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'

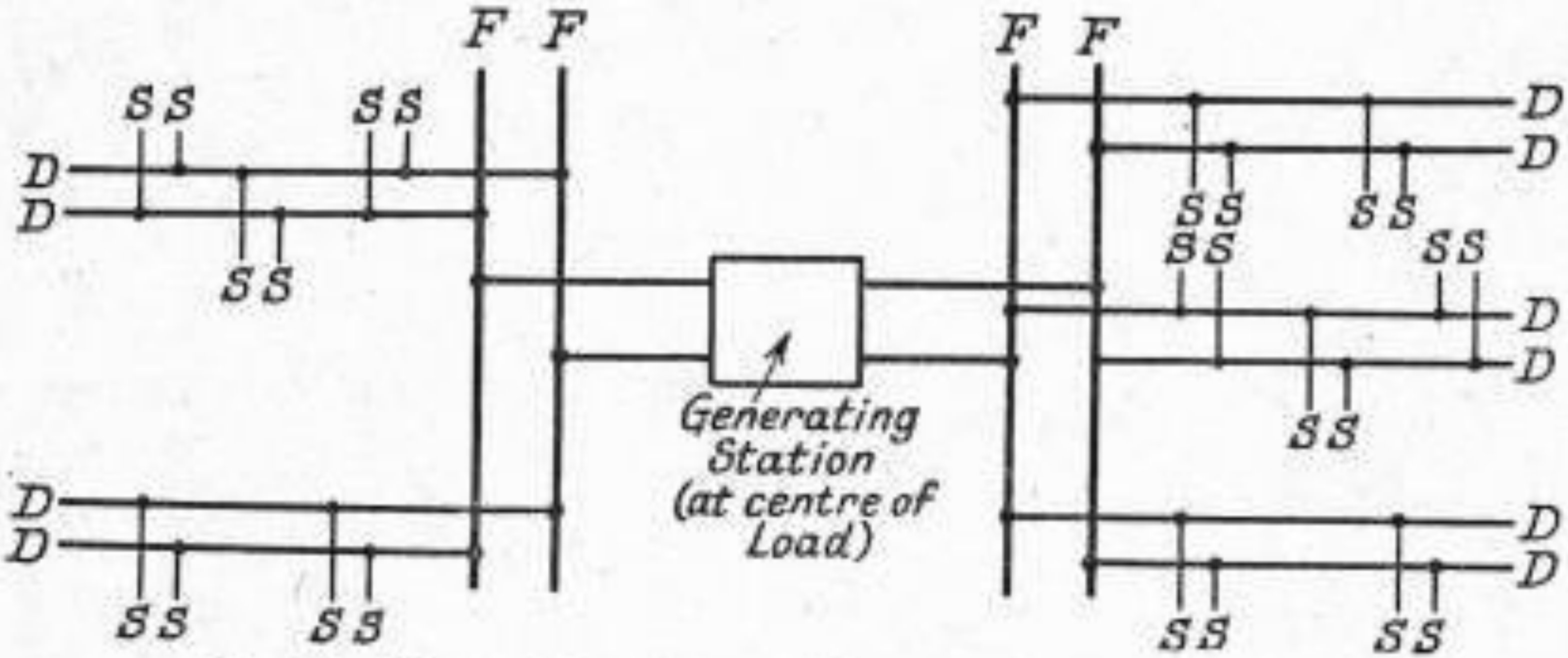


FIG. 16. EARLY DISTRIBUTION SCHEME, RADIAL SYSTEM

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

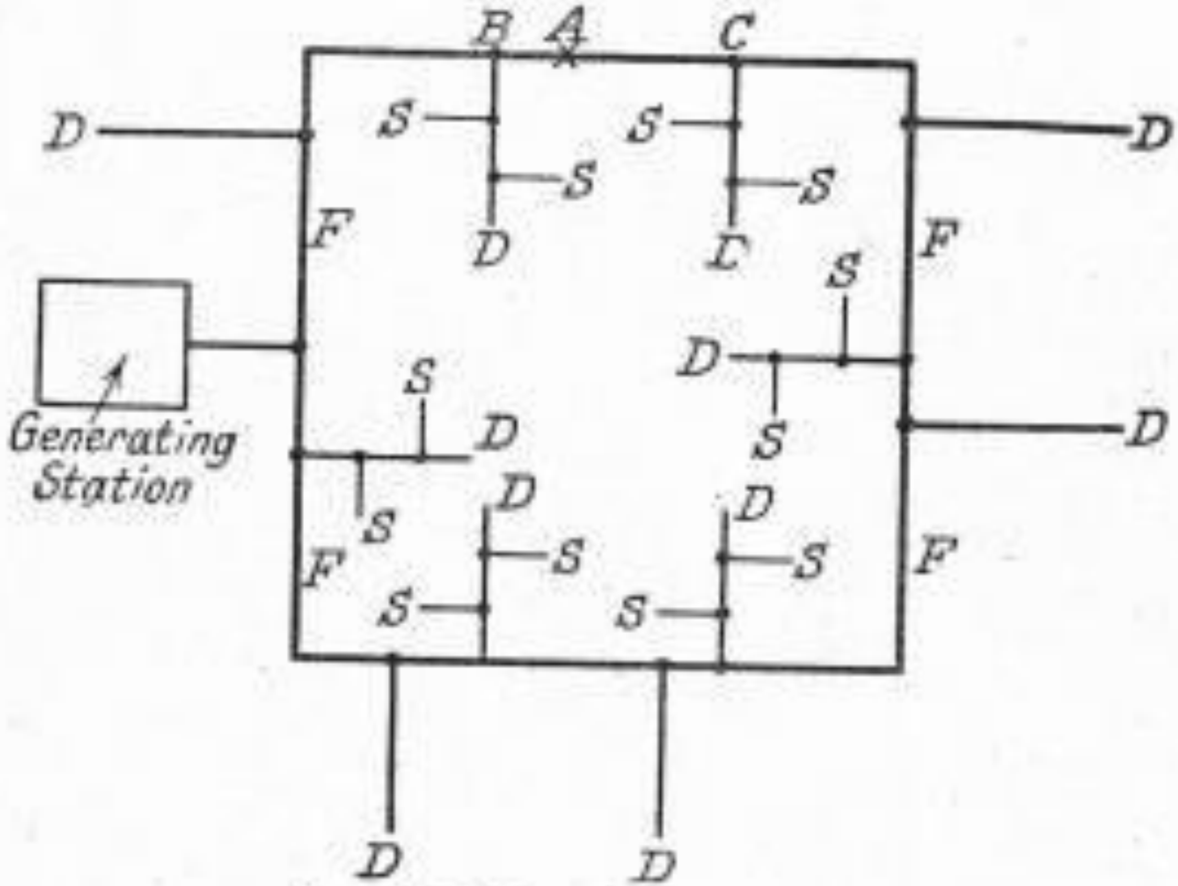


FIG. 17. RING MAIN SYSTEM

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

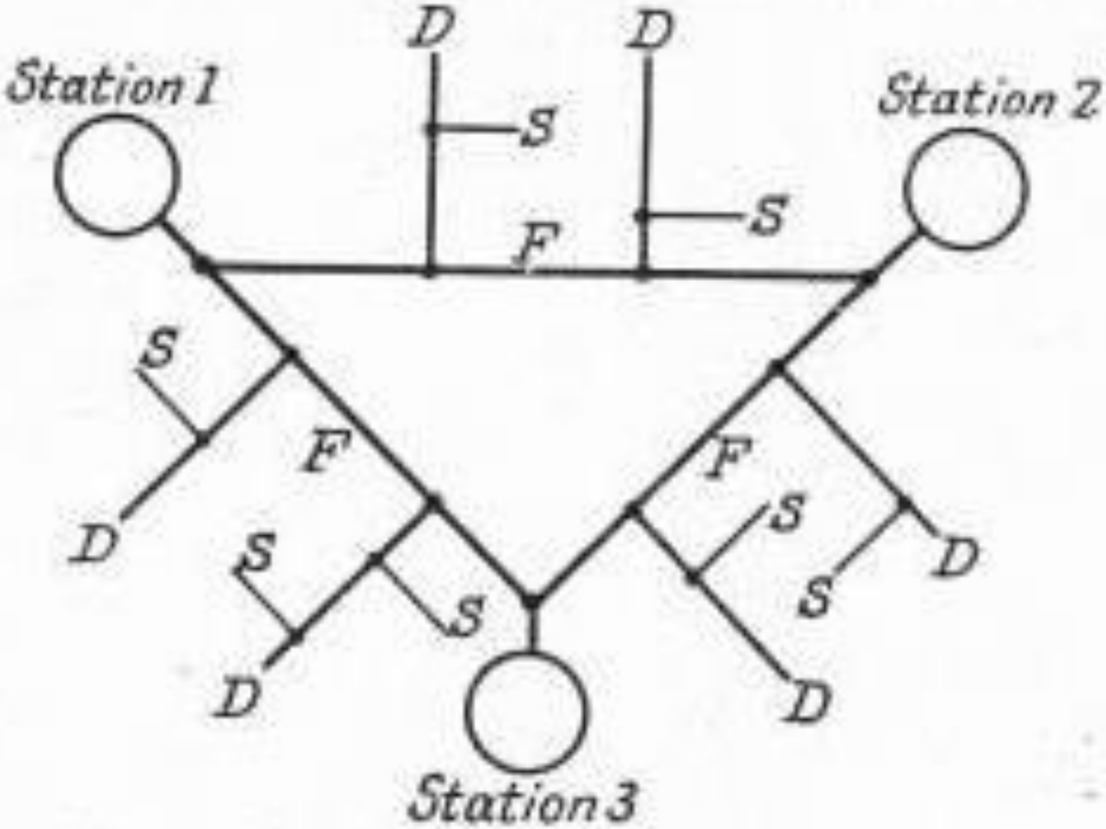


FIG. 18. SIMPLE INTERCONNECTED SYSTEM

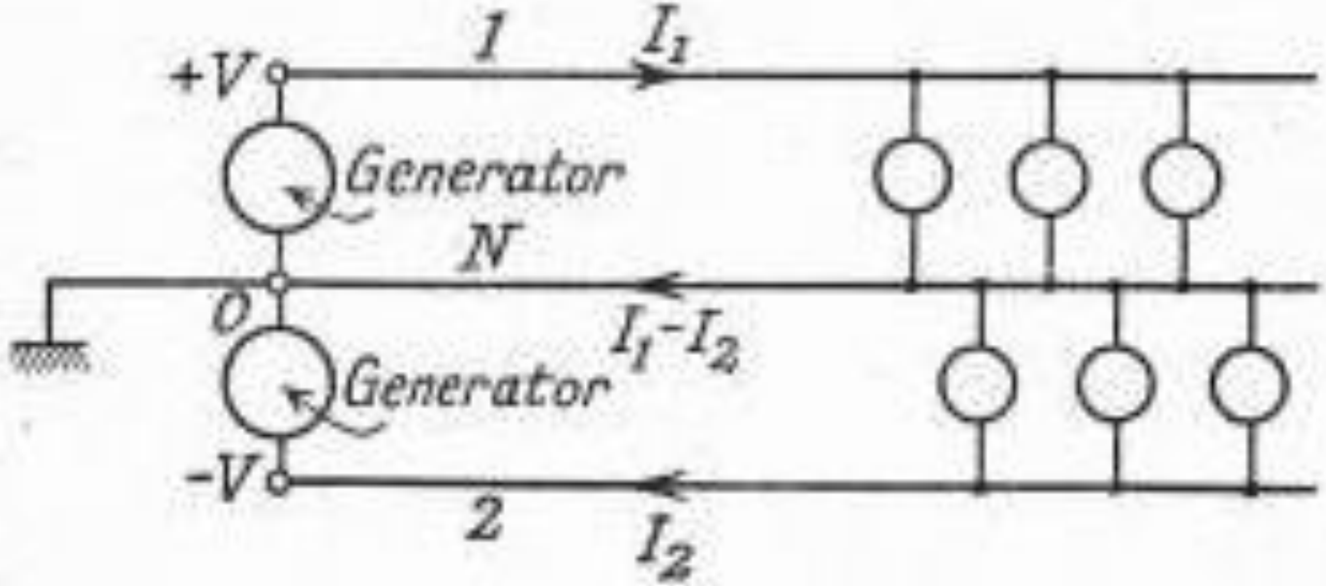


FIG. 19. THREE-WIRE SYSTEM

case, and R_2 the resistance per cm. per outer wire in the latter; the resistance of the neutral is $2R_2$ per cm., as it has half the cross-section of the outers. We have to find the relation between R_1 and R_2 so that there are the same I^2R losses in both cases. In the 2-wire case the current per wire is P/V, and the losses per cm. for the two wires are

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

In the 3-wire case, if we assume balanced loads, the current in the outers is $(P/2V)$ and zero in the neutral. The losses per cm. are

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

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-fourth of that in the 2-wire case, so that the copper ratio is

$$\frac{\text{3-wire}}{\text{2-wire}} = \frac{(2 \times \frac{1}{4}) + (\frac{1}{2} \times \frac{1}{4})}{2 \times 1} = \frac{5}{16} = 31{\cdot}25 \text{ per cent.}$$

If the neutral has the same cross-section as the outer, the ratio is

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

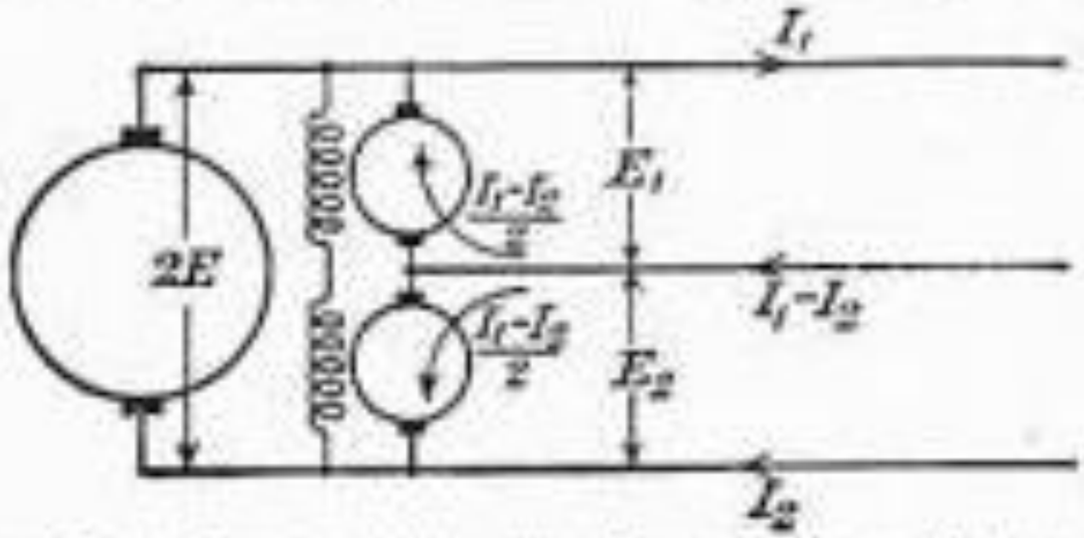


Fig. 20. Balancer for Three-wire System

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

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

$$E_1 = e - ri_1 \text{ and } E_2 = e + ri_2 \qquad \text{(ii)}$$

where r is the resistance of each armature. Let w be the windage and friction losses. Then

$$w = ei_2 - ei_1 = e(i_2 - i_1) \qquad \text{(iii)}$$

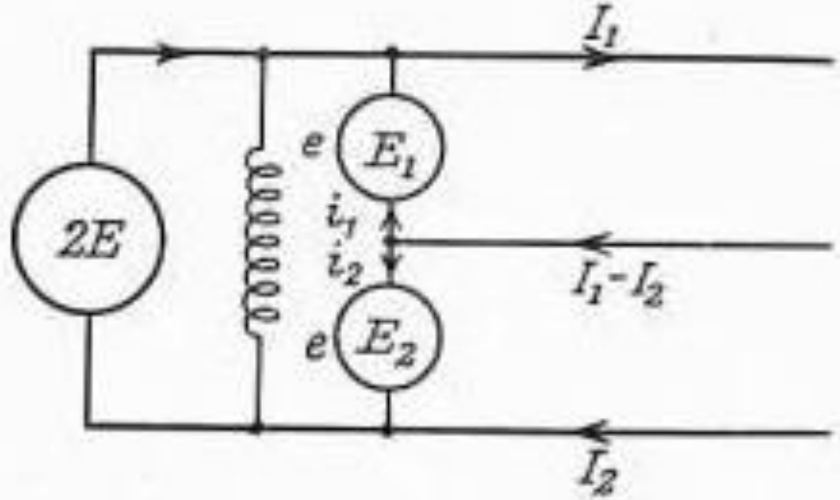


FIG. 21. BALANCER FOR THREE-WIRE SYSTEM

Equations (i), (ii), and (iii) are sufficient to determine E_1, F_2, i_1 and i_2. Eliminating e from equations (ii) we get the voltage unbalance as

$$E_2 - E_1 = r(i_2 + i_1) = r(I_1 - I_2).$$

To find i_1 and i_2 we proceed as follows. Adding equations (ii) we get

$$E_1 + E_2 = 2E = 2e + r(i_2 - i_1).$$

Substituting from this equation in (iii) for e we get

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

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

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

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

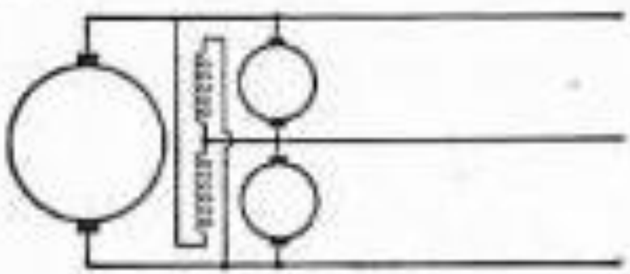


FIG. 22. CROSS-CONNECTED FIELDS FOR BALANCERS

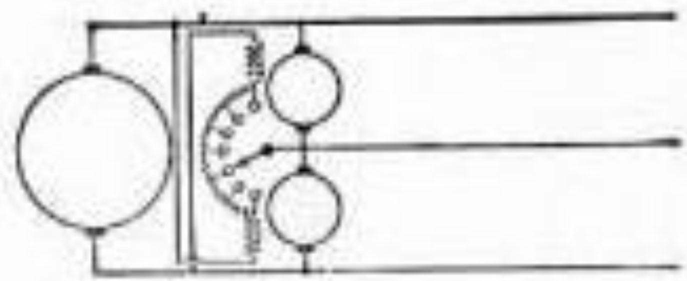


FIG. 23. RHEOSTATIC CONTROL AND CROSS-CONNECTED FIELDS

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

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

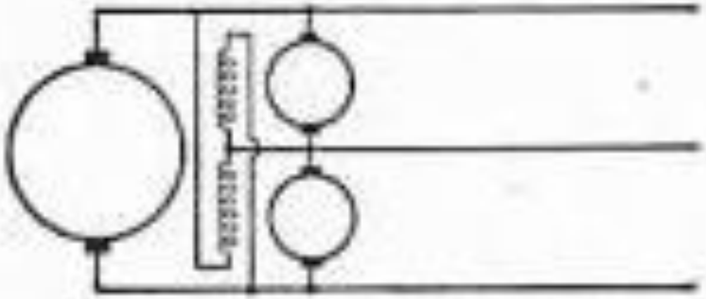


FIG. 22. CROSS-CONNECTED FIELDS FOR BALANCERS

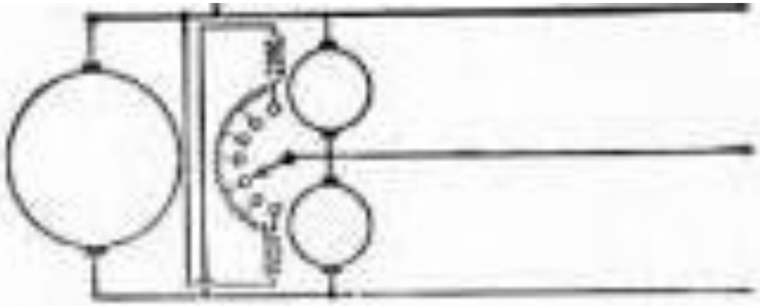


FIG. 23. RHEOSTATIC CONTROL AND CROSS-CONNECTED FIELDS

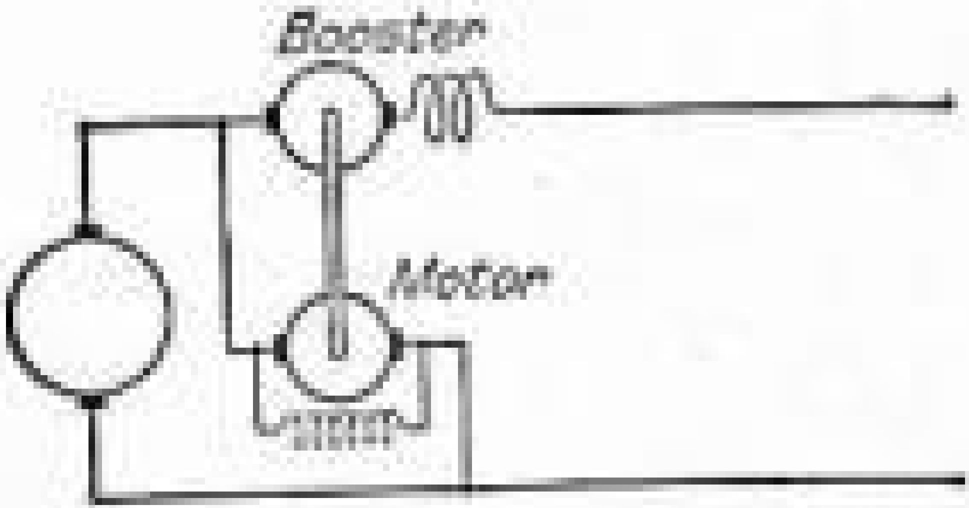


FIG. 24. FEEDER BOOSTER

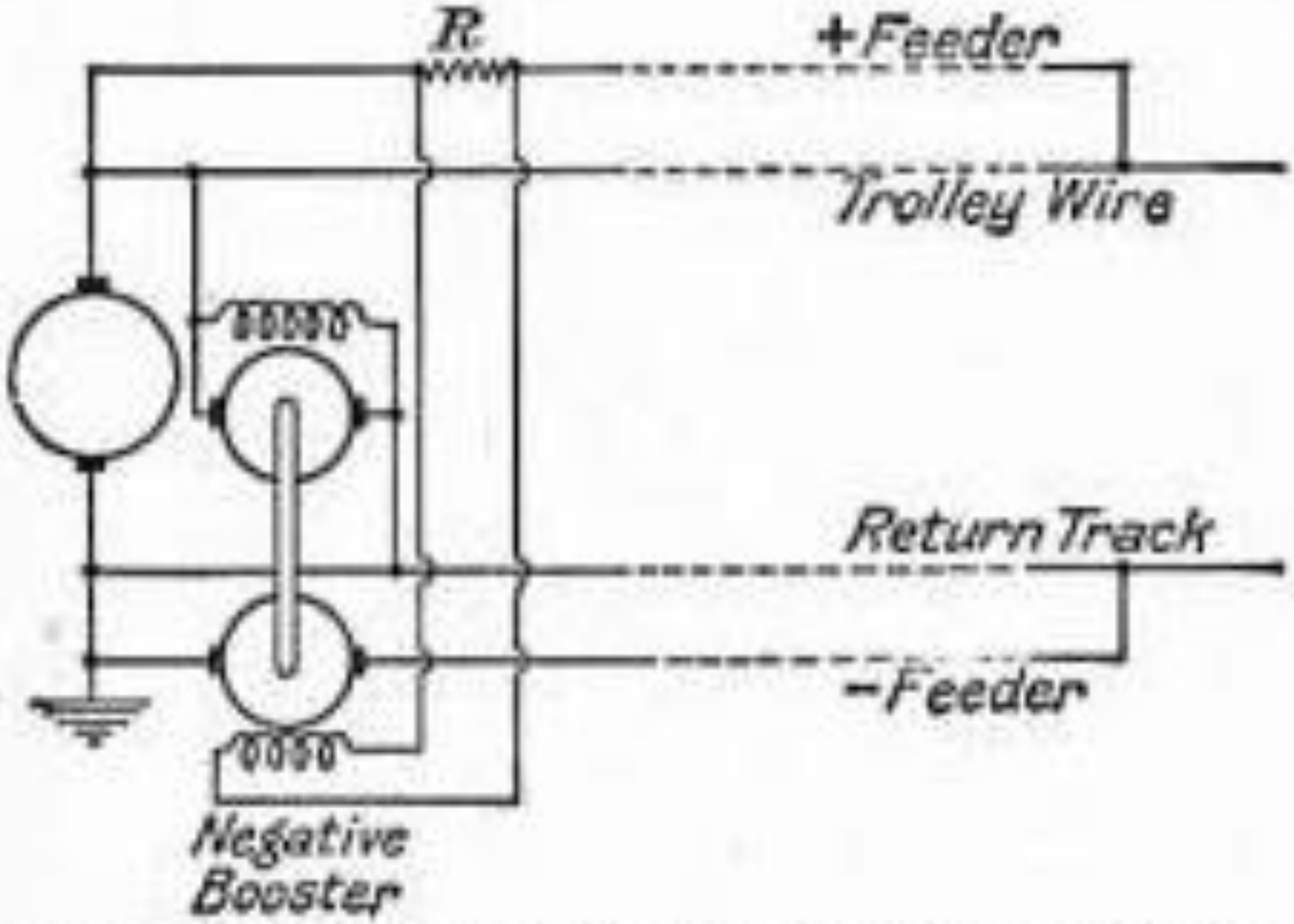


Fig. 25. Negative Booster Connections

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

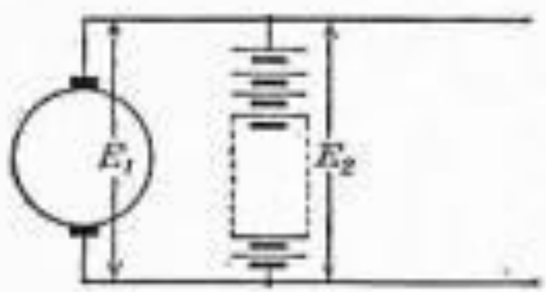


Fig. 26
Floating Battery

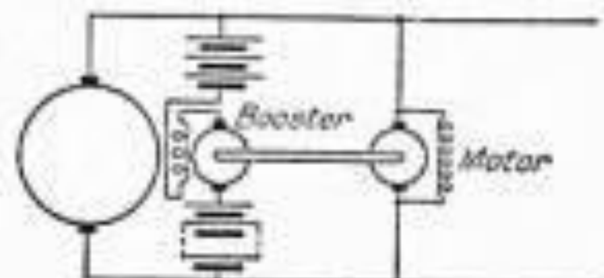


Fig. 27
Floating Battery and Booster

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.

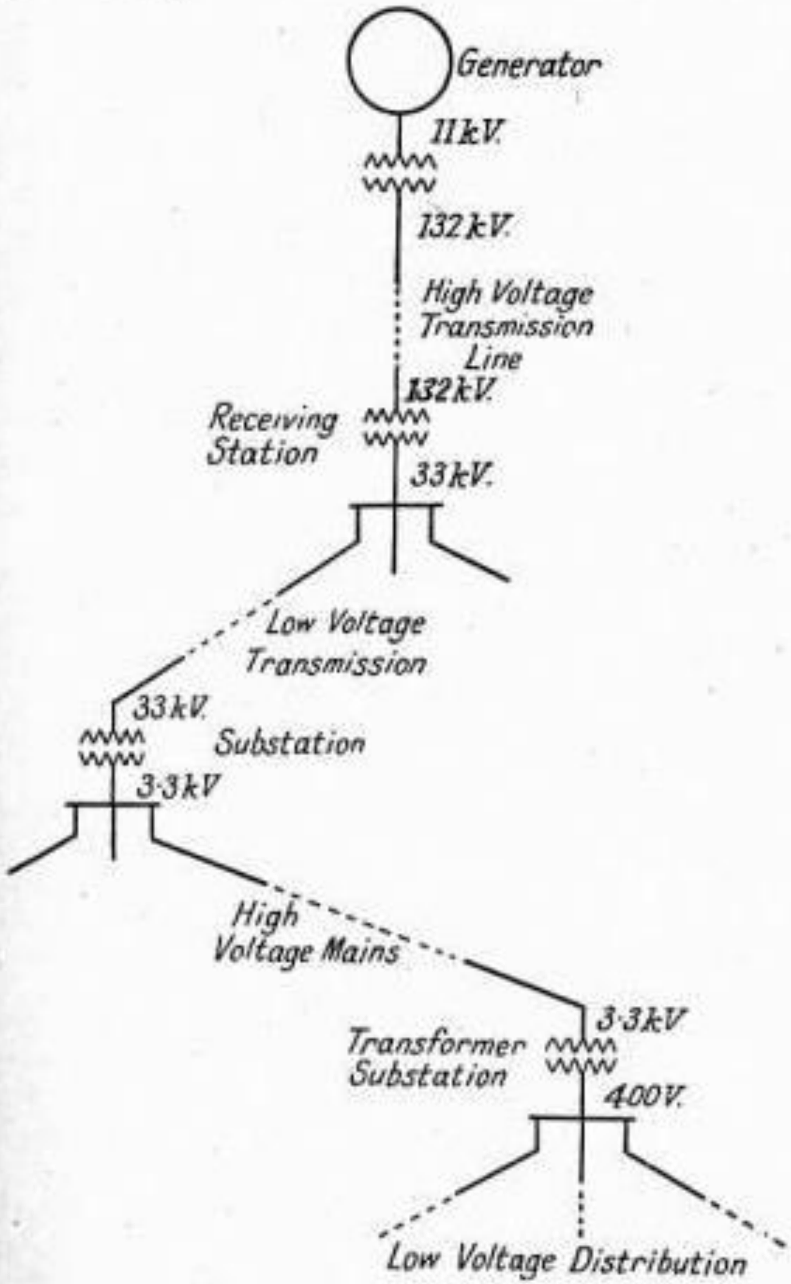
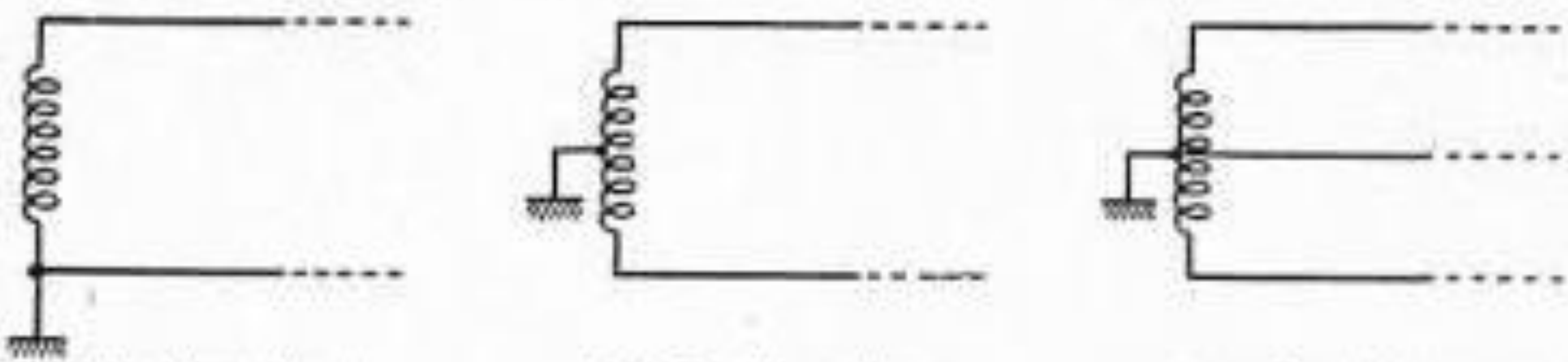


FIG. 28. TYPICAL A.C. SYSTEM

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

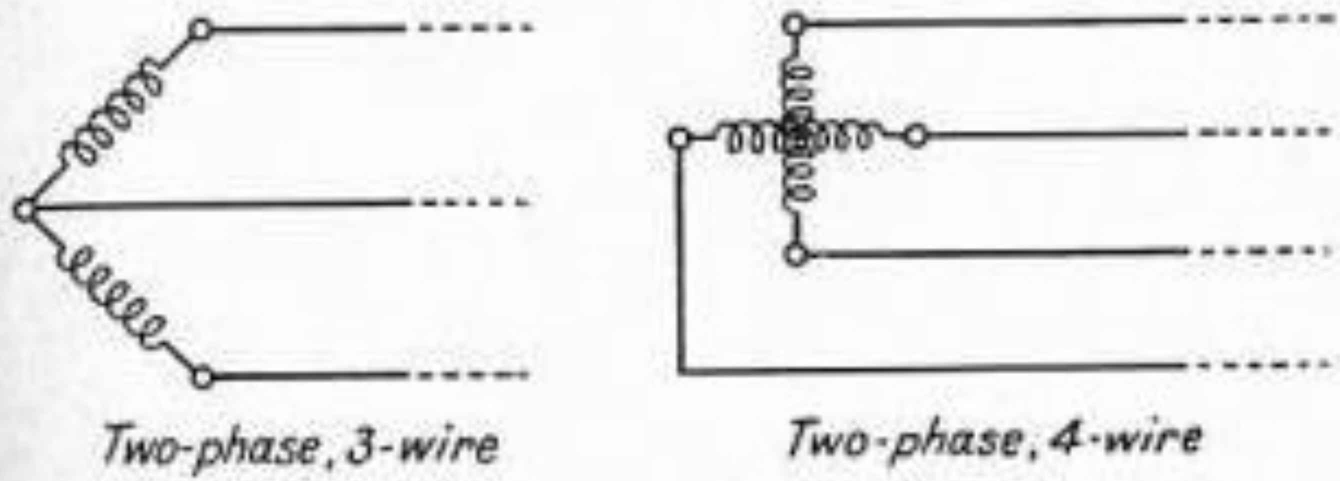


FIG. 30. TWO-PHASE SYSTEMS

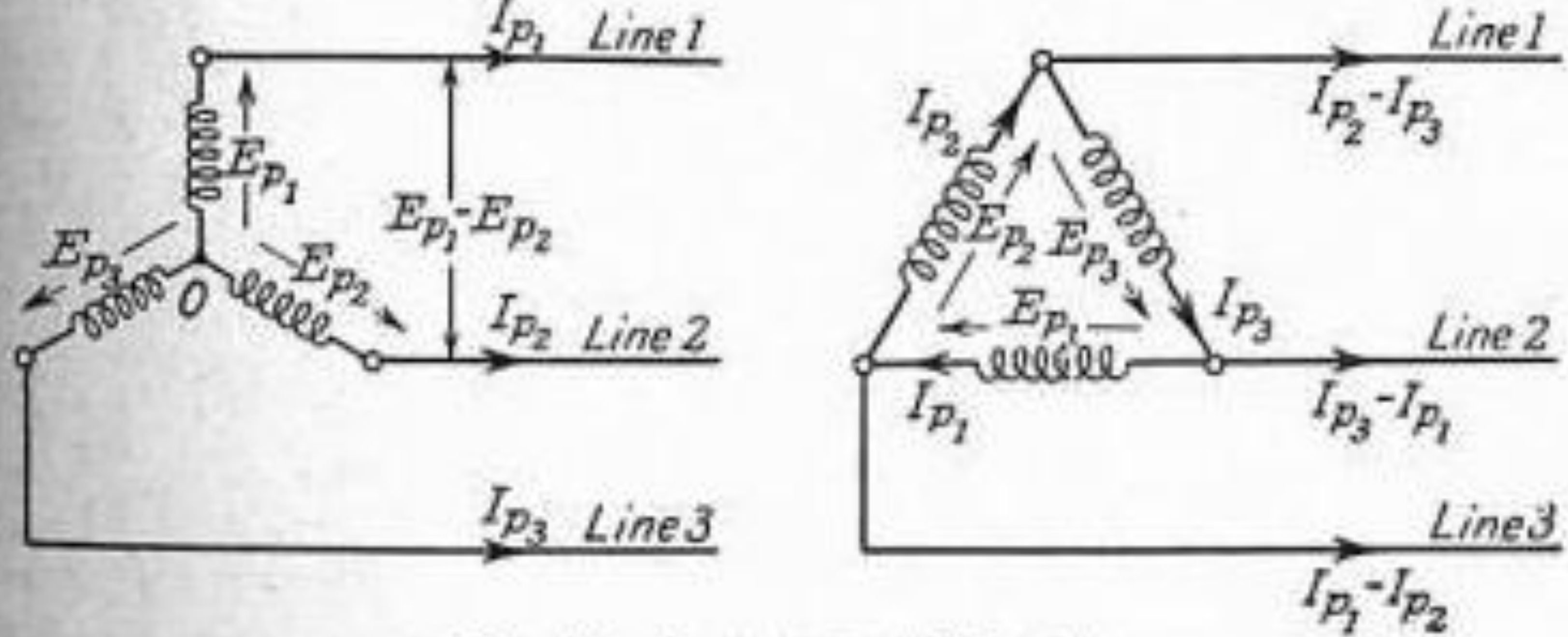


FIG. 31. THREE-PHASE SYSTEMS

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

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 = ½ × 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 . .	$0{\cdot}5/\cos^2\phi$	$2/\cos^2\phi$
Single-phase, 3-wire Neutral = ½ × outer .	$0{\cdot}625/\cos^2\phi$	$2{\cdot}5/\cos^2\phi$
Two-phase, 4-wire .	$0{\cdot}5/\cos^2\phi$	$2{\cdot}0/\cos^2\phi$
Two-phase, 3-wire .	$1{\cdot}46/\cos^2\phi$	$2{\cdot}91/\cos^2\phi$
Three-phase, 3-wire .	$0{\cdot}5/\cos^2\phi$	$1{\cdot}5/\cos^2\phi$
Three-phase, 4-wire Neutral = outer . .	$0{\cdot}67/\cos^2\phi$	$2/\cos^2\phi$

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 are 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 cent
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.

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

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.

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

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

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

DESIRED FEATURES

Electrical energy may be distributed over two or more wires. The principal features desired are safety; smooth and even flow of power, as far as is practical; and economy.

TYPES OF ELECTRIC SYSTEMS

Direct Current Systems

Direct current systems usually consist of two or three wires. Although such distribution systems are no longer employed, except in very special instances, older ones now exist and will continue to exist for some time. Direct current systems are essentially the same as single-phase ac systems of two or three wires; 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 conductors between which a relatively constant voltage is maintained, with the load connected between the two conductors; refer to Fig. 2-1.

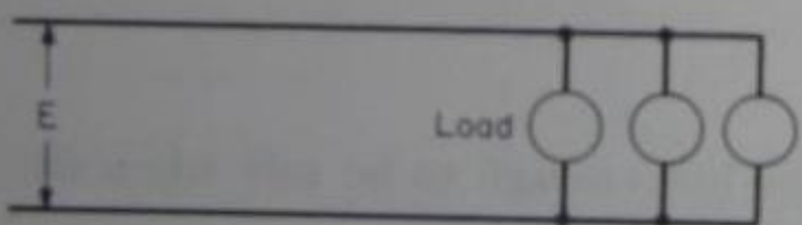
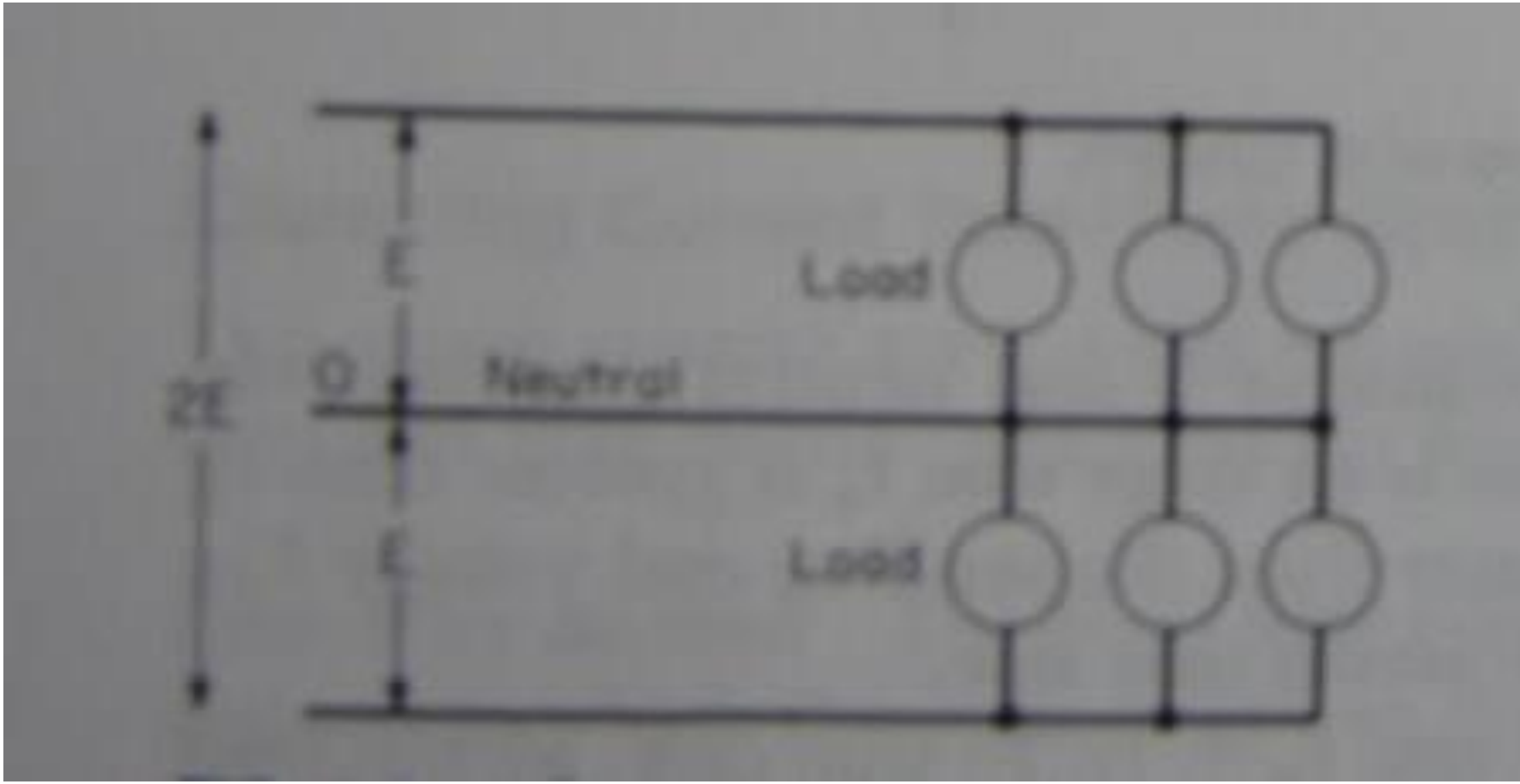


FIG. 2-1 AC single-phase two-wire system.



2E
E
O
Neutral
Load
E
Load

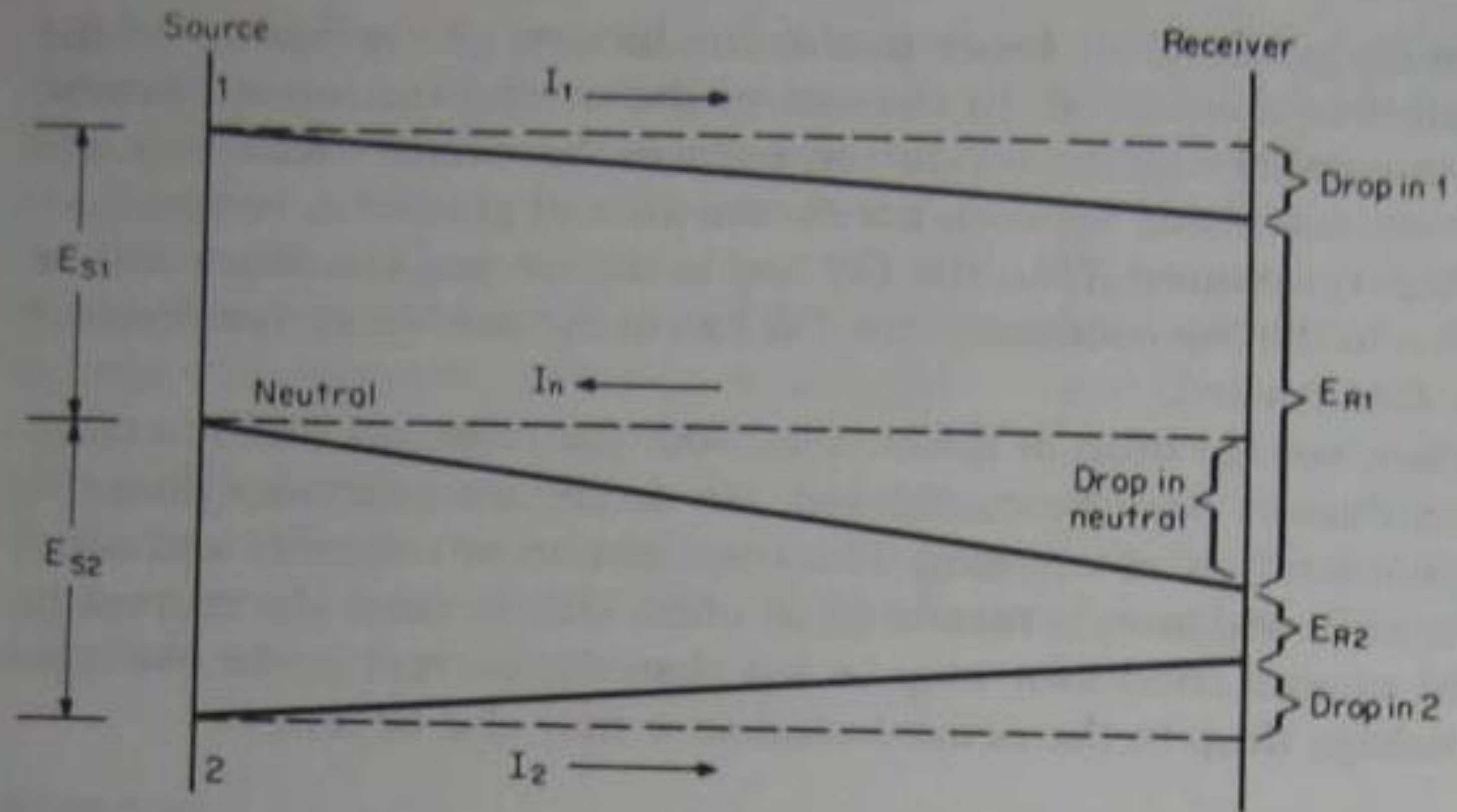


FIG. 2-3 Unbalanced load—single-phase three-wire system.

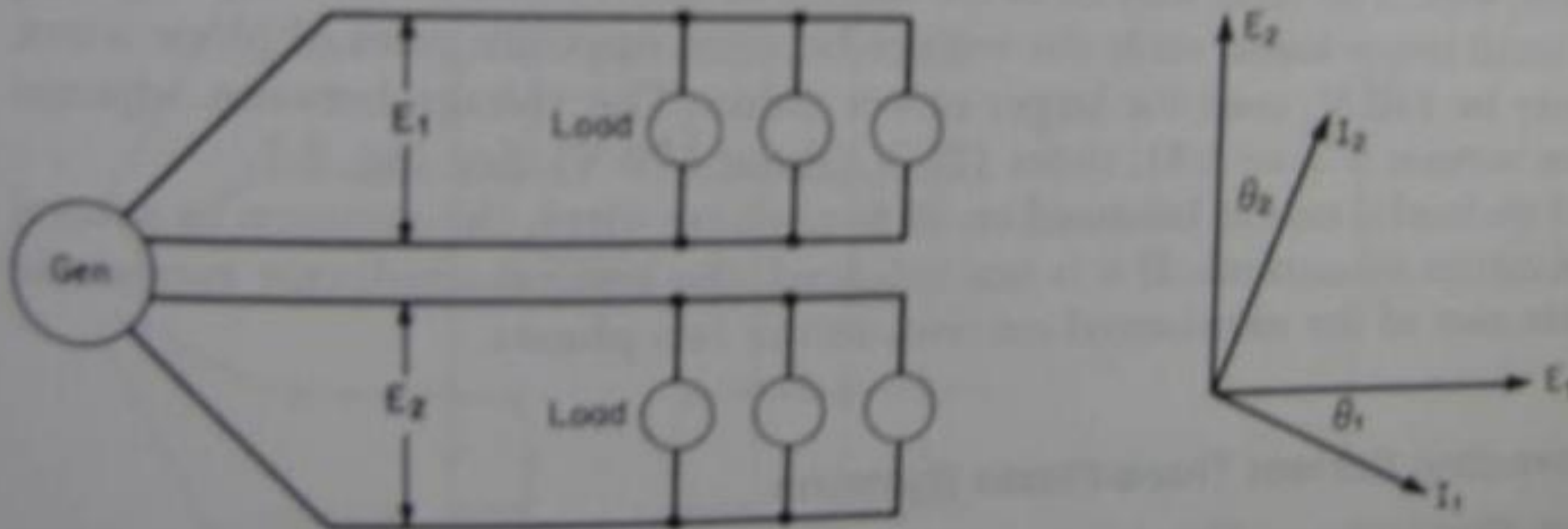


FIG. 2-5 AC two-phase four-wire system and vector diagram.

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

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

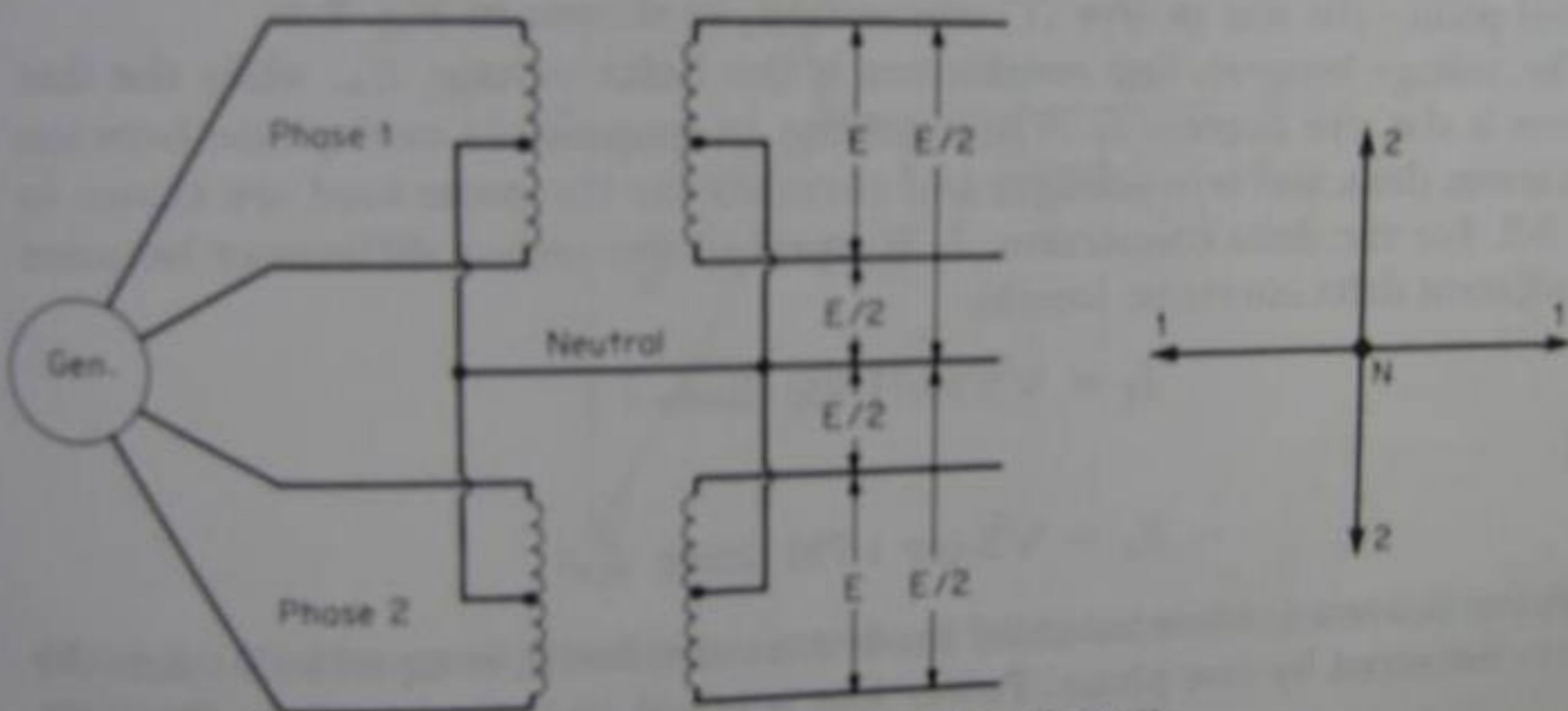


FIG. 2-7 AC two-phase five-wire system and vector diagram.

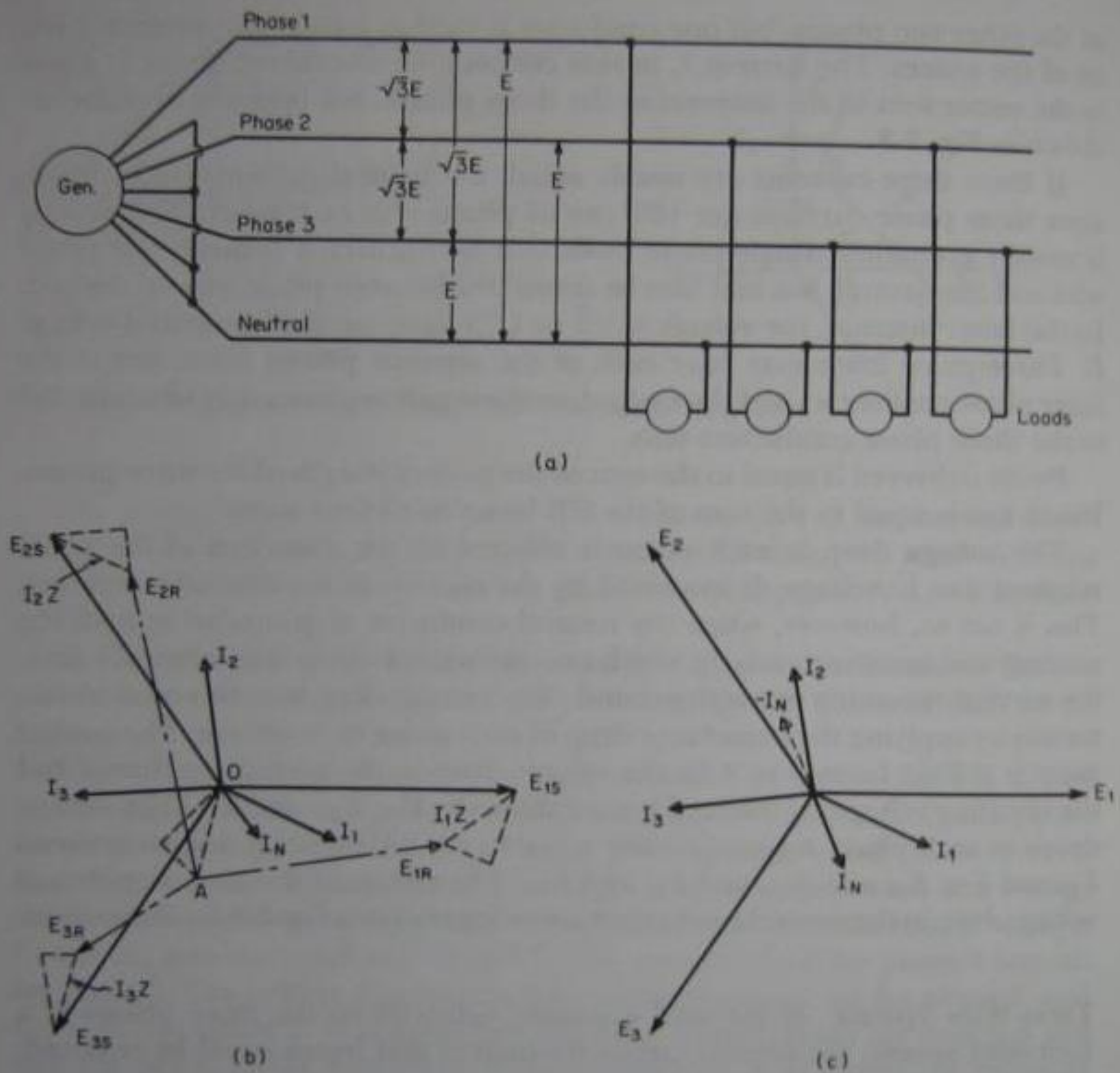
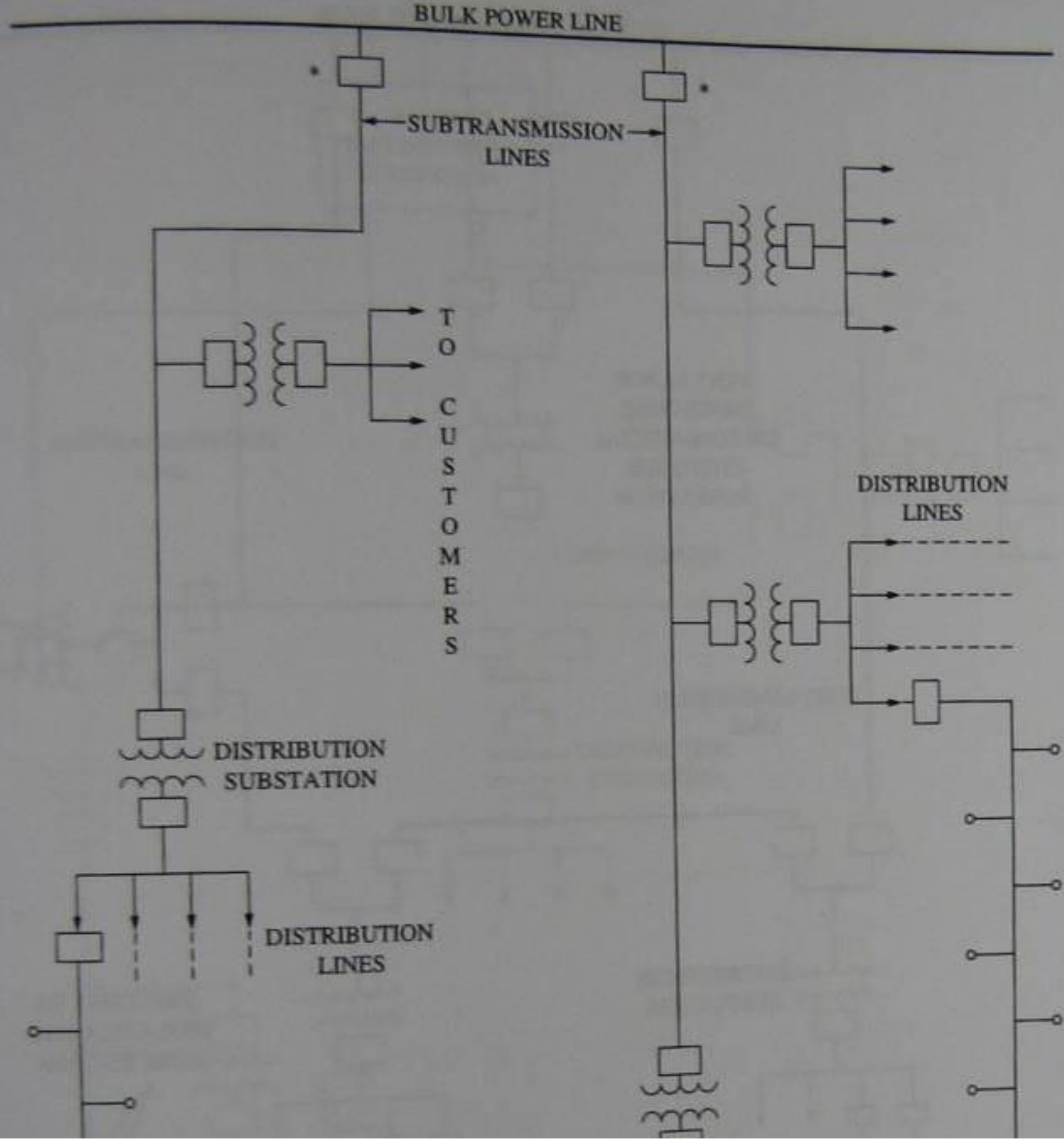
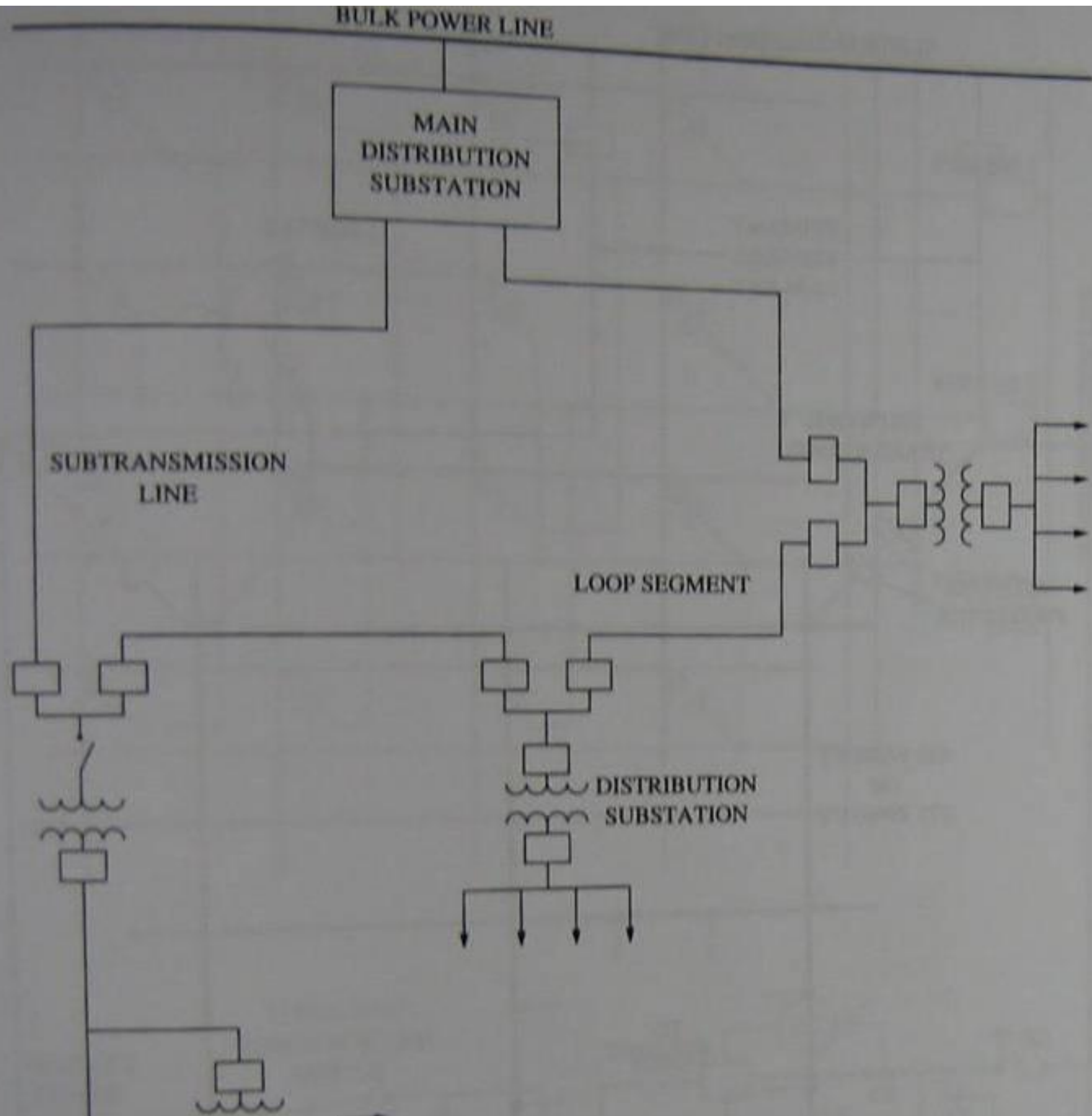
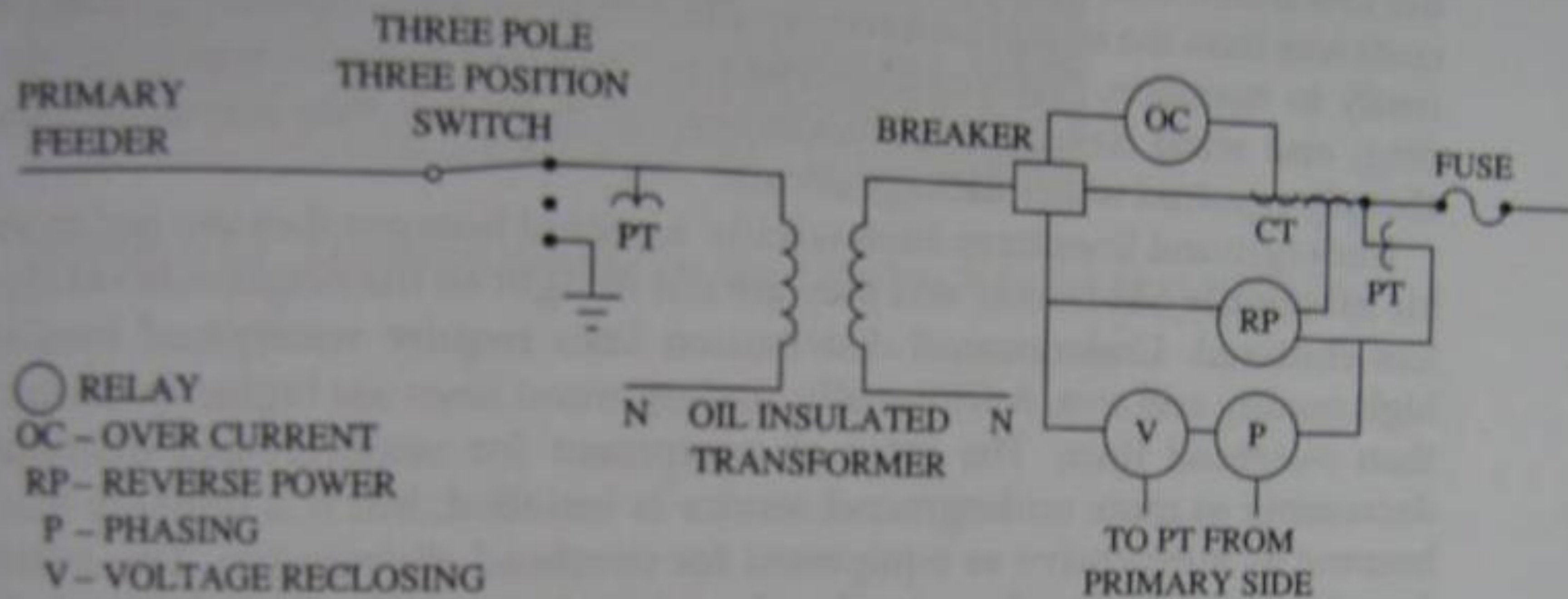


FIG. 2-8 (*a*) AC three-phase four-wire system; (*b*) voltage and current vector diagram; (*c*) current vector diagram.



BULK POWER LINE
SUBTRANSMISSION LINES
TO CUSTOMERS
DISTRIBUTION LINES
DISTRIBUTION SUBSTATION
DISTRIBUTION LINES


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



PRIMARY FEEDER
THREE POLE THREE POSITION SWITCH
PT
BREAKER
OC
FUSE
CT
PT
RP
N
OIL INSULATED TRANSFORMER
N
V
P
TO PT FROM PRIMARY SIDE
RELAY
OC – OVER CURRENT
RP – REVERSE POWER
P – PHASING
V – VOLTAGE RECLOSING

c

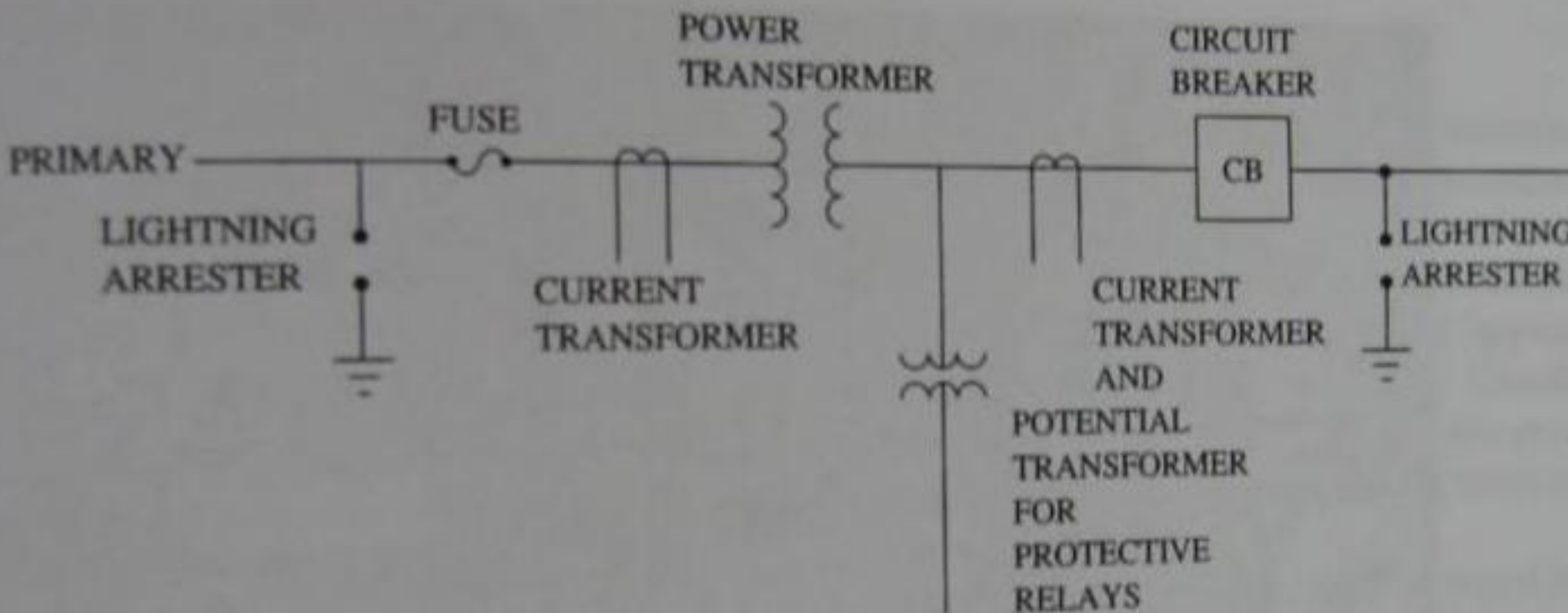
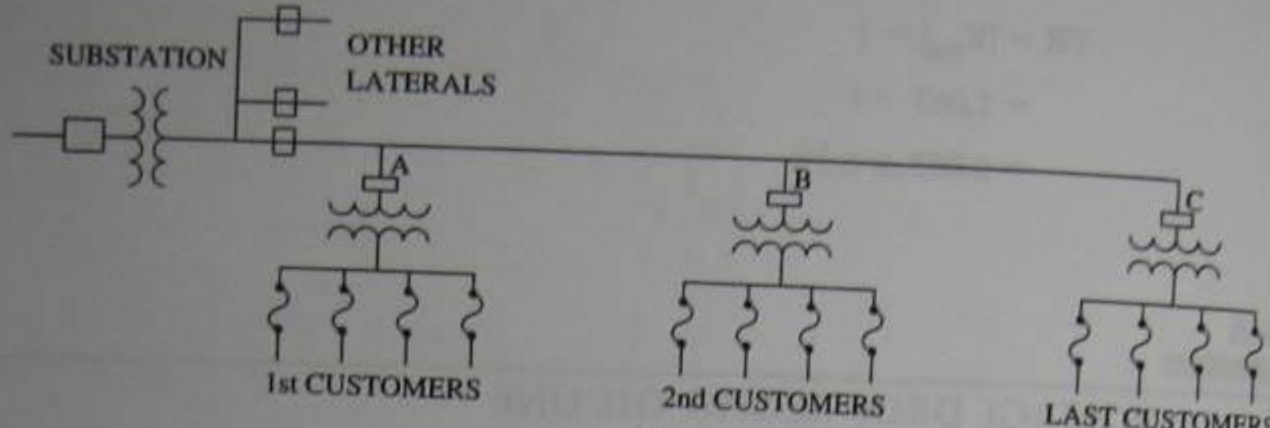
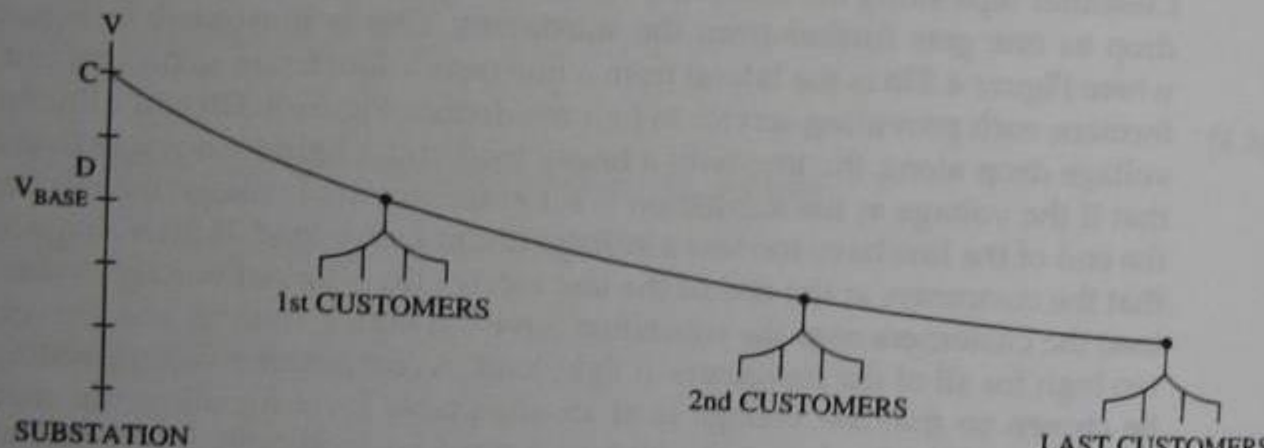


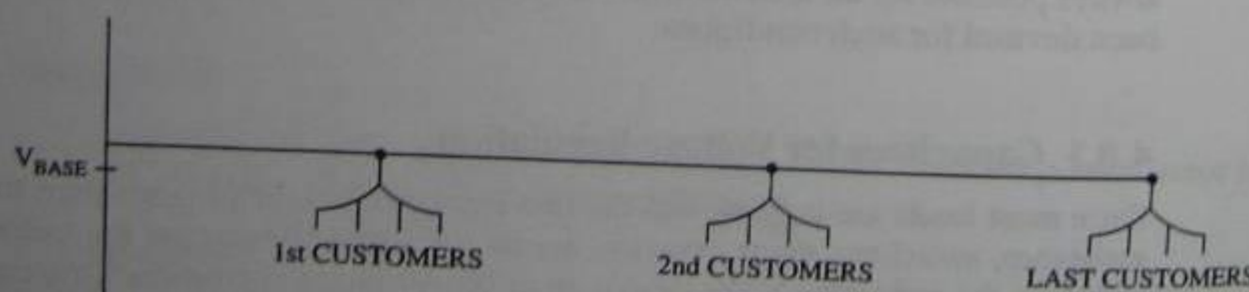
FIGURE 4.18 Power transformer one-line drawing with protection

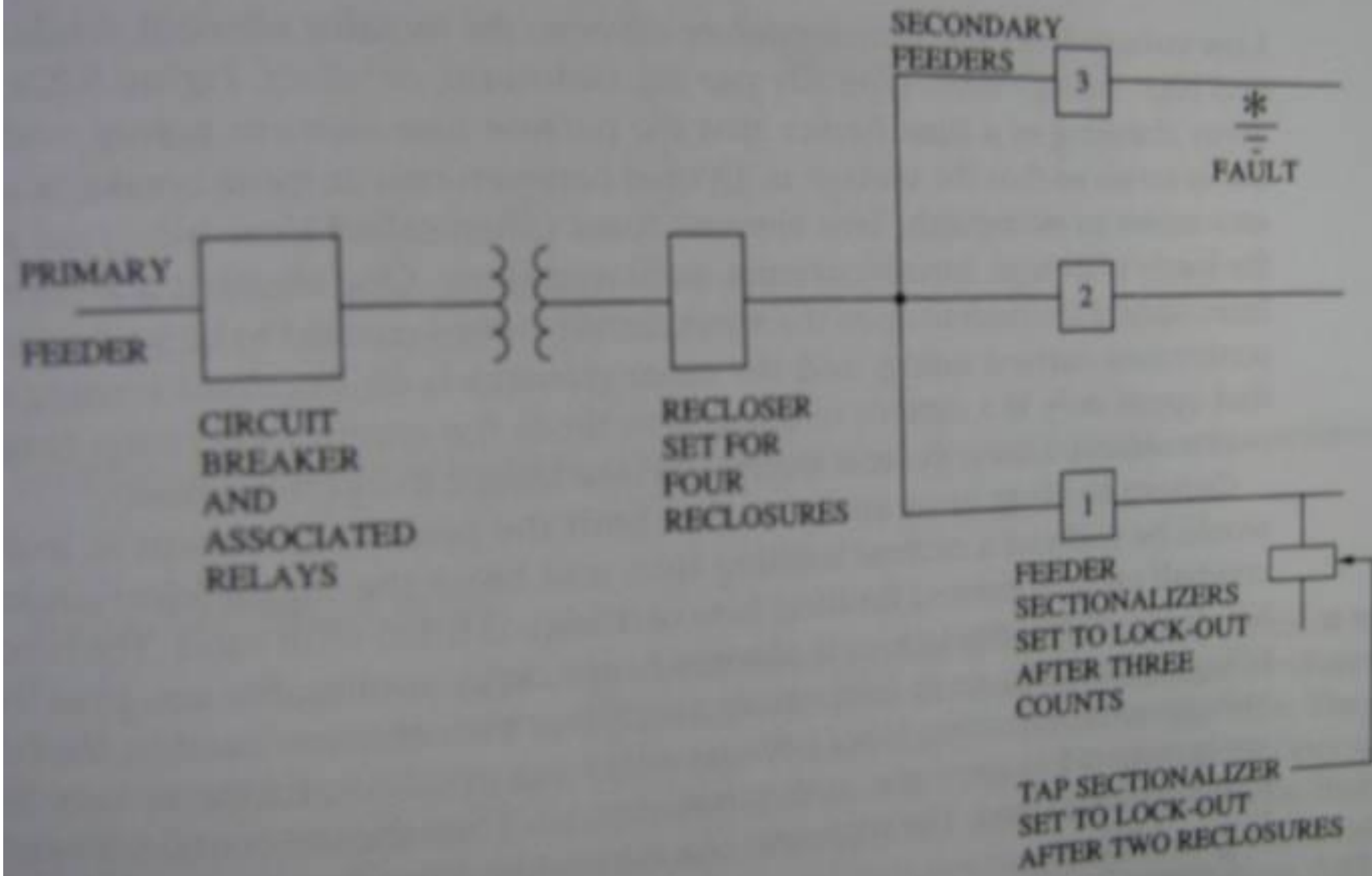

SUBSTATION
OTHER
LATERALS
A
B
C
1st CUSTOMERS
2nd CUSTOMERS
LAST CUSTOMERS

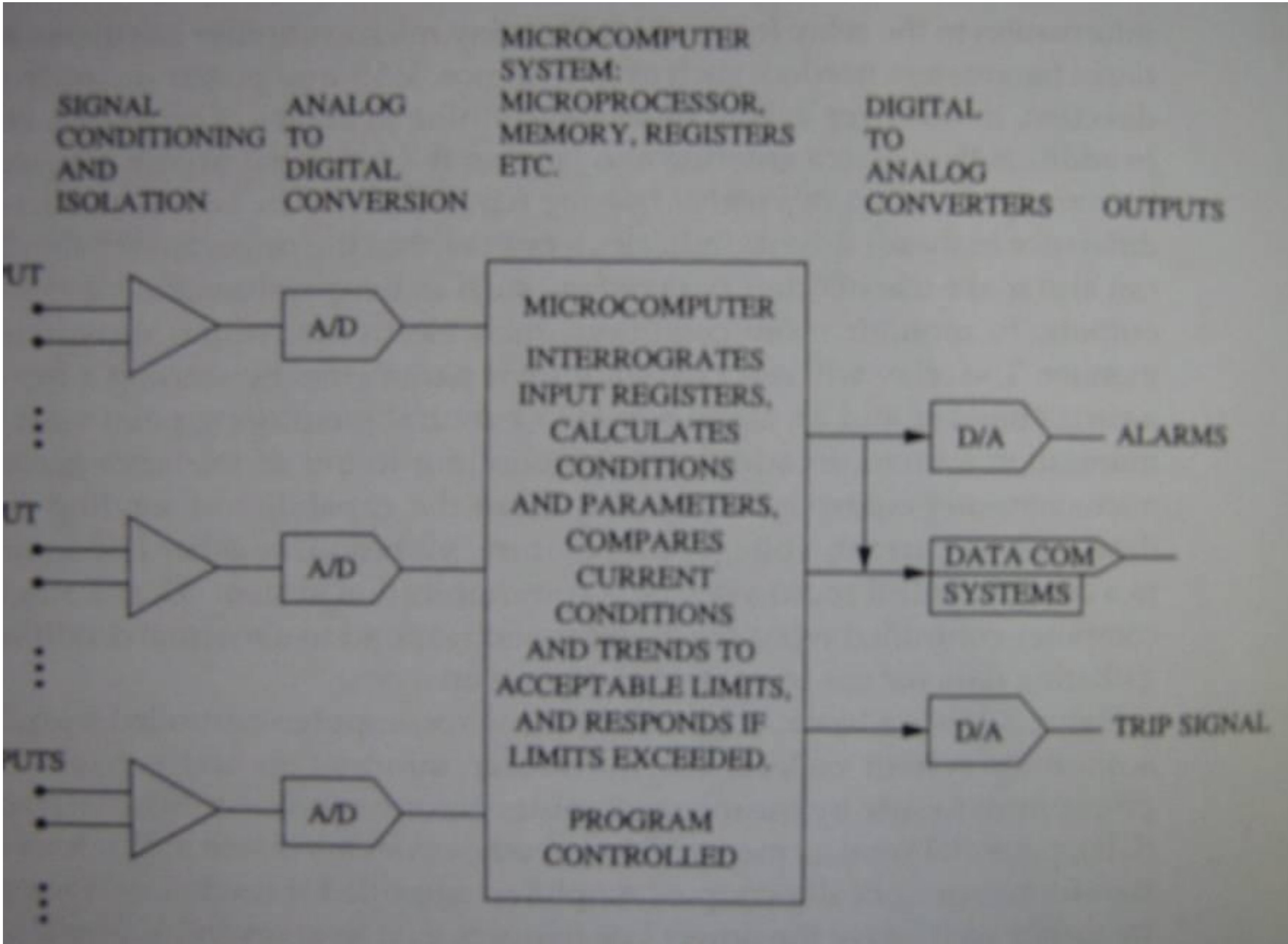
a

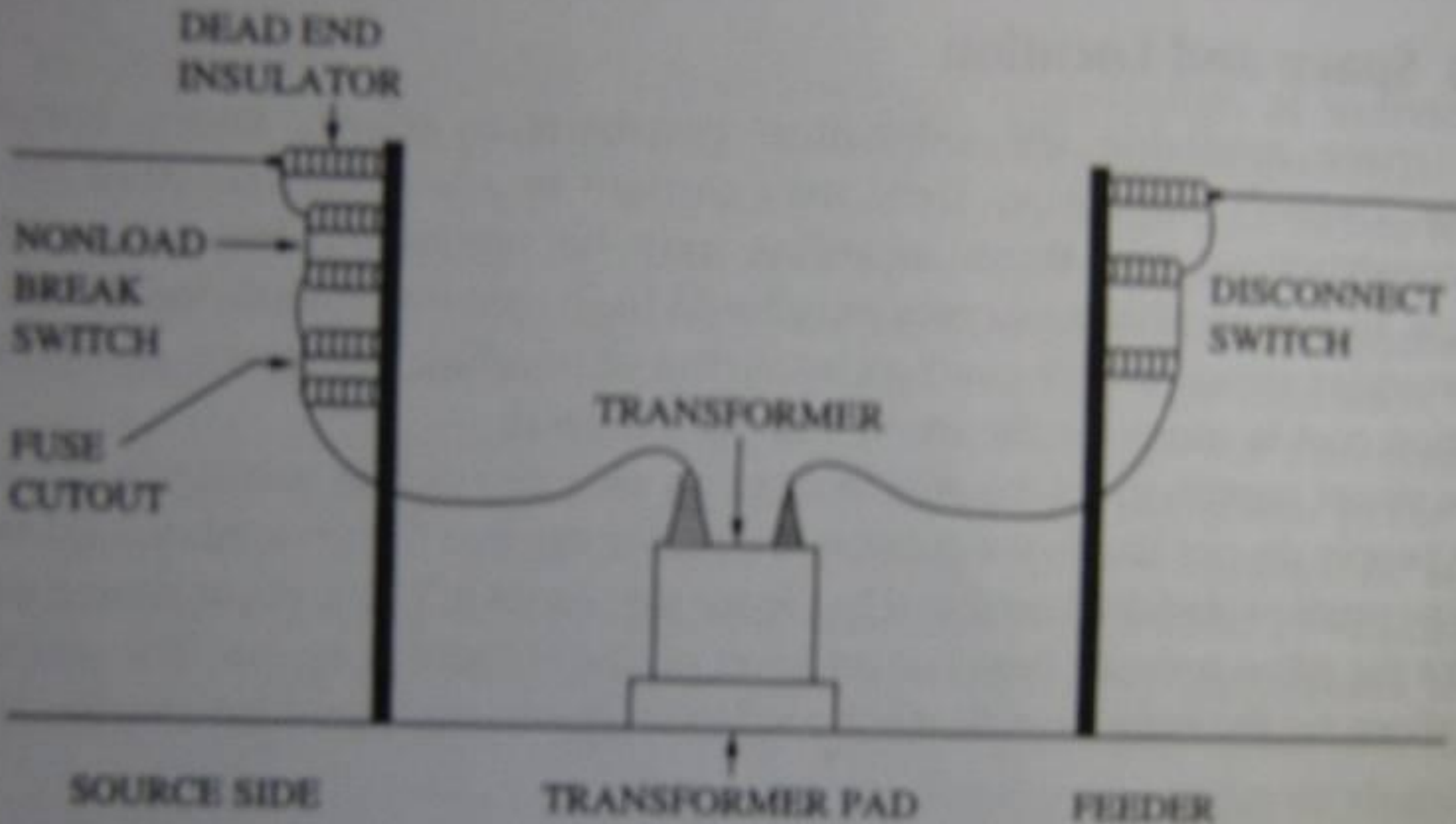

V
C
D
V_{BASE}
SUBSTATION
1st CUSTOMERS
2nd CUSTOMERS
LAST CUSTOMERS

b

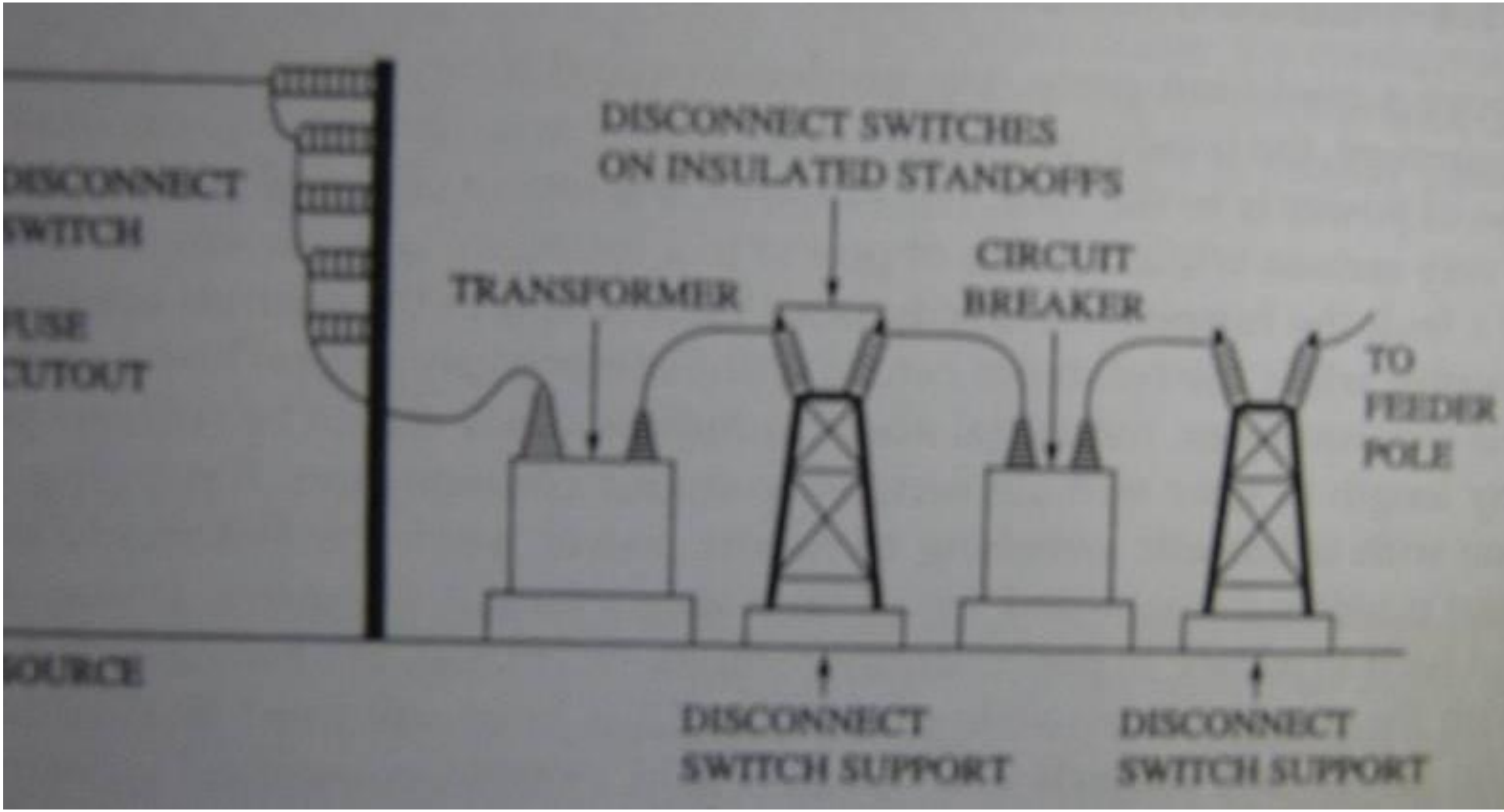

V_{BASE}
1st CUSTOMERS
2nd CUSTOMERS
LAST CUSTOMERS


SECONDARY
FEEDERS
3
FAULT
PRIMARY
FEEDER
2
CIRCUIT
BREAKER
AND
ASSOCIATED
RELAYS
RECLOSER
SET FOR
FOUR
RECLOSURES
1
FEEDER
SECTIONALIZERS
SET TO LOCK-OUT
AFTER THREE
COUNTS
TAP SECTIONALIZER
SET TO LOCK-OUT
AFTER TWO RECLOSURES


SIGNAL CONDITIONING AND ISOLATION
ANALOG TO DIGITAL CONVERSION
MICROCOMPUTER SYSTEM: MICROPROCESSOR, MEMORY, REGISTERS ETC.
DIGITAL TO ANALOG CONVERTERS
OUTPUTS
UT
UT
PUTS
A/D
A/D
A/D
MICROCOMPUTER
INTERROGATES INPUT REGISTERS, CALCULATES CONDITIONS AND PARAMETERS, COMPARES CURRENT CONDITIONS AND TRENDS TO ACCEPTABLE LIMITS, AND RESPONDS IF LIMITS EXCEEDED.
PROGRAM CONTROLLED
D/A
ALARMS
DATA COM SYSTEMS
D/A
TRIP SIGNAL


DEAD END
INSULATOR
NONLOAD
BREAK
SWITCH
FUSE
CUTOUT
TRANSFORMER
DISCONNECT
SWITCH
SOURCE SIDE
TRANSFORMER PAD
FEEDER

a


DISCONNECT SWITCHES ON INSULATED STANDOFFS
DISCONNECT SWITCH
FUSE CUTOUT
TRANSFORMER
CIRCUIT BREAKER
TO FEEDER POLE
SOURCE
DISCONNECT SWITCH SUPPORT
DISCONNECT SWITCH SUPPORT

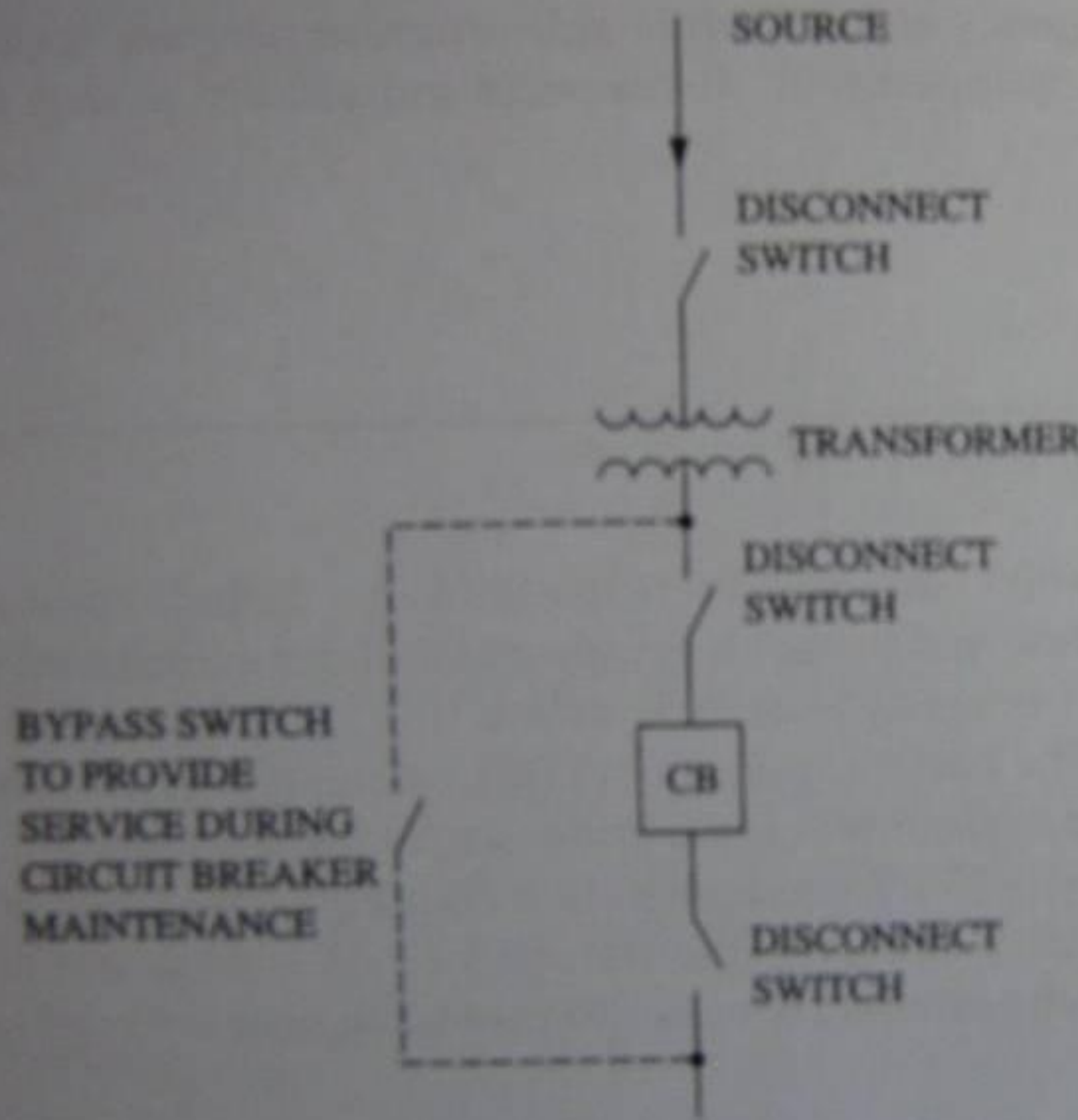
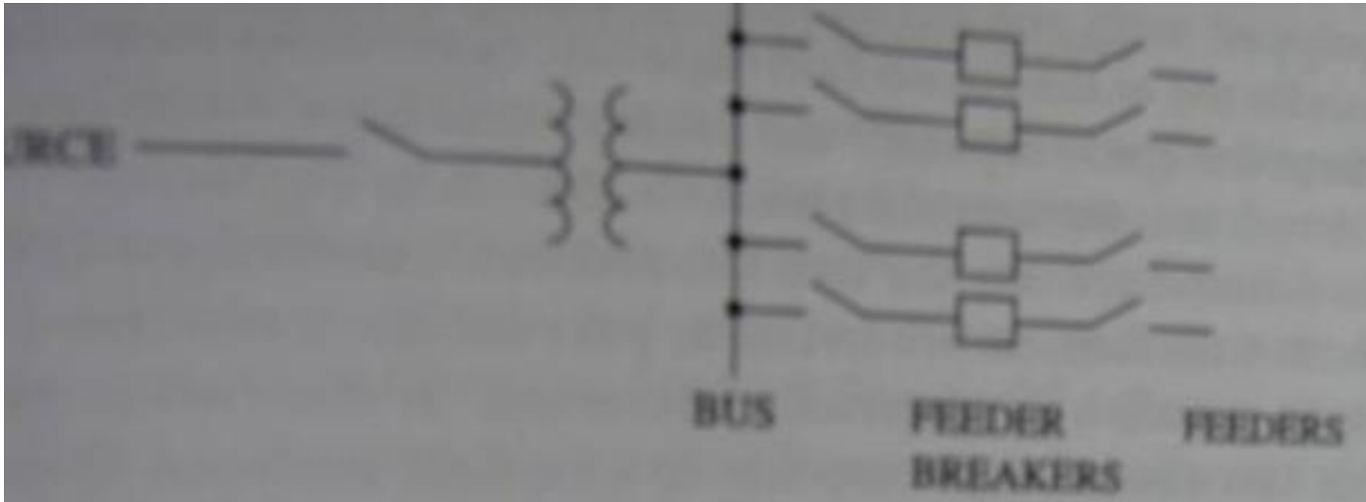
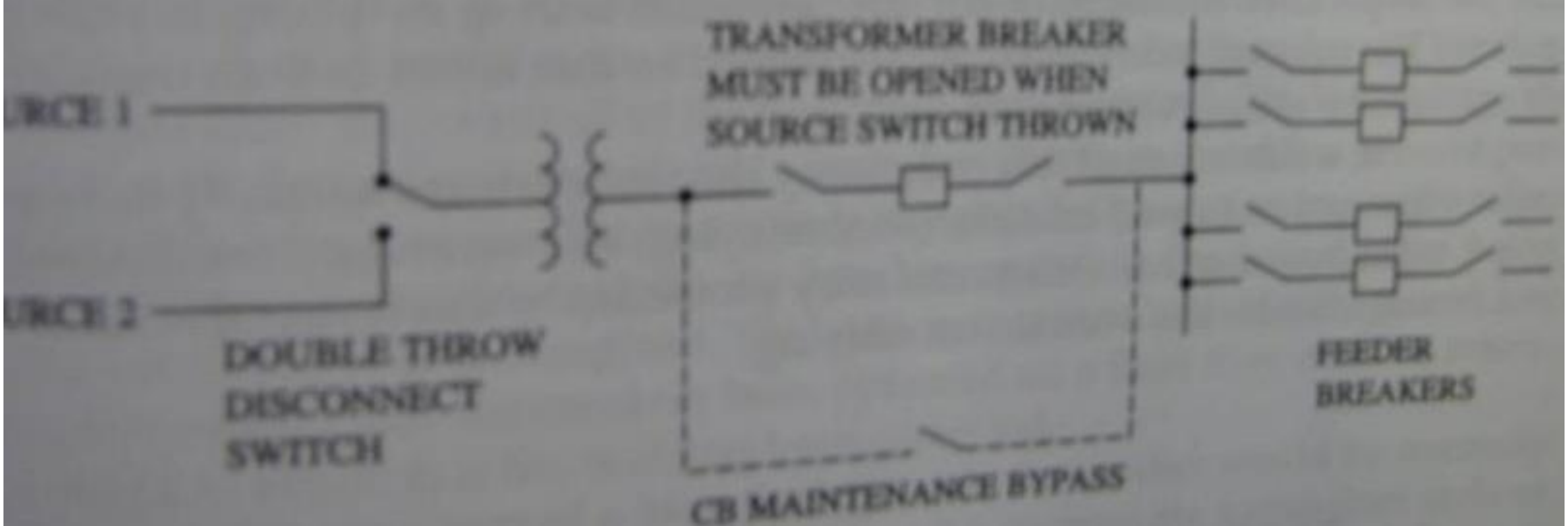


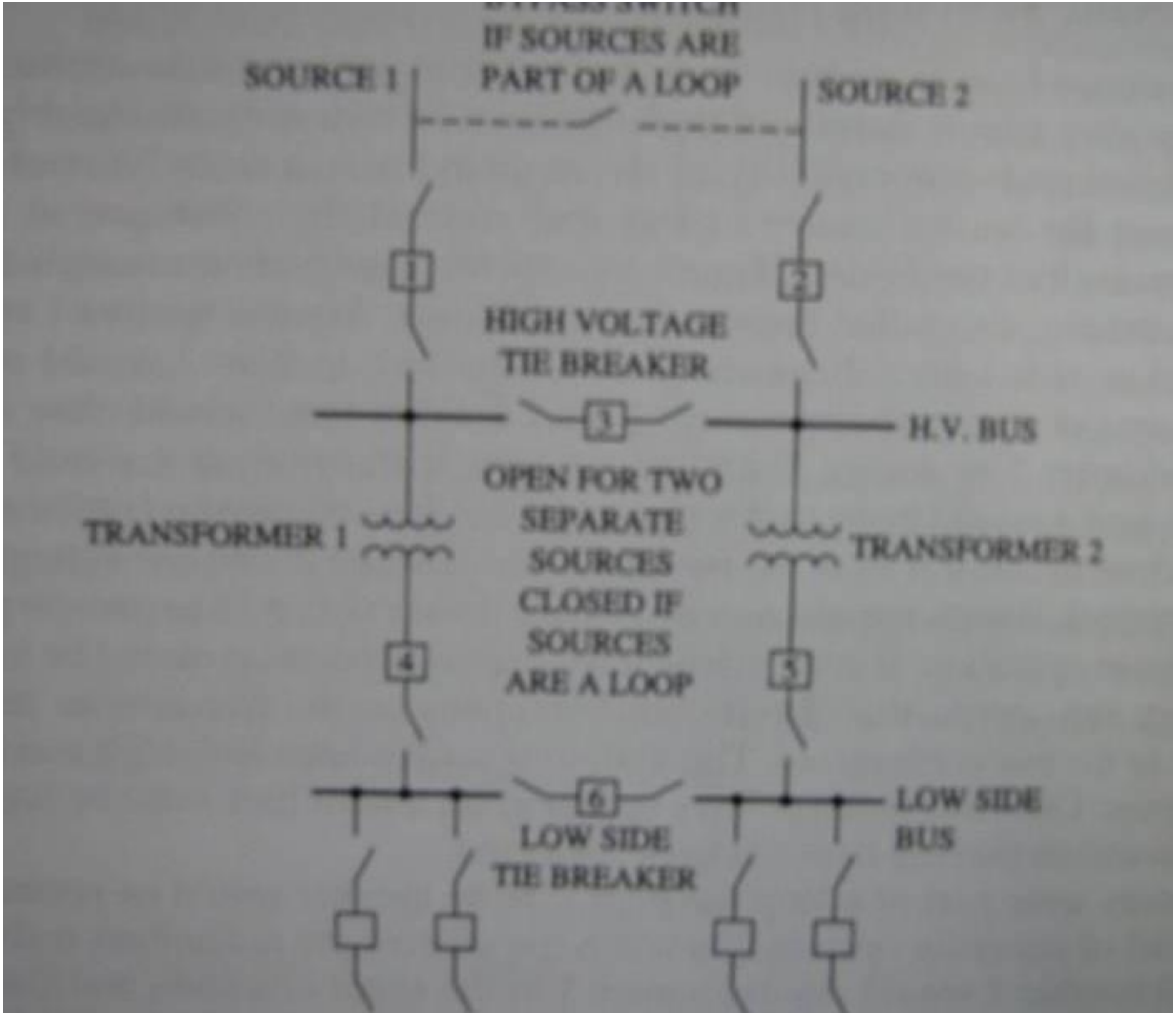
FIGURE 6.4 One-line diagram of single source, single feeder substation


BUS
FEEDER BREAKERS
FEEDERS

a


TRANSFORMER BREAKER MUST BE OPENED WHEN SOURCE SWITCH THROWN
DOUBLE THROW DISCONNECT SWITCH
FEEDER BREAKERS
CB MAINTENANCE BYPASS

b


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

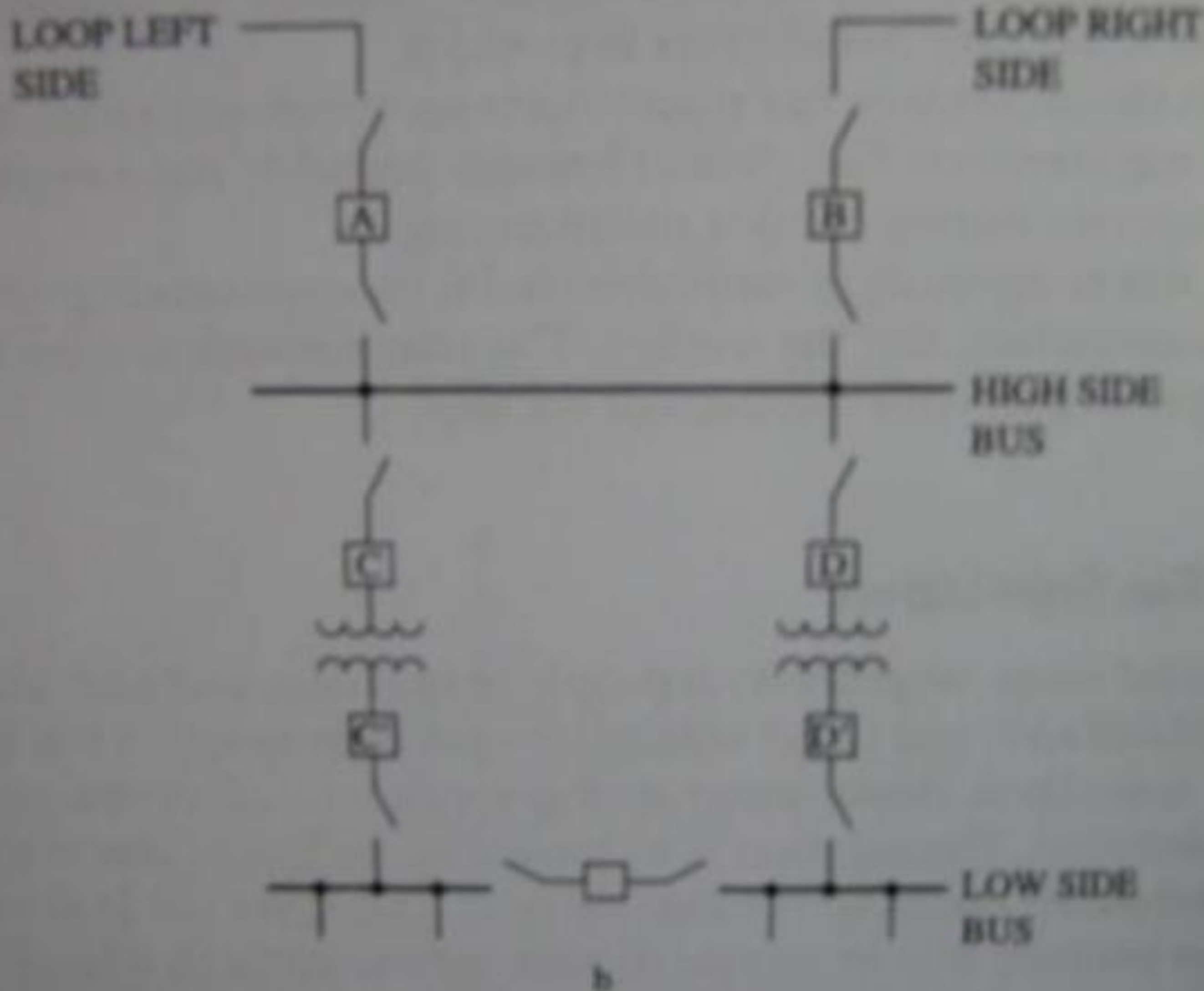
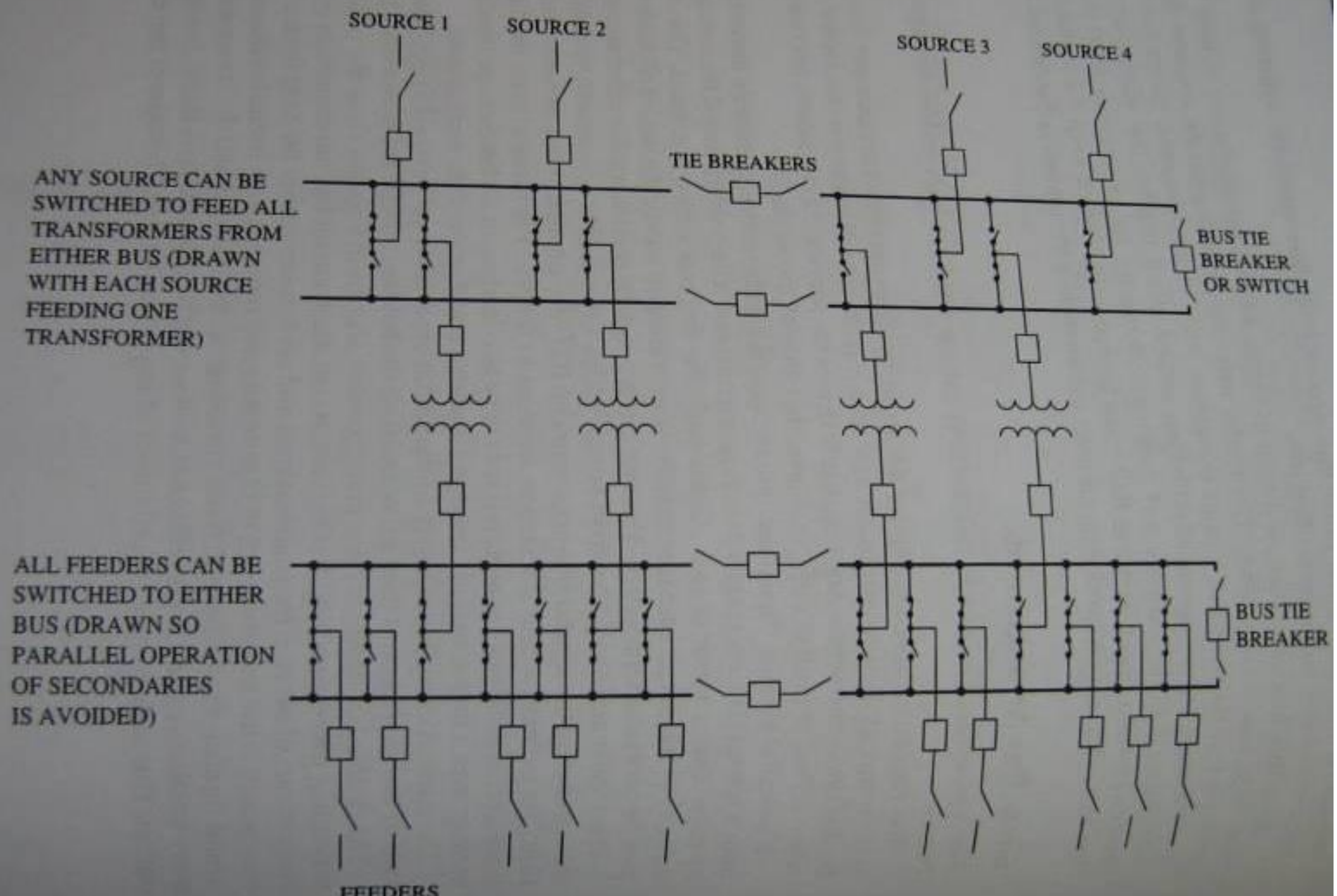


FIGURE 6.7 Automatic switching two source, two transformer substation (a) Two source, radial or loop and (b) better high side loop arrangement



SOURCE 1
SOURCE 2
SOURCE 3
SOURCE 4
TIE BREAKERS
ANY SOURCE CAN BE SWITCHED TO FEED ALL TRANSFORMERS FROM EITHER BUS (DRAWN WITH EACH SOURCE FEEDING ONE TRANSFORMER)
BUS TIE BREAKER OR SWITCH
ALL FEEDERS CAN BE SWITCHED TO EITHER BUS (DRAWN SO PARALLEL OPERATION OF SECONDARIES IS AVOIDED)
BUS TIE BREAKER
FEEDERS

Circuit breaker

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

Butt contacts. These have a line, point or plane contact area 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.

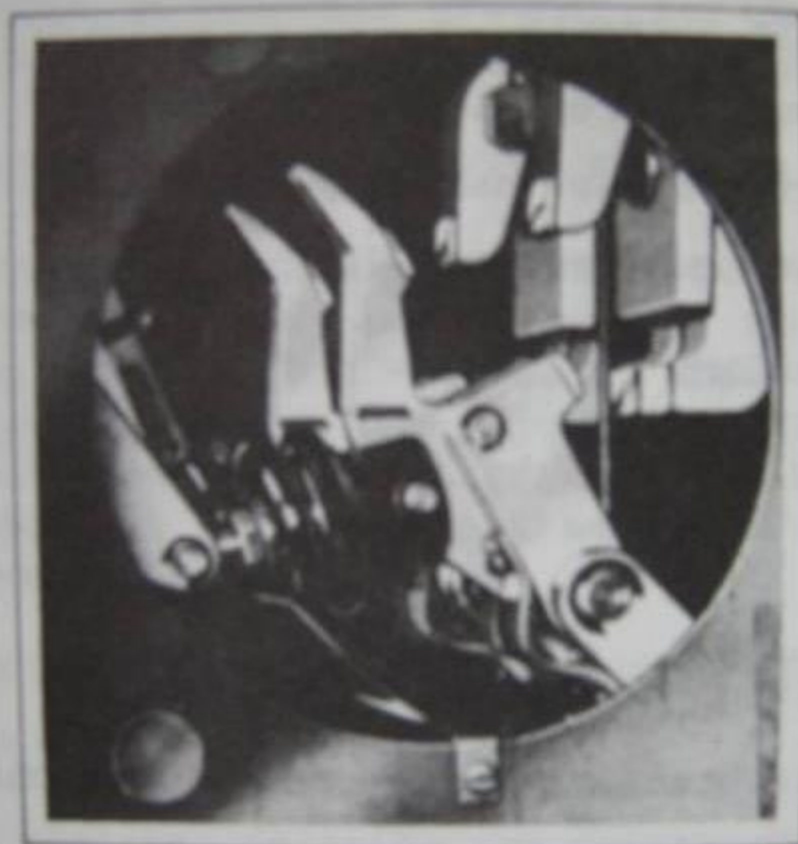
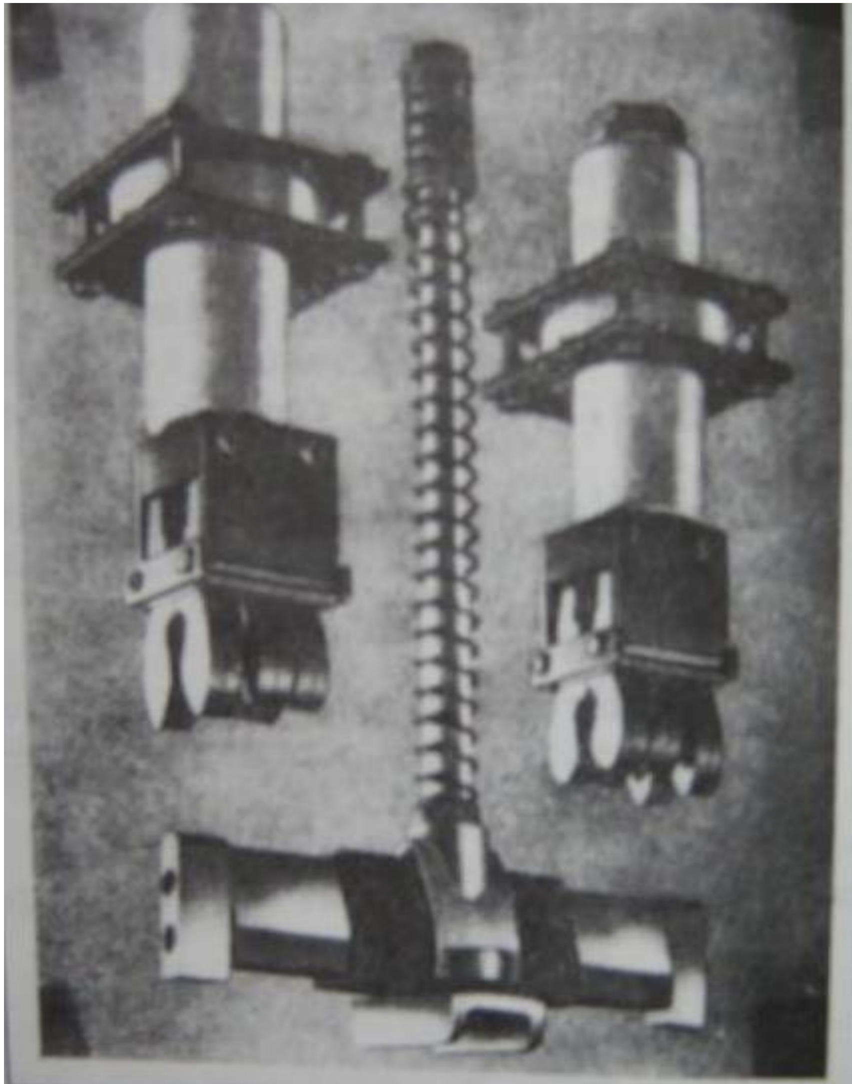


Figure 1

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 associated with circuit breakers. These definitions should be referred to as the terms are used in the notes.

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

Circuit breaker. A mechanical switching device capable of making, carrying and breaking currents under normal circuit conditions and also under predetermined conditions, making, carrying for a given time and breaking currents under abnormal conditions such as those of short circuits.

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

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

by means

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

Independent manual operation. A stored energy operation where the energy originates from manual power, stored and released in one continuous operation.

Stored energy operation. An operation by means of energy stored in the mechanism itself prior to the completion of the operation and sufficient to complete it. The operation may be subdivided 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 electric.

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

Anti-pumping device. A device which prevents a circuit breaker 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 may or may not be dependent on the voltage of the main circuit of the circuit breaker.

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

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

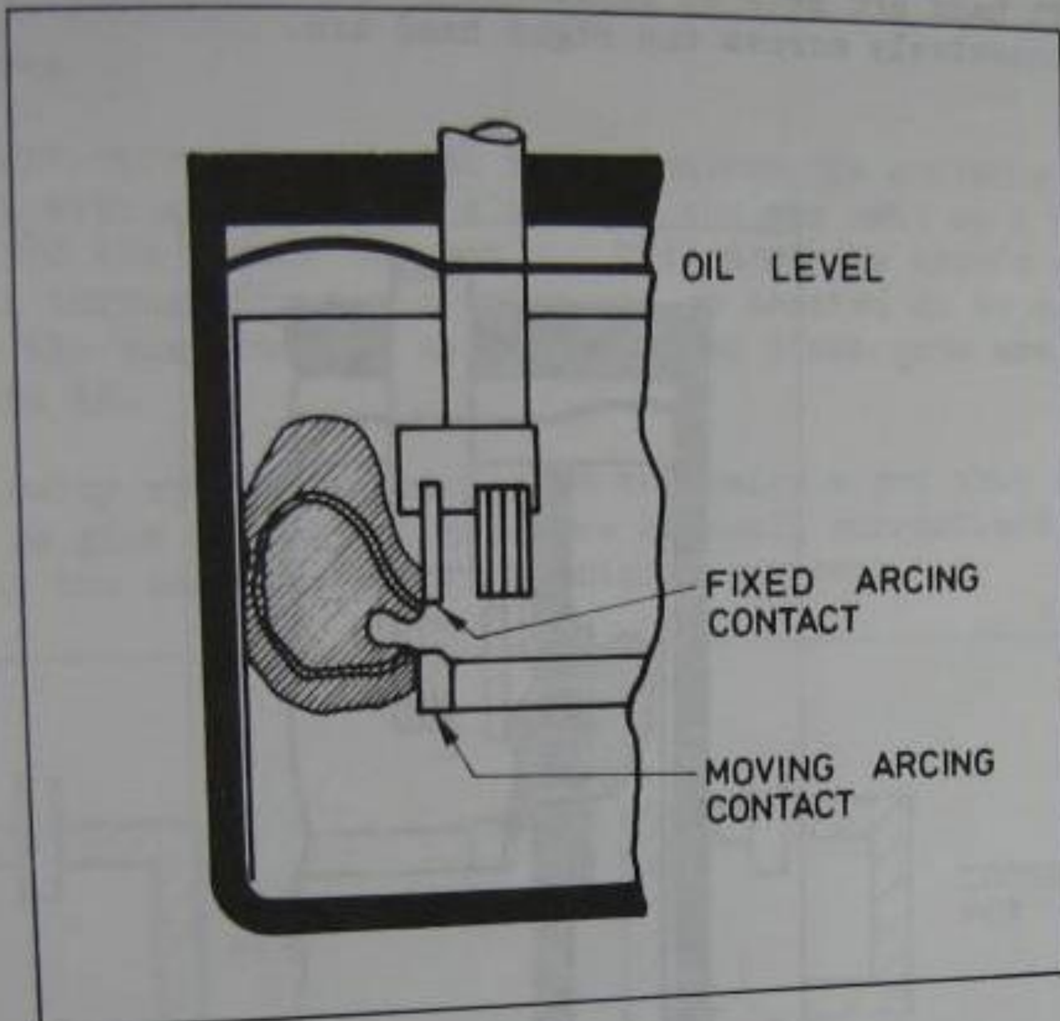


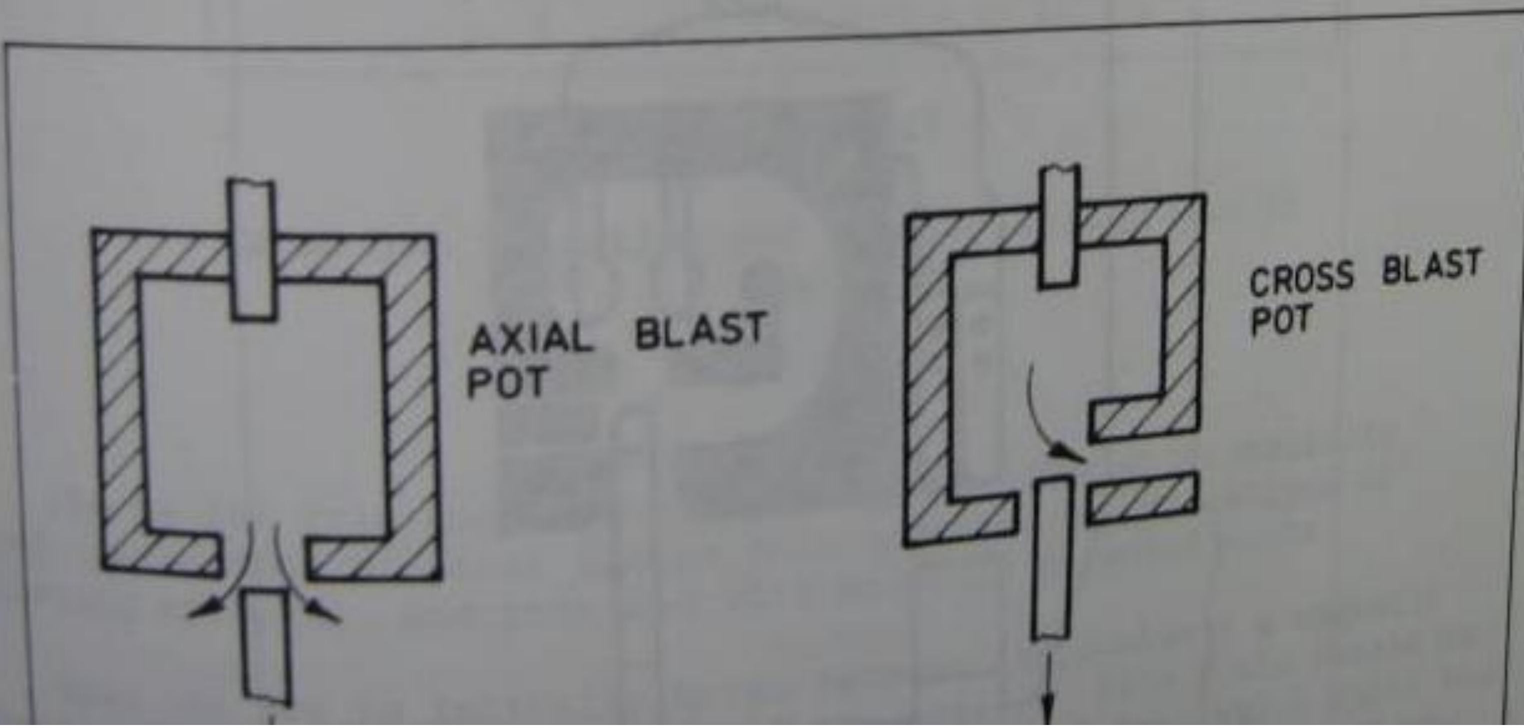
Figure 9

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.



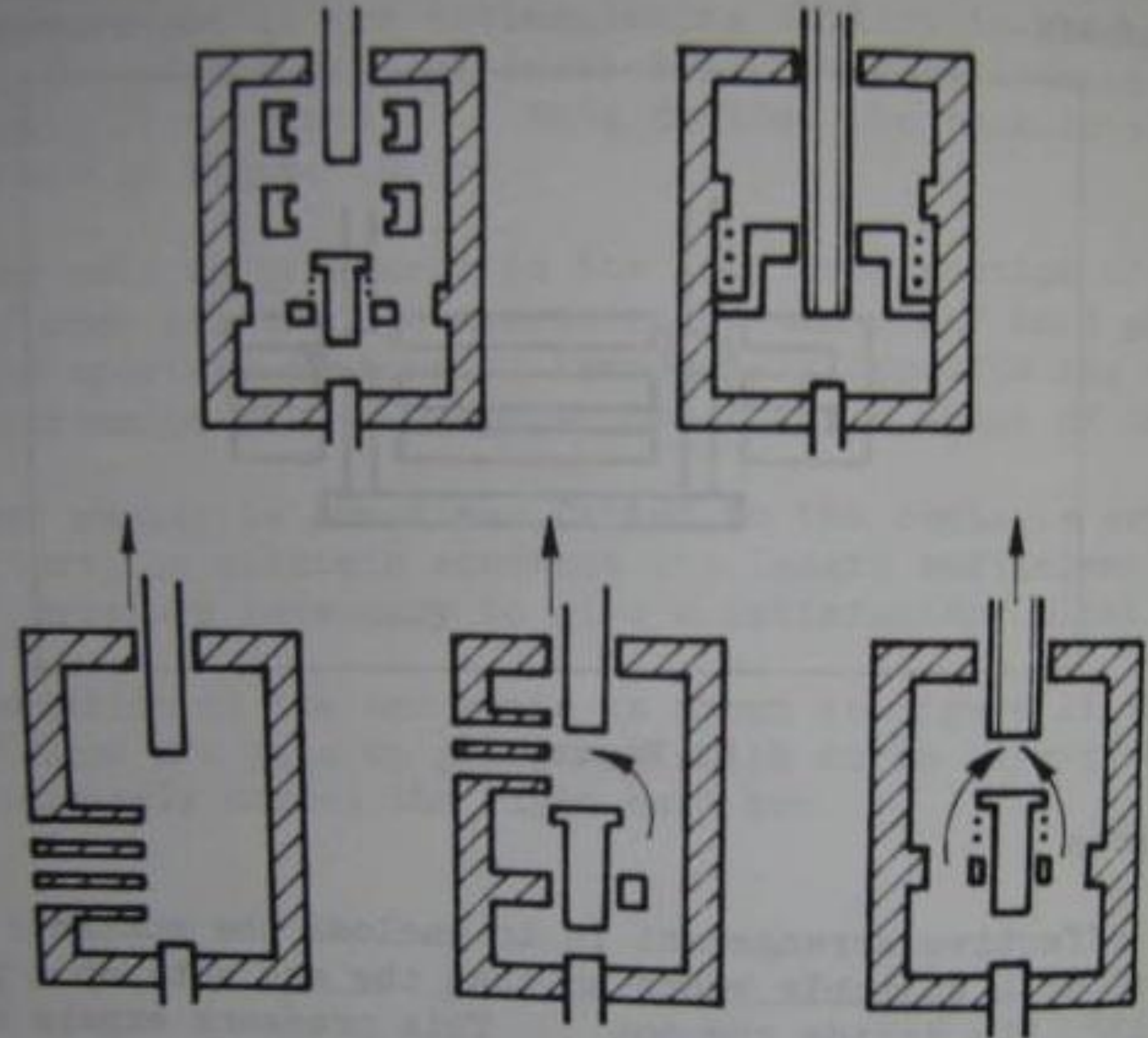
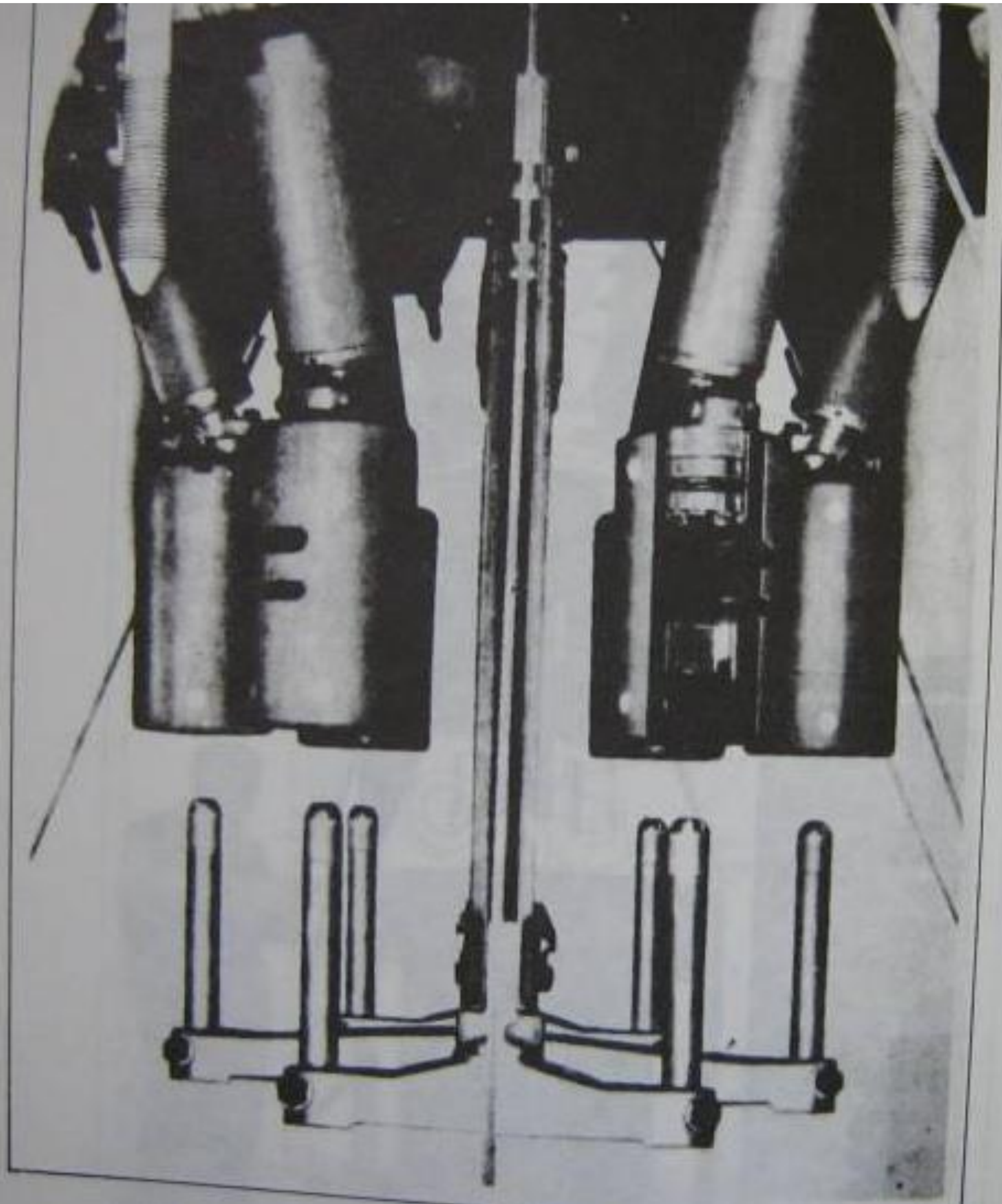


Figure 13

Modified forms of Arc Control Pots



It is clear therefore that the above sequence of events is repeated at every current zero, whilst the arc is being lengthened and progressively 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 system voltage and interruption is final and complete.

Small Oil Volume Circuit Breakers

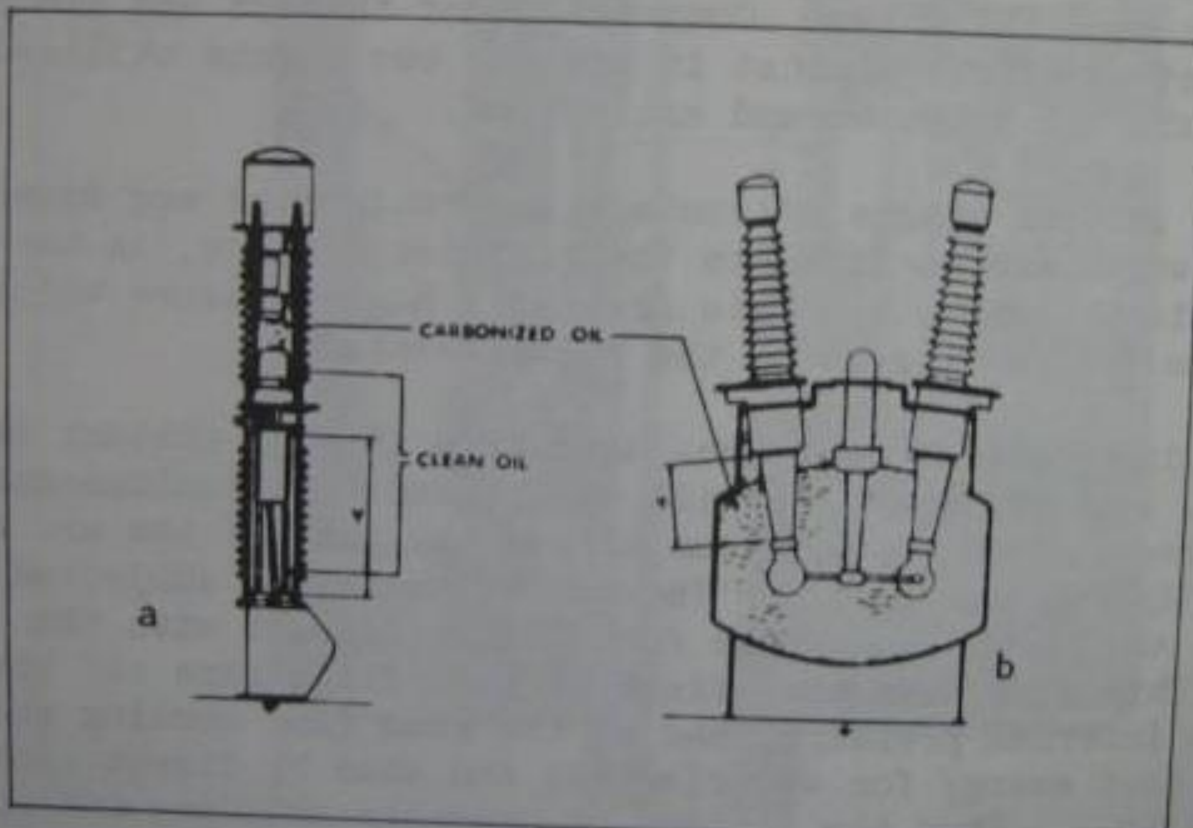
In the conventional type of oil circuit breaker the oil acts partially as the arc quenching medium and partly to insulate the live parts from earth.

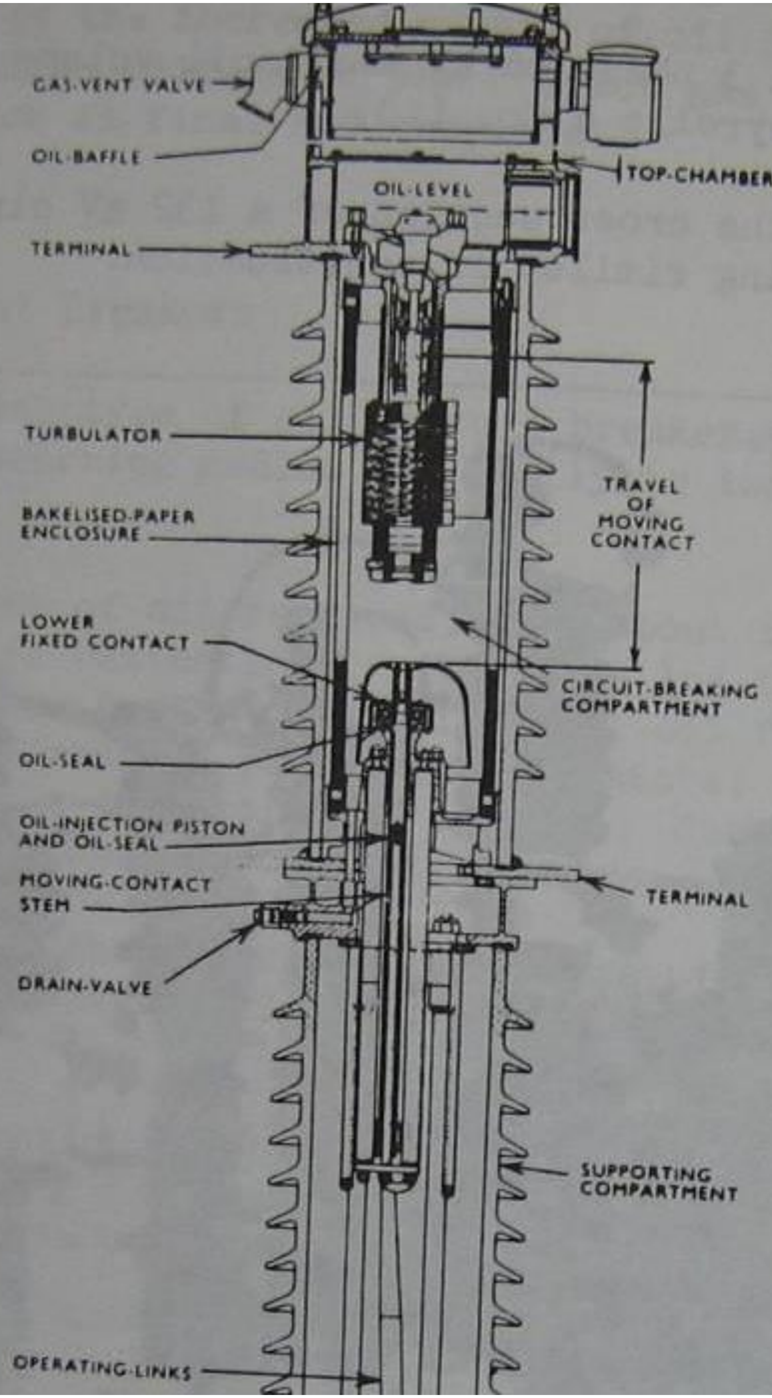
Of the large volume of oil required, only about ten per cent is actually required for arc extinction. This has led to the desirability of using a small container having only sufficient oil for arc extinction, the container being supported on porcelain insulators, to give the required insulation of the 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.

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

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.

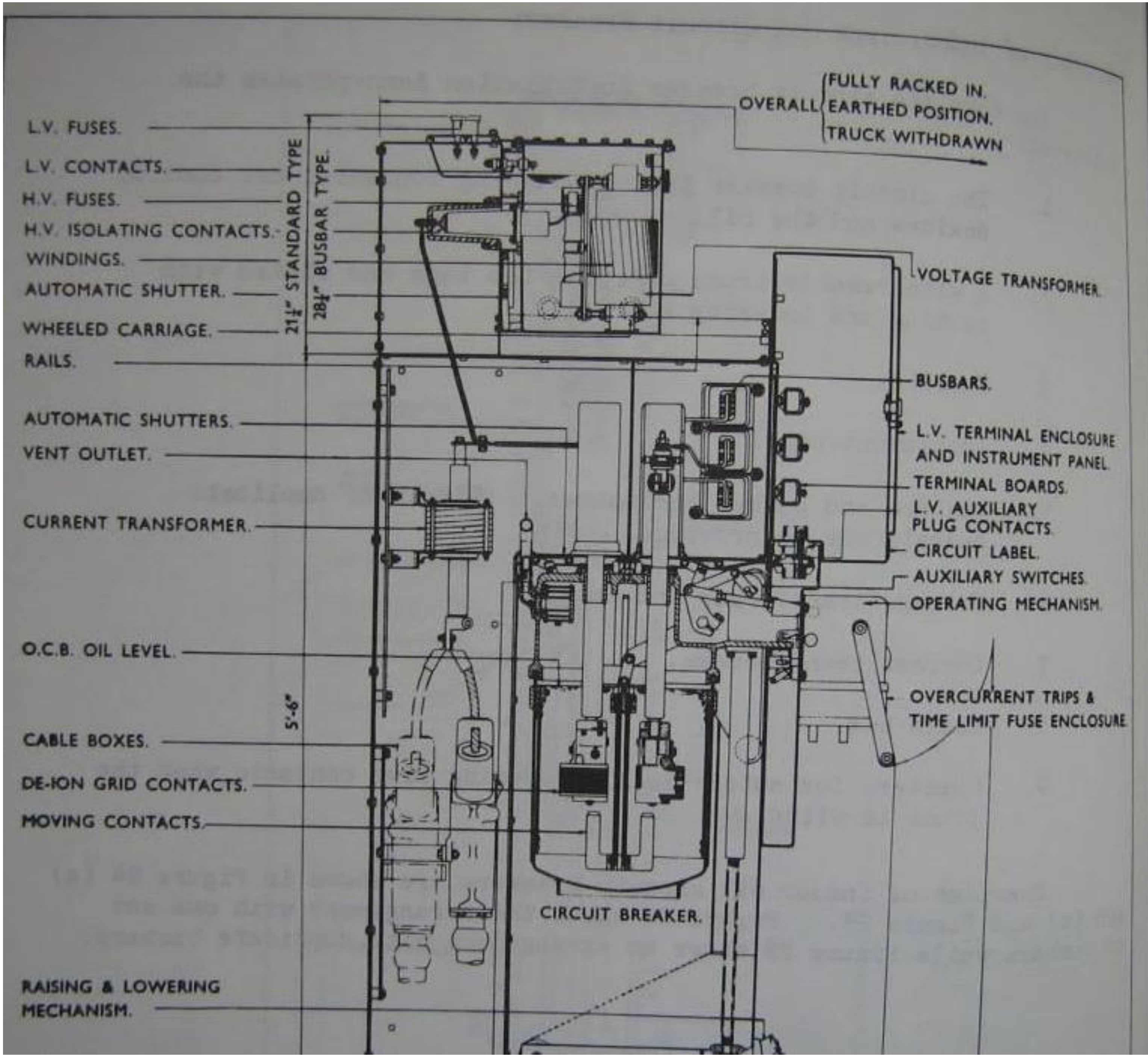
5. Busbars and busbar enclosures. Single or duplicate busbars may be provided.

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
28½" BUSBAR TYPE.
VOLTAGE TRANSFORMER.
BUSBARS.
AUTOMATIC SHUTTERS.
VENT OUTLET.
L.V. TERMINAL ENCLOSURE AND INSTRUMENT PANEL.
TERMINAL BOARDS.
CURRENT TRANSFORMER.
L.V. AUXILIARY PLUG CONTACTS.
CIRCUIT LABEL.
AUXILIARY SWITCHES.
OPERATING MECHANISM.
O.C.B. OIL LEVEL.
OVERCURRENT TRIPS & TIME LIMIT FUSE ENCLOSURE.
5'-6"
CABLE BOXES.
DE-ION GRID CONTACTS.
MOVING CONTACTS.
CIRCUIT BREAKER.
RAISING & LOWERING MECHANISM.

Co-ordination of Protection

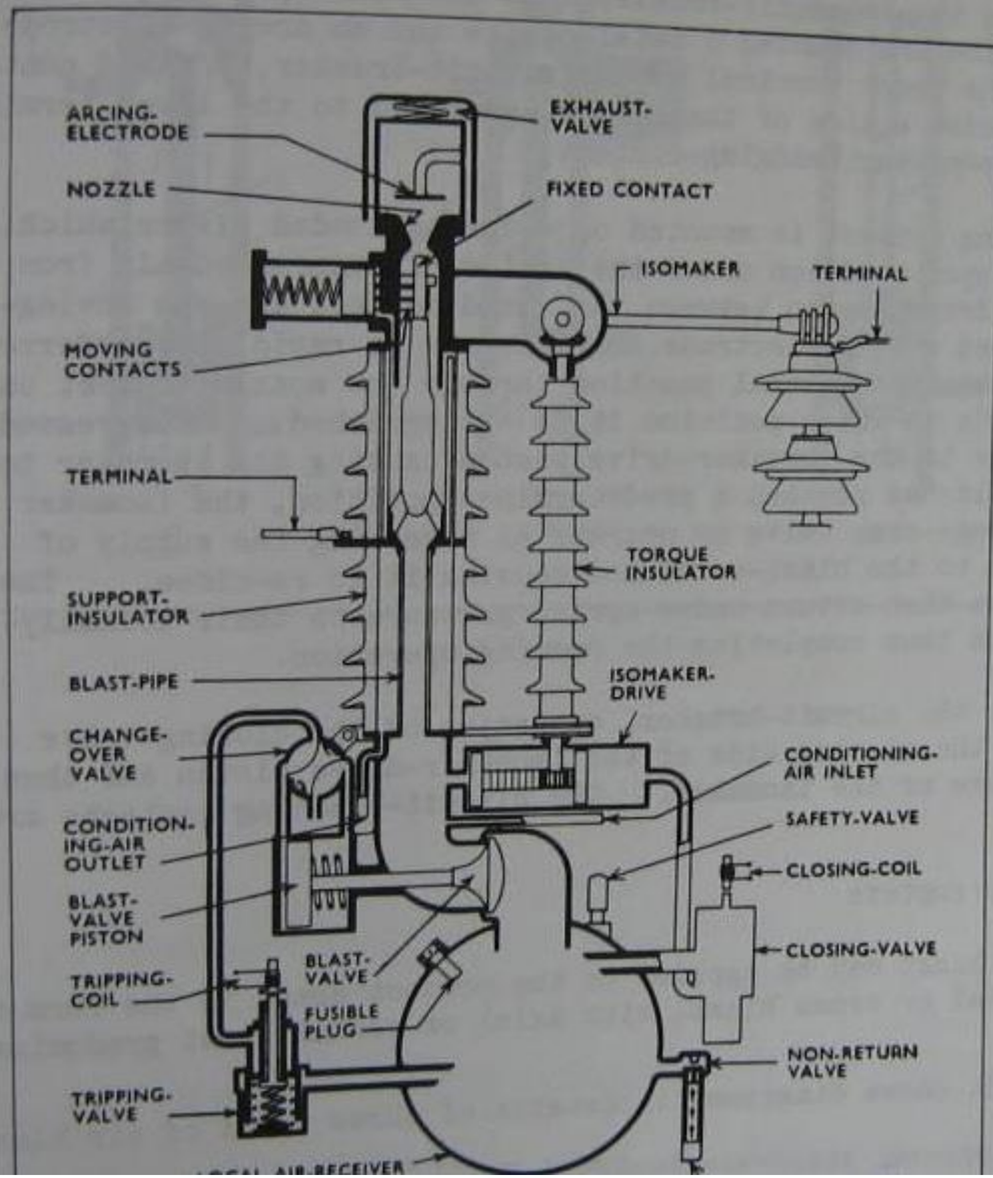
The co-ordination of the three protection units in a moulded case circuit breaker namely time delay thermal trip, instantaneous magnetic trip and current limiting protection, is arranged so that overcurrents and low magnitude faults are cleared by the thermal action, normal short-circuits are cleared by the magnetic action, and high fault-currents, above a predetermined value, are cleared by the current limiting device. 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 demand for a circuit breaker without the fire risk and other disadvantages of oil circuit-breakers.

They are particularly suitable for very high voltage systems, and are mainly used for transmission systems rather than distribution. The range of circuit breakers available is suitable for voltages of 11 kV 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.

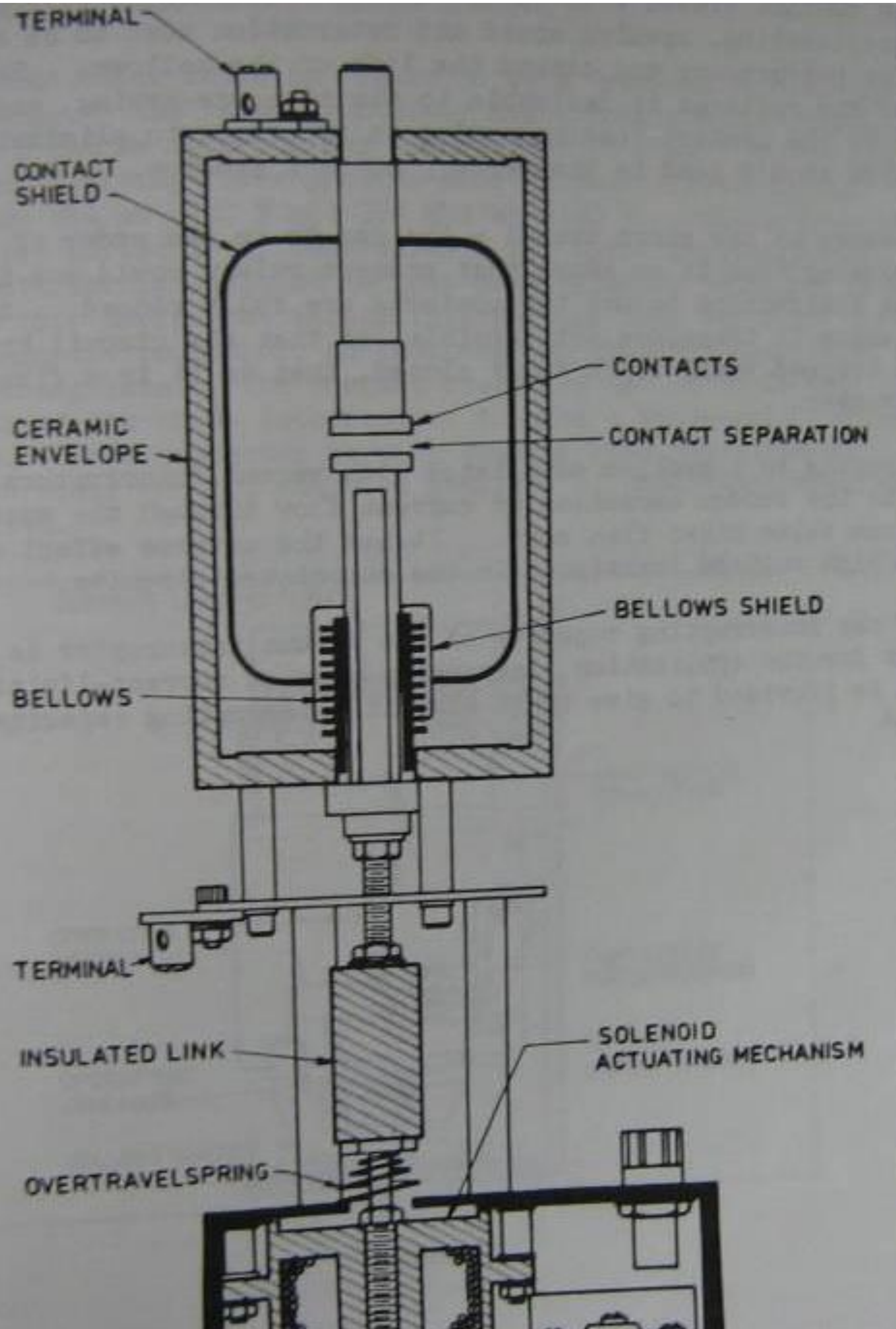
A vacuum interrupter is illustrated in Figure 35 and consists of the following parts.

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.


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

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 used under pressure as the arc extinguishing medium. The gas, however, is sealed within the circuit breaker and is recycled for all circuit breaker functions.

Sulphur hexafluoride has the important property of having a strong 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 at 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:

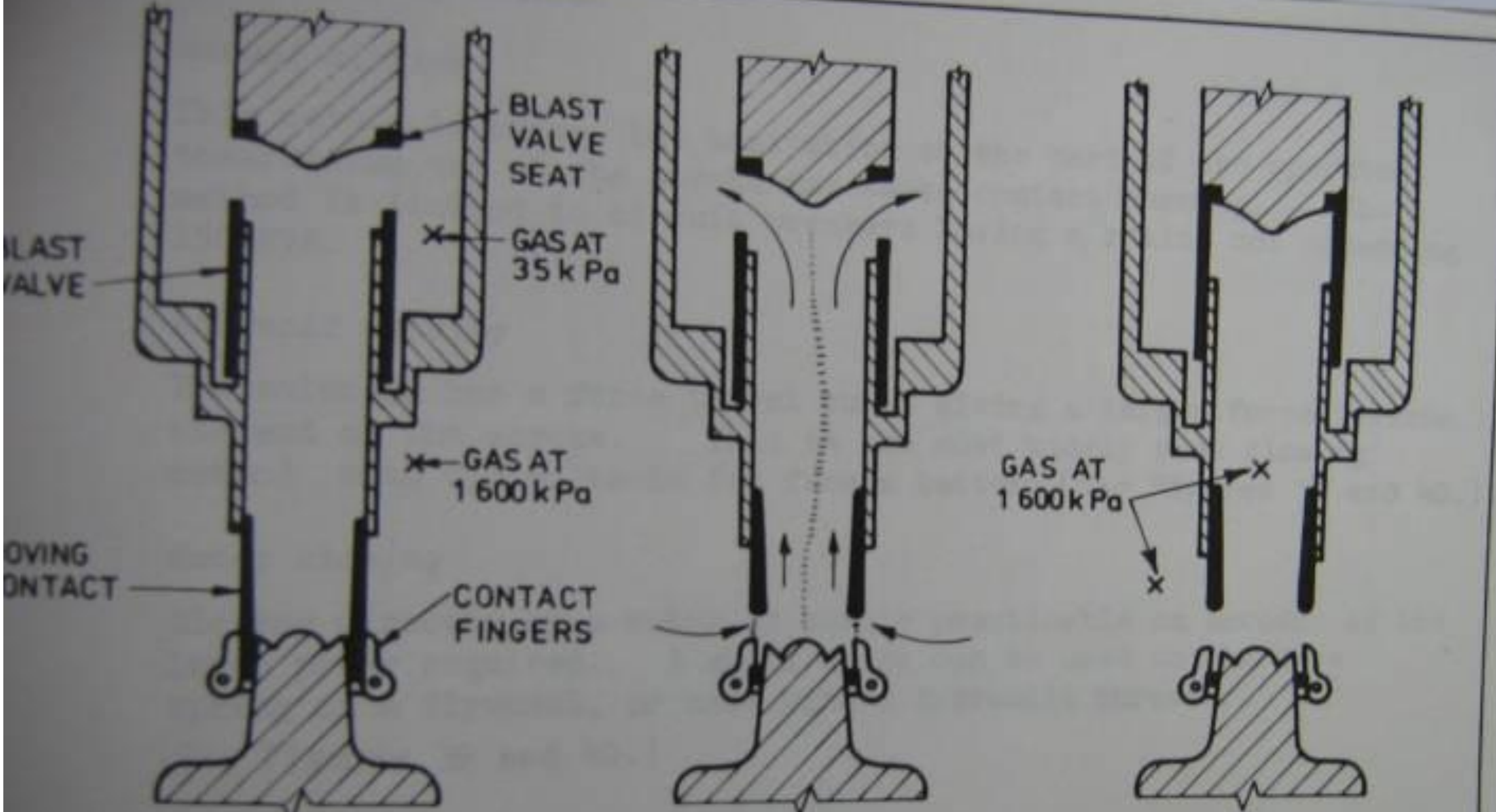
Very quiet in operation, because there is no external exhaust o the operating medium.

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

The moving parts are relatively small and require little energy

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

The circuit breaker is less bulky than a similar size air blast 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 fly-wheel 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 from an excessive current flowing in it, by opening the circuit on the meltin of a fuse element by such excessive current.

Voltage Classification

Fuses are broadly classified into two voltage classifications:

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

(ii) Fuses exceeding 1000 volts a.c.

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

Terminology

The following terms cover the characteristic quantities or compone 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 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.

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

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

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

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 following ies without damage to itself or other equipment and without danger personnel:

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

ARC INTERRUPTION THEORY

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

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

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

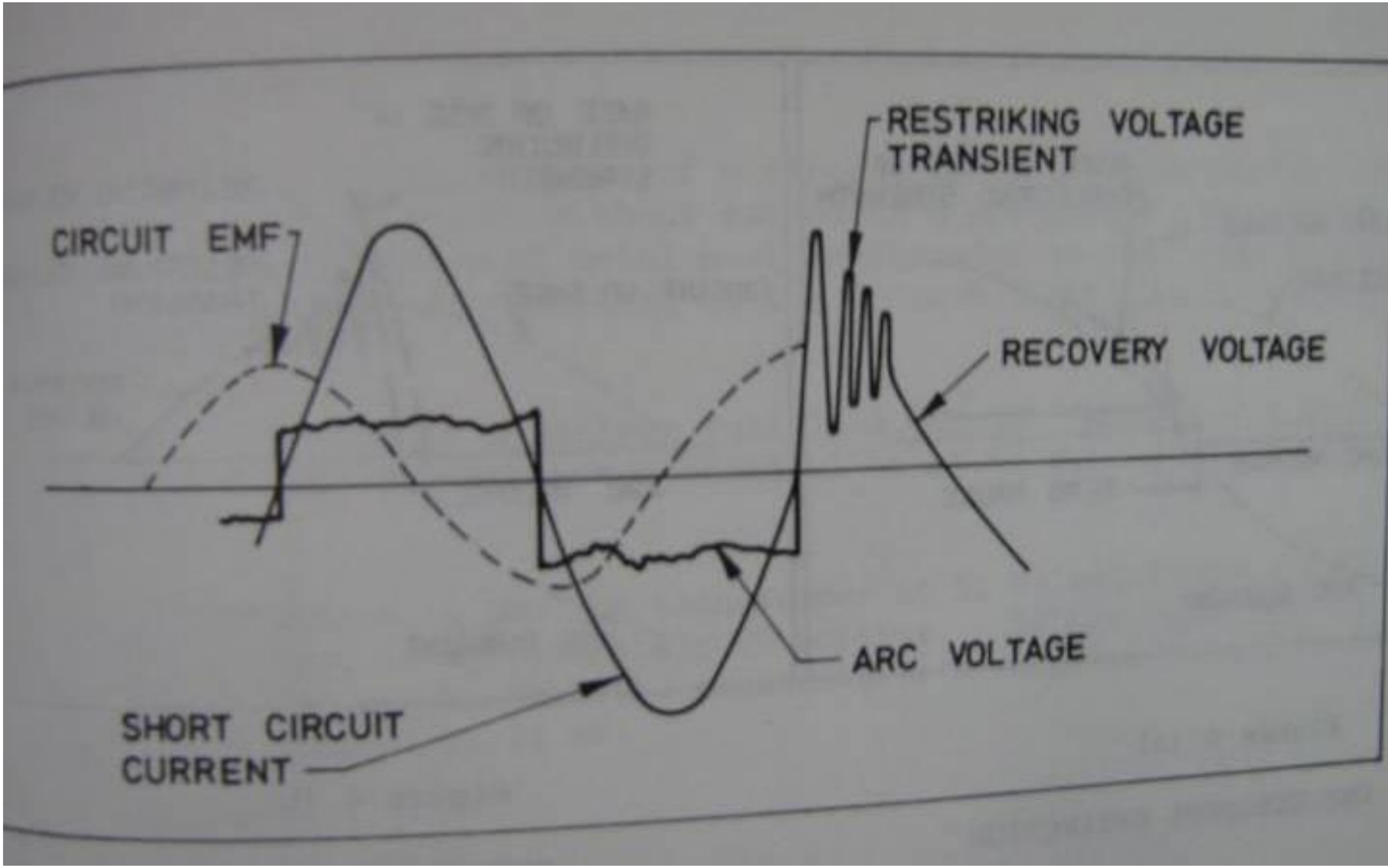
RESTRIKING VOLTAGE

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 along 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 is 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 must rise to the peak voltage of the 50 hertz frequency wave.

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


RESTRIKING VOLTAGE
TRANSIENT
CIRCUIT EMF
RECOVERY VOLTAGE
ARC VOLTAGE
SHORT CIRCUIT
CURRENT

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.

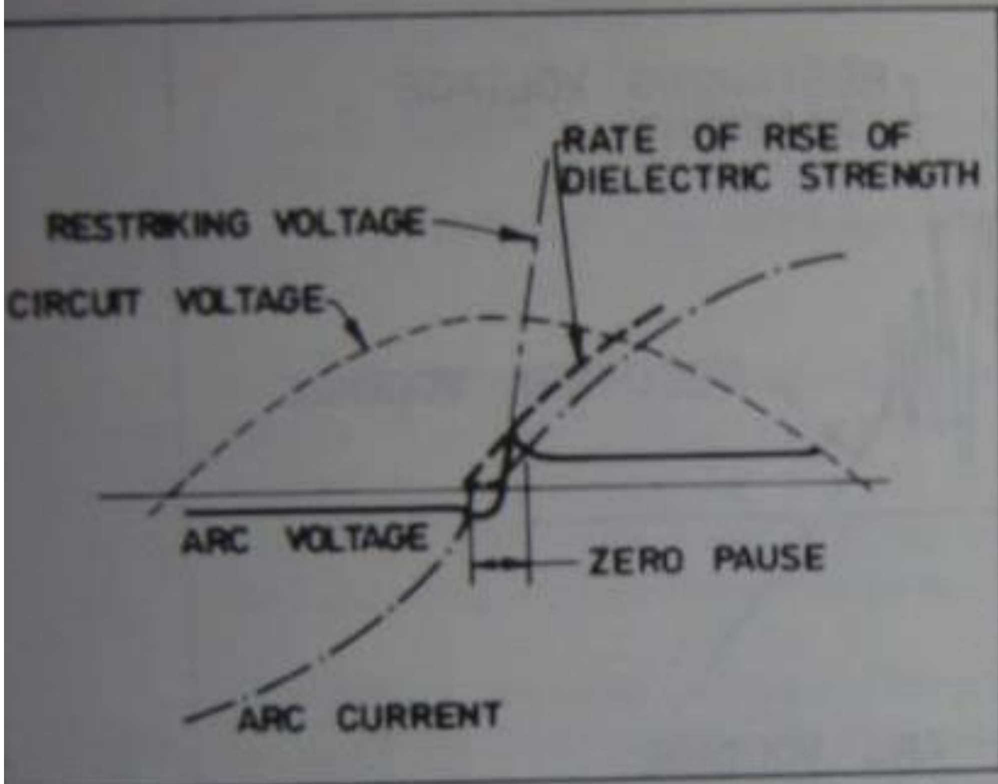


Figure 6 (a)

UNSUCCESSFUL EXTINCTION

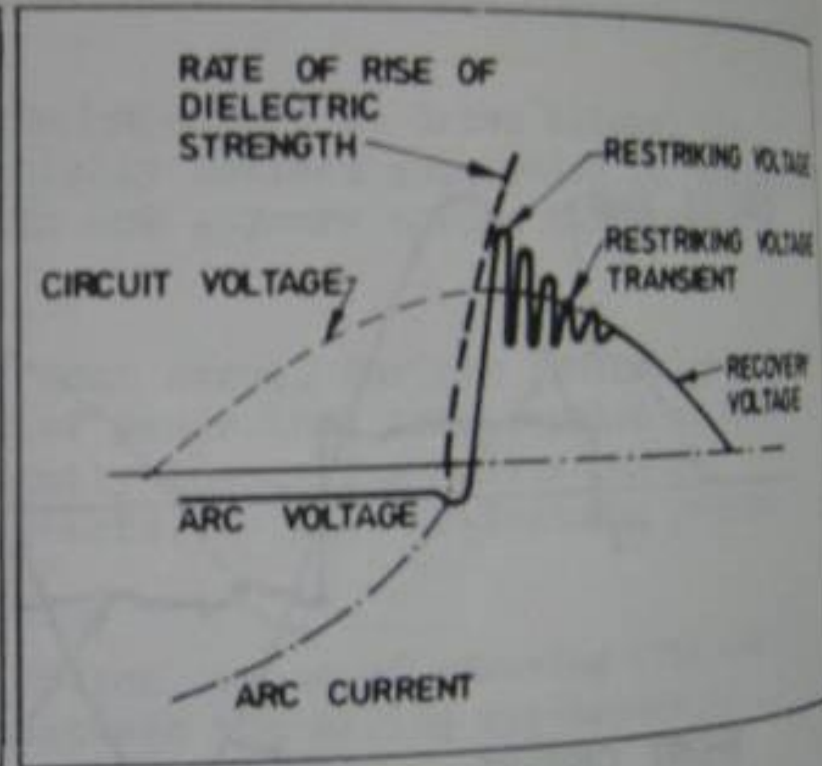


Figure 6 (b)

SUCCESSFUL EXTINCTION

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.

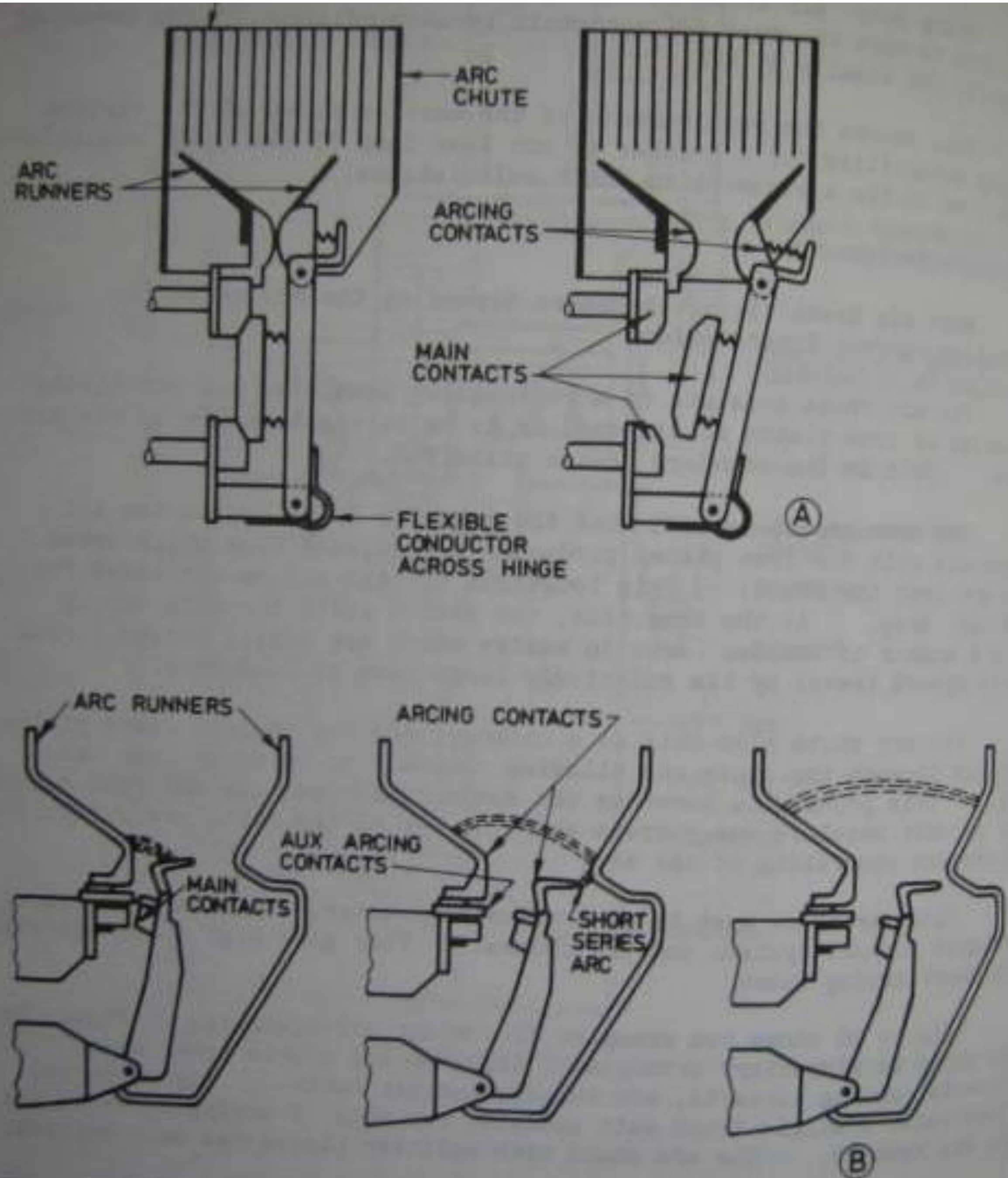
This covers the requirements of the service rules of the various Supply Authorities for a breaker of not less than 25 MVA under conditions mentioned in the assignment on fault calculations.

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.


ARC CHUTE
ARC RUNNERS
ARCING CONTACTS
MAIN CONTACTS
FLEXIBLE CONDUCTOR ACROSS HINGE
A
ARC RUNNERS
ARCING CONTACTS
AUX ARCING CONTACTS
MAIN CONTACTS
SHORT SERIES ARC
B

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 material forming an integral part of the unit. As well as being capable of 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 firms such as Westinghouse, Heinemann, Klockner Moeller and General Electric. 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.

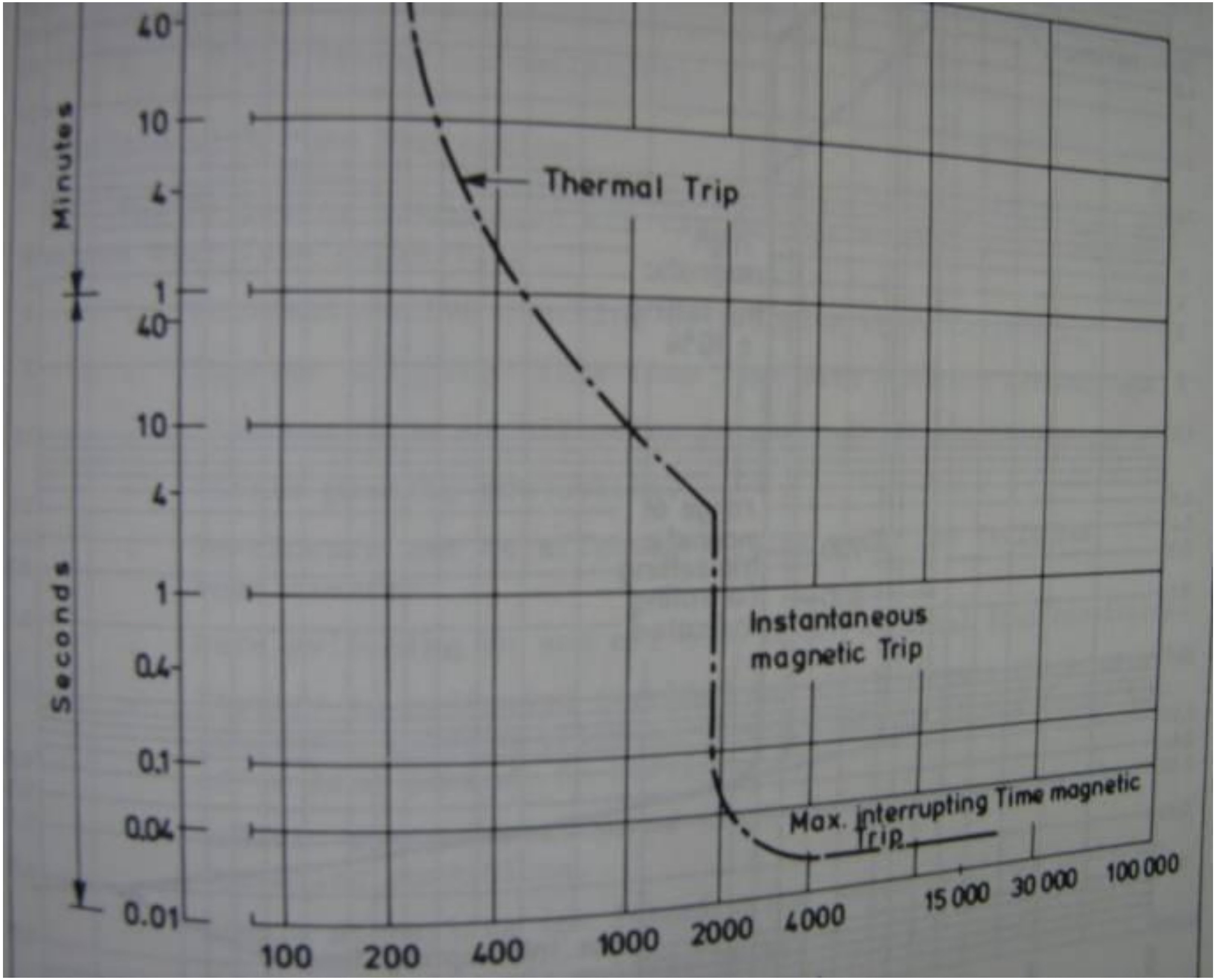
Current limiting class - usually with current-limiting devices which have interrupting ratings in the order of 100 kA.

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.

Tripping

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

The tripping characteristics of a particular circuit-breaker are 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 current 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.


Minutes
Seconds
40
10
4
1
40
10
4
1
0.4
0.1
0.04
0.01
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.

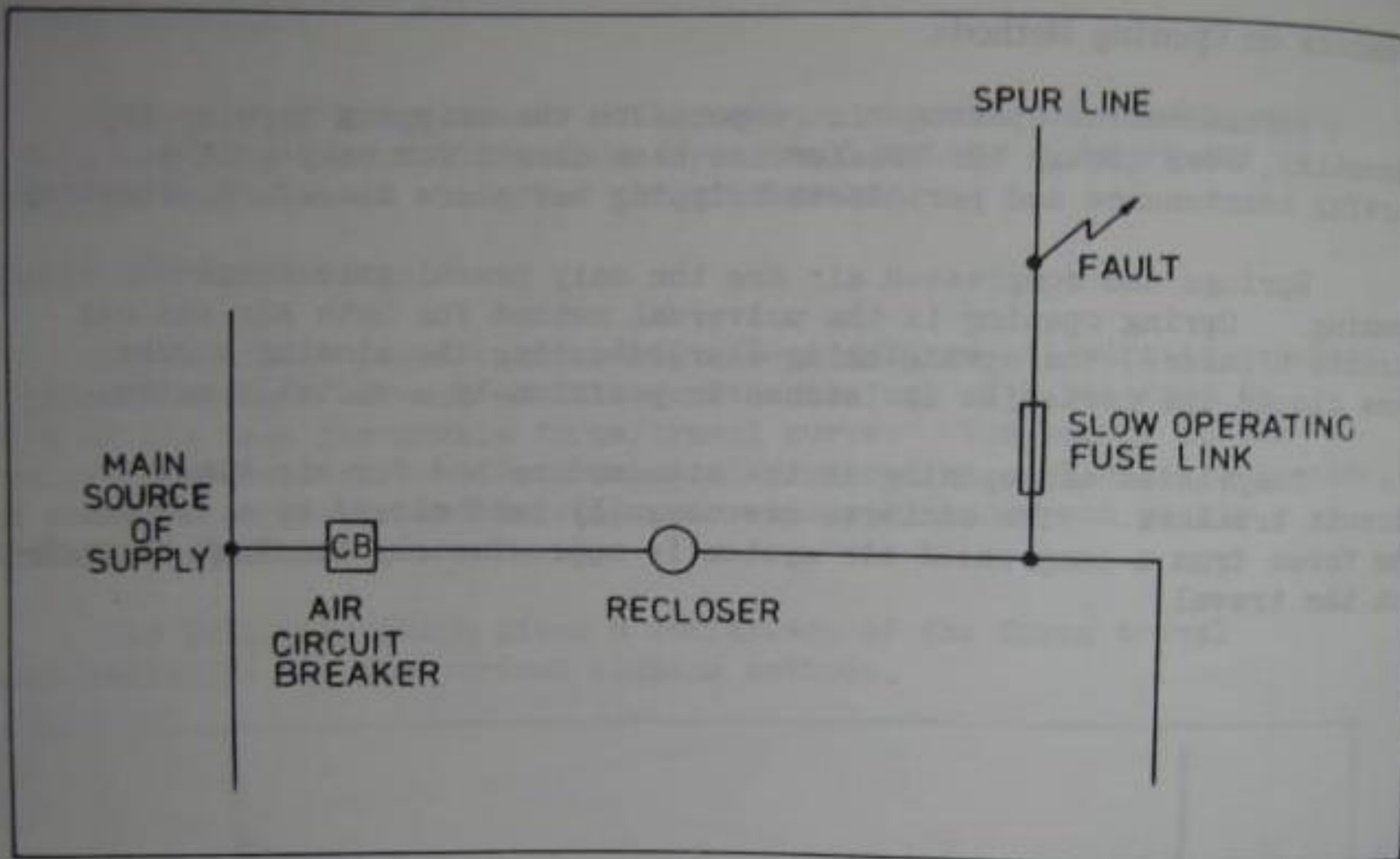
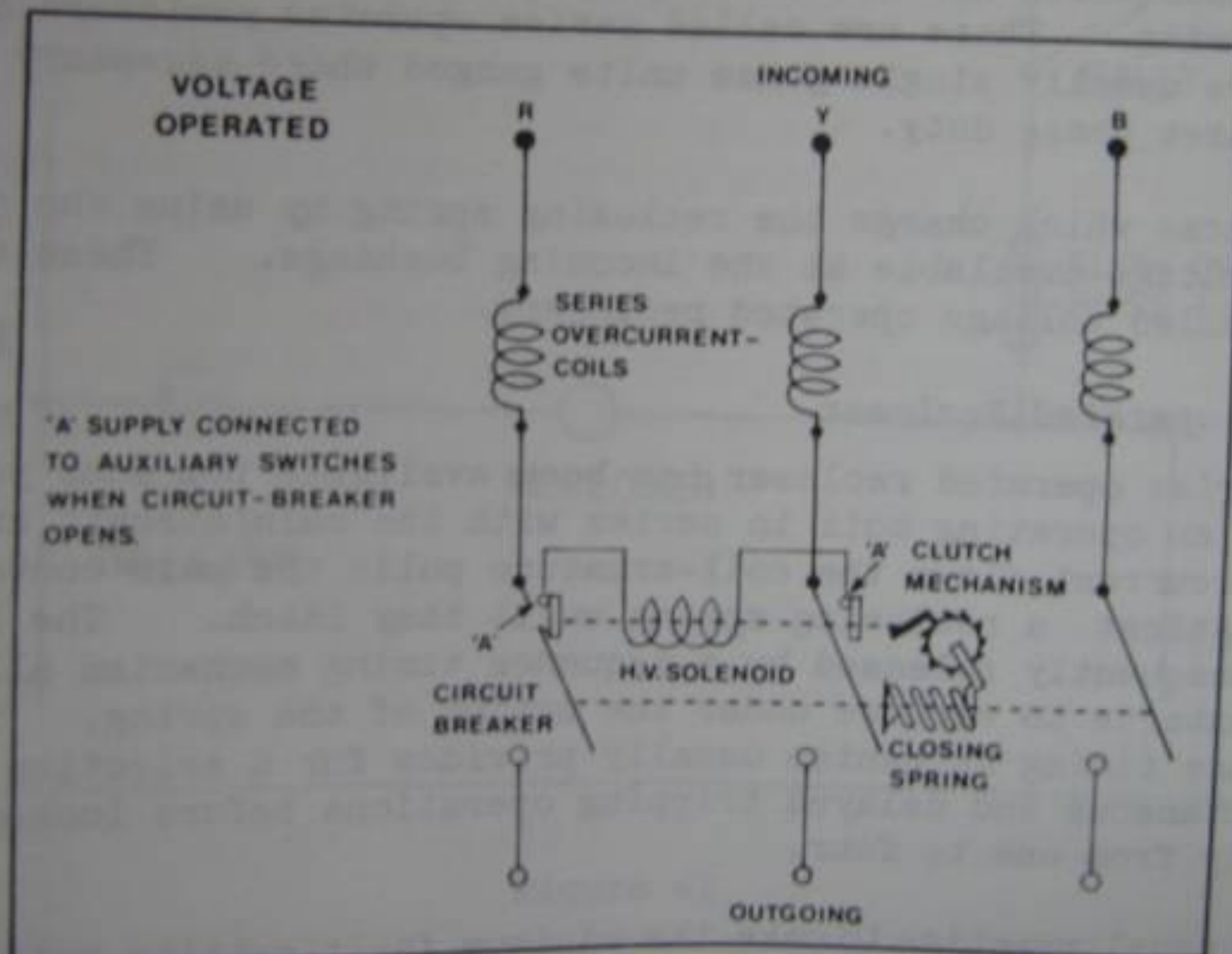
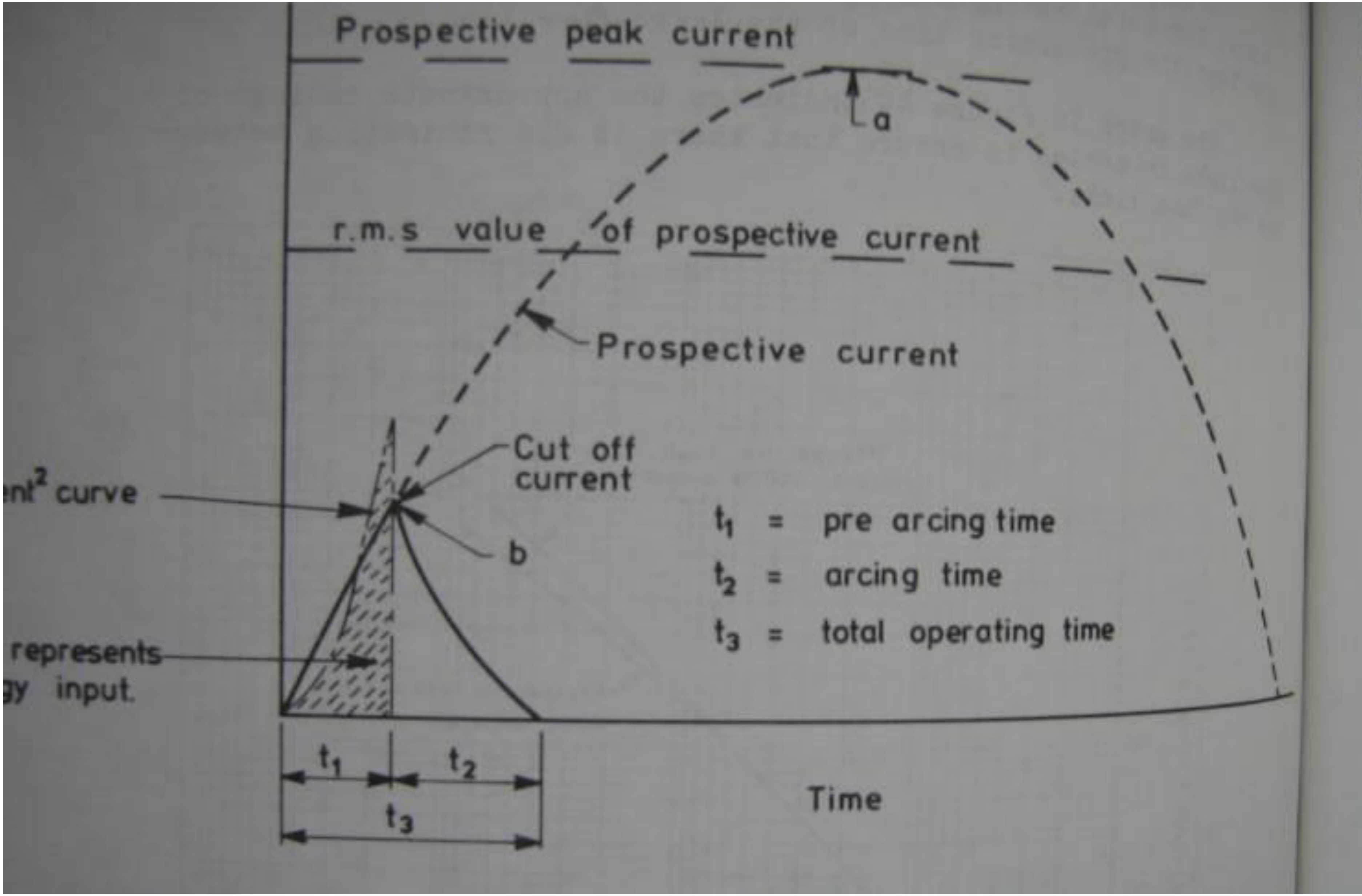


Figure 41

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.





Prospective peak current
a
r.m.s value of prospective current
Prospective current
Cut off current
ent² curve
b
represents
gy input.
t1 = pre arcing time
t2 = arcing time
t3 = total operating time
t1
t2
t3
Time

Basic d.c. Tripping Circuit

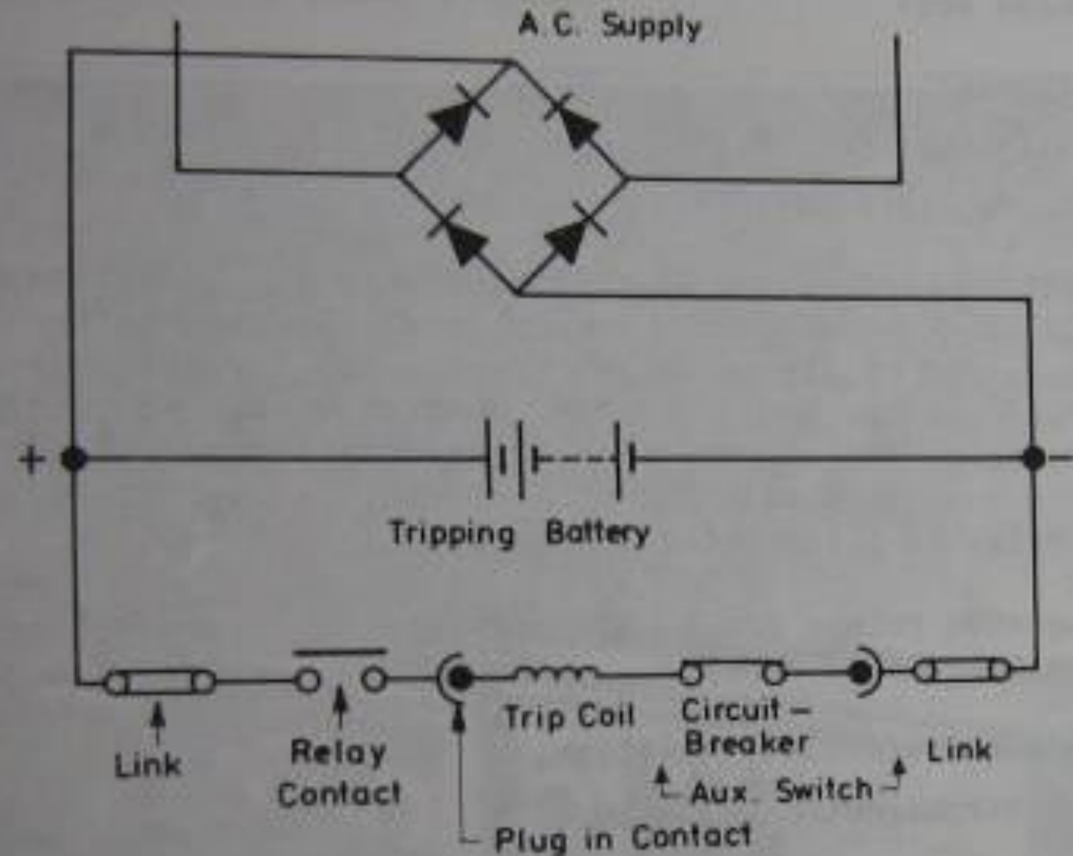


Figure 6

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.

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

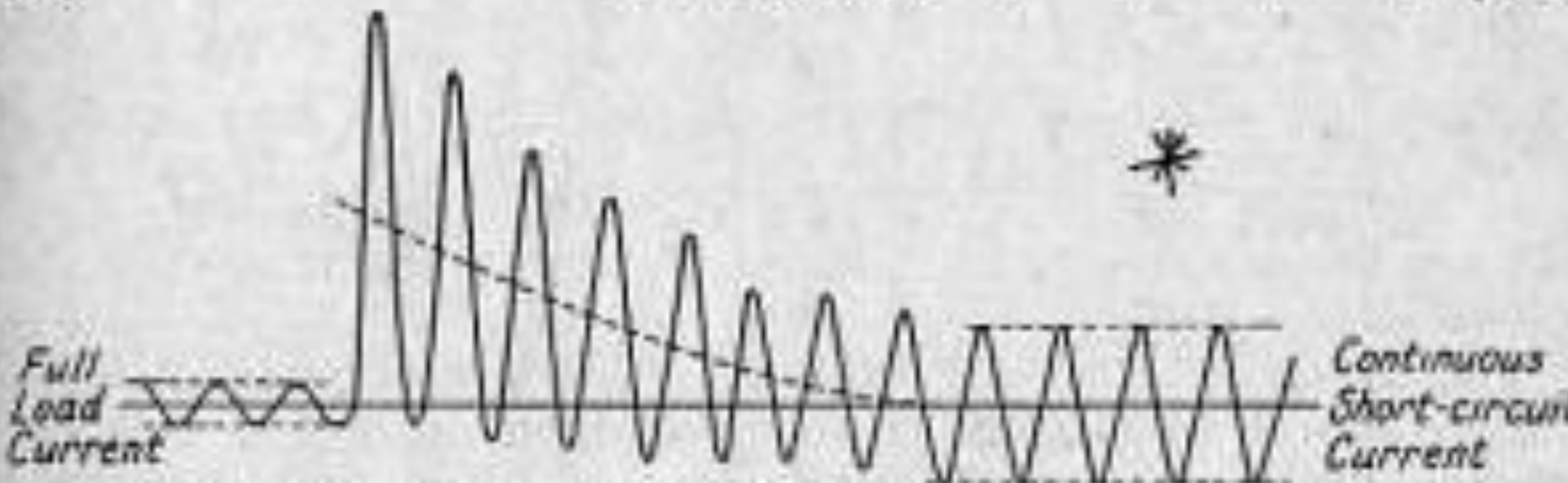


FIG. 169. DOUBLING EFFECT IN SHORT-CIRCUIT CURRENT

The particular integral is

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

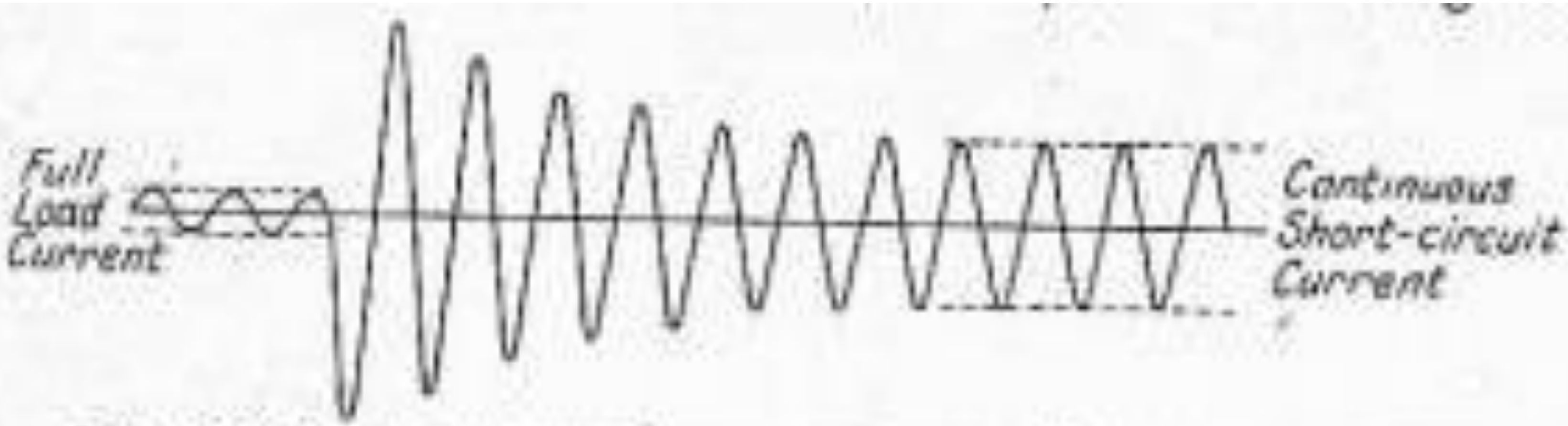


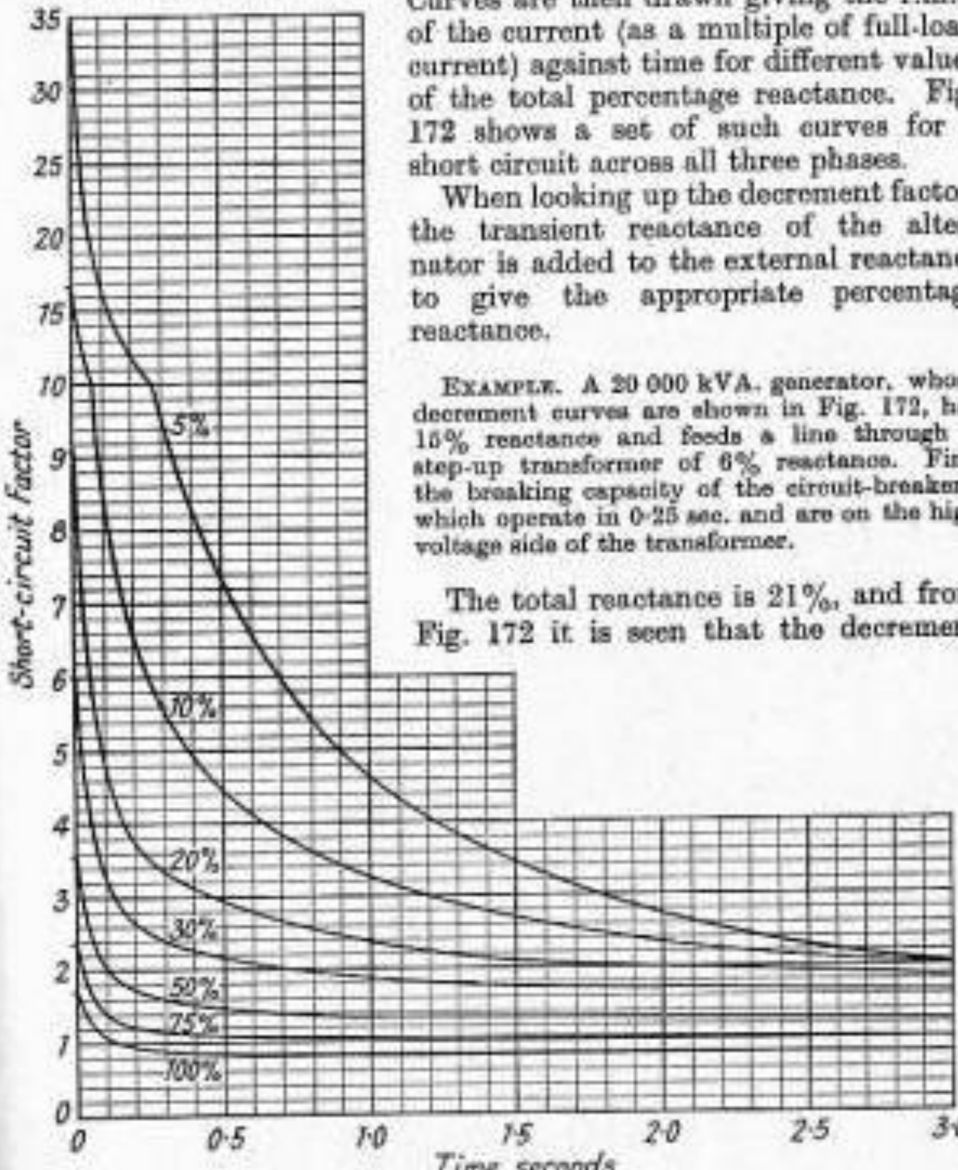
FIG. 170. SHORT-CIRCUIT CURRENT WITHOUT DOUBLING EFFECT

dotted line, and has a value $I_{s.c.}$ 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 $\sqrt{[I_{D.C.}^2 + I_{s.c.}^2]}$. 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.

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



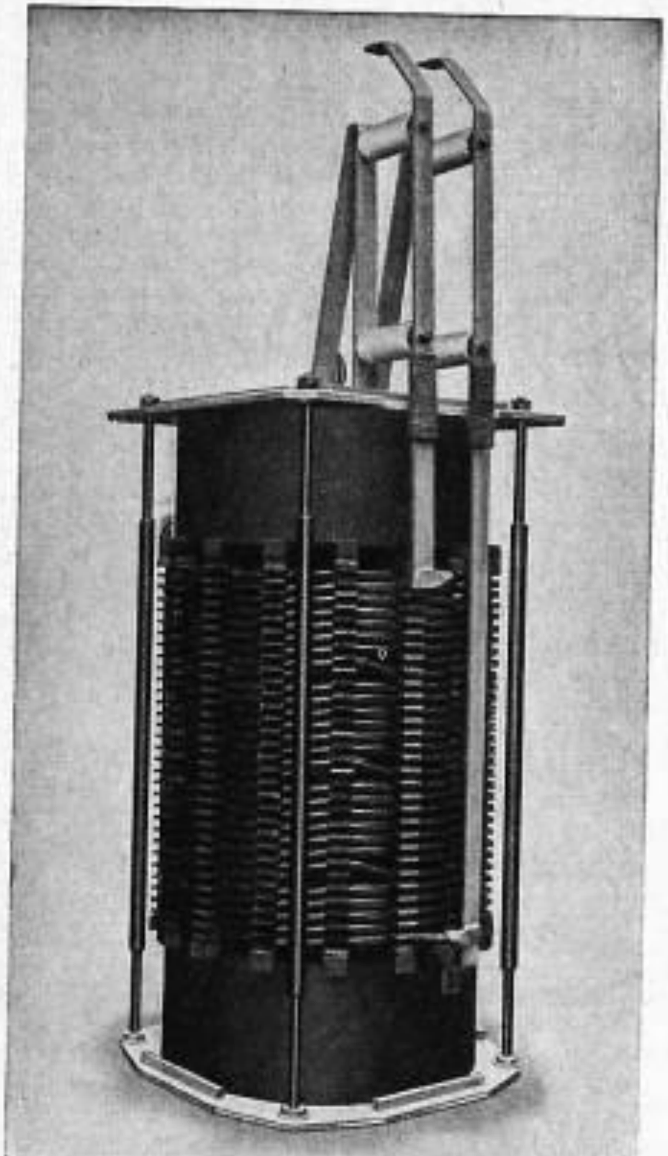


FIG. 173. CURRENT LIMITING REACTOR
(English Electric Co.)

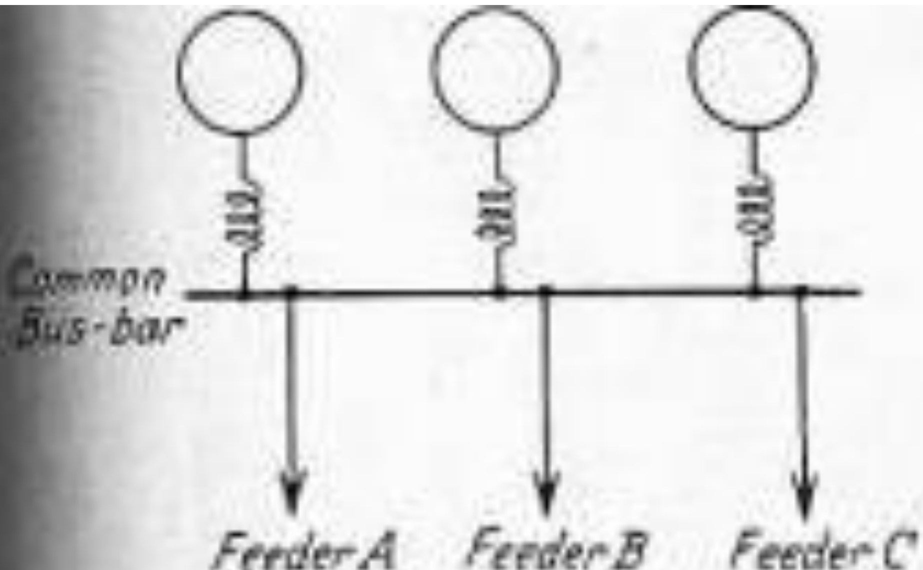


FIG. 174. GENERATOR REACTORS

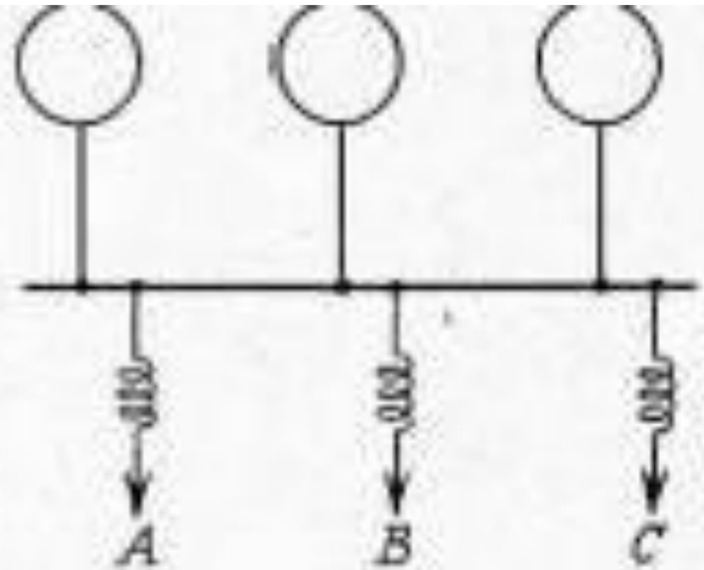


FIG. 175. FEEDER REACTORS

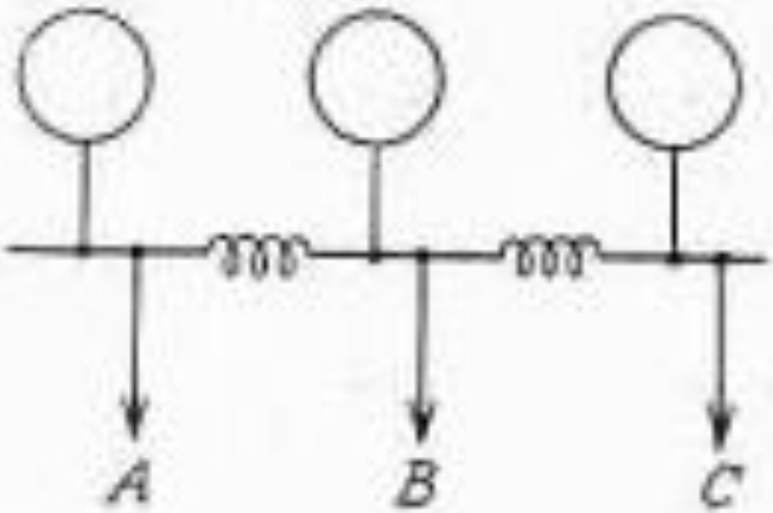


FIG. 176. BUS-BAR REACTORS, RING SYSTEM

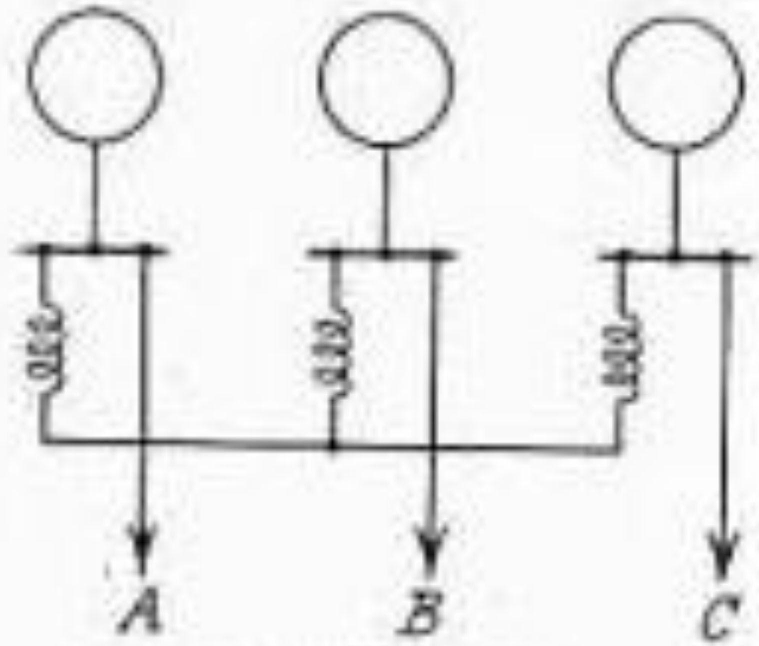


FIG. 177. BUS-BAR REACTORS, TIE-BAR SYSTEM

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.

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

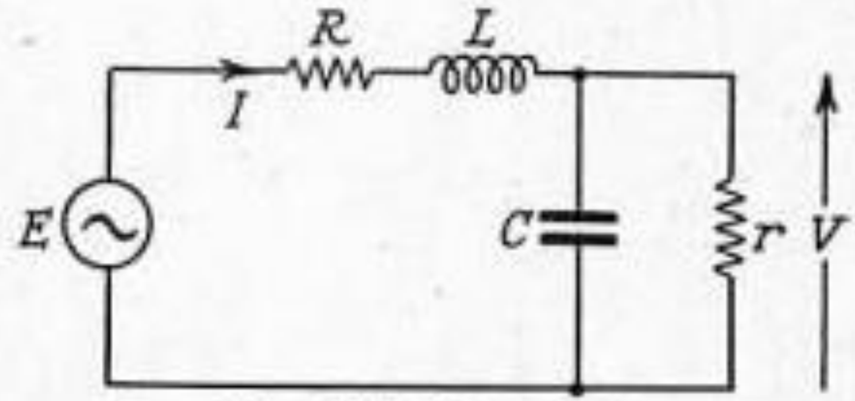


FIG. 237. RESONANCE

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

resonating capacitance is then

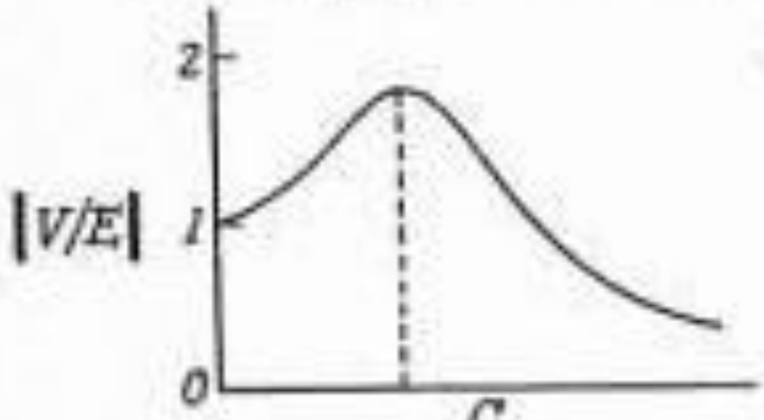


Fig. 238. Resonance

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

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

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

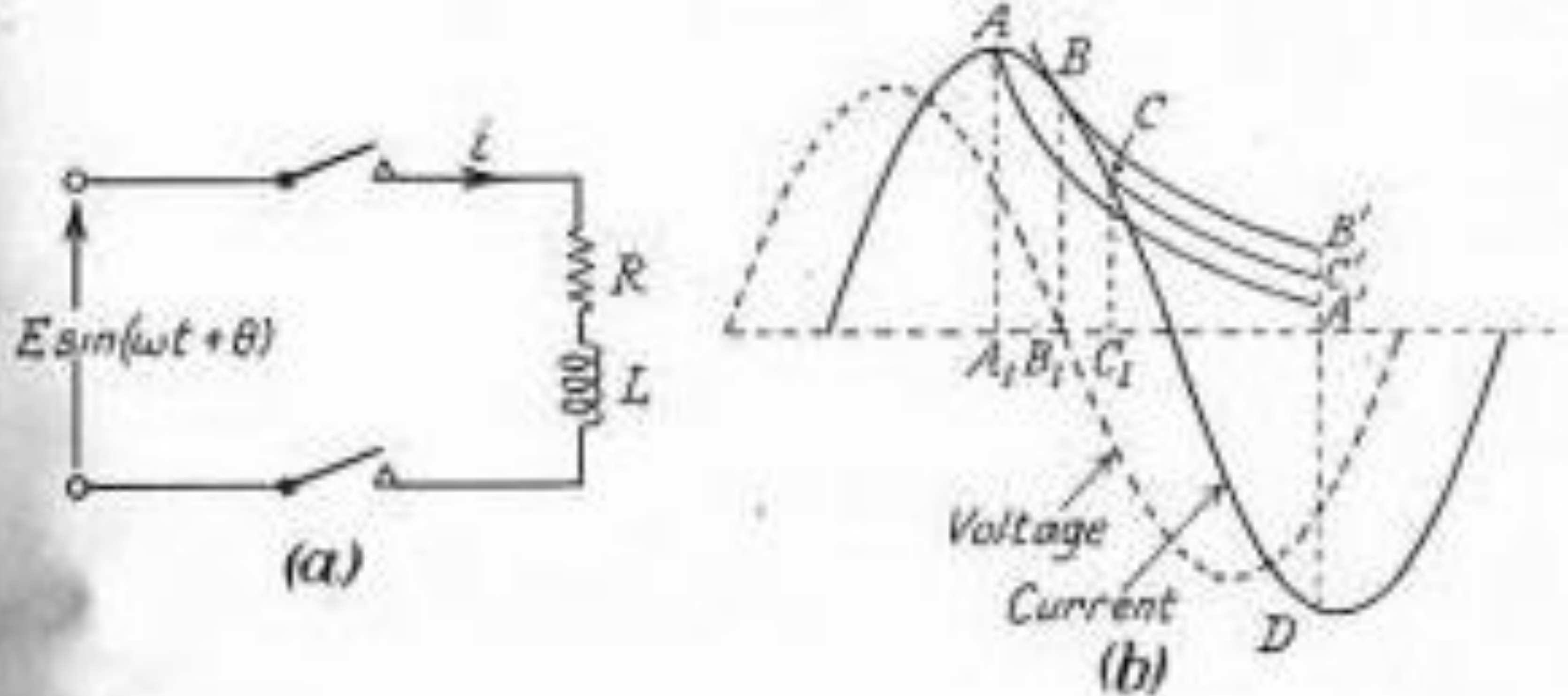


FIG. 239. SWITCHING-IN AN INDUCTIVE RESISTANCE

obtained when an alternator is short-circuited.

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)

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

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

$$= \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} [1 + 0{\cdot}34\varepsilon^{-1{\cdot}33 \times 1{\cdot}533}]$$

$$= \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} [1{\cdot}044],$$

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,

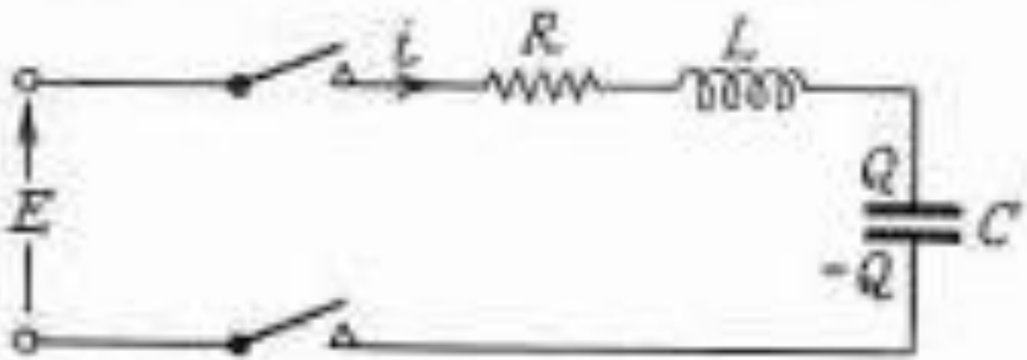


FIG. 240. SWITCHING-IN AN OPEN-CIRCUITED LINE

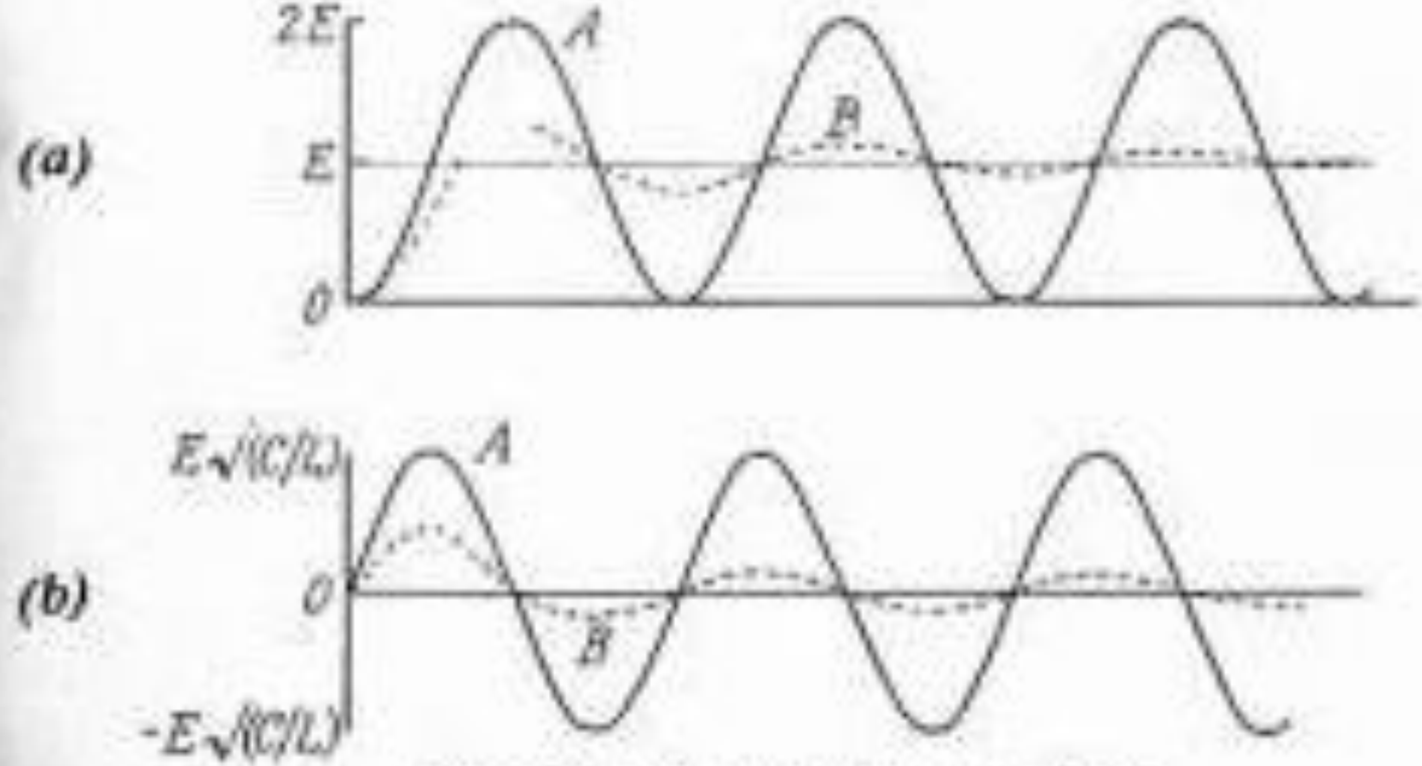


FIG. 241. OPEN-CIRCUITED LINE
(a) Voltage. (b) Current.

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

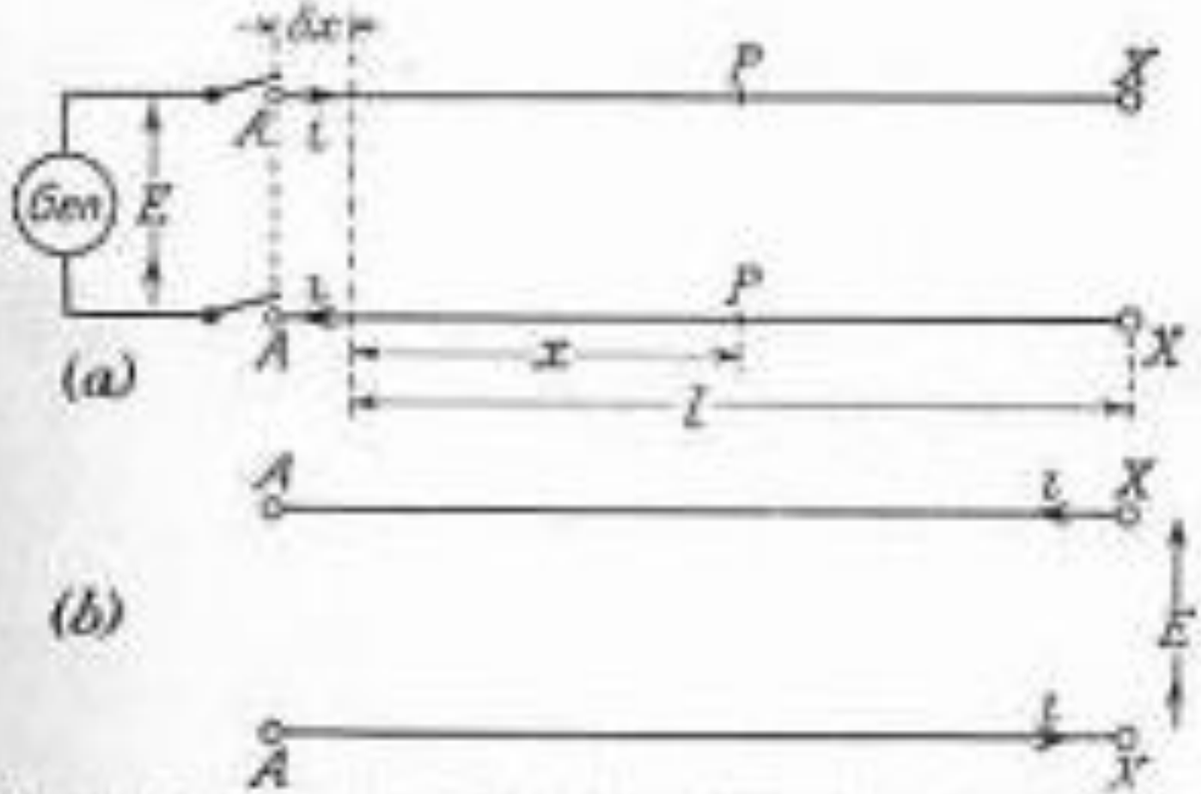


FIG. 242. SWITCHING SURGE ON OPEN-CIRCUITED LINE

$$E = iL(\delta x/\delta t)$$
$$= iLv, \quad \ldots \quad (116)$$

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

$$i\delta t = EC\delta x,$$

or

$$i = EC(\delta x/\delta t)$$
$$= ECv. \quad \ldots \quad (117)$$

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

$$Ei = iLvECv = EiLCv^2,$$

so that

$$v = 1/\sqrt{(LC)}. \quad \ldots \quad (118)$$

Substituting for v in equation (118) we find that

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

where

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

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

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

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

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

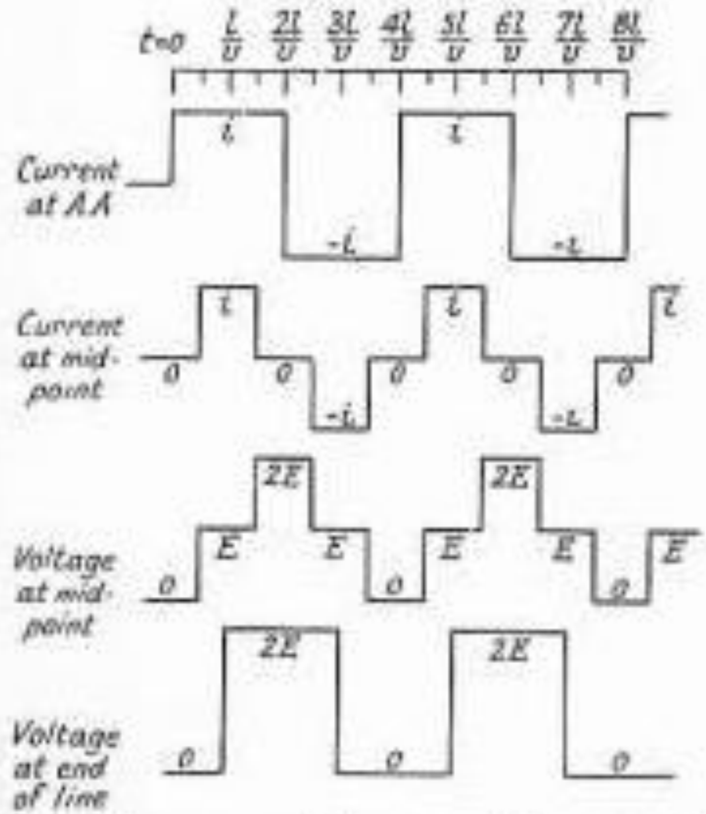


FIG. 243. CURRENT AND VOLTAGE IN SWITCHING SURGE

(116) and (117) it is seen that the magnetic and electrostatic energies delivered by a simple wave are equal, for

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

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.

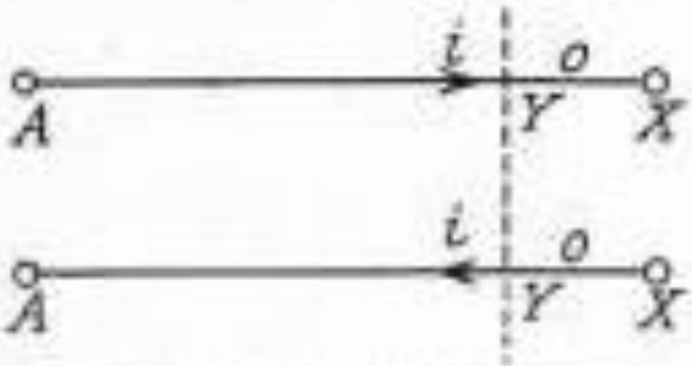


FIG. 244. ENERGY CONSIDERATIONS IN SURGES

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

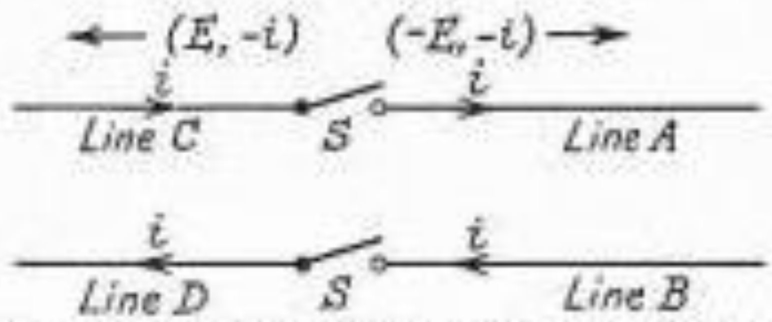


FIG. 245. SUDDEN INTERRUPTION OF A CIRCUIT

noted that if only one break is made, so that B and D are always commoned, the voltage between A and C is $2E$.

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

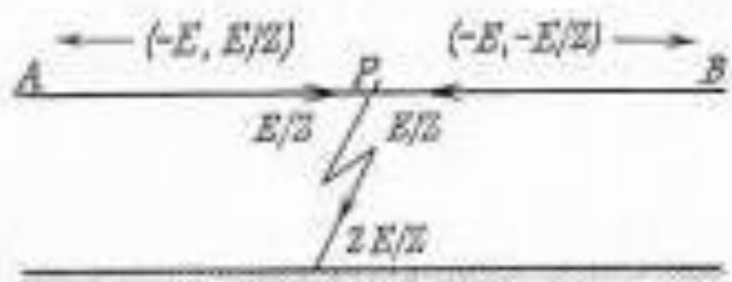


FIG. 246. SURGES DUE TO A FAILURE OF INSULATION

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 flash-over with reversals of potential on the line and currents at P until the stored energy is dissipated by damping.

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

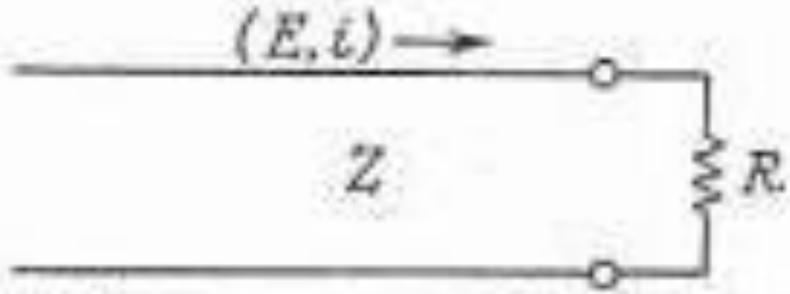


FIG. 247. REFLECTION OF A TRAVELLING WAVE

The total current and voltage are

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

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

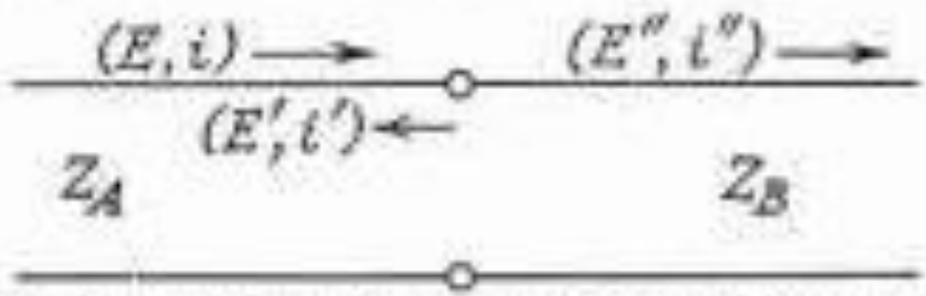


FIG. 248. EFFECT OF A SUDDEN CHANGE IN THE LINE ON TRAVELLING WAVES

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

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

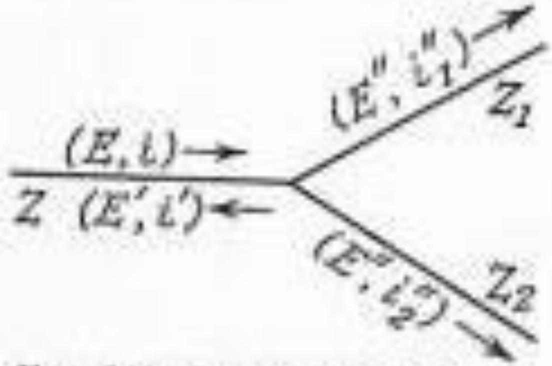


FIG. 249. TRAVELLING WAVES AT JUNCTION OF LINES

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

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

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

The voltage at the junction is

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

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

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

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

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

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

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

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

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

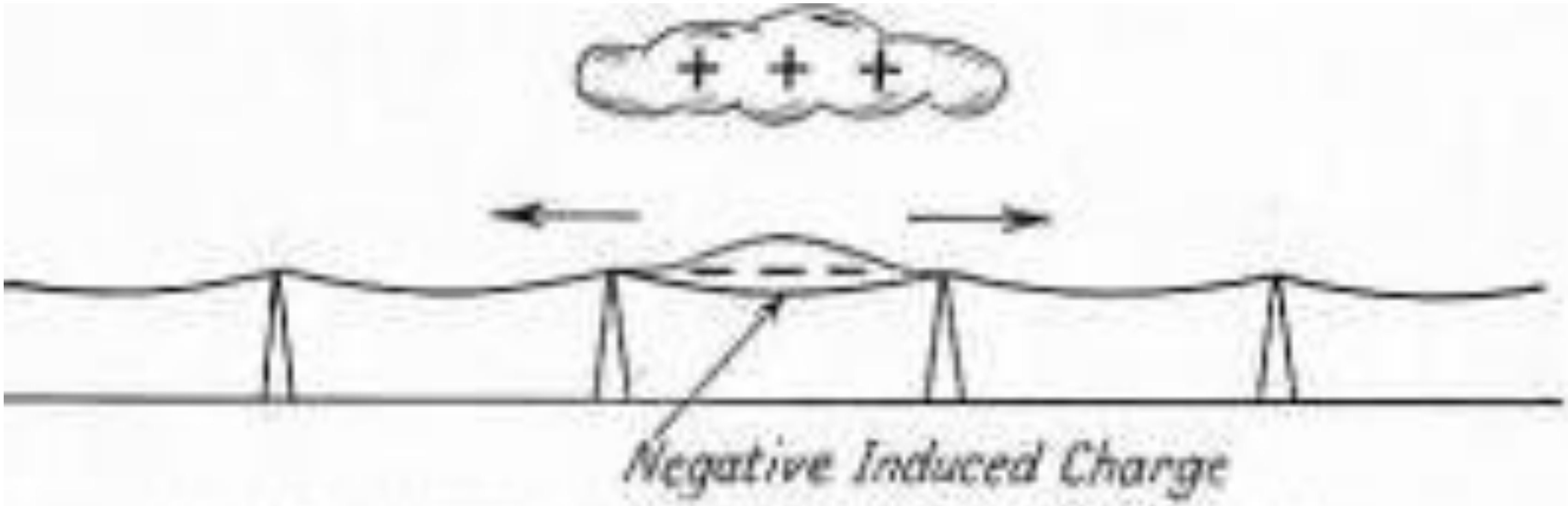


FIG. 253. SURGE DUE TO ELECTROSTATIC INDUCTION

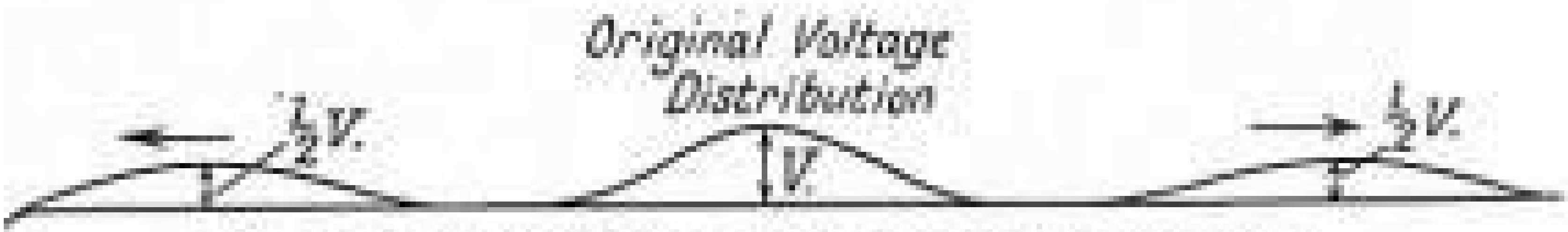


FIG. 254. PROPAGATION OF VOLTAGE DISTRIBUTION

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

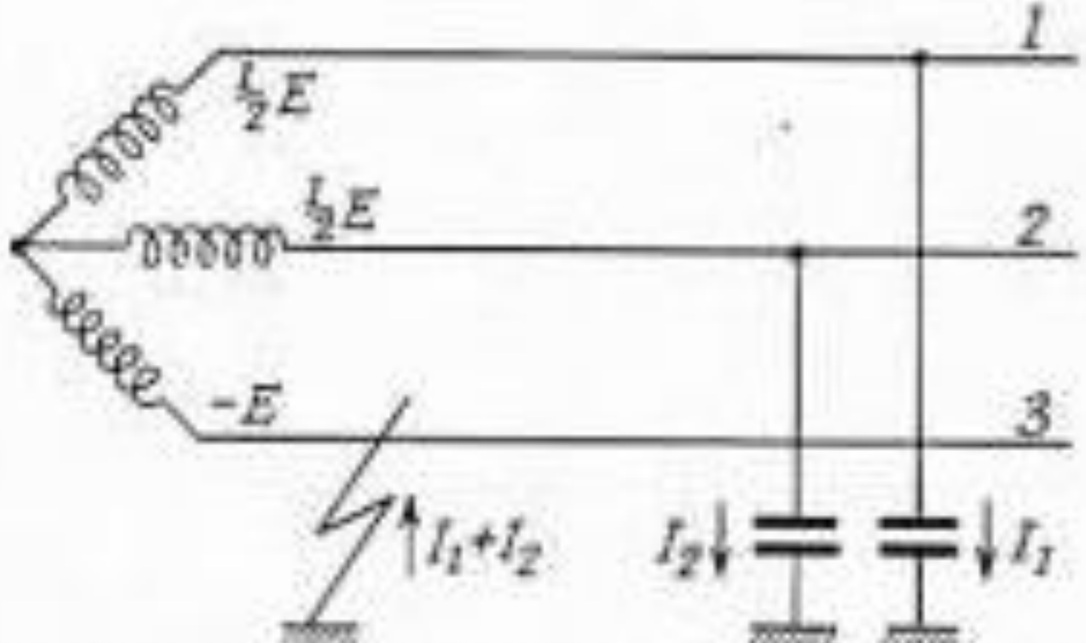


FIG. 255. ARCING GROUND IN THREE-PHASE LINE

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.

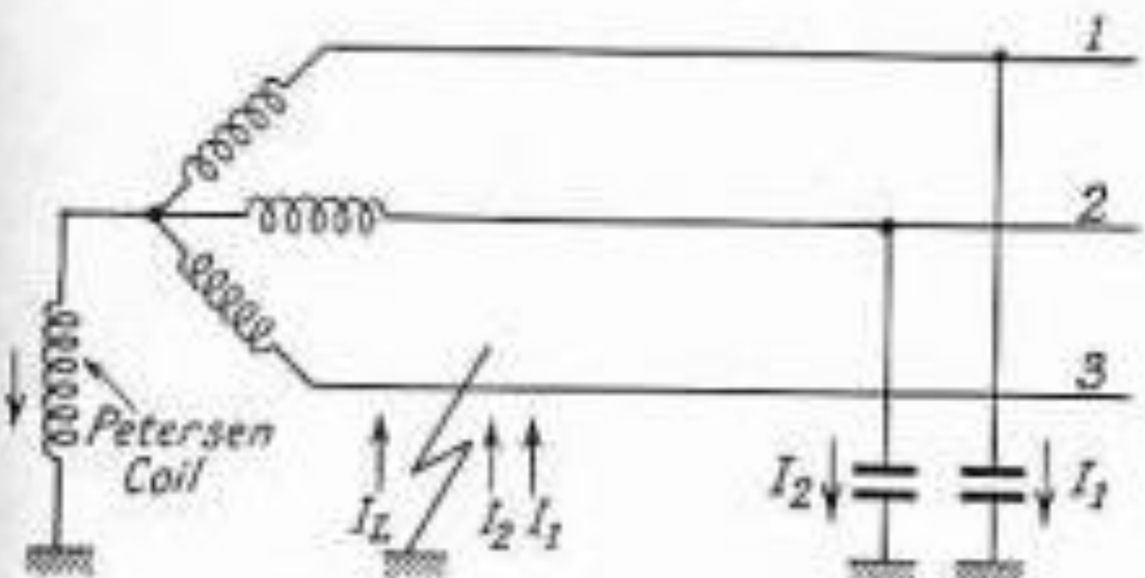


Fig. 256. Petersen Coil

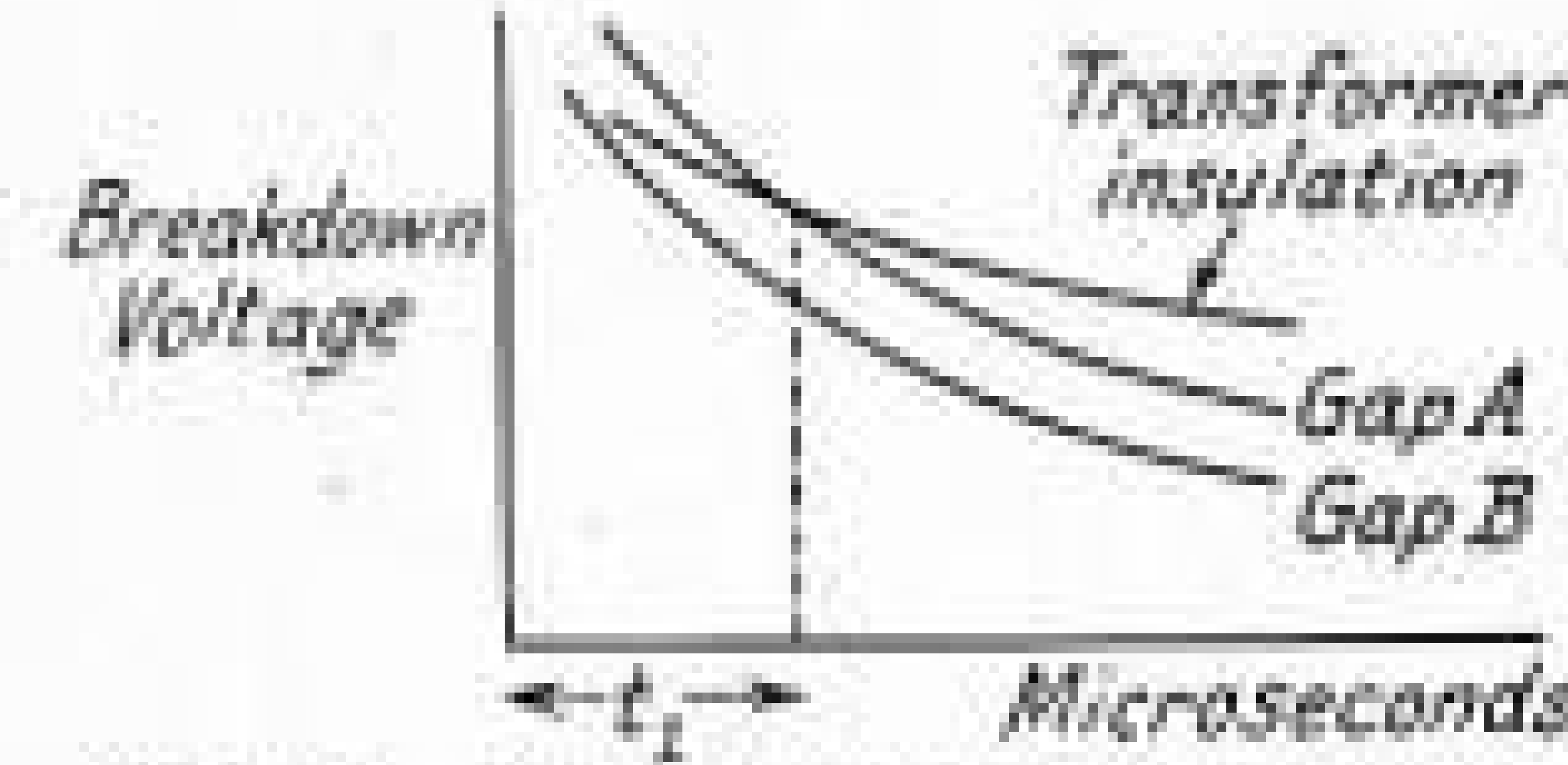


FIG. 257. VARIATIONS OF BREAKDOWN VOLTAGE WITH TIME OF APPLICATION

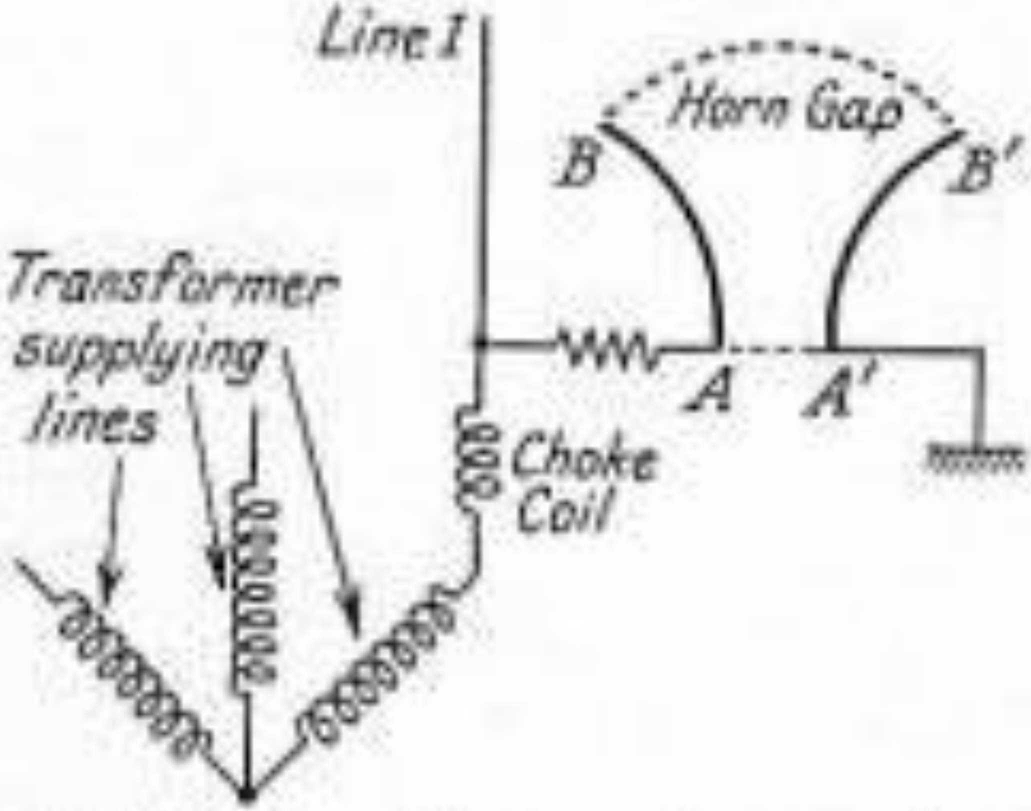


FIG. 258. HORN GAP WITH CHOKE COIL AND RESISTANCE

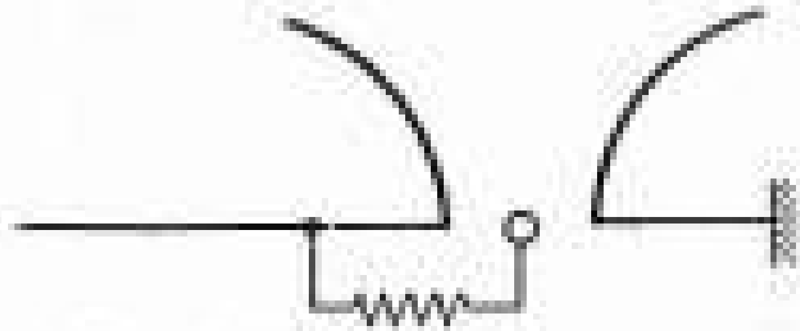


FIG. 259. HORN GAP WITH AUXILIARY ELECTRODE

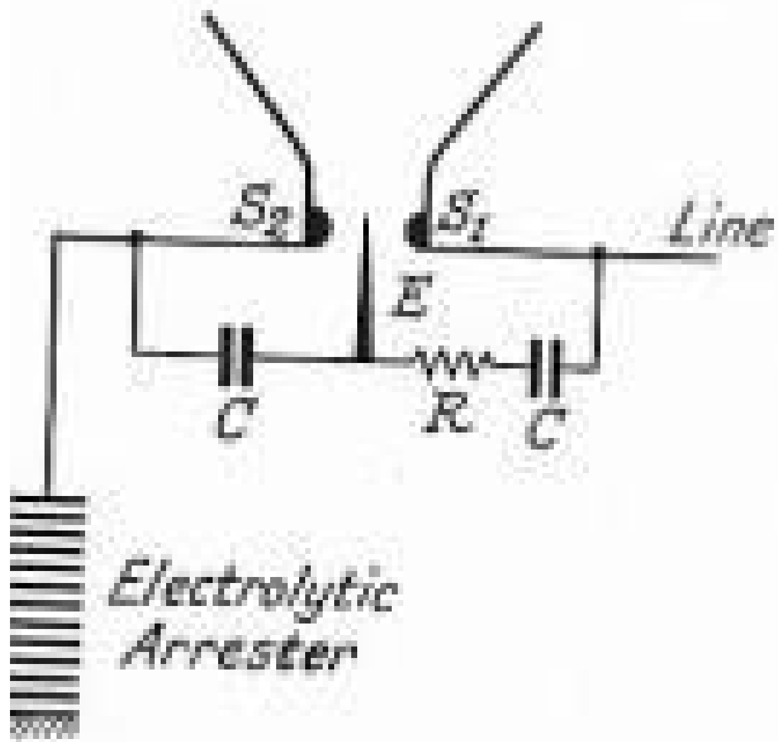


FIG. 261. IMPULSE GAP WITH ELECTROLYTIC ARRESTER

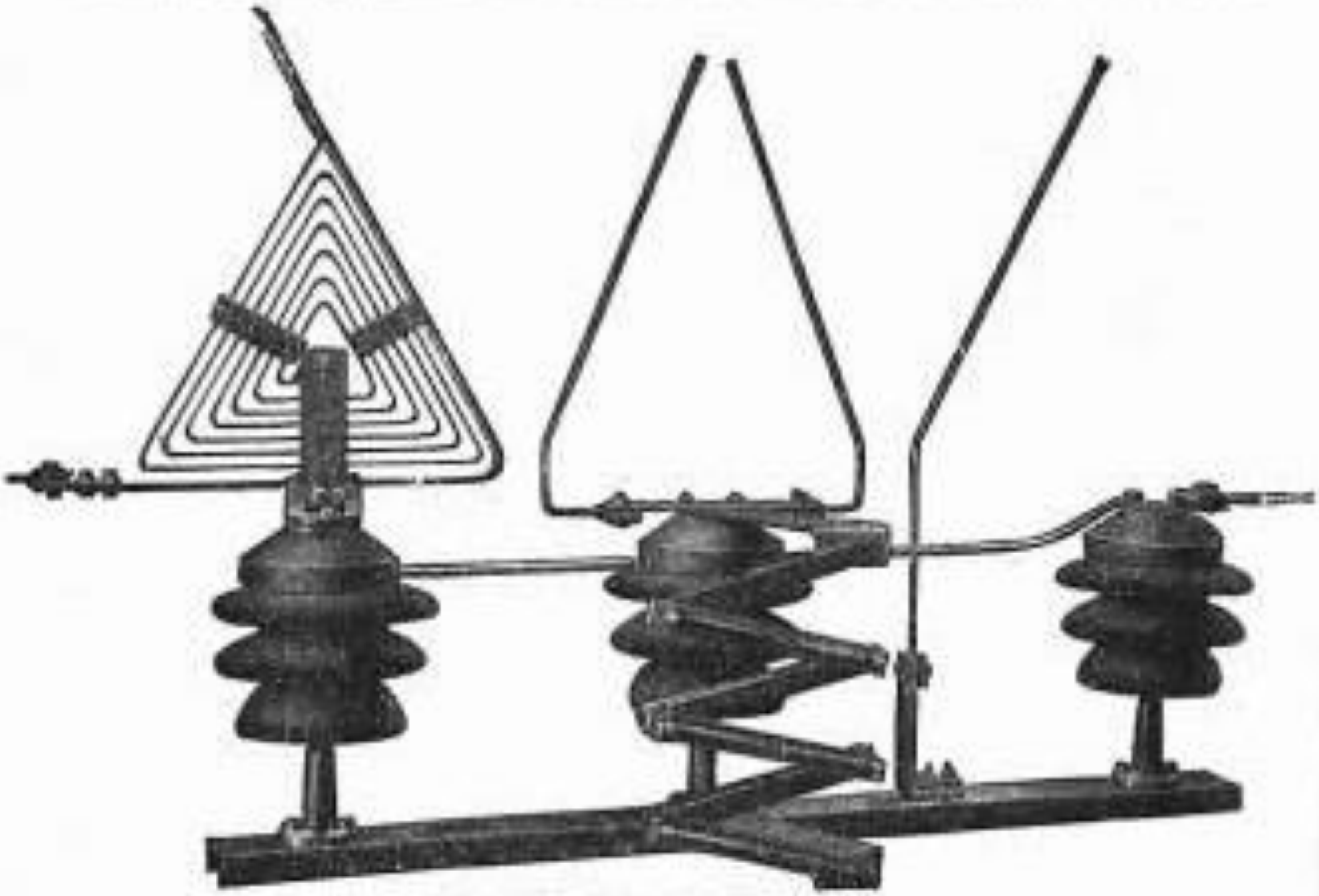


FIG. 260. BURKE ARRESTER
(*Metropolitan-Vickers*)

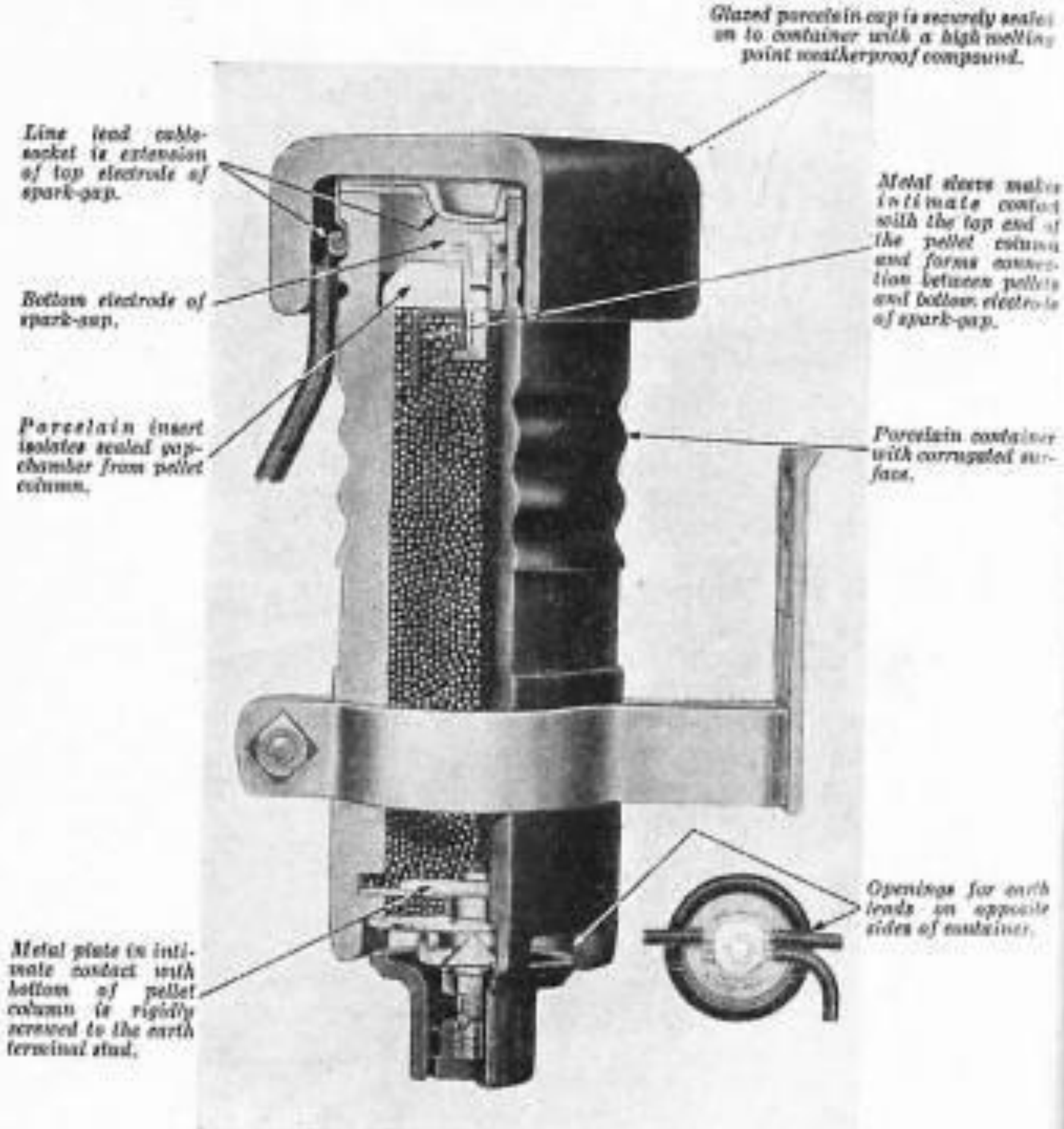


FIG. 262. OXIDE-FILM ARRESTER
(B. T.-H.)

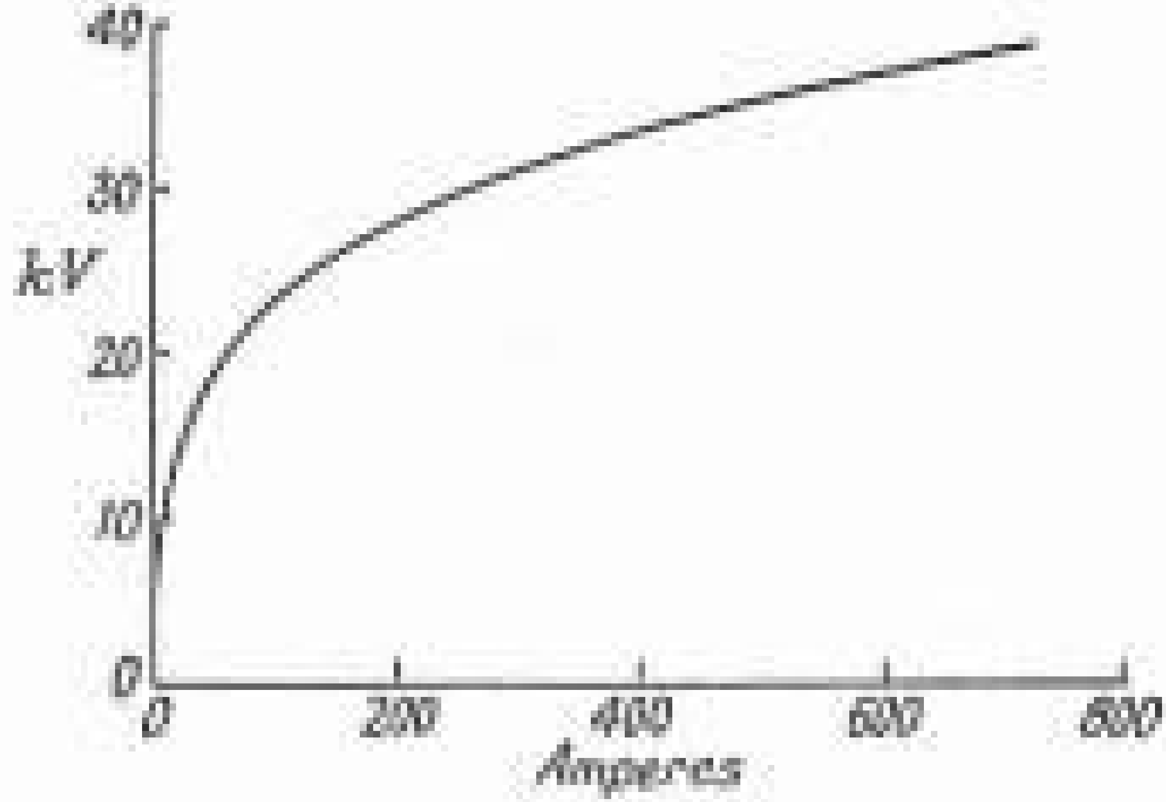


FIG. 263. VOLTAGE-CURRENT CURVE OF THYRITE ARRESTER

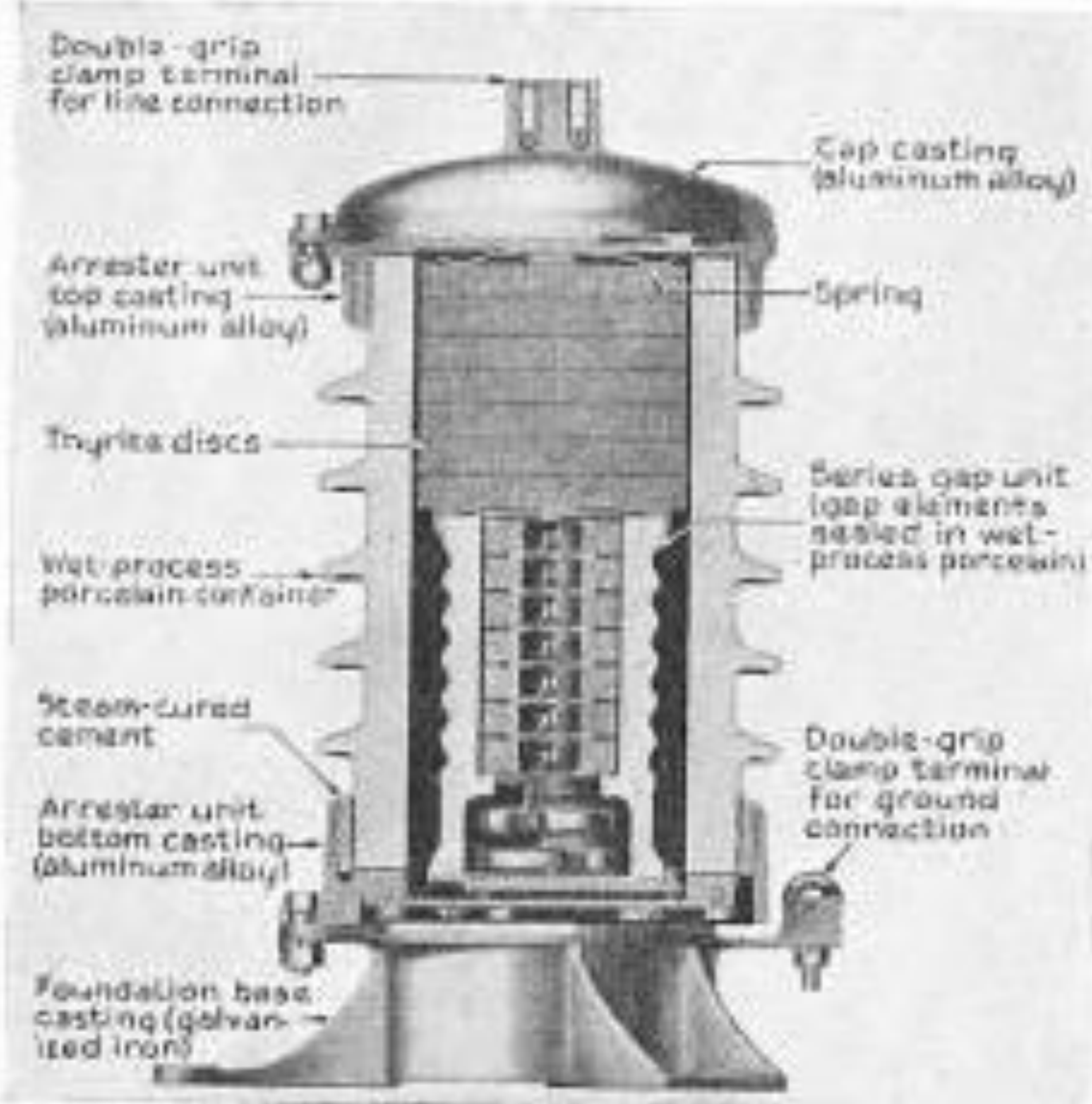


FIG. 264. 11 kV. THYRITE ARRESTER

(*International General Electric Co. of New York, Ltd.*)

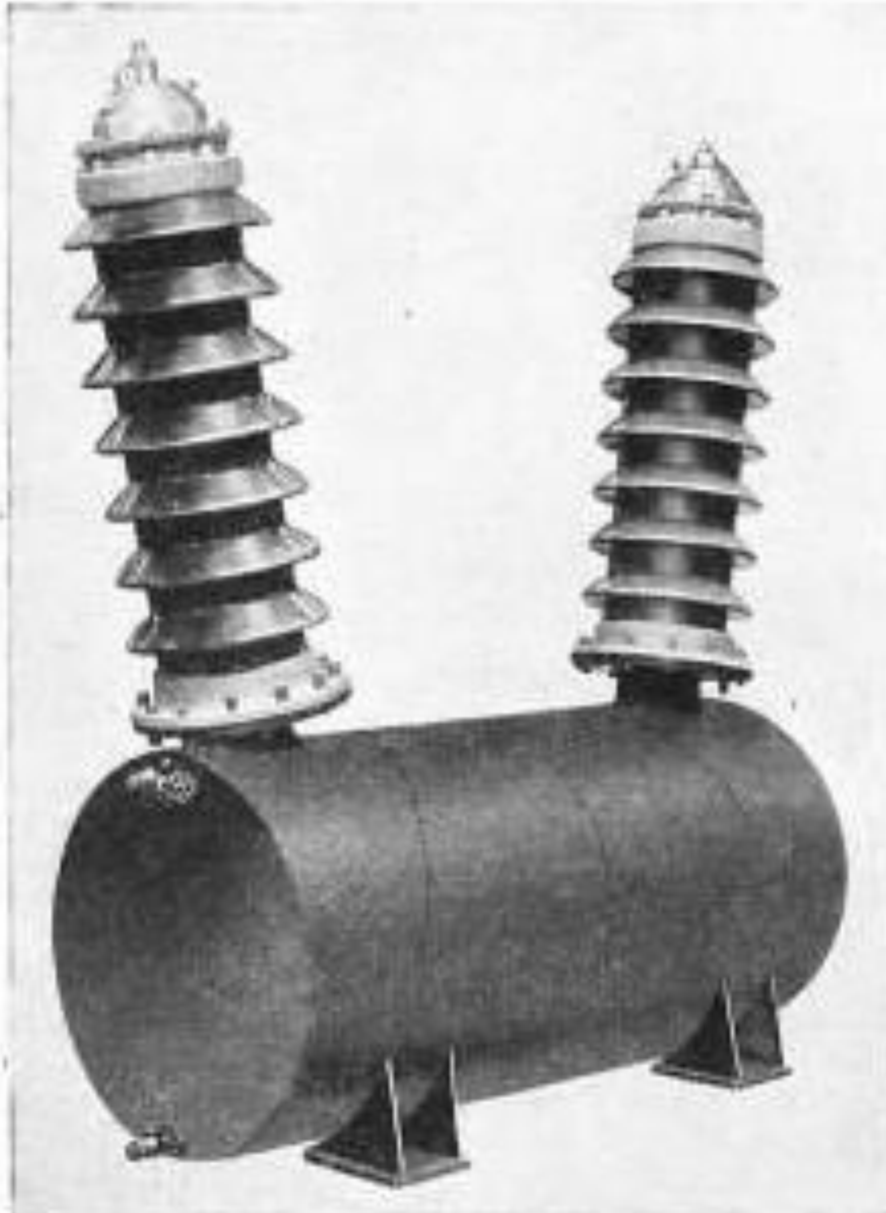


FIG. 265. FERRANTI SURGE ABSORBER
(*I.E.E. Students' Journal*)

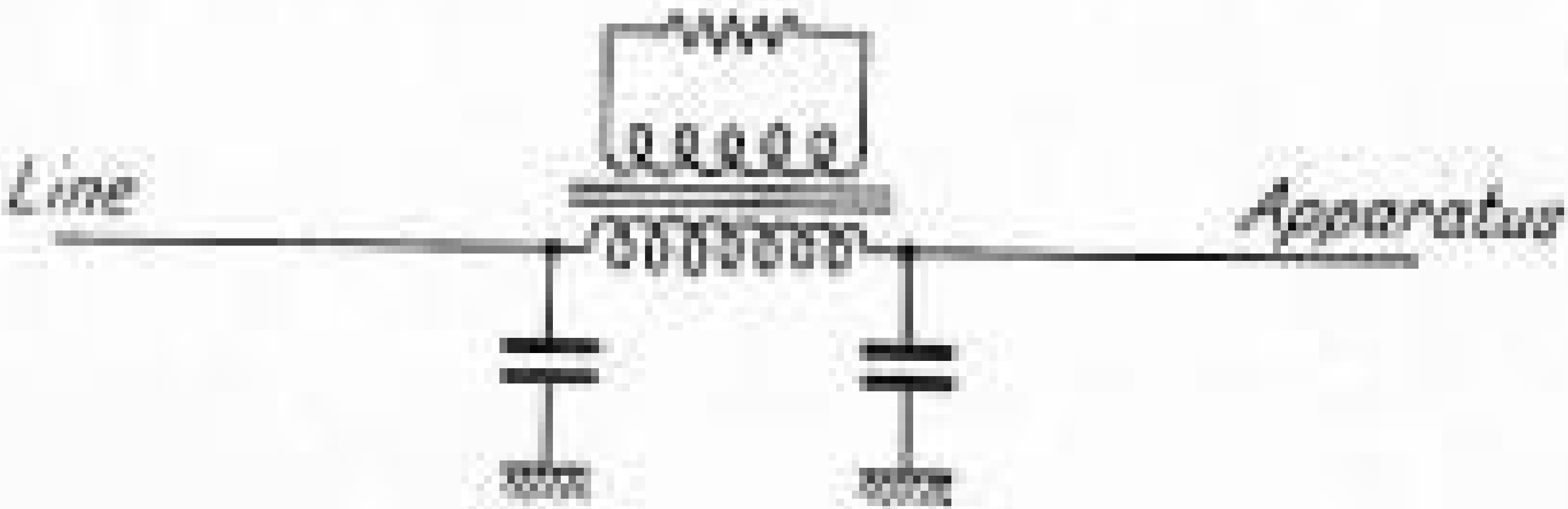


FIG. 266. EQUIVALENT CIRCUIT OF FIG. 268

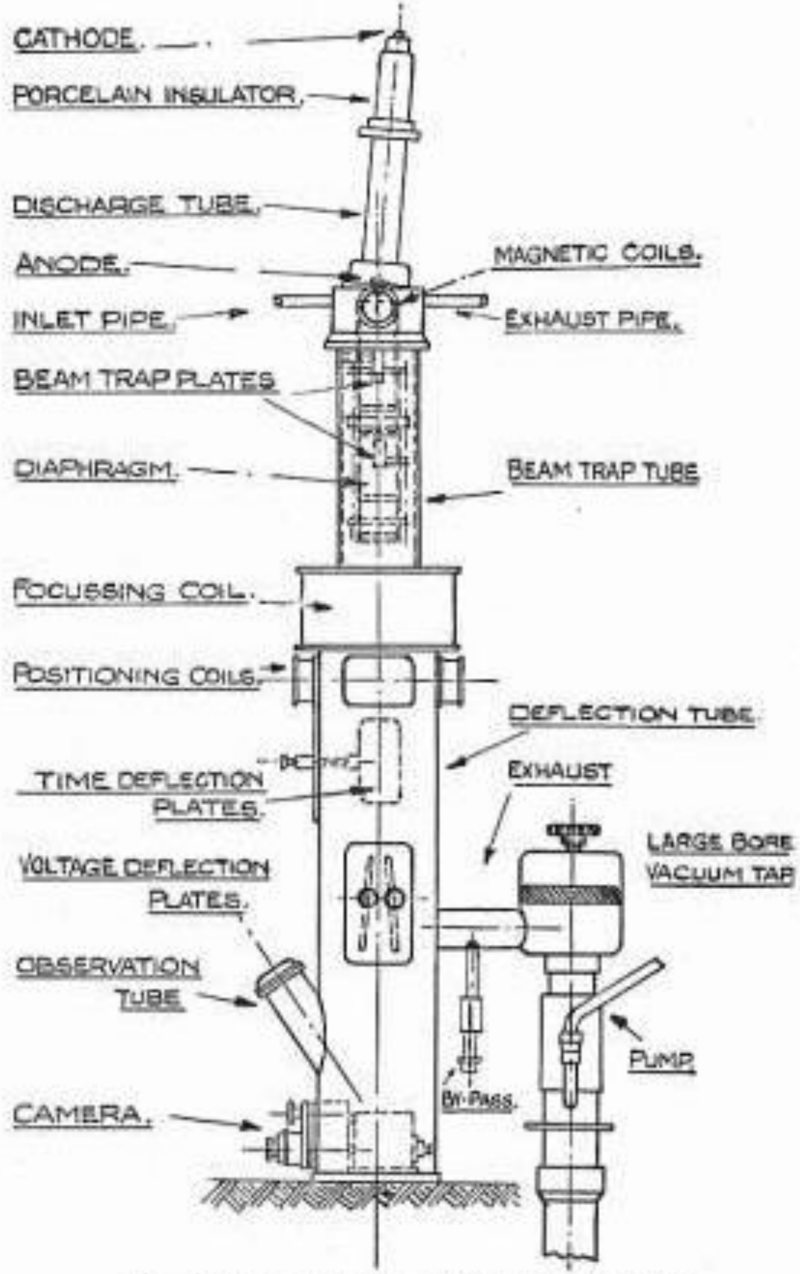


FIG. 267. HIGH-SPEED CATHODE-RAY OSCILLOGRAPH
(*Metropolitan-Vickers*)

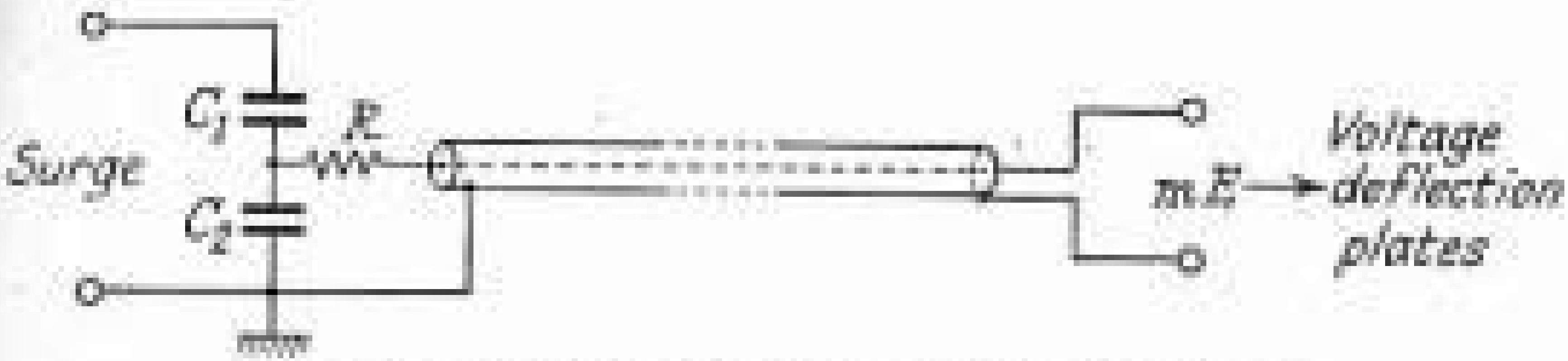


FIG. 268. POTENTIAL DIVIDER AND DELAY CABLE

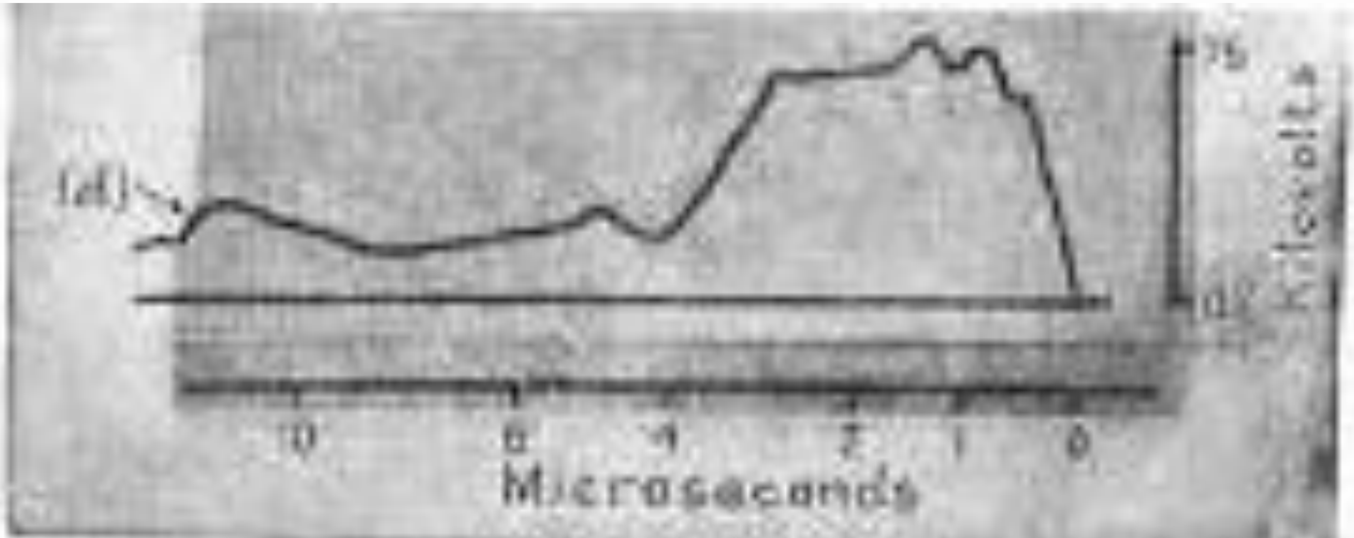


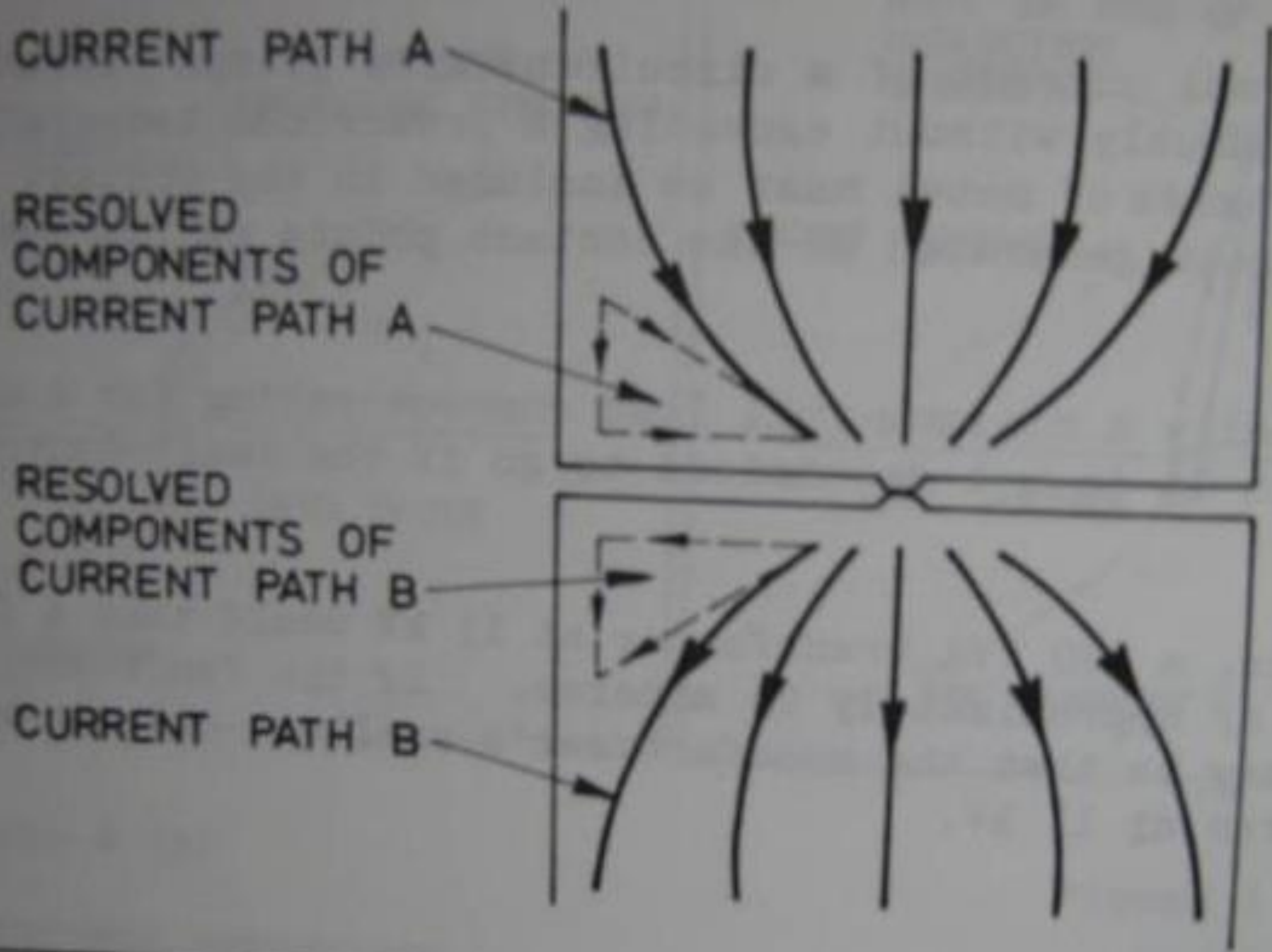
FIG. 269. VOLTAGE ACROSS LINE TURNS OF TRANSFORMER
(*I.E.E. Journal*)

(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.


CURRENT PATH A
RESOLVED COMPONENTS OF CURRENT PATH A
RESOLVED COMPONENTS OF CURRENT PATH B
CURRENT PATH B

5.1.2 Air Circuit Breakers

Air circuit breakers use air as the arc interrupting medium. Because air at atmospheric pressure ionizes easily some auxiliary equipment must be used to break the arc except for the very lowest voltage and capacity breakers. Almost all low voltage breakers use air as an interrupting medium. Figure 5.3 shows some low voltage circuit 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 oriented. As the rising arc stretches its resistance increases, its current drops, and its increased surface area is exposed to cooler air, causing its temperature to drop until the arc is finally extinguished. The longer an arc can be drawn out the easier it is to extinguish.

Arc tips (also called arcing contacts) break after the main contacts break. This prevents pitting of the main contacts. Because the arc tips travel further than the main contacts they stretch the arc further, thus making it extinguish earlier. Arc 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.

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

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

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

$$H = 2I/x.$$

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

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

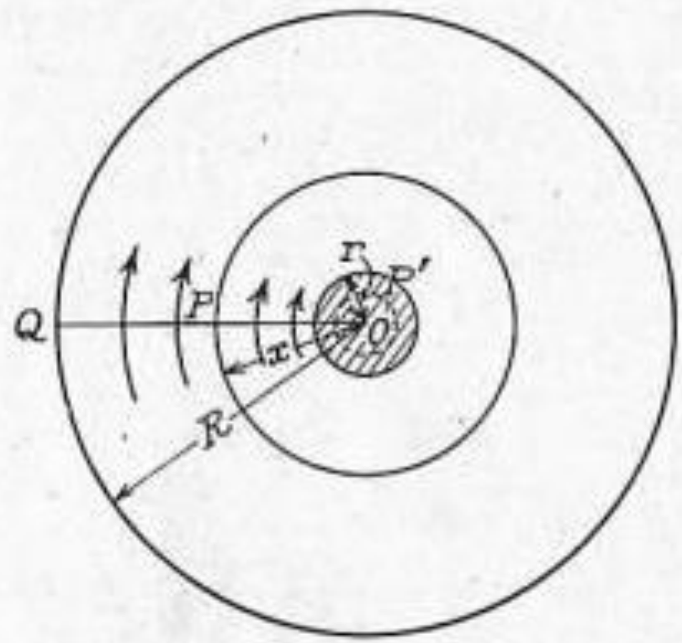


FIG. 60. MAGNETIC FIELD SURROUNDING A CONDUCTOR

linkage being the product of a current element and a flux. The linkages inside the conductor are for unit length along the axis

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

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

The linkages created by conductor 2 round conductor 1 are

$$I\int_D^R \left(-\frac{2I}{x}\right) dx = -2\, I^2 \operatorname{logh} \frac{R}{D},$$

so that the total linkages round conductor 1 are

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

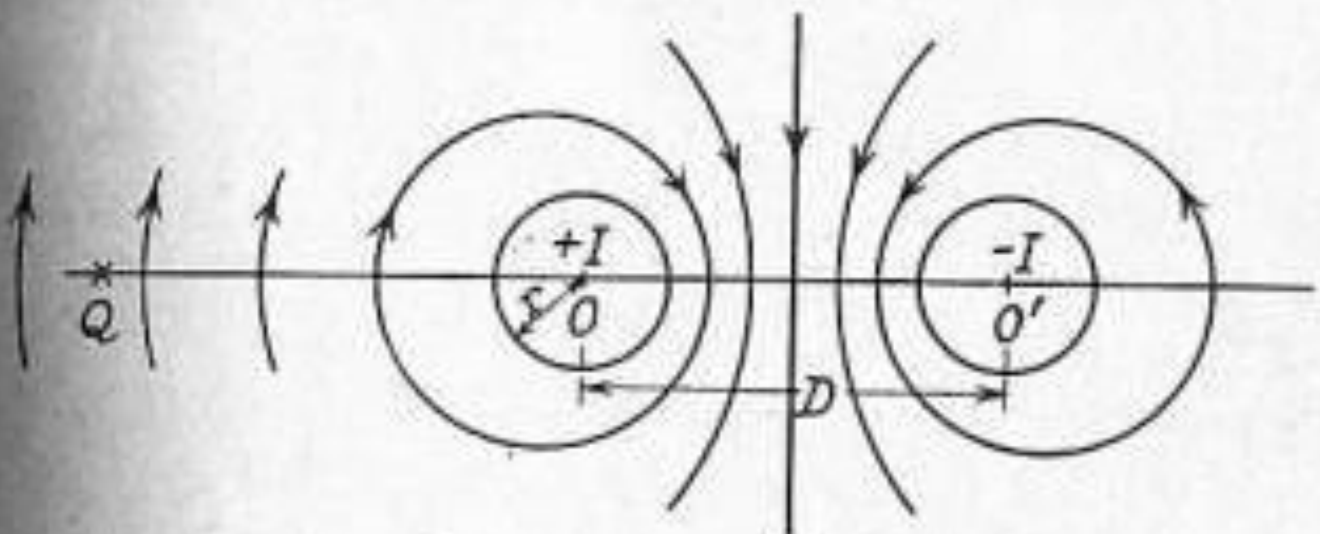


FIG. 61. MAGNETIC FIELD SURROUNDING TWO PARALLEL CONDUCTORS

Inductance of Three-phase Lines. Fig. 62 shows a cross-section of a three-phase system, consisting of three conductors A_1, A_2,

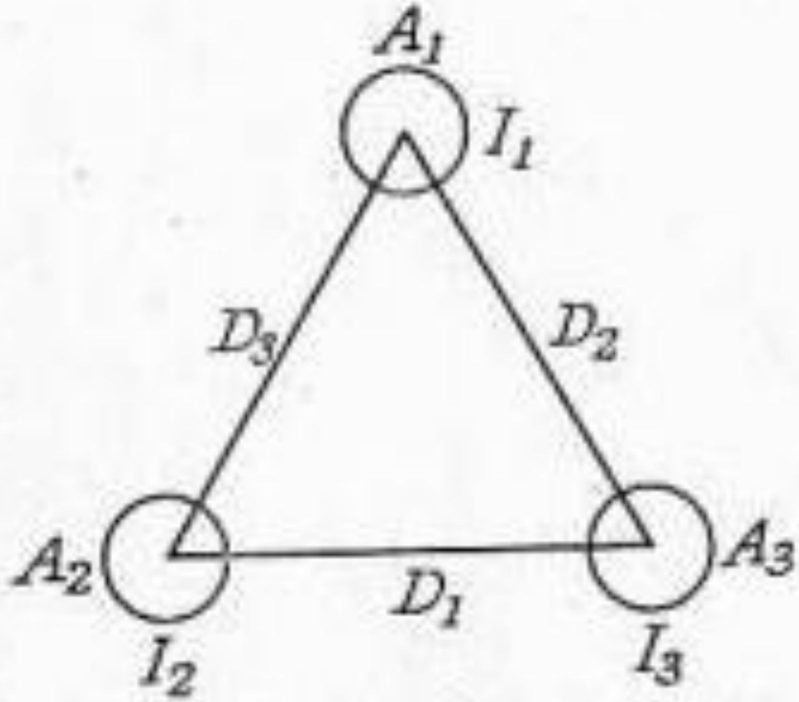


FIG. 62
CROSS-SECTION OF THREE-PHASE SYSTEM

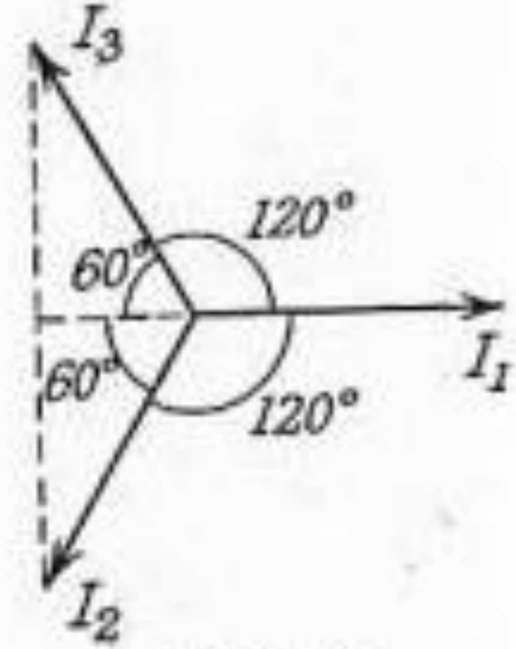


FIG. 63
CURRENTS IN BALANCED, THREE-PHASE SYSTEM

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

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

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

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

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.

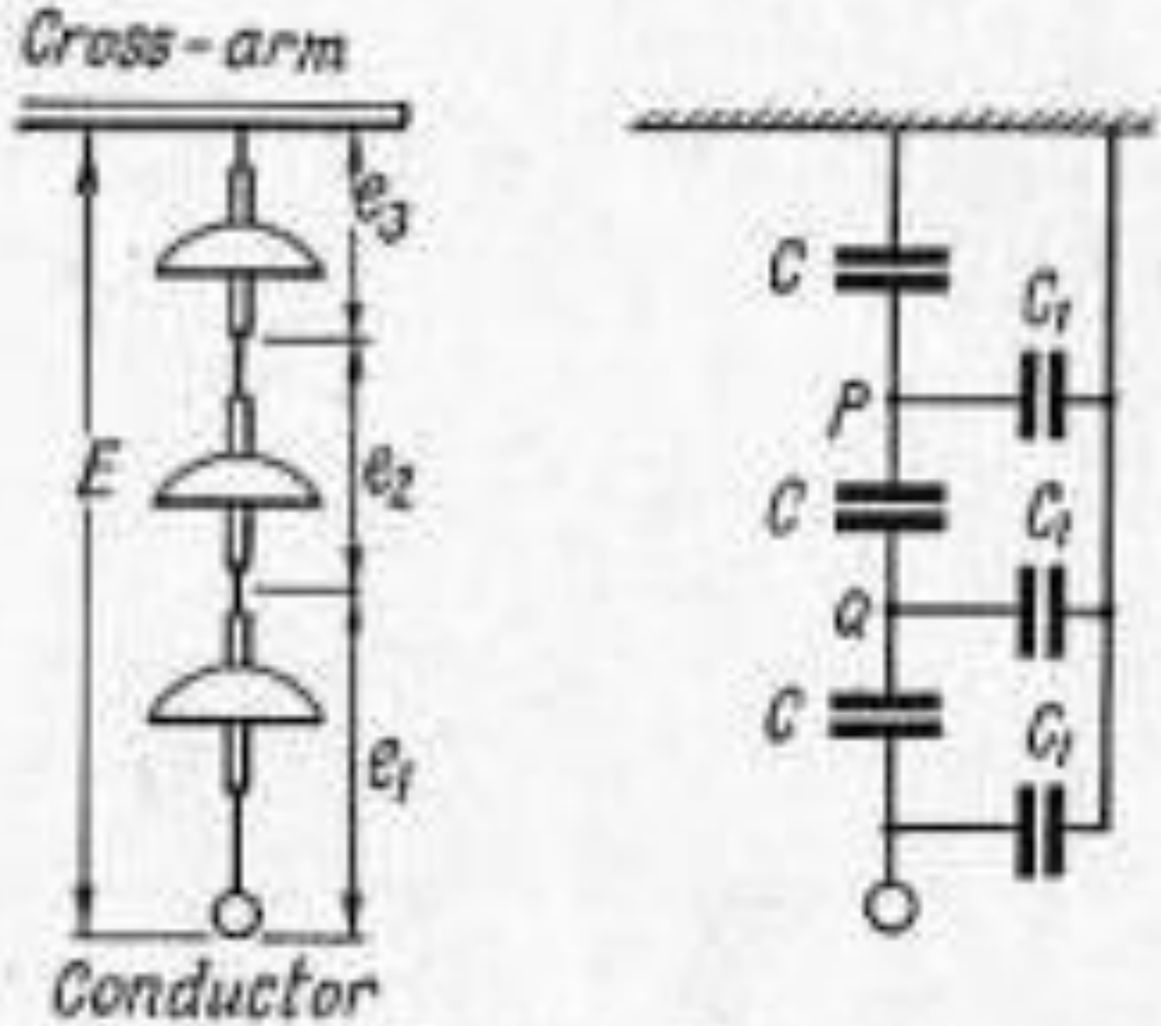


FIG. 68. STRING EFFICIENCY OF SUSPENSION INSULATOR

FIG. 251. FLATTENING OF WAVE DUE TO SHUNT CAPACITANCE

$$E_T = \frac{2E}{Z/R + 1}\left[1 - \varepsilon^{-[(Z+R)/CZR]t}\right]$$
$$= E_{TO}\left[1 - \varepsilon^{-[(Z+R)/CZR]t}\right],$$

Lightning. With the increase of high-voltage overhead lines the problem of lightning is assuming greater importance, and much

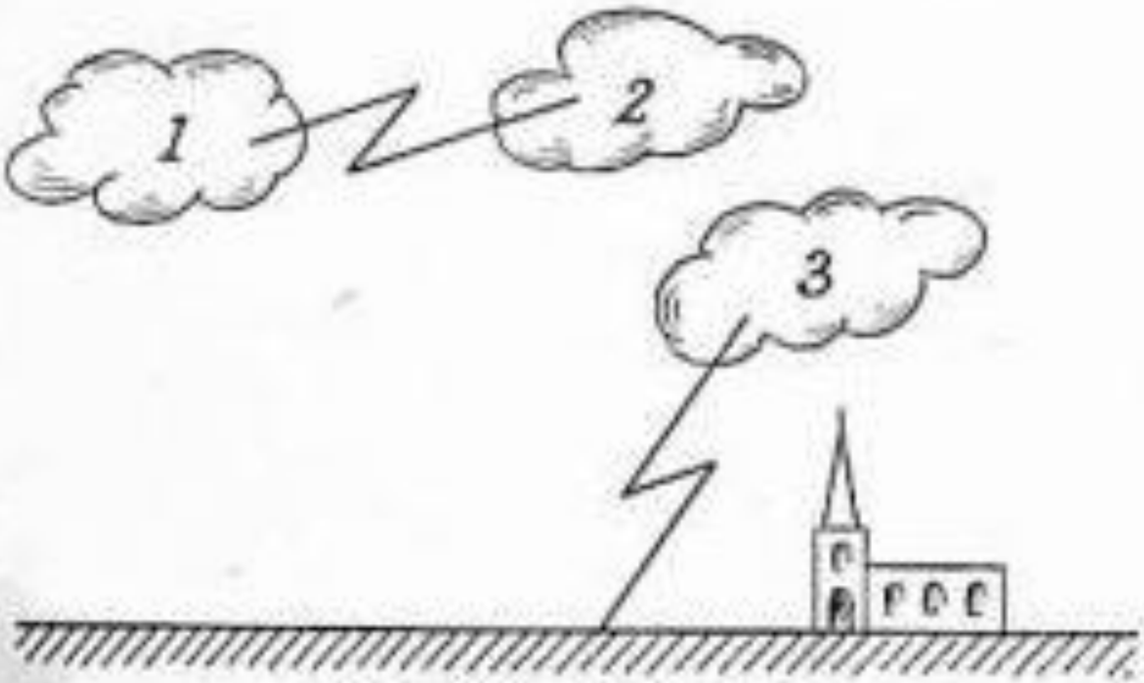
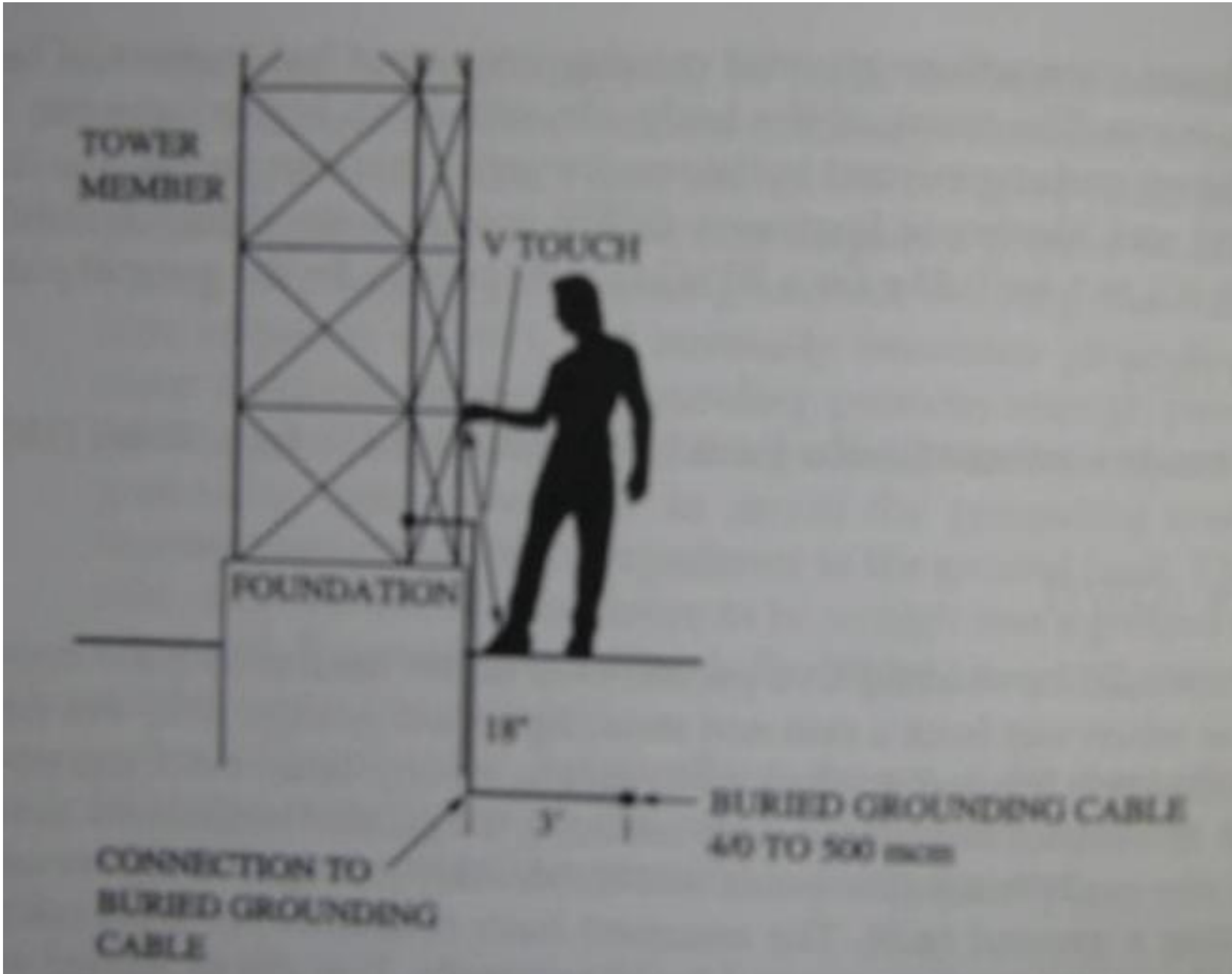


Fig. 252. B Stroke



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

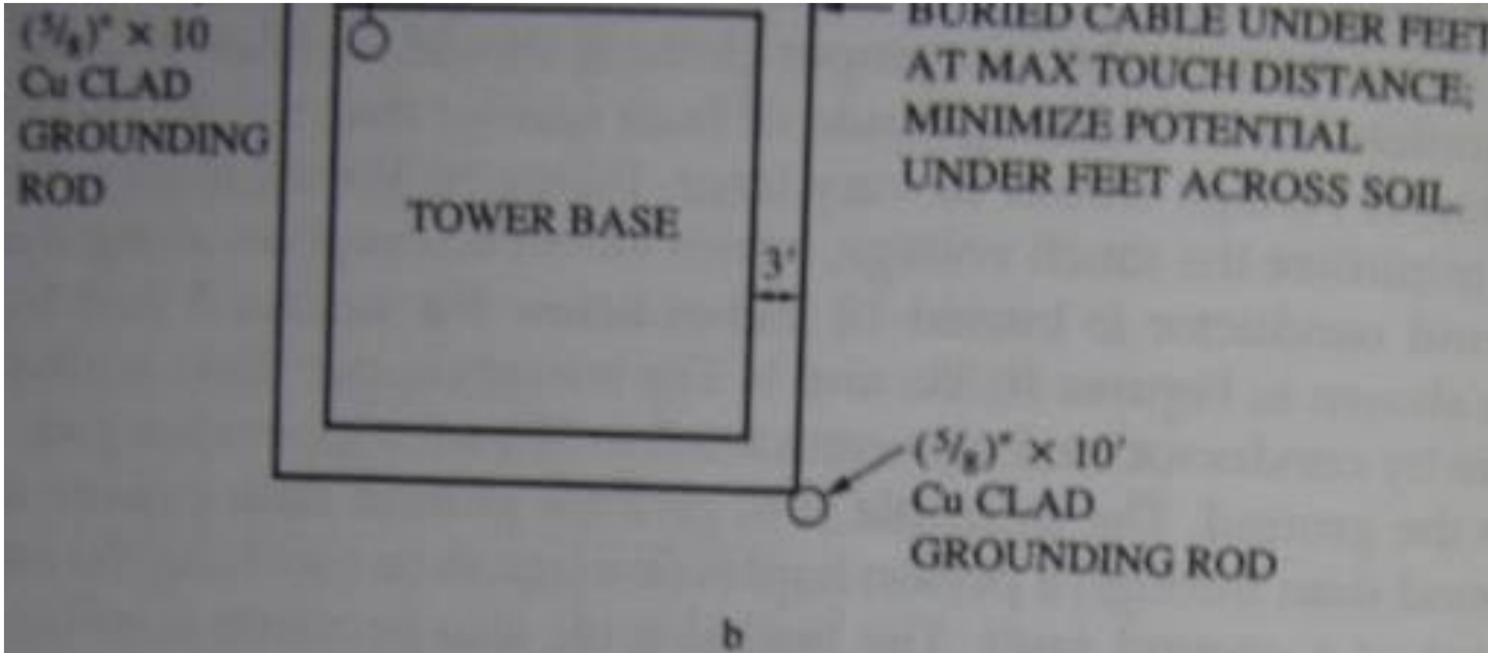
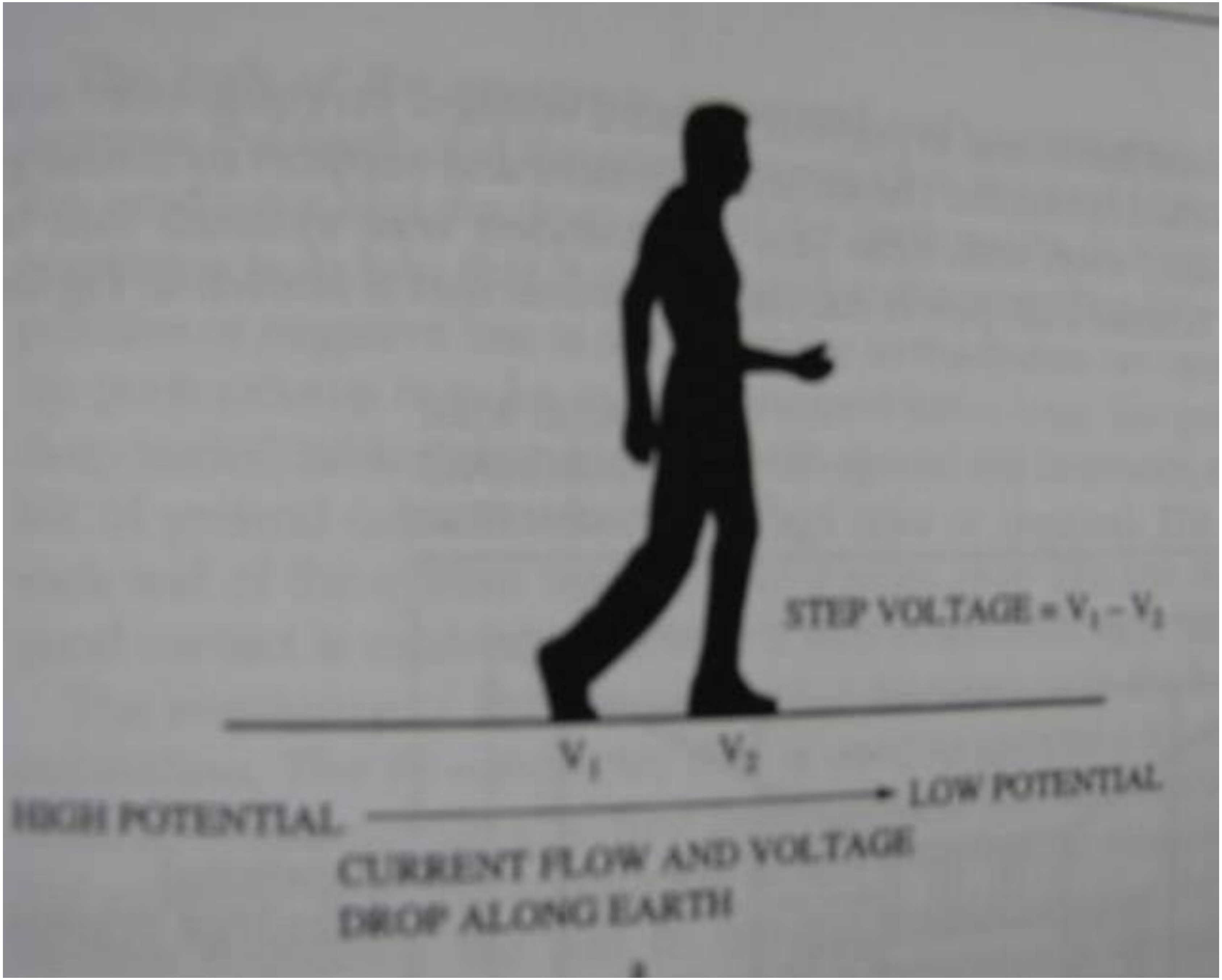


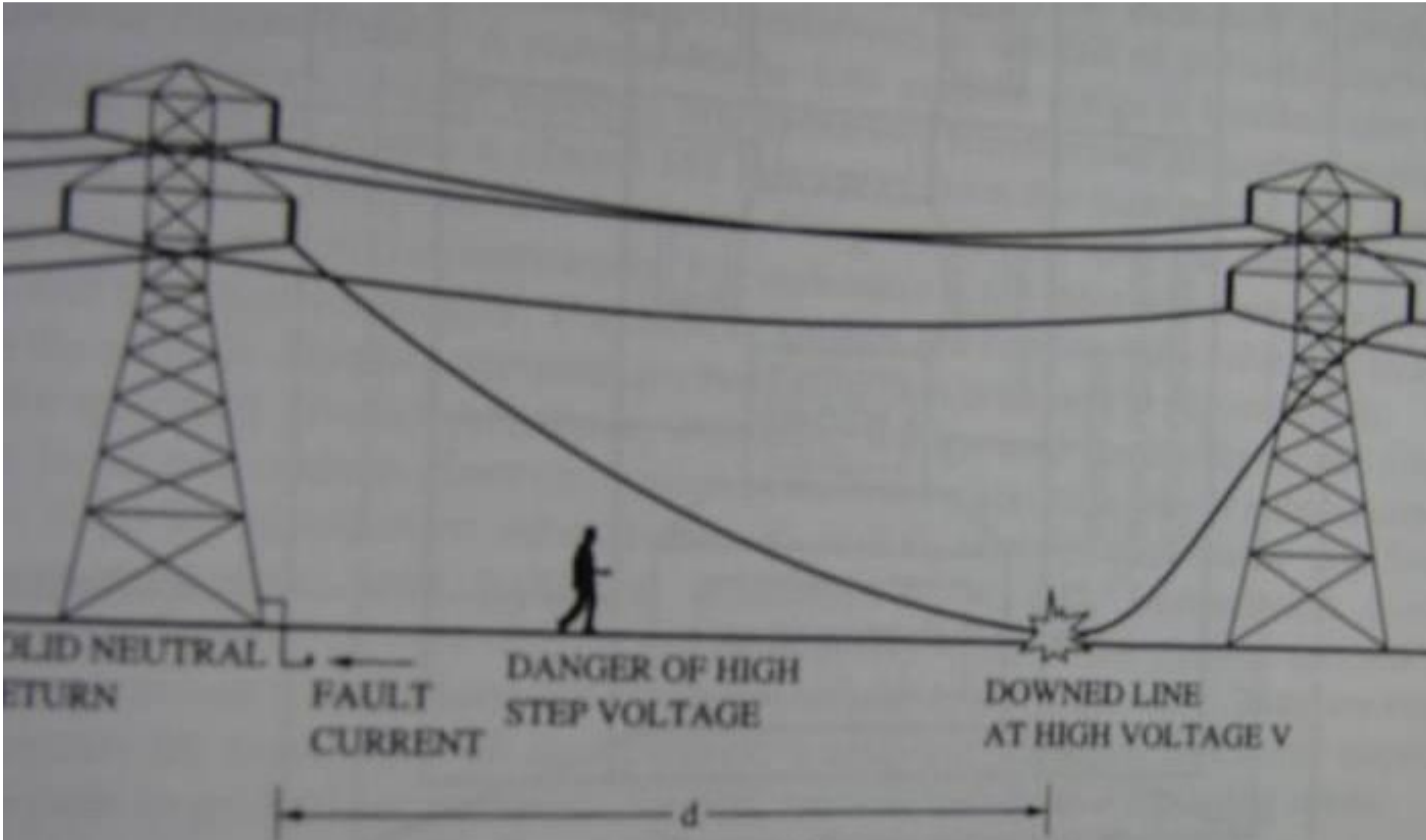
FIGURE 10.33 Touch voltage (a) Definition and (b) Minimized by grounding

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

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

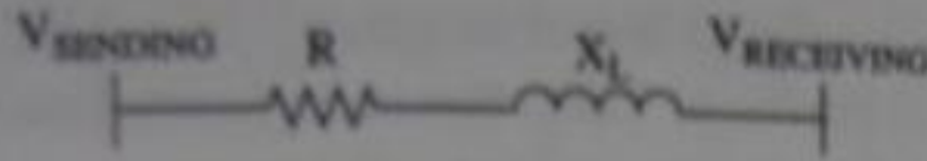
$$I_{\text{foot to foot}} = \frac{300V}{1000\Omega} = 0.3\ \text{A}$$


STEP VOLTAGE = $V_1 - V_2$
V_1
V_2
HIGH POTENTIAL
LOW POTENTIAL
CURRENT FLOW AND VOLTAGE
DROP ALONG EARTH

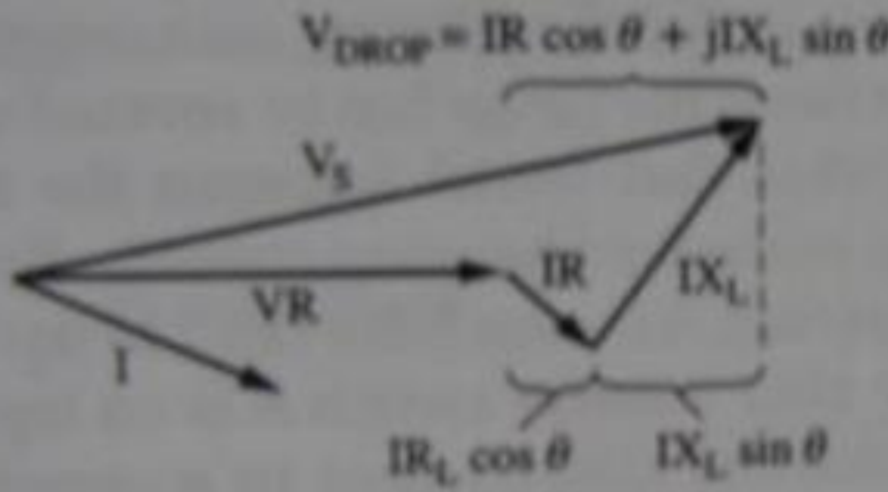


$$\frac{V}{\text{UNIT DISTANCE}} = \frac{V}{d}$$

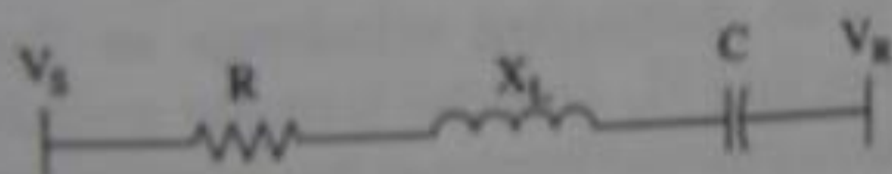
$$\frac{100\ \text{kV}}{1000'} = \frac{100\ \text{V}}{\text{STEP}}$$


V_SENDING
R
X_L
V_RECEIVING

a


$V_{DROP} = IR \cos\theta + jIX_L \sin\theta$
V_S
IR
IX_L
VR
I
$IR_L \cos\theta$
$IX_L \sin\theta$

b


V_S
R
X_L
C
V_R

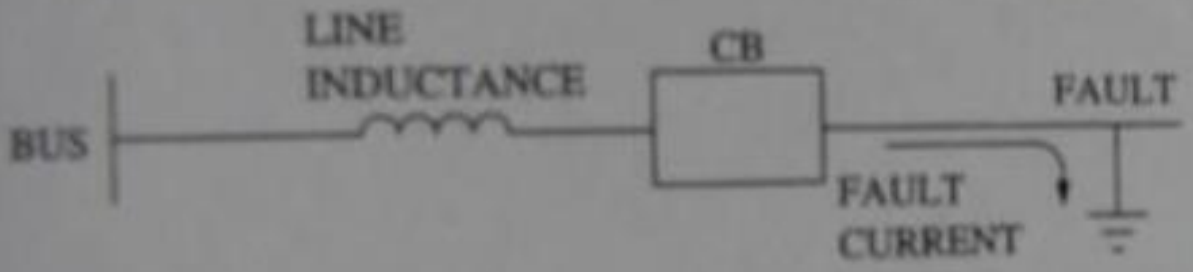
c

.1.1 The Arc

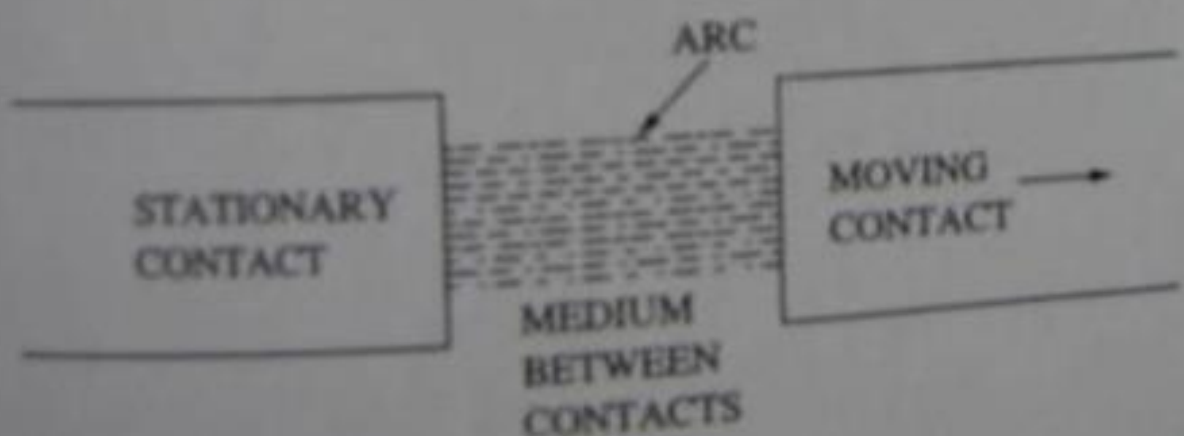
Vhen current carrying contacts open, the initial electric field between the just arted contacts is very high. The high electric field causes any gas between the ontacts to ionize and support current flow through it, or arc. The higher the voltge that the contacts are breaking the more severe the arcing.

Inductive loads make the tendency to arc even more severe because inductive oads attempt to keep the current through the opening contacts the same as it was efore they opened. Most industrial loads and faulted lines are inductive. The arc eaches very high temperatures because of the current dissipating power in the arc tself. The high temperature at the contact face causes some of the contact metal to

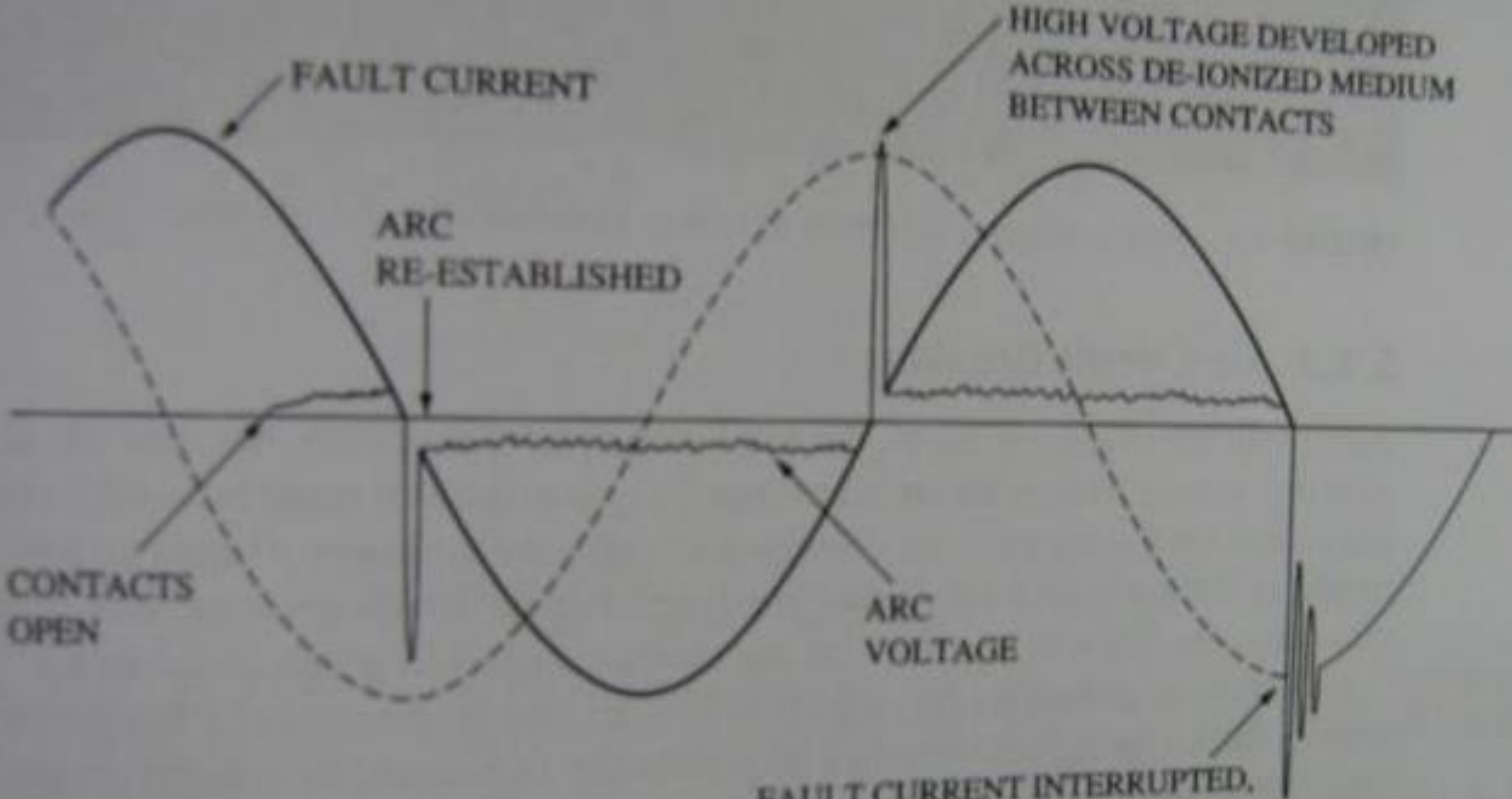
A circuit breaker must stretch and cool the arc until it breaks. Circuit breakers are classified by how they accomplish this task.



a



b

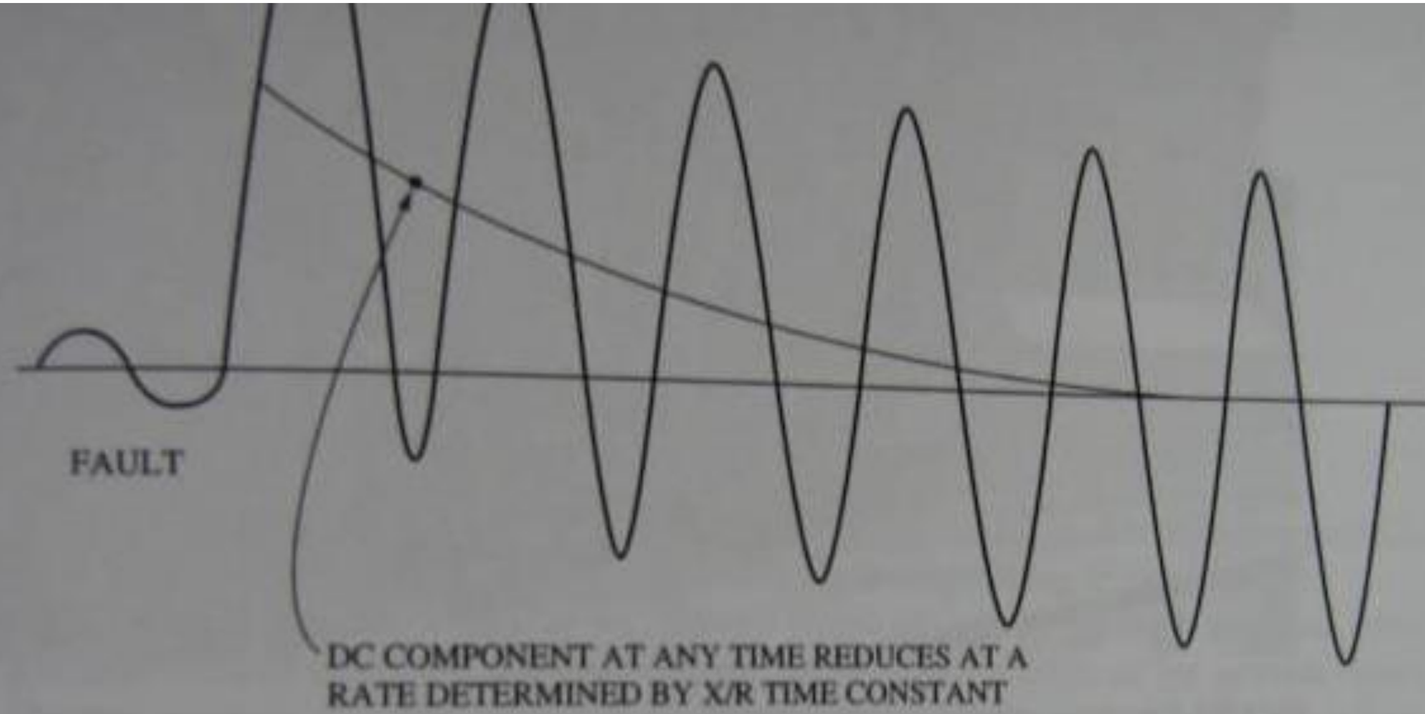

FAULT CURRENT
HIGH VOLTAGE DEVELOPED
ACROSS DE-IONIZED MEDIUM
BETWEEN CONTACTS
ARC
RE-ESTABLISHED
CONTACTS
OPEN
ARC
VOLTAGE
FAULT CURRENT INTERRUPTED,
RECOVERY OSCILLATIONS IF
ASSOCIATED REACTANCE AND
RESISTANCE VALUES ALLOW
c

5.1.2 Air Circuit Breakers

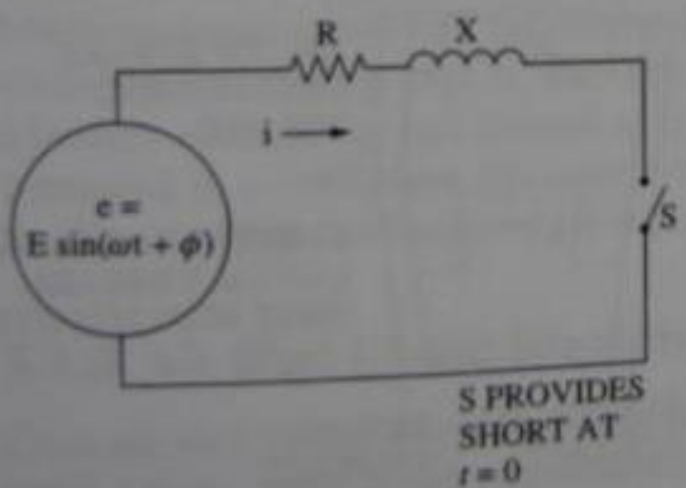
Air circuit breakers use air as the arc interrupting medium. Because air at atmospheric pressure ionizes easily some auxiliary equipment must be used to break the arc except for the very lowest voltage and capacity breakers. Almost all low voltage breakers use air as an interrupting medium. Figure 5.3 shows some low voltage circuit 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 oriented. As the rising arc stretches its resistance increases, its current drops, and its increased surface area is exposed to cooler air, causing its temperature to drop until the arc is finally extinguished. The longer an arc can be drawn out the easier it is to extinguish.

Arc tips (also called arcing contacts) break after the main contacts break. This prevents pitting of the main contacts. Because the arc tips travel further than the main contacts they stretch the arc further, thus making it extinguish earlier. Arc 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.



a



$$i = A e^{-(R/X)\omega t} + B \sin(\omega t + \phi - \theta)$$

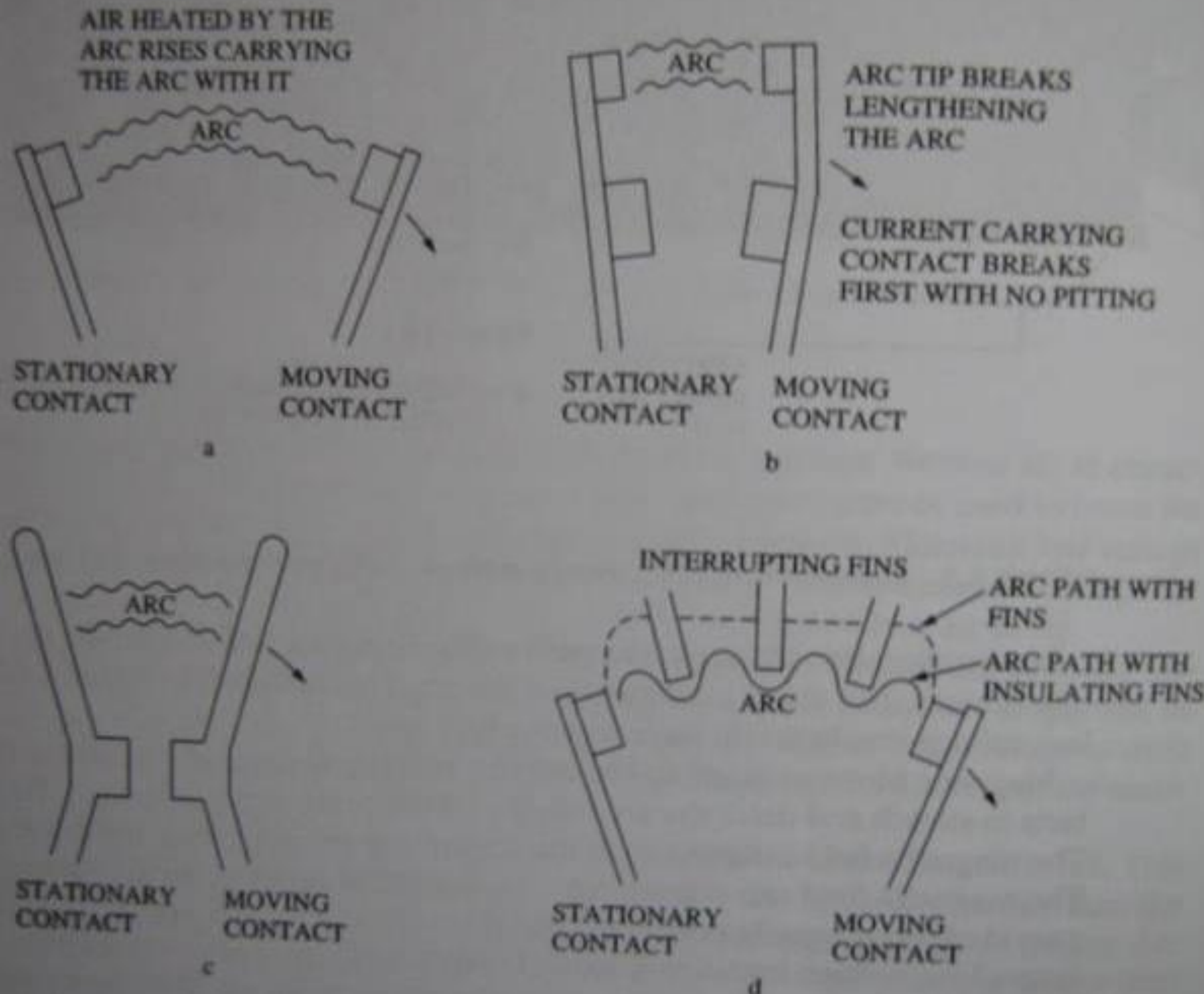
$$A = \frac{E}{\sqrt{R^2 + X^2}} \sin(\phi - \theta)$$

$$B = \frac{E}{\sqrt{R^2 + X^2}}$$

$$\theta = \tan^{-1}\left(\frac{X}{R}\right)$$

ϕ = ANGLE FROM ZERO UNTIL FAULT OCCURS

FIGURE 5.3 Low voltage circuit breakers



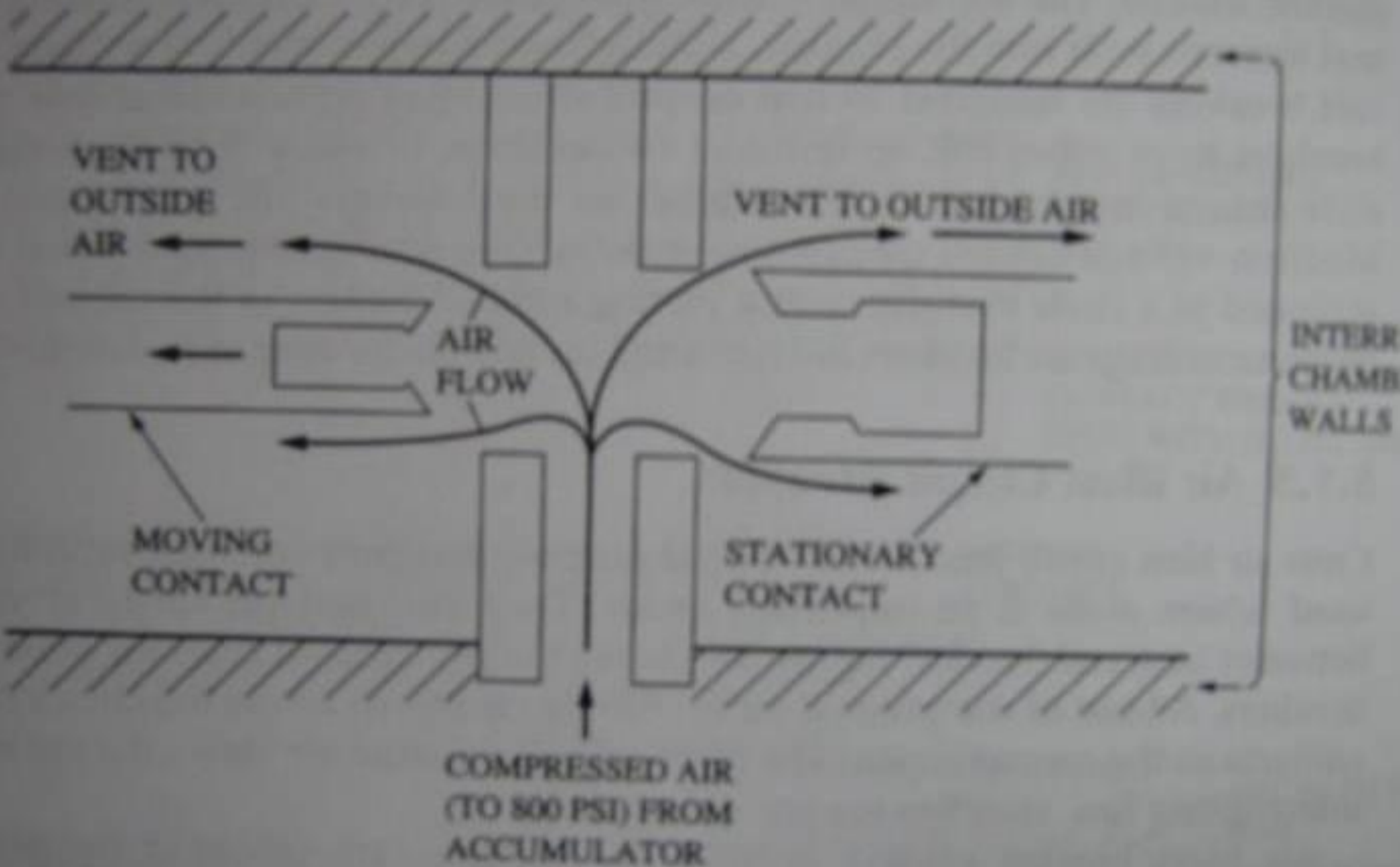


FIGURE 5.7 Axial air blast circuit breaker principle

5.1.7 Circuit Breaker Ratings

Users of circuit breakers must consider a number of ratings to select the right one. The continuous voltage rating, which may decrease at altitudes above 3300 ft, must be adequate. The rated impulse voltage (BIL) must be considered for insulation coordination, lightning, and surge protection.

The continuous current rating must be adequate for maximum loads and the interrupt capacity must be greater than the maximum fault current the breaker will have to interrupt. This means that the maximum fault current must be known. We will learn to calculate fault currents in later chapters. Additionally the MVA rating must be adequate.

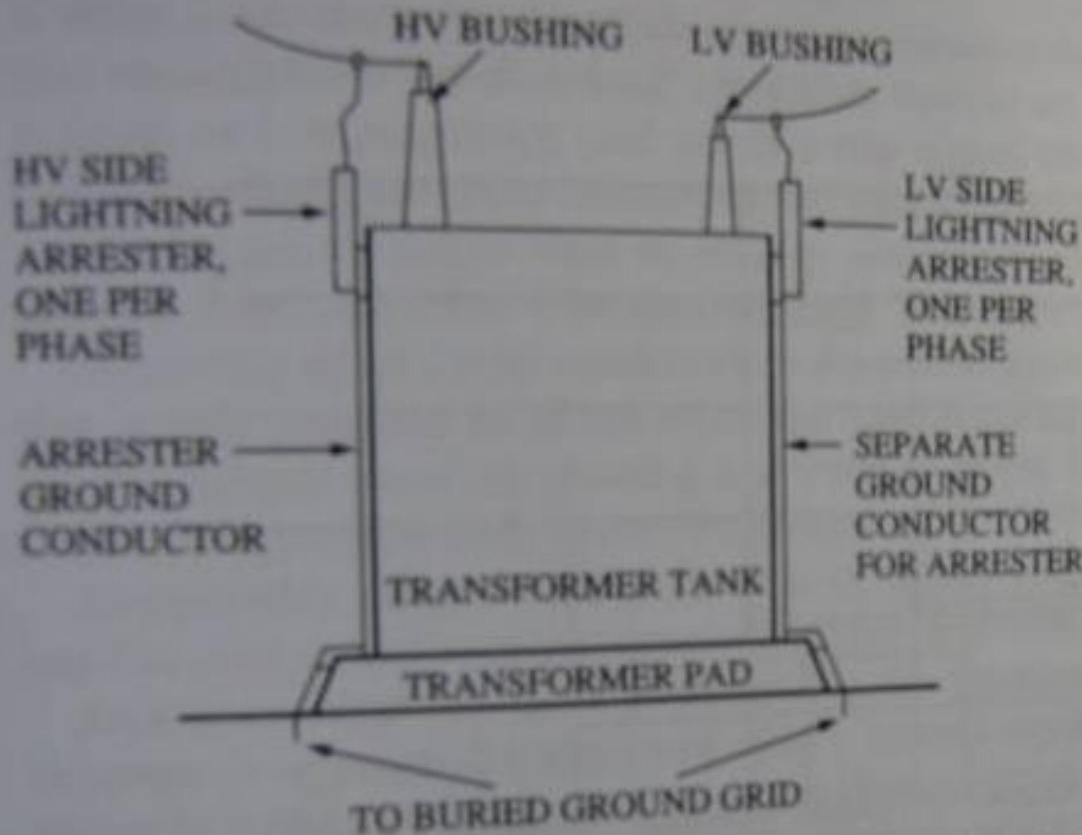


FIGURE 5.33 Lightning protection of distribution substation power transformer

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

$$PM = \frac{\text{BIL} - \text{arrester discharge voltage}}{\text{BIL}} \tag{5.1}$$

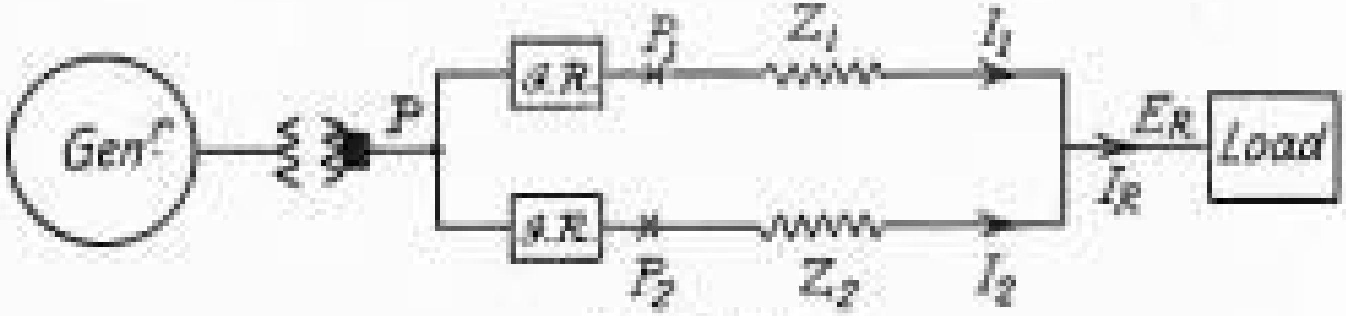
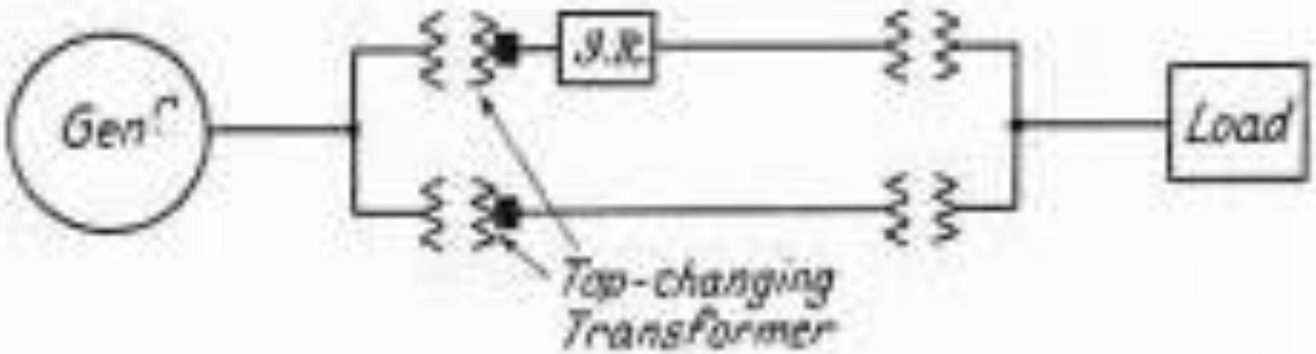

Genr
P
I.R.
P1
Z1
I1
ER
Load
IR
I.R.
P2
Z2
I2

FIG. 151


Genr
I.R.
Load
Tap-changing
Transformer


C
E2
C'
E1
O

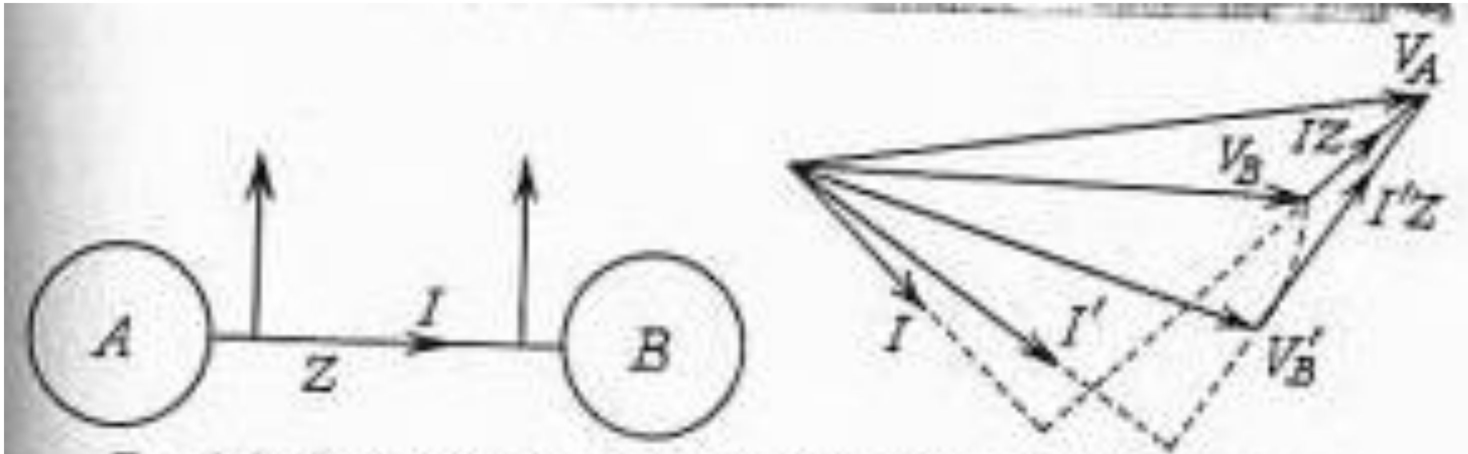
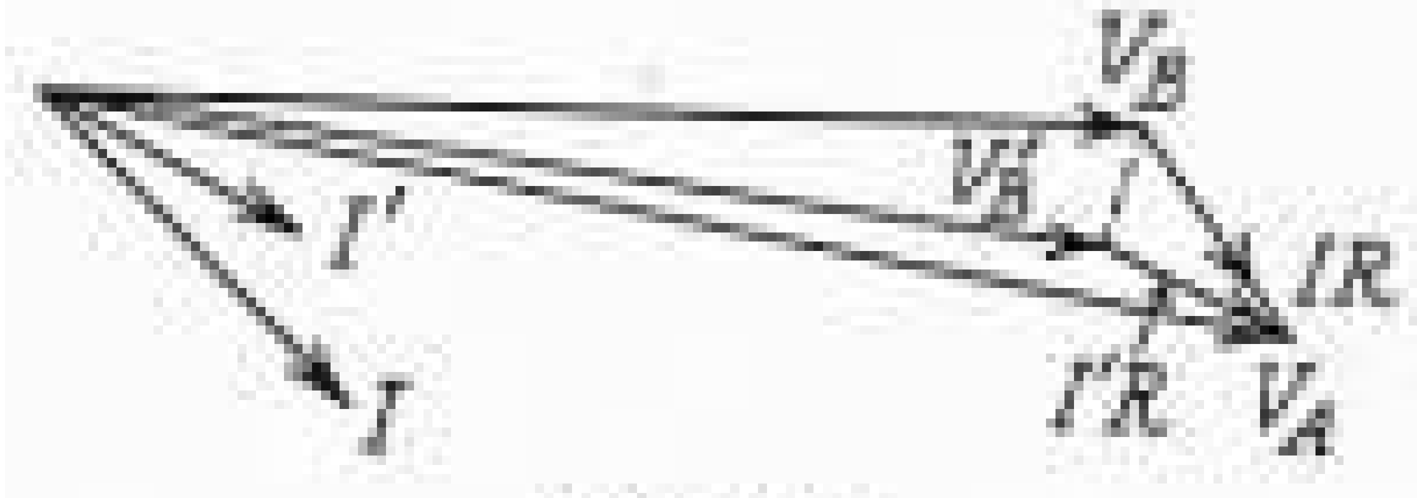
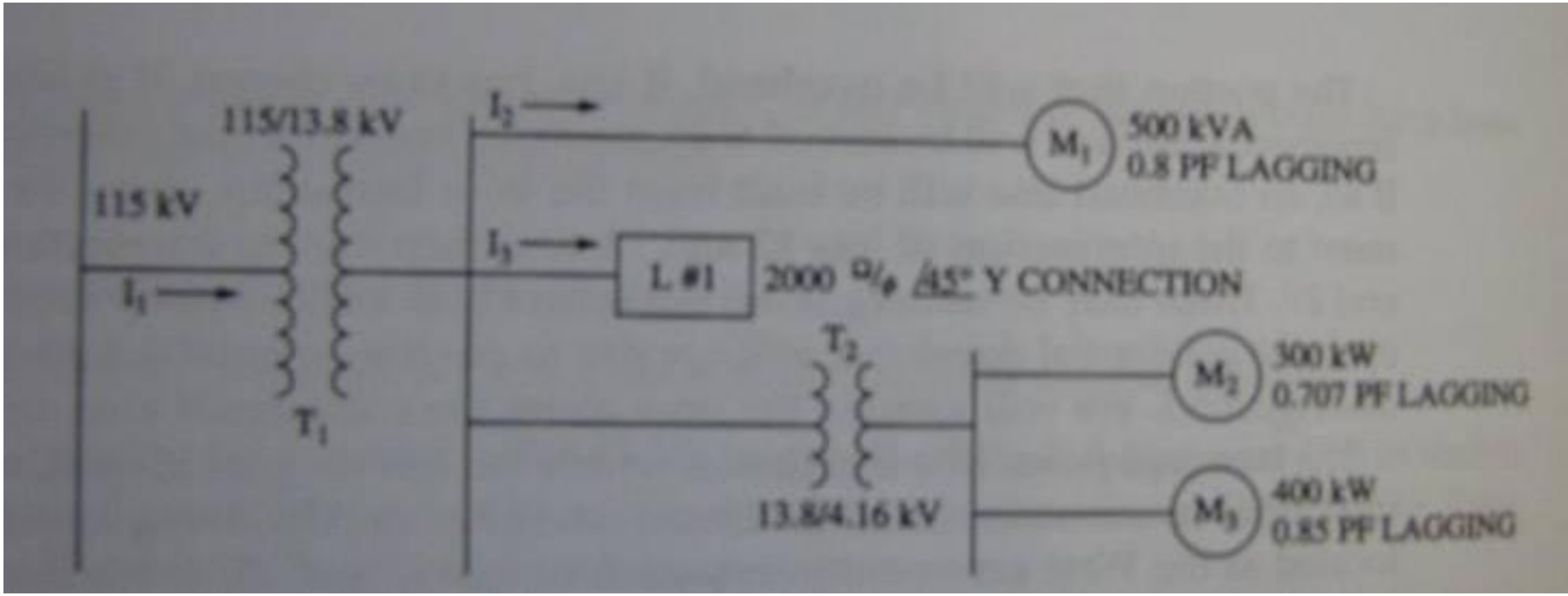


FIG. 153. PARALLEL OPERATION OF GENERATORS CONNECTED BY



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.


115/13.8 kV
115 kV
I_1
T_1
I_2
M_1
500 kVA
0.8 PF LAGGING
I_3
L #1
2000 Ω/φ ∠45° Y CONNECTION
T_2
13.8/4.16 kV
M_2
300 kW
0.707 PF LAGGING
M_3
400 kW
0.85 PF LAGGING

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

$$I_1 = \frac{P}{(\sqrt{3})V\cos\theta} = \frac{400\ \text{kW}}{(\sqrt{3})13.8\ \text{kV}\ (0.8)} = 20.92\ \text{A}\ \angle -36.87$$

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

$(\sqrt{3})V\cos\theta \quad (\sqrt{3})13.8\text{ kV }(0.8) \quad \angle -36.87$

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

$$I_3 = \frac{V_p}{Z} = \frac{7.97\text{ kV}}{2000\ \Omega\angle 45^\circ} = 3.985\text{ A}\angle -45^\circ$$

We will need P and Q later so

$P_p = I^2R = (3.985)^2(1.414\text{k }\Omega) = 22.4\text{ kW}$

$P_{3P} = 3xP_p = 67.2\text{ kW}$

By inspection we see that since the absolute values of R and X are equal

$Q_{3P} = 67.2\text{ kVAR}$

$P_T = P_{M1} + P_{L\#1} + P_{M2} + P_{M3}$

$= (400 + 67.2 + 300 + 400)\text{kW} = 1167.2 \text{ kW}$

$Q_T = Q_{M1} + Q_{L\#1} + Q_{M2} + Q_{M3}$

$= (-300 - 67.2 - 300 - 247.9) \text{ kVAR} = -915.1 \text{ kVAR}$

now $S = P + Q$ so

$S_T = 1167.2 - j915.1 = 1483.16 \text{ kVA}\angle -38.1°$

$PF = \cos\theta = P/S = 0.7870$

and from the three-phase power equation $P = (\sqrt{3})VI\cos\theta$

$= (-300 - 67.2 - 300 - 247.9)$ kVAR $= -915.1$ kVAR

now $S = P + Q$ so

$S_T = 1167.2 - j915.1 = 1483.16 \text{ kVA}\angle -38.1°$

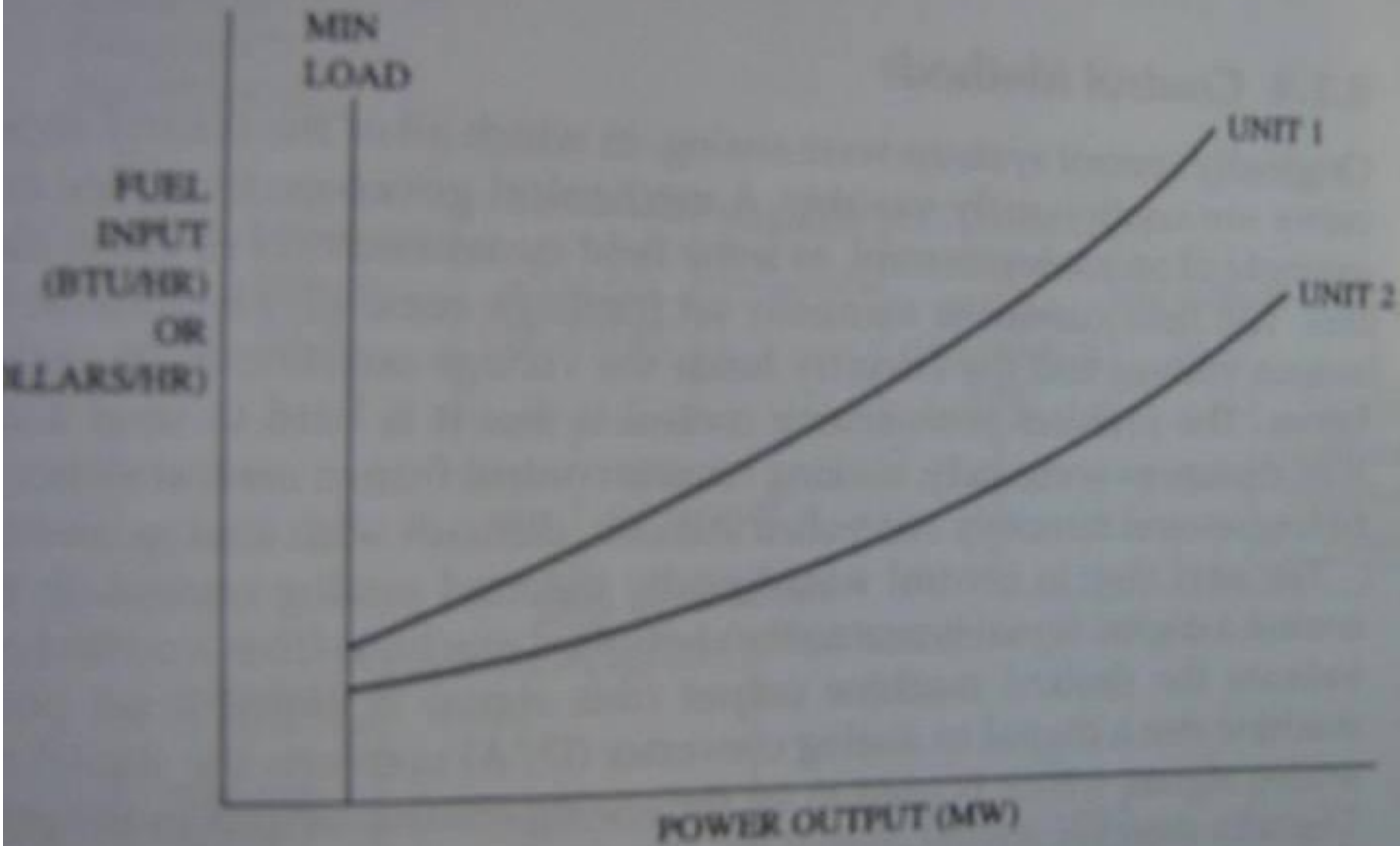
$PF = \cos\theta = P/S = 0.7870$

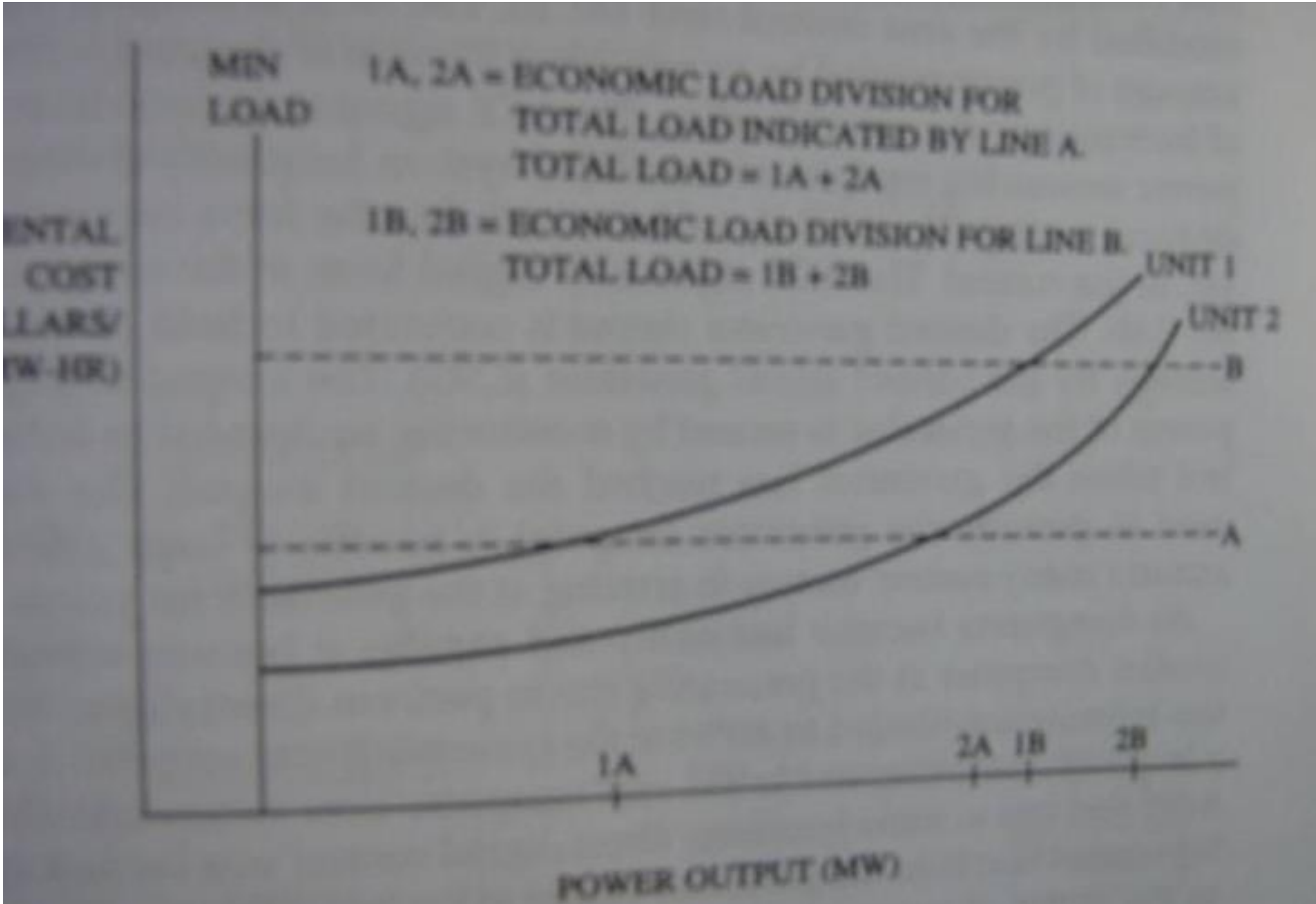
and from the three-phase power equation $P = (\sqrt{3})VI\cos\theta$

$$I_1 = \frac{P}{(\sqrt{3})V\cos\theta} = \frac{1167.2 \text{ kW}}{(\sqrt{3})\ 115 \text{ kV}\ (0.787)} = 7.45 \text{ A}\angle 21.5°$$

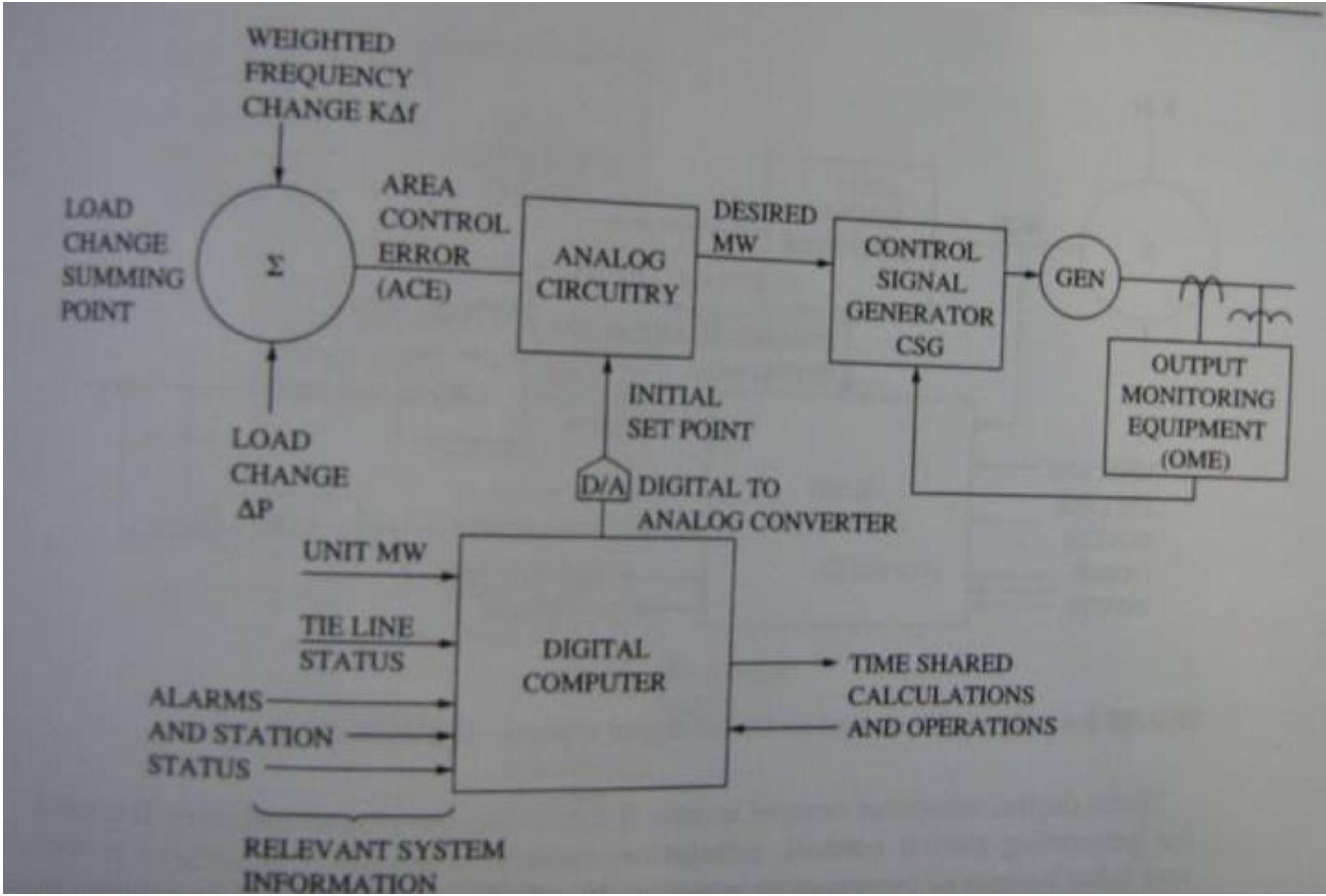
8.1.3 Economic Generation Allocation

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 2
POWER OUTPUT (MW)



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 2
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

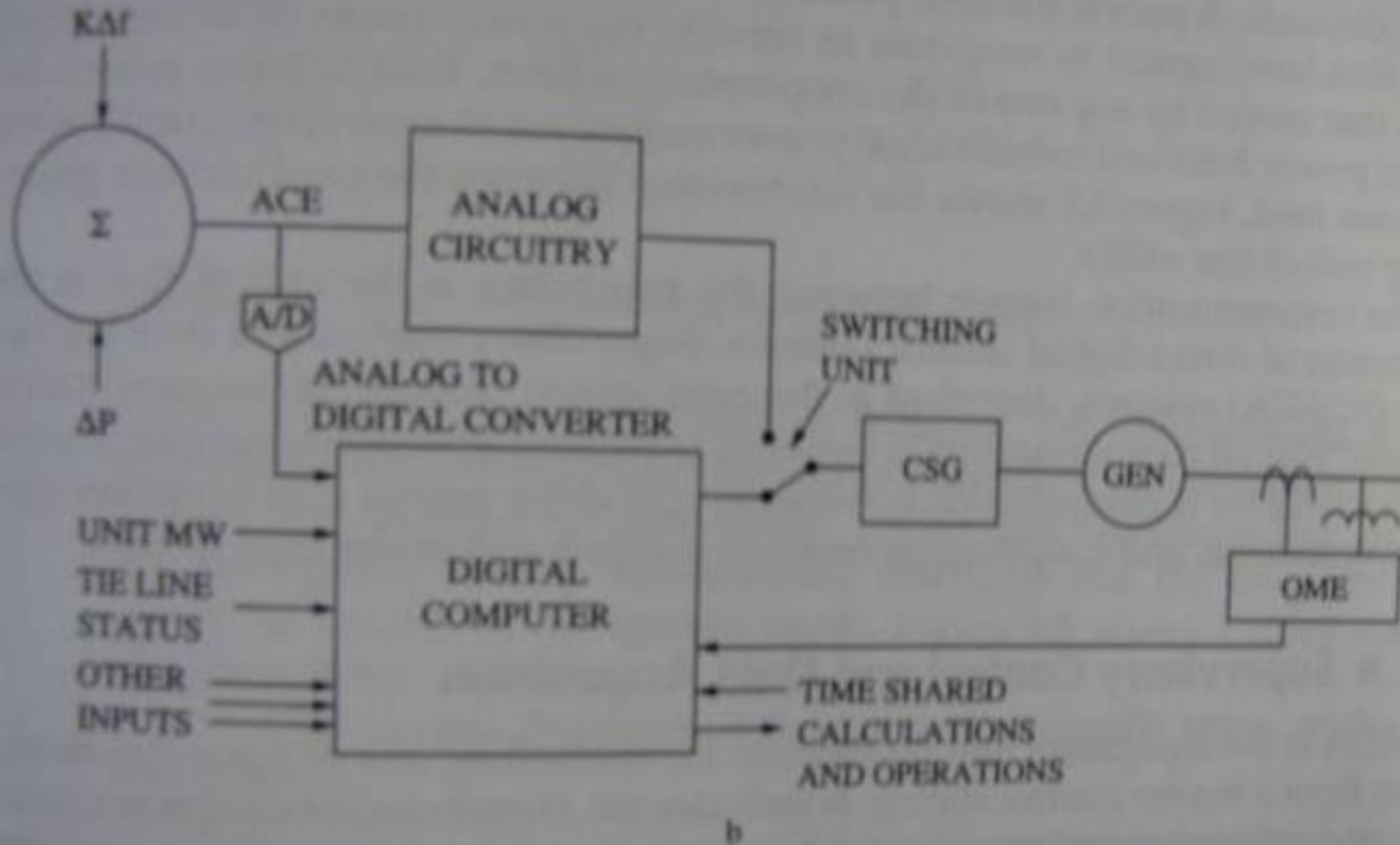


FIGURE 8.4 Generator control (a) Digitally-directed analog control (b) Direct digital control—analog backup

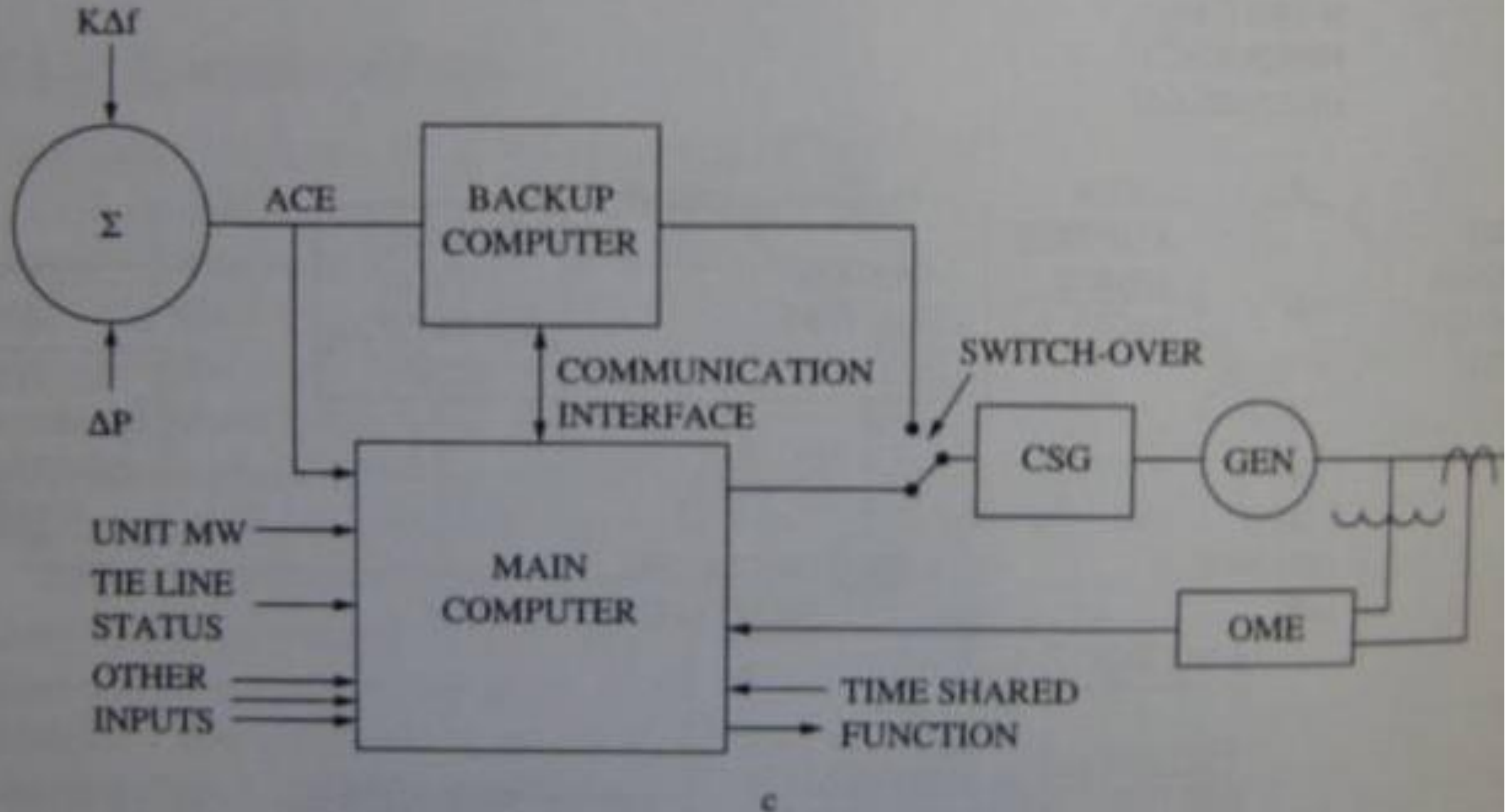
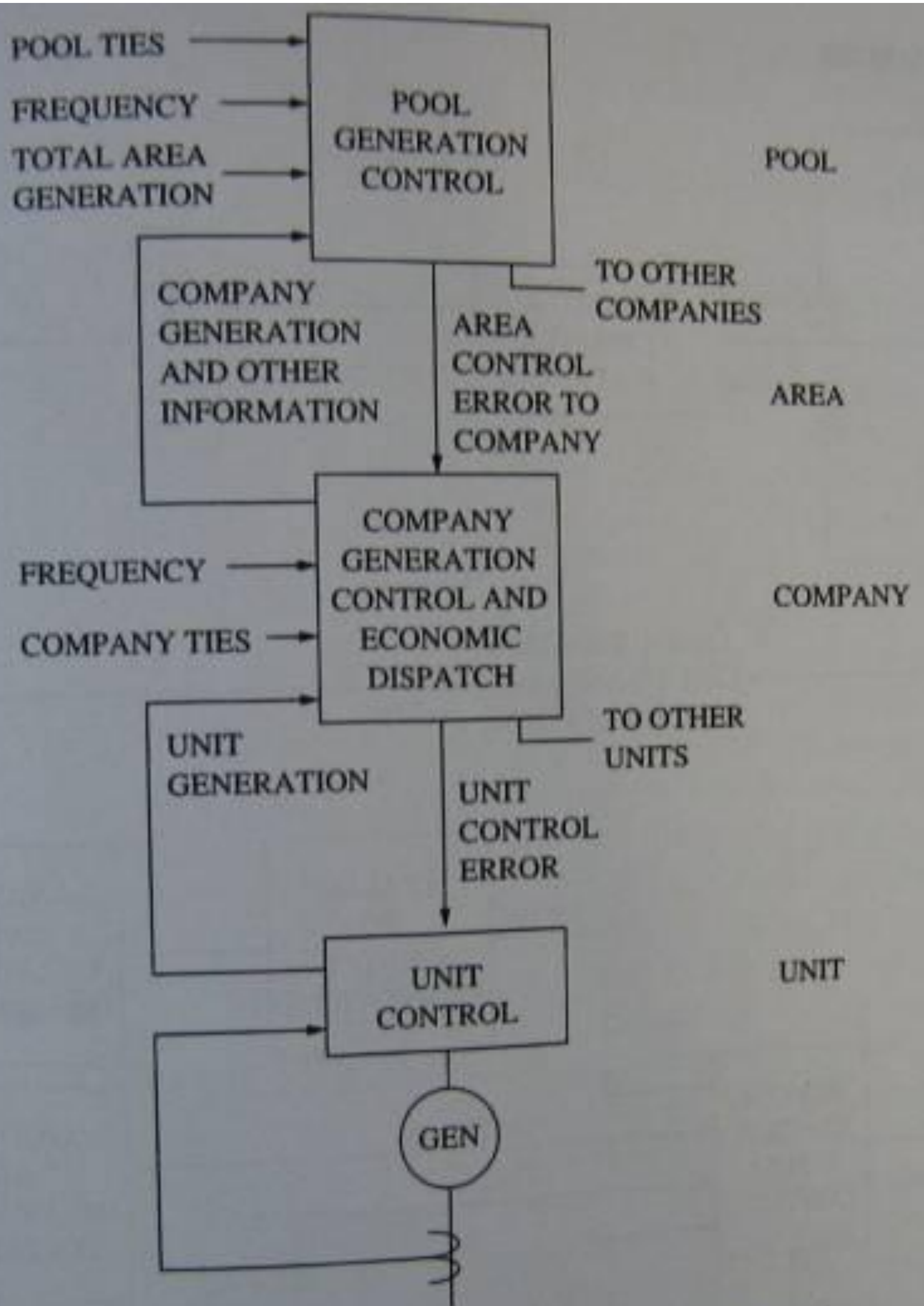


FIGURE 8.4 Generator control (c) Direct digital control—digital backup

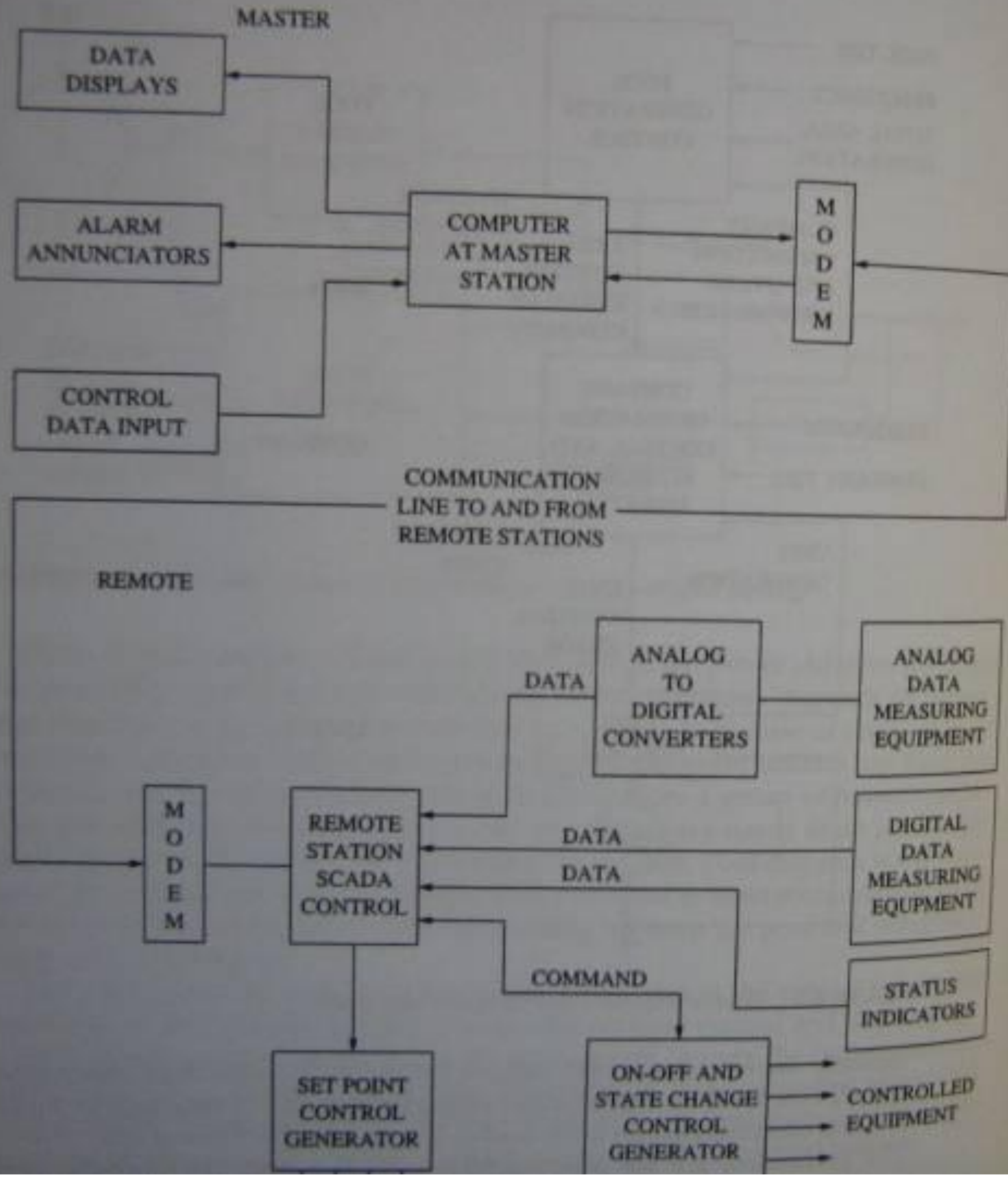


...pany and pool

remotely activate equipment such as breakers. The communications equipment includes the MODEMs (modulator-demodulator) for transmitting the digital data, and the communications links (radio, phone line, microwave link, or wire line). The procedures are the man-machine interfaces and the programs needed to match the control to the system needs. Figure 8.6 shows a block diagram of a SCADA system.

A SCADA system performs at least one, but usually more, of the following functions:

1. Alarm sensing for such things as fire or the performance of a non-commanded function.
2. Control and indication of the position of a two or three position device such 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.


MASTER
DATA DISPLAYS
ALARM ANNUNCIATORS
CONTROL DATA INPUT
COMPUTER AT MASTER STATION
MODEM
COMMUNICATION LINE TO AND FROM REMOTE STATIONS
REMOTE
ANALOG TO DIGITAL CONVERTERS
ANALOG DATA MEASURING EQUIPMENT
DATA
MODEM
REMOTE STATION SCADA CONTROL
DATA
DIGITAL DATA MEASURING EQUPMENT
DATA
COMMAND
STATUS INDICATORS
SET POINT CONTROL GENERATOR
ON-OFF AND STATE CHANGE CONTROL GENERATOR
CONTROLLED EQUIPMENT

8.2.2 Power Flow Division

If two parallel transmission lines are used to transfer power the lowest impeda line transfers the most power, all other factors being equal. Recall from ac circu 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

$$\text{path 1 power flow} = \frac{\text{(path 2 impedance)}}{\text{(total impedance)}} \text{total power flow} \qquad (8.1$$

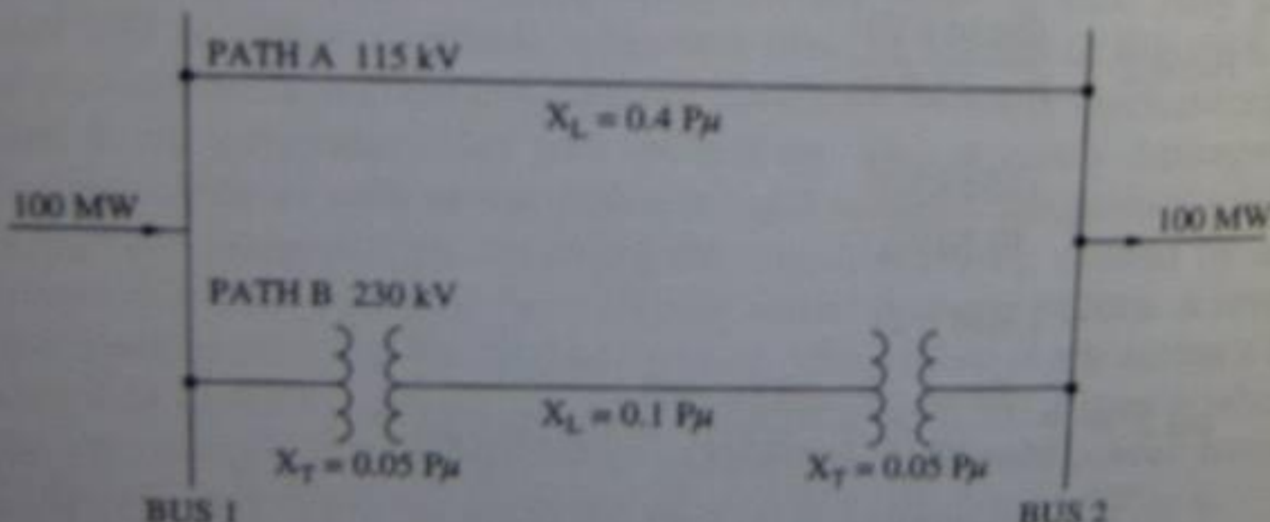
Multiplying both sides by base voltage we obtain

$$\text{path 1 power flow} = \frac{\text{(path 2 impedance)}}{\text{(total impedance)}} \text{ total power flow} \tag{8.12}$$

Similarly more apparent power flows in the lower impedance line. If the lines are not at the same voltage the line with the lower pu impedance transmits more power. The following example demonstrates this.

Example 8.2:

Calculate the power flow for each path of Figure 8.11. All pu impedances are 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.

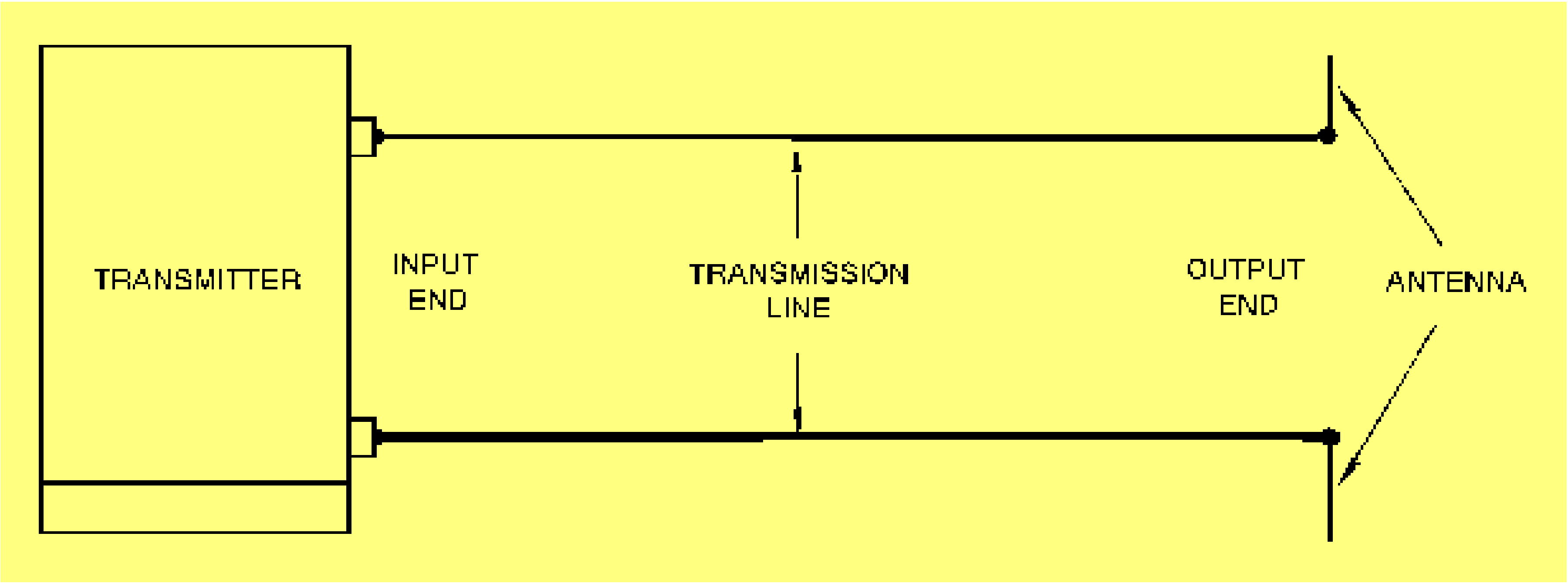
INTRODUCTION TO TRANSMISSION LINES

A TRANSMISSION LINE is a device designed to guide electrical energy from one point to another. It is used, for example, to transfer the output rf energy of a transmitter to an antenna. This energy will not travel through normal electrical wire without great losses. Although the antenna can be connected directly to the transmitter, the antenna is usually located some distance away from the transmitter. On board ship, the transmitter is located inside a radio room and its associated antenna is mounted on a mast. A transmission line is used to connect the transmitter and the antenna.

Definition

A **transmission line is the conductive connection between system elements that carry signal power**

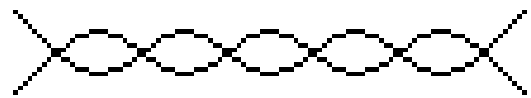
This “conductor” may at first appear to be a short circuit, but in fact will react differently when high frequencies are propagated along the line.


TRANSMITTER
INPUT END
TRANSMISSION LINE
OUTPUT END
ANTENNA

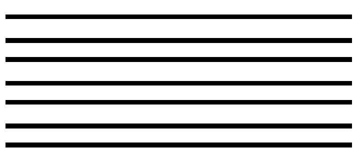
Form of transmission line

A transmission line is a pair a conducting wires held apart by an insulator or **dielectric. They come in a variety of construction geometries. The simplest and least expensive form is two-wire (ribbon) cable. Twisted pair cable consists of two wires sheathed in an insulator and twisted together. Shielded pair cable contains two wires surrounded and separated by a solid dielectric. The dielectric is contained within a copper braid, that shields the conductors from external noise sources. The entire construction is housed in a flexible, waterproof cover.**

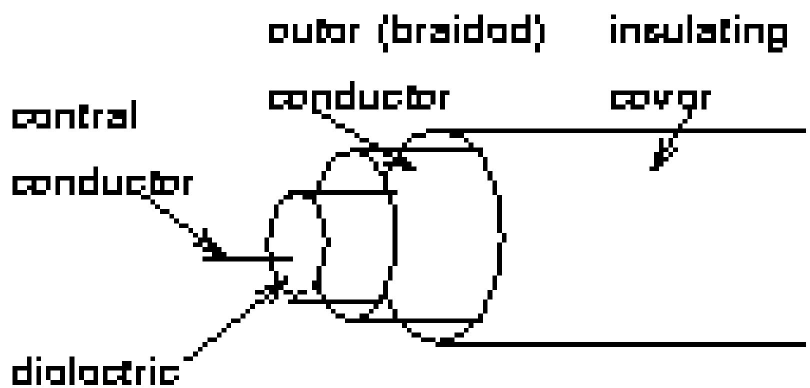
single pair



twisted pair



ribon cable



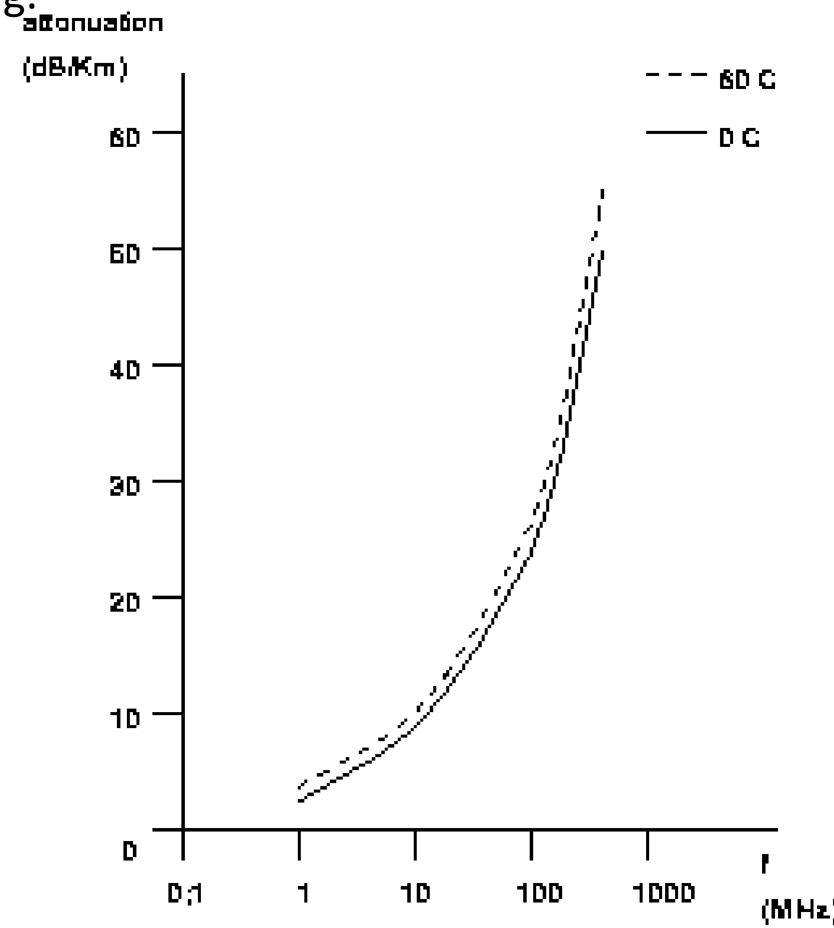
co axial cable

When a transmission line can act as an antenna, it can also act as a receiver. Lines prone to radiation loss are also susceptable to **pick-up**, or **cross-talk**. The first two types described above are particularly prone to this fault. The shielded pair is designed to reduce this pick-up.

All these lines have strong attenuation at frequencies above 1MHz. They are generally used for for low bit-rate communication. Two-wire ribbon cable is standard for the connection of individual telephone receivers. Twisted pair(s) is the normal method of connection for computer terminals and short high bit-rate connections.

Attenuation increases with both frequency and length. It is usually specified in dB/m at a particular frequency. Because of this fact, it is not possible to give hard-and-fast rules concerning the bandwidth availability of transmission lines. A twisted pair can support rates of several Mb/s over short distances (metres), but over long distances (kilometres) will be completely unsuitable at these data-rates.

For long distances, or data-rates in excess of several Mb/s, **coaxial cable** is used. Coaxial cable has a central wire, surrounded by a dielectric, in turn concentrically sheathed in a braided conductor. The cable is finally surrounded in a water-proof, flexible sheath. Coaxial cable is familiar to you -- it is the cable used to connect your television ariel. The supreme advantage of this method of construction is its resistance to radiation losses. The outer conductor acts to shield out any external fields, whist preventing any internal fields escaping.



In electric power transmission, the characteristic impedance of a transmission line is expressed in terms of the **surge impedance loading (SIL), or natural loading, being the MW loading at which reactive power is neither produced nor absorbed:**
in which *VL − L is the line-to-line voltage in volts.*

The surge impedance loading or SIL of a transmission line is the MW loading of a transmission line at which a natural reactive power balance occurs. The following brief article will explain the concept of SIL.

Transmission lines produce reactive power (Mvar) due to their natural capacitance. The amount of Mvar produced is dependent on the transmission line's capacitive reactance (XC) and the voltage (kV) at which the line is energized. In equation form the Mvar produced is:

$$\text{Mvar Produced} = \frac{kV^2}{X_C}$$

Transmission lines also utilize reactive power to support their magnetic fields. The magnetic field strength is dependent on the magnitude of the current flow in the line and the line's natural inductive reactance (X_L).

It follows then that the amount of Mvar used by a transmission line is a function of the current flow and inductive reactance. In equation form the Mvar used by a transmission line is:

$$\text{Mvar Used} = I^2 X_L$$

A transmission line's surge impedance loading or SIL is simply the MW loading (at a unity power factor) at which the line's Mvar usage is equal to the line's Mvar production. In equation form we can state that the SIL occurs when:

$$I^2 X_L = \frac{V^2}{X_C} \text{ or when:}$$

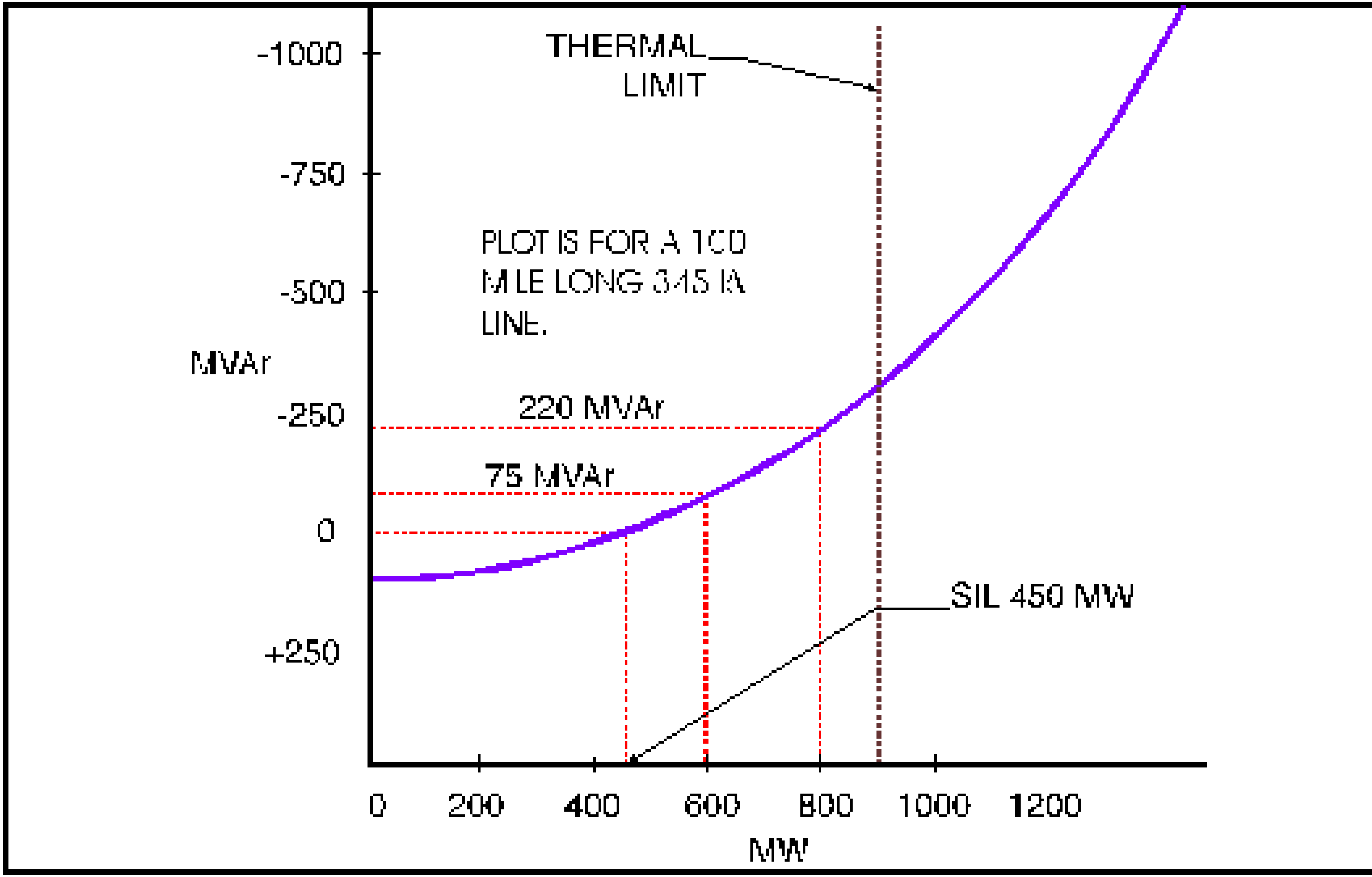
$$X_L X_C = \frac{V^2}{I^2}$$

If we take the square root of both sides of the above equation and then substitute in the formulas for X_L ($=2\pi fL$) and X_C ($=1/2\pi fC$) we arrive at:

$$I^2 X_L = \frac{V^2}{X_C} \text{ or when:}$$

$$X_L X_C = \frac{V^2}{I^2}$$

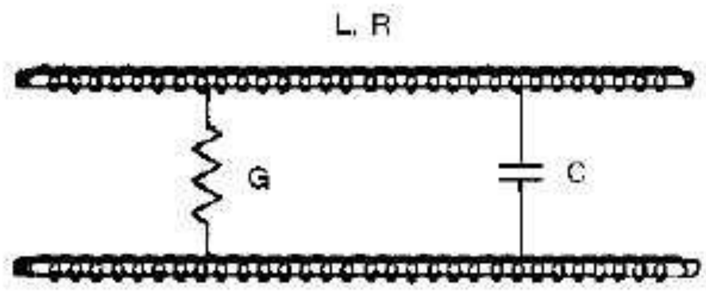
$$\text{SIL (in MW)} = \frac{kV^2_{L-L}}{\text{Surge Impedance}}$$



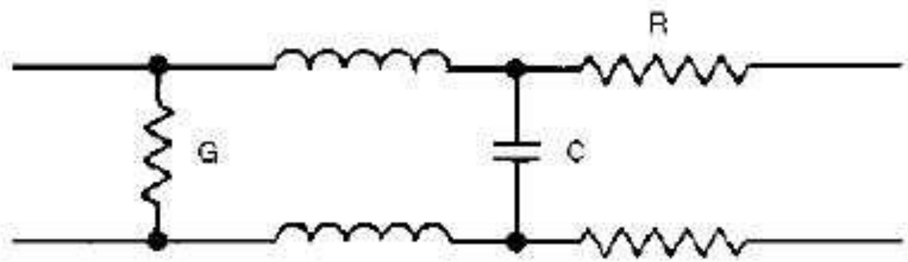
-1000
-750
-500
-250
0
+250
MVAr
THERMAL LIMIT
PLOT IS FOR A 100 MILE LONG 345 kV LINE.
220 MVAr
75 MVAr
SIL 450 MW
0
200
400
600
800
1000
1200
MW

Loaded below its SIL, a line supplies lagging reactive power to the system, tending to raise system voltages. Above it, the line absorbs reactive power, tending to depress the voltage. The Ferranti effect describes the voltage gain towards the remote end of a very lightly loaded (or open ended) transmission line.

Underground cables normally have a very low characteristic impedance, resulting in an SIL that is typically in excess of the thermal limit of the cable. Hence a cable is almost always a source of lagging reactive power.



A. SHORT SECTION OF TWO - WIRE LINE



B. EQUIVALENT CIRCUIT

$$\lambda = \frac{v}{f}$$

Where,

λ = Wavelength

v = Velocity of propagation

f = Frequency of signal

The lower-case Greek letter "lambda" (λ) represents wavelength, in whatever unit of length used in the velocity figure (if miles per second, then wavelength in miles; if meters per second, then wavelength in meters). Velocity of propagation is usually the speed of light when calculating signal wavelength in open air or in a vacuum, but will be less if the transmission line has a velocity factor less than 1.

· Coaxial cabling is sometimes used in DC and low-frequency AC circuits as well as in high-frequency circuits, for the excellent immunity to induced "noise" that it provides for signals.

· When the period of a transmitted voltage or current signal greatly exceeds the propagation time for a transmission line, the line is considered *electrically short*. Conversely, when the propagation time is a large fraction or multiple of the signal's period, the line is considered *electrically long*.

· A signal's *wavelength* is the physical distance it will propagate in the timespan of one period. Wavelength is calculated by the formula $\lambda=v/f$, where "λ" is the wavelength, "v" is the propagation velocity, and "f" is the signal frequency.

· A rule-of-thumb for transmission line "shortness" is that the line must be at least 1/4 wavelength before it is considered "long."

Propagation constant

For an electromagnetic field mode varying sinusoidally with time at a given frequency, the **propagation constant** is the logarithmic rate of change, with respect to distance in a given direction, of the complex amplitude of any field component.

The propagation constant, γ, is a complex quantity given by

$V_1/V_2 = I_1/I_2 = e^{\gamma}$

where γ is a complex number and is defined as

$\gamma = \alpha + i\,\beta$

where

α, the real part, is the attenuation constant

β, the imaginary part, is the phase constant

$(I_1 / -I_2) \times (-I_2 / -I_3) \times \ldots\ldots \times (-I_{n-1} / -I_n) = (I_1 / -I_n)$

$\Rightarrow e^{\gamma_1} \times e^{\gamma_2} \times \ldots \times = e^{\gamma}$

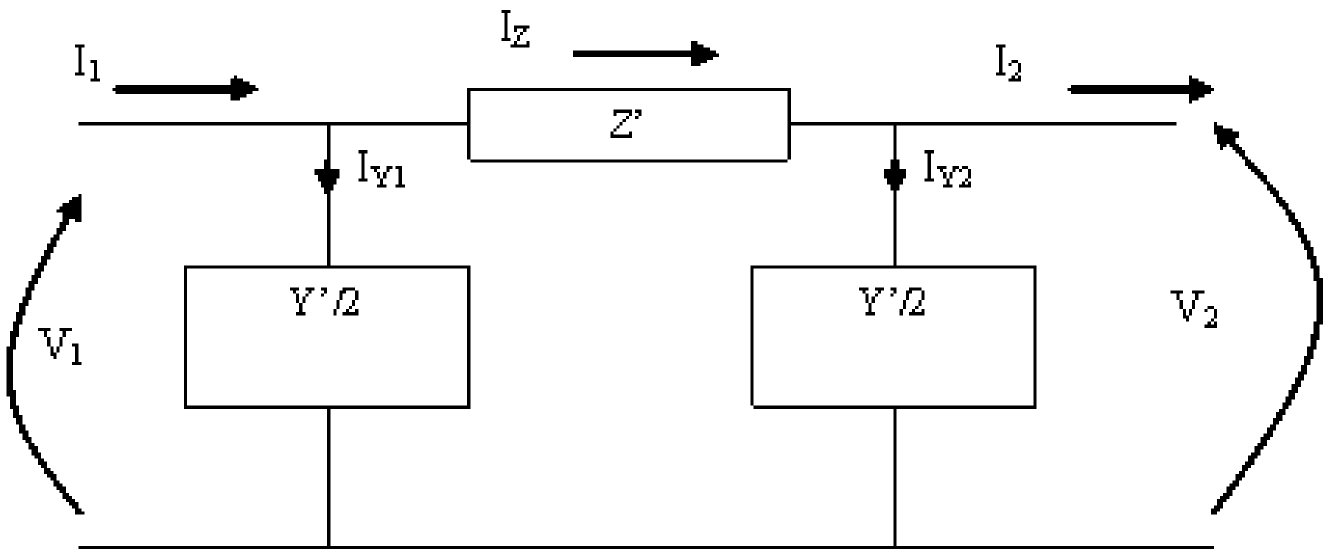
The over all propagation constant $\gamma = \gamma_1 + \gamma_2 + \ldots. + \gamma_n$

2.0 Simplified models (Section 4.5)

We recall two things. First, we have the so-called "exact" transmission line equations:

$$V_1 = V_2 \cosh \gamma l + Z_C I_2 \sinh \gamma l$$

$$I_1 = I_2 \cosh \gamma l + \frac{V_2}{Z_C} \sinh \gamma l$$



$$Z' = Z_C \sinh \gamma l = Z \frac{\sinh \gamma l}{\gamma l}$$

$$Y' = \frac{2}{Z_C} \tanh \frac{\gamma l}{2} = Y \frac{\tanh(\gamma l / 2)}{\gamma l / 2}$$

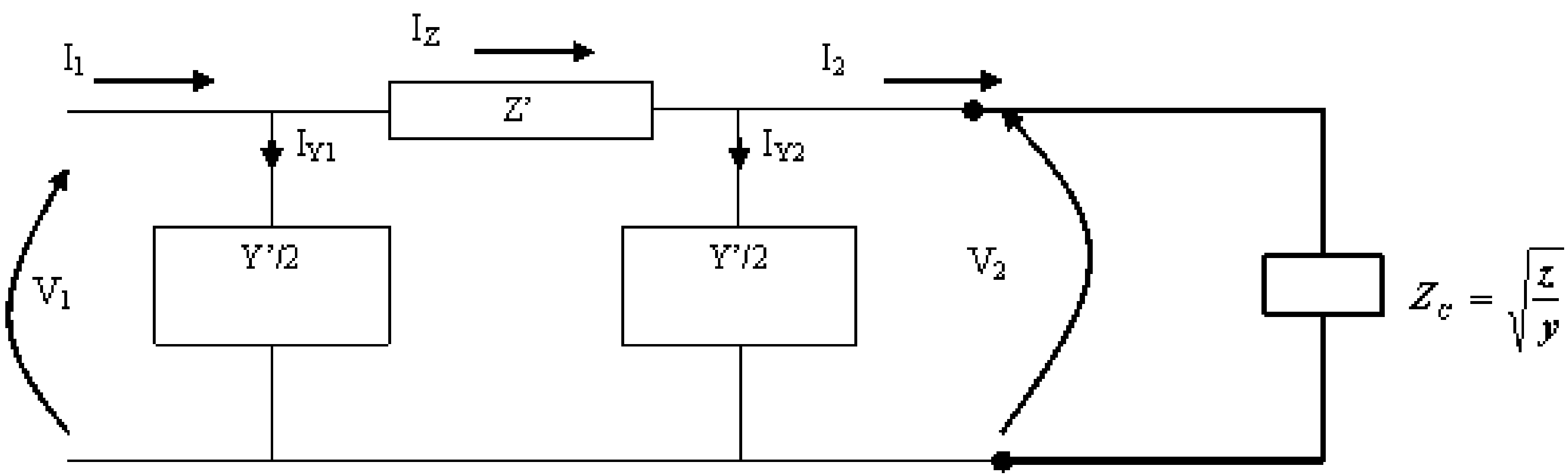
$$\sinh x = x + \frac{x^3}{3!} + \frac{x^5}{5!} + \frac{x^7}{7!} + \Lambda$$

$$\tanh x = x - \frac{x^3}{3} + \frac{2x^5}{15} - \frac{17x^7}{315} + \Lambda \qquad x^2 < \frac{\pi^2}{4}$$

Surge impedance loading

Recall our definition of characteristic impedance Z_C as:

$$Z_C = \sqrt{\frac{z}{y}}$$



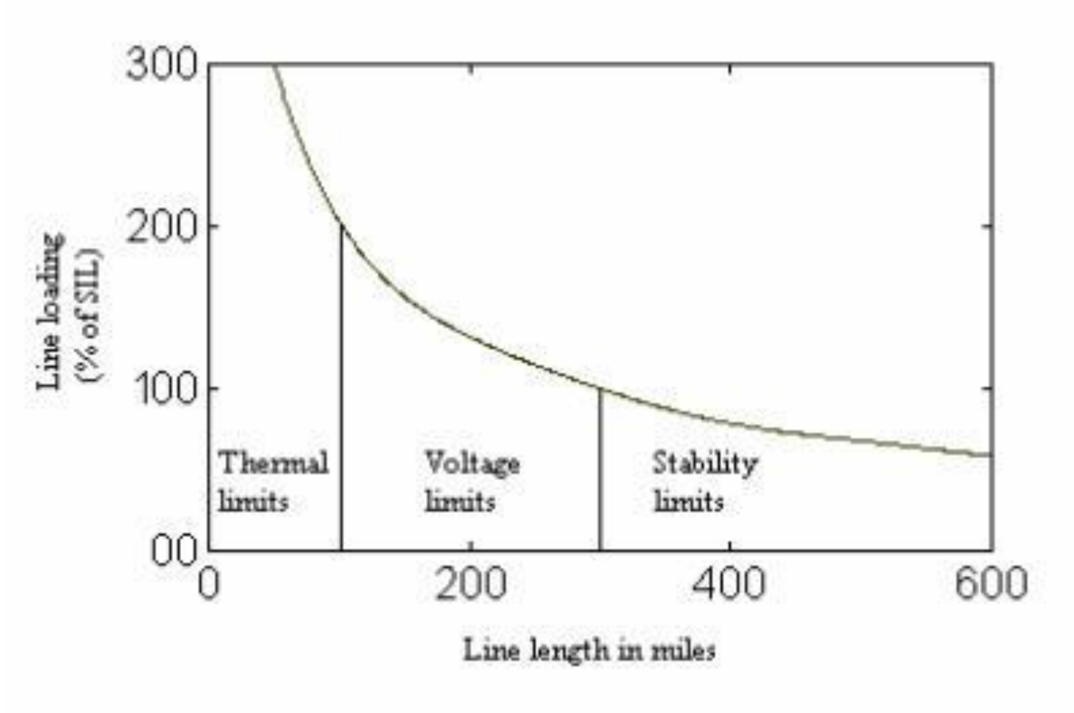
Whatever reactive power flows out of the line (and into the load) also flows into the line. So a line terminated in Z_C has a very special character with respect to reactive power: the amount of reactive power consumed by the series X is exactly compensated by the reactive power supplied by the shunt Y, for every inch of the line!

$$\frac{|V_2|}{|V_1|} = e^{-\alpha l} \qquad \frac{|V_2|}{|V_1|} = 1$$

$$Z_C = \sqrt{\frac{z}{y}} = \sqrt{\frac{j\omega l_{ind}}{j\omega c}} = \sqrt{\frac{l_{ind}}{c}} = \sqrt{\frac{l_{ind} l}{c l}} = \sqrt{\frac{L}{C}}$$

$$P_{12} = \frac{|V_2|^2}{Z_C} = \frac{|V_1|^2}{Z_C} \qquad P_{SIL} = \frac{|V_1|^2}{Z_C}$$

V_{rated} (kV)	(ohms)	(MW)
69	366-400	12-13
115	380*	35
138	366-405	47-52
161	380*	69
230	365-395	134-145
345	280-366	325-425
500	233-294	850-1075
765	254-266	2200-2300
1100	231	5238



These attributes are:

· Power limit decreases with line length

· Short lines are limited mainly by thermal problems.

· Medium length lines tend to be limited by voltage-related problems.

· Very long lines tend to be limited by stability problems.

Complex power expression

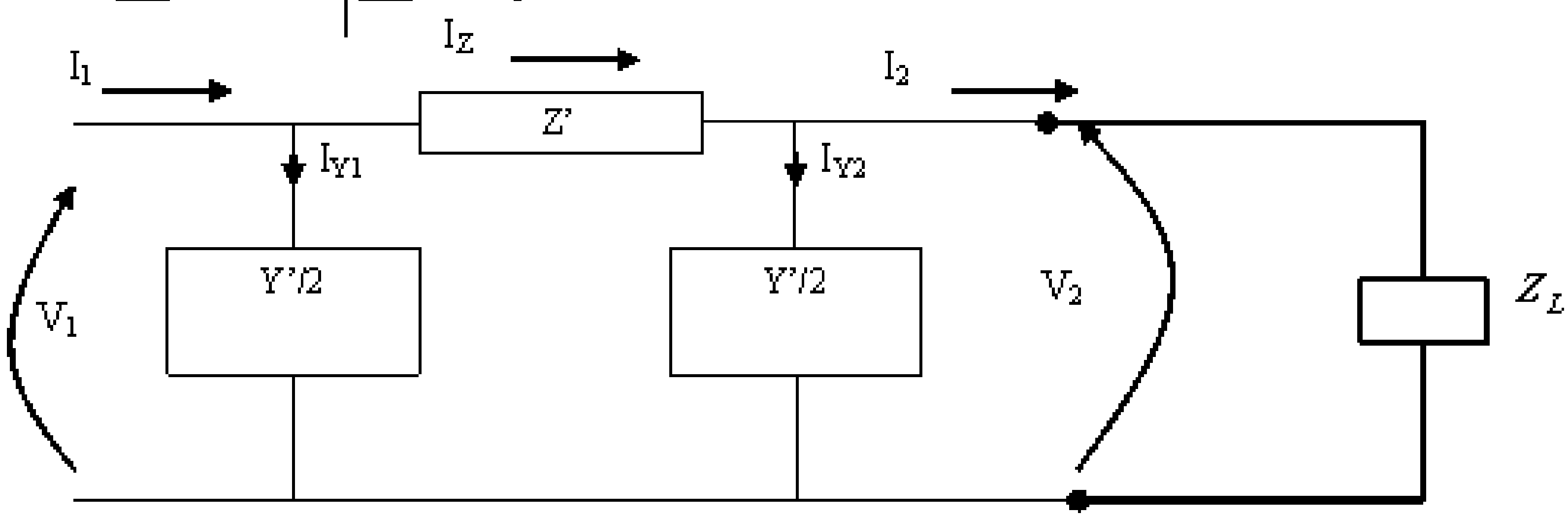
This material combines Sec. 4.6, 4.8, 4.9.

Consider the long transmission line of Fig. 4.

The voltages at the ends are specified as:

$$V_1 = |V_1| e^{j\theta_1} \qquad V_2 = |V_2| e^{j\theta_2}$$

$$Z' = |Z'| e^{j\angle Z'}$$



$$S_{12} = V_1 I_Z^* + |V_1|^2 (Y'/2)^*$$

$$I_Z = \frac{V_1 - V_2}{Z'}$$

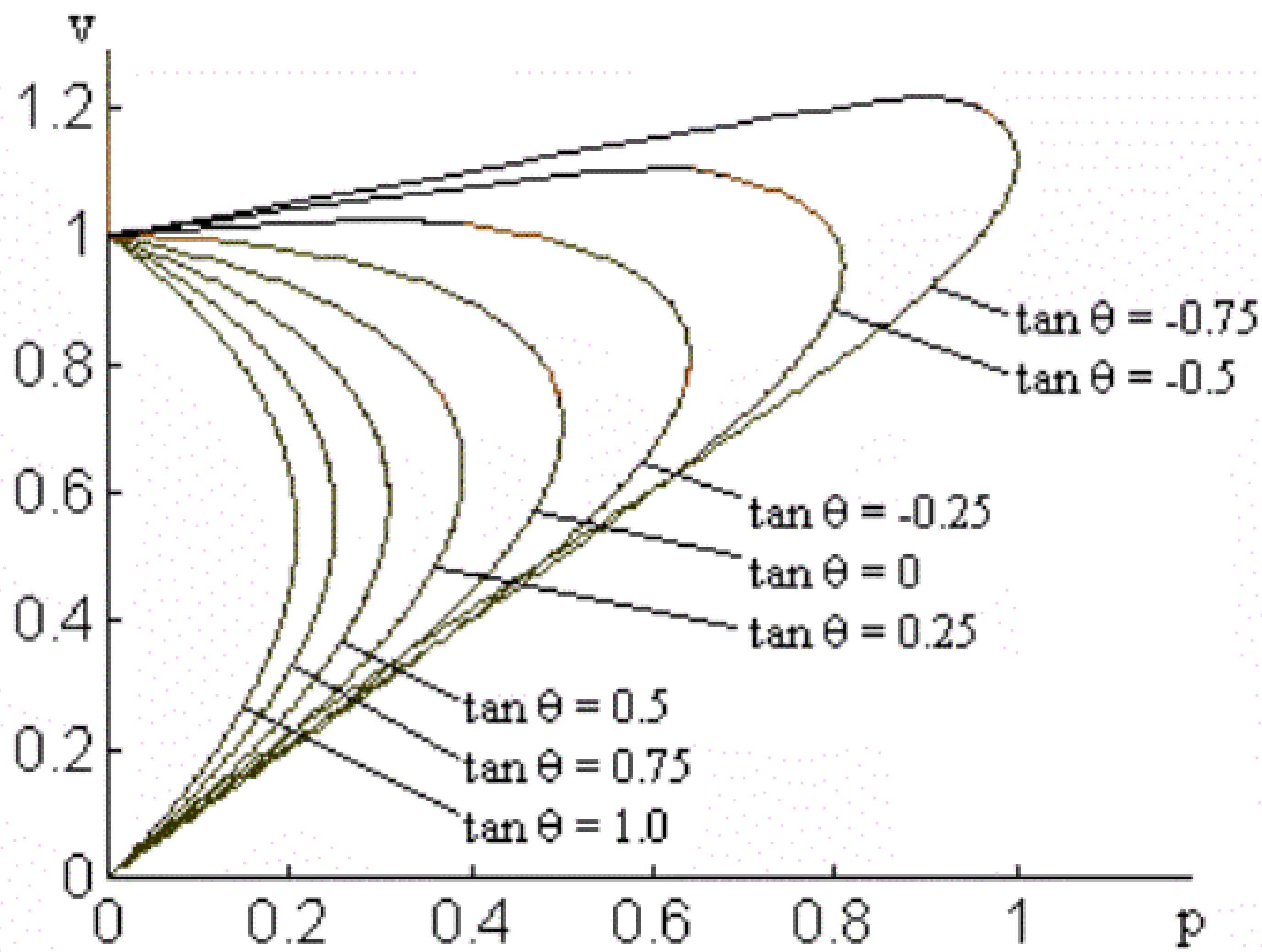
$$S_{12} = \frac{V_1 V_1^* - V_1 V_2^*}{Z'^*} + |V_1|^2 (Y'/2)^*$$

$$= \frac{|V_1|^2}{Z'^*} - \frac{|V_1||V_2| e^{j\theta_{12}}}{Z'^*} + |V_1|^2 (Y'/2)^*$$

Using $Z^*=|Z|e^{-j\angle Z}$, we get

$$S_{12}=\frac{|V_1|^2}{|Z|}e^{j\angle Z}-\frac{|V_1||V_2|}{|Z|}e^{j\angle Z}e^{j\theta_{12}}$$

$$S_{21}=\frac{|V_2|^2}{|Z|}e^{j\angle Z}-\frac{|V_1||V_2|}{|Z|}e^{j\angle Z}e^{-j\theta_{12}}$$



v
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
p
tan θ = -0.75
tan θ = -0.5
tan θ = -0.25
tan θ = 0
tan θ = 0.25
tan θ = 0.5
tan θ = 0.75
tan θ = 1.0

Unbalanced Lines

Unbalanced signal lines are characterized by the fact that the cable and connectors use only two conductors, a center conductor surrounded by a shield. Examples of unbalanced wiring are found in tip/sleeve ¼" guitar cords or the cables us ed with many CD players and tape decks which terminate with RCA phono type connectors.

Balanced Lines

Balanced lines are characterized by the fact that there are two center conductors for the signal, usually surrounded by a shield. This shield is connected to ground like unbalanced lines but it is not required as one of the signal conductors. In fact, some balanced cables like CAT-5 twisted pair data cables and analog telephone lines don't have a shield at all.

Properties of waves.
The complex amplitude of a wave may be defined in three ways. It can be a voltage amplitude, a current amplitude, or a normalised amplitude whose squared modulus equals the power conveyed by the wave. In each case we represent the wave amplitude by a complex phasor whose length is proportional to the size of the wave and whose phase angle tells us the relative phase with respect to the origin or zero of the time variable.

A complex number is an ordered pair of real numbers. These can be the magnitude ("size") and phase ("timing") or real and imaginary parts. Two numbers are needed in general to specify an alternating voltage or quantity unambiguously, assuming the frequency is already known.

Waves travelling from generator to load have complex amplitudes usually written V+ (voltage) I+ (current) or a (normalised power amplitude).

Waves travelling from load to generator have complex amplitudes usually written V- (voltage) I- (current) or b (normalised power amplitude).

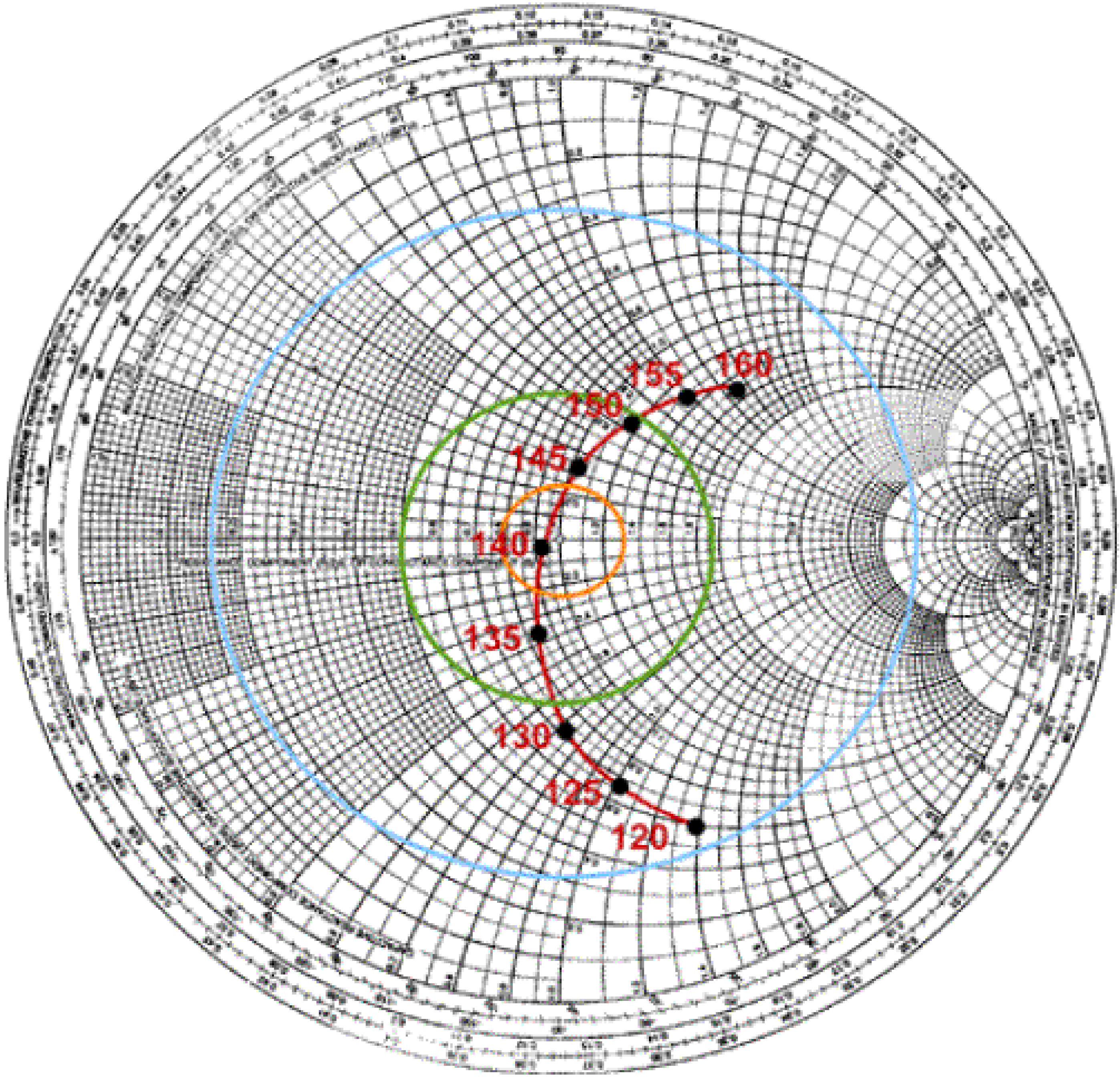
Wave amplitudes and power flow.
The forward wave complex voltage amplitude is described by the complex algebraic term V+. The modulus, or size, of this amplitude is written |V+|.

For sinusoidal signals, the rms voltage in the forward wave is |V+| (1/sqrt[2]). It conveys power in the positive x direction, and the power flow is |V+||V+|/2Zo watts.

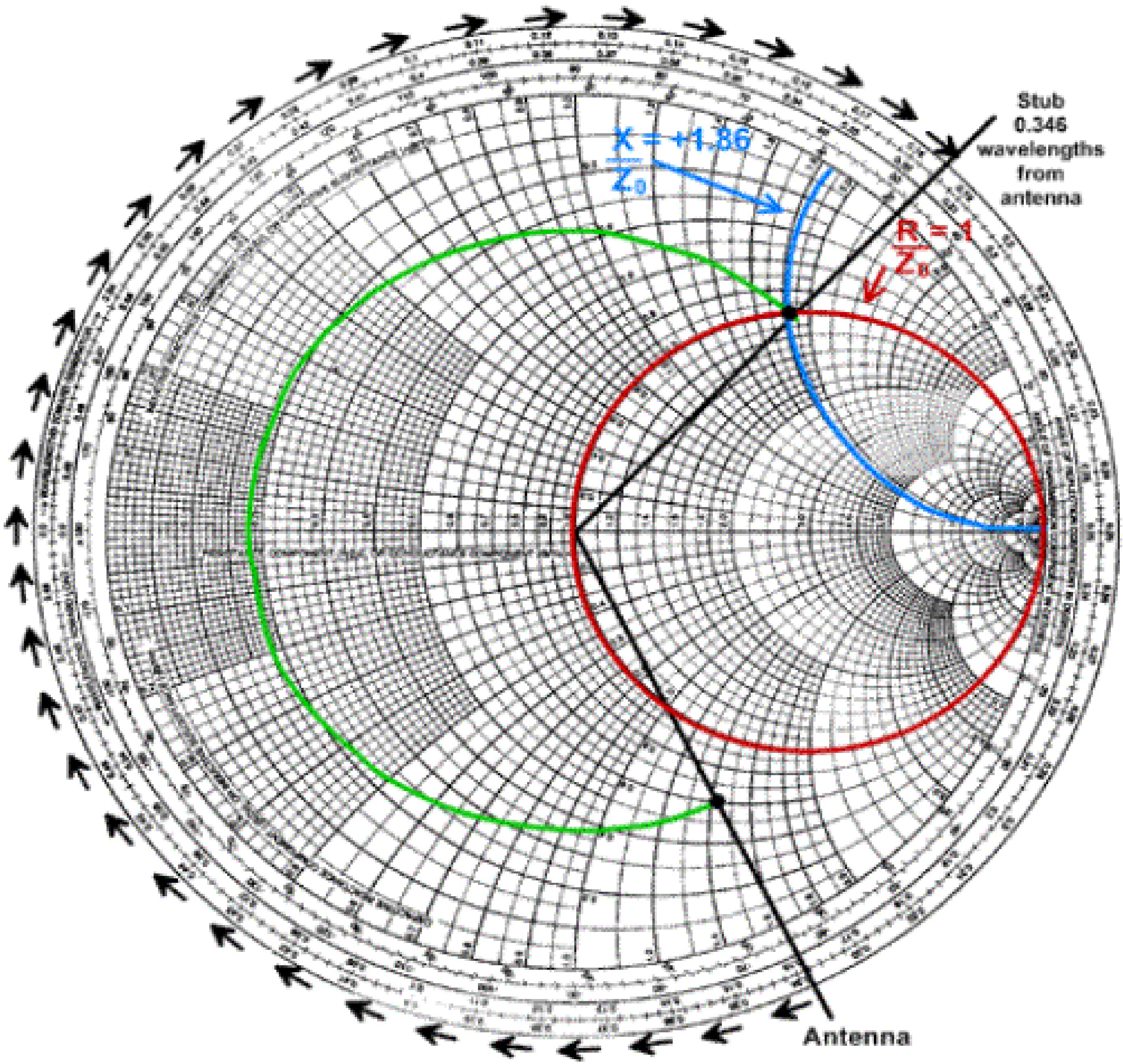
Short or open stubs?

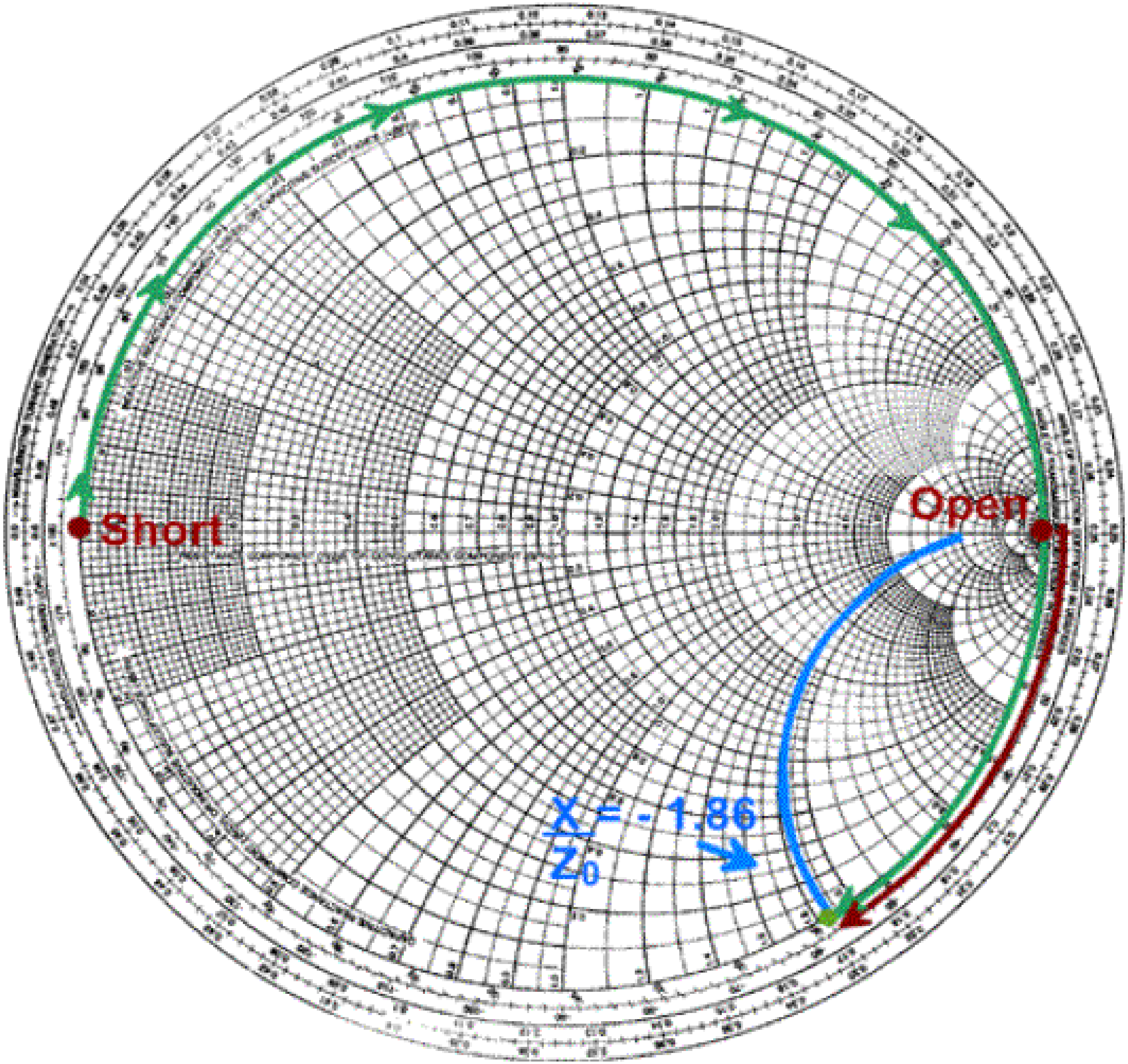
If one is allowed to use either short or open stubs at will, one can always keep the total stub length in the range 0-0.25 wavelengths. A length of transmission line of 0.25 wavelengths takes us half way round the SMITH chart and transforms an open into a short, or vice versa. On

Smith Chart

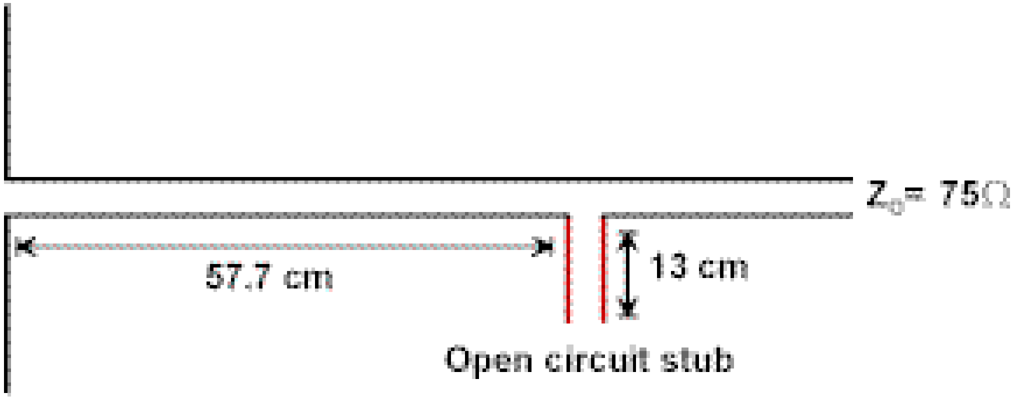


Smith Chart




Short
Open
X / Z0 = - 1.86

The practical details of the series stub match are shown below, where we display the physical lengths in centimetres, assuming a wave velocity on the coax (which we need to know to do this calculation) of 2x10^8 metres per second. This data is supplied by the cable manufacturer. The wave velocity and the frequency (120 MHz) allows us to calculate the wavelength in metres, and thus we can translate the "electrical lengths" from the SMITH chart into physical lengths of line.

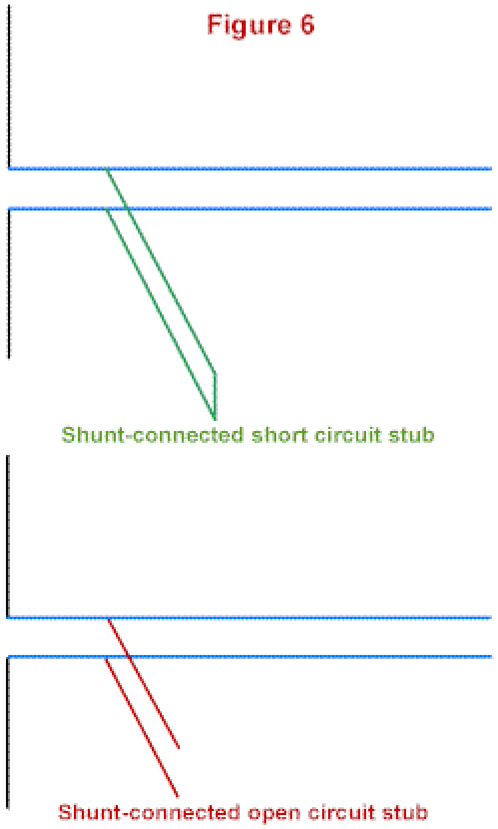


Actual dimensions.
Suppose that the 75 ohm cable has a velocity factor 2/3 or 0.67
The wave velocity is 2E8 metres per second
The wavelength at 120 MHz is 167 cms
The stub position is 0.346 lambda (57.7 cm) from the load (antenna)
The length of the required shorted stub is 0.328 lambda = 54.7 cm

or we could use an open circuit stub....
The length of the required open stub is (0.328-0.250)lambda = 13.0 cm

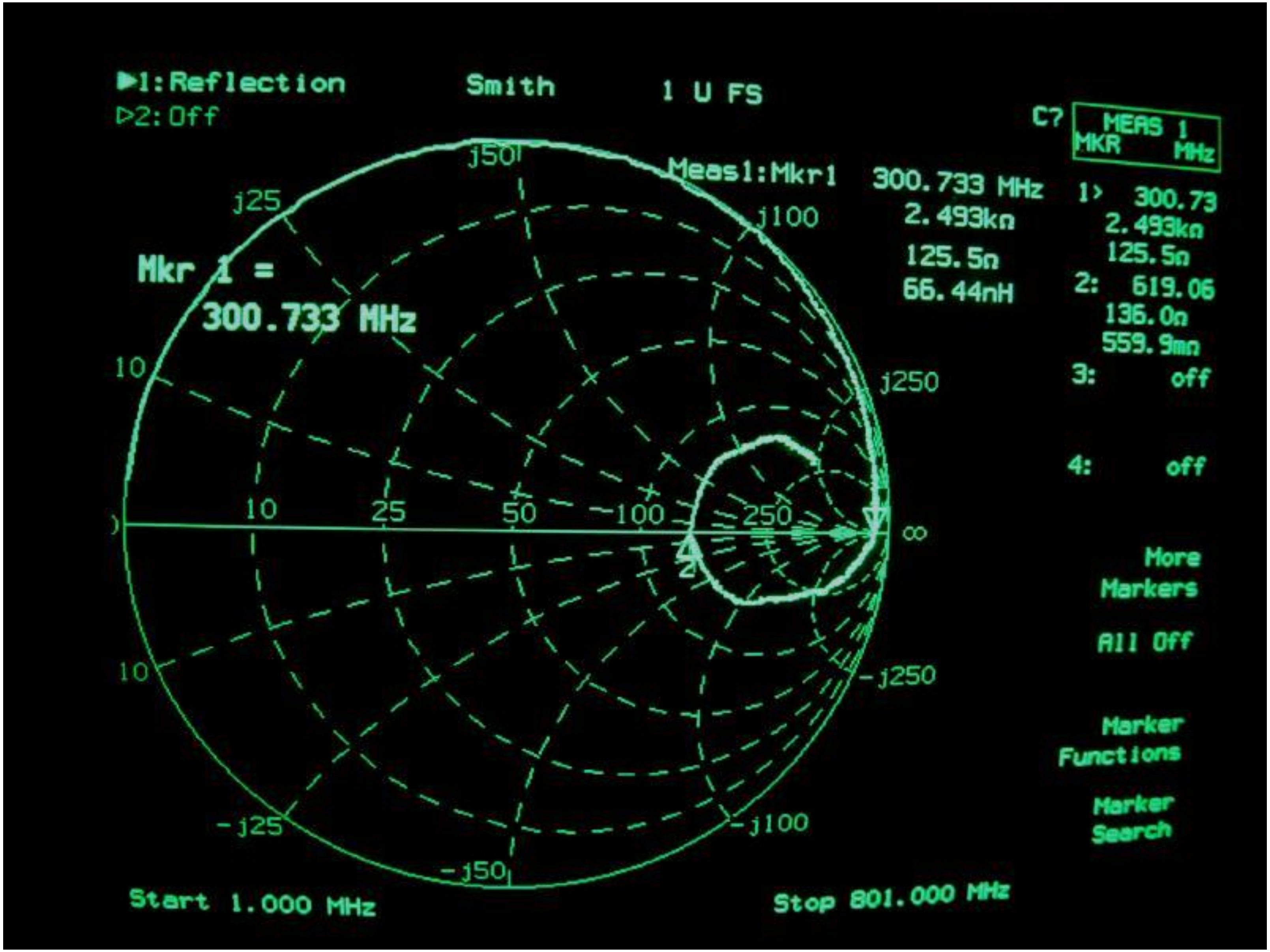
The stub illustrated above is called a "series stub". In parallel wire line, it is connected in series with one of the wires of the feed, as shown in figures 4 and 5. More usual (in coax, at least) is to use a "shunt stub", which is connected across the two wires of the feed, as shown in figure 6. Since admittances in parallel add, whereas impedances in series add, we represent the transmission line impedance as an admittance y = g + js at the point of attachment, and we look for the g=1 circle. This is 180 degrees (a quarter-wavelength) around the SMITH chart from the r=1 impedance circle. Therefore, the points of attachment of shunt stubs are a quarter wavelength along the transmission line, either side of the points of attachment of a series stub. The stub line length needs to be different also as we need to compensate the parallel js with an equal and opposite shunt susceptance -js, and the value of susceptance s is different from the value of reactance x in the series-match example.

Figure 6



$$\text{gamma} = \frac{z - 1}{z + 1} = \frac{(r-1) + jx}{(r+1) + jx}$$


▶1:Reflection
▷2:Off
Smith
1 U FS
C?
More Cal
Meas1:Mkr2
546.800 MHz
72.25Ω
-752.3mΩ
386.9pF
Refl Port Extension =
71.279 ps
(14.103 mm)
Velocity Factor
Smith Chart Z0
Cal Kit
Port Ext's ON off
Refl Port Extension
Trans Port Extension
Prior Menu
j50
j25
j100
j250
10
25
50
100
250
∞
-j250
-j25
-j100
-j50
Start 1.000 MHz
Stop 801.000 MHz

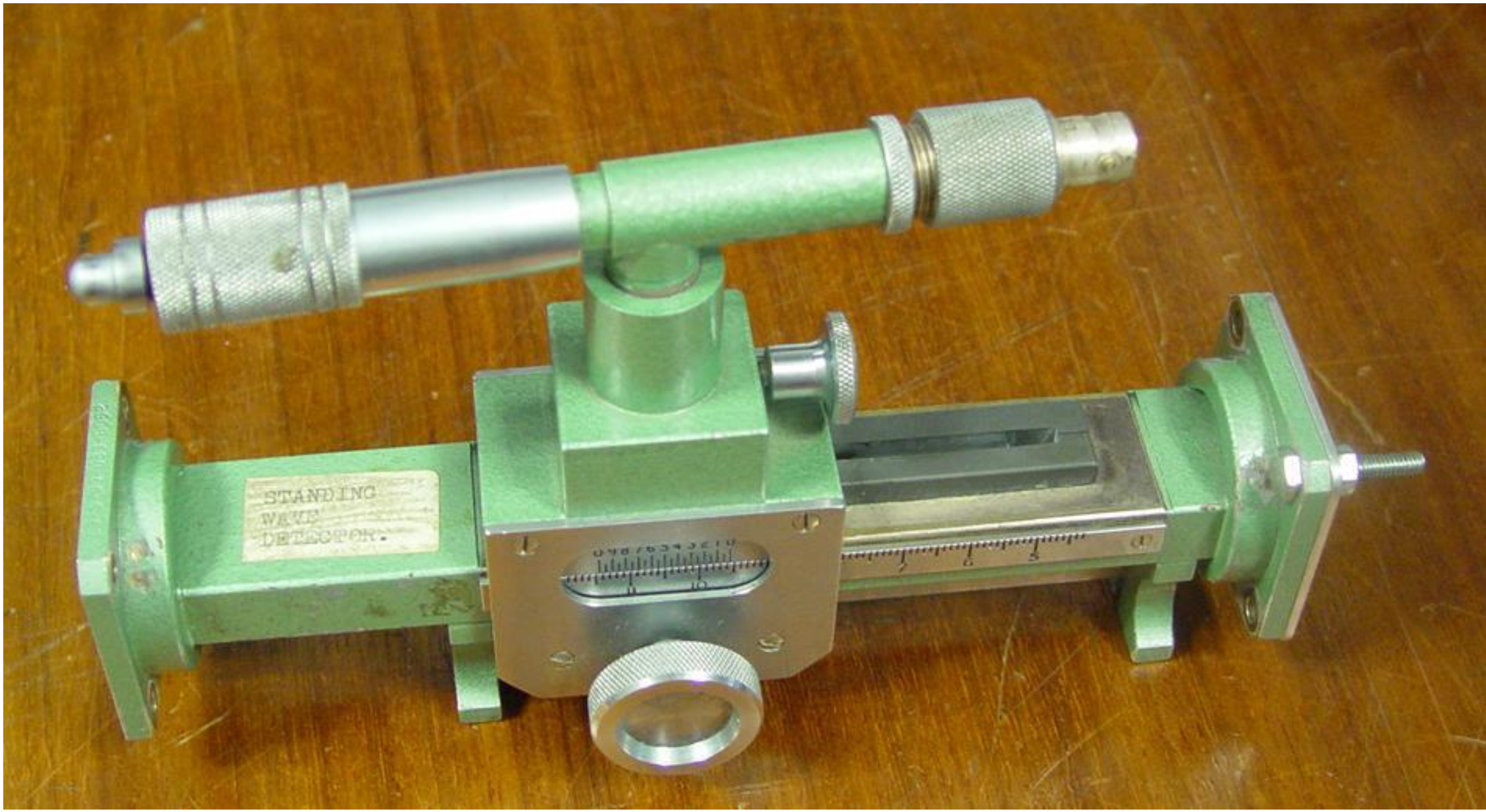

▶1:Reflection
▷2:Off
Smith
1 U FS
C?
MEAS 1
MKR MHz
Meas1:Mkr1
300.733 MHz
2.493kΩ
125.5Ω
66.44nH
1› 300.73
2.493kΩ
125.5Ω
2: 619.06
136.0Ω
559.9mΩ
3: off
4: off
More
Markers
All Off
Marker
Functions
Marker
Search
Mkr 1 =
300.733 MHz
j50
j25
j100
j250
10
10
25
50
100
250
∞
10
-j250
-j25
-j100
-j50
Start 1.000 MHz
Stop 801.000 MHz

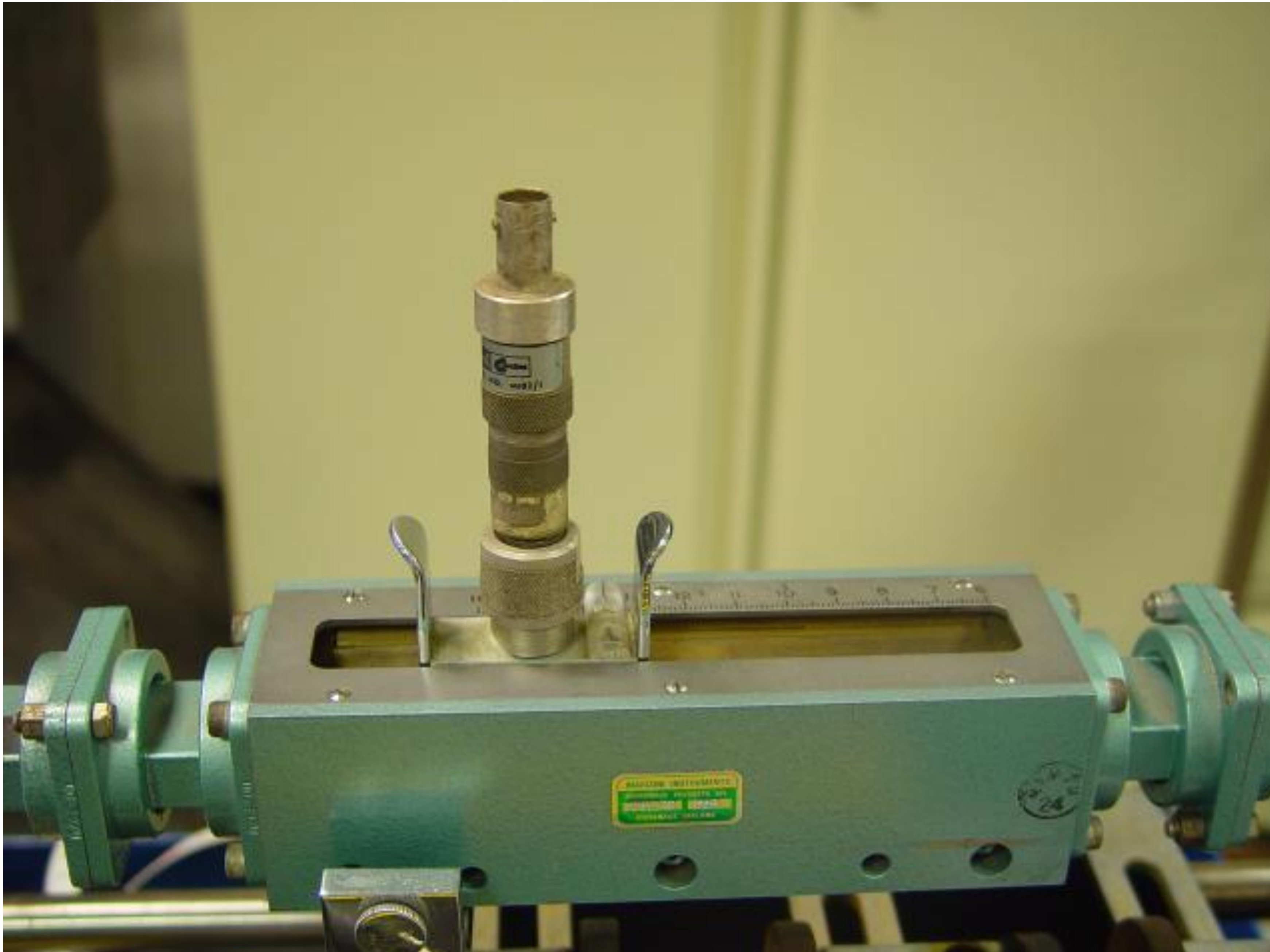
It is a direct graphical representation, in the complex plane, of the complex reflection coefficient.
It is a Reimann surface, in that it is cyclical in numbers of half-wavelengths along the line. As the standing wave pattern repeats every half wavelength, this is entirely appropriate. The number of half wavelengths may be represented by the winding number.
It may be used either as an impedance or admittance calculator, merely by turning it through 180 degrees.

The inside of the unity *gamma* circular region represents the passive reflection case, which is most often the region of interest.
Transformation along the line (if lossless) results in a change of the angle, and not the modulus or radius of *gamma* . Thus, plots may be made quickly and simply.

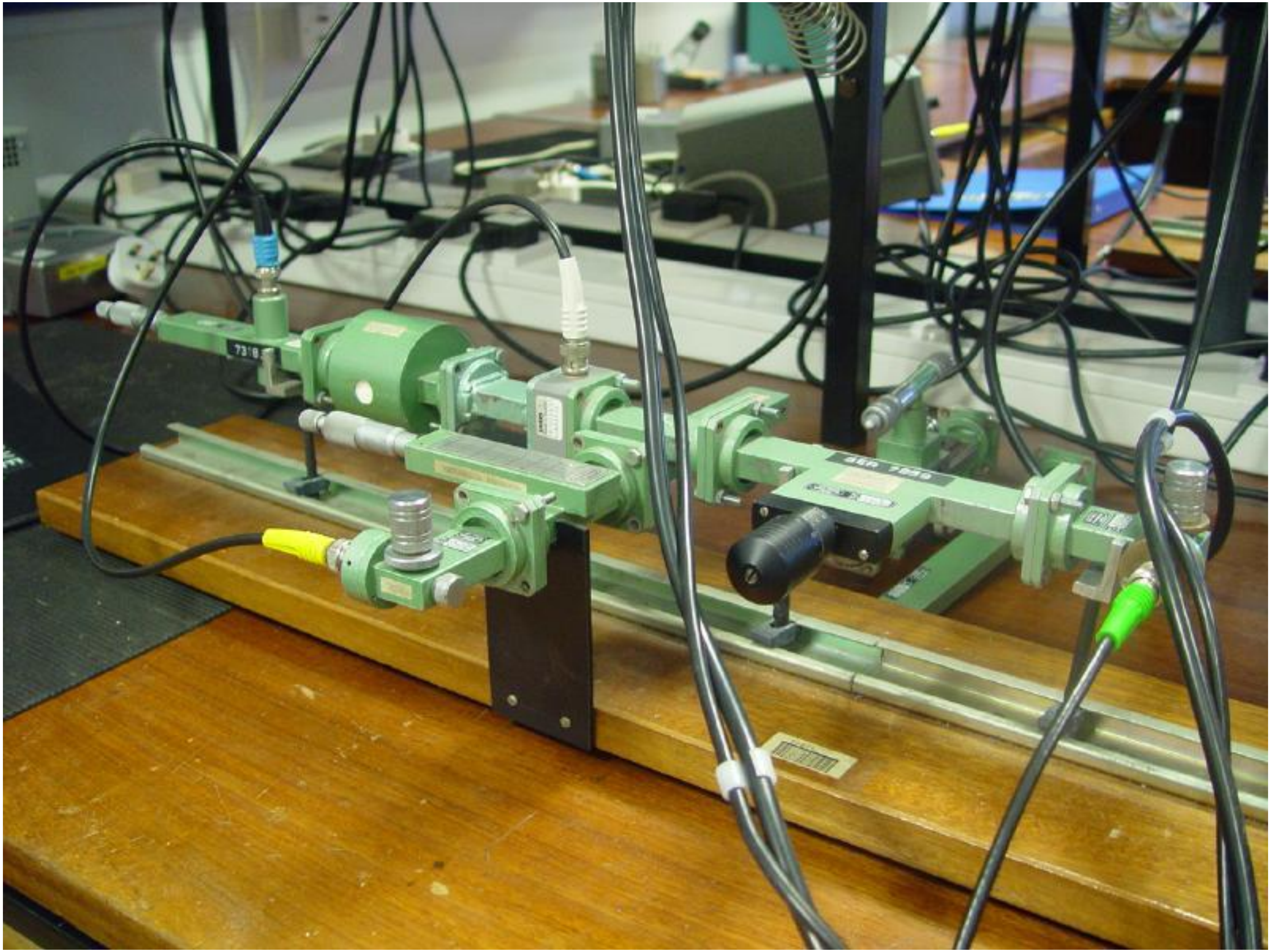
Many of the more advanced properties of microwave circuits, such as noise figure and stability regions, map onto the SMITH chart as circles.
The "point at infinity" represents the limit of very large reflection gain, and so therefore need never be considered for practical circuits.
The real axis maps to the Standing Wave Ratio (SWR) variable. A simple transfer of the plot locus to the real axis at constant radius gives a direct reading of the SWR.

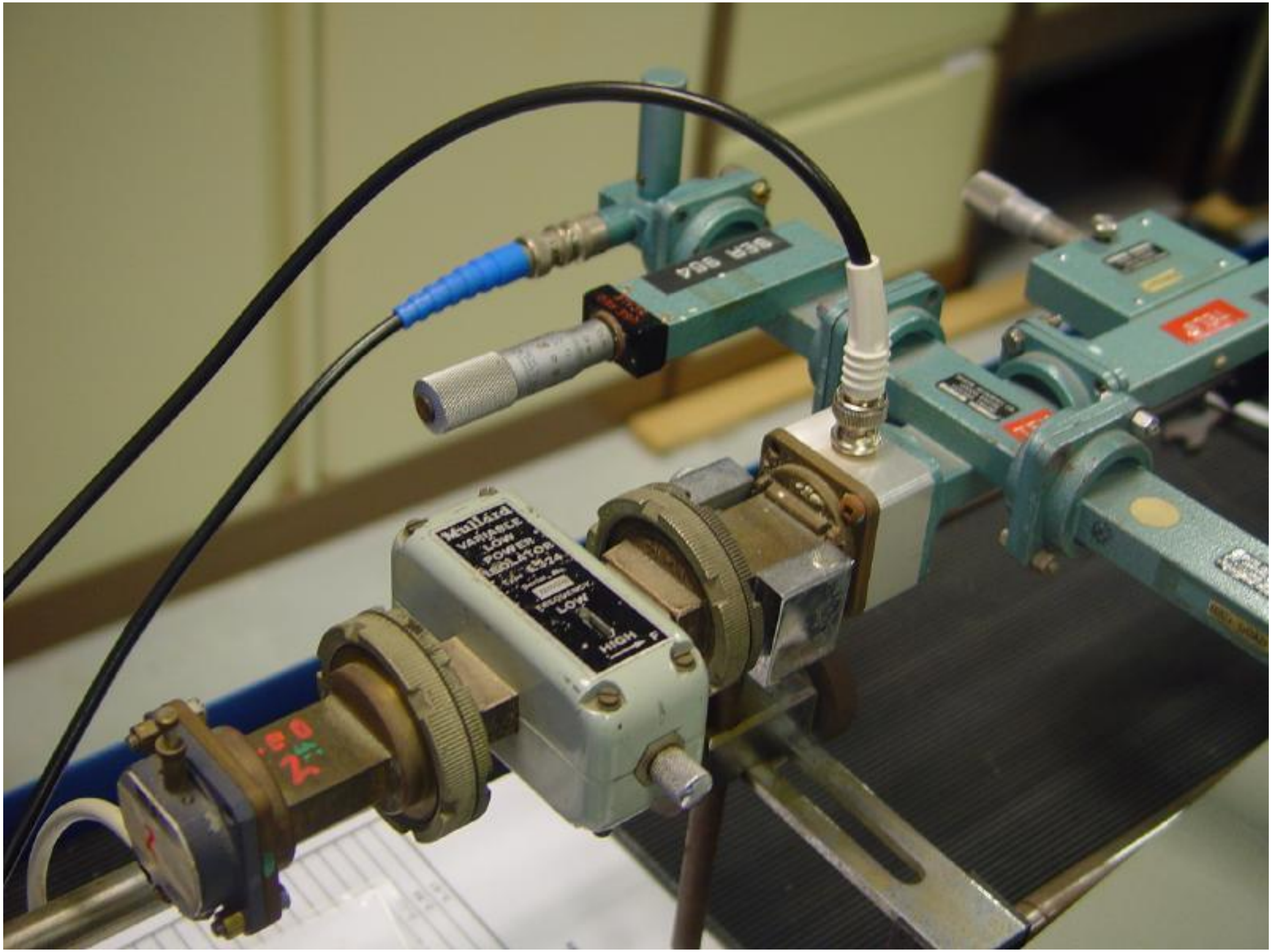
The VSWR indicator is a 1kHz tuned audio amplifier with 70dB dynamic range at least, and a calibrated attenuator sets its gain. The meter measures the size of the audio signal at 1kHz.






EXPANDED V.S.W.R.
EXP. dB
V.S.W.R.
DISCHGD
CHGD
Fine
Attenuation dB
TYPE 6593 A
VSWR INDICATOR
Mains
Off
On
Battery
On
Chg
Chk
Meter
Norm
Exp
Input
A
B
A–B
MARCONI INSTRUMENTS LTD

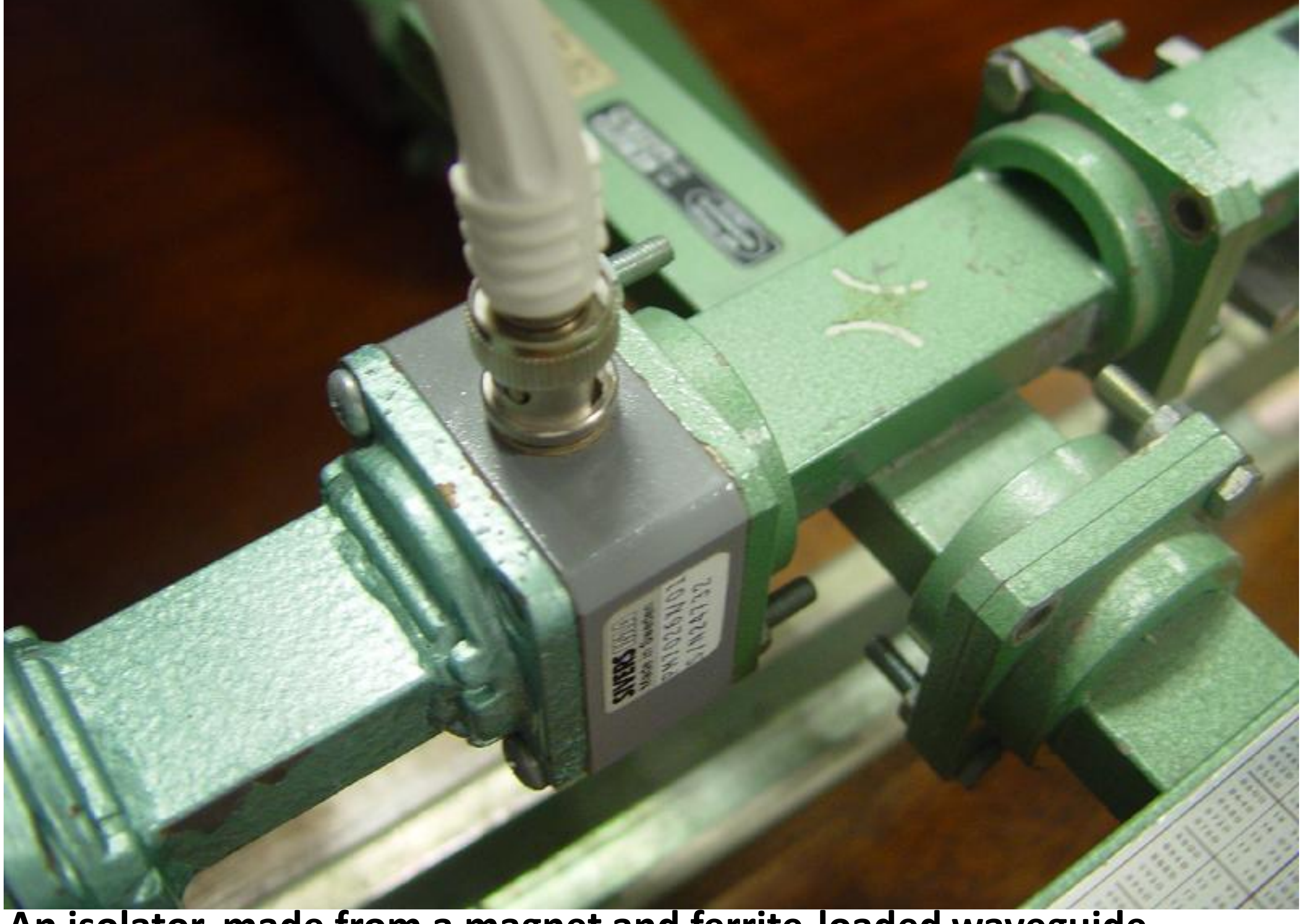




An X-band waveguide bench.

<u>Another X-band waveguide bench, used for transmitting.</u>

The benches include an attenuator, and an isolator. Both of these help to stop the reflected power from reaching the oscillator and pulling the frequency of the cavity and Gunn diode off tune when the load impedance is varied.



An isolator, made from a magnet and ferrite-loaded waveguide.

There is a dual directional coupler, arranged as a pair of crossed waveguides, which samples some of the forward wave power and couples it to a calibrated cavity wavemeter for measuring the oscillator frequency. Taken together with a measurement of guide wavelength, we have then two independent checks on the oscillator frequency. There is also a PIN modulator which chops the 10GHz signal at a frequency of 1KHz square wave.

A waveguide restricts the three dimensional "free space" propagation of the electromagnetic wave to a single dimension. Usually waveguides are
Low loss. That is, the wave travels along the guide without greatly attenuating as it goes.
Routeable. This means that we can gently bend the guiding structure without losing contact with the wave, without generating reflections, and without incurring much additional loss.

Group and phase velocity.

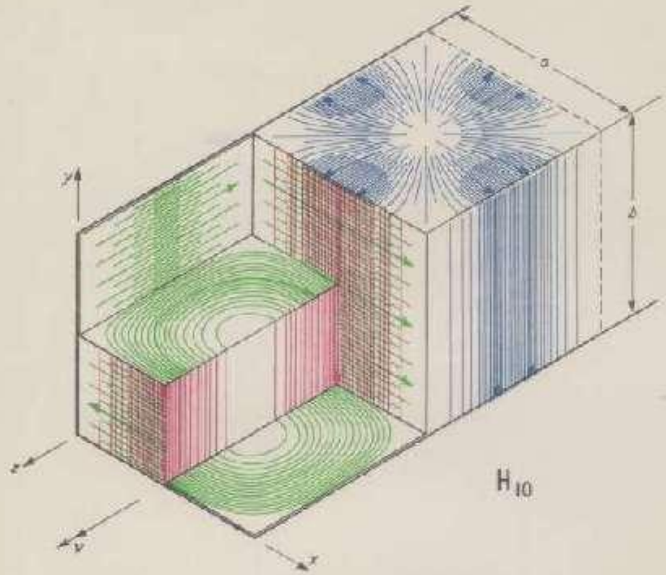
The energy and the modulations on the microwave signal going down the waveguide both travel at the "group velocity" c*cos(alpha) which is necessarily less than the velocity of light c. The pattern however travels at the "phase velocity" c/cos(alpha) which is necessarily greater than the velocity of light. The product of (group velocity)*(phase velocity) = c^2.

Modes.

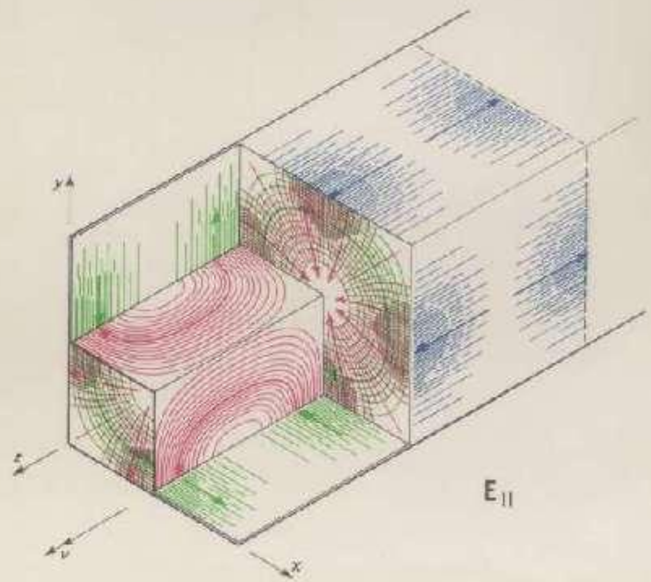
The field pattern is formed from the superposition of two plane waves travelling in different directions, (the two directions are plus and minus alpha with respect to the direction along the waveguide). These two waves have the same free space wavelength, and give the standing wave pattern along y required to make the fields vanish at the side guide walls. The whole field pattern is called a "Mode". For the TE10 mode (transverse electric), if you plot out a plan view of the field patterns carefully, you will see that the electric field is always out of the paper, but that the magnetic field forms stadia loops with repetition distance equal to a guide wavelength; there are two stadia loops per guide wavelength, in opposite senses of magnetic field circulation.

Other modes

The rectangular pipe has cross section a by b metres, with wall planes x-y and x-z. We chose the electric field to lie along the z direction in our first example. However, one can equally satisfy the boundary conditions with the electric field along the y direction, and the standing wave along z. Since the electric field in these modes is entirely transverse to the direction x of propagation, they are called "transverse electric" or TE modes. The two modes here are TE10 and TE01. The 1 refers to the number of half-wave loops across the guide. By convention, the TE10 mode has its single loop across the largest guide lateral dimension, and the TE01 mode has its loop across the smaller guide lateral dimension. Thus the cutoff frequency for the TE10 mode is the lowest frequency at which the waveguide will transmit without attenuation.



H_{10}



E_{11}

Important qualities of the dielectric substrate include

The microwave dielectric constant
The frequency dependence of this dielectric constant which gives rise to "material dispersion" in which the wave velocity is frequency-dependent
The surface finish and flatness
The dielectric loss tangent, or imaginary part of the dielectric constant, which sets the dielectric loss

The cost
The thermal expansion and conductivity
The dimensional stability with time
The surface adhesion properties for the conductor coatings
The manufacturability (ease of cutting, shaping, and drilling)
The porosity (for high vacuum applications we don't want a substrate which continually "outgasses" when pumped)

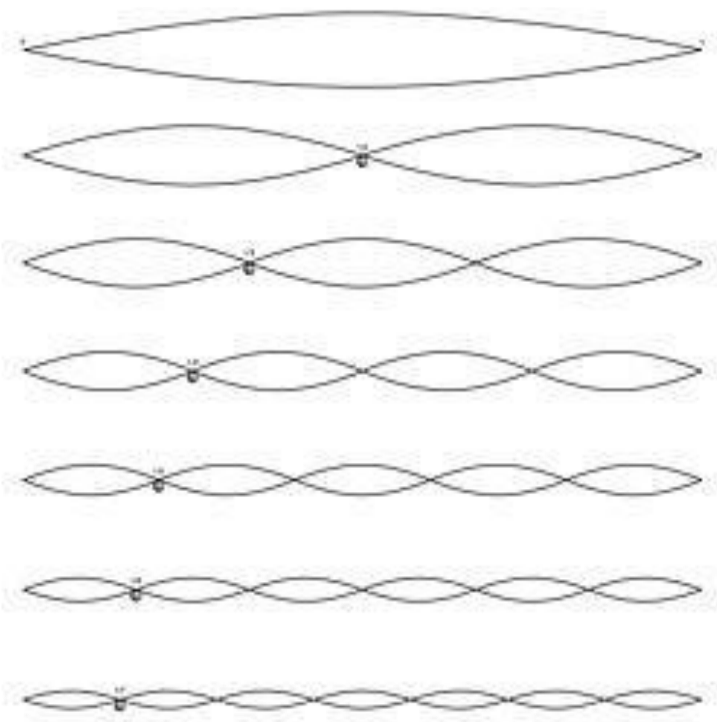
Common substrate materials

Plastics are cheap, easily manufacturable, have good surface adhesion, but have poor microwave dielectric properties when compared with other choices. They have poor dimensional stability, large thermal expansion coefficients, and poor thermal conductivity.

o Dielectric constant: 2.2 (fast substrate) or 10.4 (slow substrate)
o Loss tangent 1/1000 (fast substrate) 3/1000 (slow substrate)
o Surface roughness about 6 microns (electroplated)
o Low themal conductivity, 3/1000 watts per cm sq per degree

Ceramics are rigid and hard; they are difficult to shape, cut, and drill; they come in various purity grades and prices each having domains of application; they have low microwave loss and are reasonably non-dispersive; they have excellent thermal properties, including good dimensional stability and high thermal conductivity; they also have very high dielectric strength. They cost more than plastics. In principle the size is not limited.

o Dielectric constant 8-10 (depending on purity) so slow substrate
o Loss tangent 1/10,000 to 1/1,000 depending on purity
o Surface roughness at best 1/20 micron
o High thermal conductivity, 0.3 watts per sq cm per degree K



A **standing wave, also known as a stationary wave, is a wave that remains in a constant position. This phenomenon can occur because the medium is moving in the opposite direction to the wave, or it can arise in a stationary medium as a result of interference between two waves travelling in opposite directions. In the second case, for waves of equal amplitude travelling in opposing directions, there is on average no net propagation of energy.**

As an example of the second type, a *standing wave in a transmission line is a wave in which the distribution of current, voltage, or field strength is formed by the superposition of two waves propagating in opposite directions. The effect is a series of nodes (zero displacement) and anti-nodes (maximum displacement) at fixed points along the transmission line. Such a standing wave may be formed when a wave is transmitted into one end of a transmission line and is reflected from the other end by an impedance mismatch, i.e., discontinuity, such as an open circuit or a short. The failure of the line to transfer power at the standing wave frequency will usually result in attenuation distortion.*

Standing wave patterns from a reflection

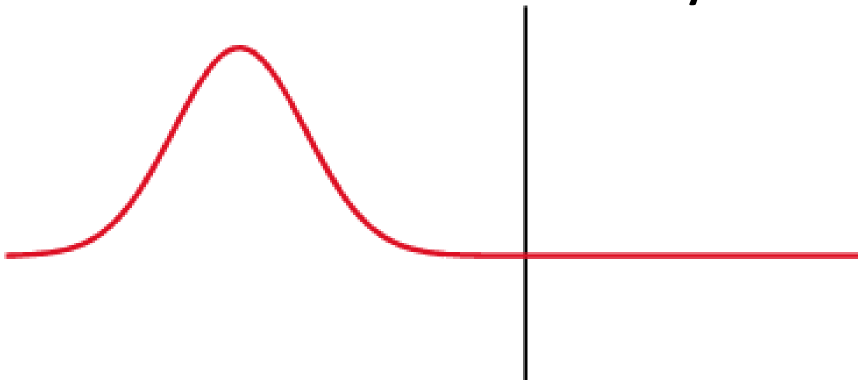
In the case of a complex reflection coefficient gamma, the phase angle of gamma determines where along the line the first standing wave minimum lies, in terms of the wavelength and the position of the load. The magnitude of gamma determines the "voltage standing wave ratio" or VSWR, which is clearly given by the formula

$$\mathrm{VSWR} = \frac{1 + |\mathrm{gamma}|}{1 - |\mathrm{gamma}|}$$

for, remembering $|\mathrm{gamma}| = |V-|/|V+|$

and substituting, we find

The **reflection coefficient is used in physics and electrical engineering when wave propagation in a medium containing discontinuities is considered. A reflection coefficient describes either the amplitude or the intensity of a reflected wave relative to an incident wave. The reflection coefficient is closely related to the *transmission coefficient.***



Telecommunications

In telecommunications, the reflection coefficient is the atio of the amplitude of the reflected wave to the amplitude of the incident wave. In particular, at a discontinuity in a transmission line, it is the complex ratio of the electric field strength of the reflected wave ($E-$) *to that of the incident wave (*$E+$ *). This is typically represented with a Γ (capital gamma) and can be written as:*

The reflection coefficient may also be established using other field or circuit quantities.

The reflection coefficient can be given by the equations below, where *ZS is the impedance toward the source, ZL is the impedance toward the load:*

Simple circuit configuration showing measurement location of reflection coefficient.

The absolute magnitude of the reflection coefficient (designated by vertical bars) can be calculated from the standing wave ratio, *SWR:*

The reflection coefficient is displayed graphically using a Smith chart.

reflection coefficient

This is the ratio of reflected wave to incident wave at point of reflection. This value varies from -1 (for short load) to +1 (for open load), and becomes 0 for matched impedance load.

reflection coefficient in power

This is a squere of the eflection coefficient which means the ratio of the reflected power to the incident power.

Voltage Standing Wave Ratio (VSWR)

This is the ratio of maxmum voltage to minimum voltage in standing wave pattern. It varies from 1 to (plus) infinit.

In telecommunications, the reflection coefficient is the ratio of the amplitude of the reflected wave to the amplitude of the incident wave. In particular, at a discontinuity in a transmission line, it is the complex ratio of the electric field strength of the reflected wave ($E-$) *to that of the incident wave* ($E+$). *This is typically represented with a Γ (capital gamma) and can be written as:*

$$\Gamma = \frac{E-}{E+}$$

The reflection coefficient can be given by the equations below, where *ZS is the impedance toward the source, ZL is the impedance toward the load:*

$$\Gamma = \frac{ZL - ZS}{ZL + ZS}$$

Simple circuit configuration showing measurement location of reflection coefficient.

$$\Gamma = \frac{SWR - 1}{SWR + 1}$$

Power flow on transmission lines
Wave amplitudes and power flow.

The forward wave complex voltage amplitude is described by the complex algebraic term V+. The modulus, or size, of this amplitude is written |V+|.

For sinusoidal signals, the rms voltage in the forward wave is |V+| (1/sqrt[2]). It conveys power in the positive x direction, and the power flow is |V+||V+|/2Zo watts. Similarly, the power flow in the negative x direction, that is from load to generator, is |V-||V-|/2Zo watts.

The ratio V-/V+ is the "complex reflection coefficient," gamma. The ratio of return power to forward power is therefore the (modulus of gamma) squared.

The "return loss" is the number of dB by which the reflected power is lower than the forward power. A return loss of 3 dB means that half the power is reflected, and half absorbed in the load. A return loss of 20 dB means that only 1% of power is returned, and 99% is absorbed in the load.

$$\rho = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Where :

ρ = Reflection Coefficient

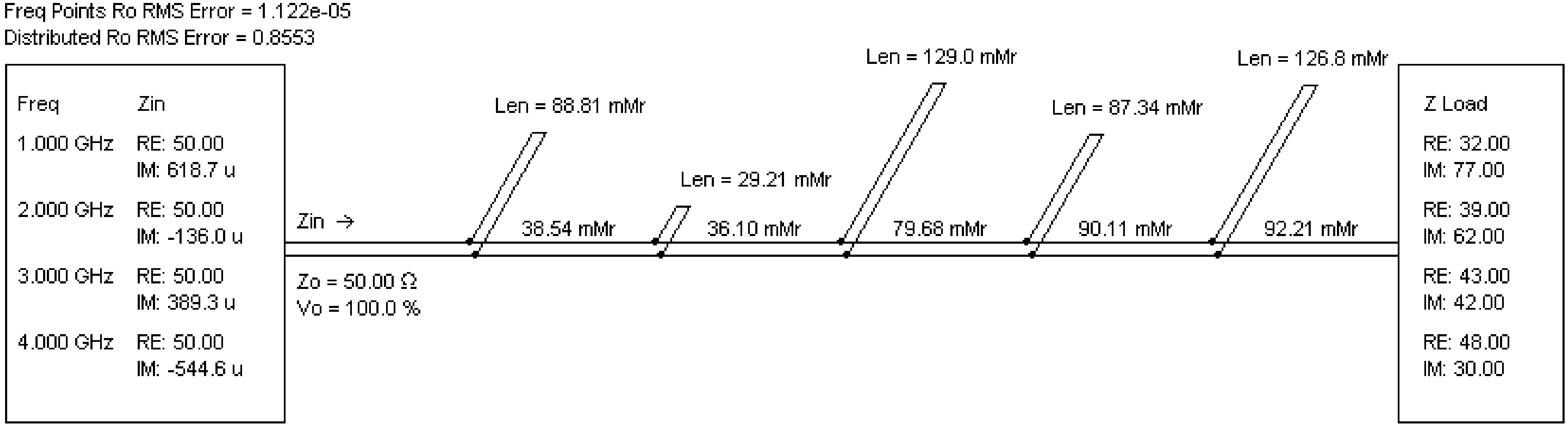
Z_L = The Impedance of the Load

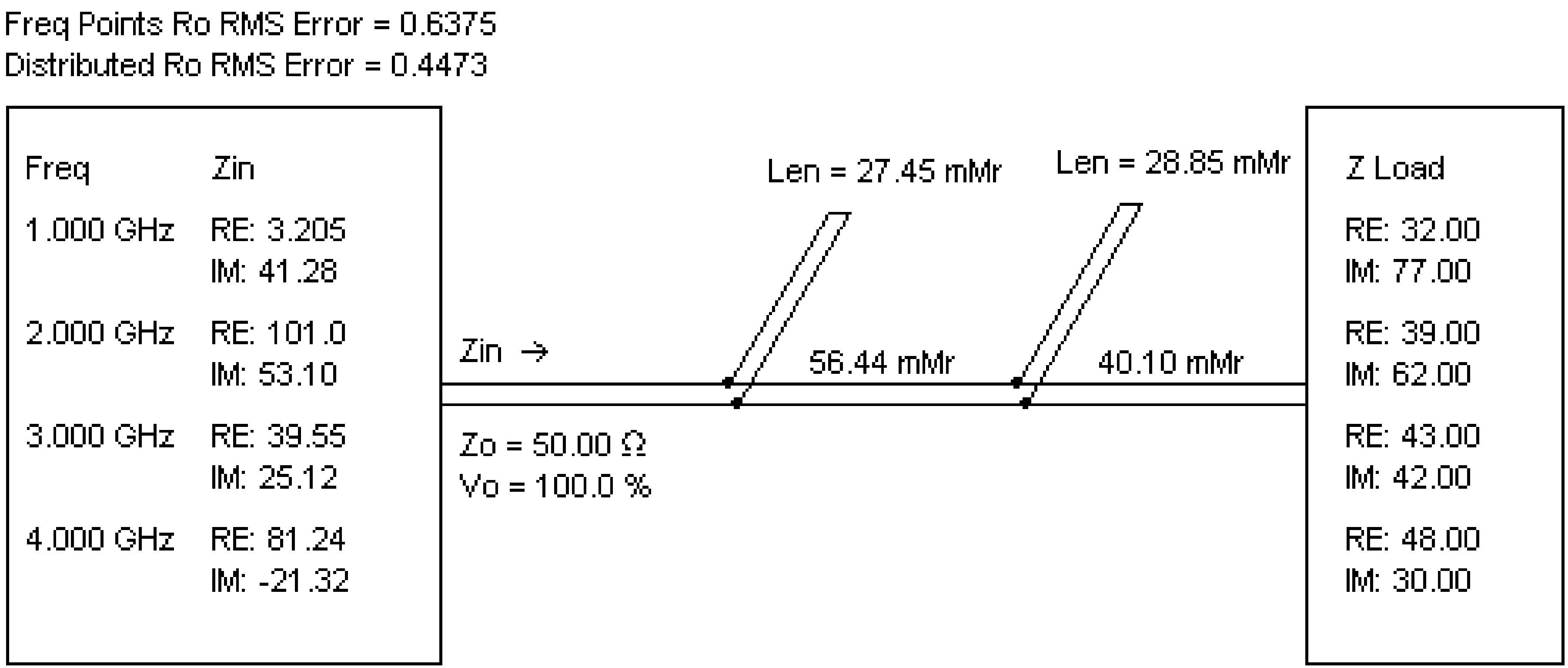
Z_0 = The Ideal Impedance of the Transmission Line

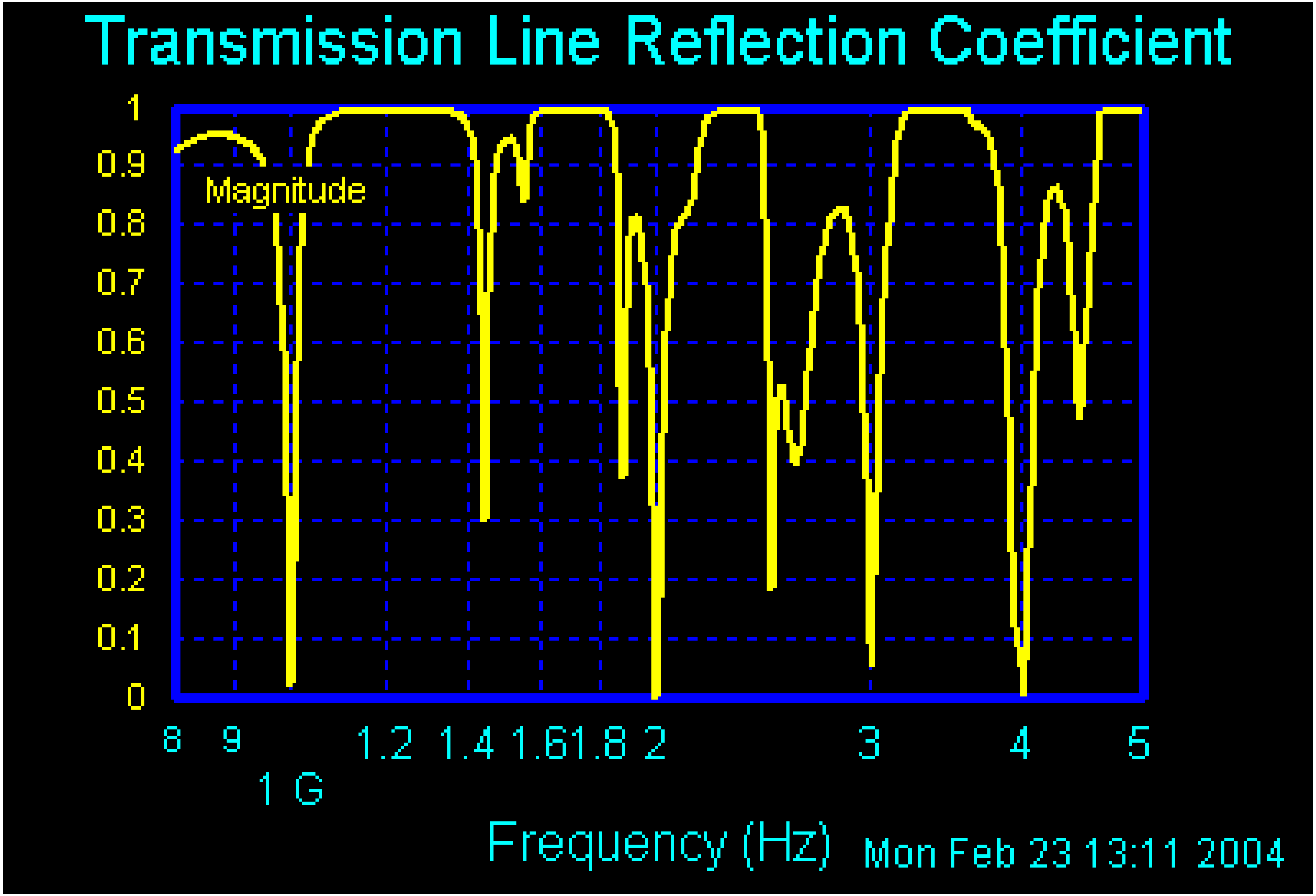
Matching Stubs

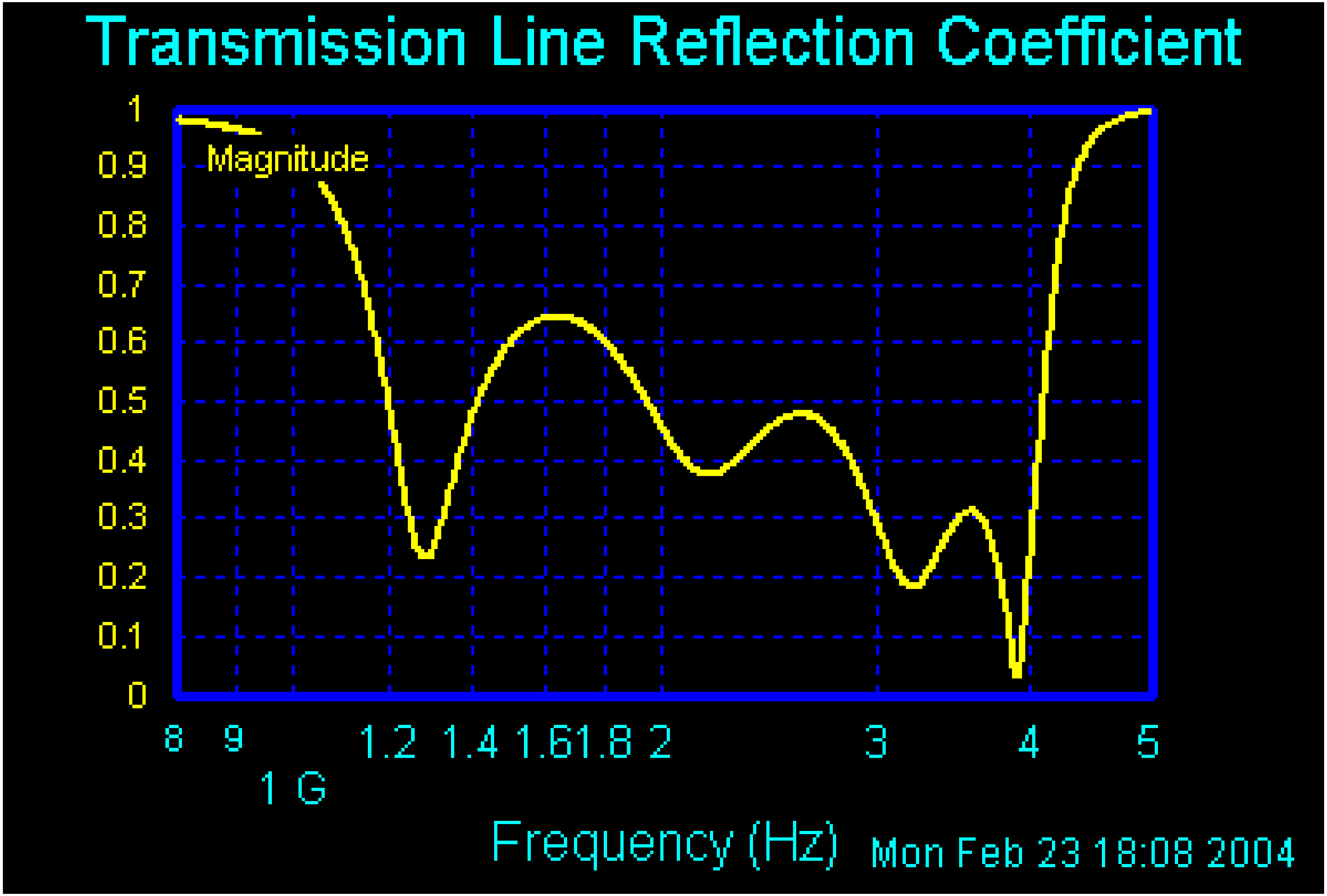
Zmatch creates matches with shorted stubs in parallel with the transmission line. If only one frequency is defined, two unique matching solutions are available. If multiple frequencies are specified, then four unique matching solutions are provided. If a perfect match cannot be found for each specified frequency, then the RMS of the reflection coefficient is minimized. If distributed match is specified, then the RMS of the reflection coefficient is minimized for the entire frequency spectrum.

The example below perfectly matches a load to a line at frequencies 1, 2, 3, and 4 GHz.


Freq Points Ro RMS Error = 1.122e-05
Distributed Ro RMS Error = 0.8553
Freq
Zin
1.000 GHz
RE: 50.00
IM: 618.7 u
2.000 GHz
RE: 50.00
IM: -136.0 u
3.000 GHz
RE: 50.00
IM: 389.3 u
4.000 GHz
RE: 50.00
IM: -544.6 u
Zin →
Zo = 50.00 Ω
Vo = 100.0 %
Len = 88.81 mMr
38.54 mMr
Len = 29.21 mMr
36.10 mMr
Len = 129.0 mMr
79.68 mMr
Len = 87.34 mMr
90.11 mMr
Len = 126.8 mMr
92.21 mMr
Z Load
RE: 32.00
IM: 77.00
RE: 39.00
IM: 62.00
RE: 43.00
IM: 42.00
RE: 48.00
IM: 30.00

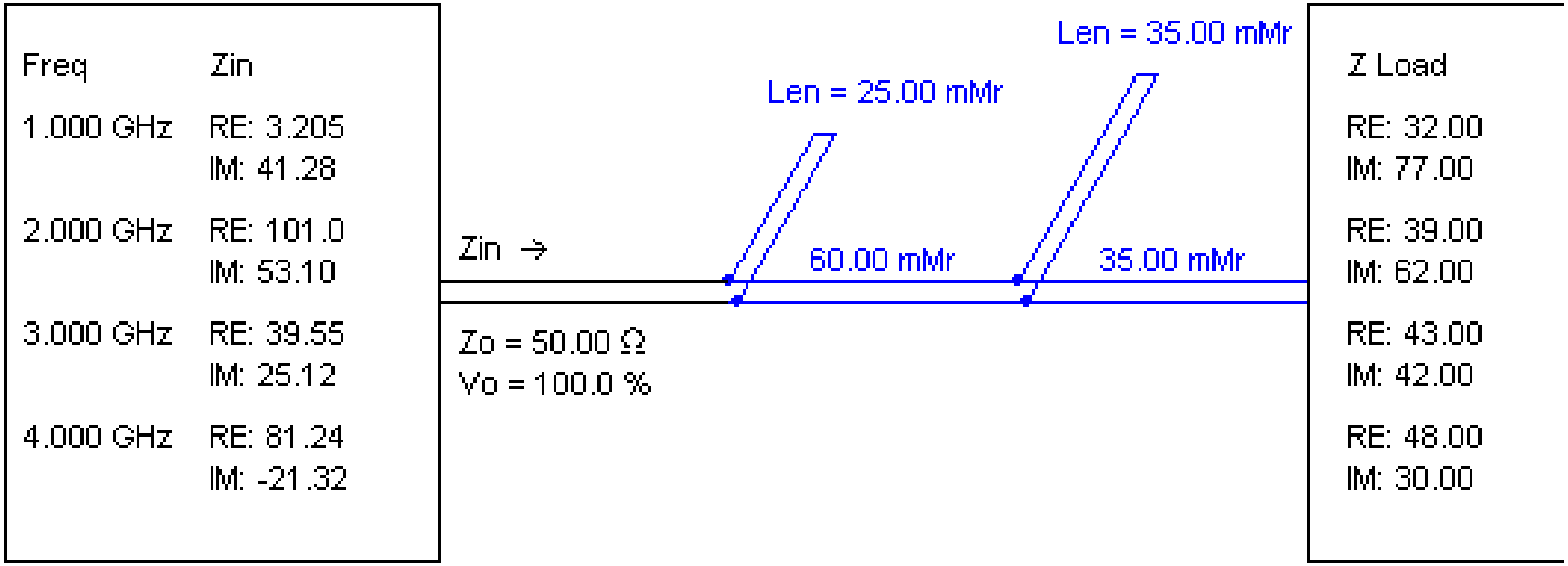

Freq Points Ro RMS Error = 0.6375
Distributed Ro RMS Error = 0.4473
Freq
Zin
1.000 GHz
RE: 3.205
IM: 41.28
2.000 GHz
RE: 101.0
IM: 53.10
3.000 GHz
RE: 39.55
IM: 25.12
4.000 GHz
RE: 81.24
IM: -21.32
Zin →
Zo = 50.00 Ω
Vo = 100.0 %
Len = 27.45 mMr
56.44 mMr
Len = 28.85 mMr
40.10 mMr
Z Load
RE: 32.00
IM: 77.00
RE: 39.00
IM: 62.00
RE: 43.00
IM: 42.00
RE: 48.00
IM: 30.00

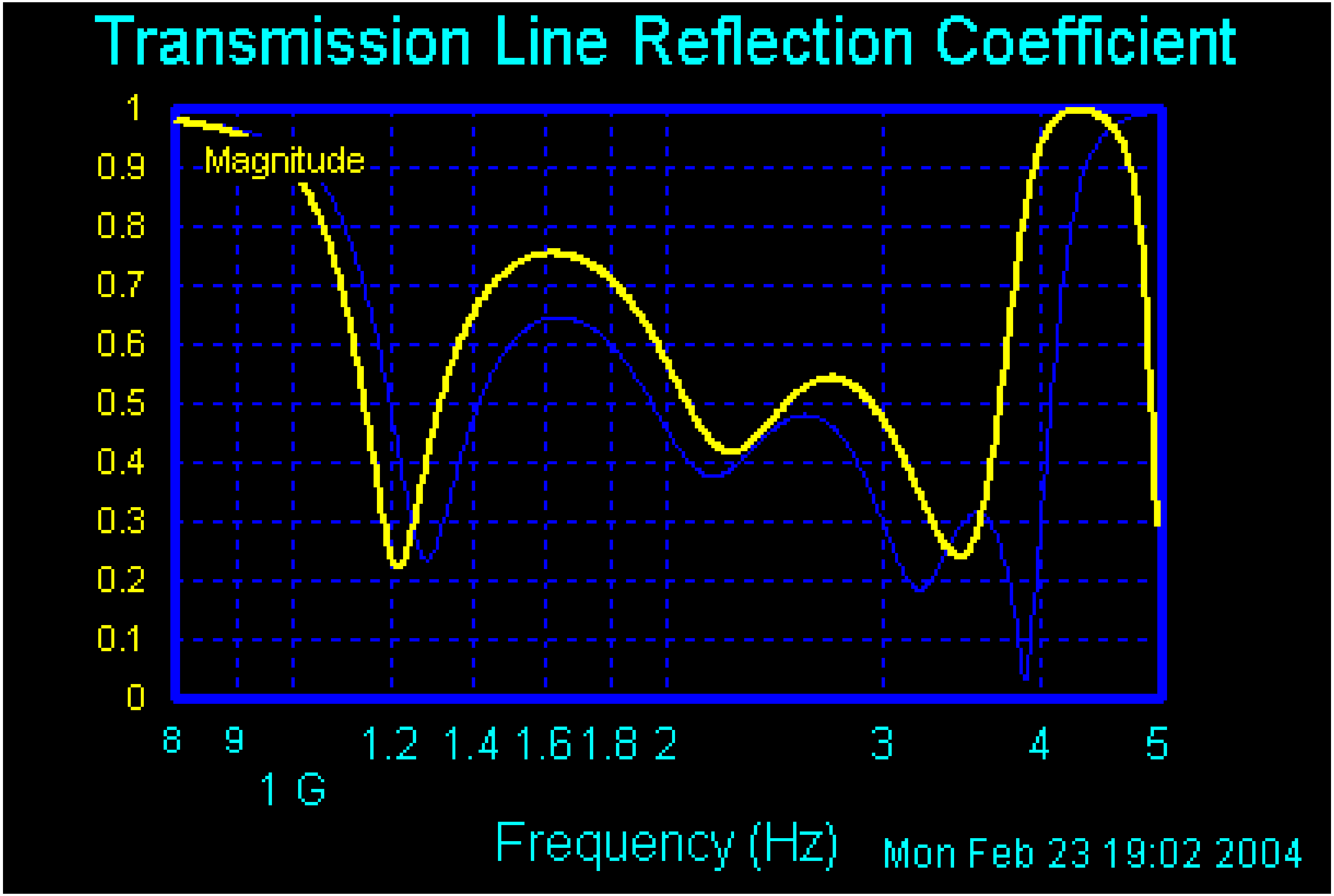

Transmission Line Reflection Coefficient
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Magnitude
8
9
1.2
1.4
1.61.8
2
3
4
5
1 G
Frequency (Hz)
Mon Feb 23 13:11 2004



Transmission Line Reflection Coefficient
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Magnitude
8
9
1.2
1.4
1.6
1.8
2
3
4
5
1 G
Frequency (Hz)
Mon Feb 23 18:08 2004

Freq Points Ro RMS Error = 0.7404
Distributed Ro RMS Error = 0.5579




Transmission Line Reflection Coefficient
Magnitude
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
8
9
1.2
1.4
1.6
1.8
2
3
4
5
1 G
Frequency (Hz)
Mon Feb 23 19:02 2004

Definition of impedance.

We consider the class of linear bipoles and we use the symbolic representation of sinusoidal quantities using phasors (rotating vectors). The impedance can be defined as:

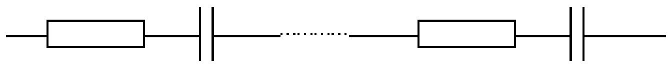
$$\dot{Z} = \frac{\overline{E}}{\overline{I}}$$

The quantities on the right side of the equation are sine functions, characterized by amplitude, frequency and phase. Because frequency is the same for E and I they can be represented by complex numbers. The impedance Z is a complex quantity, characterized by real and imaginary parts or, which is equivalent, by modulus (amplitude) and phase. The impedance is generally a function of frequency.

Examples

Impedance of a resistor with resistance R	R
Impedance of a capacitor with capacitance C	$1/(j\omega C) = jX_c$; $X_c = -1/(\omega C)$; $\omega = 2\pi f$
Impedance of an inductor with inductance L	$j\omega L = jX_L$; $X_L = \omega L$; $\omega = 2\pi f$

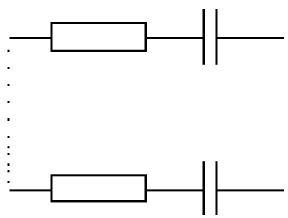
Series and parallel connection of bipoles.



$X_c = -1/2\pi fC$

$X_L = 2\pi fL$

$R_1 + jX_1 + R_2 + jX_2 = R + jX;\ R = R_1 + R_2,\ X = X_1 + X_2$



$Y = G + jB = 1/Z = 1/(R + jX)$

$G = R/(R^2 + X^2);\ B = -X/(R^2 + X^2)$

$G_1 + jB_1 + G_2 + jB_2 = G + jB;\ G = G_1 + G_2,\ B = B_1 + B_2$

Please note: we will use two different representations of quantities for series and parallel connection of bipoles.

Why impedance matching?

1) Maximization of power transfer from sources to loads.

2) Losses minimization in transmission lines.

3) Signal to noise ratio maximization in input stages of receivers.

4) Minimization of signal distortion in transmission lines, avoiding wavefront reflections and pulse superposition.

5) Voltage amplification or attenuation.

6) Current amplification or attenuation.

Passive matching networks.

a) Resistive networks for extremely wide bandwidth (lossy networks) (for application 4).

b) Transformer matching for wide band applications.

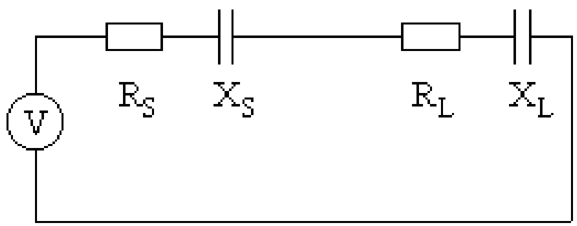
c) Inductive and capacitive matching for narrow bandwidth and high efficiency.

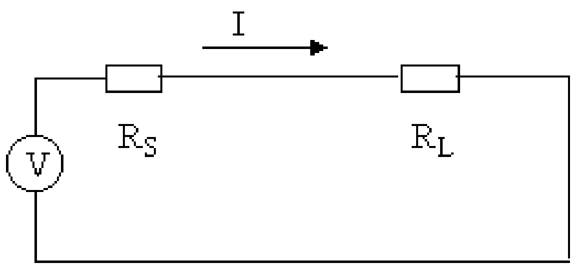
d) Coaxial lines, stub and transmission line matching for narrow bandwidth, very high frequencies and high efficiency. Matching with variable impedance transmission lines for wide band matching.

e) Combined matching.

f) No matching if we use already matched components (usually 50 ohm amplifiers).

Power transfer maximization.





Problem: Using a general equivalent circuit for a real power source, with V, R_S, X_S given, find R_L and X_L, in order to maximize the power dissipated by R_L.

Please note: as X_S ed X_L cannot dissipate power, we must choose $X_S = - X_L$ in order to maximize the current in R_L for any value of R_S and R_L. We observe the inverse proportionality of I respect to $|Z| = (R_S + R_L)^2 + (X_S + X_L)^2$. This is the first step for the maximization of the power transferred to the load resistance. The reduced problem is now:

$$I = \frac{V}{R_s + R_L}; \quad \frac{P_{RL}}{V^2} = \frac{R_L}{R_S^2 + R_L^2 + 2R_S R_L}$$

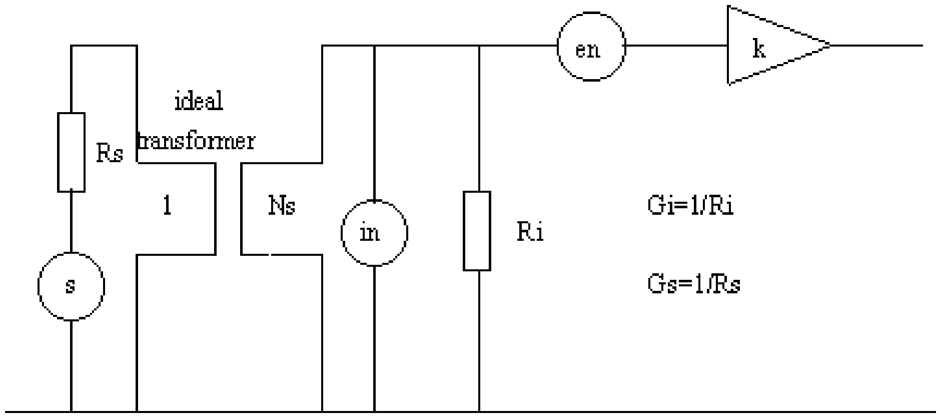
The maximum is found by derivation.

$$\frac{d\frac{P_{RL}}{V^2}}{dR_L} = \frac{R_S^2 + R_L^2 + 2R_S R_L - 2R_L^2 - 2R_L R_S}{(R_S^2 + R_L^2 + 2R_S R_L)^2} = 0$$

Because $R_S > 0$ and $R_L > 0$ the equation gives: $R_S = R_L$.

$X_S = - X_L$ and $R_S = R_L$ is defined a complex conjugate matching.

Signal to noise ratio maximization.



Problem: find Ri and Ns in order to maximize the signal to noise ratio of the circuit.

Please note: we make the hypothesis that the reactive part of the impedance has been already matched in order to avoid unnecessary attenuation.

Additional note: the transformer is the matching element.

The power of the signal is (in units of V^2):

$$Ps = \frac{s^2 Ns^2}{(Gi(1/Gi + Ns^2/Gs))^2} k^2$$

The power of the noise is (in units of V^2):
Where voltage noise, current noise and signal are uncorrelated.

$$Pn = en^2 k^2 + \frac{in^2}{(Gi + Gs/Ns^2)^2} k^2$$

Signal to noise ratio maximization (2).

Therefore the signal to noise ratio is:

$$\frac{S}{N} = \frac{\dfrac{s^2 Ns^2}{(1+Ns^2 Gi/Gs)^2}}{en^2 + in^2/(Gi+Gs/Ns^2)^2}$$

S/N has a maximum for:

$$Ns^4 = \frac{1/Rs^2}{1/Ri^2 + in^2/en^2}$$

With Ri→∞ we get:

$$Ns^2 = \frac{1}{Rs}\frac{en}{in}$$

Signal to noise ratio maximization (3).

By choosing the solution Ns=1 we get:

$$Rs = \frac{en}{in}$$

en/in is defined as the noise resistance of the amplifier.

Using a different procedure, we may first choose Ns=1 and solve for Rs.

$$Rs = Ri\sqrt{\frac{(en/in)^2}{Ri^2 + (en/in)^2}}$$

Depending on the values of Ri and en/in, we have two different approximate solutions. The first one is a noise matching, the second one is a power matching.

$$Rs \approx \frac{en}{in}; Ri >> \frac{en}{in}$$

$$Rs \approx Ri; Ri << \frac{en}{in}$$

Signal to noise ratio maximization (4).

By substitution of the optimal value of Ns in the expression of S/N we get:

$$\frac{S}{N} = \frac{s^2}{2Rs\, en^2 (1/Ri + \sqrt{1/Ri^2 + in^2/en^2})}$$

We now choose Ri=∞ and find the values of in and en in order to observe the thermal noise of Rs with a S/N=1. The signal s is therefore the thermal noise of Rs.

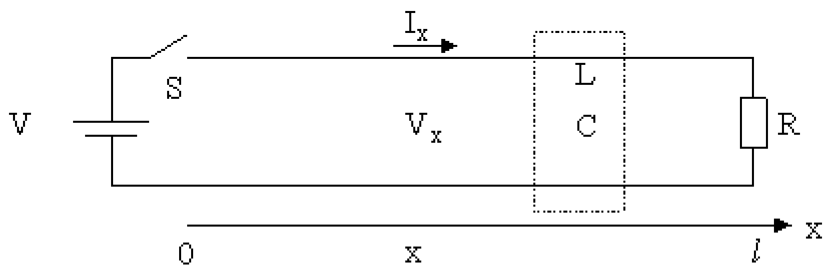
$$s^2 = 4 R_s KT = 2 R_s\, i_n\, e_n$$

We can now find the required temperature of Rs. Because we have chosen S/N=1 that temperature is the "equivalent" noise temperature of the amplifier.

$$T_n = \frac{i_n\, e_n}{2K}$$

T= temperature in Kelvin, K= Boltzmann's constant = 1.38×10^{-23} J K^{-1}

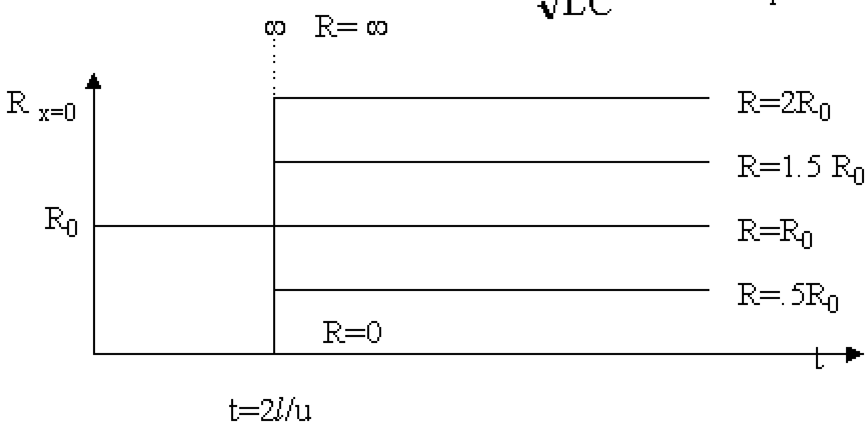
Transmission lines (simplified analysis)



Schematization of the problem.
Observation: the finite speed of light has to be applied to any electrical circuit .

From Maxwell equations we already know that, if L (H/m) and C (F/m) are constant along the pair of conductors, the propagation speed is:

$$u = \frac{1}{\sqrt{LC}} \qquad \text{Eq. 1}$$



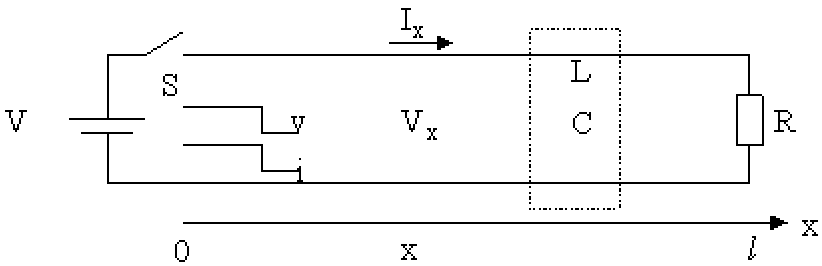
u is the speed of light, it depends on the electrical properties of the material which constitutes the line: conductors and insulators.

Observation: starting from t=0, the resistance v/i that loads the generator V is found to be R_0.

We must wait the time $2l/u$ in order to observe the resistance R connected to the end of the line.

R_0 = **characteristic impedance.**

Definition of the characteristic impedance.



Hypothesis: the transmission line is lossless.
Problem: When S is closed, voltage and current wavefronts propagate towards R. We calculate the current in the voltage source V.

When the wavefront moves of dx ⟹ The capacitance charged at voltage V is Cdx.

Using the relation Q=CV we have $dQ=VCdx$ and using Eq. 1, which describes the effects of the speed of light, we have:

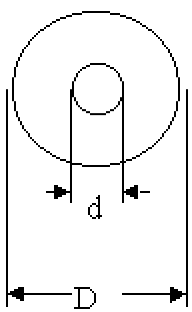
$$\mathbf{I} = \frac{d\mathbf{Q}}{dt} = \mathbf{VC}\frac{dx}{dt} = \mathbf{VC}u = \mathbf{VC}\frac{\mathbf{1}}{\sqrt{\mathbf{LC}}} = \mathbf{V}\sqrt{\frac{\mathbf{C}}{\mathbf{L}}} \equiv \frac{\mathbf{V}}{\mathbf{R}_0} \qquad \text{Eq. 2}$$

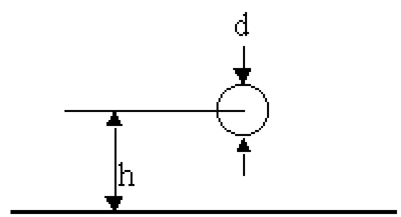
$R_0 \equiv \sqrt{(L/C)}$ is the characteristic impedance of the line, the first and the last terms of Eq 2 simply define R_0 by Ohm's law.

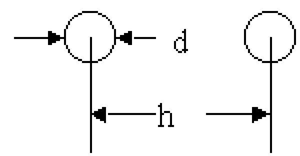
Examples of transmission lines.

Because $u = \frac{1}{\sqrt{LC}}$ is equal to the speed of light c in a vacuum or to a fraction of c in an insulating medium, we may introduce a speed factor. For instance $u=0.66\,c$ in polythene (used in RG 58 coaxial cables).

It follows that we only need to calculate the capacitance per meter, which is a problem of electrostatics .





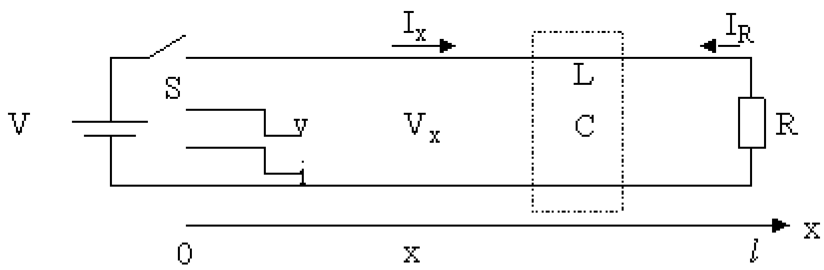


$$C = \frac{2\pi\,\varepsilon}{\ln\frac{D}{d}}$$

$$C \approx \frac{2\,\pi\varepsilon}{\ln\frac{4h}{d}}$$

$$C \approx \frac{\pi\varepsilon}{\ln\frac{4h}{d}}$$

The reflection.



Hypothesis: the transmission line is lossless.
When S is closed voltage and current wavefronts propagate toward R.
When the wavefronts reach R we might have a reflection.
Observation: on the left of the wavefronts, towards the generator, we have $V/I=R_0$.
On the load R we have $V_l/I_l=R$.
If the ratio V/I changes because of $R \neq R_0$, we have reflected wavefronts travelling in the reverse direction respect to the incident one. It follows that the sign of the current is reversed.

$$V_l = V_{incident} + V_{reflected} = V + V_{reflected}$$

$$I_l = I_{incident} + I_{reflected}$$

$$V_l = V + \rho V \quad : \rho = \text{coefficient of reflection}$$

$$-\rho V / R_0 = \text{reflected current}$$

Calculation of ρ.

Because $V_l/I_l=R$, we have:

$$\frac{V + \rho V}{V/R_0 - \rho V/R_0} = R \quad \Rightarrow \quad \rho = \frac{R/R_0 - 1}{R/R_0 + 1}$$

The reflection (2).

A generalization.

$$\rho = \frac{Z/Z_0 - 1}{Z/Z_0 + 1} = \frac{Z - Z_0}{Z + Z_0}$$

The inverted formula

$$Z/Z_0 = \frac{1+\rho}{1-\rho} = \textbf{normalized impedance}$$

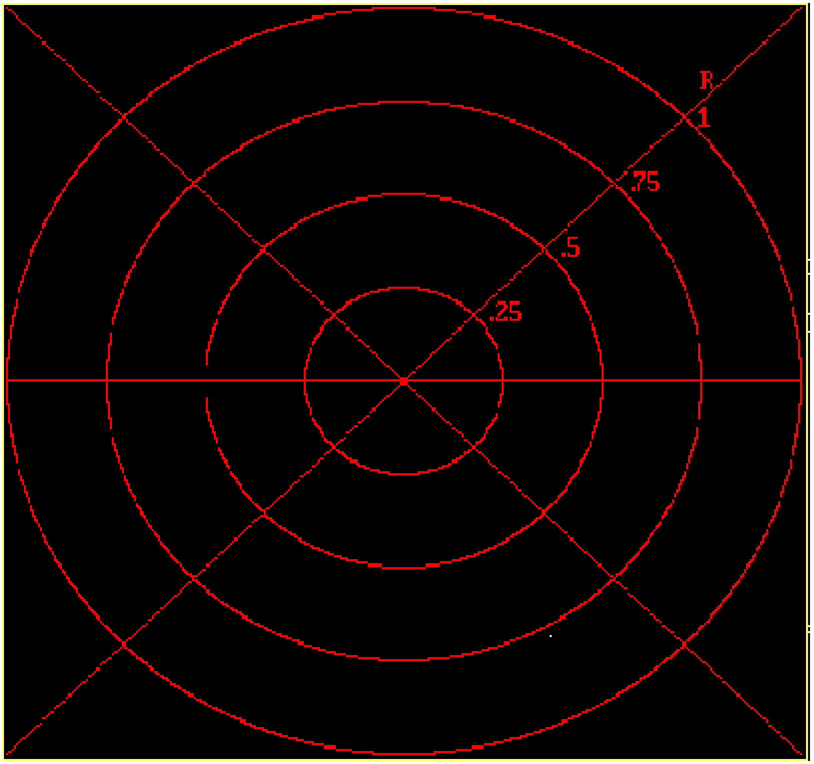
Impedances and admittances.

$$Y = \frac{1}{Z}; \quad Y_0 = \frac{1}{Z_0}; \quad \frac{Y}{Y_0} = \frac{Z_0}{Z}$$

The inverted formula

$$Y/Y_0 = \frac{1-\rho}{1+\rho} = \textbf{normalized admittance}$$

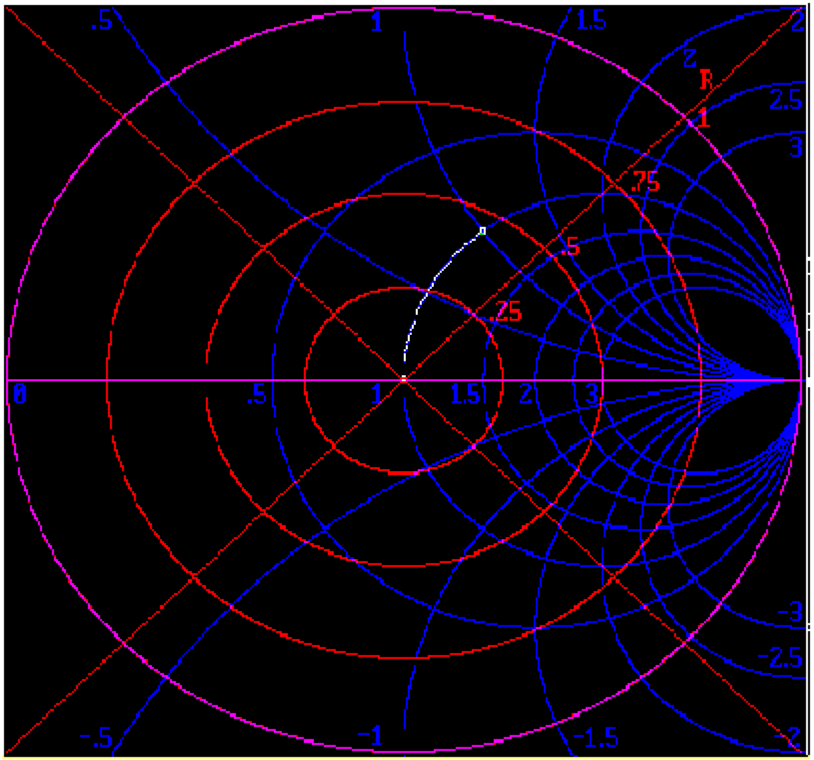
Graphical representation of impedances.



The transformations among impedance, admittance and coefficient of reflection are bilinear transformations, they are invertible transformations and geometrically transform circles to circles. As ρ is a complex quantity with $|\rho| \leq 1$, its use is convenient for representing impedances and admittances by the use of a suitable mapping .

To invert the transformations, a characteristic impedance has to be defined. If the network comprises transmission lines, the choice could be the characteristic impedance of the lines. In any case the choice of Zo is arbitrary.

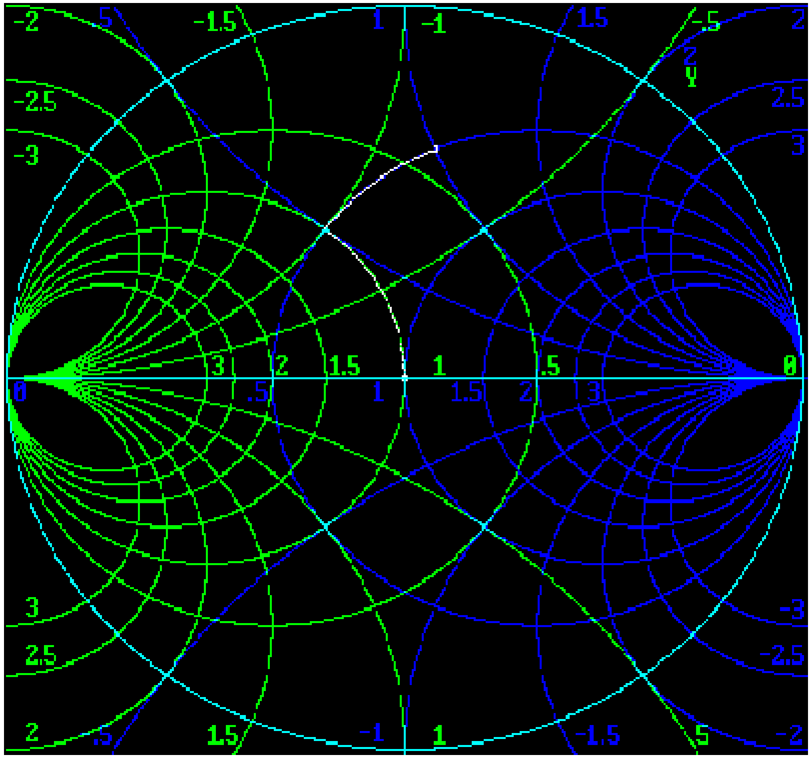
Graphical representation of impedance (2).



We now superimpose the system of coordinates for the normalized impedance Z/Zo, being Zo resistive.
In order to draw this system of coordinates we convert the normalized impedance to coefficient of reflection, keeping constant the real part and sweeping the imaginary one; then doing the reverse. We obtain the diagram shown: the Smith chart of the impedance.
With the chart we can easily add and remove resistance and reactance to and from a given impedance.
Example: with Zo=50 ohm and f=100 MHz.
Starting from Z=50 + j50 (RL series, with R=50 and L=0.795 uH, we connect in series a capacitance with Xc= -50 ohm giving C=32.1 pF.

The impedance Z is now matched to 50+j0 ohm.

Graphical representation of impedance (3).

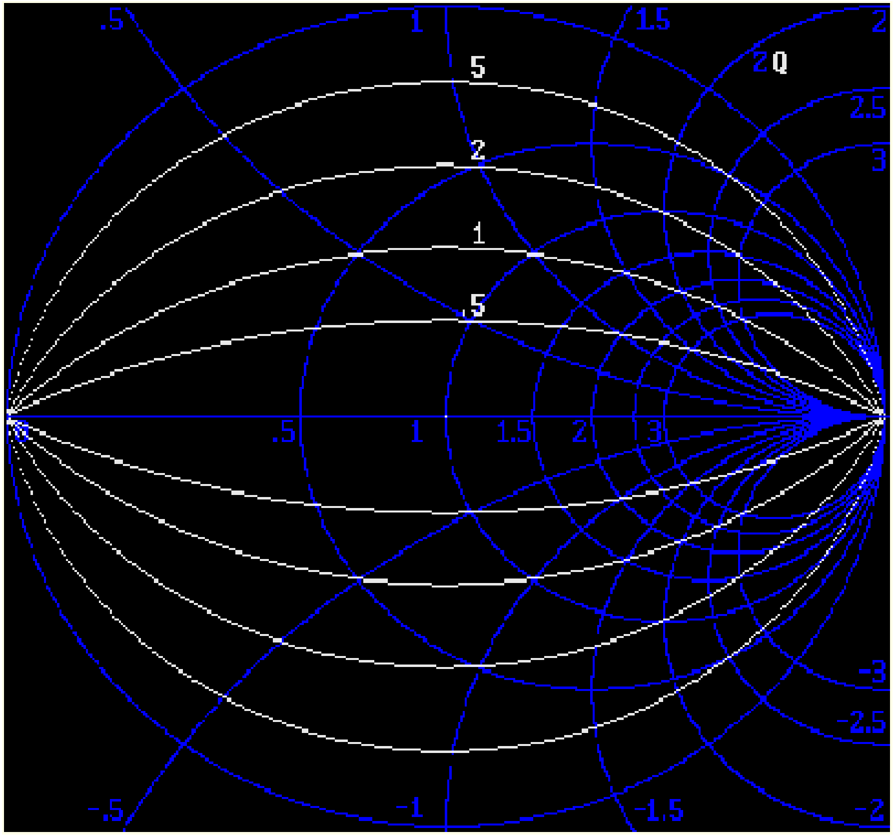


A slightly more complex example is the one presented here.

With Zo=50 ohm and f=100 MHz.
Starting from Z=25 + j50 (series RL with R=25 and L=0.795 uH), by connecting in series a capacitance with Xc= -25 ohm equivalent to C=64.2 pF. We reach the impedance Za=25 + j25.
Adding a susceptance B with a value equal to Yo=1/Zo = 1/50 equivalent to a capacitor of 32 pF in parallel, we reach the impedance of 50 + j0 ohm. For this concluding operation we use the **admittance Smith chart.**

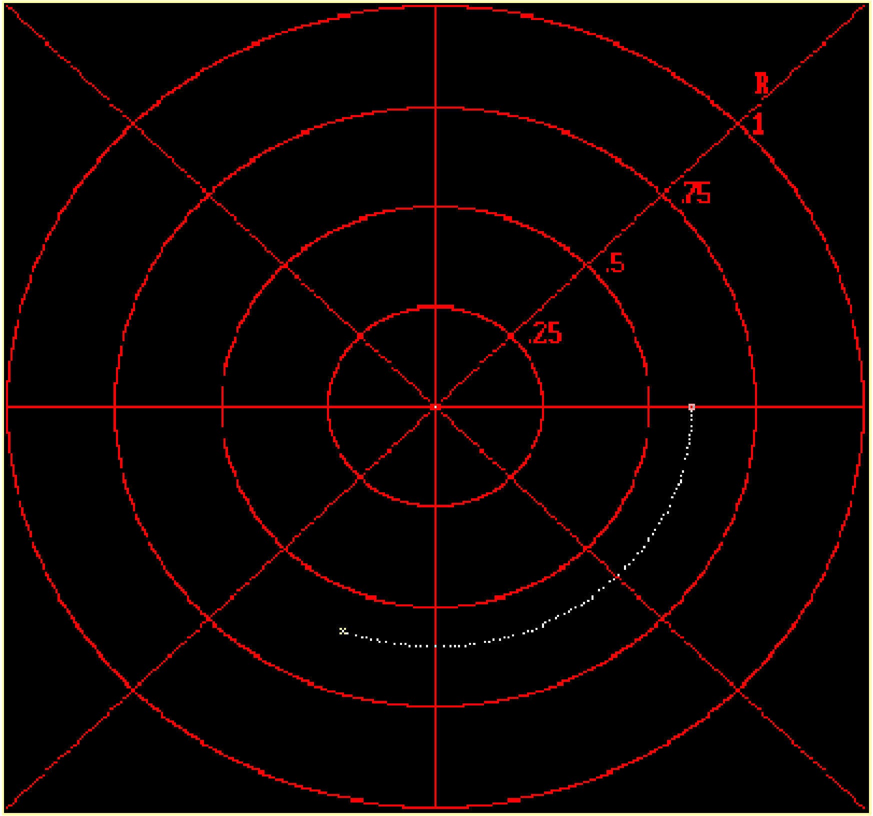
The impedance Z is now matched to 50+j0 ohm.

Graphical representation of impedance (4).



Another useful coordinate system is the Q chart, where Q=X/R. Usually a low Q is preferred, in order to have low potentials and a reduced stress for the components of the matching network.

Graphical representation of impedance (5).

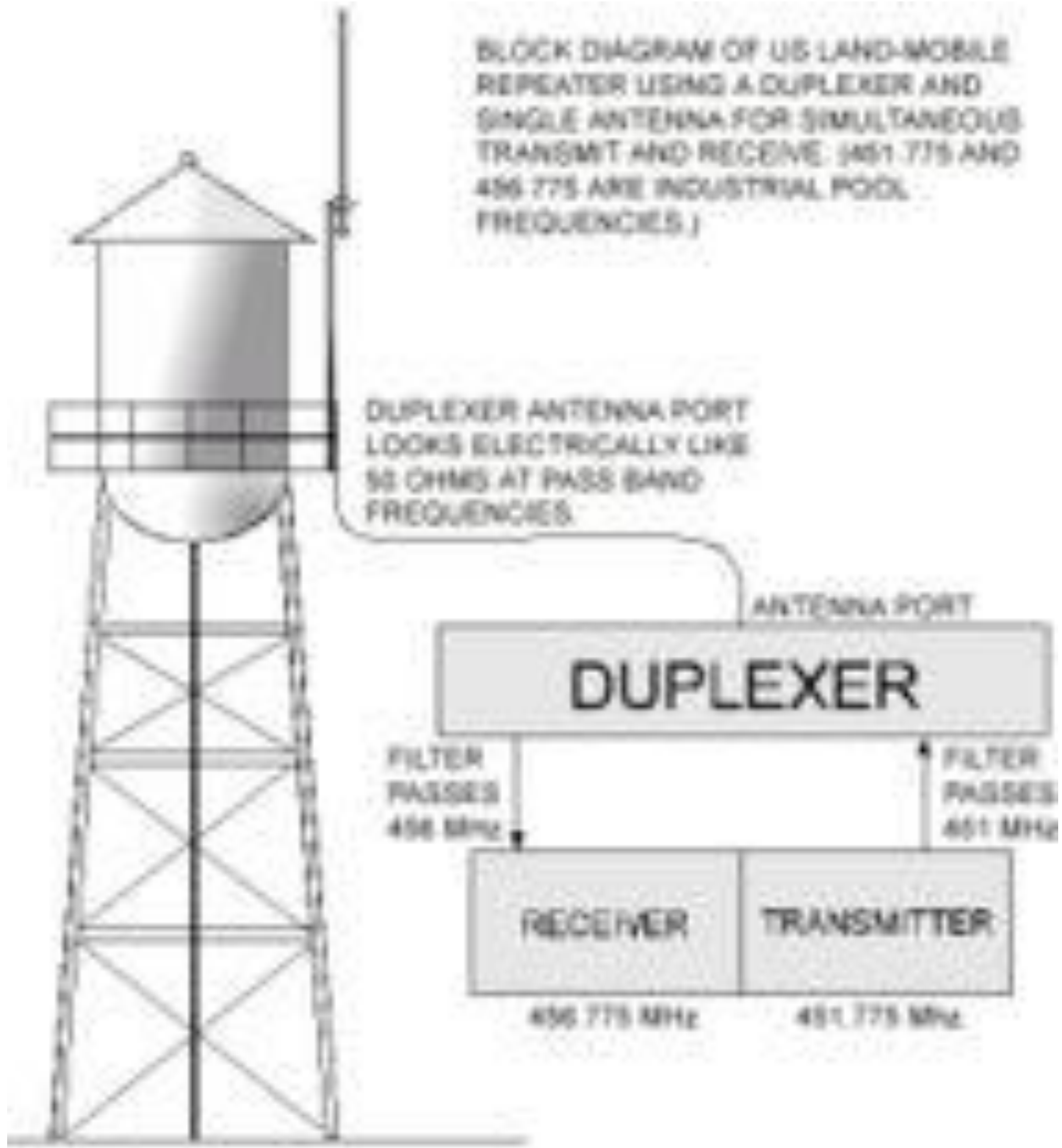


A concluding example is the graphical representation of a transmission line. With Zo=50 ohm and f=100 MHz, we represent 31cm of coaxial cable RG 58 (Zo=50 ohm, speed factor 0.66) connected to a resistive impedance of 200 ohm.

Arcs are construction that represent the impedance that could be measured if the value of a chosen parameter were different from the one presented. Here the parameter is length and it covers values from 0 to 31 cm. An arc is usually employed to graphically identify an element or component of the network.

A **diplexer** is a passive device that implements frequency domain multiplexing. Two ports (e.g., L and H) are multiplexed onto a third port (e.g., S). The signals on ports L and H occupy disjoint frequency bands. Consequently, the signals on L and H can coexist on port S without interfering with each other.

Diplexing is useful in reducing the number of radio antennas on a radio tower, reducing the weight and loading from wind and potential ice, as well as the necessary size of the tower itself. Diplexers must be carefully engineered: designed and tuned to prevent intermodulation and keep reflected power (VSWR) to a minimum for each input transmitter and frequency. While diplexers can combine a relatively wide bandwidth, the major limitation comes with the antenna itself, which must be sufficiently wideband to accept all of the signals being passed through it, and transfer them to the air efficiently.


BLOCK DIAGRAM OF US LAND-MOBILE REPEATER USING A DUPLEXER AND SINGLE ANTENNA FOR SIMULTANEOUS TRANSMIT AND RECEIVE. (451.775 AND 456.775 ARE INDUSTRIAL POOL FREQUENCIES.)
DUPLEXER ANTENNA PORT LOOKS ELECTRICALLY LIKE 50 OHMS AT PASS BAND FREQUENCIES.
ANTENNA PORT
DUPLEXER
FILTER PASSES 456 MHz
FILTER PASSES 451 MHz
RECEIVER
TRANSMITTER
456.775 MHz
451.775 MHz

A **circulator** is a passive electronic component with three or more ports in which the ports can be accessed in such a way that when a signal is fed into any port it is transferred to the next port only, the first port being counted as following the last in numeric order.

When one port of a three-port circulator is terminated in a matched load, it can be used as an **isolator**, since a signal can travel in only one direction between the remaining ports.[1]

Microstrip transmission line is a kind of "high grade" printed circuit construction, consisting of a track of copper or other conductor on an insulating substrate. There is a "backplane" on the other side of the insulating substrate, formed from similar conductor. A picture (37kB).

Looked at end on, there is a "hot" conductor which is the track on the top, and a "return" conductor which is the backplane on the bottom. Microstrip is therefore a variant of 2-wire transmission line.

If one solves the electromagnetic equations to find the field distributions, one finds very nearly a completely TEM (transverse electromagnetic) pattern. This means that there are only a few regions in which there is a component of electric or magnetic field in the direction of wave propagation.

There is a picture of these field patterns (incomplete) in T C Edwards "Foundations for Microstrip Circuit Design" edition 2 page 45. See the booklist for further bibliographic details.

Important qualities of the dielectric substrate include

The microwave dielectric constant
The frequency dependence of this dielectric constant which gives rise to "material dispersion" in which the wave velocity is frequency-dependent
The surface finish and flatness
The dielectric loss tangent, or imaginary part of the dielectric constant, which sets the dielectric loss

The cost

The thermal expansion and conductivity
The dimensional stability with time
The surface adhesion properties for the conductor coatings
The manufacturability (ease of cutting, shaping, and drilling)
The porosity (for high vacuum applications we don't want a substrate which continually "outgasses" when pumped)

Common substrate materials

Plastics are cheap, easily manufacturable, have good surface adhesion, but have poor microwave dielectric properties when compared with other choices. They have poor dimensional stability, large thermal expansion coefficients, and poor thermal conductivity.

Dielectric constant: 2.2 (fast substrate) or 10.4 (slow substrate)
Loss tangent 1/1000 (fast substrate) 3/1000 (slow substrate)
Surface roughness about 6 microns (electroplated)
Low themal conductivity, 3/1000 watts per cm sq per degree

Ceramics are rigid and hard; they are difficult to shape, cut, and drill; they come in various purity grades and prices each having domains of application; they have low microwave loss and are reasonably non-dispersive; they have excellent thermal properties, including good dimensional stability and high thermal conductivity; they also have very high dielectric strength. They cost more than plastics. In principle the size is not limited.

Dielectric constant 8-10 (depending on purity) so slow substrate
Loss tangent 1/10,000 to 1/1,000 depending on purity
Surface roughness at best 1/20 micron
High thermal conductivity, 0.3 watts per sq cm per degree K

Stripline Structures

The stripline typically consists of a line conductor trace sandwiched between two reference planes and a dielectric material. The transmission line, i.e. the trace and planes, form the controlled impedance. The value of the impedance will be determined by its physical construction and electrical characteristics of the dielectric material:

The width and thickness of the signal trace
The dielectric constant and height of the core or pre-preg material either side of the trace
The configuration of trace and planes

Single-ended Striplines

Note that in the following diagrams the signal trace is actually trapezoidal in profile and width W refers to the trace width nearest the upper surface, width W1 refers to the trace width nearest the lower surface.

A stripline differs from a microstrip in that it is a line embedded in a dielectric between two reference planes. There are two variations of stripline configuration — the *centred* or *symmetric* stripline and the *offset* stripline.

INSULATION COORDINATION

Insulation coordination is the correlation of the insulation strengths of components of the high voltage power system, to minimise damage and loss of supply caused by over voltages.

Steps taken to minimise supply interruptions due to overvoltage are:

a) to ensure that system insulation will withstand all normal stresses and most abnormal stresses,

b) to discharge or divert overvoltages which exceed the withstand strength of apparatus,

c) to ensure that breakdowns occur by external flashover, rather than internal failure of equipment such as puncture or breakdown of solid or liquid dielectrics,

d) and to control points at which breakdowns occur, thus avoiding important items of equipment.

Sources of Overvoltage

Overvoltages can be either at system frequency or due to transient surges with higher frequency components.

System Frequency Overvoltages

Overvoltages at the power frequency can be caused by:

a) sudden loss of load on a generator (20%-30% overvoltage),

b) energising an unloaded transmission line (up to 90% overvoltage),

c) unbalanced system faults which may cause unfaulted phase voltages to rise above normal.

Transient Overvoltages

Transient Overvoltages

Power system transient overvoltages may be generated either internally or externally.

Internal generation is from switching surges.

External generation is from lightning strikes.

Electrical Testing of HV Equipment

Electrical testing of HV equipment is carried out to ensure that insulation can withstand normal and surge voltages.

The two main tests carried out are:

a) HV impulse test,

b) HV power frequency test.

HV Impulse Test

The standard impulse test is intended to reproduce the effects of switching transients and lightning strikes.

Refer to FIG 2 which shows the standard 1/50 impulse test waveform.

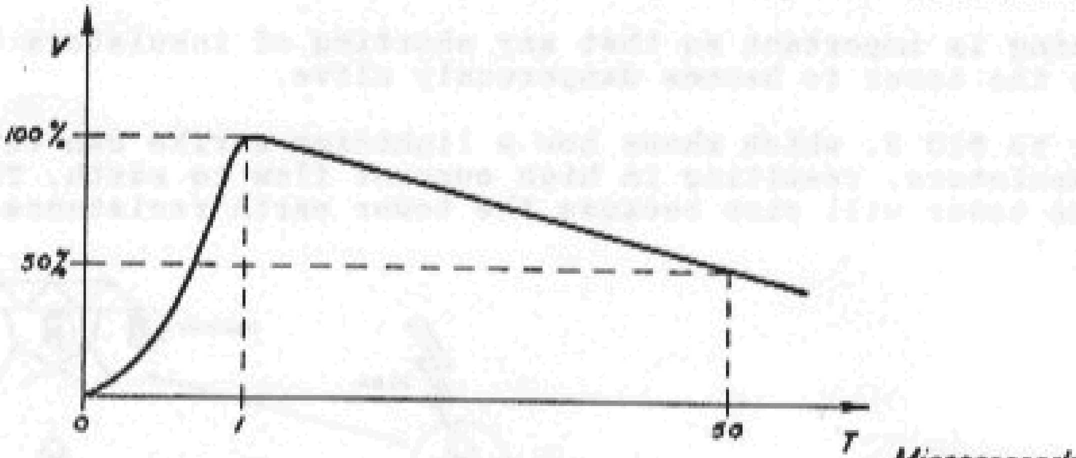


FIG 2

The wave specification of 1/50 indicates that the test voltage rises to the peak value in 1µsec and then drops to 50% of the peak value by 50µsec.

Typical value of test voltage for 330kV equipment is 1050kV (peak).

In particular, they are installed and located for protecting transformers and cables that are expensive the repair, if their paper insulation is damaged by impulse voltages.

Overhead Earthwire (Shield Conductor)

At the very top of each tower on each side, are installed earthing conductors, which run the whole length of the line, and are earthed at each tower.

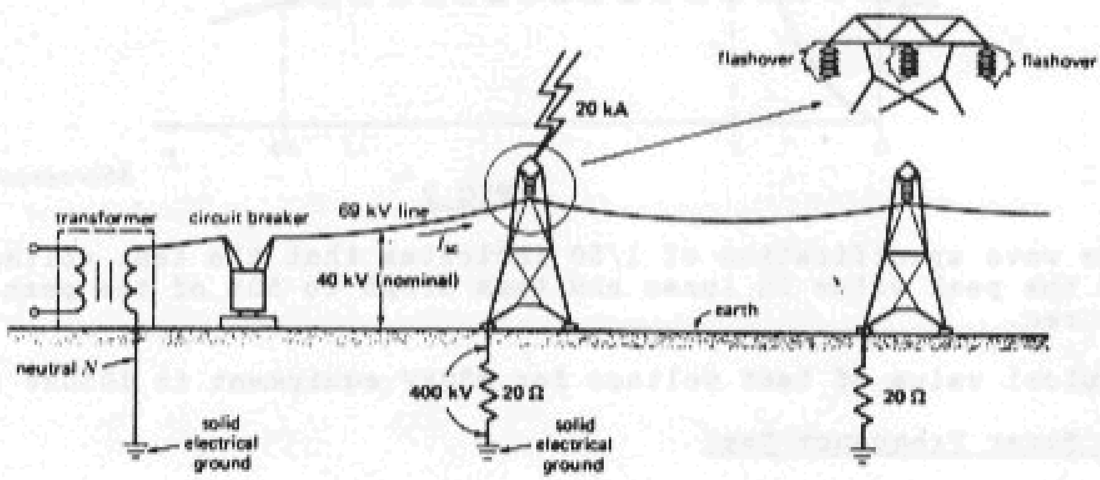
They provide an earthed shield above the live conductors and attract lightning away from the line.

Tower Earthing

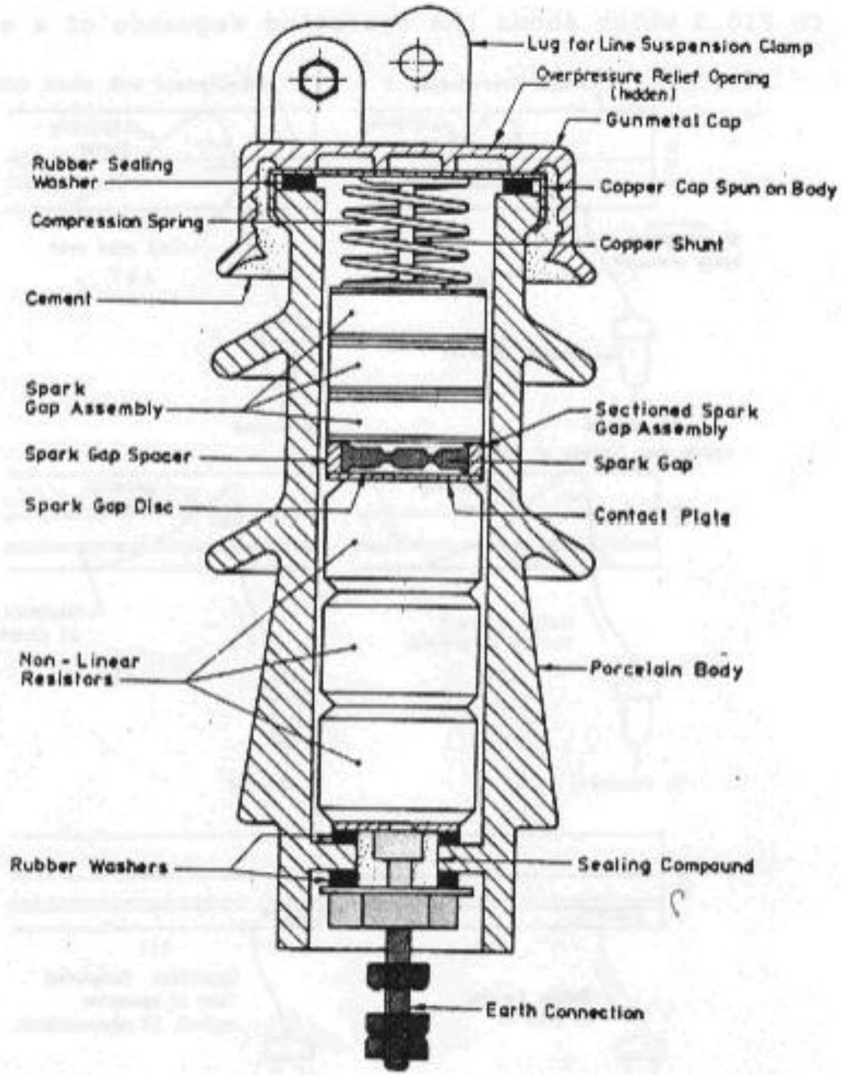
Each tower must be solidly connected to earth and earthing rods and an earth grid are installed at the base of each tower.

Earthing is important so that any shorting of insulators does not cause the tower to become dangerously alive.

Refer to FIG 3. which shows how a lightning strike can cause flashover of insulators, resulting in high current flow to earth. The potential of the tower will rise because the tower earth resistance is high.



Refer to FIG 4 which shows the construction of a typical non-linear resistor type surge diverter.

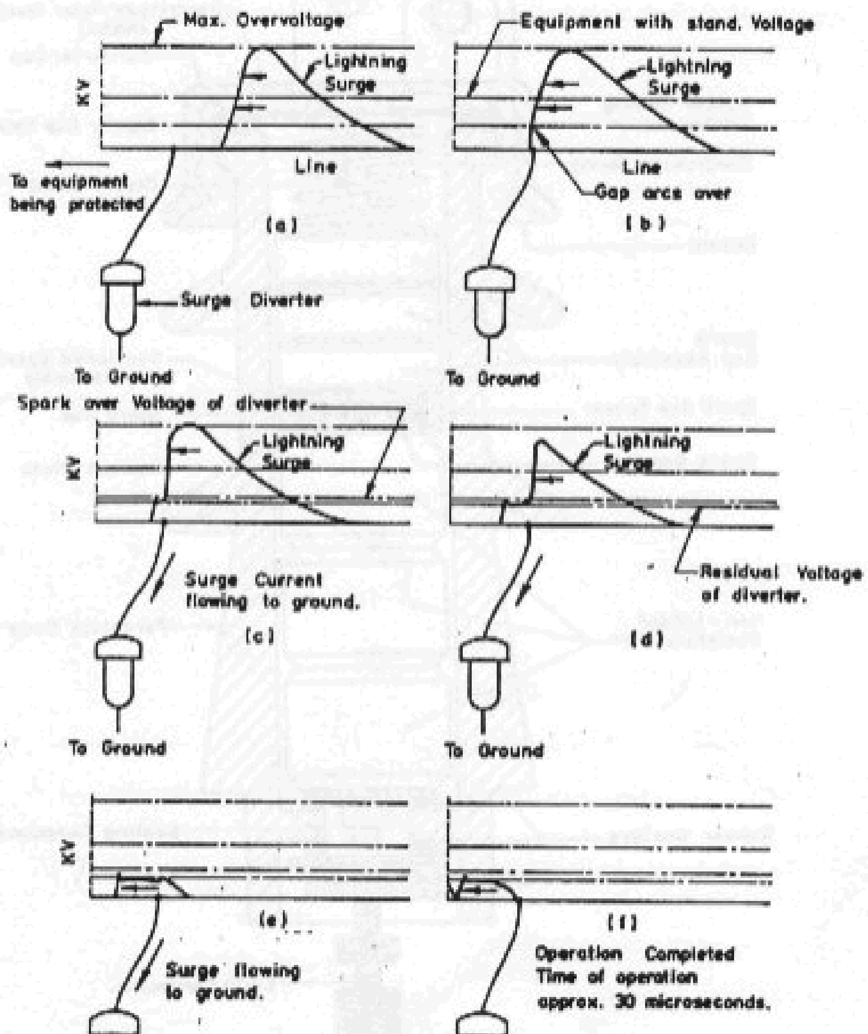


The series spark gaps keep the circuit open under normal conditions.

Sometimes grading resistors are connected in parallel with multiple gaps to assist in voltage distribution.

The assembly is usually evacuated and filled with dry nitrogen at atmospheric pressure to ensure that the operation is not affected by surrounding atmospheric conditions.

Refer to FIG 5 which shows the operating sequence of a surge diverter.



where $\log_e A$ is the constant of integration. Continuing,

$$\log_e Ai_t = -\frac{R}{L}t$$

so that

$$Ai_t = e^{-(R/L)t}$$

and

$$i_t = Be^{-(R/L)t}$$

where $B = 1/A$ = constant.

The complete solution is then

$$i = i_s + Be^{-(R/L)t}$$

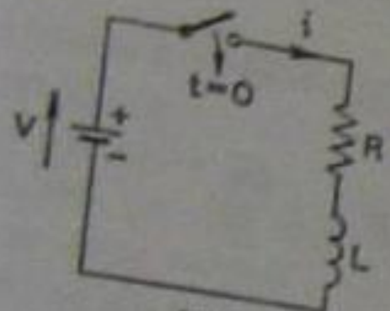
Th

$\ldots_s + Be^{-(R/L)t}$ … then

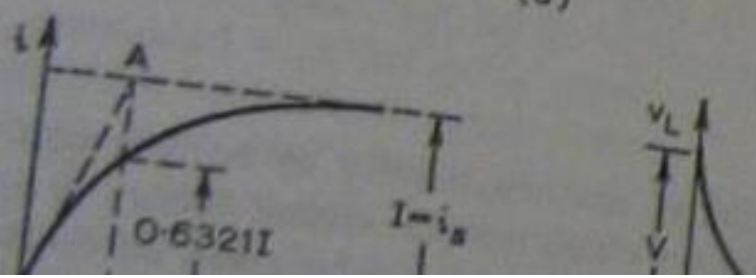
(6.5)

(6.6)

The current i_s is found from simple circuit theory, and the constant B is then determined by substituting a known set of values for i and t in eqn. (6.6). These known values are normally the initial conditions in the circuit.



(a)



Also, from d.c. theory, $i_s = V/R = I$. Substituting in eqn. (6.6) at the instant $t = 0$,

$$0 = \frac{V}{R} + Be^0 \qquad \text{whence} \qquad B = -\frac{V}{R}$$

Again from eqn. (6.6),

$$i = \frac{V}{R} - \frac{V}{R}e^{-(R/L)t}$$

$$= \frac{V}{R}(1 - e^{-(R/L)t})$$

$$= I(1 - e^{-(R/L)t}) \tag{6.7}$$

The curve of i plotted to a base of time is shown in Fig. 6.1(*b*). It is called an *exponential-growth curve*.

The rate of change of current is found by differentiating eqn. (6.7). Thus

$$\frac{di}{dt} = \frac{V}{R}\left(\frac{R}{L}e^{-(R/L)t}\right) = \frac{V}{L}e^{-(R/L)t}$$

The initial rate of change of current is then

$$\left.\frac{di}{dt}\right|_{t=0} = \frac{V}{L} \quad \text{amperes/second} \tag{6.8}$$

Consider now the value of the current when $t = L/R$ seconds. Then from eqn. (6.7),

$$i = I(1 - e^{-1}) = 0{\cdot}632I$$

6.3 Decay of Current in an Inductive Circuit

Consider the circuit shown in Fig. 6.2(*a*). At the datum time $t = 0$, the switch is opened, disconnecting the inductor L and

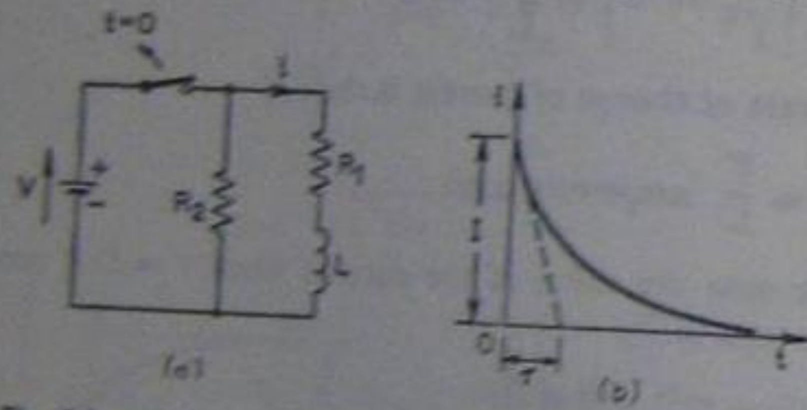


Fig. 6.2 DECAY OF CURRENT IN AN INDUCTIVE D.C. CIRCUIT

resistor R_1 from the supply. Since there is no continuous source of e.m.f. in the circuit formed by L, R_1 and R_2, the steady-state current will be zero. Hence eqn. (6.6) becomes,

$$i = Be^{-(R/L)t} \qquad (6.11)$$

where R = total circuit resistance = $R_1 + R_2$.

As before, at the instant of switching the current through the inductor remains momentarily unchanged, i.e. it has the same value (V/R_1 amperes) as it had before the switch was operated. Hence at $t = 0$, $i = V/R_1 = I$. Therefore from eqn. (6.11),

$$\frac{V}{R_1} = B$$

EXAMPLE 6.1 A coil of 10 H inductance, and 5 Ω resistance is connected in parallel with a 20 Ω resistor across a 100 V d.c. supply which is suddenly disconnected. Find:

(*a*) The initial rate of change of current after switching.
(*b*) The voltage across the 20 Ω resistor initially, and after 0·3 s.
(*c*) The voltage across the switch contacts at the instant of separation.
(*d*) The rate at which the coil is losing stored energy 0·3 s after switching.

(*H.N.C.*)

(*a*) The steady-state current is zero; hence

$$i = Be^{-(R/L)t}$$

where R is the total circuit resistance after switching (25 Ω).

At $t = 0$, the current is 100/5 = 20 A, i.e. the current through the coil immediately prior to the opening of the switch is 20 A. Thus

$$20 = Be^{0} = B$$

whence

$$i = 20e^{-2 \cdot 5t}$$

$$\text{Initial rate of change of current} = \left.\frac{di}{dt}\right|_{t=0} = -20 \times 2{\cdot}5e^{-2 \cdot 5t}\Big|_{t=0}$$

$$= \underline{\underline{-50\ \text{A/s}}}$$

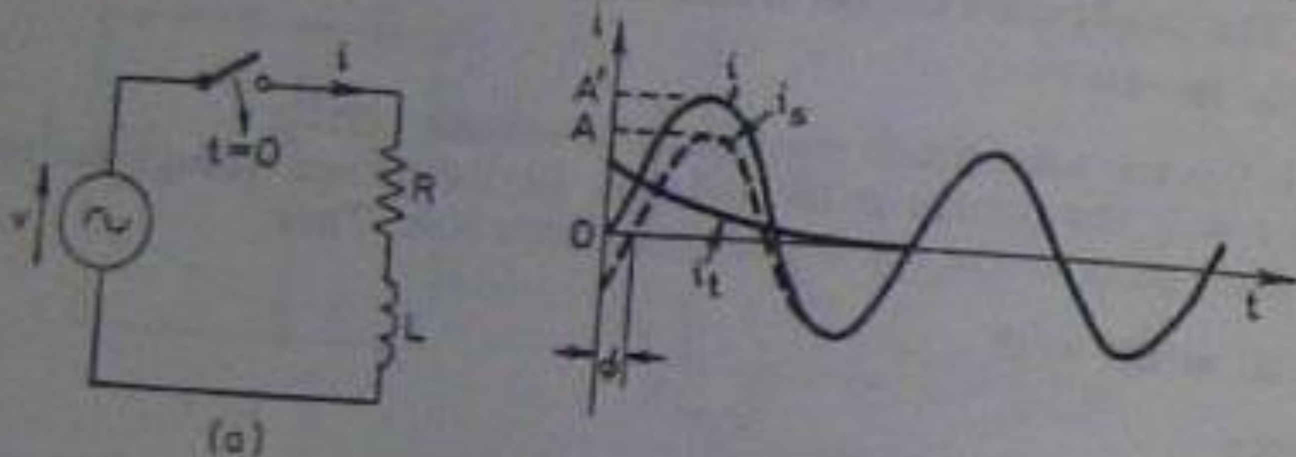
The negative sign indicates that the current is decreasing.

(*b*) The current through the 20 Ω resistor after the supply has been disconnected is i ampere.

...stored energy.

6.4 Growth of Current in an Inductive Circuit (A.C.) (Fig. 6.3)

Let a voltage given by $v = V_m \sin(\omega t + \psi)$ be suddenly applied to an RL series inductive circuit at the instant $t = 0$, i.e. the voltage



(b)

Fig. 6.3 A.C. SWITCHING TRANSIENTS

6.7 Discharge of a Capacitor through a Resistor

Suppose that a capacitor which is originally charged to V_c volts is discharged through a resistor of R ohms (Fig. 6.5(*a*)). Since there is

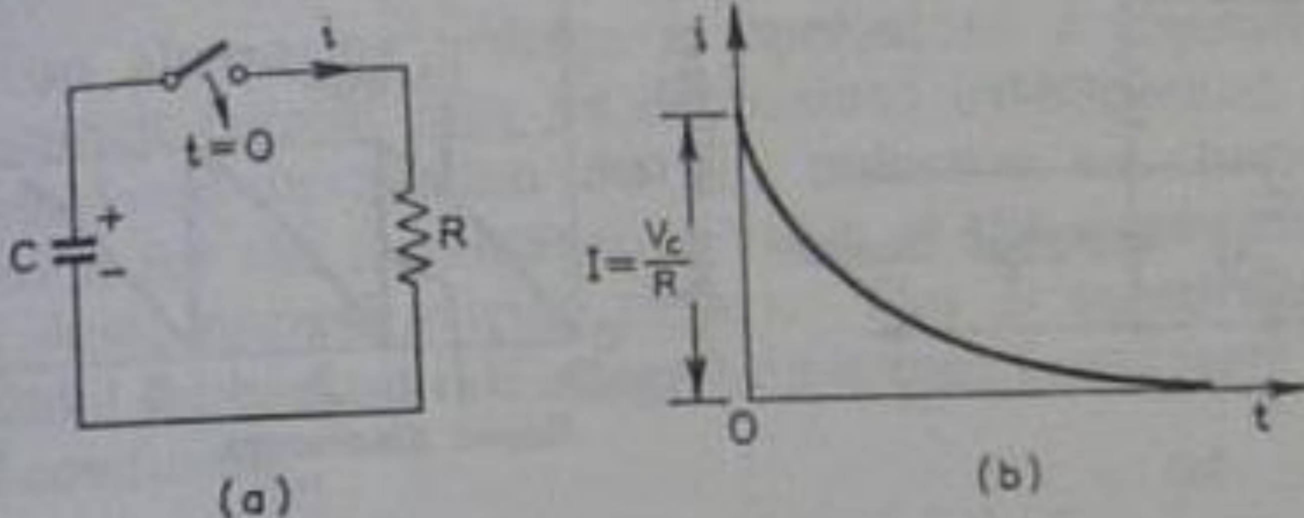


Fig. 6.5 DISCHARGING A CAPACITOR THROUGH A RESISTOR

...discussed in Section 3-2

EXAMPLE 3-1. In the basic circuit of Fig. 3-1 the load consumes 1500 W at a power factor of 0.80 and a voltage of 460 V. The transmission impedance $Z = 2 + j5\ \Omega$. Calculate the sending-end voltage V_s for:

a. a lagging power factor.

b. a leading power factor.

Solution:

a. arc cos 0.80 = 36.9°

$$I = \frac{1500}{460 \times 0.8} = 4.08\ \text{A}$$

$$\bar{V}_r = 460 \underline{/0^\circ}\ \text{V}$$

$$\bar{I} = 4.08 \underline{/-36.9^\circ} = 3.26 - j2.45\ \text{A}$$

$I_p = 3.26 \qquad I_q = -2.45$

$$
\begin{aligned}
\bar{V}_s &= \bar{V}_r + \bar{I}Z \\
&= 460\angle 0^\circ + (4.08\angle -36.9^\circ)(2 + j5) \\
&= 460\angle 0^\circ + (4.08\angle -36.9^\circ)(5.39\angle 68.2^\circ) \\
&= 460\angle 0^\circ + 22.0\angle 31.3^\circ \\
&= 460 + 18.8 + j11.4 \\
&= 479 + j11.4 \\
&= 479\angle 1.4^\circ \text{ V}
\end{aligned}
$$

or,

$$
\begin{aligned}
\bar{V}_s &= 460 + (3.26 - j2.45)(2 + j5) \\
&= (460 + 6.52 + 12.3) + j(-4.9 + 16.3)
\end{aligned}
$$

$I_pR = 6.52 \qquad I_qX = 12.3 \qquad$ direct parts of $\bar{I}Z$

$I_qR = -4.9 \qquad I_pX = 16.3 \qquad$ quadrature parts of $\bar{I}Z$

$$
\begin{aligned}
\bar{V}_s &= 479 + j11.4 \\
&= 479\angle 1.4^\circ
\end{aligned}
$$

Note how the quadrature parts of $\bar{I}Z$ contribute insignificantly to the magnitude V_s.

b. $\bar{I} = 4.08\,\underline{/36.9^\circ} = 3.26 + j2.45$

$I_p = 3.26 \qquad I_q = 2.45$

$$
\begin{aligned}
V_s &= 460\,\underline{/0^\circ} + (4.08\,\underline{/36.9^\circ})(5.39\,\underline{/68.2^\circ}) \\
&= 460\,\underline{/0^\circ} + 22.0\,\underline{/105.1^\circ} \\
&= 460 + (-5.73 + j21.2) \\
&= 454 + j21.2 \\
&= 455\,\underline{/2.7^\circ}\text{ V}
\end{aligned}
$$

EXAMPLE 3-2. In the basic circuit of Fig. 3-1 the load consumes 4000 W at a power factor of 0.8 lagging. The sending-end voltage is 600 V and the impedance $Z = 1 + j4\ \Omega$. Determine the load voltage.

Solution. Taking $\bar{V}_r$ as reference,

$$\bar{V}_r = V_r \angle \theta$$

$$\bar{V}_s = 600 \angle 0^\circ$$

$$Z = 1 + j4 = 4.12 \angle 76^\circ$$

$$\bar{I} = \frac{\bar{V}_s - \bar{V}_r}{Z} = \frac{600 \angle 0^\circ - V_r \angle \theta}{4.12 \angle 76^\circ}$$

$$\text{arc cos } 0.8 = 36.9^\circ$$

$$P_{ar} = \frac{4000}{0.8} = 5000 \text{ VA}$$

$$S_r = 5000 \angle 36.9^\circ$$

$$= \bar{V}_r \bar{I}^*$$

$$= (V_r \angle \theta)\left(\frac{600 \angle 0^\circ - V_r \angle -\theta}{4.12 \angle -76^\circ}\right)$$

Hence,

$$\frac{600 \angle 0^\circ - V_r \angle -\theta}{4.12 \angle -76^\circ} = \frac{5000 \angle 36.9^\circ}{V_r \angle \theta}$$

Multiplying through by $4.12 \angle -76^\circ$,

$$600 \angle 0^\circ - V_r \angle -\theta = \frac{20{,}600 \angle -\theta - 39.1^\circ}{V_r}$$

$$V_r \angle{-\theta} = 600 \angle{0^\circ} - \frac{20{,}600}{V_r} \angle{-\theta - 39.1^\circ}$$

Taking conjugates,

$$V_r \angle{\theta} = 600 \angle{0^\circ} - \frac{20{,}600}{V_r} \angle{\theta + 39.1^\circ}$$

This equation is solved iteratively in the following manner: using an estimate of $\bar{V}_r$, the right-hand side of the equation produces a new estimate of $\bar{V}_r$. The latter is used in its turn in the equation to obtain another $\bar{V}_r$, and so on. The process is repeated until $\bar{V}_r$ remains practically constant. Taking $\bar{V}_r = 590 \angle{0^\circ}$ as a starting estimate,

$$V_r \angle{\theta} = 600 - \frac{20{,}600}{590} \angle{0 + 39.1^\circ} = 573.3 \angle{-2.2^\circ}$$

Repeating the procedure,

$$V_r \angle{\theta} = 600 - \frac{20{,}600}{573.3} \angle{-2.2^\circ + 39.1^\circ} = 571.7 \angle{-2.2^\circ}$$

$$V_r \angle{\theta} = 600 - \frac{20{,}600}{571.7} \angle{-2.2^\circ + 39.1^\circ} = 571.6 \angle{-2.2^\circ}$$

This, then, is the receiving-end voltage.

EXAMPLE 3-4. Solve Example 3-3 by the single-phase equivalent method.

Solution:

$$P = 3000 \text{ kW}$$

$$\text{power factor} = 0.8 \text{ lag}$$

$$V_r = 22{,}000 \text{ V} \qquad \text{(reference)}$$

$$Z = 3 + j10 = 10.5 \underline{/73.3^\circ} \ \Omega$$

$$I_E = \frac{P_{3\phi}}{V_{LL} \cos \phi} \qquad (3\text{-}13)$$

$$= \frac{3{,}000{,}000}{22{,}000 \times 0.8}$$

$$\bar{I}_E = 171 \underline{/-37^\circ} \text{ A}$$

$$\bar{V}_{LLS} = \bar{V}_{LLr} + \bar{I}_E Z \qquad (3\text{-}16)$$

$$= 22{,}000 \underline{/0^\circ} + (171 \underline{/-37^\circ})(10.5 \underline{/73.3^\circ})$$

$$= 22{,}000 \underline{/0^\circ} + 1790 \underline{/36.3^\circ}$$

$$= 22{,}000 + 1440 + j1060$$

$$= 23{,}440 + j1060 = 23{,}450 \underline{/2.6^\circ} \text{ V}$$

The power lost is

$$P = I_E^2 R \qquad (3\text{-}15)$$

$$= (171)^2 \times 3 = 87{,}500 \text{ W}$$

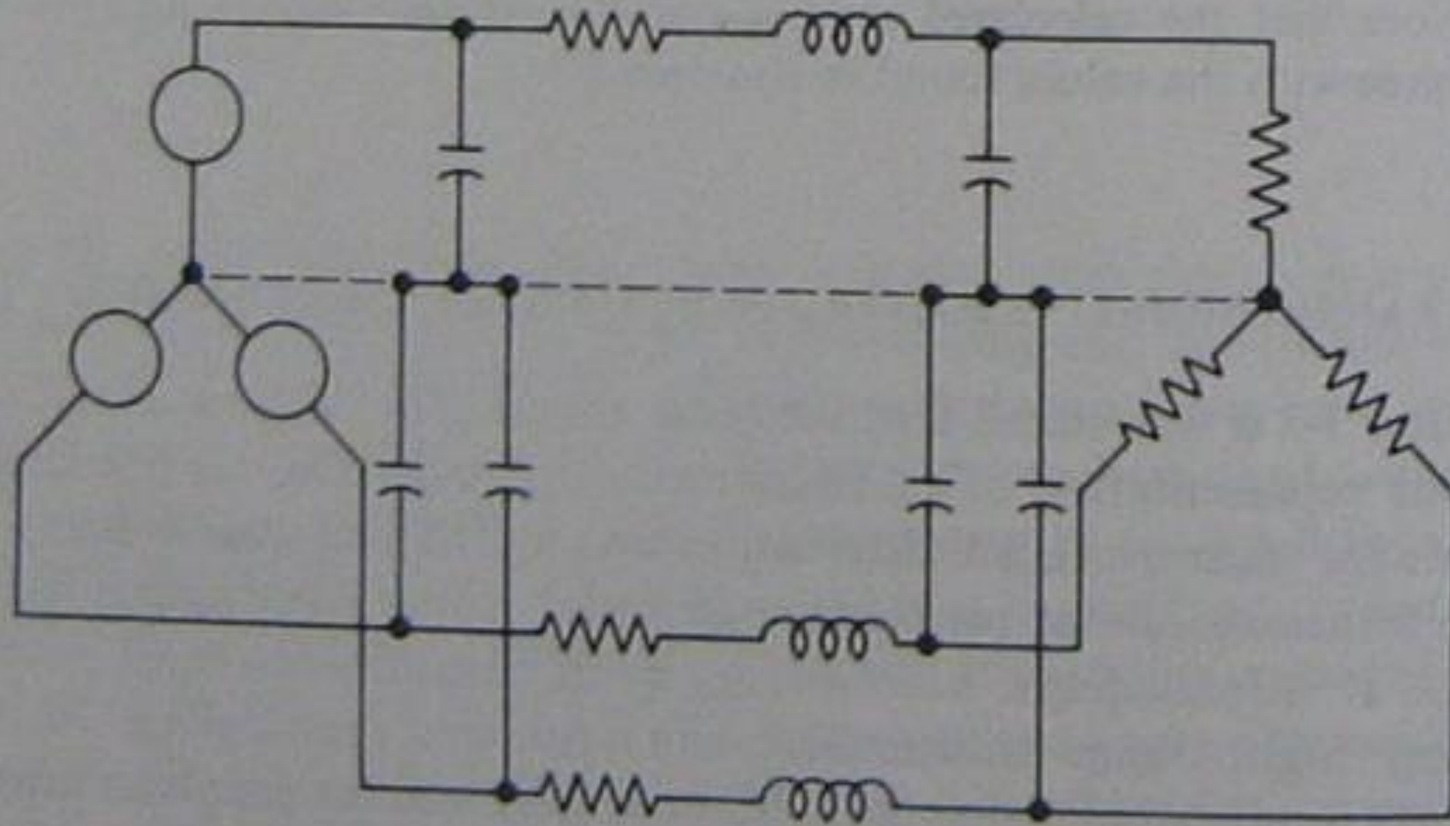


FIG. 3-20. A three-phase system showing the resistance, the inductance, and the capacitance of the transmission line. Pi-line representation.

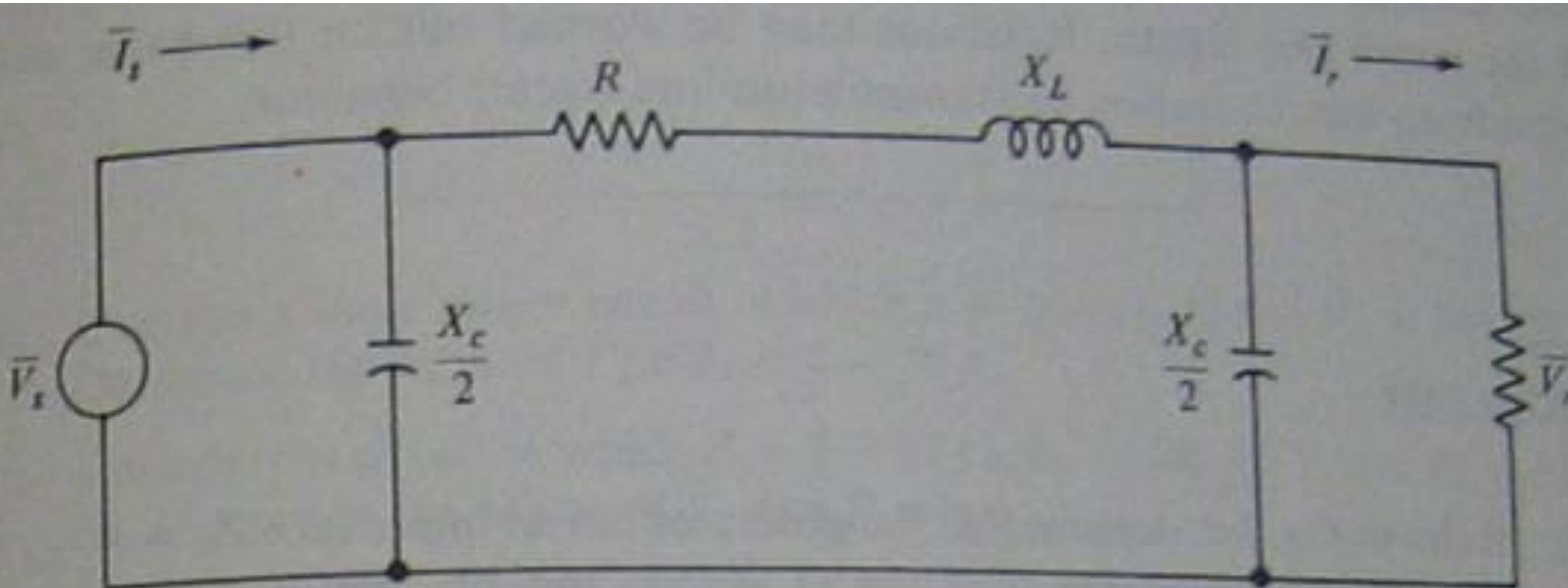


FIG. 3-21. The line-to-neutral (or single-phase equivalent) representation of the three-phase system, Fig. 3-20. *R*, *L*, and *C* are the total circuit resistance, inductance, and capacitance per conductor. The π-line representation.

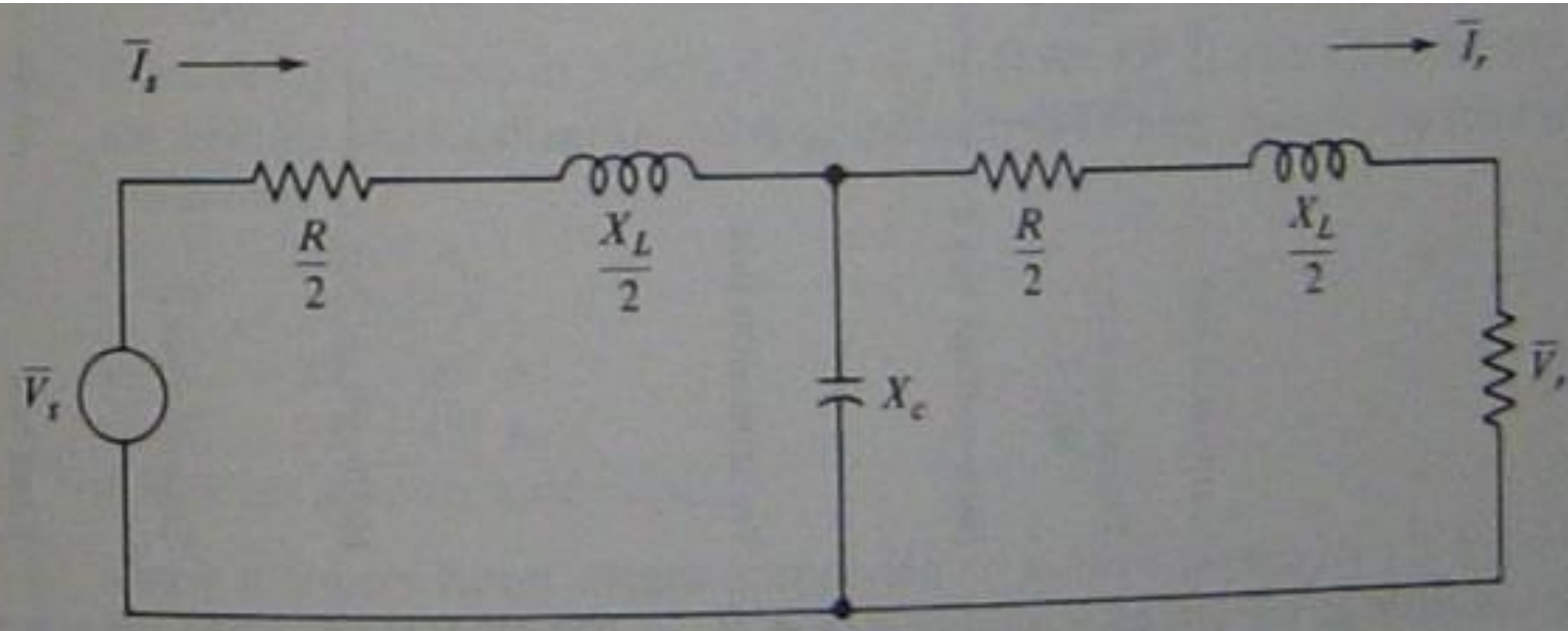


FIG. 3-22. The T-line representation of a transmission system.

4-6. SPECIFICATION OF LINES AND CABLES

Using known wire size and spacing the designer of an overhead line and cable circuit is able to calculate the ohms impedance of the circuit. To convert this impedance to per unit impedance it is necessary to determine base ohms for the circuit. This is done by assuming an arbitrary base voltampere rating and an arbitrary base voltage rating. The volt-ampere rating may be that assigned to other pieces of equipment on the system. The voltage rating is usually the nominal voltage of the line as determined by the voltage rating of the transformer supplying the circuit. The base impedance may then be determined from Eqs. (4-1) and (4-2). With line impedance (in ohms) calculated, the per unit impedance of the line may be determined from Eq. (4-3) as

$$Z_{pu} = \frac{Z_{ohms}}{Z_{base}} = Z_{ohms} \frac{VA_{base}}{V_{base}^2} \qquad (4\text{-}7)$$

$$Z_{ohms} = Z_{1pu} Z_{B1} = Z_{1pu} \frac{V_{B1}}{I_{B1}} = Z_{1pu} \frac{V_{B1}}{VA_{B1}/V_{B1}}$$

$$= Z_{1pu} \frac{V_{B1}^2}{VA_{B1}}$$

Similarly, in system 2,

$$Z_{ohms} = Z_{2pu} \frac{V_{B2}^2}{VA_{B2}}$$

Since the actual ohms of the machine are unchanged by a change of base, we can equate these two expressions for Z_{ohms} to obtain

$$Z_{1pu} \frac{V_{B1}^2}{VA_{B1}} = Z_{2pu} \frac{V_{B2}^2}{VA_{B2}}$$

Solving for Z_{2pu} we obtain

$$Z_{2pu} = Z_{1pu} \frac{V_{B1}^2}{V_{B2}^2} \frac{VA_{B2}}{VA_{B1}} \tag{4-8}$$

This equation provides us with a means for expressing the per unit impedance of a machine in one base when its per unit impedance has already been expressed on a different base.

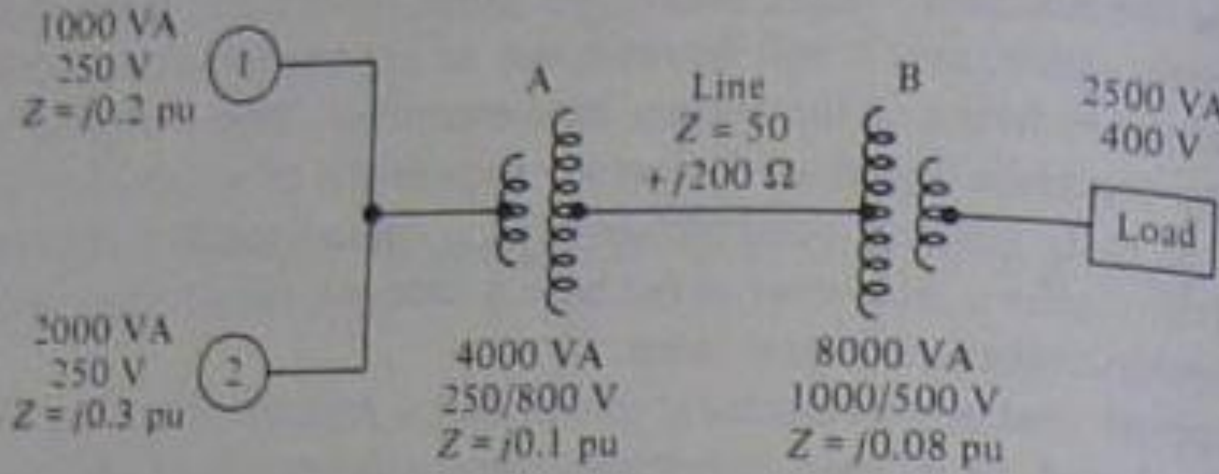


FIG. 4-7. An example power system with the characteristics of each component expressed independently.

taken as the base voltage for this part of the system, the line has a base voltage of 800 volts as determined by the turns ratio of transformer *A*. Transformer *B* was obviously not designed for this particular installation, as it is rated at a higher voltage than necessary. However, its turns ratio is proper to supply the load at its rated voltage, 400 volts.

To solve a problem involving this system by the per unit method, it is necessary to determine the impedance of all components on the same base. The base selected is arbitrary. For illustration, let 5000 VA be chosen as the base and determine the per unit impedance of each part. The determination for the machines and transformers may be made using Eq. (4-8), while that for the line may be made by Eq. (4-7).

Machine 1

$$Z_{pu(5000)} = j0.2\frac{250^2}{250^2}\frac{5000}{1000} = j1.0 \text{ pu}$$

Machine 2

$$Z_{pu(5000)} = j0.3\frac{250^2}{250^2}\frac{5000}{2000} = j0.75 \text{ pu}$$

Transformer *A*

$$Z_{pu(5000)} = j0.1\frac{250^2}{250^2}\frac{5000}{4000} = = j0.125 \text{ pu}$$

Line

$$Z_{pu(5000)} = (50 + j200)\frac{5000}{800^2} = (0.39 + j1.56) \text{ pu}$$

The entire system may now be represented by the impedance diagram of Fig. 4-8, in which *all* components are represented on a common 5000-VA base. It is seen that the system is now a simple combination of several basic power circuits, which may be further simplified if desired.

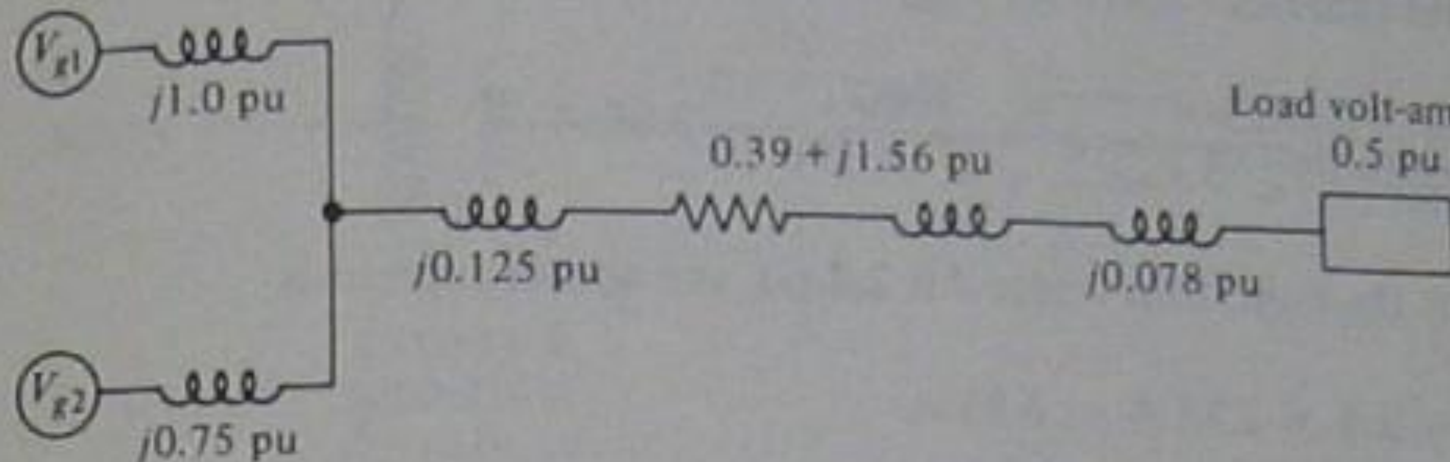


FIG. 4-8. The example system of Fig. 4-7 with the impedance of each component expressed on a 5000-VA base.

EXAMPLE 4-1. Consider the three-phase system shown in Fig. 4-9. Draw for it an impedance diagram, expressing all impedances in per unit referenced to

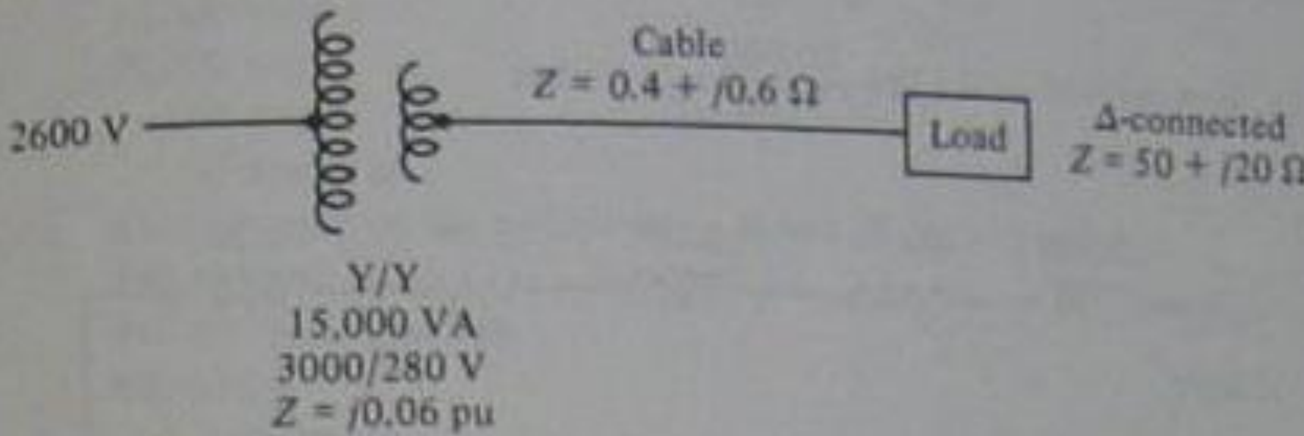


FIG. 4-9. An example of a three-phase system with component characteristics expressed independently.

a common base of 20,000 volt-amperes and 2600 volts on the high-voltage side. Using this impedance diagram, calculate the high- and low-voltage line currents.

Solution.

$$V_{base} \text{ on h.v. side} = 2600 \text{ V}$$

$$V_{base} \text{ on l.v. side} = 2600\,\frac{280}{3000} = 242.7 \text{ V}$$

Transformer:

$$Z_{pu} = j0.06\frac{(3000)^2}{(2600)^2}\frac{20{,}000}{15{,}000} = j0.107 \text{ pu}$$

Cable:

$$Z_{pu} = (0.4 + j0.6)\frac{20{,}000}{(242.7)^2} = 0.136 + j0.204 \text{ pu}$$

Load:

$$Z_{pu} = (50 + j20)\frac{20{,}000/3}{(242.7)^2} = 5.66 + j2.26 \text{ pu}$$

or

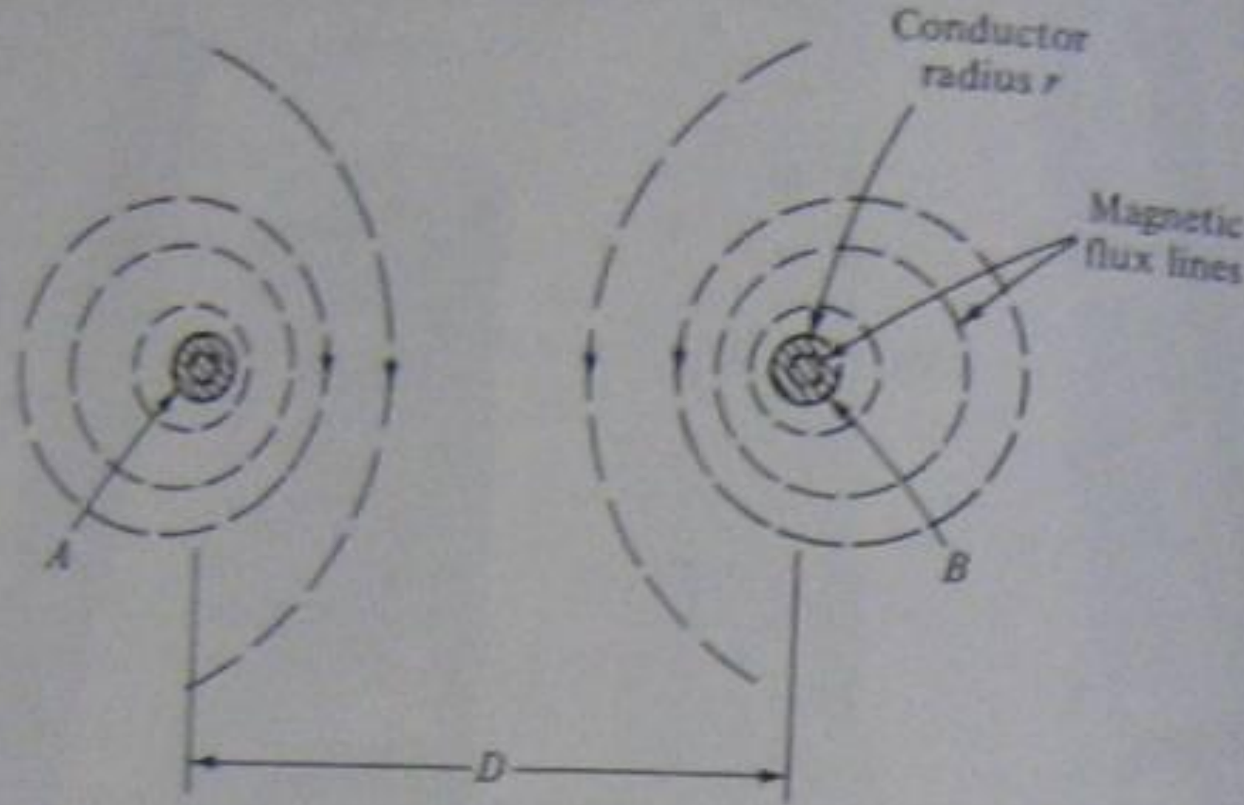


FIG. 5-2. The magnetic field associated with a single-phase line.

The inductance of a circuit as shown in Fig. 5-2 may be calculated from electromagnetic field relations, a subject beyond the scope of the present discussions. Assuming solid conductors carrying direct current, the inductance per meter is found to be

$$L = 2 \times 10^{-7}\left(\log_e \frac{D}{r} + \frac{1}{4}\right) \tag{5-1}$$

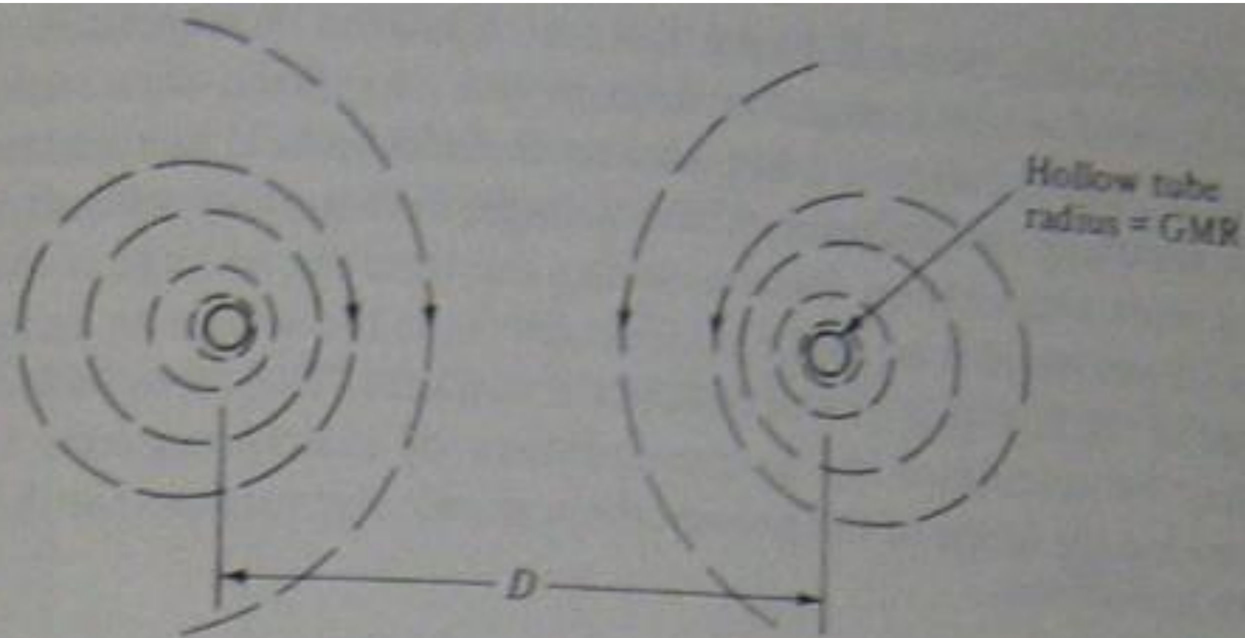


FIG. 5-3. A single-phase line with conductors of hollow tubes illustrating the meaning of geometric mean radius.

With the inductance known, we may apply Eq. (2-65),

$$X_L = 2\pi f L \tag{2-65}$$

nd write an expression for the inductive reactance line to neutral (or per onductor):

$$X_L = 2\pi f 0.741 \times 10^{-3} \log_{10} \frac{D}{\text{GMR}} \quad \text{ohms/mile} \tag{5-4}$$

c. Capacitance and Capacitive Reactance. The physical nature of the capacitance of a transmission circuit is illustrated with reference to Fig. 5-4. The two conductors, A and B, similar to those of Fig. 5-2, are

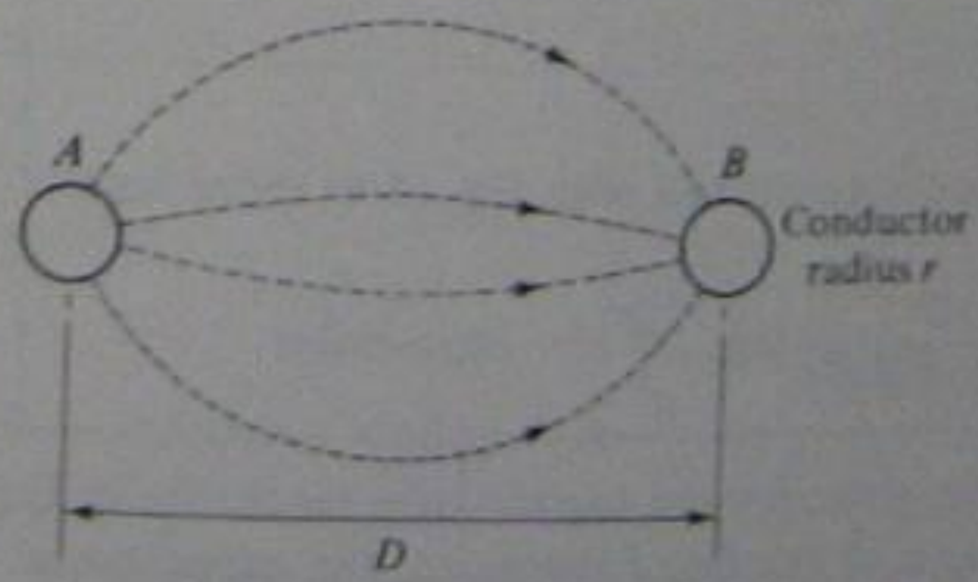


FIG. 5-4. The electric field associated with a single-phase line.

$$C = \frac{2\pi\epsilon}{\log_e (D/r)} \quad \text{farad/meter} \qquad \epsilon = \frac{10^{-9}}{36\pi}\ \text{F/m} \quad \text{for air} \tag{5-5}$$

$$C = \frac{0.0388}{\log_{10} (D/r)} \quad \text{microfarad/mile} \tag{5.6}$$

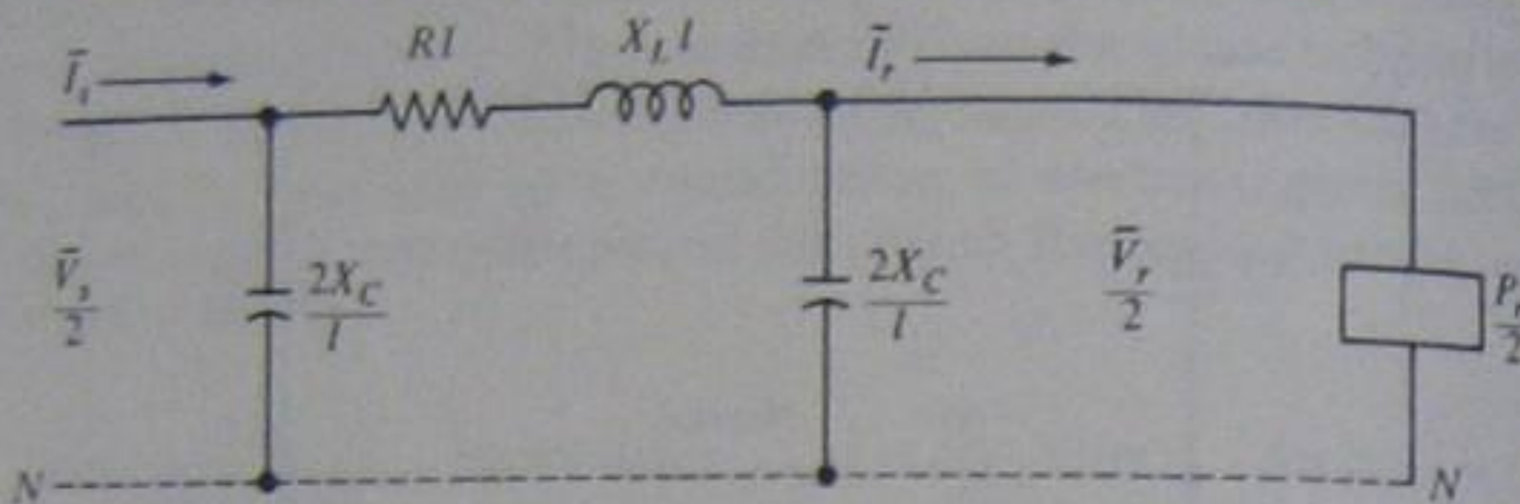


FIG. 5-8. A line-to-neutral model of one leg of a single-phase line. This may be used as the line-to-neutral model of a three-phase line or the single-phase equivalent of a three-phase line.

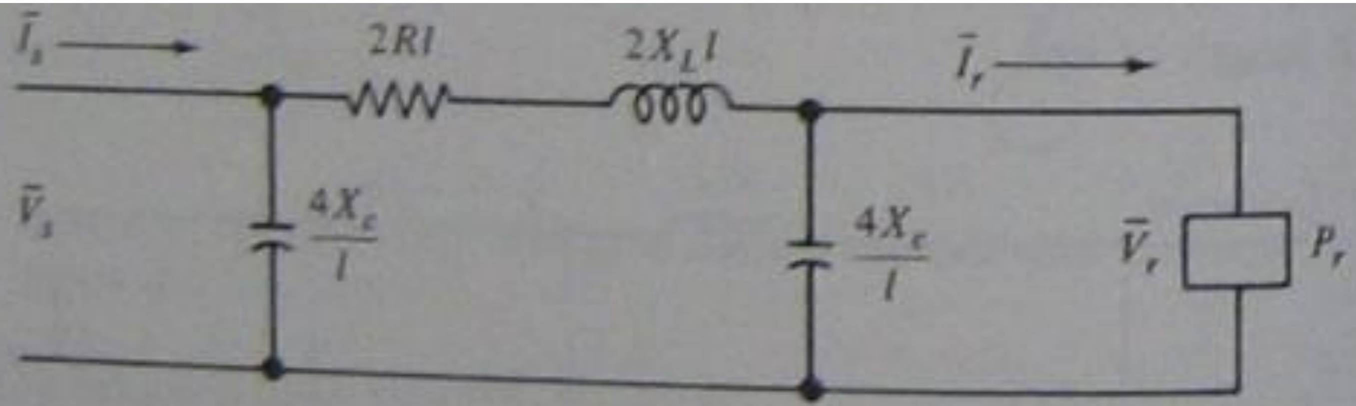


FIG. 5-9. The complete circuit model of a single-phase line.

EXAMPLE 5-2. Determine the constants and π-line model of a single-phase line having the following specifications:

conductor	300,000 cir mil, 19-strand copper
spacing D	12 ft
length l	25 miles
frequency	60 Hz

Solution. From Table A-2 it may be seen that this conductor has the following characteristics:

outside diameter	0.629 in. ($r = 0.0262$ ft)
geometric mean radius	0.01987 ft
resistance per mile	0.1966 Ω (at 25°C)

R_t, total resistance (per conductor) is $R \times l$, or

$$R_t = 0.1966 \times 25 = 4.92\ \Omega$$

The inductance (per conductor) is

$$L = 0.741 \times 10^{-3} \log_{10} \frac{D}{\text{GMR}} \tag{5-3}$$

$$= 0.741 \times 10^{-3} \log_{10} \frac{12}{0.01987}$$

$$= 2.06 \times 10^{-3}\ \text{H/mile}$$

The total inductance per conductor is, therefore,

$$L_t = L \times l = (2.06 \times 10^{-3})(25)$$

$$= 51.5 \times 10^{-3}\ \text{H}$$

The capacitance (per conductor) is

$$C = \frac{0.0388}{\log_{10}(D/r)} \qquad (5\text{-}6)$$

$$= \frac{0.0388}{\log(12/0.0262)}$$

$$= 0.0146\ \mu\text{F/mile}$$

The total capacitance per conductor is

$$C_t = C \times l = 0.0146 \times 25 = 0.365\ \mu\text{F}$$

The π-line circuit model (line to neutral) with half of the capacitance on each end is as shown in Fig. 5-10. If the line operates at 60 Hz, the imped-

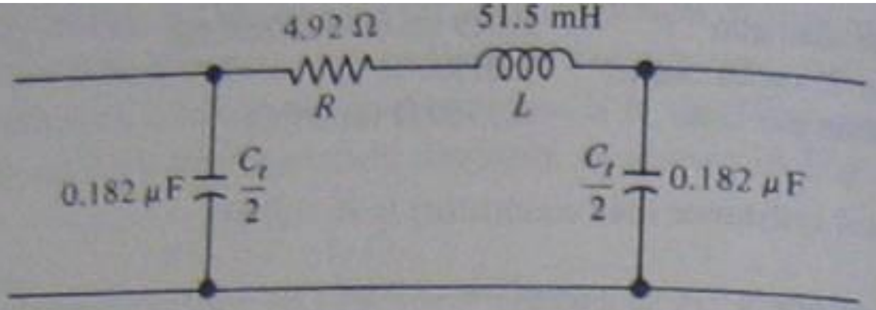


FIG. 5-10. π-line circuit model showing resistance, inductance, and capacitance, line-to-neutral.

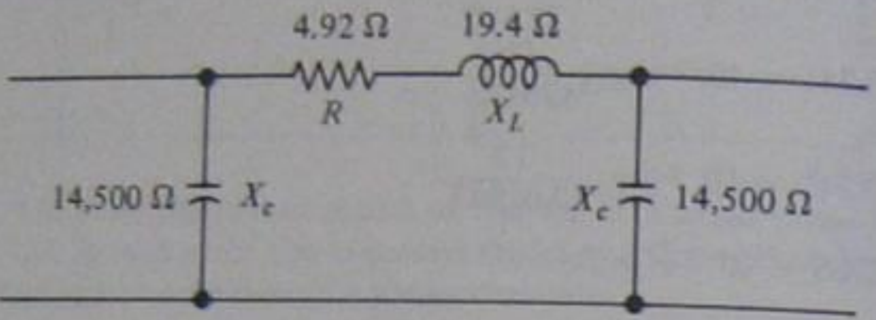


FIG. 5-11. Sixty-hertz line-to-neutral circuit model of Fig. 5-10.

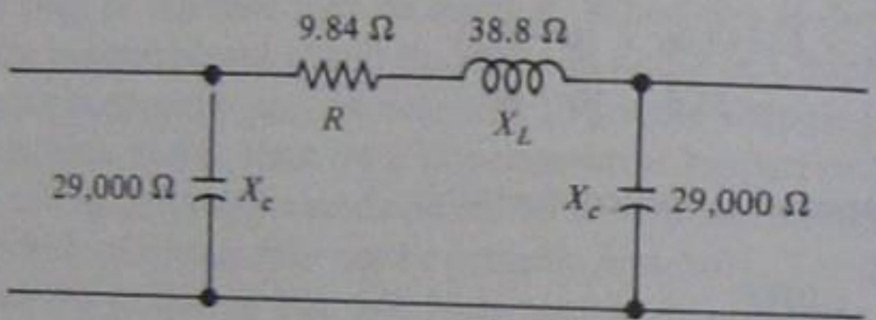


FIG. 5-12. Total circuit model.

$$D = \sqrt[3]{D_{XY} D_{YZ} D_{ZX}}$$

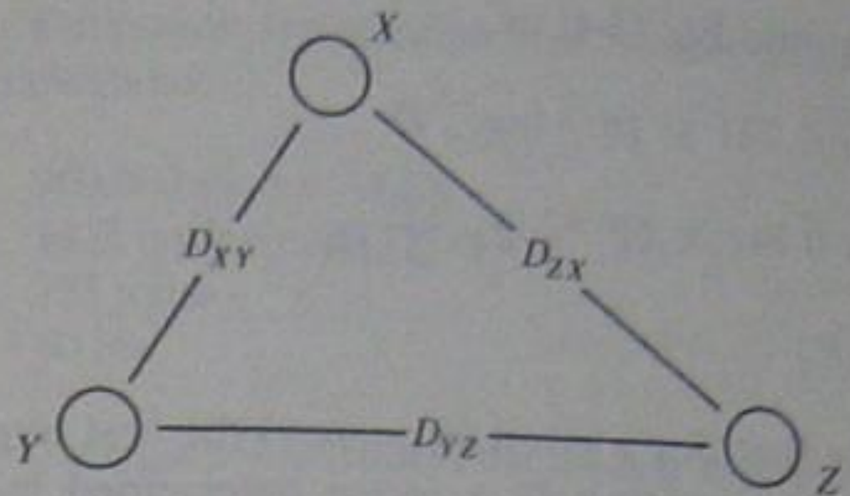


FIG. 5-13. A three-phase power line with unequal spacings between the three conductors X, Y, and Z.

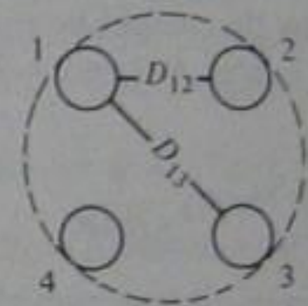


FIG. 5-14. A conductor formed by a bundle of four cables.

calculations the equivalent geometric mean radius is given by Eq. (5-9). In this equation GMR_1 is the GMR applying to the individual cables making up the bundle. Capacitive reactance calculations are made using an equivalent radius given by Eq. (5-10), in which r_1 is the physical radius of the individual cables making up the bundle. With these two modifications, Eqs. (5-4) and (5-7) may be used to calculate the inductive reactance and the capacitive reactance per mile of line.

$$GMR_{eq} = \sqrt[n]{GMR_1 D_{12} D_{13} \cdots D_{1n}} \tag{5-9}$$

$$r_{eq} = \sqrt[n]{r_1 D_{12} D_{13} \cdots D_{1n}} \tag{5-10}$$

f. Tables of Line Constants. Data have been prepared in tabular form which make possible determination of overhead-line constants without resorting to use of equations for calculation. The construction of these tables may be explained by reference to Eqs. (5-4) and (5-7). From the well-known relation

$$\log \frac{A}{B} = \log A + \log \frac{1}{B}$$

it is possible to rewrite Eq. (5-4) as

$$X_L = 2\pi f \times 0.741 \times 10^{-3} \log_{10} D + 2\pi f \times 0.741 \times 10^{-3} \log_{10} \frac{1}{\text{GMR}} \tag{5-11}$$

$$X_L = X_d + X_a \tag{5-12}$$

We may note that (for a given frequency) the first term of Eq. (5-11) is dependent only on the spacing D, a factor determined by the geometrical arrangement of the conductors. The second term of Eq. (5-11) (for a given frequency) is dependent only on the GMR, a value which depends upon the particular conductor design selected for the line. It is therefore possible to make a tabulation (Table A-4) in which the value of

$$X_d = 2\pi f \times 0.741 \times 10^{-3} \log_{10} D \tag{5-13}$$

is represented for each of a number of different values of D covering the range of conductor separations that might be expected in practical line construction. Other tabulations (Tables A-2 and A-3) may be prepared showing the value of

$$X_a = 2\pi f \times 0.741 \times 10^{-3} \log_{10} \frac{1}{\text{GMR}} \tag{5-14}$$

for each of the many conductor designs available for use in construction. Now, to determine X_L for a given line design, it is only necessary to select the appropriate value of X_d from Table A-4 and to add it to the appropriate value of X_a obtained from Table A-2 or A-3.

The preparation of tables for the determination of capacitive reactance may be explained by rewriting Eq. (5-7) as

$$X_c = \frac{10^6}{2\pi f \times 0.0388} \log_{10} D + \frac{10^6}{2\pi f \times 0.0388} \log_{10} \frac{1}{r} \tag{5-15}$$

$$X_c = X'_d + X'_a \tag{5-16}$$

$$X'_d = \frac{10^6}{\cdots}$$

EXAMPLE 5-3. Determine the constants of a three-phase line having the following specifications:

conductor	900,000 cir mil ACSR
spacing	14 ft horizontally ○ 14 ft ○ 14 ft ○
length l	125 miles
frequency	60 Hz

Solution. For computation purposes the spacing D is determined by

$$D = \sqrt[3]{D_{XY} D_{YZ} D_{ZX}}$$
$$= \sqrt[3]{14 \times 14 \times 28} = 17.6 \text{ ft} \tag{5-8}$$

From here on the determination of the impedance values for the circuit model could proceed by the method shown in Example 5-2. Instead, we shall make use of tabular values. From Table A-3 we obtain the following values:

resistance per mile (60 Hz) = 0.104 ohm

$$X_a = 0.393 \text{ ohm/mile}$$
$$X'_a = 0.0898 \text{ megohm-mile}$$

From Table A-4 we obtain for $D = 17.6$ ft, 60 Hz,

$$X_d = 0.3480 \text{ ohm/mile (by interpolation)}$$

From Table A-5 we obtain for $D = 17.6$ ft, 60 Hz,

$$X'_d = 0.0851 \text{ megohm-mile}$$

Then, by Eq. (5-12),

$$X_L = X_d + X_a = 0.348 + 0.393 = 0.741 \text{ ohm per mile}$$

and, by Eq. (5-16),

$$X_c = X'_d + X'_a = 0.0851 + 0.0898 = 0.1749 \text{ megohm-miles}$$

[illegible] be formed (see Fig. 5-15) exactly

EXAMPLE 5-4. Suppose that the three-phase load on the end of the line is 12,000 kilowatts, unity power factor, supplied at 120 kilovolts (Fig. 5-16).

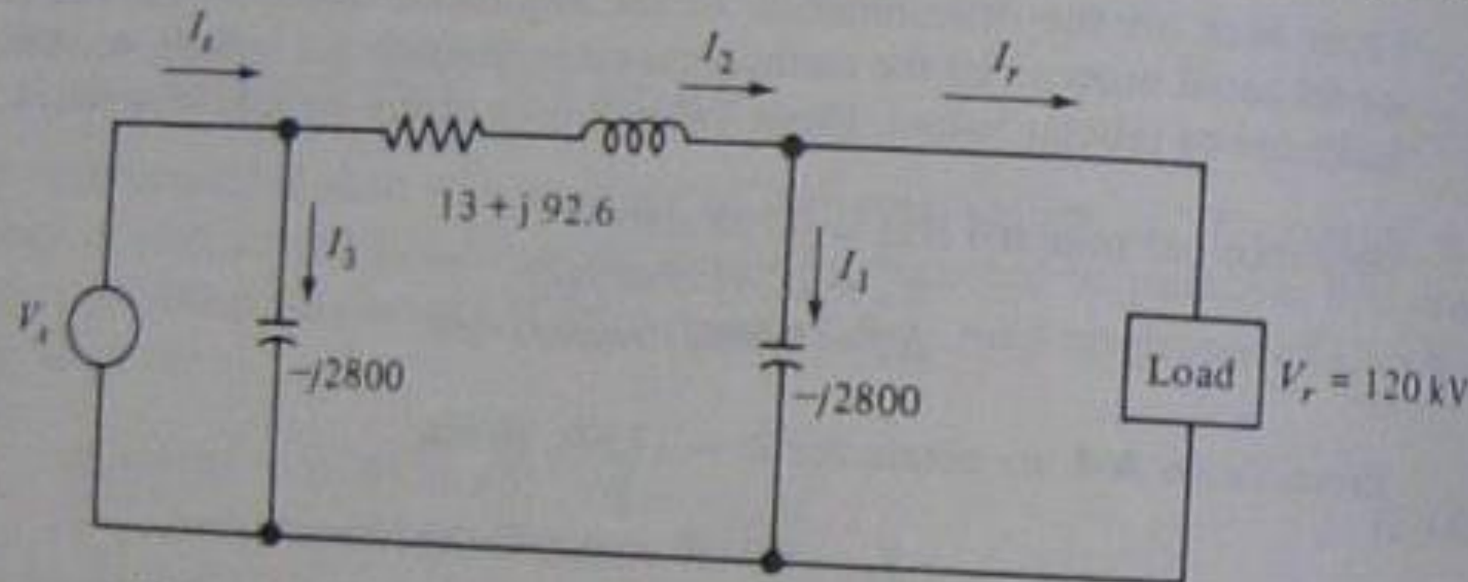


FIG. 5-16. Line of Example 5-3 carrying load. Single-phase equivalent model.

Considering the single-phase equivalent solution,

$$\bar{V}_r = 120{,}000 \underline{/0^\circ} \text{ V}$$

$$I_r = \frac{P}{V \cos\phi} = \frac{12{,}000{,}000}{120{,}000 \times 1} = 100 \text{ A}$$

$$\cos\phi \quad 120{,}000 \times 1 = 100 \text{ A}$$

$$\bar{I}_r = 100 \angle 0^\circ \text{ A}$$

$$\bar{I}_1 = \frac{\bar{V}_r}{-jX_{C1}} = \frac{120{,}000 \angle 0^\circ}{-j2800} = j42.9 \text{ A}$$

$$\bar{I}_s = \bar{I}_r + \bar{I}_1 = 100 + j42.9 = 109 \angle 23.2^\circ \text{ A}$$

$$\bar{V}_s = \bar{V}_r + \bar{I}_s Z$$

$$= 120{,}000 + (100 + j42.9)(13 + j92.6)$$

$$= 120{,}000 - 2670 + j9820$$

$$= 117{,}300 + j9820 = 117{,}700 \angle 4.8^\circ \text{ V}$$

$$\bar{I}_3 = \frac{\bar{V}_s}{-jX_{c3}} = \frac{117{,}300 + j9820}{-j2800} = -3.51 + j41.9 \text{ A}$$

$$\bar{I}_s = \bar{I}_2 + \bar{I}_3$$

$$= 100 + j42.9 - 3.51 + j41.9 = 96.5 + j84.8$$

$$= 128.5 \underline{/41.3^\circ} \text{ A}$$

$$\cos \phi_s = \cos(41.3^\circ - 4.8^\circ) = \cos 36.5^\circ = 0.804$$

$$P_s = V_s I_s \cos \phi_s = 117{,}700 \times 128.5 \times 0.804$$

$$= 12{,}160 \text{ kW}$$

In the actual three-phase system (see Section 3-8),

$$I_r = \frac{100}{\sqrt{3}} = 57.7 \text{ A}$$

$$I_s = \frac{128.5}{\sqrt{3}} = 74.2 \text{ A}$$

EXAMPLE 6-1. Determine voltage condition on a system of the type shown in Fig. 6-7, assuming that

$V_s = 5000$ V

$P_s = 600$ kW 0.8 power-factor lag

$Z_1 = 4\,\underline{/70^\circ}\ \Omega$

$P_2 = 400$ kW 0.707 power-factor lag

$Z_2 = 2.5\,\underline{/60^\circ}\ \Omega$

Solution.

a. At the source,

$$I_1 = \frac{P_s}{V_s \cos \varphi_s} = \frac{600{,}000}{5000 \times 0.8} = 150 \text{ A}$$

Considering V_s as reference,

$$\bar{V}_s = 5000\underline{/0^\circ}\text{ V}$$

$$I_1 = 150\underline{/-36.9^\circ}\text{ A}$$

$$I_1Z_1 = 150\underline{/-36.9^\circ} \times 4\underline{/70^\circ} = 600\underline{/33.1^\circ}\text{ V}$$

$$\bar{V}_A = \bar{V}_S - I_1Z_1 = 5000\underline{/0^\circ} - 600\underline{/33.1^\circ}$$

$$= 5000 + j0 - (503 + j328)$$

$$= 4497 - j328$$

$$= 4510\underline{/-4.2^\circ}\text{ V}$$

b. At A,

$$I_2 = \frac{P_2}{V_A \cos\varphi_2} = \frac{400{,}000}{4510 \times 0.707} = 125\text{ A}$$

Since $\bar{V}_A = 4510\underline{/-4.2^\circ}$ V,

$$I_2 = 125\underline{/-45^\circ - 4.2^\circ} = 125\underline{/-49.2^\circ}\text{ A}$$

$$I_2Z_2 = 125\underline{/-49.2^\circ} \times 2.5\underline{/60^\circ} = 313\underline{/10.8^\circ} = 307 + j58.7\text{ V}$$

$$\bar{V}_B = \bar{V}_A - I_2Z_2 = 4497 - j328 - (307 + j58.7)$$

$$= 4190 - j387$$

$$= 4210\underline{/-5.3^\circ}\text{ V}$$

6-3. FOUR-TERMINAL NETWORKS; *A, B, C, D* CONSTANTS

a. General Four-Terminal Network. The general four-terminal network is described with the aid of Fig. 6-8. This network is described by two source-terminals between which there is a voltage V_s and through which a current I_s flows, as shown in the diagram. There are also

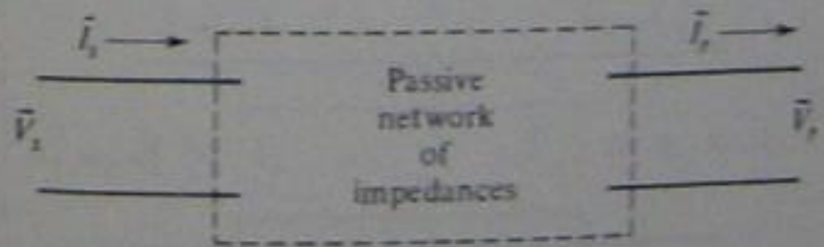


FIG. 6-8. The general 4-terminal network consisting of passive impedances connected in any fashion.

$$\bar{V}_s = A\bar{V}_r + B\bar{I}_r$$

$$\bar{I}_s = C\bar{V}_r + D\bar{I}_r$$

$$AD - BC = 1$$

b. Series Impedance. Our study of the basic power circuit containing a simple series impedance (Fig. 6-9) is, in fact, an analysis of one of the elementary forms of the four-terminal network. For the network in

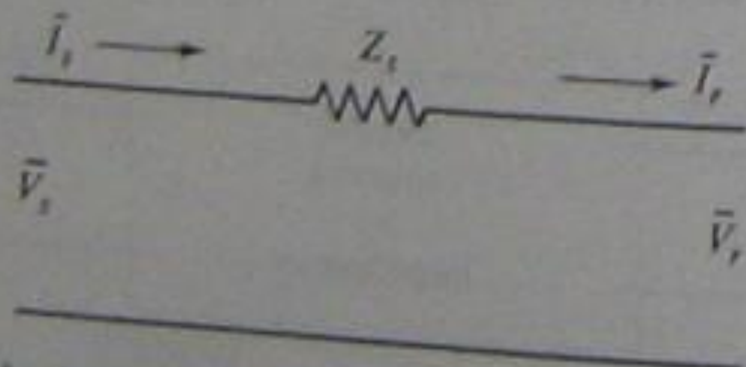


FIG. 6-9. A 4-terminal network consisting of a single series impedance.

Fig. 6-9 we may write expressions for $\bar{V}_s$ and $\bar{I}_s$ in terms of $\bar{V}_r$ and $\bar{I}_r$ as follows:

$$\bar{V}_s = \bar{V}_r + Z_s \bar{I}_r$$

$$\bar{I}_s = 0\bar{V}_r + \bar{I}_r$$

A comparison of these two equations with Eqs. (6-2) and (6-3) permits us to write the A, B, C, and D constants as follows:

$$A = 1.0 \qquad B = Z_s \qquad C = 0 \qquad D = 1.0 \tag{6-5}$$

c. **Shunt Admittance.** Another simple four-terminal network consists of a single shunt admittance, Y_p, connected as shown in Fig. 6-10.

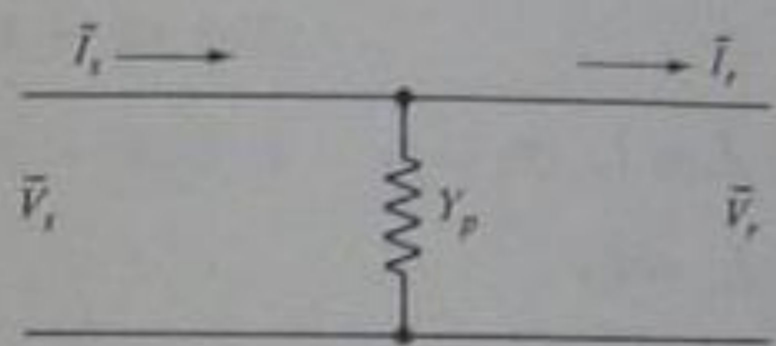


FIG. 6-10. A 4-terminal network consisting of a single shunt admittance.

For this network we may write expressions for $\bar{V}_s$ and $\bar{I}_s$ in terms of $\bar{V}_r$ and $\bar{I}_r$ as follows:

$$\bar{V}_s = \bar{V}_r + 0\bar{I}_r$$

$$\bar{I}_s = Y_p\bar{V}_r + \bar{I}_r$$

Again comparing these equations with Eqs. (6-2) and (6-3) we may declare values of A, B, C, and D as follows:

$$A = 1.0 \qquad B = 0 \qquad C = Y_p, \qquad D = 1.0 \tag{6-6}$$

d. **Two Four-Terminal Networks in Tandem.** Two four-terminal networks may be connected in tandem as shown in Fig. 6-11, 1 has the constant A_1, B_1, C_1, and D_1, while network 2 has the the constant A_2, B_2, C_2, and D_2. The two in combination form a system that has input $\bar{V}_s$ and $\bar{I}_s$ and output $\bar{V}_r$ and $\bar{I}_r$. Considering only network 2 we may write

$$\bar{V}_{s2} = A_2\bar{V}_{r2} + B_2\bar{I}_{r2} = A_2\bar{V}_r + B_2\bar{I}_r$$

$$\bar{I}_{s2} = C_2\bar{V}_{r2} + D_2\bar{I}_{r2} = C_2\bar{V}_r + D_2\bar{I}_r$$

Considering only network 1 we may write

$$\bar{V}_{s1} = A_1\bar{V}_{r1} + B_1\bar{I}_{r1}$$

$$\bar{I}_{s1} = C_1\bar{V}_{r1} + D_1\bar{I}_{r1}$$

Noting that

$$\bar{V}_s = \bar{V}_{s1} \qquad \bar{I}_s = \bar{I}_{s1}$$

$$\bar{V}_{r1} = \bar{V}_{s2} \qquad \bar{I}_{r1} = \bar{I}_{s2}$$

$$\bar{V}_{r2} = \bar{V}_r \qquad \bar{I}_{r2} = \bar{I}_r$$

we may write that

$$\bar{V}_s = A_1(A_2\bar{V}_r + B_2\bar{I}_r) + B_1(C_2\bar{V}_r + D_2\bar{I}_r)$$

$$\bar{I}_s = C_1(A_2\bar{V}_r + B_2\bar{I}_r) + D_1(C_2\bar{V}_r + D_2\bar{I}_r)$$

Collecting terms necessary to put the expressions for $\bar{V}_s$ and $\bar{I}_s$ in standard form we have

$$\bar{V}_s = (A_1A_2 + B_1C_2)\bar{V}_r + (A_1B_2 + B_1D_2)\bar{I}_r \tag{6-7}$$

$$\bar{I}_s = (C_1A_2 + D_1C_2)\bar{V}_r + (C_1B_2 + D_1D_2)\bar{I}_r \tag{6-8}$$

these equations in turn may be rewritten as

$$\bar{V}_s = A_0\bar{V}_r + B_0\bar{I}_r$$

EXAMPLE 6-2. Determine the equivalent *ABCD* constants of network 1 connected in tandem with network 2 as indicated in Fig. 6-12.

Solution.

a. In network 1, by Eq. (6-5),

$$A_1 = 1.0 \qquad B_1 = 20\underline{/30^\circ}\ \Omega \qquad C_1 = 0\ \mho \qquad D_1 = 1.0$$

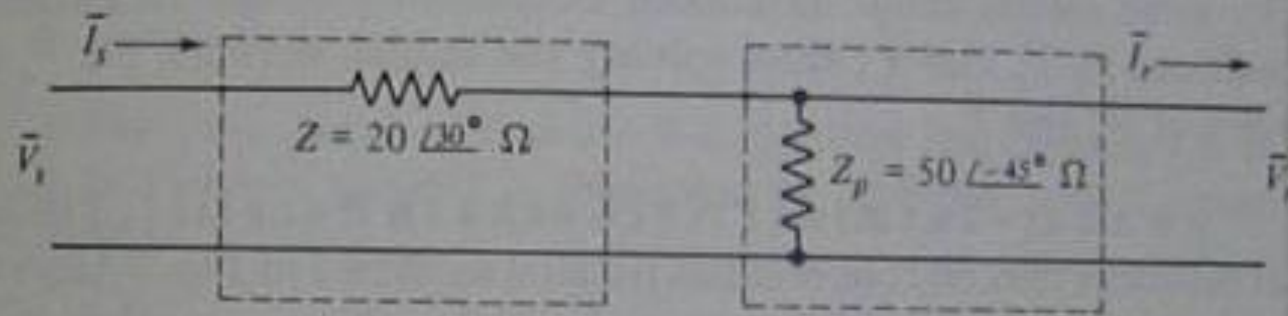


FIG. 6-12. Two networks in tandem, Example 6-2.

b. In network 2,

$$Y_p = \frac{1}{Z_p} = \frac{1}{50\underline{/-45^\circ}} = 0.02\underline{/45^\circ}\ \text{mho}$$

By Eq. (6-6),

By Eq. (6-10),

$$B_{eq} = A_1 B_2 + B_1 D_2$$
$$= 1.0\angle 0^\circ \times 0 + 20\angle 30^\circ \times 1.0\angle 0^\circ$$
$$= 20\angle 30^\circ \ \Omega$$

By Eq. (6-11),

$$C_{eq} = C_1 A_2 + D_1 C_2$$
$$= 0 \times 1.0 + 1.0 \times 0.02\angle 45^\circ$$
$$= 0.02\angle 45^\circ \ \mho$$

By Eq. (6-12),

$$D_{eq} = C_1 B_2 + D_1 D_2$$
$$= 0 \times 0 + 1.0 \times 1.0$$
$$= 1.0 \ \angle 0^\circ$$

TRANSMISSION LINE CONSTRUCTION

Transmission involves moving large quantities of electrical energy over long distances between generating stations and load centres. The transmission system consists of 500kV and 330kV overhead transmission lines of steel tower construction. The sub-transmission system consists of 132kV and 66kV overhead lines on steel towers and wood poles and also underground cables.

Route Selection for Transmission Lines

The easement space required for overhead transmission lines means that the route taken by a line is an environmentally sensitive issue.

Ideally, the transmission line should take the shortest route to reduce its capital and installation cost.

However, the selection of the route of a transmission line, will depend on a number of important considerations:

a) shape of the terrain, affecting cost of construction,
b) acquisition of easement land,
c) proximity to housing,
d) ease of maintenance and access to easement.

Components of Transmission Lines

Conductor Support Structures

Support structures are required to keep the conductors at a safe height above the ground and also to keep them apart.

Refer to FIG 1 which shows various arrangements of support structures.

arrangements of support structure