}}{Z + Z_1} = \frac{6{\cdot}94}{0{\cdot}04 + 0{\cdot}08875} = \frac{6{\cdot}94}{0{\cdot}12875} = \underline{53{\cdot}9} \text{ A.}$$

The method of circulating currents may be considered as an extension of Thévénin's theorem. Thus we have just found that the insertion of the feeder AB causes a current of 53·9 A. to flow from A to B. This current must flow along B to C, from C to E by the paths through D and F, then from E to A. If we add the currents due to I_1 to those given in Fig. 126 we get the full solution.

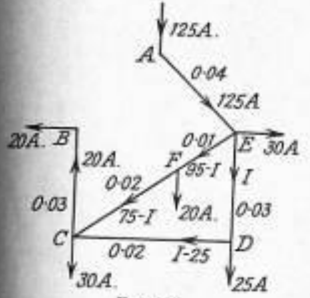


Fig. 126

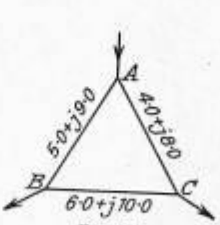


Fig. 127

A.C. Interconnected Systems. The method is the same as for d.c. but complex algebra is required. In systems that are not too complicated a vector diagram helps one to visualize what is happening. The following example illustrates the method.

Example. A three-phase distribution system is as shown in Fig. 127. Power is supplied at A at 11 kV. (line voltage) and balanced loads of 50 A. per phase at 0·8 lagging power factor and 70 A. at 0·9 lagging power factor are taken at B and C respectively. The impedances of the feeders are $AB = (5{\cdot}0 + j9{\cdot}0)\,\Omega$., $BC = (6{\cdot}0 + j10{\cdot}0)\,\Omega$., $CA = (4{\cdot}0 + j8{\cdot}0)\,\Omega$. Calculate the voltage at B and C and the current in each branch. Power factors are assumed with respect to voltage at A. (*Lond. Univ.*, 1933.)

The simplest method of solution is by means of Thévénin's theorem or the method of circulating currents. We take the voltage at A as the basic vector. Then the current at B is

$$I_B = 50\,|\overline{\cos^{-1} 0{\cdot}8} = 40 - j30$$

and the current at C is

$$I_C = 70\,|\overline{\cos^{-1} 0{\cdot}9} = 63 - j30{\cdot}5.$$

The current at A is

$$I_A = I_B + I_C = 103 - j60{\cdot}5 = 119{\cdot}5\,|\overline{30^\circ\,9'},$$

so that A supplies at a power factor of 0·868.

If we assume that the feeder BC is removed, the current in AB is I_B and in AC it is I_C. The voltage drop per phase in AB is

$$\begin{aligned}(5{\cdot}0 + j9{\cdot}0)I_B &= (5{\cdot}0 + j9{\cdot}0)\,(40 - j30)\\ &= 470 + j210,\end{aligned}$$

and in AC

$$\begin{aligned}(4{\cdot}0 + j8{\cdot}0)I_C &= (4{\cdot}0 + j8{\cdot}0)\,(63 - j30{\cdot}5)\\ &= 496 + j382.\end{aligned}$$

The potential of B is above that of C by

$$\begin{aligned}E &= 496 + j382 - 470 - j210\\ &= 26 + j172.\end{aligned}$$

The impedance of the network is

$$Z_1 = 5{\cdot}0 + j9{\cdot}0 + 4{\cdot}0 + j8{\cdot}0 = 9{\cdot}0 + j17{\cdot}0$$

and

$$Z = 6{\cdot}0 + j10{\cdot}0.$$

The current in BC is thus

$$\begin{aligned}\frac{E}{Z + Z_1} = \frac{26 + j172}{15{\cdot}0 + j27{\cdot}0} &= \frac{174\,|\underline{81^\circ\,24'}}{30{\cdot}9\,|\underline{61^\circ\,0'}}\\ &= \underline{5{\cdot}6\,|\underline{20^\circ\,24'}\text{ A.}} = 5{\cdot}3 + j1{\cdot}96.\end{aligned}$$

The current in AB is thus

$$40 - j30 + 5{\cdot}3 + j1{\cdot}96 = 45{\cdot}3 - j28{\cdot}0 = \underline{53{\cdot}3\,|\overline{31^\circ\,42'}\text{ A.}}$$

and in AC

$$63 - j30{\cdot}5 - 5{\cdot}3 - j1{\cdot}96 = 57{\cdot}7 - j32{\cdot}5 = \underline{66{\cdot}2\,|\overline{29^\circ\,48'}\text{ A.}}$$

The voltage drop between lines from A to B is

$$(\sqrt{3})(5{\cdot}0 + j9{\cdot}0)\,(45{\cdot}3 - j28{\cdot}0) = 846 + j463,$$

and from A to C

$$(\sqrt{3})(4{\cdot}0 + j8{\cdot}0)\,(57{\cdot}7 - j32{\cdot}5) = 850 + j474.$$

The voltage at B is therefore

$$11\,000 - 846 - j463 = 10\,154 - j463 = \underline{10\,164\,|\overline{2^\circ\,36'}}$$

and the voltage at C is

$$10\,150 - j474 = \underline{10\,160\,|\overline{2^\circ\,40'}}.$$

EXAMPLES VI

1. A 12·5 kV. transmission line connected with transformers at each end delivers 250 kVA. at a p.f. of 0·8 lagging to the low voltage bars in the substation. The line has a total resistance of 10 Ω. and an inductive reactance of 30 Ω.; each transformer has a ratio 2 000/11 000. The resistance and reactance on the low and high voltage sides are 0·04 Ω. and 0·125 Ω., 1·3 Ω. and 4·5 Ω. respectively.

Calculate the bus-bar voltage and p.f. at the generating end and the overall efficiency of transmission for a receiver pressure of 2 000 V.

2. A 3-phase overhead transmission line, in which the line voltage at each end is maintained constant at 33 kV., has a resistance per phase of 5 Ω. and a reactance per phase of 13 Ω.

Deduce an expression for the power delivered over the lines in terms of the angle between the sending-end voltage and the receiving-end voltage.

Plot to scale a curve of power to a base of angles and explain how to use this curve to determine the dynamic stability of the line.

(*Lond. Univ.*, 1948.)

3. Discuss the advantages of interconnecting generating stations (as in the National Grid) compared with the operation of stations as isolated plants. Explain, with the aid of convections and vector diagrams, the conditions governing the transference of power from one station to another, assuming the same bus-bar voltage at each station. Explain also how the magnitude, direction, and power factor of such power transference are controlled.

(*Lond. Univ.*, 1950.)

4. A 30-mile three-phase transmission line delivers 8 000 kW. at 33 kV. 0·8 p.f. lagging. The impedance of single conductors is 0·60 + j0·72 Ω. per mile. Find the regulation, efficiency, generator voltage and power factor.

5. Construct a line chart for a three-phase line delivering a balanced load at 30 kV., the impedance of each conductor being (1·6 + j3·3) Ω. Find the generator voltage at 1 000 kW. at power factors of 0·9 and 0·7 leading and lagging.

6. In the preceding example find the power that can be received at 0·8 p.f. lagging at 30 kV. if the generator voltage is 33 kV.

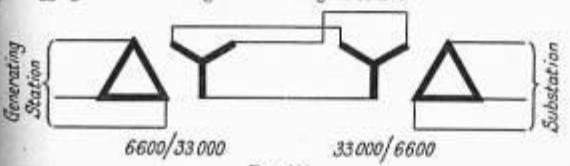


Fig. 128

7. A substation receives 6 000 kVA. at 6 kV. 0·8 p.f. lagging on the low voltage side of a transformer from a generating station through a three-phase cable system having a resistance of 7 Ω. and reactance of 2 Ω. per phase. Identical 6 600/33 000 transformers are installed at each end, the 6 600 V.

equivalent system reduced to the receiving station voltage. Let the currents I_1 and I_2 along the feeders be postulated by considerations of the current carrying capacities of the feeders: given the magnitudes of I_r, I_1, and I_2, the phase positions of the latter two are fixed in either of two positions by a parallelogram of currents, and are shown in Fig. 150. The most economical condition occurs when $I_1 + I_2$ is a minimum, and this is when they lie on I_r so that $I_1 + I_2 = I_r$. Let the impedances of the feeders and transformers referred to the receiving-end voltage be Z_1 and Z_2. The voltages at P_1 and P_2 are $E_r + I_1Z_1$ and $E_r + I_2Z_2$, and are shown as E_1 and E_2.

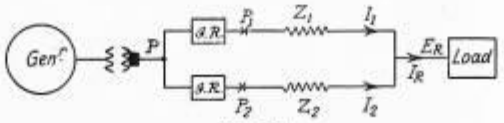


FIG. 151

It is possible to produce these voltages at P_1 and P_2 by means of two similar three-phase induction regulators and one common tap-changing transformer, as shown in Fig. 151, in the following way. Let the voltage circles of the induction regulators intersect at C and C'. If the regulators are set in positions corresponding to one of these points, the voltage at P is given by OC or OC' and may be achieved by the use of the tap-changing transformer.

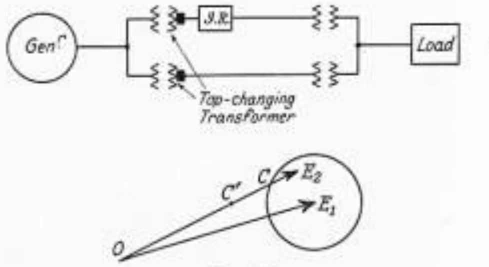


FIG. 152

Another way is to use two tap-changing transformers and one three-phase induction regulator, as shown in Fig. 152. Let the voltage circle of the induction regulator intersect E_2 at C. Let the generating voltage be represented by OC'. The first tap-changing transformer must increase the voltage from OC' to OC, and the second from OC' to E_2. If the generator voltage can be increased to OC by increasing the excitation, there is no need for a transformer in series with the induction regulator, and then the second transformer needs a tap-ratio of $OC : E_2$; we require then only an induction regulator in one feeder and a tap-changing transformer in the other. It is, of course, understood that the steam has been regulated to provide the required load.

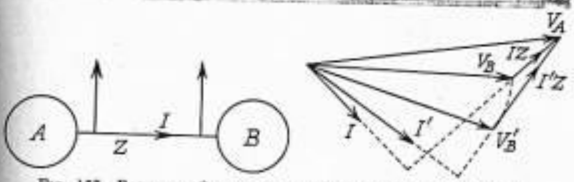


FIG. 153. PARALLEL OPERATION OF GENERATORS CONNECTED BY A LINE

If the regulation is not very large and the load is not sensitive to voltage, it will be sufficient to keep a fixed generator voltage. Then all other voltages and the load will be reduced in the proportion OC' to OC. The *division of the load* will remain as above merely by the use of one induction regulator and one tap-changing transformer.

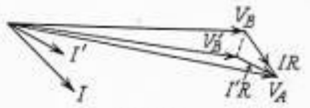


FIG. 154

PARALLEL OPERATION OF GENERATORS CONNECTED BY A LINE

Parallel Operation of Generators. Suppose that the two generating stations A and B are supplying loads and that current I flows from A to B. The voltages V_A and V_B at the stations are given in the vector diagram of Fig. 153. Suppose now that additional load is thrown on to the bus-bars of station B. The generator voltage at B will fall back in phase to V_B', so that the voltage difference becomes $V_A - V_B'$ and the current increases to I', which is larger than I and more in phase with V_A. Thus station A sends more power to B and the steam governor adjusts itself to meet the condition. The reverse happens when load is taken off the bus-bars of B or load is thrown on to the bus-bars at A. In the vector diagram shown in Fig. 153 we have represented Z, the impedance of the interconnector, as a pure reactance. When the interconnector is a pure resistance, the vector diagram is as shown in Fig. 154. It is seen that when load is thrown on to B the current I diminishes so that less power flows from A to B, and B is therefore called upon to supply more load. This is progressive and leads to hunting and instability The presence of reactance in the interconnector is thus essential for stability.

The synchronous capacity of an interconnector is defined as the change of kilowatts transmitted per radian change of angular displacement of the voltages of the two systems. It can be shown to be

$$(E^2X/1\,000Z^2)\ \text{kW}.$$

It is stated that if the total capacity of the plant in the smaller station is less than this, the interconnector has sufficient reactance to hold the stations in step.

Voltage Control by Power Factor. The effect of power factor on voltage regulation has been worked out on pages 137–42, and a line chart for a particular example is shown in Fig. 106. Thus with a given receiving-end voltage of 10 kV. and load of 1 000 kW., the sending-end voltage is 16·8 kV. at a power factor of 0·5 lagging, 14·6 at 0·7 lagging, 13·3 at 0·9 lagging, 10·8 at 0·9 leading, 9·7 at 0·7 leading, and 8·6 at 0·5 leading. By control of the power factor we can therefore vary the voltage of the line over a very wide range of values.

For example, we can make the voltages at the sending- and receiving-ends equal by a proper choice of the power factor in the following way.

Putting $E_s = E_r$ we see that equation (69) gives

$$R\cos\phi_r + X\sin\phi_r = -IZ^2/2E_r, \quad . \quad . \quad . \quad (69)$$

or $$R\cos^2\phi_r + X\sin\phi_r\cos\phi_r = -P(R^2 + X^2)/2E_r^2$$

or $$R\cos 2\phi_r + X\sin 2\phi_r = -(PZ^2/E_r^2) - R.$$

Substituting for R and X in terms of the line impedance angle we get

$$\begin{aligned}\cos\psi\cos 2\phi_r + \sin\psi\sin 2\phi_r &= -(PZ/E_r^2 + R/Z)\\ &= \cos(\psi - 2\phi_r),\end{aligned}$$

so that

$$\phi_r = \tfrac{1}{2}\psi + \tfrac{1}{2}\cos^{-1}(\cos\psi + PZ/E_r^2) - (\pi/2) \quad . \quad (92)$$

For example when $P = 0$ this reduces to

$$\begin{aligned}\phi_r &= \tfrac{1}{2}\psi + \tfrac{1}{2}\psi - \pi/2\\ &= \psi - \pi/2.\end{aligned}$$

Example. Find the power factor for equal sending- and receiving-end voltages in the above system when the load is 1 000 kW.

$R = 16$, $X = 30$, $Z = 34$, $\psi = 90^\circ - 28^\circ\,3' = 61^\circ\,57'$, $\cos\psi = 0{\cdot}47$.

$$PZ/E_r^2 = 0{\cdot}34.$$

$$\begin{aligned}\therefore \qquad \phi_r &= 30^\circ\,58' + \tfrac{1}{2}\cos^{-1}0{\cdot}81 - \pi/2\\ &= 30^\circ\,58' + 17^\circ\,57' - 90^\circ\\ &= -41^\circ\,1',\end{aligned}$$

and the power factor is 0·75 leading.

From Fig. 106 it is seen that at equal sending- and receiving-end voltages of 10 kV. and load of 1 000 kW. the reactive kVA. is 860 kVAR. leading, giving

$$\tan\phi_r = -0{\cdot}86,$$

or $$\phi_r = -41^\circ,$$

in agreement with what we have found.

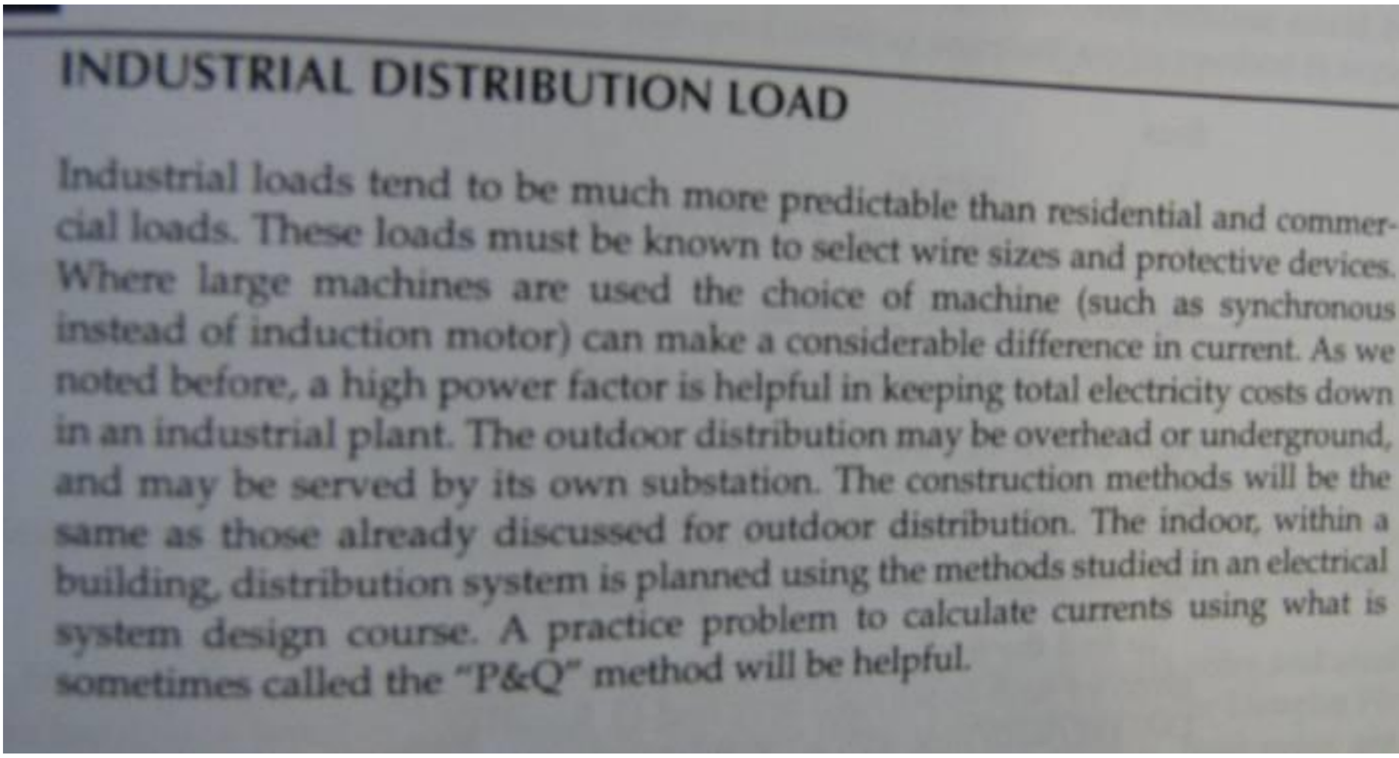
In this case the in-phase current is 100 amperes and the wattless current 86 amperes, so that the total current is 133 amperes.

It may be noted that at unity power factor the sending-end voltage is 12·0 kV. and the current is 100 amperes. It is then a question of economics whether it is worth while raising the current from 100 amperes to 133 amperes in order to achieve zero regulation. If the phase angle is adjusted to the necessary negative value to give zero regulation, no other regulating equipment is required. But the current-carrying capacity of the alternator and line or cable must be greater in the ratio of 133 : 100 than for the case when the power factor is unity; in the latter case, however, regulating equipment, in the form of tap-changing or booster transformers, is required. In practice it is found worth while to operate as near unity power factor as possible, as then the plant can be used to the maximum advantage and the line losses for a given transmitted load are a minimum. Thus in the case just discussed, the losses at unity power factor are only nine-sixteenths of those at the condition of equal sending- and receiving-end voltages.

The advantages of advancing the phase to as near unity power factor as possible are thus, (1) the load output of a given plant is increased and with it the earning capacity, (2) line losses are reduced to a minimum, (3) voltage regulation is considerably reduced, and (4) there is a beneficial effect upon the stability of the system.

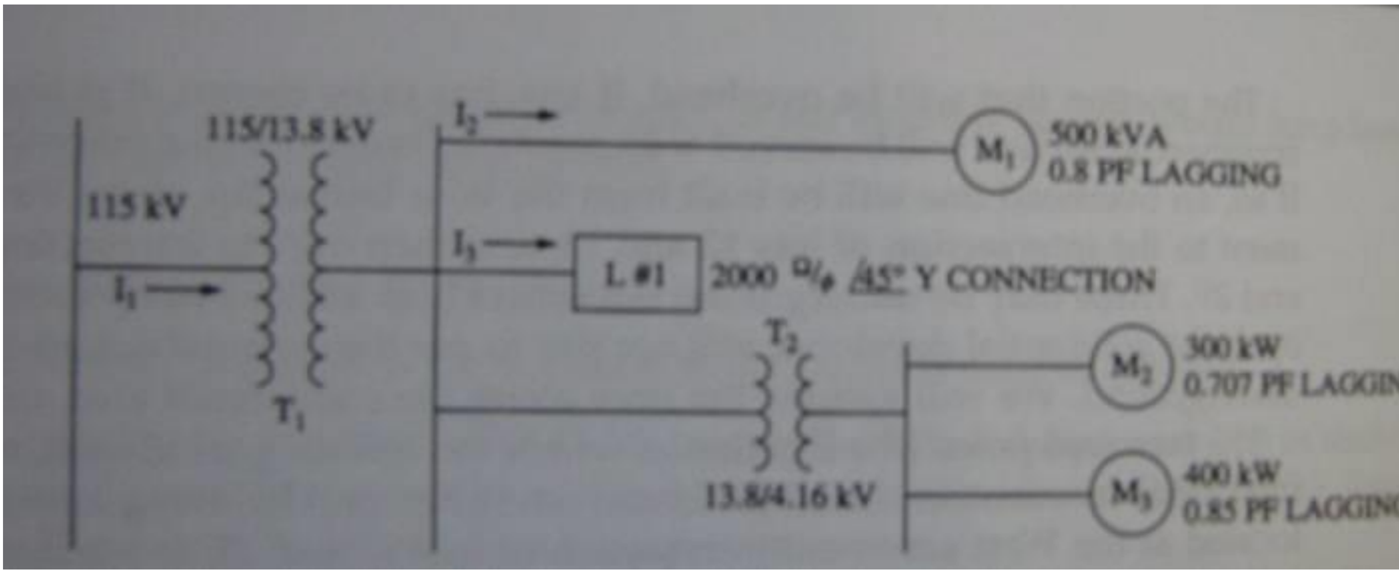
Average values of power factor for different kinds of loads are the following—

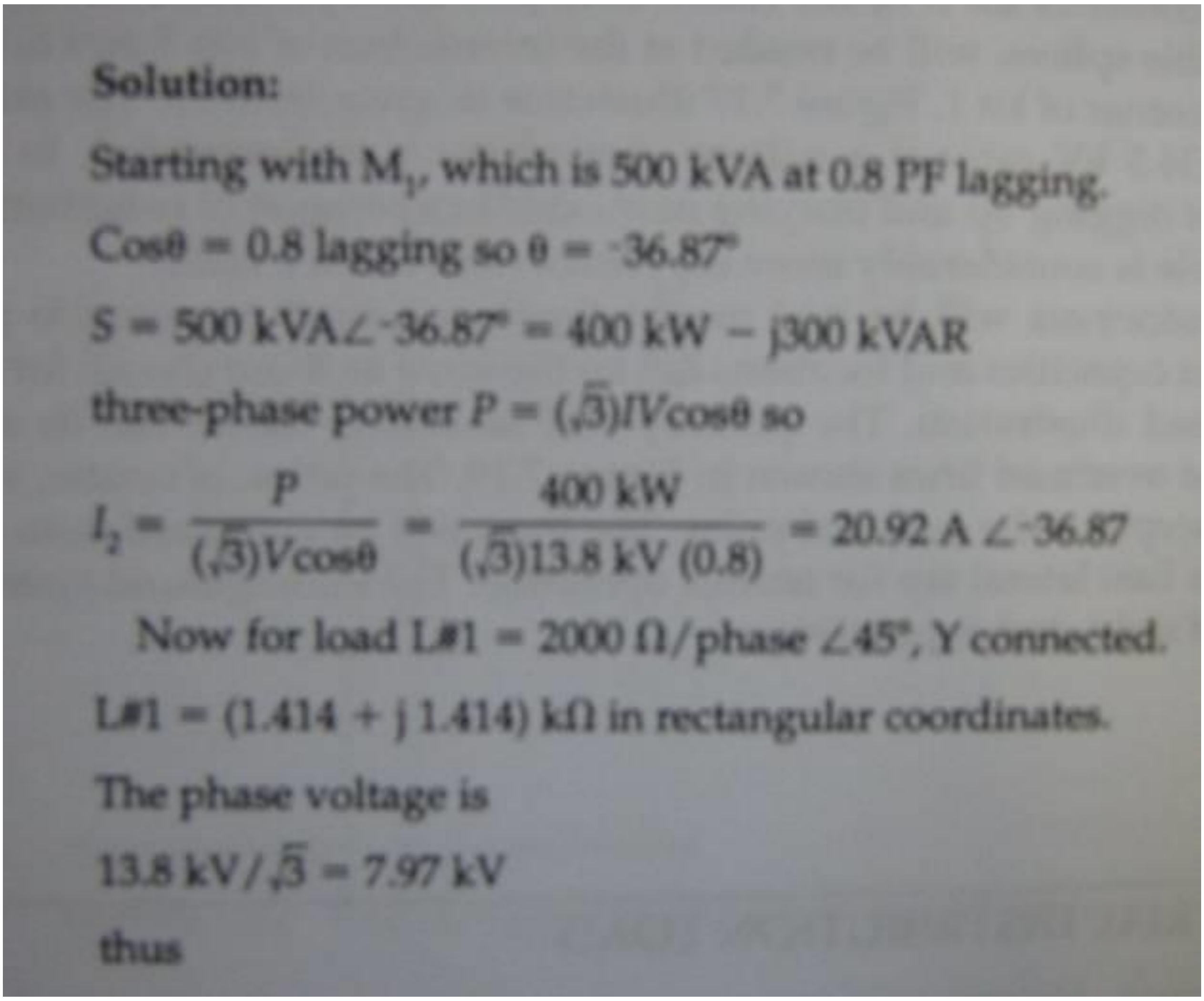
Lighting	0·95
Lighting and power, mainly the former	0·8–0·85
Lighting and power, mainly the latter	0·75
Power	0·65–0·70
Single-phase power	0·5



INDUSTRIAL DISTRIBUTION LOAD

Industrial loads tend to be much more predictable than residential and commercial loads. These loads must be known to select wire sizes and protective devices. Where large machines are used the choice of machine (such as synchronous instead of induction motor) can make a considerable difference in current. As we noted before, a high power factor is helpful in keeping total electricity costs down in an industrial plant. The outdoor distribution may be overhead or underground, and may be served by its own substation. The construction methods will be the same as those already discussed for outdoor distribution. The indoor, within a building, distribution system is planned using the methods studied in an electrical system design course. A practice problem to calculate currents using what is sometimes called the "P&Q" method will be helpful.





Solution:

Starting with M_1, which is 500 kVA at 0.8 PF lagging.

$\cos\theta = 0.8$ lagging so $\theta = -36.87°$

$S = 500\text{ kVA}\angle{-36.87°} = 400\text{ kW} - j300\text{ kVAR}$

three-phase power $P = (\sqrt{3})IV\cos\theta$ so

$$I_2 = \frac{P}{(\sqrt{3})V\cos\theta} = \frac{400\text{ kW}}{(\sqrt{3})13.8\text{ kV }(0.8)} = 20.92\text{ A}\angle{-36.87}$$

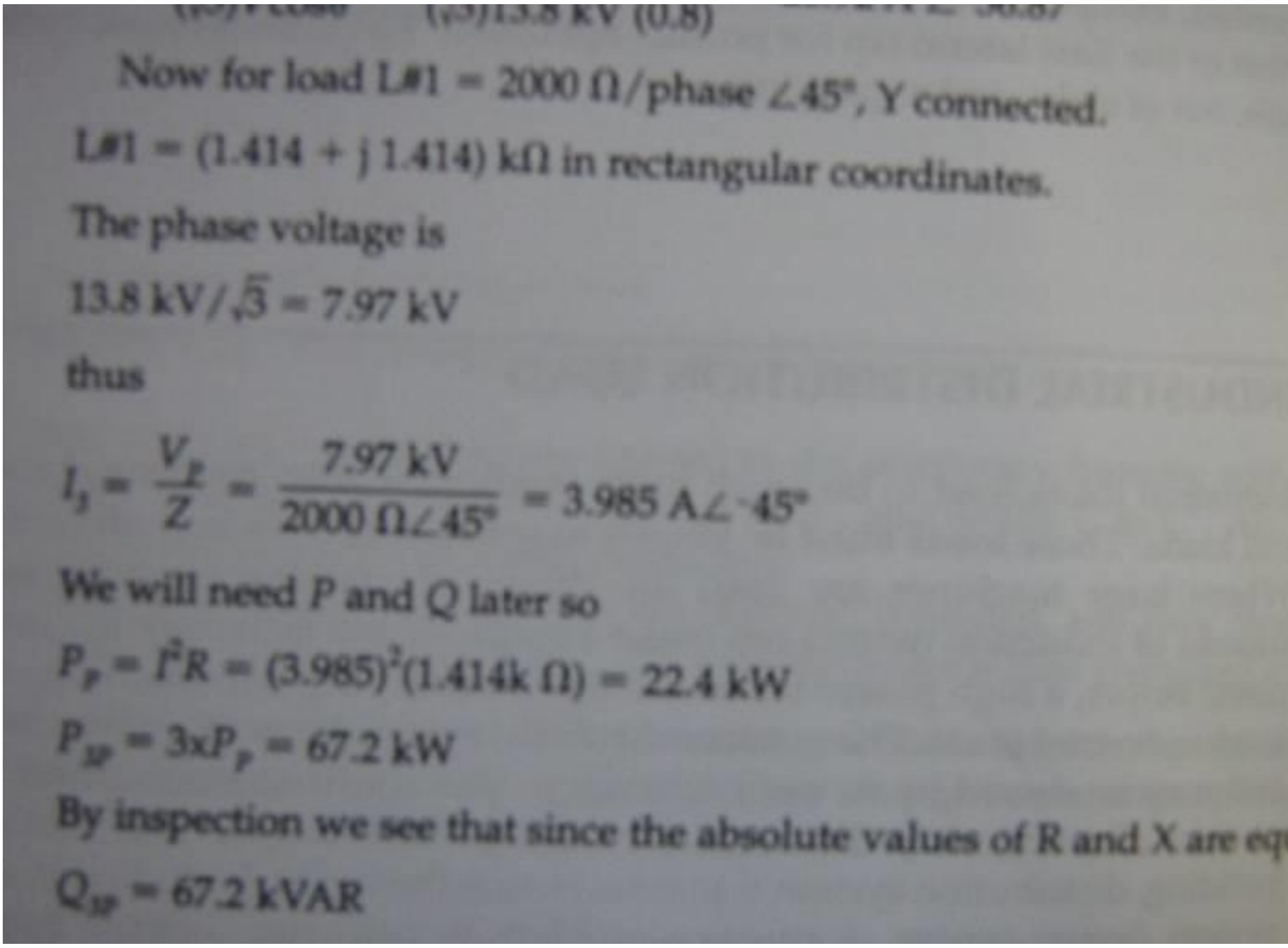
Now for load L#1 = 2000 Ω/phase ∠45°, Y connected.

L#1 = (1.414 + j 1.414) kΩ in rectangular coordinates.

The phase voltage is

$13.8\text{ kV}/\sqrt{3} = 7.97\text{ kV}$

thus



$(\sqrt{3})13.8\text{ kV}\ (0.8)$

Now for load L#1 = 2000 Ω/phase ∠45°, Y connected.

L#1 = (1.414 + j 1.414) kΩ in rectangular coordinates.

The phase voltage is

$13.8\text{ kV}/\sqrt{3} = 7.97\text{ kV}$

thus

$$I_3 = \frac{V_P}{Z} = \frac{7.97\text{ kV}}{2000\ \Omega\angle 45^\circ} = 3.985\text{ A}\angle -45^\circ$$

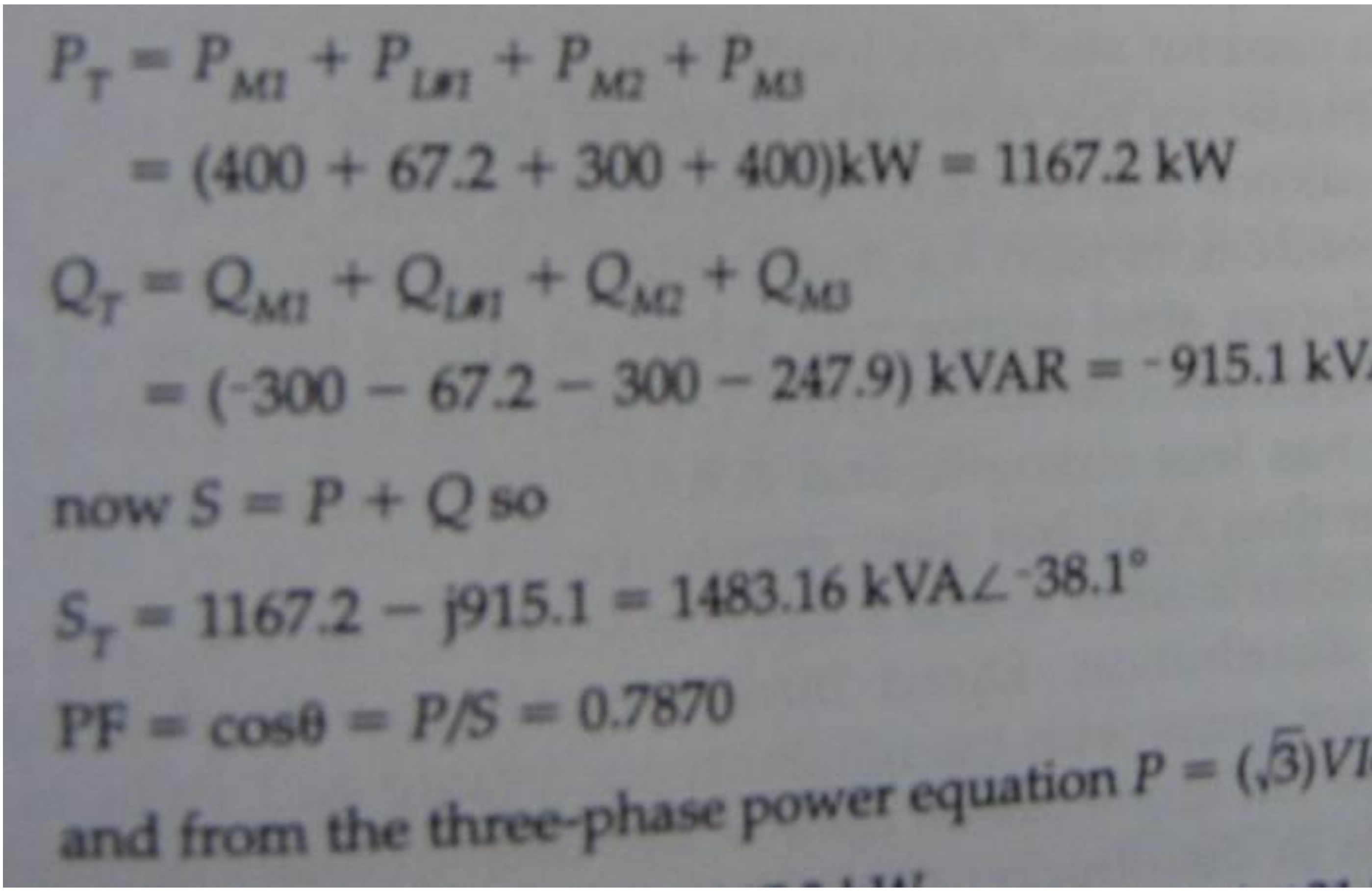
We will need P and Q later so

$P_p = I^2R = (3.985)^2(1.414\text{k }\Omega) = 22.4\text{ kW}$

$P_{3\phi} = 3xP_p = 67.2\text{ kW}$

By inspection we see that since the absolute values of R and X are eq

$Q_{3\phi} = 67.2\text{ kVAR}$



$P_T = P_{M1} + P_{L\#1} + P_{M2} + P_{M3}$

$= (400 + 67.2 + 300 + 400)\text{kW} = 1167.2\text{ kW}$

$Q_T = Q_{M1} + Q_{L\#1} + Q_{M2} + Q_{M3}$

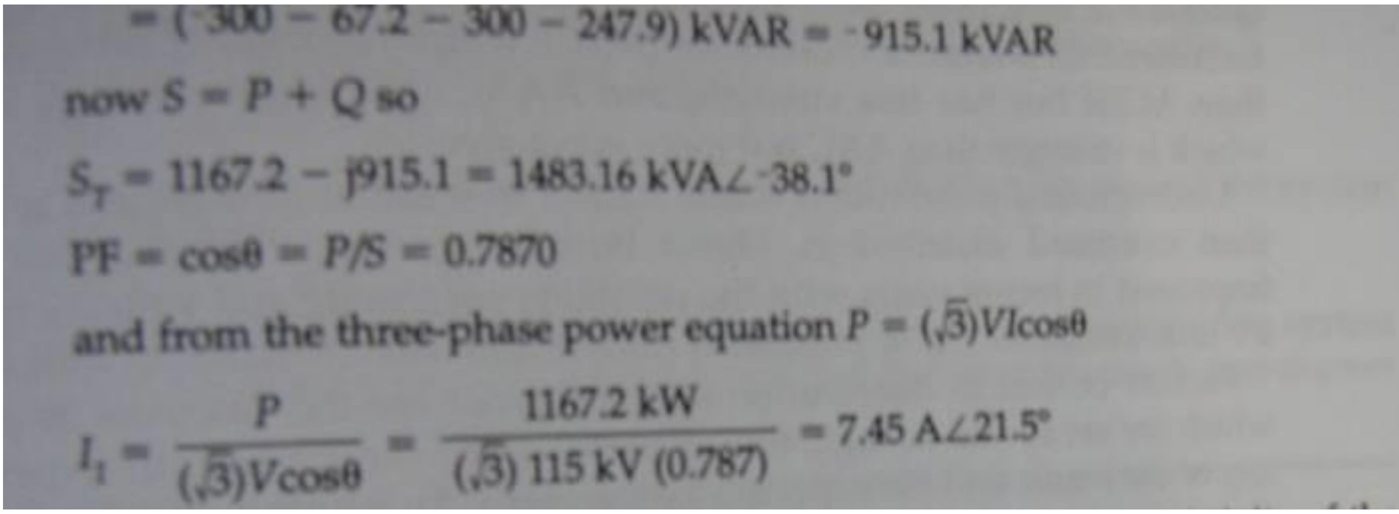
$= (-300 - 67.2 - 300 - 247.9)$ kVAR = -915.1 kV

now $S = P + Q$ so

$S_T = 1167.2 - j915.1 = 1483.16\text{ kVA}\angle -38.1^\circ$

$\text{PF} = \cos\theta = P/S = 0.7870$

and from the three-phase power equation $P = (\sqrt{3})VI$



$= (-300 - 67.2 - 300 - 247.9)\text{ kVAR} = -915.1\text{ kVAR}$

now $S = P + Q$ so

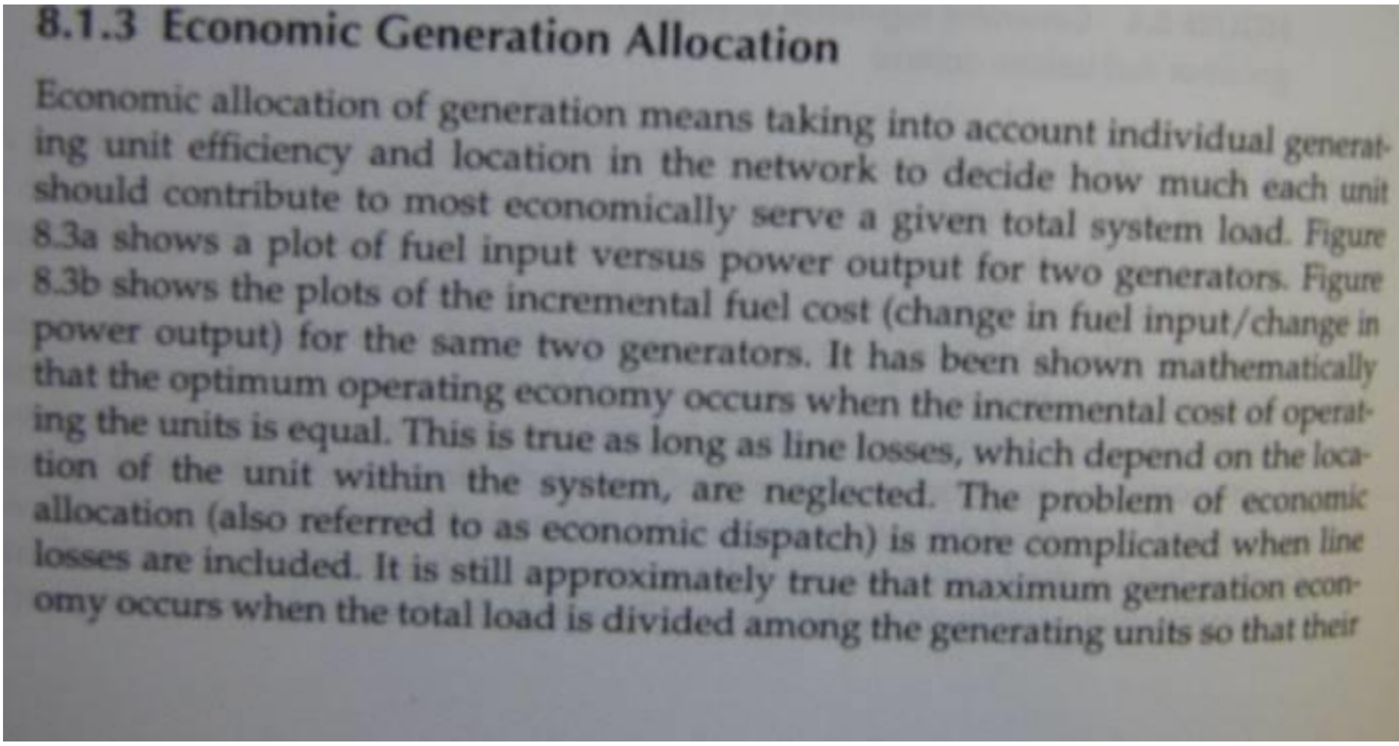
$S_T = 1167.2 - j915.1 = 1483.16\text{ kVA}\angle -38.1^\circ$

$\text{PF} = \cos\theta = P/S = 0.7870$

and from the three-phase power equation $P = (\sqrt{3})VI\cos\theta$

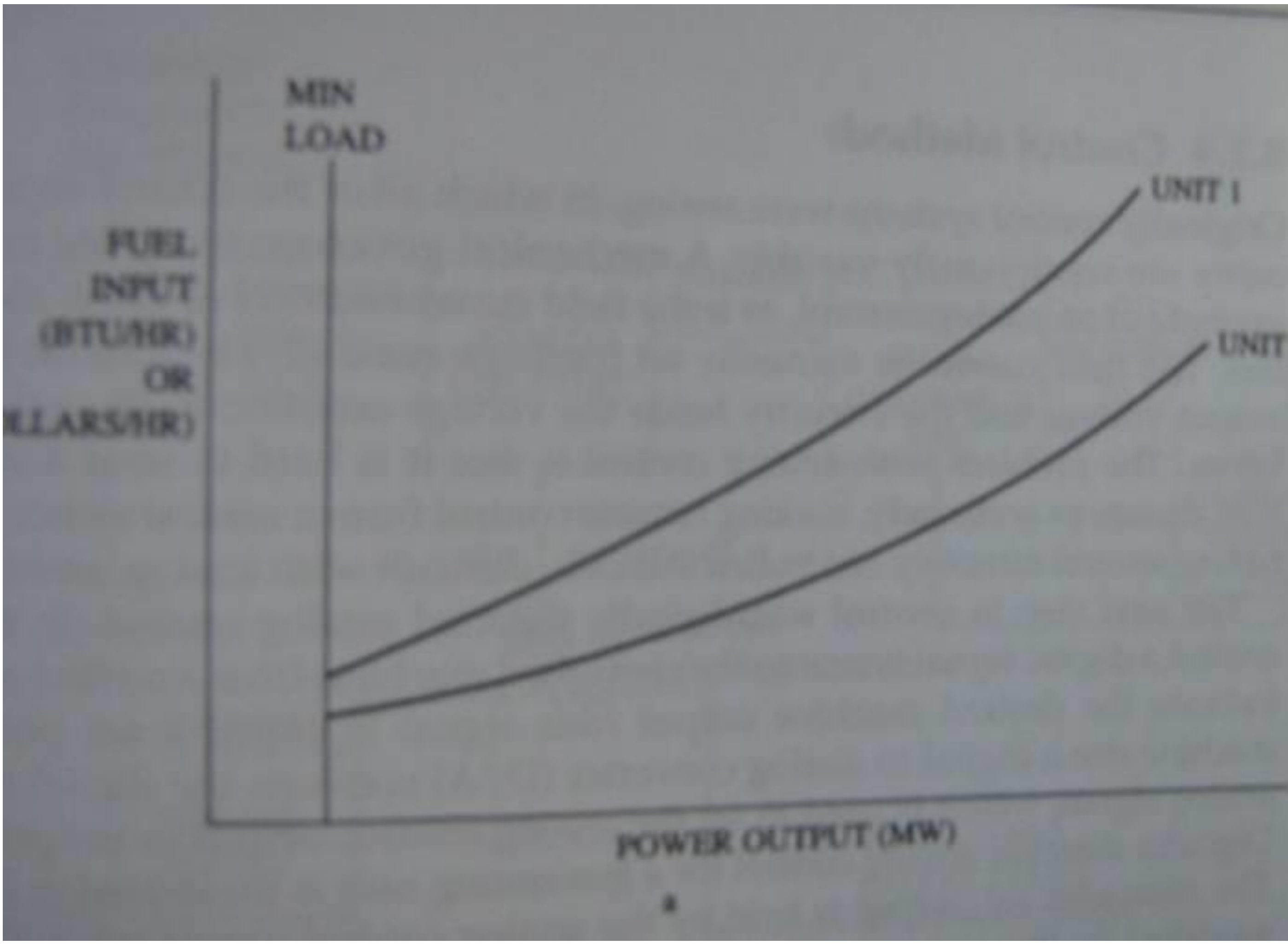
$$I_1 = \frac{P}{(\sqrt{3})V\cos\theta} = \frac{1167.2\text{ kW}}{(\sqrt{3})\ 115\text{ kV}\ (0.787)} = 7.45\text{ A}\angle 21.5^\circ$$

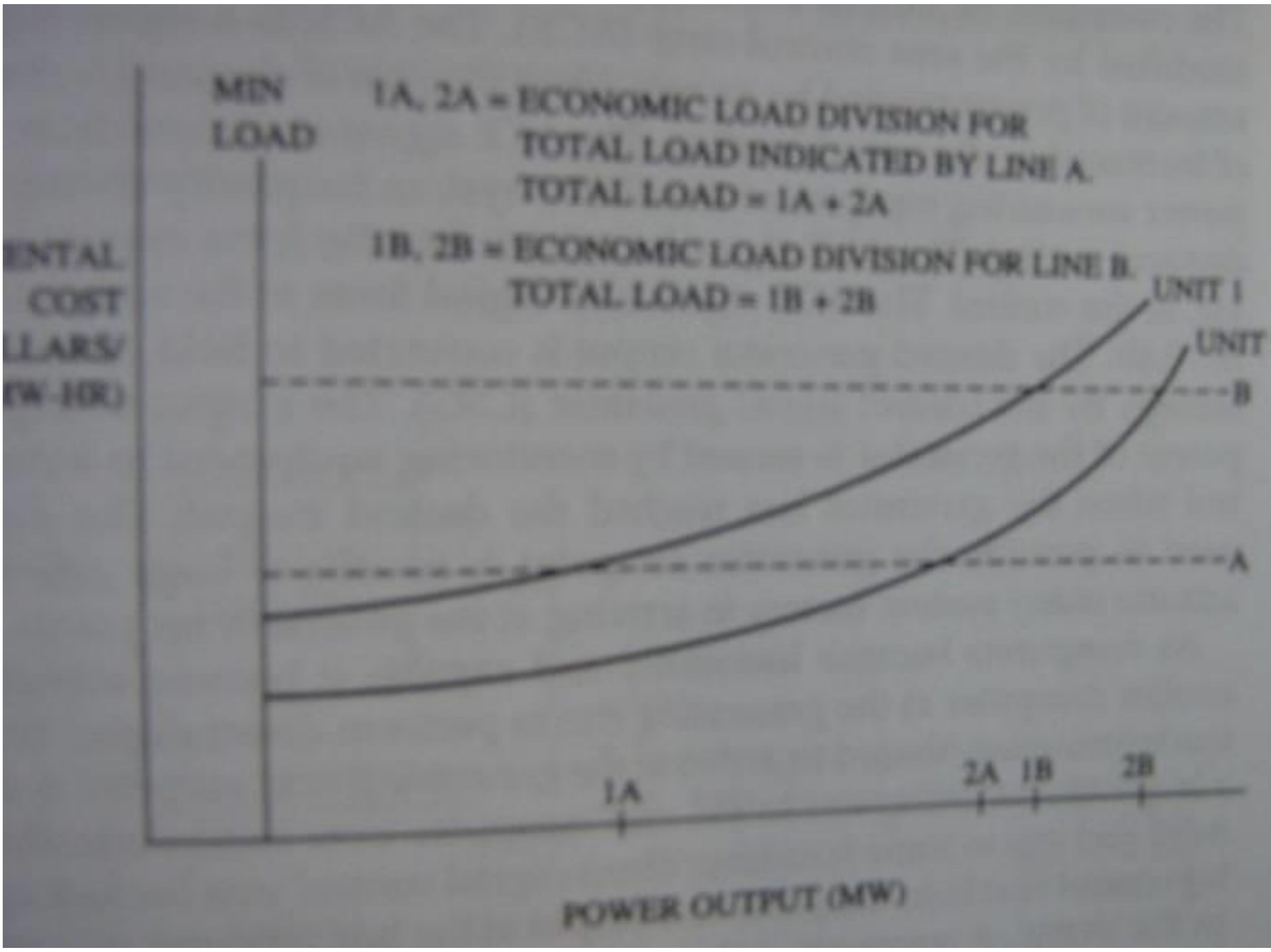
(5) Line Characteristics (Part 5)

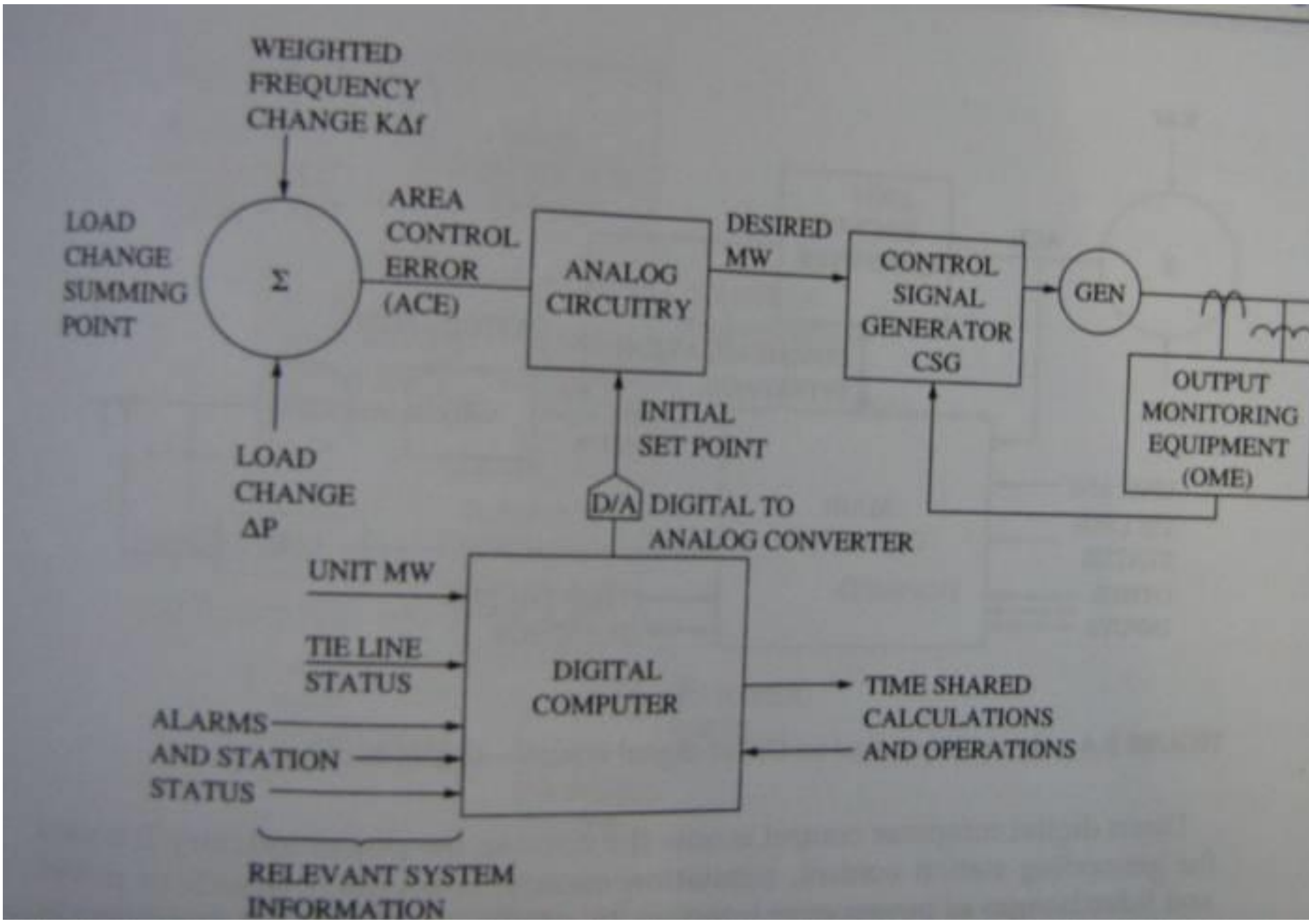


8.1.3 Economic Generation Allocation

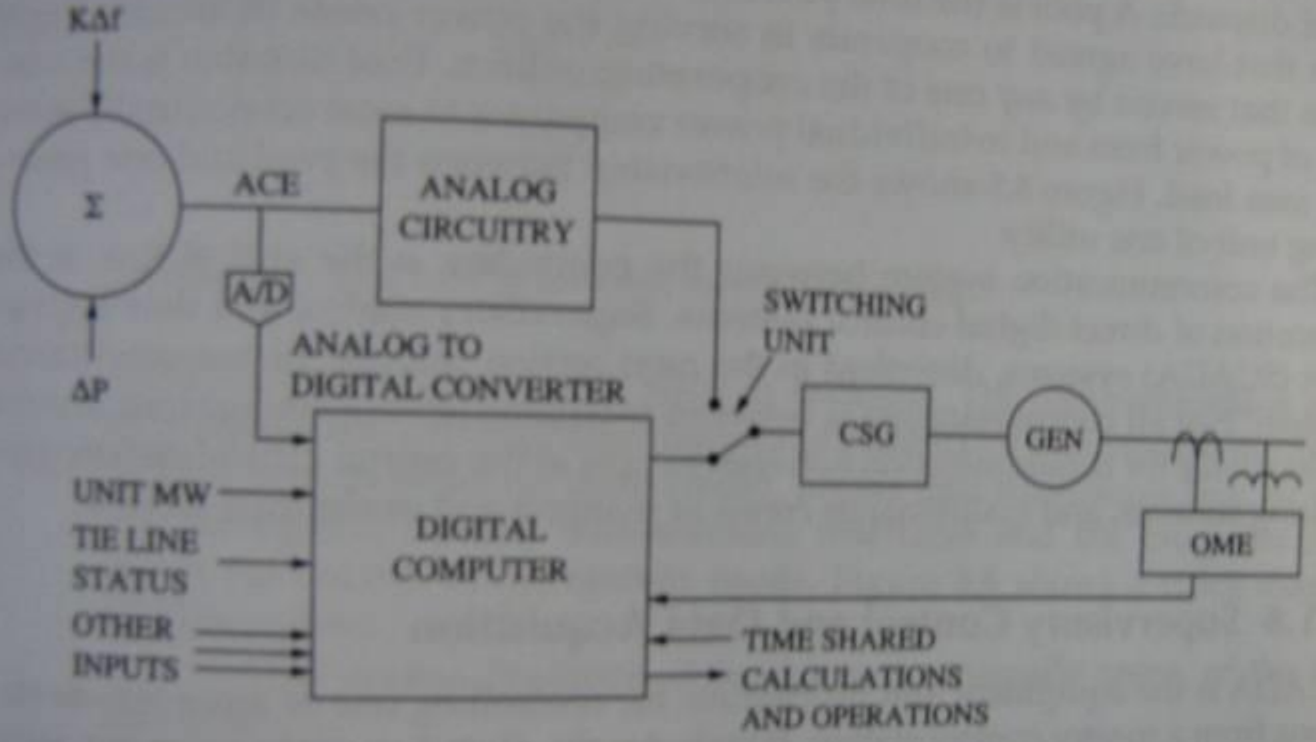
Economic allocation of generation means taking into account individual generating unit efficiency and location in the network to decide how much each unit should contribute to most economically serve a given total system load. Figure 8.3a shows a plot of fuel input versus power output for two generators. Figure 8.3b shows the plots of the incremental fuel cost (change in fuel input/change in power output) for the same two generators. It has been shown mathematically that the optimum operating economy occurs when the incremental cost of operating the units is equal. This is true as long as line losses, which depend on the location of the unit within the system, are neglected. The problem of economic allocation (also referred to as economic dispatch) is more complicated when line losses are included. It is still approximately true that maximum generation economy occurs when the total load is divided among the generating units so that their


MIN
LOAD
FUEL
INPUT
(BTU/HR)
OR
LLARS/HR)
UNIT 1
UNIT
POWER OUTPUT (MW)
a


MIN
LOAD
1A, 2A = ECONOMIC LOAD DIVISION FOR
TOTAL LOAD INDICATED BY LINE A.
TOTAL LOAD = 1A + 2A
1B, 2B = ECONOMIC LOAD DIVISION FOR LINE B.
TOTAL LOAD = 1B + 2B
ENTAL
COST
LLARS/
W-HR)
UNIT 1
UNIT
B
A
1A
2A
1B
2B
POWER OUTPUT (MW)


WEIGHTED FREQUENCY CHANGE KΔf
LOAD CHANGE SUMMING POINT
Σ
AREA CONTROL ERROR (ACE)
ANALOG CIRCUITRY
DESIRED MW
CONTROL SIGNAL GENERATOR CSG
GEN
OUTPUT MONITORING EQUIPMENT (OME)
INITIAL SET POINT
LOAD CHANGE ΔP
D/A
DIGITAL TO ANALOG CONVERTER
UNIT MW
TIE LINE STATUS
DIGITAL COMPUTER
TIME SHARED CALCULATIONS AND OPERATIONS
ALARMS AND STATION STATUS
RELEVANT SYSTEM INFORMATION

a



b

FIGURE 8.4 Generator control (a) Digitally-directed analog control (b) Direct digital control—analog backup

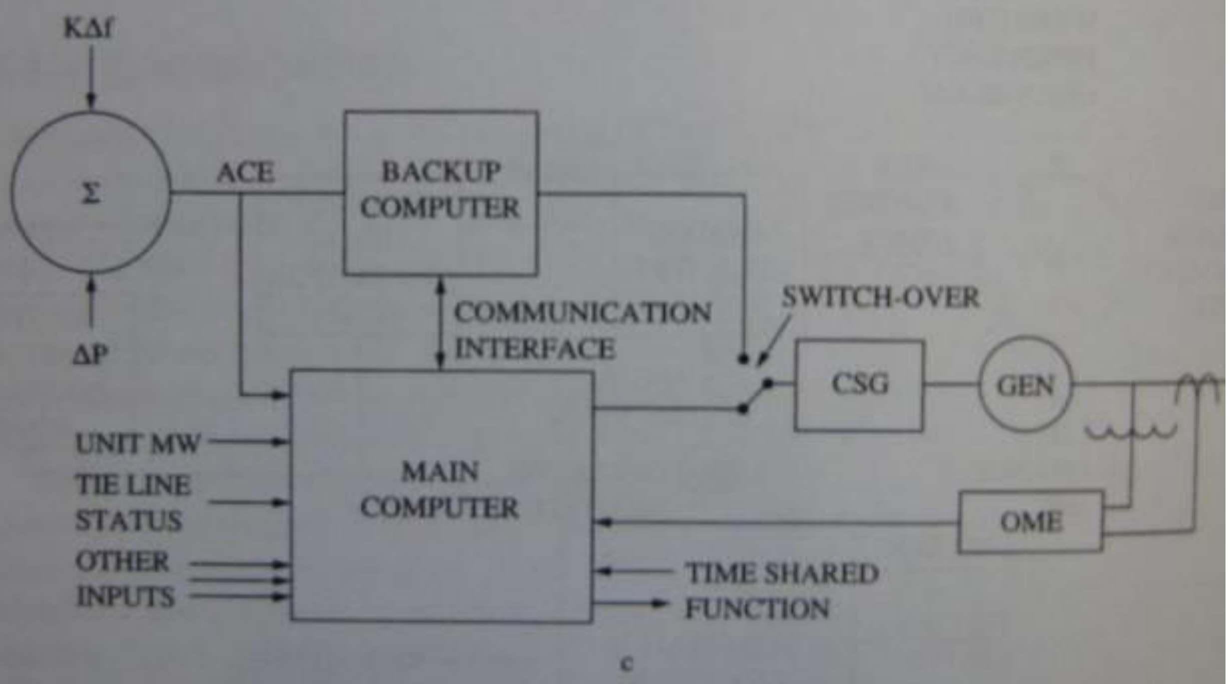


FIGURE 8.4 Generator control (c) Direct digital control—digital backup

The communication system between the computers is the critical link in peration of direct digital control systems. Supervisory control and data acqu ion (SCADA) systems, described in the next section, supply the communicati ystem. Not all communication is between machines. Voice communication mu e available for communication between people at the central control station, ge rating stations, and maintenance crews at manned and unmanned stations.

8.1.5 Supervisory Control and Data Acquisition

SCADA is the equipment and procedures for controlling one or more remote st tions from a master control station. It includes the digital control equipment, sen ing and telemetry equipment, and two-way communications to and from th master station and the remotely controlled stations.

The SCADA digital control equipment includes the control computers and ter minals for data display and entry. The sensing and telemetry equipment include the sensors, digital to analog and analog to digital converters, actuators, and relays used at the remote station to sense operating and alarm conditions and to

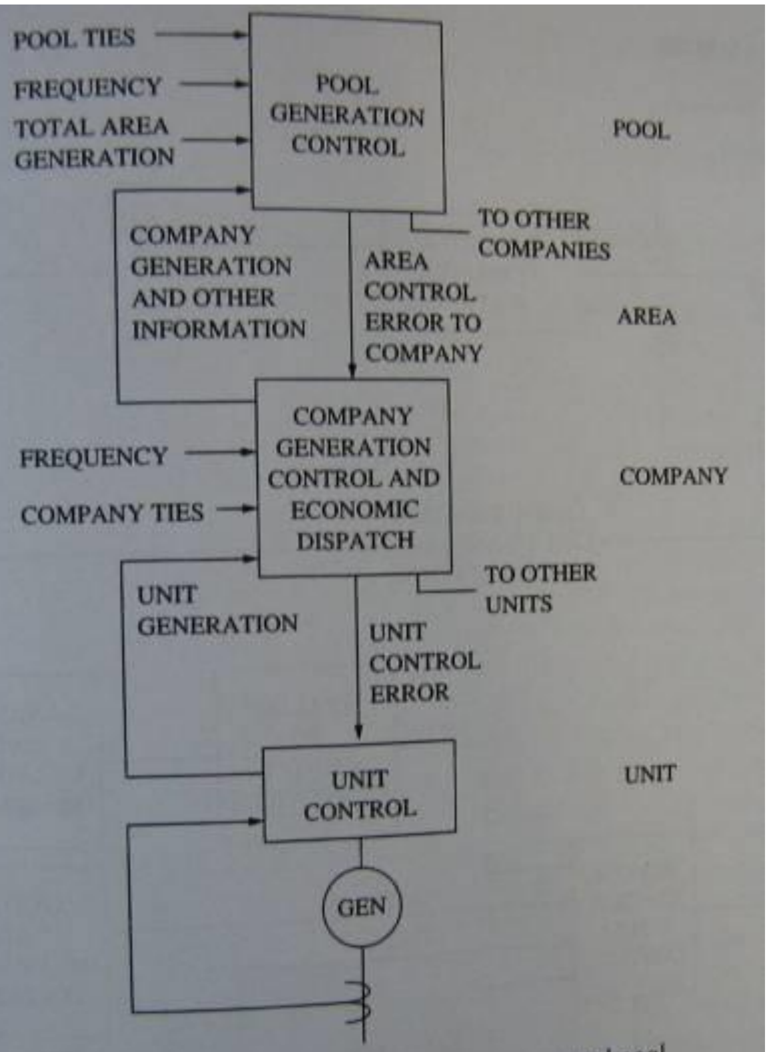
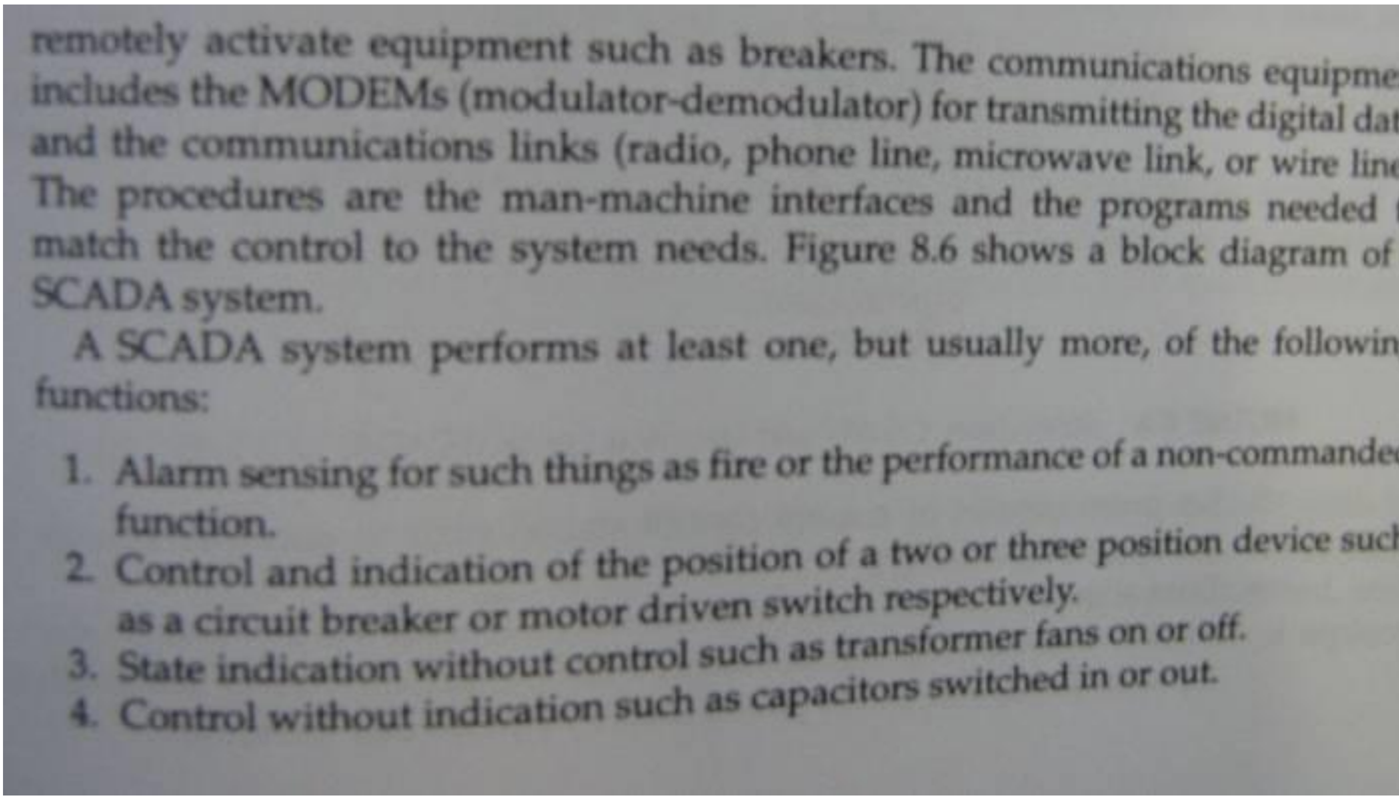


FIGURE 8.5 Relationship between company and pool

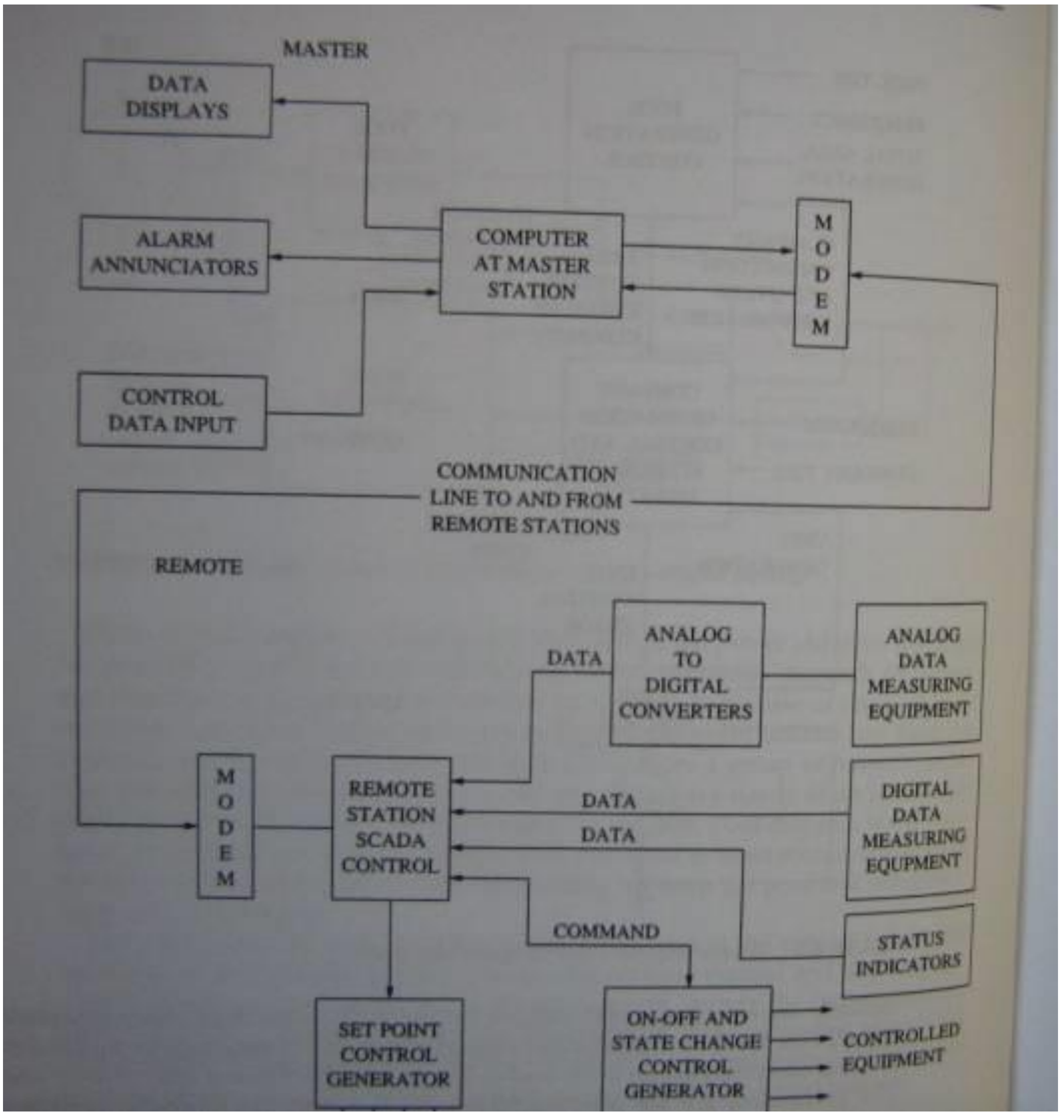


remotely activate equipment such as breakers. The communications equipme
includes the MODEMs (modulator-demodulator) for transmitting the digital dat
and the communications links (radio, phone line, microwave link, or wire line
The procedures are the man-machine interfaces and the programs needed
match the control to the system needs. Figure 8.6 shows a block diagram of
SCADA system.

A SCADA system performs at least one, but usually more, of the followin
functions:

1. Alarm sensing for such things as fire or the performance of a non-commande
function.
2. Control and indication of the position of a two or three position device suc
as a circuit breaker or motor driven switch respectively.
3. State indication without control such as transformer fans on or off.
4. Control without indication such as capacitors switched in or out.

(5) Line Characteristics (Part 6)


MASTER
DATA DISPLAYS
ALARM ANNUNCIATORS
CONTROL DATA INPUT
COMPUTER AT MASTER STATION
MODEM
COMMUNICATION LINE TO AND FROM REMOTE STATIONS
REMOTE
DATA
ANALOG TO DIGITAL CONVERTERS
ANALOG DATA MEASURING EQUIPMENT
MODEM
REMOTE STATION SCADA CONTROL
DATA
DATA
DIGITAL DATA MEASURING EQUPMENT
COMMAND
STATUS INDICATORS
SET POINT CONTROL GENERATOR
ON-OFF AND STATE CHANGE CONTROL GENERATOR
CONTROLLED EQUIPMENT

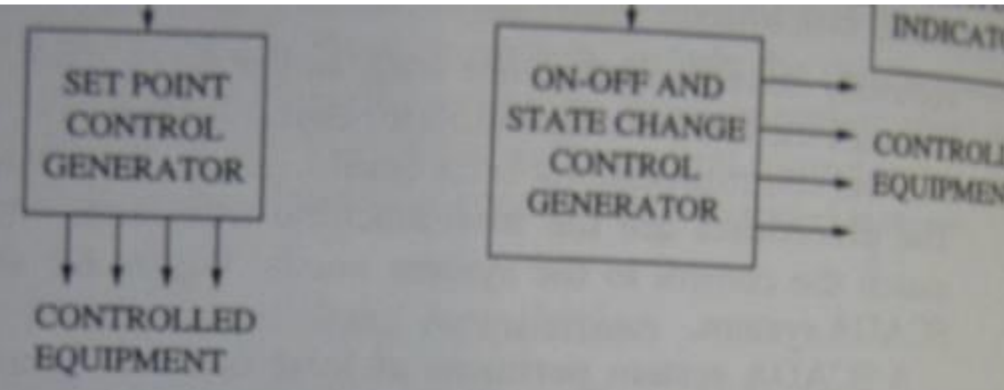
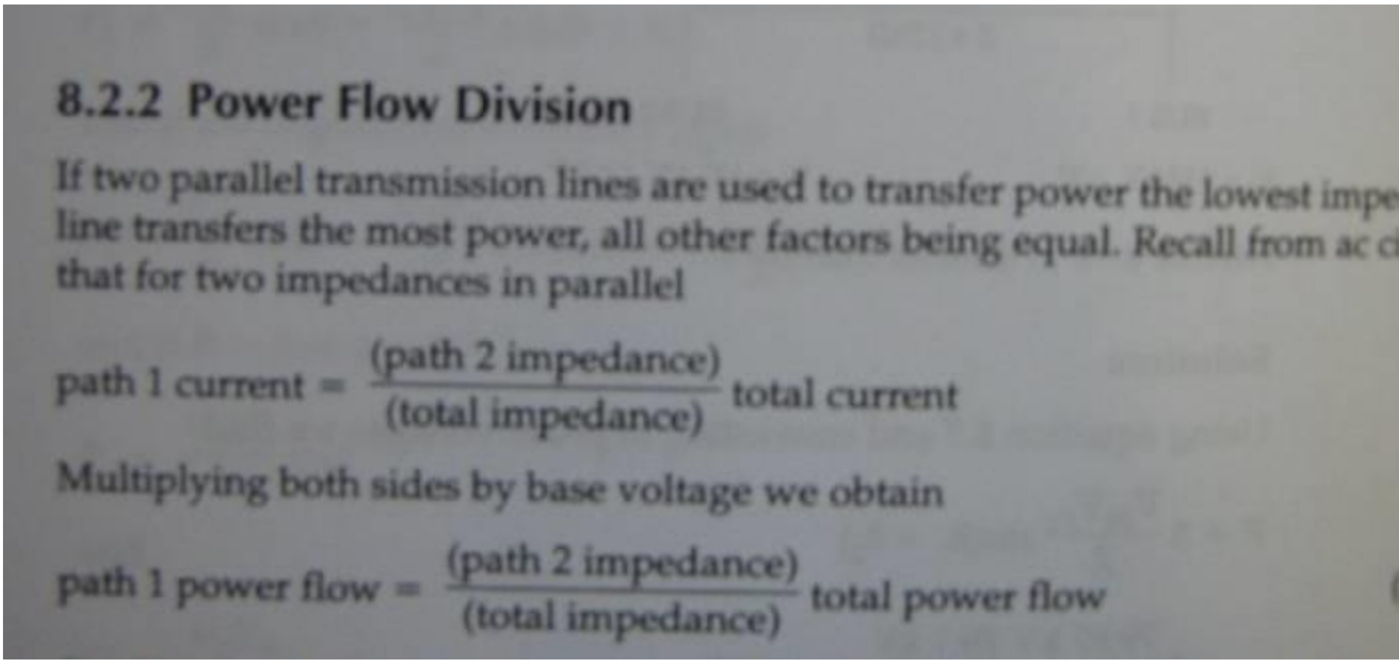


FIGURE 8.6 Supervisory Control and Data Acquisition (SCADA)

5. Set point control of remote control station such as nominal voltage for automatic tap changer.
6. Data acquisition from metering equipment, usually via an A/D converter digital communication link. Examples of this are the power transmitted a particular tie line or the power used by a particular customer.
7. Initiation and recognition of sequences of events such as sectionalizing a bus with a fault on it or routing power around a bad transformer by opening and closing circuit breakers.
8. Allow operators to initiate operations at remote stations from a central control station.

SCADA systems have enough capabilities that it has been many years since there has been a manned substation in the United States. Almost all routine substation functions are remotely controlled. A complete SCADA system, with the appropriate relays and auxiliary equipment, can perform the following substation control functions: synchronism check, automatic reclosing after a fault, protection of equipment in a station, automatic bus sectionalizing, voltage and VAR control, fault reporting, transformer load balancing, equipment condition monitoring, data acquisition, status monitoring, and data logging.



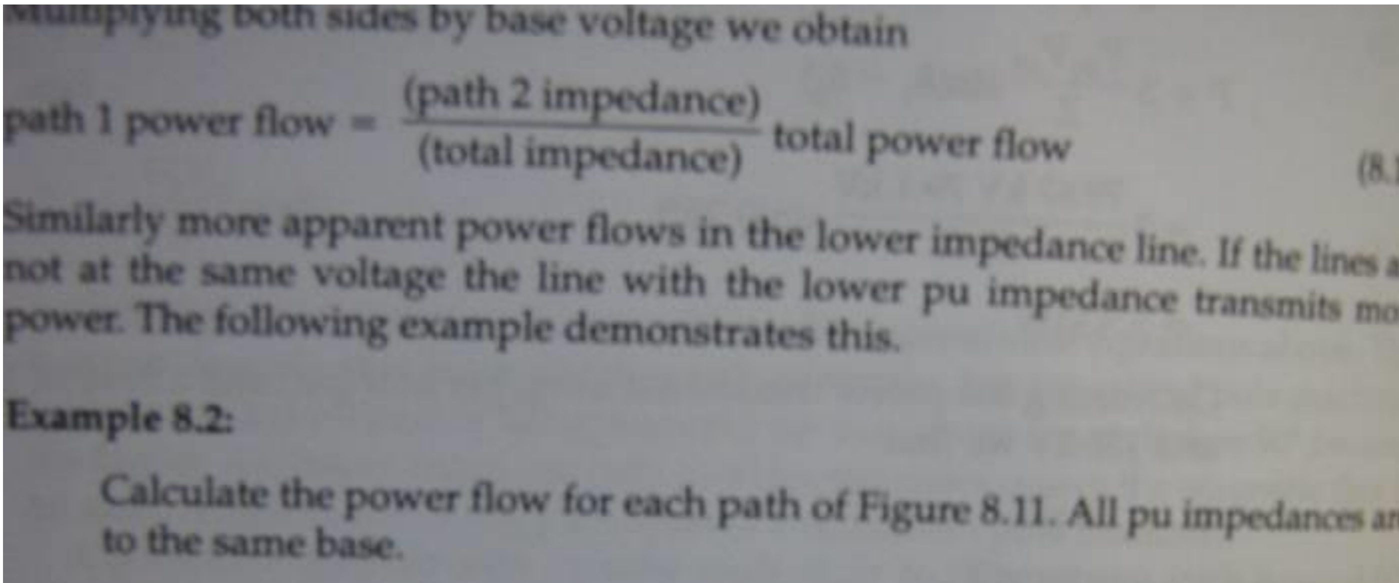
8.2.2 Power Flow Division

If two parallel transmission lines are used to transfer power the lowest impe
line transfers the most power, all other factors being equal. Recall from ac ci
that for two impedances in parallel

$$\text{path 1 current} = \frac{\text{(path 2 impedance)}}{\text{(total impedance)}}\ \text{total current}$$

Multiplying both sides by base voltage we obtain

$$\text{path 1 power flow} = \frac{\text{(path 2 impedance)}}{\text{(total impedance)}}\ \text{total power flow}$$



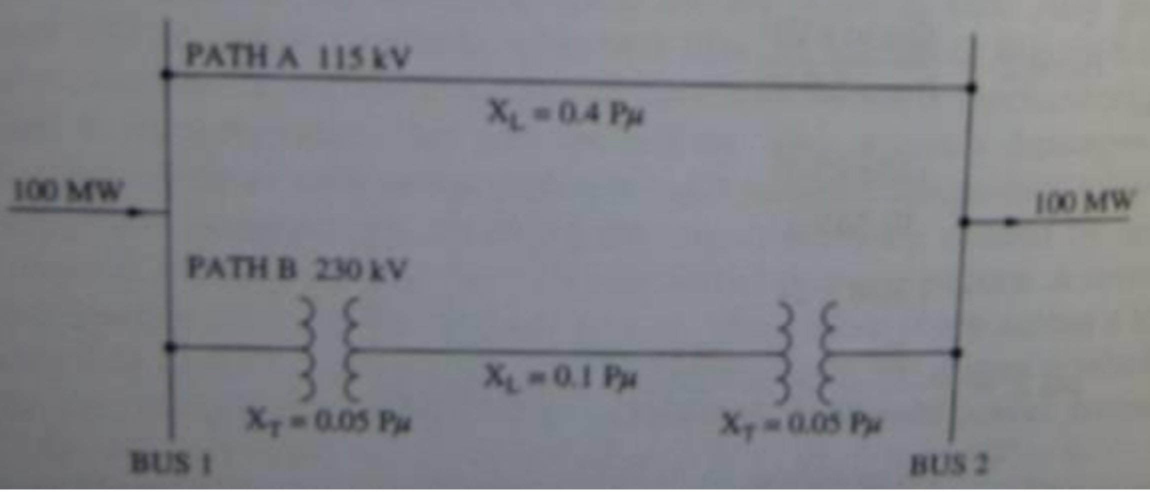
Multiplying both sides by base voltage we obtain

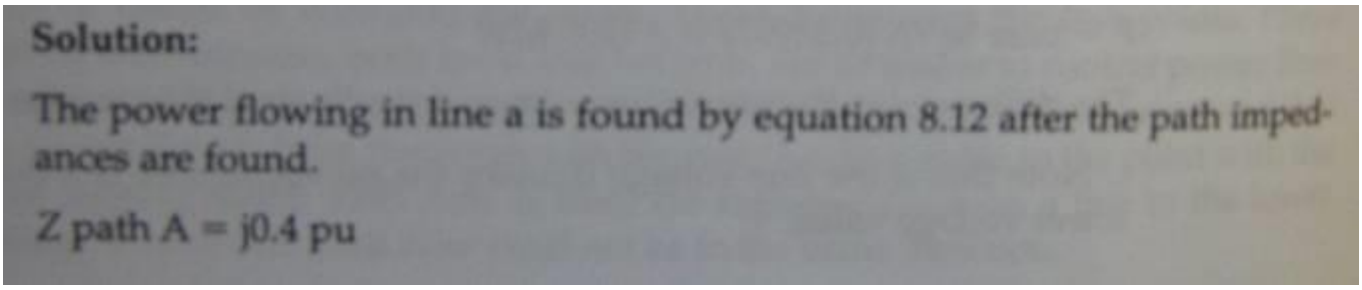
$$\text{path 1 power flow} = \frac{\text{(path 2 impedance)}}{\text{(total impedance)}}\ \text{total power flow} \qquad \text{(8.}$$

Similarly more apparent power flows in the lower impedance line. If the lines a
not at the same voltage the line with the lower pu impedance transmits mo
power. The following example demonstrates this.

Example 8.2:

Calculate the power flow for each path of Figure 8.11. All pu impedances ar
to the same base.

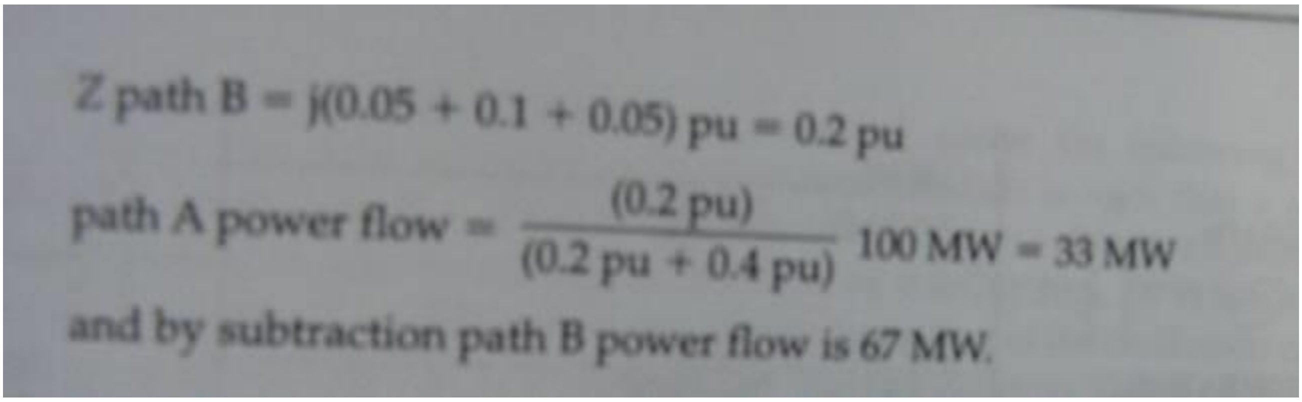




Solution:

The power flowing in line a is found by equation 8.12 after the path impedances are found.

Z path A = j0.4 pu



Z path B = j(0.05 + 0.1 + 0.05) pu = 0.2 pu

$$\text{path A power flow} = \frac{(0.2\ \text{pu})}{(0.2\ \text{pu} + 0.4\ \text{pu})}\ 100\ \text{MW} = 33\ \text{MW}$$

and by subtraction path B power flow is 67 MW.